GENERALIZED EMITTANCE MEASUREMENTS IN A BEAM TRANSPORT LINE[*]

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ABSTRACT

Motivated by the need to commission 3 beam transport lines for the new AGS Booster project, we have developed a generalized emittance-measurement program; beam line specifics are entirely resident in data tables, not in program code. For instrumentation, the program requires one or more multi-wire profile monitors; one or multiple profiles are acquired from each monitor, corresponding to one or multiple tunes of the transport line. Emittances and Twiss parameters are calculated using generalized algorithms. The required matrix descriptions of the beam optics are constructed by an on-line general beam modeling program. Design of the program, its algorithms, and initial experience with it will be described.

INTRODUCTION

Measurement of the transverse emittance and Twiss parameters for a particle beam transport line is commonly accomplished using one or several profile monitors to determine the width of the beam.[1] The subsequent calculation of the desired beam properties is then performed by a computer program that can calculate and apply the beam transport matrices for this problem; conventionally the detailed properties of the transport line are represented in the program code. We report here the development of an application program for the Brookhaven AGS accelerator complex that incorporates several recent computing advances to provide a generic program that can be used with any transport line. Our immediate motivation was the need to commission three new transport lines for the AGS Booster. In addition, the program can be applied to existing beam transport lines.

CONCEPTUAL DESIGN

We formulate the problem in the usual way, as one of determining the properties of a beam at some initial point S_0, by measuring the widths of the beam profiles at one or more profile monitors farther down the line at points S_1, S_2, etc. The Twiss parameters α_i, β_i, γ_i at each point S_i are related to those at S_0 by the beam transport matrices for the line.[1] Then if the beam has an emittance ϵ, the measured widths w_i are given by

$$w_i^2 = \epsilon \beta_i = f_i(\epsilon \alpha_0, \epsilon \beta_0, \epsilon \gamma_0) \qquad (1)$$

for functions f_i determined by the transport matrices (neglecting dispersion). The three unknowns $\epsilon \alpha_0$, $\epsilon \beta_0$, and $\epsilon \gamma_0$ can then be determined if three of more widths are measured. If more than three widths are measured, a least squares approach is used to minimize the sum of the squares of the residuals R_i:

$$R_i = w_i^2 - \epsilon \beta_i \qquad (2)$$

The error matrix for the resulting beam parameters can also be determined from the sum of the squares of the residuals.[1]

If the beam transport line in questions does not have enough profile monitors to satisfy the requirements set forth above, an alternate approach is to vary the tune of the transport line (that is, the focusing strengths of the quadrupoles) and measure the widths of the profiles for each tune used in the beam line. If the transport line has only one profile monitor, this approach is the only one possible; in this case, one attempts to vary the tune of the transport line enough that the β function at the profile monitor exhibits a minimum as a function of the quadrupole strength being varied, and the phase advance at the profile monitor varies through a range comparable to $90°$.

In a transport line instrumented with multiple profile monitors, one can improve the quality of the measurement of the beam parameters by measuring the profile widths as the tune of the transport line is varied.

PROGRAM FEATURES

We have implemented this approach in an emittance program developed at the AGS. We incorporate several features which maintain generality in the program, permitting it to be used with any beam transport line.

The calculation of the beam transport matrices in our approach is carried out by a generalized modeling program for beam transport lines, the program MAD as developed at CERN.[2] We require the user to describe the beam transport line in MAD vocabulary; focusing strength are parameterized in terms of currents supplied to the quadrupole magnets, and these currents are interactively obtained from the control system. For each tune of the transport line, MAD is instructed to perform a TWISS analysis of the line, and the results of the MAD analysis are made available to the emittance program. The emittance program then calculates the beam transport

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matrices from the MAD results. MAD requires initial values for the beam properties at the entrance to the transport line (emittance ϵ, Twiss parameters α and β), but the resulting transport matrices do not depend to first order on the initial values. These calculational techniques were validated in an earlier test on the proton injection line for the AGS.[3,4]

The emittance program is designed and written in a modern object-oriented language, C^{++}. The result of this object-oriented approach is that details of beam-line models, and of beam-line hardware (magnets and instrumentation) are concealed within object-oriented library routines, and are neither visible nor of concern to the emittance program proper; generality of the emittance program is enhanced and much easier to implement.

The selection of options within the emittance program (e.g. choice of beam line, segment within the beam line, measurement strategy) is governed by descriptions of the possibilities which are maintained in a directory structure of data files. Adding new options, e.g. new beam lines or new measurement strategies for existing beam lines, is accomplished by describing these options in the appropriate data files; the emittance program code need not be changed. The emittance program itself offers options for creating new measurement strategies (which quadrupoles to vary, which profile monitors to employ) and tactics (detailed choice of setpoints for each magnet for each profile measurement).

The emittance program offers an extensive graphical interface, which is implemented using an object-oriented graphics package. The object-oriented approach to the graphical interface preserves generality of the program and offers considerable efficiency in program development.

The emittance program offers a convenient graphical interface to the MAD modeling results. A potential emittance measurement strategy can be modeled and the results examined without actually using beam time. The strategy can be revised as appropriate, until the user is satisfied that the strategy will yield a successful emittance measurement; only then is beam time needed to obtain the final measurements.

Subsequent to a successful emittance measurement, the MAD modeling program may again be invoked, this time using the measured beam parameters to describe the initial beam, and using the on-line control values for the currents in the focusing beam elements; this final model of the beam line can be used to predict the beam properties at any location in the line. Locations upstream or downstream of the segment in which the measurement was performed can also be modeled with such a technique.

PROGRAM IMPLEMENTATION

The emittance program is implemented in the AGS Distributed Control System (AGSDCS). The AGSDCS comprises a network of approximately 50 Apollo workstation nodes on a Domain token-ring network which spans the AGS accelerator complex. The AGSDCS is interfaced to some 5800 accelerator devices via some 100 so-called device-controllers. Version 7.2 of the MAD program[2] has been implemented on this computer network. Apollo workstations situated in the AGS Main Control Room Consoles offer a windowing high-resolution (1280x1024) graphical color display, with a multiprogramming environment; each workstation may have several programs concurrently available via separate windows on the display. The emittance program employs a standard AGSDCS user interface, with interactive pull-down menus, a library of pop-up displays, and a standardized graphics package. Access to the control system interface to accelerator devices is accomplished in object-oriented tools which employ standard library routines and a database of available accelerator hardware.

APPLICATION TO BOOSTER PROTON INJECTION LINE

The proton injection line is some 35 meters in length and comprises 13 quadrupoles and 4 bending dipoles producing a net horizontal bend of $126°$. The emittance program was used in commissioning this line to measure beam parameters in two straight sections of the line which each have a single profile monitor. Figures 1 through 3 are copies of on-line displays from the program. Figure 1 illustrates graphical displays of these two sections of the beam line. Figure 2 exhibits a typical set of profiles, and Fig. 3 plots the widths of these profiles (widths defined as enclosing 98% of the profile area) against a quadrupole current. The parameters resulting from a least squares fit to these data are shown in Table I.
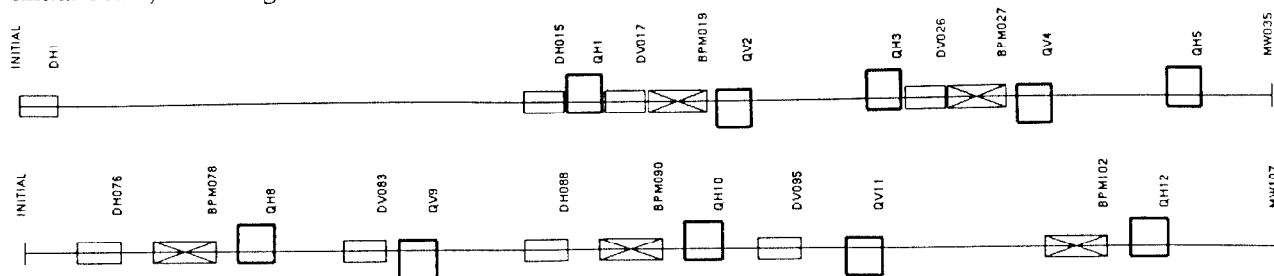

Fig. 1. Graphical layouts of two of the sections of the Linac-to-Booster (LTB) proton injection line; upper layout is LTB1, lower layout is LTB3.
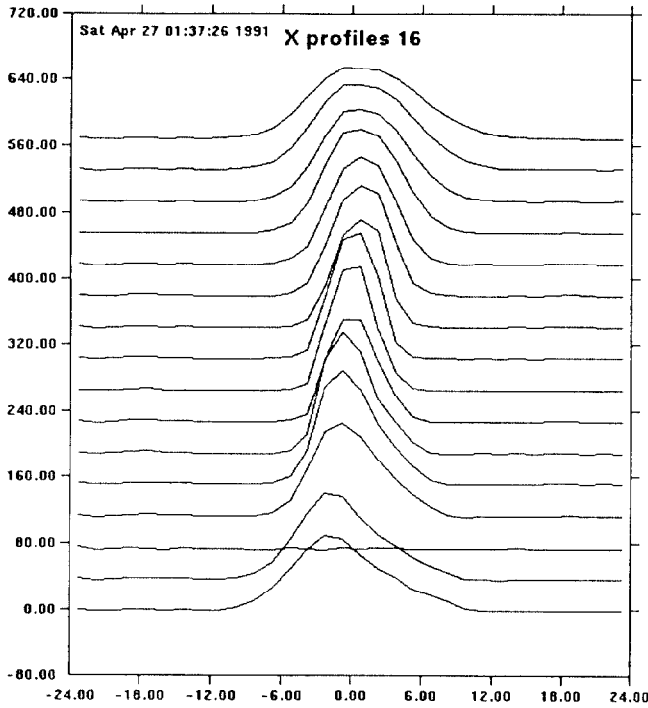
Fig. 2. Horizontal profiles from multiwire MW035 in LTB1, as quadrupoles QV2, QH3, and QV4 are varied together as a triplet.

APPLICATION TO HEAVY-ION TRANSPORT LINE

The basic optical cell of the HITL consists of a drift, followed by a quadrupole doublet, followed by another drift. The doublet is tuned so that the cell images a waist to a waist in both the horizontal and vertical planes. Profile monitors provide beam widths near the waists. Emittance and twiss parameters are determined from profile widths acquired as the current in the doublet is swept through a series of setpoints. A least squares fit to the profile widths yields the desired parameters.

TABLE I

Beam parameters resulting from least squares fit to data of Fig. 3.

ϵ	=	$4.47 \pm 0.19 \, \pi$ mm-mr
β	=	10.35 ± 0.67 m
α	=	-2.47 ± 0.47

OTHER APPLICATIONS

The emittance program will be used in commissioning the Booster extraction line and Booster Heavy-Ion injection line later this year. There are a number of other beam transport lines at the AGS in which we anticipate useful application of this program as well.

REFERENCES

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3. A. Luccio, private communication.
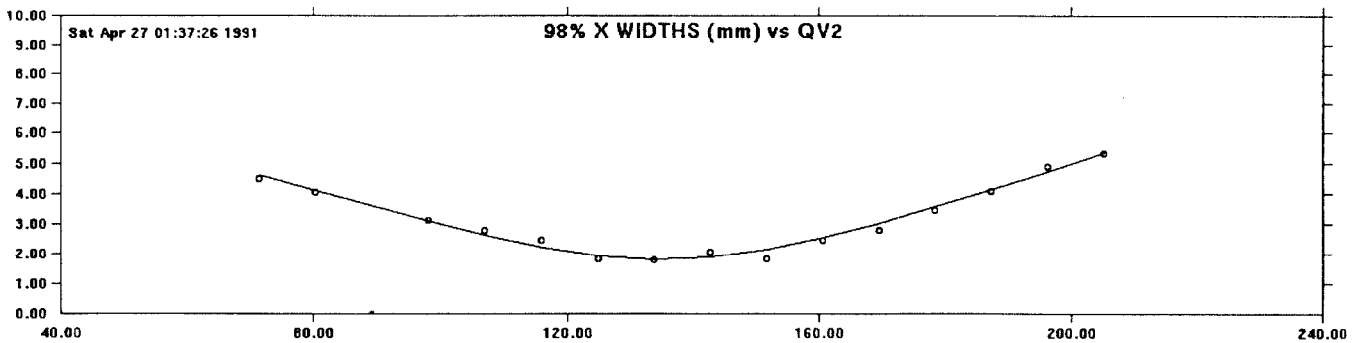4. A. Kponou & A. Luccio, private communication.

Fig. 3. The width from the profiles in Fig. 2 are plotted (open circles) against the current in QV2. The curve through the points is the result of the least squares fit to these widths.

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