MEASURING AND MATCHING TRANSPORT OPTICS AT JEFFERSON LAB

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Abstract

Well-controlled optical transport over long range is important for many types of nuclear and high energy physics experiments. It is essential in achieving the desired beam parameters, minimizing optical sensitivity, and ensuring acceptable helicity correlated orbit differences for parity-type experiments. A precise and rigorous program for evaluating optical matching errors, and a deterministic algorithm for obtaining global matching solutions thus holds considerable promise for both accelerator design and operation, although the latter has defied attempts so far due to its almost intractable complexity. For the CEBAF accelerator at Jefferson Lab, this difficulty is further exacerbated by the extreme matching condition necessary for a 5 pass recirculating linac, elements that can introduce considerable optical error, and loss of long-range difference orbit orthogonality due to these effects, all of which impose a very tight demand on the accuracy of the measured transfer matrix as input to the matching algorithm. Research in methods for both measuring and matching optical transport has led to recent successful demonstration of deterministic matching of the optical transport of CEBAF. The global nature of the matching algorithm allows efficient exploration of solutions not easily accessible by traditional methods and serves to signal configuration flaws in the machine.

INTRODUCTION

The CEBAF accelerator at Jefferson Lab is a 6 GeV, recirculating linac where CW electron beam is recirculated 5 times through 2 linacs before being delivered to 3 nuclear physics experiment targets. Complex longitudinal and transverse beam manipulations take place during this 6-kilometer journey. The need to maintain good transport optics at CEBAF is mandated by the following reasons: 1). containment of beam envelope and orbit fluctuation; 2). minimal optical sensitivity due to intermediate betatron blowup, even if corrected at the end; 3). control of phase space damping and betatron mismatch to levels acceptable to parity experiments in eliminating undesirable helicity-correlated beam coordinates on target; 4). manageable beam profile on target.

To meet the ever more stringent demands for matching transport optics at CEBAF, a program has been developed and tested online. It is in the process of being turned into a standard operational tool. In this paper we will discuss the challenges encountered, the detail of the methods developed, and experience from online application.

CHALLENGES

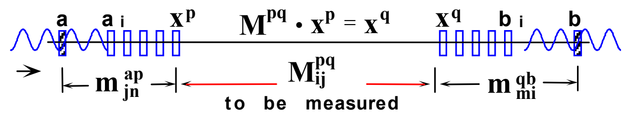

Figure 1: Concept of transfer matrix measurement.

1.1 Measuring Optical Transport

Figure 1 shows the concept of measuring transfer matrix across an unknown section of the beam line. Difference orbits are launched across a beam line section where optical model is known reliably at both end segments **p** and **q**, but not in between. The models of **p** and **q** are then used to interpret the transfer matrix **M** in between. This scheme has many advantages over similar methods relying on knowledge of kickers used to launch the difference orbits, and is capable of supporting rigorous analysis of errors in **M** [1]. The error covariance between elements of **M** obtained under this scheme is given in equation (1) for x-plane where indices i, j, k, m run from 1 to 2 for x & x'. The error in **M** depends on data parameters (red): the sample size **No**, the signal-to-noise ratio $\mathbf{S_B}$, a measure of the correlation among the difference orbits $\mathbf{T_d}$, and machine parameters (blue): numbers of BPM's $\mathbf{N_B}$, lattice-dependent form factors $\mathcal{M}$, and momentum ratio $\mathbf{P_p/P_q}$. To minimize measurement error, one needs high statistics, high signal-to-noise ratio, and minimal correlation among the difference orbits used. Unfortunately this correlation, no matter how carefully one prepares the difference orbits, tends to increase as the orbit covers progressively more distance and optical errors while $\mathbf{T_d}$ approaches 0 in extreme cases[1].

$$\left\langle \delta M^{pq}_{ij}\cdot\delta M^{pq}_{km}\right\rangle = 2\cdot\frac{1}{N_O}\cdot S_B^{jm}\cdot\frac{1}{T_{(d)}^{jm}}\cdot\left[\frac{1}{N_{Bp}}\cdot\mathcal{M}_b^{i}\cdot\mathcal{M}_b^{k}+\frac{1}{N_{B_q}}\cdot\mathcal{M}_a^{i}\cdot\mathcal{M}_a^{k}\cdot\left(\frac{P_p}{P_q}\right)\right],\quad i,j,k,m=1,2.$$

$$S_B^{jm}=\frac{\sigma_B^2}{\sigma_O^{pj}\cdot\sigma_O^{pm}},\qquad T_{(d)}^{jm}=\begin{cases}\left(1-R_p^2\right), & j=m\\ \left(1-R_p^{-2}\right), & j\neq m\end{cases},\qquad R_p^2=\frac{\left\langle x_1^p\cdot x_2^p\right\rangle^2}{\left\langle x_1^p\cdot x_1^p\right\rangle\cdot\left\langle x_2^p\cdot x_2^p\right\rangle}. \tag{1}$$

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[1] This reflects the fact that symplectic maps are not unitary.

1.2 Matching Optical Transport

The challenge for effective transport matching is that the method needs to work in a control room on beam lines possibly far from a well-matched state. Open-ended search for initial conditions good enough for local-minimum type of algorithms to find a decent solution is highly undesirable. In addition, one needs to know when matching system configuration is defective or matching goal itself is unattainable for the given system, such that refinement of the system or goal should be considered rather than more futile attempts. This is impossible via local-minimum algorithms.

THE PROGRAM USED AT CEBAF

1.3 Measuring Optical Transport

At CEBAF an existing difference orbit program (FOPT) has been upgraded to meet the challenges outlined above for high precision transfer matrix measurement. Main features include: 1). ability to launch difference orbits at any location in order to ensure orbit orthogonality; 2). automatic scaling of amplitude to allowed maximum; 3). ability to form phase space coverage as specified by user; 4). ability to generate high statistics data. In addition post-processing programs perform data screening, further orthogonalization of difference orbits, and symplectification of the measured transfer matrix. Interface to the energy feedback system is being planned, which will further reduce data error caused by dispersion leak.

The recirculating arcs, with their well-calibrated model, serve as the sections where difference orbit data is interpreted and used in turn to calculate the transfer matrix and degree of mismatch across the region between the arcs. This region includes the linac, the beam separation and recombination systems, and the path length control "doglegs", where most of the transverse and longitudinal beam manipulations take place and betatron matching is performed more as a routine during machine setup and tuning. Future plan includes sub-dividing this structure even further to reduce optical sensitivity caused by intermediate betatron blowup at the Arc-Linac interface.

Difference orbits generated by this program has also been propagated over the entire 5 passes to study various aspects of the global transport, most notably the damping of phases space and overall betatron matching. Due to its ability to support high precision analysis, the global transport picture thus derived is very reliable and serves as a useful basis for evaluating overall accelerator performance.

To quantify mismatch and assess effectiveness of the matching program, Courant Snyder (CS) parameters are used. For a given design optics and a difference orbit, it is given by equation (2) where Σ represents the design twiss matrix and **X** the difference orbit vector. This parameter can be calculated for the 2 sections on either end of the region of interest, one for each orbit. The mismatch is quantified as the maximal possible ratio between these 2 CS parameters for any orbit. An equivalent picture is visualized via design beam envelopes on both ends of the section of interest brought to a common point by the measured transfer matrix of this section. In the normalized phase space of one beam the other is an ellipse, whose semi-major axis has the length equal to the maximal CS ratio described above.

$$C = X^T \cdot \Sigma^{-1} \cdot X,$$
$$\Sigma = \begin{pmatrix} \beta_D & -\alpha_D \\ -\alpha_D & \gamma_D \end{pmatrix}, \ X = \begin{pmatrix} x \\ x' \end{pmatrix}. \quad \textbf{(2)}$$

1.4 Matching Optical Transport

In the spirit of the previous section, the problem of transport matching is cast in the form of twiss parameter matching with the aim of turning arbitrary incoming $\alpha_{x/y}$ and $\beta_{x/y}$ into desired outgoing $\alpha_{x/y}$ and $\beta_{x/y}$ using 4 thick quadrupole lenses. This is not exactly the same as restoring the design transfer matrix, for which 6 quadrupoles would be required, but ensures proper transport of the design beam and, for all practical purposes, proper containment of betatron blowup.

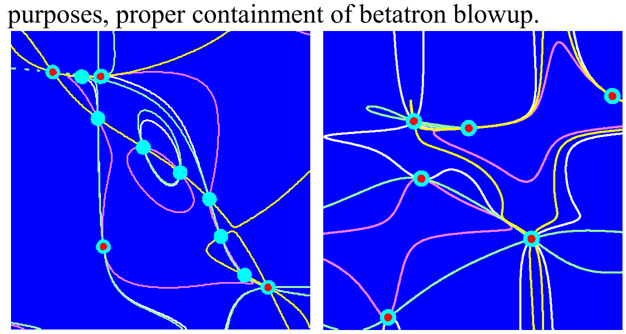

Figure 2: Real & spurious roots of the matching system.

The matching problem as posed processes considerable complexity. An algorithm capable of solving for global solutions of such systems has nonetheless been developed [2]. The advantage over local optimization algorithms is obvious: 1). single-path deterministic process requiring no open-ended tuning or "inspired human intervention"; 2). ability to explore solution space not possible with local methods; 3). elimination of need to "condition" the system before matching; 4). ability to reveal configuration or target problems when real solution is absent. Figure 2 shows the equivalent 2-dimensional solution space to the matching system in 2 examples. The lines represent zero contours of the quadruploe strengths satisfying partial matching conditions. Their intersections (cyan dots) represent real solutions., while red dots are spurious solutions arising from variable elimination. The system on the left has many solutions, while the one on the left has none due to unrealistic matching target. User has the option to choose among the global solutions the one with minimal quad strength, minimal quad change, or minimal intermediate blowup. A mechanism to allow partial matching is also available, where the mismatched beam ellipse in the normalized phase space of the design beam is allowed to take on reduced semi-major axis while keeping the same orientation, corresponding to a reduced CS mismatch value. This is conjectured to be the most adiabatic path for partial matching targets. Option of different matching quads can also be invoked to yield preferable alternative solutions.

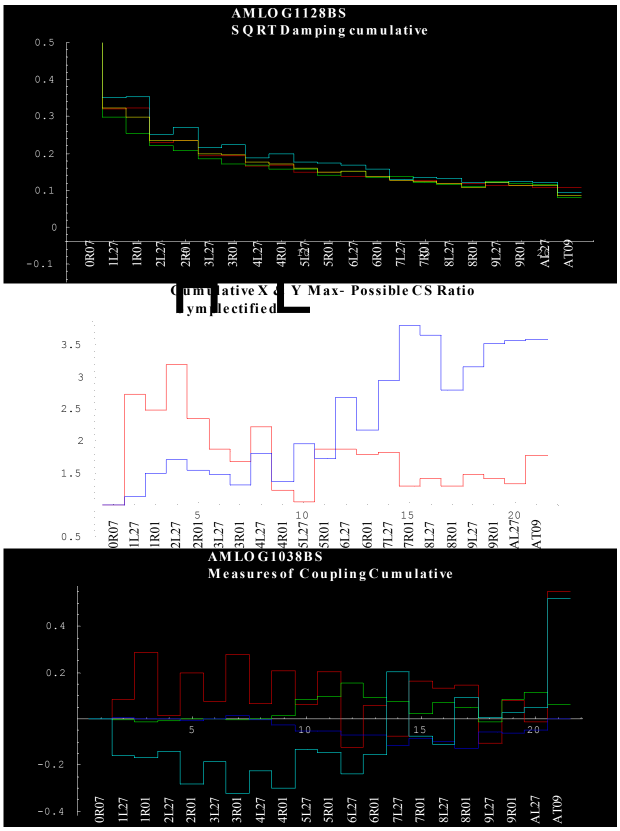

Figure 3 Transport parameters from 50 MeV to 5 GeV.
1) phase space area (sqrt), red: theory; yellow: measured.
2). CS parameter (squared), red: X; blue: Y.
3). 4 measures of coupling based on determinants of sub-matrices of the measured 4 by 4 transfer matrix.

OPERATIONAL EXPERIENCE

The transport measurement and matching programs have been demonstrated to work successfully at CEBAF. Figure 3 shows various transport properties over the entire 5 passes measured using difference orbits launched at 50 MeV and propagated to 5 GeV over 6 kms. The phase space damping closely follows theoretical values. Another measurement based on this technique demonstrated the damping of phase space to within a few 10^{-3} of the theoretical value.

Table 1 summarizes some of the online applications of the transport matching program. Although not necessarily among the most impressive of the tests, these are among tests where transport was measured after matching. Three cases are shown with blue and red ellipses representing design & measured X (left) & Y (right) phase space. The first shows the initial measurement, the predicted outcome, and the final measurement after applying partial matching. The second shows a solution involving non-local quad solutions. The third demonstrates, apart from the algorithm itself, the level of measurement resolution, machine reproducibility and settability that allows the ability to fine tune an already good match to 100%. All solutions were obtained with a single run of the matching algorithm.

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REFERENCES

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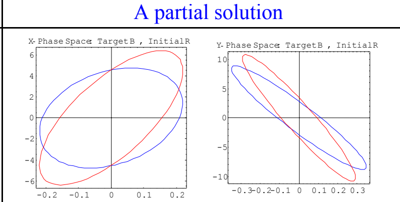
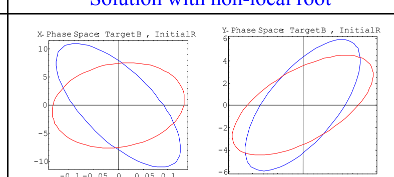
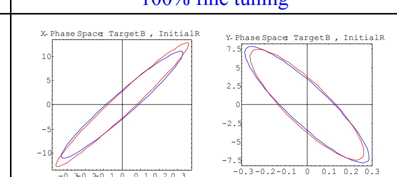
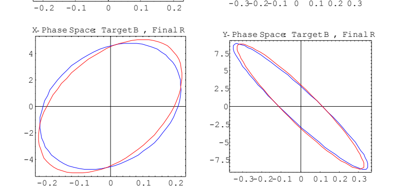
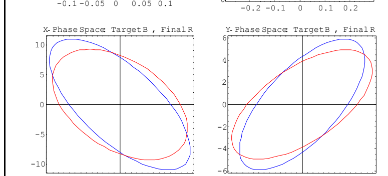
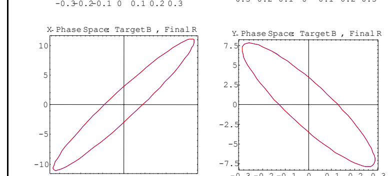
[2] Y. Chao, "A full-order, almost deterministic optical matching algorithm", Proceeding of the 2001 Particle Accelerator Conference, Chicago, 2001.

Table 1. Results of On-line Application of Transport Matching Program

	A partial solution	Solution with non-local root	100% fine tuning
Initial measured			
predicted			
Final measured