Some New Approaches to Solving Constrained Transfer Line Matching Problems

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SOME NEW APPROACHES TO SOLVING CONSTRAINED TRANSFER LINE MATCHING PROBLEMS

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Abstract

A common type of matching problem involves finding the strengths for four (4) quadrupoles in a transfer line, that will transport a particular beam at the entrance, to produce a beam at the exit of the line with a specified set of horizontal and vertical Twiss parameters. A number of optics programs may be used to find a solution to this type of problem, but the quadrupole strengths obtained are not always satisfactory or optimal with regard to other requirements. The non-uniqueness of the solutions (different solutions have different phase advances) offers the possibility that some of these other requirements could be used to differentiate between solutions. The constrained, nonlinear, optimization program NPSOL has been integrated into a software package that can use the outputs of various optics codes to formulate nonlinear constraints and objective (merit) functions. The package has been used to look for different solutions for the SLAC transfer lines between linac sectors 1 and 2 for three configurations involving (a) the electron damping ring, (b) the damping ring by-pass, and (c) the positron damping ring. The software is briefly described and a summary of selected results obtained to date is presented.

1 INTRODUCTION

The Particle Beam Optics Laboratory (PBO Lab) is a set of accelerator related software applications designed to provide advanced tools for beamline design [1], personnel training [2], and accelerator operations [3]. The PBO Lab provides an easy-to-use intuitive interface for graphically constructing, manipulating and editing computer models of accelerators and beamlines. Interactive tutorials, training aids and expert system features provide an enhanced environment that significantly improves the scientific productivity of both novice and advanced users. Several Application Modules incorporating TRANSPORT [4], TURTLE [5], DECAY-TURTLE [5], MARYLIE [6] or TRACE 3-D [7] are available that allow users to carry out extensive particle optics studies without knowledge of the I/O format or syntax for the individual codes – the PBO Lab automatically handles the setup of all inputs, the execution of the codes, and the visualization of results.

A new Optimization Module [8] has been developed to extend the capabilities of PBO Lab to address beamline optimization problems that are more complex than can be addressed by the individual Application Module optics codes [4-7]. The Optimization Module includes both the NPSOL [9] and MINOS [10] nonlinear, constrained, optimization programs. The integrated package has been used to look for different solutions for the SLAC transfer lines between linac sectors 1 and 2 for the three configurations described in the abstract. This paper summarizes selected results for an example problem and for the SLAC transfer line problems.

2 OPTIMIZATION MODULE

A summary of key features of the Optimization Module has been presented elsewhere [8]. The development followed the basic guidelines used in the development of all applications for the PBO Lab software [1-3]. Optimization problems are set up and executed graphically, using intuitive graphic user interface (GUI) components. No user-written FORTRAN subroutines are required for either NPSOL or MINOS: the nonlinear constraints and objective (merit) functions are constructed using the simple GUI tools of the Optimization Module.

Any input parameter to an optics code can be declared as an Optimization Module variable. Output parameters from the optics codes can be defined as store parameters, and the store parameters can then be used (in addition to the variables) to formulate nonlinear constraints and merit functions. Multiple optics codes may be included in a problem, and hierarchical optimization/fitting problems can also be formulated.

3 OPTIMIZATION PROBLEMS

3.1 An Example Transfer Line Problem

An example transfer line problem has been used to study different choices for nonlinear constraints and merit functions [8]. The problem is a variation of the linac intertank matching section named "Example B" in reference [7] with the radiofrequency elements removed so that the line has only magnetic elements and drifts. This transfer line is referred to as "Example B – Modified". Figure 2 of reference [8] shows a PBO Lab iconic representation of the transfer line, and Table 1 of that reference gives data (the four quadrupole strengths) for previously known solutions to the matching requirements.

The goal of this type of matching problem is to find values for the four (4) quadrupole strengths that will transport a beam with a given set of initial horizontal and vertical Twiss parameters (β_{xi}, α_{xi}, β_{yi}, α_{yi}) through the transfer line and produce a beam with a specified set of final output Twiss parameters (β_{xf}, α_{xf}, β_{yf}, α_{yf}). While there are 4 constraints to satisfy (the final Twiss

parameters) and 4 unknowns to find (the quad strengths), the solutions are not unique. The transverse phase advances (ψ_x and ψ_y) are different for each solution. It is difficult using traditional optics codes alone to determine if a solution exists that also meets other criteria such as a minimum quadrupole power requirement.

The output Twiss parameter requirements impose four nonlinear constraints on the Example B – Modified optimization problem. Four different objective functions (labeled A,B,C,D) were studied previously [8], both with (+) and without (-) an additional (fifth) nonlinear constraint on the sum of the magnitudes of the quadrupole gradients (Σ|Gradient i|). Comparison of the solutions found using the PBO Lab NPSOL Optimization Module, TRANSPORT alone, and TRACE 3-D alone, for several different initial conditions indicated that only the NPSOL optimization formulations using the additional (Σ|Gradient i|) constraint (labeled A+,B+,C+,D) always found the lowest excitation solutions (labeled ID #1).

Table 1 gives additional solutions to the Example B – Modified problem that were found starting from initial quadrupole gradients that are "far" from the desired solution, including one set of initial gradients with opposite polarity to that of the desired solution. Similar to the previous results [8] only the NPSOL formulations with the additional nonlinear constraint on the field gradients consistently found the solution labeled ID #1.

Table 1: Additional solutions found by NPSOL, TRANSPORT (TRN) and TRACE 3-D (T3D) for the "Example B – Modified" problem with different initial quadrupole gradients (G). Results for eight different NPSOL problem formulations (see Reference [8]) are given. T3D and TRN results give the percentage of times each solution was found.

	Initial G:	±6.5	T/m		-/+26.5	T/m		±46.5	T/m
ID	NPSOL	TRN	T3D	NPSOL	TRN	T3D	NPSOL	TRN	T3D
1	A+,B+,C+,D+	0%	- %	A±,B±,C+,D±	0%	- %	A±,B+,C+,D±	0%	26%
2	B-, C-	0%	- %		0%	- %	C-	100%	12%
3	A-, D-	100%	- %		0%	- %	B-	0%	34%
4		0%	- %	C-	0%	- %		0%	38%

3.2 SLAC Transfer Line Matching Problem

This problem involves finding simultaneous optics solutions for matching the electron (e-) and positron (e+) beams exiting the North Damping Ring (NDR) and South Damping Ring (SDR) respectively into sector 2 of the SLAC linac, together with the additional requirement that the electron beam must also remain matched when the NDR is by-passed.
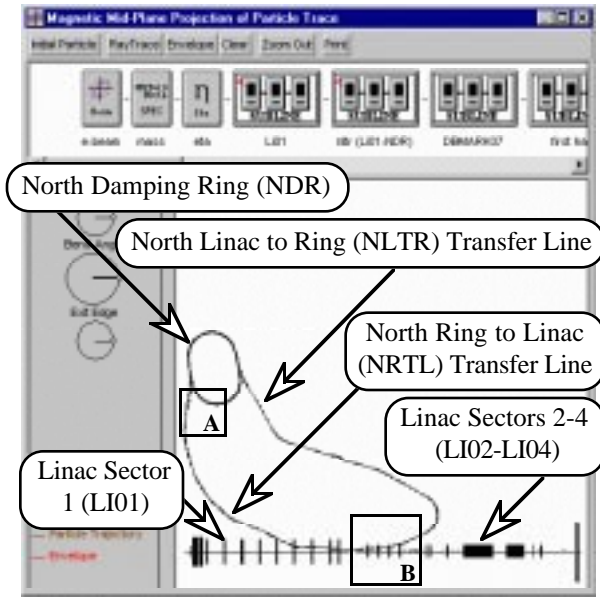

Figure 1. Layout of the SLAC linac sectors, the north (electron) damping ring, and the associated transfer lines.

The layout of the SLAC linac, north damping ring, and associated transfer lines are illustrated in Figures 1 and 2. The SLAC problem can be divided into three problems, each of which is similar to the Example B – Modified transfer line problem described in Section 3.1. Three effective transfer lines, between SLAC linac sectors 1 and 2, correspond to the three configurations involving (a) the electron damping ring, (b) the damping ring by-pass, and (c) the positron damping ring. Figures 1 and 2 show the locations A and B of the four matching quadrupoles for configurations (a) and (b). Region C (not shown) for the south ring to linac (SRTL) transfer line contains four matching quadrupoles for configuration (c).

Twiss parameter constraints were defined for both (e- and e+) beams at the center of the solenoid that is shown in zoom region **B** of Figure 2. The requirements are for a round beam, with waists in both transverse phase planes:

$$\alpha_{xf} = \alpha_{yf} = 0.0,$$
and $$\beta_{xf} = \beta_{yf} = 3.172 \text{ meter/radian.} \quad (1)$$

Table 2 summarizes one solution found for the SLAC transfer lines. The constraints (1) on Twiss parameters were utilized, but no additional constraint on the quadrupole gradients analogous to Σ|Gradient i|$<4G_{max}$ was used. The merit function was the sum of the mismatch factors [7] for the two transverse phase planes, so the optimization problem formulation corresponded to that labeled C- for Example B – Modified [8]. The solution given in Table 2 had not been found previously using only the TRANSPORT (or MAD) fitting capabilities.

Further application of the approach described in Reference [8] should identify additional solutions, including the determination of the lowest excitation solution.
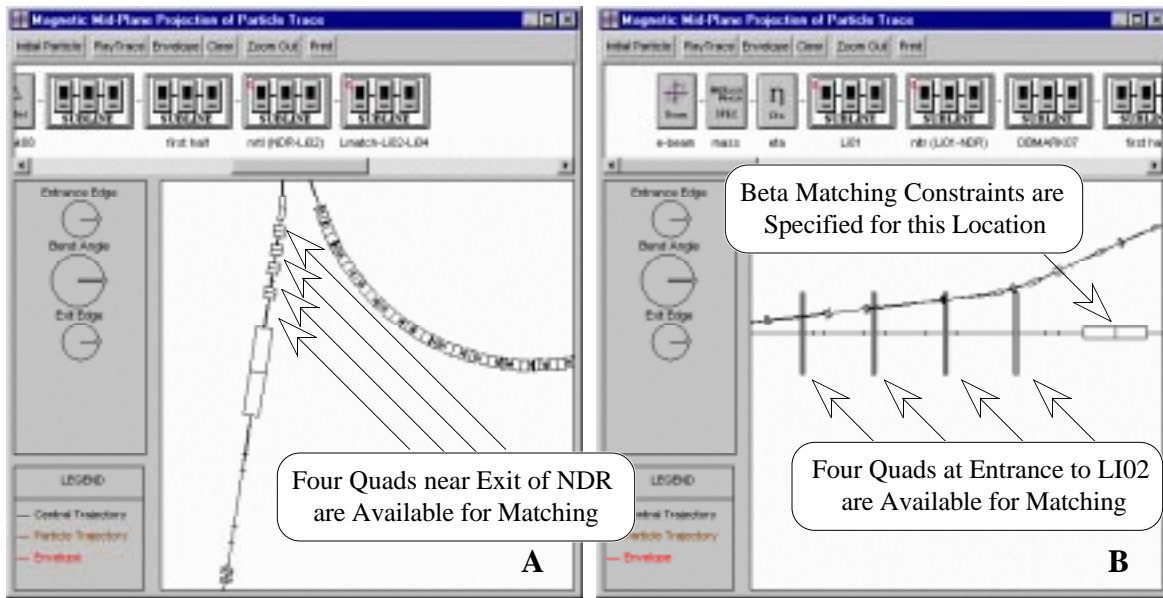

Figure 2: Zooms of Figure 1 showing the matching quadrupole regions of (A) the north ring-to-linac (NRTL) transfer line and (B) the entrance to linac sector two (LI02).

Table 2: Quadrupole strengths for one solution to the simultaneous transfer line matching problem obtained by the PBO Lab Optimization Module using NPSOL.

SLAC Sector	Region (Figs. 1,2)	Quad Name (TRN)	Gradient (kG/cm)
NRTL	A	Q420094T	- 4.75848
NRTL	A	Q420104T	4.20456
NRTL	A	Q420114T	1.80926
NRTL	A	Q420124T	- 6.28709
LI02	B	Q020114T	- 4.75848
LI02	B	Q020121T	1.82822
LI02	B	Q020127T	1.62334
LI02	B	Q020134T	0.51871
SRTL	C	Q340095T	- 4.52881
SRTL	C	Q340105T	2.77519
SRTL	C	Q340115T	4.18409
SRTL	C	Q340125T	- 8.03107

SUMMARY

A C-language version of the nonlinear, constrained, optimization code NPSOL has been integrated into an Optimization Module for the PBO Lab software. Initial application of the PBO Lab Optimization Module to transfer line problems at SLAC have shown the ability of the package to find (new) solutions not previously found by standard optics codes.

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