USING THE PBO LAB™ OPTIMIZATION AND TRANSPORT MODULES TO GAIN AN IMPROVED UNDERSTANDING OF THE LLUMC PROTON THERAPY BEAMLINES

G. H. Gillespie[a], O. V. Voronkova[a], G. B. Coutrakon[b], J. A. Hubbard[b], and E. Sanders[b]
[a]G. H. Gillespie Associates, Inc., P. O. Box 2961, Del Mar, CA 92014, USA
[b]Loma Linda University Medical Center., 11234 Anderson Street, Loma Linda, CA 92354, USA

Abstract

The Particle Beam Optics Laboratory (PBO Lab) has an advanced Optimization Module that works in concert with beam optics codes (also modules in PBO Lab) to solve optimization and fitting problems that are difficult or impossible to address with optics code alone. The PBO Lab Optimization Module has been used in conjunction with the TRANSPORT Module to study the beamlines of the proton therapy center at the Loma Linda University Medical Center (LLUMC). The primary goal of the study was to establish a fast, efficient and reliable procedure for determining the parameters of the beam extracted from the synchrotron accelerator that best fit the extensive wire scanner profile data used to monitor the LLUMC proton therapy beamlines. This paper summarizes how the PBO Lab Optimization Module is applied to this problem and presents selected results from the LLUMC proton therapy beamline study.

INTRODUCTION

The PBO Lab software is a suite of accelerator related application modules developed to support beamline design [1], personnel training [2], and accelerator operations [3]. The PBO Lab Basic Package provides a common graphic interface for constructing and editing sophisticated iconic objected-based computer models of accelerators and beamlines. The ease-of-use provided by the graphic interface, and the broad range of applications that may be addressed, has made the software a popular package for more than eighty laboratories in over twenty countries [4].

The design and optimization of beamlines is one of the most important applications of PBO Lab. Several Application Modules are available for different types of accelerators and beamlines. Modules that incorporate TRANSPORT [5], TURTLE [6], DECAY-TURTLE [6], MARYLIE [7] or TRACE 3-D [8] are available. These Modules provide users with tools to carry out extensive particle optics studies without any knowledge of the I/O format or syntax for individual codes – the PBO Lab software automatically handles the setup of all inputs, the execution of the codes, and the visualization of results.

A sophisticated Optimization Module has been developed to extend the capabilities of PBO Lab to address beamline optimization problems that are more complex than can be handled by the optics codes of the individual Application Modules. GUI components have been developed and other software elements implemented within the context of the PBO Lab beamline object model for the NPSOL [9] and MINOS [10] programs developed in the Operations Research Department at Stanford University. NPSOL and MINOS are both constrained nonlinear optimization programs, but the two packages use different approaches and are applied to different types of optimization problems. Both programs are included in the Optimization Module in order to provide users with alternate approaches to solving a particular problem.

Any input parameter to a PBO Lab optics code can be declared as an Optimizer Variable. Output parameters from the optics codes can be defined as Stored Parameters. The Stored Parameters and Optimizer Variables may then be used to formulate the nonlinear constraints and/or merit function for NPSOL or MINOS. More than one optics code may be included in a problem. Hierarchical problems can be formulated using the fitting/optimization capabilities of the optics codes at each step inside of a larger optimization problem. This paper summarizes the application of the Optimization Module to solving an important initial value problem encountered at the LLUMC proton therapy center. The MINOS optimization code was used in conjunction with the TRANSPORT optics code for the problem.

EXAMPLE APPLICATION

The PBO Lab Optimization Module has been used in conjunction with the TRANSPORT optics Application Module to examine previously published fits to beam size data for selected LLUMC beamlines [11]. Table 1 of reference [11] gives the beam parameters at the extraction septum for three beam energies (70, 150, 250 MeV) determined by an iterative trial and error procedure that compares TRANSPORT calculations for beam sizes to wire scanner beam size measurements. Figures 5 and 6 of the same reference display plots that compare the TRANSPORT results for the Table 1 beam data to the wire scanner data, for 250 MeV beams directed into the gantry 1 (G1) and gantry 2 (G2) treatment rooms. In this section we briefly described the setup of the PBO Lab Optimization Module, and report on the extracted beam parameters determined using the MINOS program, for the beamline into G2 at 250 MeV. We then compare the results obtained to those reported in [11].

Setup of the Optimization Problem

The basic user procedure for setting up a problem with the PBO Lab Optimization Module has been summarized previously and some applications illustrated [12]. The initial setup of a PBO Lab optimization problem involves three primary steps. The first step is to select the model parameters to be varied by the Optimization Module codes (NPSOL and/or MINOS). In the LLUMC example considered here, the Optimizer Variables are the initial beam parameters at the start of the transfer lines, i.e. the parameters for the beam at the extraction septum. The second step is to specify which TRANSPORT outputs are to be used in the problem. In this case, the x and y beam sizes at the locations of the wire scanners were assigned as TRANSPORT Stored Parameters, making them available to the Optimization Module. The third step is to use the Optimizer Variables and Stored Parameters to construct an Objective Function to be minimized, as well as any linear and nonlinear constraints to be satisfied simultaneously. For the problem considered here a simple mean square minimization was utilized. The Objective Function was taken to be the sum of the squares of the difference between the TRANSPORT computed beam sizes and those measured by the wire scanners. PBO Lab windows utilized to complete the 3 steps are illustrated in Figure 1.

If we denote the Objective Function by $\Sigma|\Delta i|^2$, then the standard deviation σ for a fit to the wire scanner data is:

$$\sigma = [(1/N)\, \Sigma|\Delta i|^2\,]^{1/2} \quad , \qquad (1)$$

where N is the number of data points included in the summation. For the problem considered here N=24, corresponding to x and y beam sizes for 12 wire scanners.

The standard deviation (1) provides an overall measure of the quality of a given fit. The error in each beam size measurement has been estimated at 1 mm [13]. A standard deviation of the order of 0.2 mm would thus constitute a good fit: the standard deviation being about the same as the estimated rms uncertainty of the measured data.

Optimizer Results for Example Problem

The MINOS program in the PBO Lab Optimization Module was used to look for a minimum in the Objective Function, which corresponds to a minimum in the standard deviation σ via equation (1). Additional linear and nonlinear constraints can be added to any problem formulated with the Optimization Module, and the use of nonlinear constraints can be especially helpful for solving certain types of problems [12]. However, in the example considered is this section the only additional constraints imposed were simple (constant) bounds on the Optimizer Variables, which are discussed further below.

Table 1 summarizes four sets of initial values for the Optimizer Variables, labeled ID=1-4, as well as the upper and lower bounds imposed on the Optimizer Variables, labeled ID=U and L. In addition, the starting values of the standard deviations (1), corresponding to the use of those beams at the extraction septum, are given in Table 1.

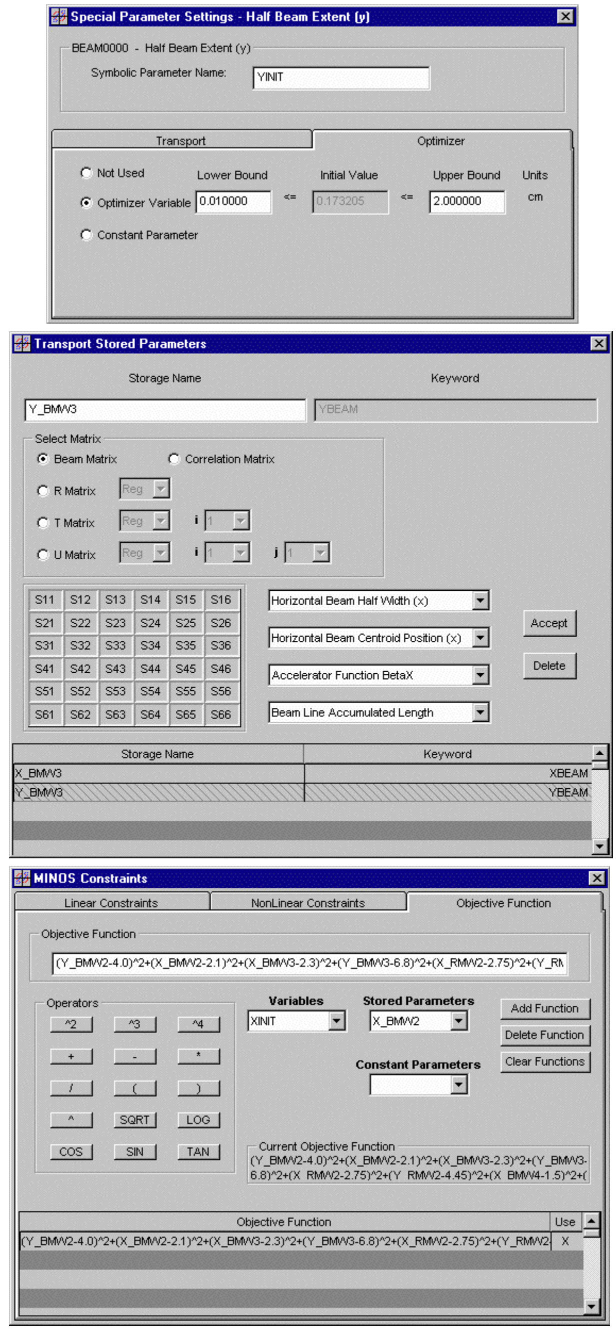

Figure 1: Example windows used to set up Optimizer Variables (top), TRANSPORT Stored Parameters (middle), and Objective Function (bottom).

The case ID=1 corresponds to the fit reported in [11]. A single MINOS optimizer run found an improved solution. This solution is shown in Table 2 as ID=O. Note that the standard deviation for the ID=1 beam is only about 1/3 larger than that for the optimal solution (ID=0), and both are close to that anticipated for a “good” fit. This confirms that the Ref. [11] results were close to optimum.

MINOS found the same optimal solution for all of the initial condition beams summarized in Table 1, including those corresponding to the upper and lower limits of the Optimizer Variables. The results indicate that the solution found corresponded to a "global" and not a "local" minimum of the Objective Function, when the solution is constrained by the Optimizer Variable bounds.

Table 1: Different initial conditions used as the starting point for the Optimization Module to find the best beam parameters at the extraction septum of the LLUMC synchrotron to fit the wire scanner data for the beamline into gantry G2 at 250 MeV. The case ID=1 is the fit reported in Reference [11] obtained without the PBO Lab Optimization Module. The other cases correspond to beams that are "far" from the solution, as indicated by the large (initial) σ values. The cases label ID=U and ID=L give the upper and lower bounds imposed on the Optimizer Variables.

ID	XINIT (mm)	XPINIT (mr)	r12INIT	YINIT (mm)	YPINIT (mr)	r34INIT	σ (mm)
1	3.240	0.1906	- 0.8742	1.732	0.8832	- 0.1961	0.4746
2	10.00	0.5000	0.0000	10.00	0.5000	0.0000	14.038
3	5.000	1.0000	0.0000	5.000	1.0000	0.0000	9.4747
4	0.500	0.5000	- 0.5000	0.500	0.5000	0.5000	3.2886
U	20.00	1.0000	0.9999	20.00	1.0000	0.9999	34.618
L	0.100	0.0100	- 0.9999	0.100	0.0100	- 0.9999	2.5444

Table 2: Fits obtained for the beam parameters at the extraction septum of the LLUMC synchrotron using the wire scanner data for the beamline into gantry G2 at 250 MeV. The identifier case ID=1 is the fit reported in Reference [11] obtained without the PBO Lab Optimization Module. The ID=O case are the results obtained in this work using the Optimization Module. The comparison shows that the results in Reference [11] are quite close to an optimum solution.

ID	XINIT (mm)	XPINIT (mr)	r12INIT	YINIT (mm)	YPINIT (mr)	r34INIT	σ (mm)
1	3.240	0.1906	- 0.8742	1.732	0.8832	- 0.1961	0.4746
O	3.045	0.1727	- 0.8654	1.590	0.9705	- 0.3296	0.3548

SENSITIVITY STUDIES

Several sensitivity studies were undertaken in order to further explore the best possible description of the beam at the extraction septum. These were easy to implement using the PBO Lab Optimization Module, but would have been quite tedious (if not infeasible) without it. The sensitivity studies confirmed that the most important beam properties were included in the Optimizer Variables.

SUMMARY

The optimization code MINOS, when used in conjunction with TRANSPORT via the PBO Lab environment, has proven to be a useful tool for obtaining fast, accurate and reliable sets of initial beam parameters for the LLUMC proton therapy transfer lines [13]. Previously reported fits [11] to wire scan beam profile data have been improved upon, and sensitivity studies confirm that the important beam correlations have been included.

REFERENCES

[1] G. H. Gillespie and B. W. Hill, Nucl. Instr. Meth. B 139, 476-480 (1998).

[2] N. A. Brown, G. H. Gillespie B. W. Hill, M. C. Lampel, H. Martono and J. M. Moore, Proc. 1998 Euro. Particle Accel. Conf., 1183-1185 (1998).

[3] G. H. Gillespie, B. W. Hill, H. Martono and J. M. Moore, Nucl. Instr. Meth. B 161/3, 1168-1173 (2000).

[4] PBO Lab is available from AccelSoft Inc., San Diego, California, www.ghga.com/accelsoft.

[5] D. C. Carey, K. L. Brown and F. Rothacker, "Third-Order TRANSPORT with MAD Input - A Computer Program for Designing Charged Particle Beam Transport Systems," SLAC-R-530, 316 pp (1998).

[6] D. C. Carey, "TURTLE with MAD Input (Trace Unlimited Rays Through Lumped Elements), a Computer Program for Simulating Charged Particle Beam Transport Systems, and DECAY-TURTLE Including Decay Calculations," Fermilab-Pub-99/232, 196 pp (1999).

[7] A. J. Dragt, et al, "MARYLIE 3.0 User's Manual, A Program for Charged Particle Beam Transport Based on Lie Algebraic Methods," 901 pp (2003).

[8] K. Crandall and D. Rusthoi, "TRACE 3-D Documentation," LA-UR-97-886, 106 pp (1997).

[9] P. E. Gill, W. Murray, M. A. Saunders, M. H. Wright, "User's Guide for NPSOL 5.0: A Fortran Package for Nonlinear Programming," Stanford Univ. Dept. Op. Research, Rpt. SOL 86-2R, 44 pp (1998).

[10] B. A. Murtagh and M. A. Saunders, "MINOS 5.5 User's Guide," Stanford Univ. Dept. Op. Research, Rpt. SOL 83-20R, 145 pp (1998).

[11] G. Courtrakon, J. Hubbard, P. Koss, E. Sanders, M. Panchal, Proc. AIP Conf. Proc. 680, 1116-20 (2002).

[12] G. H. Gillespie B. W. Hill and J. M. Moore, Proc. 2000 Euro. Particle Accel. Conf., 1375-1377 (2000).

[13] G. Courtrakon, J. Hubbard, E. Sanders and G. H. Gillespie, to be presented at the 18th Inter. Conf. on the App. of Accelerators in Res. and Industry (2004).