RESULTS OF BEAM MEASUREMENTS AT THE SUPERHILAC*

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Introduction

The SuperHILAC has been operating on a limited basis since April 1972. Beam studies which have been made so far have consisted of measurements of the beam as tuned up to deliver maximum beam to the experimental area. We have been interested in seeing how the properties of these beams agree with our expectations. Studies have been made of 1) injector emittance and injection line transmission properties, 2) acceptance and transmission of the linac cavities, 3) measured emittance, and 4) tuning properties. With respect to studies that have been made so far, the SuperHILAC behaves about as expected. At an rf duty factor of 6%, a 7.2 MeV/A carbon beam of 1.1×10^{13} pps has a measured emittance of 0.9π cm mrad and a FWHM energy spread less than 1%. Raising the duty factor to 30% and adding a buncher will increase the intensity by at least a factor of 10.

SuperHILAC Components

The major rebuilding of the Berkeley HILAC, causing it to be dubbed the SuperHILAC, was described by Robert Main at the last Linac Conference. (1) There are two injectors, each with its own transport system (See Fig. 1). Injector I1 is a pressurized high-voltage generator for the acceleration of ions of mass $A \geq 40$. (2) It operates at voltages up to 2.5 MV to accelerate ions to prestripper injection energy of 113 KeV/A. The injector I2 is a conventional Cockcroft-Walton for acceleration of ions of mass numbers ≤ 40, requiring up to 750 KV. I2, and its associated transport system T2, were used for the measurements described in this paper. The accelerating column axis of I2 is perpendicular to the prestripper axis and 0.7 m above it. The magnet T2M bends the beam 90° in a horizontal plane and 15° downward. The magnet PM1 then bends the beam again so as to align it with the prestripper axis, which lies in a horizontal plane. PM1 also bends the beam from I1, which arrives from below, into the prestripper axis. Line T2 contains two triplets for focusing and 5 dipoles for alignment steering. The line is operated dc; to date no buncher has been used.

The prestripper is an Alvarez linac, 3 m in dia. by 18.6 m long, which accelerates ions to 1.2 MeV/A. It is divided into two electrically independent tanks, of which the first, a short one, is 4.2 m. Focusing is by magnetic quadrupoles excited in the +-+-.... (N=1) configuration. Four alignment magnets are installed in the prestripper, BAH1, BAH3 for horizontal steering and BAV2, BAV4 for vertical steering (Fig. 1). The minimum q/A accepted by the prestripper is .046; for this q/A, and for $\varphi_s = -20^\circ$, the first tank requires an average electric gradient of 1.35 MV/m, the second tank 1.8 MV/m.

A transport system C, 3.7 m long, is provided between pre- and poststripper. Four quadrupole singlets are used for focusing and matching. Four dipoles are used for alignment steering. Beams from I1 need to be stripped here; beams from I2 do not.

The poststripper is an Alvarez linac 30.9 m long. It contains 5 partitions which divide the linac into 6 independently driven tanks of approximately equal length. At present the maximum energy is given by tank D7 and is nominally 7.2 MeV/A. In the near future the addition of a rf station to D8 will raise the energy to 8.5 MeV/A. The minimum q/A is 0.17, requiring an average electric gradient of 1.8 MV/m for full acceleration.

Injection System

Heavy ion injectors have inherent problems from which proton injectors are immune. The ion source of I2 consists of a penning type arc discharge with high voltage extractor which supplies a beam containing many charge states of the ion desired as well as ions of any contaminant present in the arc - such as from a compound source gas. The source analyzing magnet I2M, followed by a collimator can separate the desired q/A to a resolution of about 12%. However, charge exchange processes can result in many neighboring charge states reappearing in the beam following analysis. For this reason, additional bending magnets in the injection line are essential for the best operation of a heavy ion linac. Fig. 2 shows a simple example of an argon beam emerging from I2, which has been analyzed by T2M. In this case although argon 7+ is the ion desired, 6+ is more abundant in the source. The 5+ should be rejected by the source magnet, and in this case is probably due to a recombination of 6+ ions before acceleration by the column.

Injection transport. A calculation of the beam profiles expected in the injector I2 and injection transport system T2 is shown in Fig. 3. The important features are: a waist, in both x and y, at three places: inside the column, at the center of T2M, and at the prestripper entrance. It proves to be easy to tune the triplets for maximum transmission. Reproducibility, as judged by quadrupole currents, is difficult to achieve. This is because when the beam is off-axis (and for one reason or another it often is) the focusing action of the column and of T2M are changed. It has been found that making the column weaker in focusing by lowering the gradient to half value for a distance of one-tenth of the column length, results in beam of greater intensity and better quality reaching cup T2XC1 at the column exit. It is important that the beam be centered at the column entrance, and be aimed along the column axis. Steering dipoles at the column entrance are necessary in order to accomplish this.

Injector Tuning and Reproducibility. Selection of the proper charge state ion is easy with system T2. As the beam rigidity is then known from the 90° bending magnet, the Cockcroft-Walton voltage does not need to be precisely calibrated. Focusing for maximum transmission can be accomplished satisfactorily with the aid of a faraday cup, BXC, at the prestripper entrance. Injector beams with the same q/A reproduce satisfactorily, but beam performance does not scale with q/A. The injector and transport parameters must be optimized anew for each ion.

Injector Emittance Measurements. Two carbon paddles, T2XP1 and T2XP2 were used. Each paddle contained a slit 1.6 mm wide. Paddle separation was 30 cm. They were operated remotely using electric motors. Position readout was by linear potentiometer, accuracy ±0.1 mm. For a measurement, one slit was fixed at successive positions along a line transverse to the beam axis, and at each position the other slit was used to scan the beam. The beam transmitted through both slits was read on a downstream faraday cup. The faraday cup signal and the linear pot signal were digitized and punched on paper tape for later analysis. With the knowledge of slit positions at the time a given beam current was read, the transverse emittance could then be calculated. A single emittance measurement required about 15 minutes. Repeated checks showed no significant change in beam properties over much longer periods. After measurements were made in a horizontal plane, the paddles were rotated 90° around the beam axis and the measurements were repeated with the same tuning conditions. Emittance curves obtained for a beam of carbon ions are shown in Figs. 4 and 5, as the solid curves. The contours refer to beam properties at the fixed slit T2XP2, but of ions which are actually transmitted through T2 and are measured on cup BXC. The emittance area of a carbon beam is seen to be 7.2π cm-mrad in the horizontal plane, 5.7π in the vertical plane. The curves indicate the point at which ion intensity was 2% of maximum. The beam intensity distribution is shown in Fig. 6.

Transmitted Emittance. The transverse acceptance of the prestripper is a function of the transverse focusing strength θ_0^2, and also depends upon the degree which quadrupoles are misaligned. (3) For the beam used in these measurements $\theta_0^2 = 1.4$ in the prestripper. The calculated acceptance, assuming no misalignment is 11π cm mrad, as obtained using a PARMILA-type program. To get an idea of the actual transverse phase acceptance of the prestripper, the emittance measurements were repeated exactly as described above, but with faraday cup current from CXC2 read out instead of from BXC. Thus we are now taking data exactly as before, again showing what the emittance looks like at T2XP2, only now in terms of the surviving ions that reach CXC2. The beam intensities are not directly comparable because of longitudinal losses - rf trapping efficiency is about 25% for carbon. After a suitable normalization curves, were obtained which are also shown in Figs. 4 and 5, as dotted lines. These curves show that, within the uncertainty of the measurement, the prestripper acceptance is adequate to transmit all of the beam.

A third set of measurements was made, this time using faraday cup EXC1 at the poststripper exit. The curves obtained are shown as dashed lines in Figs. 4 and 5. Transmission in the y plane is excellent, but a considerable loss of area occurs in the x plane. At present we do not understand the cause of this.

Prestripper

Tuning. Quadrupoles are energized so that the transverse focusing forces, which are proportional to $B'\ell$ (gradient times effective length), are constant. The first and last quadrupoles are shunted so as to run at one-half this $B'\ell$ in order to obtain the best matching conditions. A value of $B'\ell$ is chosen such that the operating point for the linac lies inside the region of stability for N=1, as given by the matrix theory of transverse stability.(4) This theory appears to be accurate in predicting stability boundaries. If transverse focusing were the whole story, the prestripper magnets could be operated passively, i.e. no tuning would be required. Unfortunately the quadrupoles do more than focus. Small quadrupole misalignments can cause a wandering of the beam relative to the linac axis serious enough so that beam would be scraped off on the drift tube bore. Also changing the electric gradient level will cause focusing and steering effects. In order to provide sufficient tuning to cope with these effects, a power supply connecting the first five quadrupoles in series, and a power supply connecting the last five quadrupoles in series are used, as well as the four dipoles BAH1, BAV2, BAH3, BAV4. These six tuning parameters, together with the two tank gradients and the relative tank phase appear to be adequate for the optimization of beam quality.

Prestripper Emittance. The emittance of a 1.2 MeV/A carbon beam was measured at CXP using the slotted plate apparatus, see below, with sensitized paper at CXG. Results are shown in Fig. 7. An estimated 95% of the beam lies within 1.5π cm mrad in the horizontal plane and 1.8π in the vertical plane, with about ±0.5π uncertainty in each figure. These areas can easily be transported through area C without loss. Fig. 8 shows the result of a calculation which attempts to reconstruct the beam envelopes in this area using ellipses, fitted to the data of Fig. 7, and measured quadrupole currents which were converted to appropriate magnetic gradients. A surprising feature of this beam is that it emerges from the prestripper with a small waist in both planes, and with larger divergence than would be expected from the magnitude of the transverse focusing forces. Figure 9 shows the beam size we would expect for $\theta_0^2 = 1.4$ in the prestripper. At the prestripper exit there is a waist in each plane of about 7 mm. One way to explain the much smaller waist size which was measured is to take into account the effect of acceleration on the transverse focusing. According to some computer runs which have been made, interaction between transverse and longitudinal forces can produce a modulation of the beam envelope in the linac. This coupled motion has been studied by Ohnuma (5) and others. Whether not this coupling can explain the present observations is not known. Some more observations and some more calculations might answer this question. Another bit of evidence which points to important longitudianl-transverse coupling effects was obtained when a scintillating screen was placed in the area C, near CXC2. It was observed that changing nothing but the electric gradient in tank B2 caused the beam image to move laterally on the screen. On some occasions the sensitivity was such that a centimeter of lateral motion could be accomplished by varying the gradient by only a few percent.

Poststripper

Tuning. Transverse matching of the beam to the poststripper entrance is done with the four quadrupoles in area C. Corrections to beam alignment are made with the four dipoles in this area. However, the area C transport system is too short to permit making all of the changes to the beam necessary for best acceptance. It is usually necessary to go back and retune the prestripper and the injection transport system to get the best beam. Poststripper quadrupoles are also set for θ^2 = const. Commonly, the value of $\theta_0^2 = 0.6$ is used, which corresponds to a long betatron wavelength and makes the beam less sensitive to perturbations in the focusing structure, such as those caused by missing quadrupoles. Just as is done with the prestripper, two sets of quadrupoles are used for tuning control. The entrance set contains 12 quadrupoles in series, the exit set 7 in series. No dipoles have been provided inside the poststripper tanks for steering control. Since the emittance transmission measurement (Fig. 4) indicates some losses which could be attributed to beam wandering we consider that addition of such magnets might be beneficial. However, understanding beam steering behavior in the poststripper is not simple, because the many separately excited rf cavities also contribute.

Poststripper Emittance. Measurements have been made of the carbon 2+ beam, with results shown in Figs. 10 and 11. A slotted plate was used at EXP, with a glass slide at EXG, as described below. Energy is 7.2 MeV/A, peak current 80μA, duty factor 6%. Essentially all of the beam lies within 1.9π cm mrad in the horizontal plane, 1.7π in the vertical, but much of this area is due to a low-intensity halo which, very likely, is the result of imperfect tuning of rf in the tanks D3, ..., D7. The curves labeled 70% are measured at 30% of peak intensity, and include most of the beam. They exclude this low intensity halo, and are our best measure of poststripper emittance, 0.9π cm-mrad in each plane. The divergence of this beam is small, falling within a total angle of 5 mrad. This low divergence allows the beam to travel from DQ75, the last focusing quadrupole, to faraday cup EXC2, a distance of 7 meters, without appreciable loss. It is unlikely that this result is fortuitous but rather the outcome of the tuning process, the mechanisms of which we do not as yet fully understand.

Energy Tuning and Measurement. Two tools have been helpful for setting rf gradient and phase in the poststripper. One is a crystal placed at a small angle to the exit line at EXE. A gold foil can be inserted into the beam at this point so that a few ions are elastically scattered into the crystal giving an output proportional to total energy. Pulses are displayed on an oscilloscope. This device is useful for studying the behavior of each tank in trapping and accelerating particles. For example when tuned for full energy, the effect of mis-tuning the gradients and phases is to cause particles to slip out of acceleration and drift on through the machine at some partial energy.

Use of the poststripper to obtain energies that are continuously variable above 2.6 MeV/A appears to work as expected, and as was described at the last Linac Conference. (6)

Measurement of energy spread at full energy gives a FWHM less than 1%. Somewhat greater widths are observed at lower energy. Here the contribution to energy spread by the crystal, scatter foil and electronics is not negligible, and we must make a more careful measurement than we have done so far to get an accurate energy spread.

Another tool which is most useful in energy tuning is the magnet EM2, which when bending through a large angle into a faraday cup, eliminates unwanted charge states and energies and permits maximizing beam intensity at the desired energy.

Tank phase, with reference to tank B2, is regulated to ±1 degree. Electric gradient amplitude is regulated to ±0.5%. This is adequate, although we believe that better beams will be obtained with improved regulation of gradient.

Slotted Plate Measuring Equipment

A thin (1.25 mm) aluminum plate has cut in it a series of parallel slots 0.2 mm wide, spacing 2.5 mm on centers. A recording screen is placed 0.5 m downstream. The spacing of the slots and the distance to the screen are chosen so that no overlapping of images occurs.

In area E ordinary glass is used as a recording medium. At 7.2 MeV/A an incident beam exposure of about 5 particle μA-sec/cm^2 produces a satisfactory image of the slots in the form of a brown discoloration in the glass. The darkening appears to be proportional to beam intensity. These images are scanned with an optical micro-densitometer to get a graphical output of intensity vs. position. These records are then used to obtain the emittance area as it appears at the slotted plate.

At 1.2 MeV/A in the area C, glass does not darken. Treated paper gives a contrasty image which can be measured directly but which is not as satisfactory in recording detail. We have found that a clear plastic film, said to be mylar, does darken. This will probably give better results than treated paper because it can be scanned with the microdensitometer.

Acknowledgments

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calibration of the crystal detector energy measuring apparatus.

References

(1) R. M. Main, Proceedings of the 1970 Proton Linear Accelerator Conference pp. 949-970.

(2) D. A. Spence et al, Proceedings of the 1971 Particle Accelerator Conference pp. 97-101.

(3) F. B. Selph, Proceedings of the 1971 Particle Accelerator Conference pp. 538-539.

(4) L. Smith and R. L. Gluckstern, Rev. Sci. Instr. 26, (1955) 220-228.

(5) S. Ohnuma, Proceedings of the 1966 Proton Linear Accelerator Conference, pp. 214-219.

(6) F. B. Selph, Proceedings of the 1970 Proton Linear Accelerator Conference, pp. 869-879.

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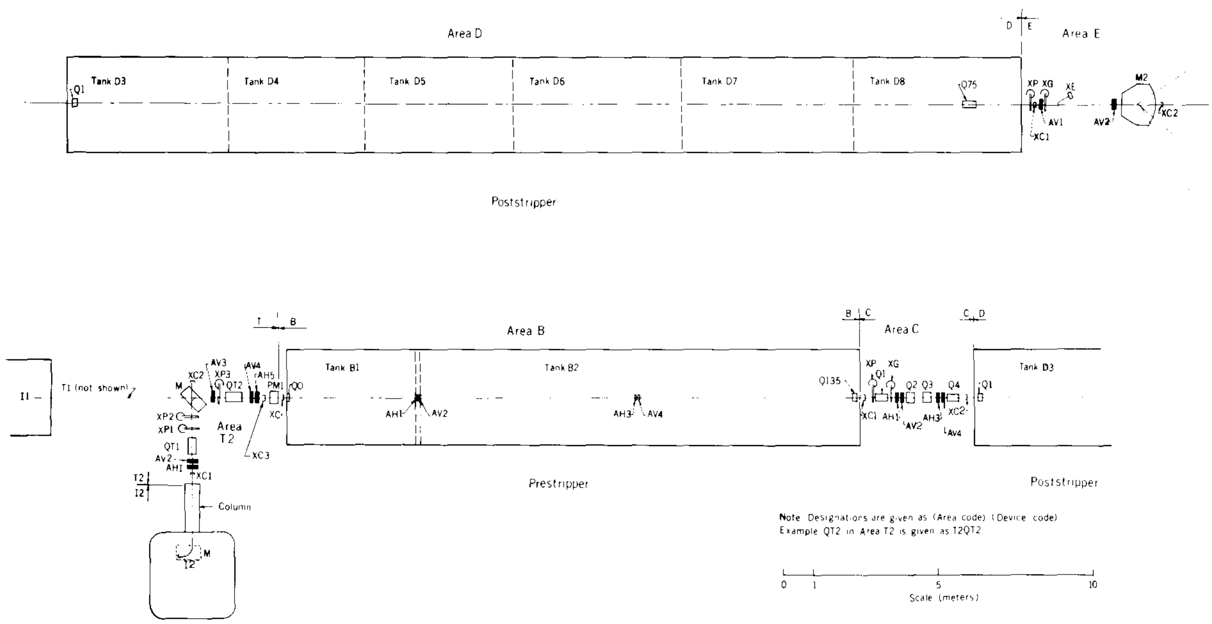

Fig. 1. Schematic plan of SuperHILAC showing beam handling components with their designations.

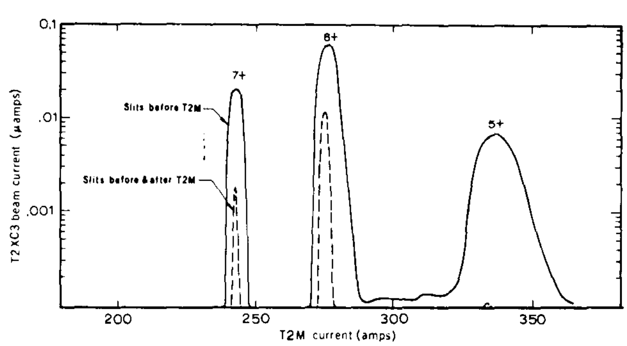

Fig. 2. Analysis of an argon beam in the T2 injection line. Charge states 5,6,7 are resolved.

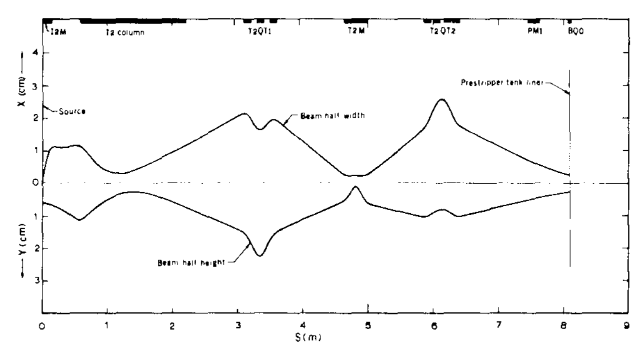

Fig. 3. Calculation of beam envelope in the injector and transport line.

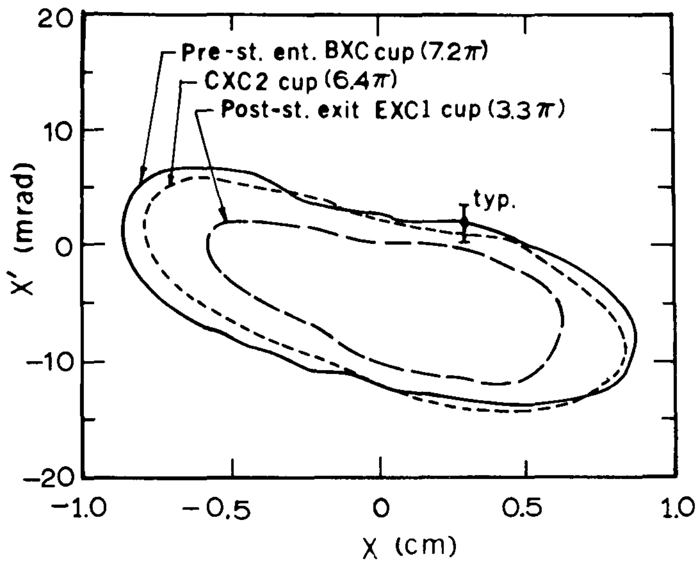

Fig. 4. Measurement of injector emittance for a carbon beam (horizontal plane) and of transmitted emittance to area C and area E.

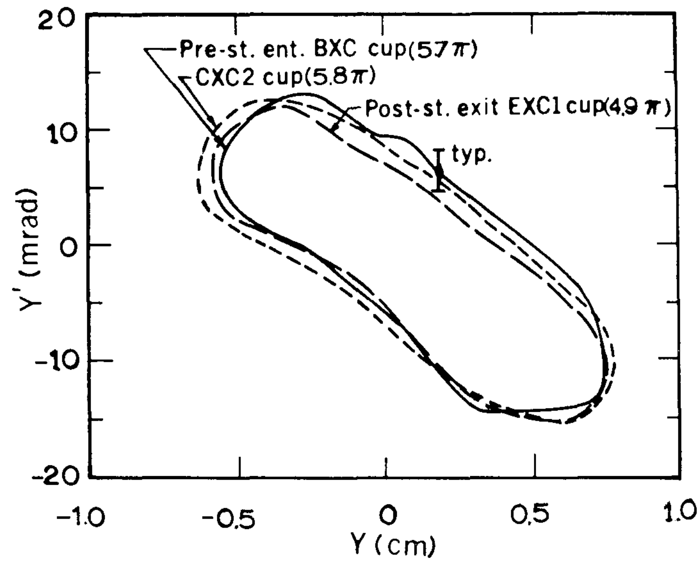

Fig. 5. Measurement similar to Fig. 4, in the vertical plane.

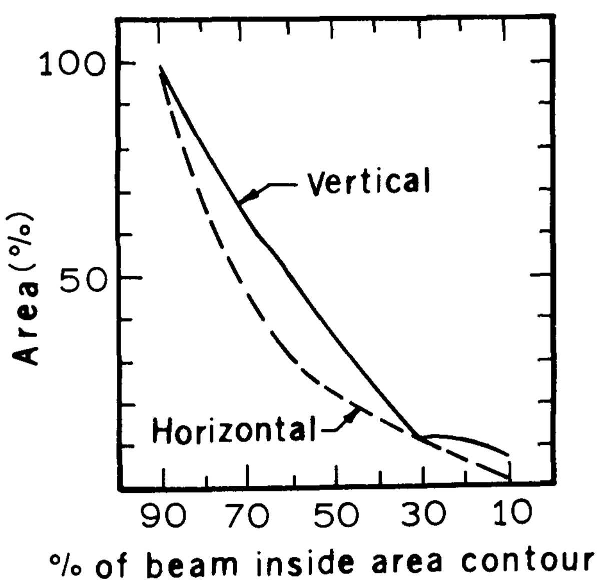

Fig. 6. Beam intensity distributions for the emittance curves of Figs. 4 and 5.

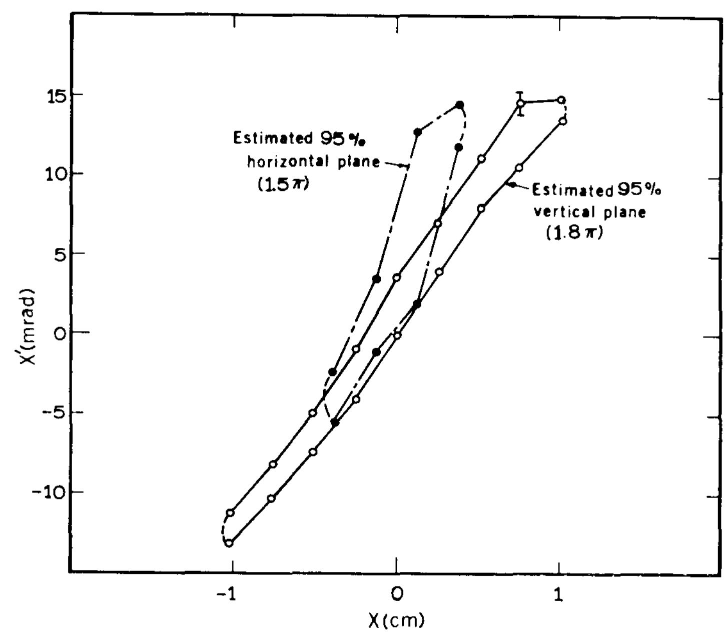

Fig. 7. Emittance for a carbon beam, measured in area C.

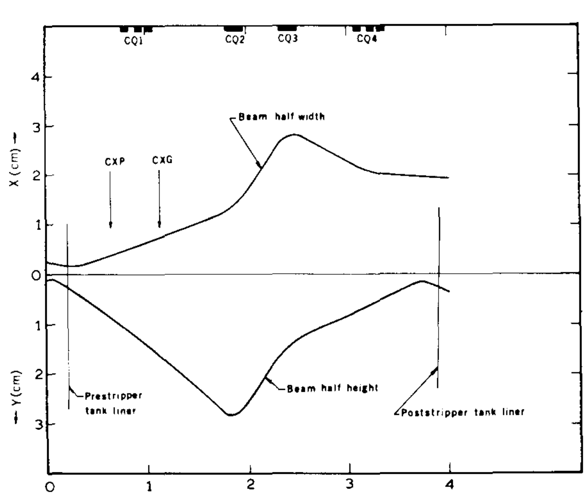

Fig. 8. Beam profile in area C extrapolated from measured emittance and quadrupole excitations.

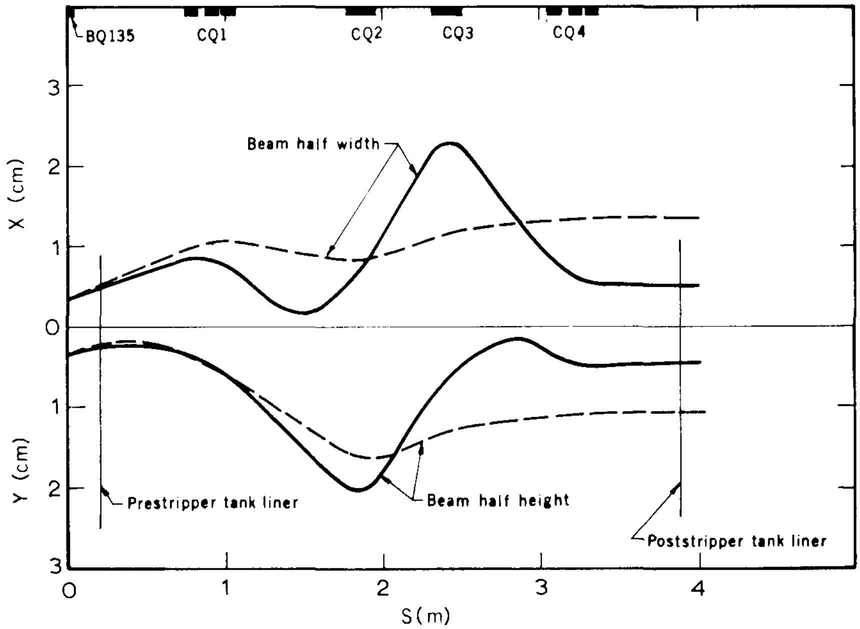

Fig. 9.
Calculated beam profiles in area C, assuming linac transverse focusing forces are decoupled from longitudinal forces. The curves result from different quadrupole strengths assumed for the poststripper; solid lines $\theta_0^2 = 0.61$, dotted lines $\theta_0^2 = 0.43$.

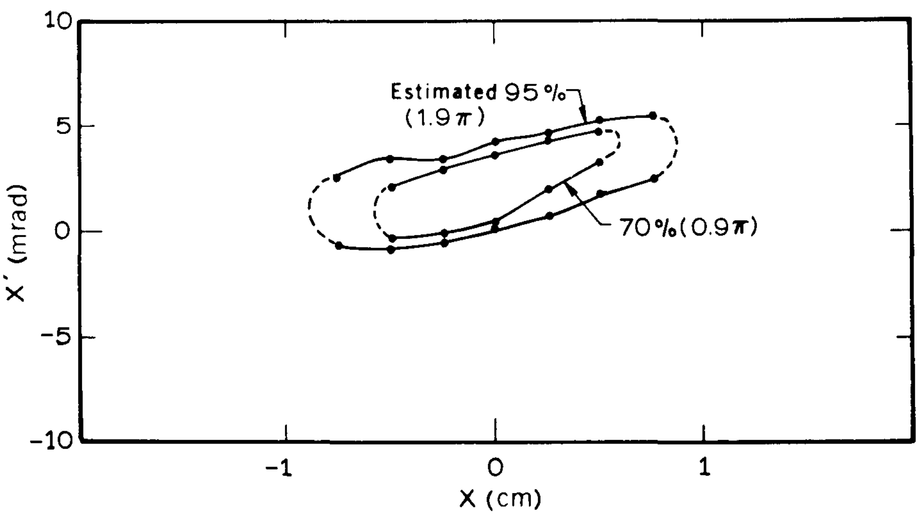

Fig. 10.
Measured emittance at 7.2 MeV/A in area E (horizontal plane).

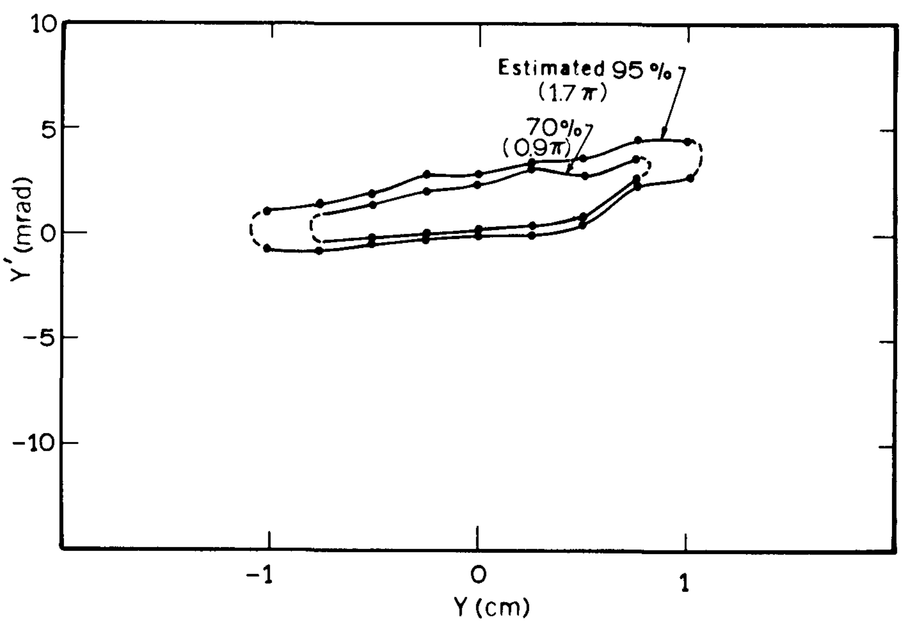

Fig. 11.
Measured emittance at 7.2 MeV/A in area E (vertical plane).