AUTOMATED EMITTANCE MEASUREMENTS IN THE SLC*

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Abstract

The emittance of the SLC beam is determined from measurements of the beam width on a profile monitor as a quadrupole field is varied. An automated system has been developed to allow this to be done rapidly and accurately. The image on a fluorescent screen profile monitor (resolution about $20\ \mu m$) is read out through an electronic interface and digitized by a transient recorder. A high level software package has been developed to set up the hardware for the measurements, acquire data, fit the beam width, and calculate the emittance.

Introduction

The optical matching of various SLC subsystems as well as optimizing the beam luminosity at interaction point requires accurate determination of the beam ellipsoid (σ-matrix) and emittance (ϵ_x, ϵ_y) at key points throughout SLC. The beam ellipsoid will be used as input to modelling programs such as COMFORT to calculate quadrupole strengths to achieve matched beam lines. Additionally, since emittance growth adversely affects the collider luminosity, an accurate estimate of its magnitude is valuable in controlling its growth and thereby improving the system performance. The phase space measurements in the vicinity of the injector also serves as a figure of merit for its operation. In view of the complexity of the measurement process and the number of locations where these measurements are required it was deemed desirable to automate the entire process as much as possible.

The basic idea behind the emittance measurements is to determine the horizontal and vertical beam size ($\sqrt{\sigma_{11}}$, $\sqrt{\sigma_{33}}$), with a profile monitor as function of the strength(s) of an upstream quadrupole(s)[1] as shown in fig. 1. Knowledge of the beam size at a particular location in the beam line for three different quadrupole strengths is sufficient to calculate the beam sigma anywhere along the beam line.
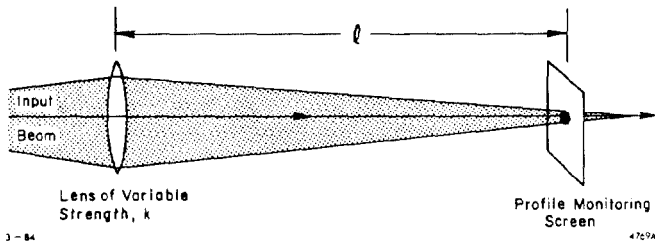

Fig. 1 Typical Emittance Measurement Profile Monitor Installation from the digitized beam profile

Theory of Measurements

Consider a quadrupole Q of strength $k = \int gdL/(B_0\rho)$ separated from a down stream screen S by a transfer matrix $\mathbf{S}$. The total transfer matrix of the measurement system is given by

$$\mathbf{R} = \mathbf{SQ}$$

where $\mathbf{Q}$ is the transfer matrix of the quadrupole

The σ matrix is propagated through the system by the relation[2]

$$\sigma^S = \mathbf{R}\sigma^Q\mathbf{R}^T \qquad \text{where}$$

$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 \\ R_{21} & R_{22} & 0 & 0 \\ 0 & 0 & R_{33} & R_{34} \\ 0 & 0 & R_{43} & R_{44} \end{pmatrix}, \quad \sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & 0 & 0 \\ \sigma_{21} & \sigma_{22} & 0 & 0 \\ 0 & 0 & \sigma_{33} & \sigma_{34} \\ 0 & 0 & \sigma_{43} & \sigma_{44} \end{pmatrix}$$

then, for the above uncoupled system

$$\sigma_{11}^S = R_{11}^2\sigma_{11}^Q + 2R_{11}R_{12}\sigma_{12}^Q + R_{12}^2\sigma_{22}^Q$$

$$\sigma_{33}^S = R_{33}^2\sigma_{33}^Q + 2R_{33}R_{34}\sigma_{34}^Q + R_{34}^2\sigma_{44}^Q$$

The measured x–plane spot size at the screen is $\sqrt{\sigma_{11}^S}$, (y–plane may be deduced by analogy.)

Thin Lense Formulation

For a measurement setup where the length of the varying quadrupole is short compared to its focal length a simple relationship describes the emittance as a function of the lens strength.[3] . The transfer matrix for the quad in the thin lens approximation is

$$\mathbf{Q} = \begin{pmatrix} 1 & 0 \\ k & 1 \end{pmatrix}$$

Hence the spot size as a function of the quad strength is given by

$$\begin{aligned} \sigma_{11}^S = {}& S_{11}^2\sigma_{11}^Q + 2S_{11}S_{12}\sigma_{12}^Q + S_{12}^2\sigma_{22}^Q \\ & + k(S_{11}\sigma_{11}^Q + S_{12}\sigma_{12}^Q)2S_{12} \\ & + k^2\sigma_{11}^Q S_{12}^2 \end{aligned}$$

The measured σ_{11}^S may be fit to a parabola

$$\sigma_{11}^S = A(k - B)^2 + C$$
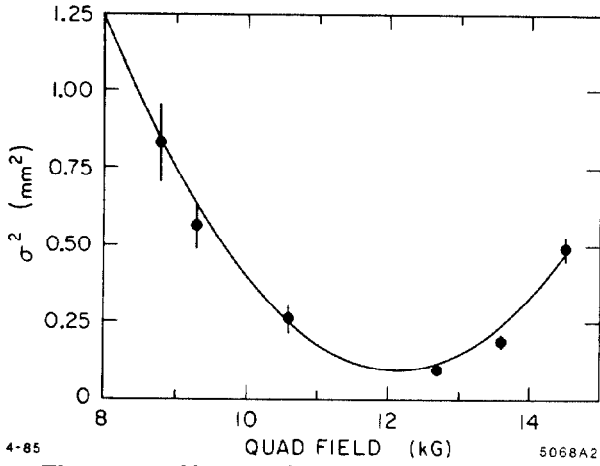
from which we can obtain the value of the σ matrix at the

Fig. 2 The square of beam width as a function of the upstream quadrupole strength

quadrupole, σ^Q,

$$\sigma_{11}^Q = \frac{A}{S_{12}^2}$$

$$\sigma_{12}^Q = \frac{1}{S_{12}^2}(AB^2 + 2\frac{S_{11}}{S_{12}}AB + (\frac{S_{11}}{S_{12}})^2 A + C)$$

$$\sigma_{12}^Q = -\frac{A}{S_{12}^2}(B + \frac{S_{11}}{S_{12}})$$

Figure 2shows the quadratic dependence of the measured σ^S on the quadrupole strength.

The emittance is then given by

$$\epsilon_x = \sqrt{\sigma_{11}^Q \sigma_{22}^Q - \sigma_{12}^Q} = \sqrt{\frac{AC}{S_{12}^4}}$$

The beam Twiss parameters are given by

$$\beta^Q = \sqrt{\frac{A}{C}} \qquad \alpha^Q = \sqrt{\frac{A}{C}}(B + \frac{R_{11}}{R_{12}})$$

THICK LENS FORMULATION

When the length of the varied quadrupole is not small with respect to its focal length, the thin lens approximation is not valid. In this case the transfer matrix from the entrance of the quad to the screen is considered in full and without approximation.[1]

For n measurements denote

$$\Sigma^S = \begin{pmatrix} \sigma_{x1} \\ \vdots \\ \sigma_{xn} \end{pmatrix} \quad \text{and} \quad \Sigma^Q = \begin{pmatrix} \sigma_{11}^Q \\ \sigma_{12}^Q \\ \sigma_{22}^Q \end{pmatrix}$$

then

$$\Sigma^S = A\Sigma^Q$$

where

$$A = \begin{pmatrix} R_{11}^2(1) & 2R_{11}(1)R_{12}(1) & R_{12}^2(1) \\ \vdots & \vdots & \vdots \\ R_{11}^2(n) & 2R_{11}(n)R_{12}(n) & R_{12}^2(n) \end{pmatrix}$$

The least squares solution of the σ matrix at the entrance of the stepping quad is:

$$\Sigma^Q = (A^T A)^{-1} A^T \Sigma^S$$

As before, Emittance and Twiss parameters are determined from the calculated σ matrix.

Hardware

The automated emittance system uses closed circuit television to view and record beam generated images on phosphor screens. At selected points in the collider complex, where the contribution to the beam size from energy spread is small, high resolution profile monitors are installed and associated with upstream quadrupole magnets. Since beam sizes may be quite small, (0.05 mm) and the measured emittance depends strongly on the system resolution, care must be taken to ensure that no component in the system causes the resolution to deteriorate. The mechanical and optical components of this system have been described before[3], we will only review them briefly and discuss the electronic system in more detail.

In order to minimize optical resolution limitations, the lens and camera are placed as close as possible to the screen. Figure 3shows a typical layout. The camera to screen distances 15 cm. Typical magnification is close to one; a 7mm × 6mm target is viewed by a camera with a 6.6mm × 8.8mm active area. The central area of the target is surrounded by a rectangular hole pattern which is used to determine the magnification.

Figure 4shows the data acquisition scheme. Only a small fraction of the television picture is digitized. This cuts down the data handling load but introduces the need to control the digitization region as well as the sampling density. Two CAMAC units are used, the video digitizer clock interface (VDCI) and a commercially available 30MHz bandwidth 8K × 8 bit transient waveform recorder (TWR). The raw video from the camera is input directly into the VDCI which loops it through to the digitizer, generates various control signals for the 2008F and regenerates it for transmission to the main console monitors via the SLC broadband cable system. The digitizer control signals consist of a "clock" indicating to the 2008F when to sample and a stop trigger which determines which data should be frozen for subsequent readout. The stop trigger is derived from a beam time trigger from the SLC timing system and the video vertical sync; it always occurs at the sync boundary following the beam trigger. These devices are used at a maximum beam rate of 10Hz, so that the digitized image contains data from only one beam pulse. An ambiguity exists since the SLC beam is locked to the AC mains, just as the camera is. This means that the best data from the camera may occur before or after the stop trigger. Thus the 2008F uses the stop trigger to mark the halfway point in its rotating data buffer leaving a 4K maximum buffer size. This is adequate for an accurate determination of the beam size. The signal sampling points are controlled via CAMAC by the VDCI. The maximum sampling density corresponds to 512 (horizontal) by 256 (vertical) points. The lower vertical resolution results from the vertical video frame interlacing. The density of points along either dimension of the rectangle as well as its aspect ratio and location are remotely controllable.
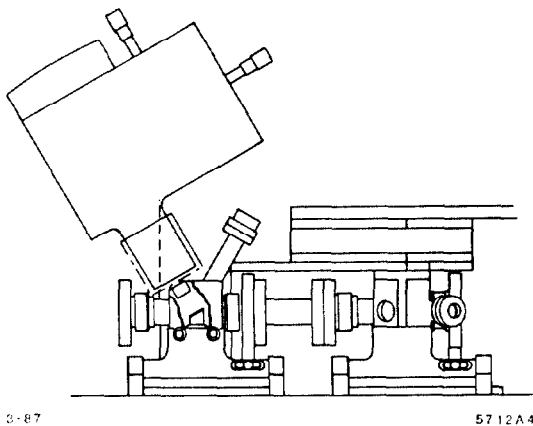
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Fig. 3 The beam strikes the screen at a 30 degree angle. This expands the scale along the tilt direction, increasing the resolution. Two profile monitors are needed for an x and a y measurement. Because of the lower resolution in the vertical video direction, the expanded dimension is aligned with the horizontal camera sweep.

Software

In developing the online software every effort was made to automate the numerous steps required for the measurement of the emittance. A modular approach was taken to separate the logical steps and to layer the software on top of existing application and diagnostic programs. The basic stages of the measurement process are:

1. Setup the beam profile digitizer system

2. Step a desired quadrupole through a selected range and acquire the digitized beam data

3. Analyse the data and compute the beam emittance

Three separate software packages have been developed to correspond to each of the required functions. Each program performs a well defined task and is capable of operating independently as well as serving as a module in the measurement system.
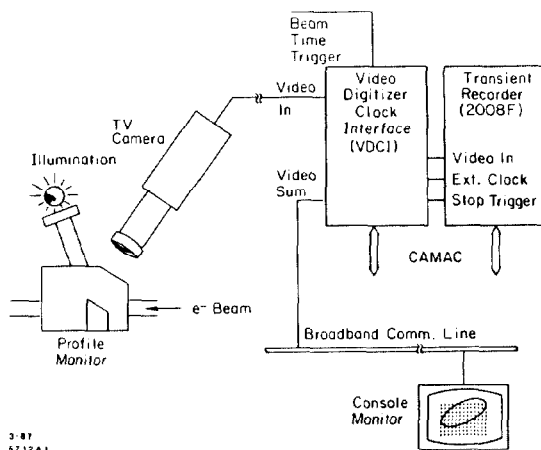

Fig. 4 Raw video emittance measurement data are digitized in a transient waveform recorder controlled by a custom built interface module (VDCI). The VDCI generates a sequence of clock pulses that determine the sampling time. It also adds these pulses to the raw video forming a highlighted region on the picture.

1. **Beam profile digitization:** The SLC Control Program[4] allows interactive selection and insertion of a large number of profile monitors in various beamlines. Every monitor has an associated digitizer (as pointed to in the data base) which is activated upon selection. The software permits complete adjustment of the digitization window superimposed over the beam profile. These include the window location, size, and mesh density; automatic beam-finding and optimum resolution selection functions are also provided. Once the hardware has been setup the software performs the following steps:

   (a) Measure the background intensity while the beam is inhibited

   (b) Scan the monitor, subtract the background and provide graphics displays

   (c) Compute beam σ by fitting integrated x and y data to gaussian curves (figure 5).

2. **Data acquisition:** To collect a complete set of data points as effortlessly and as quickly as possible it is desirable to have an online data acquisition program which is capable of perturbing (almost) any device while sampling any beam or machine parameter synchronously. This function is performed by the online CORRELATIONS PLOT program which additionally provides for display of collected data as well as fitting the data to a wide range of models. For our purpose, the CORRELATIONS
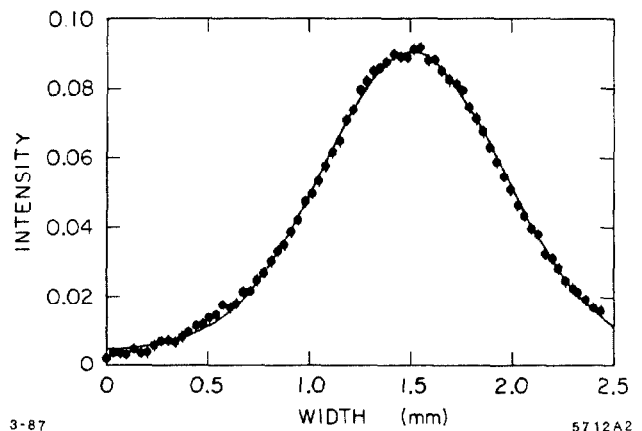

Fig. 5 Integrated beam intensity in x (or y) direction. The beam widths (σ_x, σ_y) are obtained from a gaussian approximation to the measured data.

PLOT package is used to vary a quadrupole through a predefined range and number of steps while at each step calling the digitizer software to sample the beam profile and extract its parameters.

3. **Data analysis and emittance calculation:** once a set of data points (σ_i, k_i) have been collected one of the above methods may be used to evaluate (ϵ_x, ϵ_y) as well as β^Q and α^Q. Both of these methods require a knowledge of the machine model to calculate the transfer matrices. Online models are used to calculate and store in the data base the required information (Twiss parameters) from which the matrices may be computed.[5]

For the Thin lens model the (σ_i, k_i) collection is fit to a quadratic function Fig. 8 and from the parabolic coefficients (ϵ_x, ϵ_y) is calculated

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For thick lens computation, the matrix $Q(k_i)$ is evaluated from the online model and the resulting least squares problem is solved with the optimization package LSSOL[6]

User Interface

The objective in designing the user interface was to allow the users to concentrate on the analysis and interpretation of the results rather than on the data collection. Once a profile monitor has been setup all the relevant parameters are kept permanently in the database. these include the digitizer and window setup, the quads to be stepped and their parameters. This reduces the subsequent emittance calculations to little more than selecting the location and initiating the measurement process. Additionally the experimenters have the facility to edit the collected set of data and recompute the results. Graphics interface provide for displaying full beam profiles as well as digitized slices (figures 6 and 7).
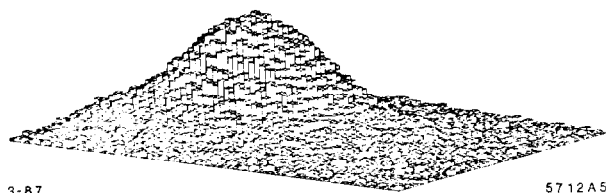

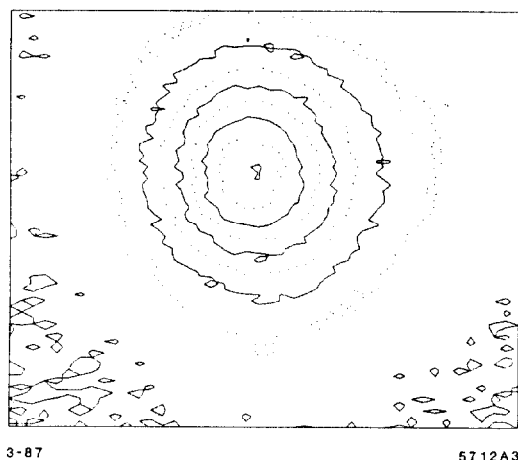Fig. 6 Computer generated histogram of beam intensity

Fig. 7 Contours of beam intensity on the profile monitor.

Current Status

All of the hardware and the associated software is currently operational and used for commissioning various SLC systems. The next phase of the development includes converting the procedure to an autonomous process which may be initiated at regular intervals to track the quality of beam delivery in the SLC. Additionally efforts are under way to tie these measurements to the online modelling software for optically matching (adjusting) the beamlines components to achieve the specified lattice properties.

ACKNOWLEDGEMENT

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