TRANSVERSE EMITTANCE SYSTEMATICS MEASURED FOR HEAVY-ION BEAMS AT ATLAS

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The horizontal and vertical beam emittances and ellipse parameters are determined at the ATLAS superconducting heavy-ion linac by the well-known method of measuring the beam width at a profile monitor downstream of a quadrupole magnet as a function of the magnet current. Typically six base-to-base beam widths are measured and used in a least-squares fit to an algebraic expression for the three unknown ellipse parameters. The algorithm was derived from the first order matrix equation for the beam sigma matrix transform through the quadrupole singlet and drift to the profile monitor. To date the emittances of five beams from $^{12}C^{4+}$ to $^{238}U^{26+}$ have been measured at the entrance of the Positive-ion Injector Linac, yielding normalized values mostly in the range of 0.25-0.30 π mm-mr. These measurements will be extended systematically to several locations to identify possible sources of emittance growth and to develop more systematic beam tuning procedures.

I. INTRODUCTION

The ATLAS superconducting linac delivers a wide variety of heavy ion beams to several experimental areas for basic research in nuclear physics. The chart above in Fig. 1 shows the beams used for research in FY1993.

Most of these beams are produced in the ECR ion source of the Positive-Ion Injector shown in the facility layout in Fig. 2 below. The low energy beamline between the ECR ion source and the injector linac must be tuned to match the horizontal and vertical emittance ellipses at the linac entrance. The present work is directed towards developing a simple and rapid method of measuring both the transverse emittance envelopes and the ellipse orientation parameters at the linac entrance.

A very simple method of measuring the x- and y- emittances and ellipse parameters is the "three gradient" method discussed, for example, by Qian, et al. [1,2]. The method consists of measuring the x- and y- beam envelope widths at a profile monitor downstream of an adjustable quadrupole magnet, as a function of the quadrupole gradient or current. The basic elements of the method are shown schematically in Fig. 3 below. The scanner which displays the beam profiles at the indicated position is a commercial moving-wire device marketed by the National Electrostatics Corporation. The beam profile displayed as a function of z in Fig. 3 is one calculated from measurements done for one of the beams listed below in Table I.

II. BEAM OPTICS ALGORITHM

The algorithm for extracting the beam parameters from beam width measurements was presented, for example, in reference [2]. We have written a Mathcad routine to process our data assuming the beam can be represented by ellipses in the xx' and yy' transverse planes.

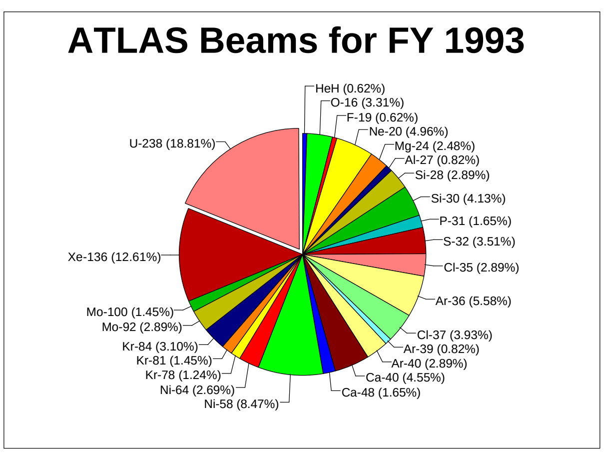


Figure 1. Chart showing the types of ion beams and the relative number of hours that each was used for research in fiscal year 1993.

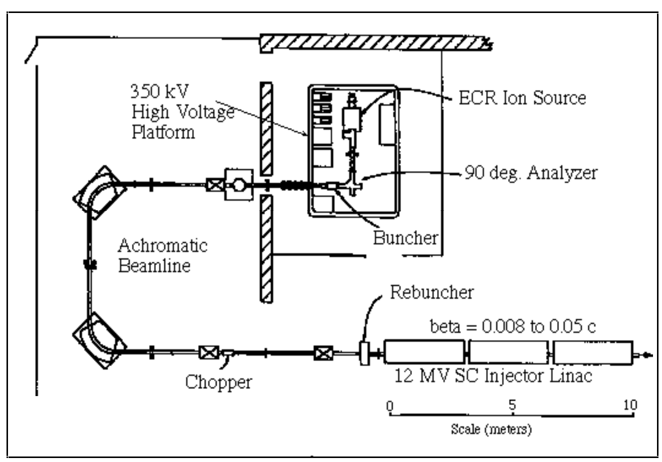


Figure 2. Layout of the Positive-Ion Injector of ATLAS. The emittance measurements reported here were made at the profile monitor located at the Injector Linac entrance, just after the rebuncher in this figure.

*Undergraduate Research Participants, supported by the ANL Division of Educational Programs.

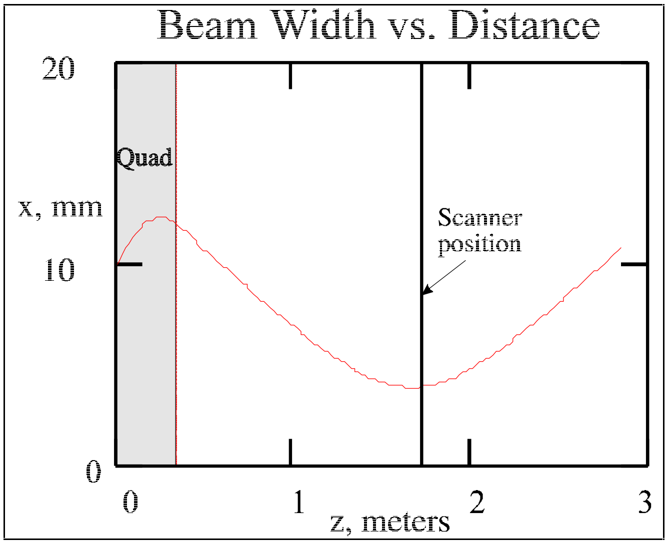


Figure 3. The essential elements of the "quad-drift" or "three-gradient" method of measuring beam emittance envelopes. The actual calculated beam profile vs. distance for one of the cases measured below is shown here.

The beam emittance, ε, and the phase space ellipse parameters, in the Courant-Snyder notation, are related by:

$$\varepsilon = \gamma \cdot x^2 + 2 \cdot \alpha \cdot x \cdot x' + \beta \cdot x'^2 .$$

The Courant-Snyder parameters are also related by:

$$\beta \cdot \gamma - \alpha^2 = 1 .$$

Hence, there are three independent parameters to be determined about the beam. The beam ellipse can be expressed in matrix notation as the sigma matrix:

$$\boldsymbol{\sigma} \equiv \varepsilon \cdot \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}.$$

The matrix equation for propagation of the sigma matrix through a section of beamline represented by the transformation matrix **R** is:

$$\boldsymbol{\sigma}_1 = \mathbf{R} \cdot \boldsymbol{\sigma}_0 \cdot \mathbf{R}^{\mathrm{T}} \qquad (1)$$

where $\boldsymbol{\sigma}_0$ is the initial sigma matrix and $\boldsymbol{\sigma}_1$ is the final. For the simple quad-drift geometry used here the transformation matrix (in the focusing plane of the quadrupole) is:

$$\mathbf{R} = \mathbf{D} \cdot \mathbf{Q}_{\mathbf{f}} ,$$

with

$$\mathbf{Q}_{\mathbf{f}} = \begin{pmatrix} \cos(kw) & \frac{1}{k} \cdot \sin(kw) \\ -k \cdot \sin(kw) & \cos(kw) \end{pmatrix} \text{ and } \mathbf{D} = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}.$$

Using the fact that the beam half-width, x_{max} , at the scanner location is related to the ellipse parameters by:

$$x_{\max} = \sqrt{\beta \cdot \varepsilon} ,$$

a series of measurements of x_{max} at the scanner location as a function of the quadrupole strength data can be used with equation (1) to solve for the three independent beam ellipse parameters at the entrance to the quadrupole. If more than three gradients and widths are recorded a least squares fit for the best parameters is done. Typical input and output parameters are presented below. The matrix equations and the least squares fit are done with a Mathcad routine.

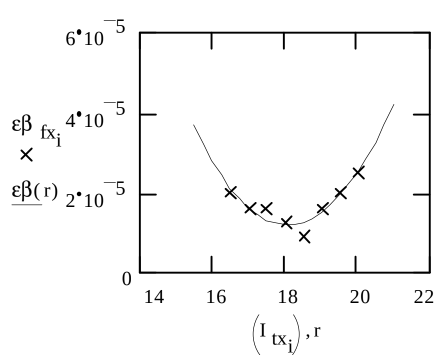
III. RESULTS

A typical array of input data, quadrupole currents and corresponding base-base beam widths in the x-plane are:

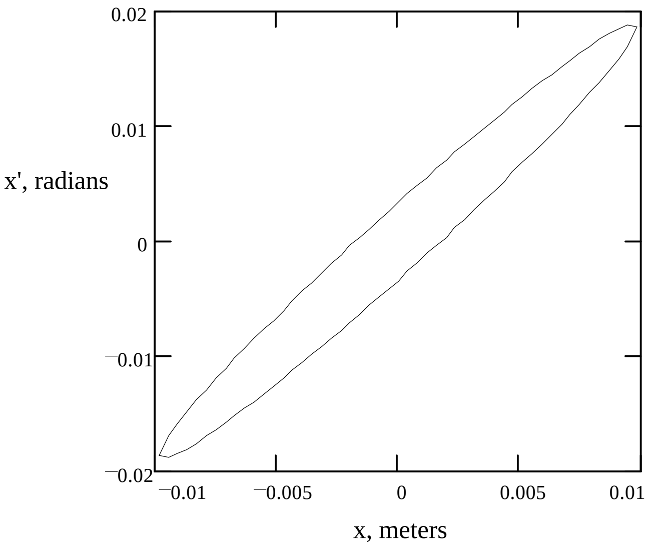
$$\mathbf{I}_{\mathbf{x}} = \begin{pmatrix} 16.5 \\ 17.0 \\ 17.5 \\ 18.0 \\ 18.5 \\ 19.0 \\ 19.5 \\ 20.0 \end{pmatrix} \text{ Amps} \qquad \mathbf{X}_{\mathbf{bb}} = \begin{pmatrix} 9 \\ 8 \\ 8 \\ 7 \\ 6 \\ 8 \\ 9 \\ 10 \end{pmatrix} \text{ mm.}$$

There are corresponding data for the y-dimension which are not shown here.

The least-squares fit to the parameter $x^2 \equiv \beta\varepsilon$ yields the following fit to the data:



And the following plot of the ellipse in the x-plane at the entrance to the quadrupole:



normalized emittance:

$$\varepsilon_{nx} := \frac{v}{c} \cdot \varepsilon_x$$

$$\varepsilon_{nx} = 2.819 \cdot 10^{-7} \quad \pi \text{ m-rad}$$

$$\varepsilon_{nx} \cdot 10^{6} = 0.282 \quad \pi \text{ mm-mrad}$$

The numerical results for five beams measured with these method are listed in Table I. The values for the x- and y-normalized emittances vary from 0.14-0.54 π mm-mr. This range of values is typical for ECR ion sources [3-8]. These values are also in the range expected due to the axial magnetic fields of such ion sources [6-8]. The smallest emittances from ECR ion sources occur for the lowest and very highest charge states of a given ion type [8].

The sample data in the example above are from the $^{238}U^{26+}$ beam of Table I. The beam envelope plotted in Fig. 3 is also for this uranium beam. Since these data are for the x-plane, and the quadrupole is focusing in this plane, the tilt of the ellipse shown above at the quadrupole entrance corresponds to a diverging beam.

Table I . Emittances Measured for Five Beams*

Beam	ε_x	ε_{xn}	ε_y	ε_{yn}
$^{12}C^{4+}$	56	0.48	35	0.30
$^{16}O^{6+}$	22	0.19	16	0.14
$^{130}Te^{22+}$	32	0.27	28	0.24
$^{208}Pb^{23+}$	37	0.30	63	0.54
$^{238}U^{26+}$	33	0.28	34	0.29

*All values in π mm-mr and beam velocities were 0.008c.

The uncertainties on the emittance values given in Table I have not been estimated quantitatively. Currently the largest uncertainties are associated with reading the base-base beam widths from the profile monitors. A qualitative indication of the uncertainties in the emittance values was obtained by randomly changing the beam width data within a range of ± 1 mm and refitting. The variations in the fit results were on the order of 10% or less. Digitization of the analog signals from these monitors will be implemented to permit computer automation of the emittance measuring process.

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