Use of Design Codes for On-Line Beam Diagnostics at the MIT-Bates Accelerator*

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Abstract

The MIT-Bates Accelerator Center consists of a one GeV electron linac with a beam recirculation system, and a storage ring which was initially commissioned in early 1993. For proper operation of this facility, on-line beam measurements and analysis are important. To this end we have developed codes for simulating and measuring beam optics and the transverse beam phase space. One of the beam optics simulators is an extension of the DIMAD based simulator which originated at CEBAF. It has been modified to include the capability of directly reading the machine magnetics values and thereby predict the beam envelope, as well as automatically set up the desired theoretical beam phase space. Two types of on-line transverse phase space measuring codes are in operation. It is envisioned that these phase space measurement systems will eventually be linked with the optics simulator to allow semi-automatic beam tuning procedures. Another code for automatically measuring optical matrix elements has been in use for several years. A description of the codes, their bases and their operation are presented here.

I. Introduction

The MIT Bates Accelerator Center has recently begun commissioning the South Hall Ring (SHR)[1]. This 1 GeV 190 m circumference ring is filled from the 1 % duty factor electron linac. It is designed to provide high duty factor beams to targets internal to the ring and also to external targets, for nuclear physics experiments. Proper operation of the beam lines and the ring, including maintaining the high quality of the beam, requires achieving the proper optical matrix elements and matching the phase space of the beam to the beam line or ring design phase space.

In order to accomplish this matching, we use computer programs to automatically measure the transfer matrix elements and the transverse phase space of the beam at various points along the beam line. An optics simulation program is then used to set the beam line magnetic elements to achieve the proper phase space match. These programs are, to varying degrees, extensions and modifications of programs used in the design of the ring and beam lines. Each of them operates interactively, and is interfaced with the control system and instrumentation, to provide real-time tuning capability.

II. Ring Controls and Instrumentation

The Ring Control System (RCS) comprises a number of distributed Local Area Computers (LACs) and workstations interconnected by Ethernet[2]. The LACs control and monitor all beam line devices, as well as collect data from instrumentation such as beam position monitors and wire scanners. Available data is sent out on the network at a rate of 4 Hz. The workstations are used for displaying this data, for operator interface, and to run application software such as that described here. Thus, the applications have access to all information on the present state of the beam and magnetic elements. In addition, the applications can control the magnetics and instrumentation.

*Work supported by the U.S. Department of Energy

III. Phase Space Programs

We use two independent techniques for measuring the transverse phase space of the beam. The first uses the beam size measured at three locations along the beam line. It has the advantage of not perturbing the beam transport, but its precision suffers when measuring small emittance beams in certain optics configurations. The second technique involves measuring the beam size at a fixed location as a function of the strength of an upstream quadrupole. Although this perturbs beam transport, and tends to be slower than the three profile method, it is able to make good measurements over a wider range of phase space. In addition, this method can be used in situations where it is not possible to measure the beam size at three different locations.

A. Three profile method

By measuring the horizontal and vertical beam sizes at three different locations along a beam line, the transverse phase space in both planes can be determined. We are using an extension of an earlier technique[3] which allows for general beam transport between the three locations. Beam sizes are measured using wire scanners driven by stepper motors. The horizontal beam size at location i is $x_i = \sqrt{\beta_i \epsilon}$ where

$$\beta_i = \mathrm{R}_{11}^2(i)\beta_0 - 2\mathrm{R}_{11}(i)\mathrm{R}_{12}(i)\alpha_0 + \mathrm{R}_{12}^2(i)\gamma_0 \qquad (1)$$

is the β function at location i, and $\mathrm{R}_{lm}(i)$ is the lm component of the transfer matrix $\mathbf{R}$ from location 0 to location i. The beam emittance is ϵ. The variables β_0, α_0 and γ_0 are the Twiss parameters at location 0. At locations 1, 2 and 3, then,

$$\begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} = \mathbf{M} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix}, \qquad (2)$$

where

$$\mathbf{M} = \begin{pmatrix} \mathrm{R}_{11}^2(1) & -2\mathrm{R}_{11}(1)\mathrm{R}_{12}(1) & \mathrm{R}_{12}^2(1) \\ \mathrm{R}_{11}^2(2) & -2\mathrm{R}_{11}(2)\mathrm{R}_{12}(2) & \mathrm{R}_{12}^2(2) \\ \mathrm{R}_{11}^2(3) & -2\mathrm{R}_{11}(3)\mathrm{R}_{12}(3) & \mathrm{R}_{12}^2(3) \end{pmatrix} \qquad (3)$$

Using $\epsilon\beta_i = x_i^2$ and inverting the matrix $\mathbf{M}$, Eq. 2 can be solved to give $\epsilon\beta_0$, $\epsilon\alpha_0$ and $\epsilon\gamma_0$. Thus β, α and γ at location 0 can be determined by measuring the beam size x and three different locations, knowing the transfer matrices from the three locations to location 0, and using $\epsilon = \sqrt{(\epsilon\beta_0)(\epsilon\gamma_0) - (\epsilon\alpha_0)^2}$. Standard propagation of errors is used to calculate the precision of the measurement.

The core of the program used to make these measurements is based on a design program used to determine the optimal locations of the wire scanners. We have added a graphical user interface for data display and control of the wire scanners. Figure 1 shows the user interface for this application. Displayed are the raw and processed data from the wire scanners, and the wire scanner control parameters. In order to calculate the phase space, the application program reads the settings of the magnetic elements along the beam line and calculates the appropriate transfer matrices. Combining the beam widths and the transfer matrices, the phase space can be calculated, along with the precision of the measurement. The resulting horizontal and vertical phase space ellipses are then displayed. A complete set of beam profiles is typically acquired in 10–30 seconds. Processing of the data takes 1–2 seconds.

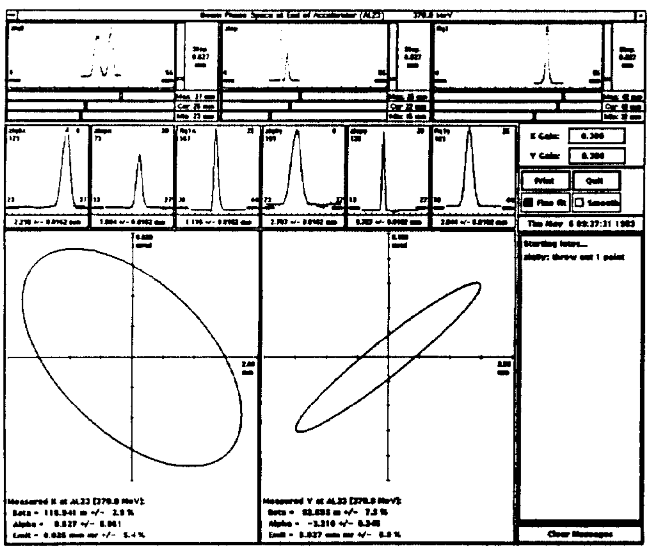

Fig. 1: User interface for measuring the transverse phase space using three beam profiles.

This application, written in C and using Motif, gives a real time measurement of the beam transverse phase space. The wire scanners scan on a continuous basis, sending out data at the end of each scan. Any change in the setting of a beam line element is recognized by the program and taken into account. Thus, the most current data available is displayed. There is an option for saving all raw data on disk, for later replay. In addition, the measured phase space can be projected to any point along the beam line.

B. Varying quadrupole method

By varying a quadrupole in the beam line and observing the beam size at a point downstream, the transverse phase space may be determined for a point upstream of the quadrupole[4]. This method is normally used for one plane at a time. The beam size is measured with a wire scanner, as in the three profile method.

The square of the beam size at the wire scanner (σ_{11} in x and σ_{33} in y) is determined by the beam sigma matrix σ^0 at a point upstream by

$$\sigma_{11} = R_{11}^2\sigma_{11}^0 + 2R_{11}R_{12}\sigma_{12}^0 + R_{12}^2\sigma_{22}^0 \tag{4}$$

for x, and similarly for y. The R_{ij} are the elements of the beam transfer matrix between the upstream location and the wire scanner.

A weighted least-squares fit of the square of the beam size as a function of quadrupole settings is made, yielding the complete beam sigma matrix. From this the beam emittance ϵ and the Twiss parameters β and α are given by $\epsilon = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$, $\beta = \sigma_{11}/\epsilon$, and $\alpha = -\sigma_{12}/\epsilon$ in the x plane. Similar expressions hold in the y plane.

This application is written in C, using Motif for the user interface, which is shown in Fig. 2. The wire scanner controls and the profile display are identical to those used in the three profile application. The transfer matrix is calculated for each setting of the quadrupole, reading the settings of the beam line elements from the network. The measured data points and the function fitted to them are plotted, and the phase space ellipse is displayed, as projected to any point in the beam line. Acquisition of each beam profile to determine the beam width typically takes a few tens of seconds. One complete scan of the quadrupole, to make one phase space measurement, may take 5–10 minutes. Data analysis requires only a few seconds.

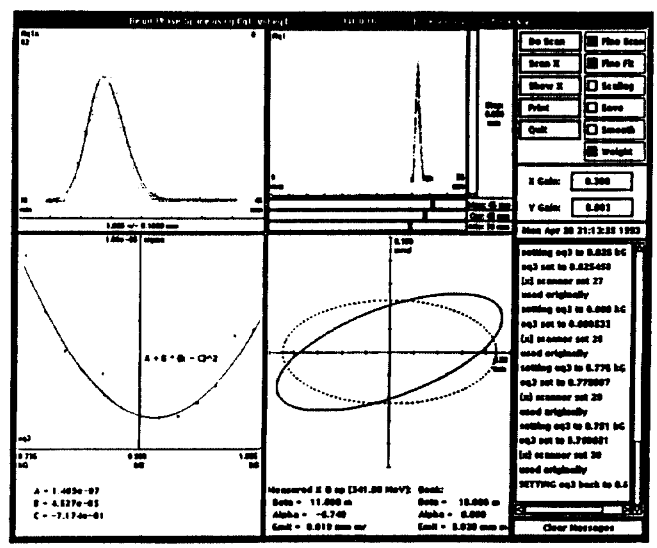

Fig. 2: User interface for measuring the transverse phase space by measuring the beam size as a function of the strength of an upstream quadrupole.

IV. Optics Simulator

This application is based on the beam line simulation code DIMAD[5] and a graphical interactive interface to it developed at CEBAF[6]. This interface, based on the X Window System, is itself an extension of the original

DIMAD text-based interactive interface allowing graphical display of the computed results, and the manipulation of beam line element settings using graphical display objects.

The program has been further modified for use as an on-line diagnostic and machine tuning tool. An interface to the RCS allows the settings of beam line elements to be incorporated into the simulation in real time. Selected elements may also be set by the application from calculations based on data supplied by the user. A graphical display of the beam beta functions for the modeled beam line is provided.

There are two basic modes of operation. In the first, the parameters of the beam phase space at the beginning of the beam line are specified by the user, along with a set of desired beam parameters at some other point in the beam line, usually the end. A selected group of elements are then used as parameters in a least squares fitting procedure, with the desired beam parameters as the fitting conditions. The calculated settings for the beam line elements can then be applied directly from the program on command from the user. This allows a complex beam line to be tuned in a simple and deterministic fashion.

In the second mode of operation, the actual settings of all the beam line elements are continuously read from the RCS, and the simulation is performed based on them. This allows a real-time display of the beam line tune, as elements are adjusted by the operator. The display update rate is limited by the computation of the beam line transfer matrices and thus by the number of elements in the beam line. For beam lines with 20–30 elements, updates can be provided about once a second on a mid-range workstation.

The graphical interface, shown in Fig. 3, is written in C, using DECwindows for the user interface. The CEBAF code has been modified and extended to incorporate new functions, and some features have been deleted. DIMAD is written in FORTRAN, and modifications were made to it at CEBAF to allow access to data and functions from the C interface code. We have made further modifications and additions, particularly to the least squares fitting routines.

V. Transfer Matrix Element Measurements

The operation of some beam lines depends on the proper set-up of the optical matrix elements. To verify that this has been achieved, we have developed an automatic OPTICS measurement system. This application uses steering dipoles to independently vary the position and angle in x and y of the beam entering the beam line. The beam positions at downstream BPMs are then measured, and the resulting optical matrix elements are calculated and displayed.

The graphical interface, shown in Fig. 4, is written in C, using X10. There is provision to interact with the program as the data is taken, or to allow the program to operate automatically. The results are used to modify the quadrupole and dipole trim settings in the beam line to obtain the desired optics.

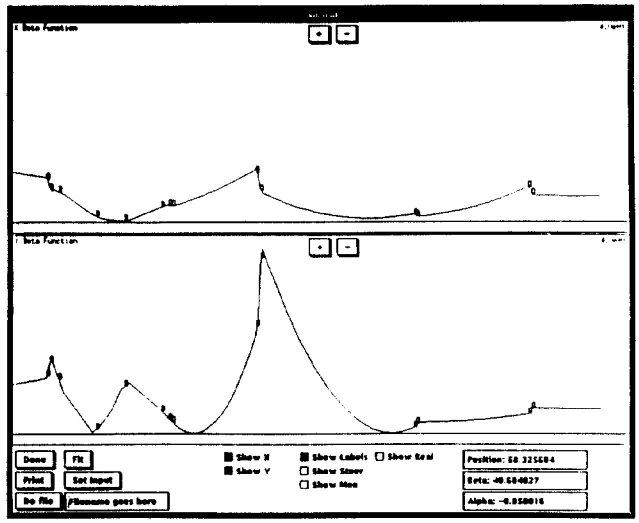

Fig. 3: User interface for the DIMAD optics program.

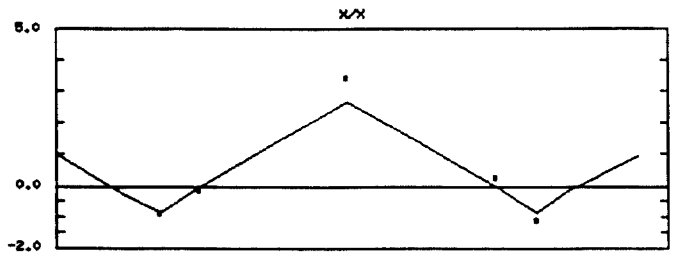

Fig. 4: Sample result from the OPTICS program. The solid lines indicate the desired optics, the points are the measured optics.

VI. References

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