

SOFTWARE TOOLS FOR EMITTANCE MEASUREMENT AND MATCHING FOR 12GeV CEBAF *

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Abstract

This paper discusses model-driven setup of the Continuous Electron Beam Accelerator Facility (CEBAF) for the 12GeV era, focusing on `qsUtility`. The `qsUtility` software toolset was developed to perform emittance measurements, analyze those measurements, and compute optics corrections based upon the measurements. Its goals include reducing machine configuration time, improving reproducibility by way of an accurate accelerator model, and providing Operations staff with tools to measure and correct machine optics with minimal assistance from optics experts.

INTRODUCTION

During the 6GeV CEBAF era, optics tuning was an empirical process, and the results were often subjective. Optics matching often required the assistance of optics experts. The process was time-consuming and not deterministic, often resulting in non-reproducible machine setups.

The previous emittance measurement tool was not transparent to the operator. It provided little feedback concerning the quality of the measurement while the measurement was taking place. It relied on an expert to analyze the data offline, after the measurements were taken. Often measurements did not provide useful data, but the operator had no direct way of knowing.

`qsUtility` is a set of software tools for deterministically and reproducibly measuring and correcting transverse optics for 12GeV CEBAF. From the start, `qsUtility` was designed to be generic, flexible, and transparent to the user. The tools are designed such that emittance measurement and matching can be performed by operators with little assistance from accelerator scientists. The quality of the measurements and corrections can be easily verified and adjustments to measurement and matching parameters can be made by operators and non-experts.

`qsUtility` is a major component of the new infrastructure and operational paradigm supporting model-driven setup and operation of 12GeV CEBAF. The toolset is highly model-driven, and relies heavily upon model data from the CEBAF Element Database (CED) [1].

COMPONENTS OF `qsUtility`

`qsUtility` consists of three major components: a data collection tool (`dataCollector`), an analysis tool (`analyzer`), and an optimization tool (`matchingTool`).

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Data Collection

The `dataCollector` provides an automated method to perform emittance measurements. An emittance measurement consists of varying one or more quadrupole focusing strengths in steps while scanning a downstream wire scanner and measuring the beam size at each step.

To save time, the `dataCollector` uses a “zig-zag” method, where the wire scanner is stroked in and out across the beam over a partial range of the scanner rather than using the full stroke of the scanner as was done previously. Avoiding the dead time of full-stroke scanner sweeps for each optics setting reduces the execution time from 30-45 minutes for each single-plane measurement down to less than five minutes [2]. Since a full setup of CEBAF requires emittance measurements at 12-14 different locations around the machine, the speedup from using the “zig-zag” method reduces setup time dramatically. The speedup in emittance measurements also enabled studies that were not previously feasible due to time, such as routine comparison of matching and emittances for different beams and beam intensities.

The `dataCollector` GUI presents textual and graphical results after each measurement step so the quality of the measurement can be assessed by the operator while the measurement is in progress. The GUI displays plots of beam size (σ) as a function of quadrupole focusing strength ($K1$) and σ^2 as a function of focal length so that the operator can see that the quadrupole scan range is adequate to focus the beam through a minimum beam size and to ensure enough points are sampled to properly analyze the measurement. The GUI also displays a plot of the most recent wire scanner profile along with a Gaussian fit so that the operator can evaluate the quality of the profile measurements. The final plot is one of measured beam sizes projected back to the scanning quad overlaid onto the design phase-space ellipse in normalized Floquet coordinates [3]. The phase-space plot gives the operator a sense of how far the measured optics deviate from the design optics. The plots are updated after each measurement step to give the operator a sense of the quality of the measurement while the measurement is in progress. If the measurement appears to be less than optimal, one can abort rather than continue a fruitless measurement, thus saving time. See Fig. 1.

The selection of quadrupoles and their focusing strength ranges, wire scanner and its parameters, and other measurement parameters are configured in an XML configuration file. The format of the configuration files is straightforward and can be edited by operators and optics experts as needed to achieve quality measurements.

The `dataCollector` creates an elegant [4] deck from CED using `ced2elegant` [1]. The `elegant` deck consists

of the beamline elements from the most upstream quad involved in the measurement to the wire scanner, inclusive. The dataCollector then uses elegant to compute the transport matrix elements and design beam size for each measurement step. The measured beam size and quadrupole strengths for each measurement step, along with the transport matrix elements and design beam size, are assembled into an SDDS [5] file to input into the analyzer tool.

solving the matrix equation

$$\begin{pmatrix} (\sigma_x^{(1)})^2 \\ (\sigma_x^{(2)})^2 \\ (\sigma_x^{(3)})^2 \\ \dots \\ (\sigma_x^{(n)})^2 \end{pmatrix} = \begin{pmatrix} (R_{11}^{(1)})^2 & 2R_{11}^{(1)}R_{12}^{(1)} & (R_{11}^{(1)})^2 \\ (R_{11}^{(2)})^2 & 2R_{11}^{(2)}R_{12}^{(2)} & (R_{11}^{(2)})^2 \\ (R_{11}^{(3)})^2 & 2R_{11}^{(3)}R_{12}^{(3)} & (R_{11}^{(3)})^2 \\ \dots & \dots & \dots \\ (R_{11}^{(n)})^2 & 2R_{11}^{(n)}R_{12}^{(n)} & (R_{11}^{(n)})^2 \end{pmatrix} \begin{pmatrix} \beta(s_0)\epsilon \\ -\alpha(s_0)\epsilon \\ \gamma(s_0)\epsilon \end{pmatrix} \tag{1}$$

for ϵ , β , and α by a least-squares fit. The superscript index in parentheses refers to the measurement step.

Both methods normally give similar results, and the average of the two is used for matching. The two methods giving very dissimilar results is an indication of a bad measurement.

The columnar data table on the analyzer GUI displays the measured beam size, transport matrix elements, and quadrupole strengths for each step of the measurement. Individual wire scanner profile plots can be displayed to evaluate to quality of the profile measurement. The user can select data points to be omitted from the analysis if necessary.

For small beam sizes, comparable to the wire diameter of the scanner, the user can apply a correction to the measured beam sizes as outlined in [6].

At CEBAF, the tuning quadrupoles for a given beamline segment are often located upstream of the quadrupoles scanned during an emittance measurement. The analyzer GUI provides a field into which an operator can enter an upstream element to which to back-propagate the computed Twiss parameters for input into the matchingTool.

Plots of beam size vs. quadrupole strength and measured vs. design phase-space plots are available from the GUI (Fig. 3).

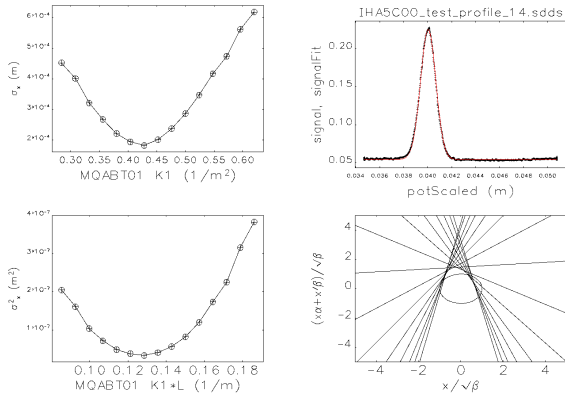


Figure 1: Example of dataCollector GUI Plots.

Analysis

The analyzer takes as input an SDDS file containing the design beam sizes, measured beam sizes, quadrupole strengths, transport matrix elements, and other data generated by the dataCollector. From the input data, the analyzer computes the emittance and Twiss parameters at the entrance of the most upstream element involved in the measurement. The computed beam parameters are displayed on the GUI along with the design parameters from CED (Fig. 2).

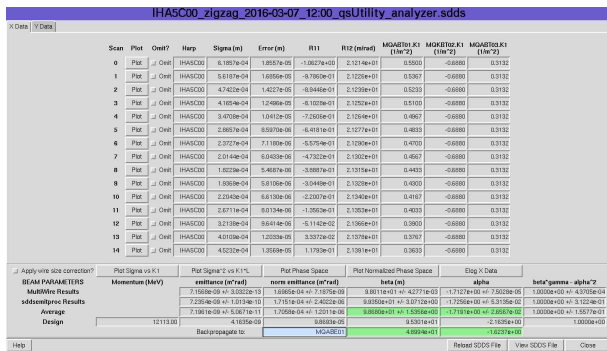


Figure 2: analyzer Main GUI Window.

The emittance and Twiss parameters are computed by two methods. The first uses the sddsemipro tool, which is included in the elegant [4] toolset. The other method utilizes the Multiple Wire Measurement method outlined in [3]. The Multiple Wire Measurement method consists of

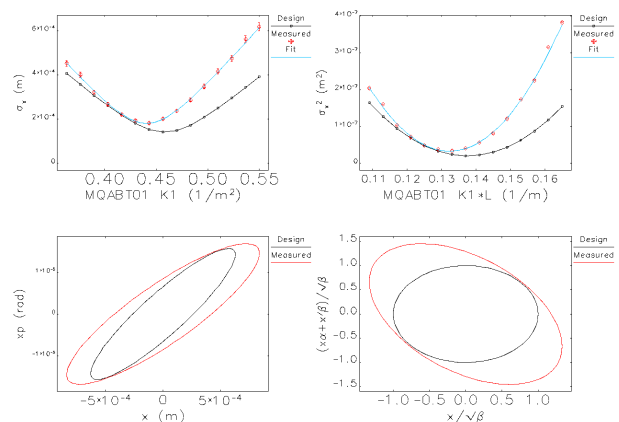


Figure 3: analyzer Plots of Beam Size vs. Quadrupole Strength and Phase Space.

The analyzer tool was originally developed by Marie Keesee in the AHLA group and heavily modified by the author.

Optimization

In the past, matching at CEBAF was typically performed empirically with online diagnostic tools, or computed offline by accelerator scientists. The empirical matching was rather time consuming, and the results were often subjective.

The matchingTool provides a tool for operators and accelerator scientists to rapidly perform matching with deterministic, reproducible results based directly upon measured beam parameters

The matchingTool performs automated matching, using elegant, based on input beam Twiss parameters at the beginning of a beamline segment and optical design parameters at the end of a segment.

The matchingTool is configured in an XML configuration file. The configuration file contains the input and output parameter names, the start and end elements of the section to be matched, the designated tuning quadrupoles, and other parameters relevant to the matching process.

The matchingTool takes as input the measured input Twiss parameters as computed by the analyzer. The design Twiss parameter values to which the match is computed are retrieved from CED for the element at the match point. The CED design values can be overridden on the GUI or in the configuration file if desired.

Given the start and end elements, input Twiss parameter values, tuning quadrupoles, and design Twiss parameter values, the matchingTool constructs an elegant deck from CED using ced2elegant. The matchingTool uses elegant's built-in optimizer to compute the tuning quadrupole strengths required to achieve the design Twiss parameter values at the match point.

The matchingTool is generic enough to optimize for beam parameters other than the usual Twiss parameters. One could use the matching tool to optimize for beam size, phase advance, or any other parameter available to the elegant optimizer. For example, Hall D optics matching includes constraints on matching section phase advances for transverse fast feedback orthogonality.

The matchingTool GUI provides fields into which the user can enter the input Twiss parameter values computed with the analyzer, and perhaps back-propagated to an upstream element. The GUI provides a means for experts to manually edit the elegant files if desired. Options are provided to allow the elegant optimizer to change the quadrupole polarities, and to start with the lattice either on design or set to the setpoints that are currently in the machine. See Fig. 4.

Once the optimizer is started, a window is presented to the user displaying the progress of the elegant optimizer (Fig. 5). The user can observe the output to determine how quickly the match is converging, and can abort the optimizer if convergence does not appear likely within a reasonable amount of time. Upon completion of optimization, the user is presented with a list of computed tuning quadrupole strengths. The user can then download the new quadrupole

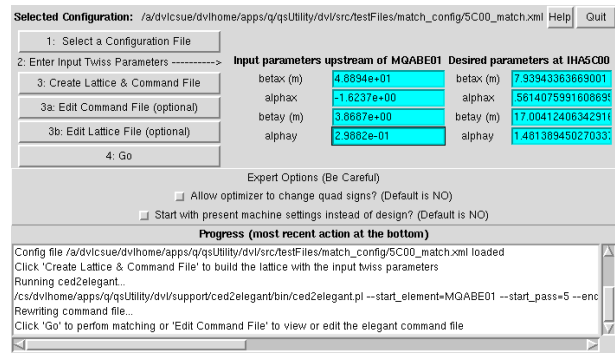


Figure 4: matchingTool Main GUI Window.

settings into the machine using the elegant Download Tool (eDT) [7].

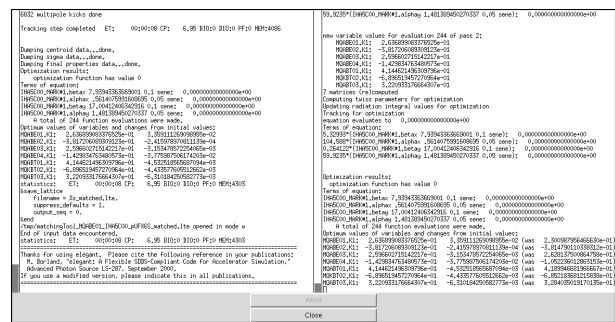


Figure 5: matchingTool Optimizer Output Window.

PATH FORWARD

The qsUtility toolset continues to be improved with operational experience and input from operators and accelerator scientists. Future plans include the use of digitized YAG beam images rather than wire scanners to provide faster emittance measurements, on-the-fly quadrupole and wire scan range adjustments, and further automation.

CONCLUSION

The qsUtility toolset has provided measurable reduction in necessary tune time for new machine configurations and improved CEBAF operational beam quality. qsUtility and the new model-driven operational paradigm have seen great success in the initial commissioning and subsequent operation of 12GeV CEBAF [8].

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