INITIAL OPERATION OF THE BEAM-TRANSPORT SYSTEM IN THE LAMPF INJECTOR COMPLEX*

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ABSTRACT

The high-intensity proton beam line in the LAMPF injector complex has been constructed and is now in operation. This beam line, which is part of the planned dual beam transport system, employs four bending magnets and six quadrupole focusing lens systems in order to transport 750-kV proton beams a distance of 12 meters from a Cockcroft-Walton (C-W) high-voltage generator to the first tank of a drift-tube linac. The beam line is capable of transporting beams of 50-mA current with several cm-mrad emittance.

Of particular interest is the use of quadruplet matching elements in order to obtain more versatile beam handling and the use of two buncher cavities for longitudinal phase space matching to the linac.

A variety of beam diagnostic devices and automatic control systems has been planned for use in the beam line. The results of initial operation and beam measurements will be presented.

Introduction

The high-intensity proton beam-transport system in the injector complex of LAMPF has successfully transported full power proton beams required for LAMPF from the Cockcroft-Walton (C-W) injector to an intermediate beam stop in the system. Detailed beam diagnostic studies on this beam line are now being carried out together with beam studies on the first tank of the drift-tube linac. The operation of this initial portion of LAMPF at full beam power will be carried out after the buncher cavities are in operation.

Basic Design

A layout showing the proton beam-transport line is presented in Fig. 1. The beam line is modular in concept and may be divided into five sections, all having waist-to-waist transfer from one module to another. The system basically functions in order to (1) transport and match the beam extracted from the accelerating column to a

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90° bending module, then (2) transport the beam from the exit of this module to a pair of beam translation magnets, and subsequently (3) translate the beam into the final common beam line, and finally (4) match the beam to the required phase space acceptance of the drift-tube linac. The beam profiles predicted for a 25-mA, π cm-mrad emittance beam are shown in Fig. 2. These profiles were calculated using the LASL beam transport code BEAMCAL and its variant BEAMY-17 for bunched beams. These codes, which are based on a Kapchinskij-Vladimirskij[1] phase-space distribution, calculate the beam envelopes and quadrupole magnet gradients required for a specified transport system. The calculations in the latter portions of the high-intensity proton beam line have been checked using the linac code, PARMILA, and the profiles obtained were in good agreement with these envelope calculations.

The choice of a modular, waist-to-waist transfer beam line was made in order to make the x and y beam profiles more nearly equal over most of the beam line so as to minimize aberrations associated with the transport of eccentric, high current beams. This design also permits easier determination of the beam properties at various points along the beam line. The layout of the beam line was dictated by the requirements of future beam lines in the planned dual beam transport system.[2] The design procedure was to calculate the transport of circular beams through this transport line with appropriate waists being formed at the two buncher cavities.

Two quadruplet focusing lenses have been employed in this beam line in order to achieve greater flexibility in matching various input beams to specified waists. Design calculations carried out with the transport code, BEAMCAL, showed that for a fixed magnet layout, a quadruplet focusing system permits matching of any beam extracted from the accelerating column to a specified double waist. Initial beam diagnostic studies demonstrate the flexibility afforded by this system, although beams with as small a double waist as indicated on the profiles shown in Fig. 2 have not yet been obtained. Similar calculations were carried out for the quadruplet in front of the beam translation magnets.

The beam line will incorporate two buncher cavities, a prebuncher and a main buncher, each operating at 201.25 MHz. The initial prebuncher cavity will operate at relatively low power levels and will be used to facilitate beam diagnostic studies in the longitudinal phase space of the drift-tube linac. It is expected that the use of the prebuncher will also result in greater bunching efficiency and possibly less beam loss at the high-energy portion of the linac. The main buncher cavity has just been installed, and initial operation indicates that this cavity increases the transverse phase-space emittance by less than π cm-mrad at design proton current.

Consideration of dispersion in the bending magnets is not an important factor in the design of this beam line since the energy spread in the beam coming from the C-W generator is less than 0.1% at 750 keV. The prebuncher will introduce approximately ± 4 keV of energy spread when it is operating, but this spread is reduced to ± 1 keV when the beam subsequently reaches the beam translation magnets by virtue of the space charge repulsion that will take place in the partially bunched beam. The subsequent effect of the dispersion in these magnets is expected to introduce less than 0.5 π cm-mrad emittance into the beam.

Description of the Beam Line

A photograph of the beam-transport system as initially constructed is shown in Fig. 3. This system employs six magnetic quadrupole lens systems and four horizontal bending magnets. The quadrupole lens systems employ long, low field quadrupole magnets in order to minimize aberrations in this long transport line.[3] The horizontal bending magnets have bending radii of 0.5 meter and nominally run at 2.5 kilogauss. The quadrupole magnet gradients are uniform to 1/500 for beams of interest, and the bending magnet fields have $\int Bdl$ uniform to 1/2000. Sufficient margin on magnet strengths was specified so that H_2^+ beams could also be transported. Vacuum considerations favored the use of 3-in. diam beam tubing so that there is almost a factor of three margin in the required aperture of the quadrupole lenses. Bending magnet gaps of 1.75 in. were specified so that the beam clearance in the bending magnet vacuum chambers is almost twice the maximum size of the beam at these points. The only other constrictions in the beam line are three beam scrapers which serve as beam-position monitors and have a 0.75-in. square aperture. Two of these beam scrapers are located in the buncher cavities and will prevent any beam impingement on the cavities. High-conductance pumping is provided around the small apertures so as not to limit the pumping speed of the beam line at these points.

Six 200-liter/sec ion pumps are used along the 12.5-meter length of beam line. The pumps are conductance limited and provide a base vacuum of 2×10^{-7} torr under normal operating conditions, except at the initial section of beam line at the exit of the accelerating column which runs at 5×10^{-6} torr when the ion source is in operation. The beam-line vacuum system is divided into four sections by in-line gate valves which permit a given section to be let up to atmosphere. Most components in the beam line are of stainless steel construction and were either vacuum baked or hydrogen fired before insertion into the beam line. The only difficulties encountered with the vacuum system have arisen from minor leaks in the beam scraper elements and excessive outgassing from additional beam diagnostic equipment, which has recently been put into the beam line without a vacuum bake.

A number of beam diagnostic tees and beam boxes have been installed in the beam line in order to permit convenient insertion of a variety of beam diagnostic elements into the system. Viton O-rings with a thin film of Apiezon L vacuum grease have been used as sealing gaskets for beam-line joints while copper gaskets and standard vacuum flanges have been used on the beam diagnostic tees. Insulating vacuum joints have been built into the beam line at beam current transformer locations by means of anodized aluminum rings; care has been taken to shield all insulators in the beam line from the beam. An insulating section of beam line has been installed at the exit of the Faraday cage of the C-W high-voltage generator to isolate the rest of the beam line from the high-voltage generator. No difficulty has been experienced with extraneous voltage pulses getting into beam-line equipment upon sparkdown of the C-W generator, except for minor disturbances in computer circuits.

A variety of beam diagnostic equipment has been included in this beam line to facilitate the efficient transport of these high current beams and subsequently to permit determination of beam properties. The initial tune-up of any beam in this system is carried out by observing the beam current along the beam line by means of six beam current transformers with 0.5 V/A sensitivity, while using five sets of steering magnets and three beam-position monitors to thread the beam through the transport line. Final tuning of a given beam is done by making small adjustments in the quadrupole lenses to optimize transmission and then by using beam diagnostic equipment to check the final beam properties. Each steering magnet set has both horizontal and vertical steering; three of the sets are conventional window-frame magnets, while the other two sets simply employ fine current control on two of the bending magnets in conjunction with special vertical steering magnets located in front of these bending magnets. Additional beam diagnostics may be carried out using viewing screens, pepper-pot emittance devices, and electronic emittance scanners. The electronic emittance scanners employ water-cooled jaws and current pickup electrodes powered by linear actuators and used in conjunction with a NOVA computer system. These scanners are described in another paper in these proceedings.

The beam transport elements are supported on stands and rails made of aluminum in order to prevent concentration of stray magnetic fields over the long transport line.

Power supplies with 0.03% current regulation have been used for the bending magnets and 0.05% current regulation for the quadrupole lens systems. The power supplies and control equipment are located directly below the beam transport line in a beam transport service area; all controls and beam line data are brought both to the injector control room and to the computer control room.

Initial Operation

During the past three months the high-intensity proton injector system has been providing beams both for studying the beam-transport system and for conducting tests with the first tank of the drift-tube linac. In general, the beam transport system has proven to be quite stable and reproducible in performance and has met most of the design goals. Full beam power tests into the linac will be conducted after the buncher cavities are in operation.

Proton beams at the design current of 25 mA and full duty factor of 6% have been transported to an intermediate stop at the exit of the first beam translation magnet. The beam-current transformer signals for this beam from various points along the beam line are presented by the CRO traces in Fig. 4. The transmission of the proton beam through this section of the beam line is better than 95%. Beam currents as high as 38 mA have been transported at low duty factor (0.3%) to this beam stop, although for most of the initial beam diagnostic studies 20-mA beams at 0.3 or 0.6% duty factor have been used. The transmission to the linac for these beams has been typically 90%; most of the beam loss occurs in the beam translation module.

Initial beam diagnostic studies were carried out with pepper-pot emittance measuring devices at low beam currents. In Fig. 5 is presented the pepper-pot pattern obtained at the straight-through exit of the first bending magnet in the 90° bending module with the initial quadruplet turned off. The three sets of dots are the H^+, H_2^+, and H_3^+ ion species present in the beam, which at design current (25 mA of protons) are in the ratio of 66/25/9. When the initial quadruplet is turned on, the proton fraction of the beam is preferentially focused, as shown in Fig. 6.

Further beam diagnostic work at higher beam currents has recently been started using the electronic emittance scanner. The details of the operation of the scanner are presented in another paper in these proceedings. The first experiments with this scanner were conducted at the entrance of the first 45° bending magnet where the initial quadruplet is to form a double waist 1.4 cm in diam. The beam size obtained with calculated gradients was approximately 3 cm in diam. The quadruplet was then adjusted to produce a smaller beam at this point by increasing the gradients of the first two lenses. The beam obtained was then 1.8 cm in diam with a waist in the x-x' phase space and a slightly converging beam in the y-y' phase space; this beam has been used in subsequent high current tests. The phase-space patterns obtained with this beam at this point are presented in Fig. 7. The discrepancy between calculated and observed beam sizes is believed to result from a larger initial beam coming into the quadruplet than was assumed in the calculation, possibly resulting from the H_2^+ contamination of the beam. The proton portion of this beam (the high central region) was 25 mA, while the other ion species (the long inclined pattern) were 13 mA.

Using this same beam, phase-space scans were then run at the entrance to the drift-tube linac and are presented in Fig. 8. The beam contains only protons (23 mA) at this point, the other ion species being lost at the first bending magnet. The lenses in the quadruplet at the entrance to the beam translation magnets were adjusted to produce a double waist at this point with ∿ 0.6-cm beam diam, as predicted in the design calculations. The wings evident in these phase-space plots are presumed to result from distortions in the plasma surface at the ion source. The tuning of the second quadruplet has proved to be much less critical than that for the first quadruplet.

Conclusions

The initial operation of the high-intensity proton beam line has demonstrated the capability of this system to transport the required proton beams needed for LAMPF with stable, reliable operation. Beam diagnostic studies confirm that the desired beams are being produced at the exit of the transport line but that the beam size in the initial portion of the beam line is larger than anticipated. Study of the transport of these beams is continuing.

References

1. I. M. Kapchinskij and V. V. Vladimirskij, Limitations of Proton Beam Current in a Strong Focusing Linear Accelerator Associated with the Beam Space Charge, Conference on High Energy Accelerators and Instrumentation, Session 3, p. 274, CERN, Geneva, 1959.
2. P. W. Allison, C. R. Emigh, and R. R. Stevens, Jr., The Injector Complex for the LAMPF Accelerator, Proc. of the 1969 Particle Accelerator Conference, p. 135.
3. P. W. Allison and R. R. Stevens, Jr., The Beam-Transport Design for the LAMPF Injector, Proc. of the 1968 Proton Linear Accelerator Conference, p. 364.

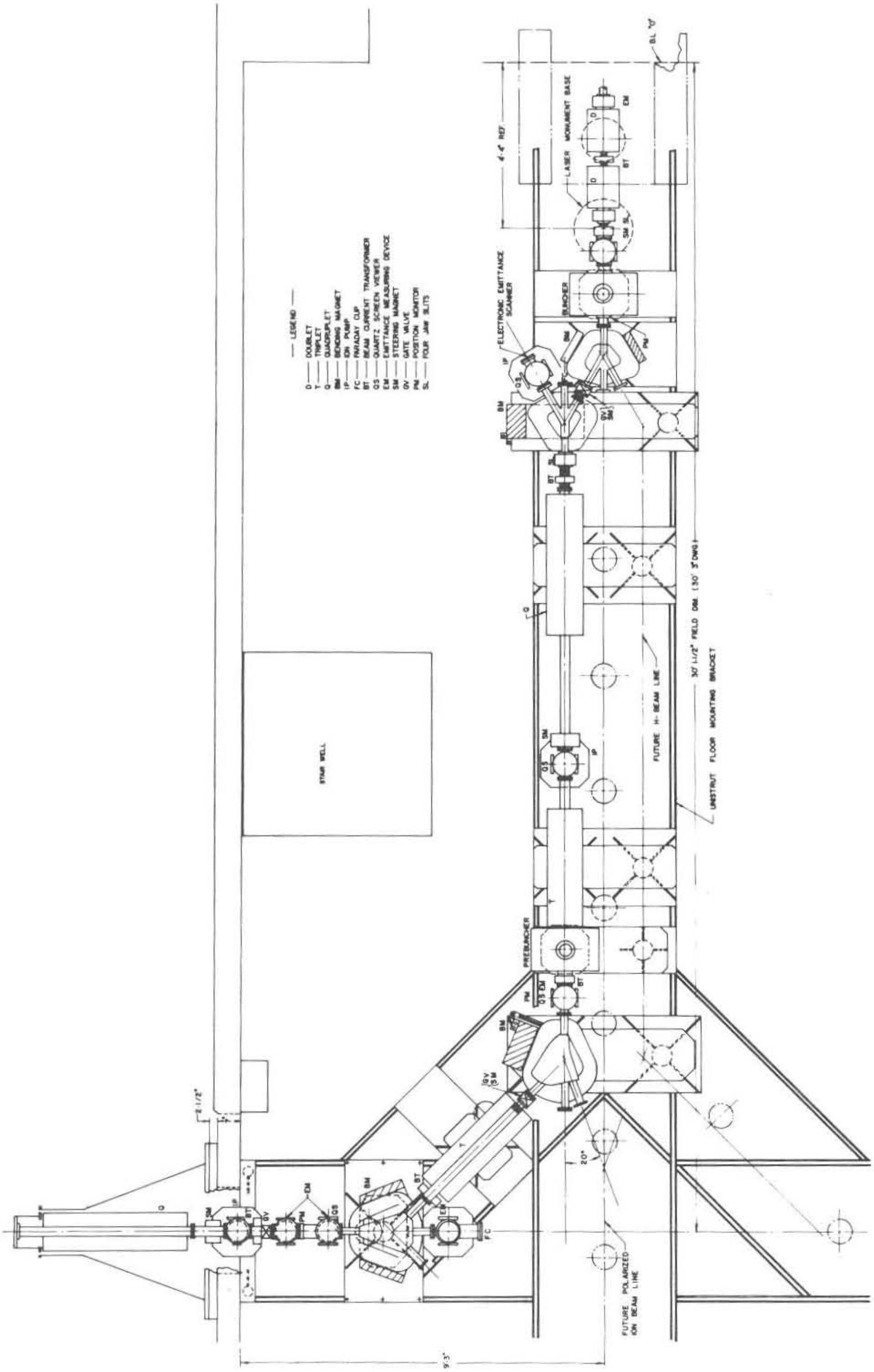


Fig. 1. Beam transport layout for the high-intensity proton beam line.

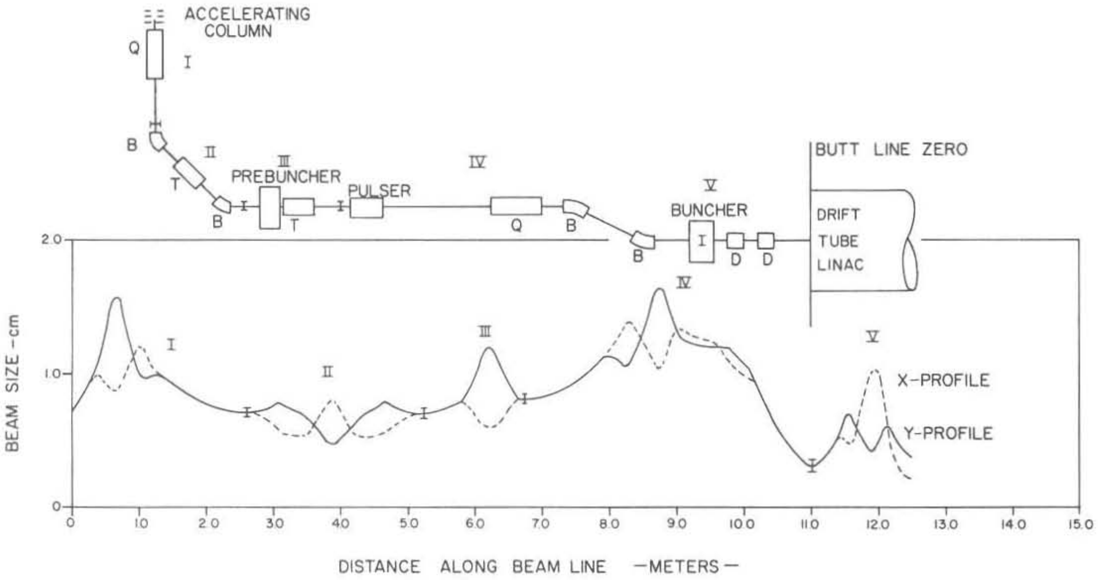


Fig. 2. Beam profiles for a 25-mA, π cm-mrad emittance beam in the high-intensity proton beam line as calculated.

Fig. 3. The high-intensity beam-transport system as initially constructed.

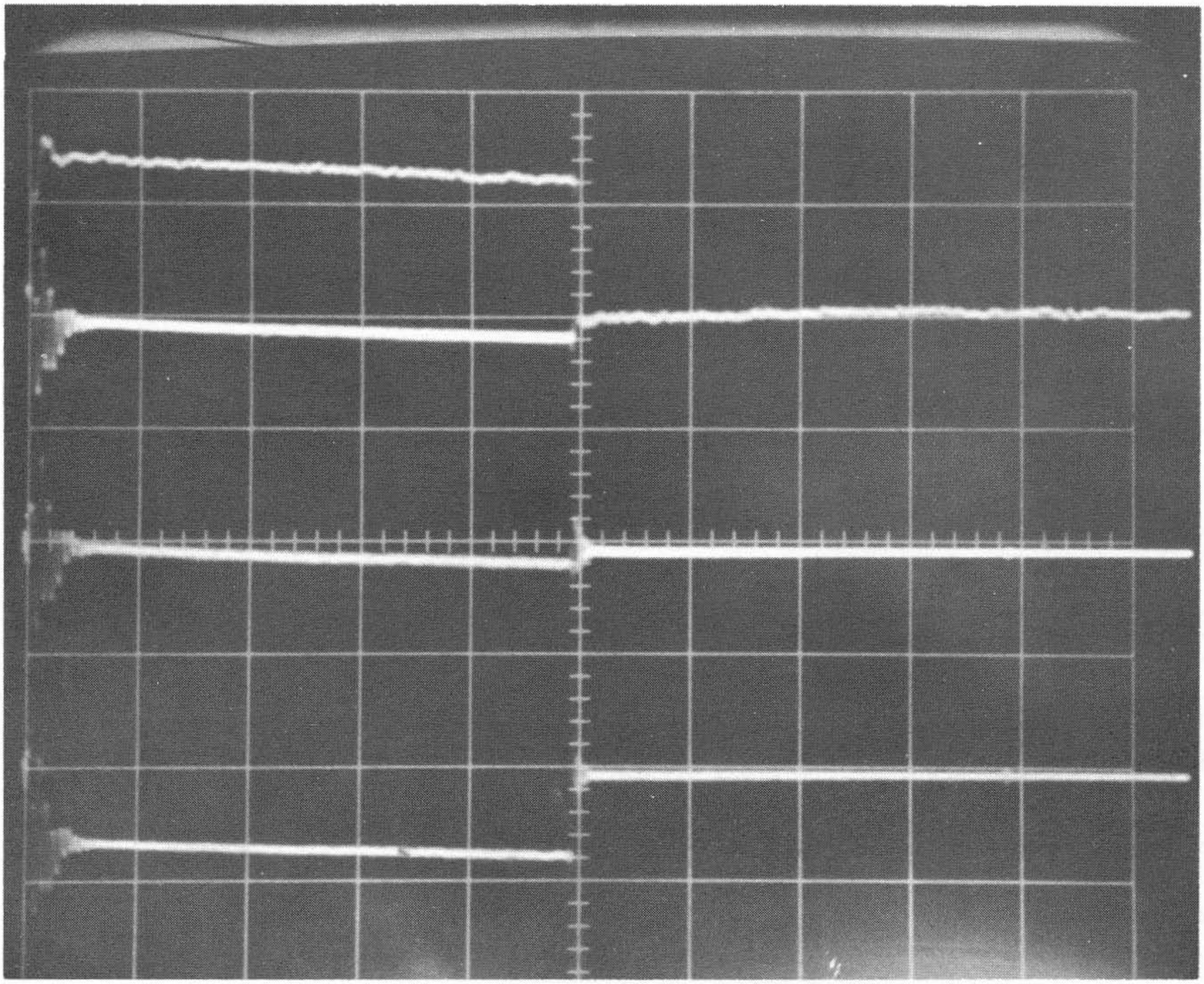


Fig. 4. CRO traces showing (1) arc current at 20 A/cm and beam current transformer signals from (2) TACM01, (3) TACM02, (4) TACM03 at 20 mA/cm. A 500-μsec, 38-mA beam at 120 cps was extracted at TACM01 of which 25 mA (TACM03) were protons.

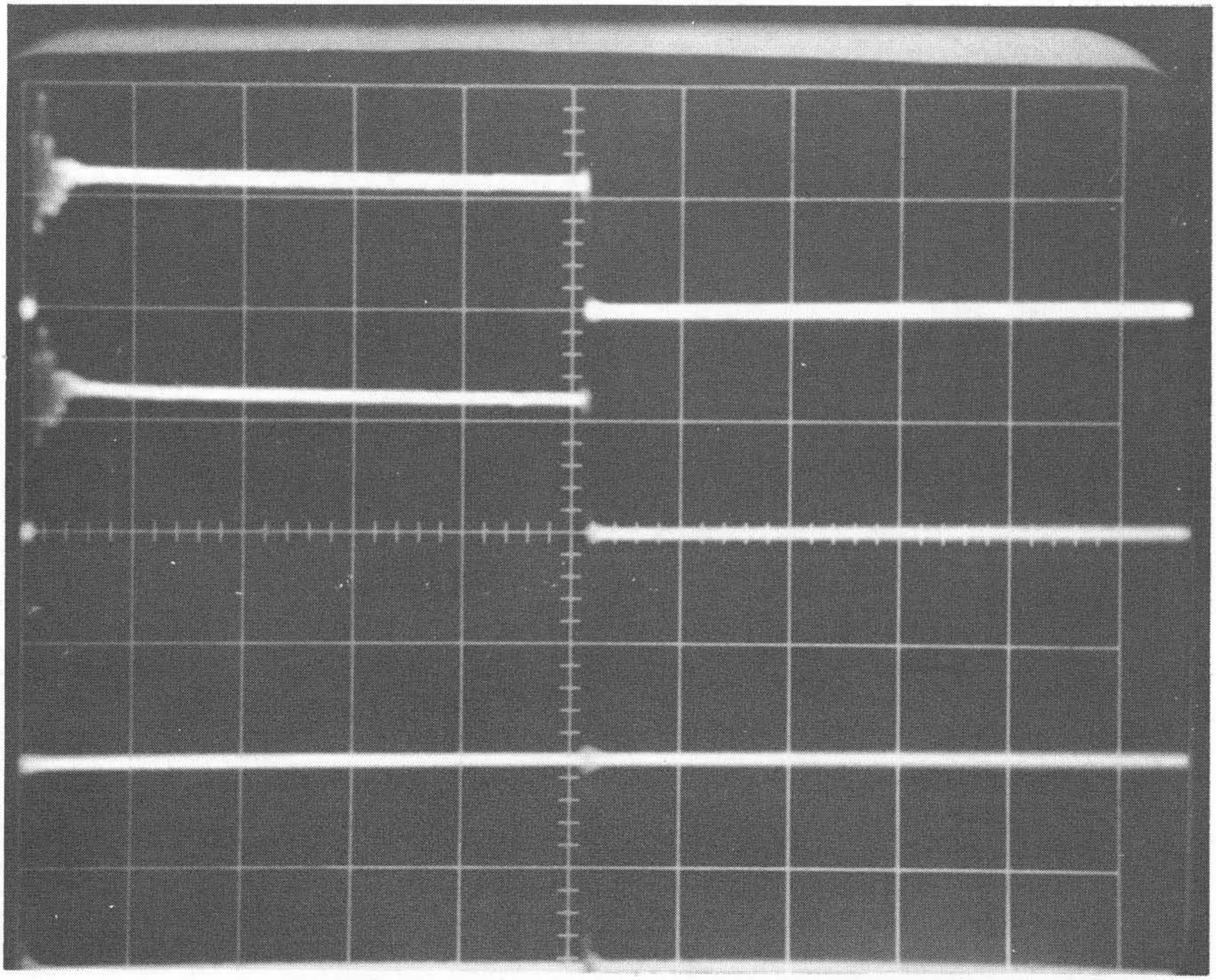


Fig. 5. CRO traces showing the beam current transformer signals from (1) TDCM01 and (2) TDCM02. The 25-mA, 500-μsec pulse of protons was transported to an intermediate beam stop just after TDCM02 in the beam line at the exit of the first beam translation magnet.

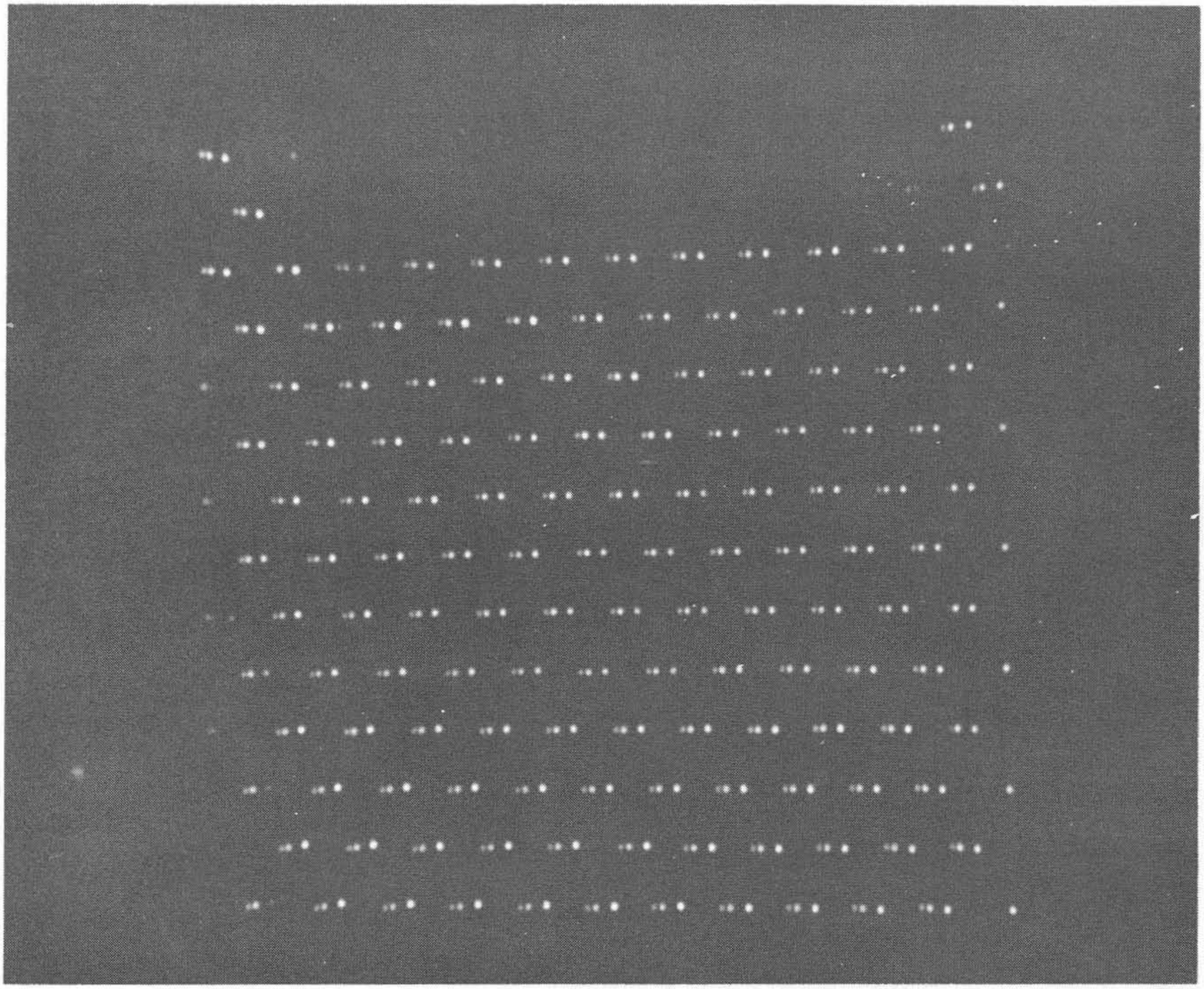


Fig. 6. Pepper-pot emittance pattern observed on the beam line at the exit of the column. The three sets of dots are the H^+, H_2^+, and H_3^+ ion species present in the extracted beam.

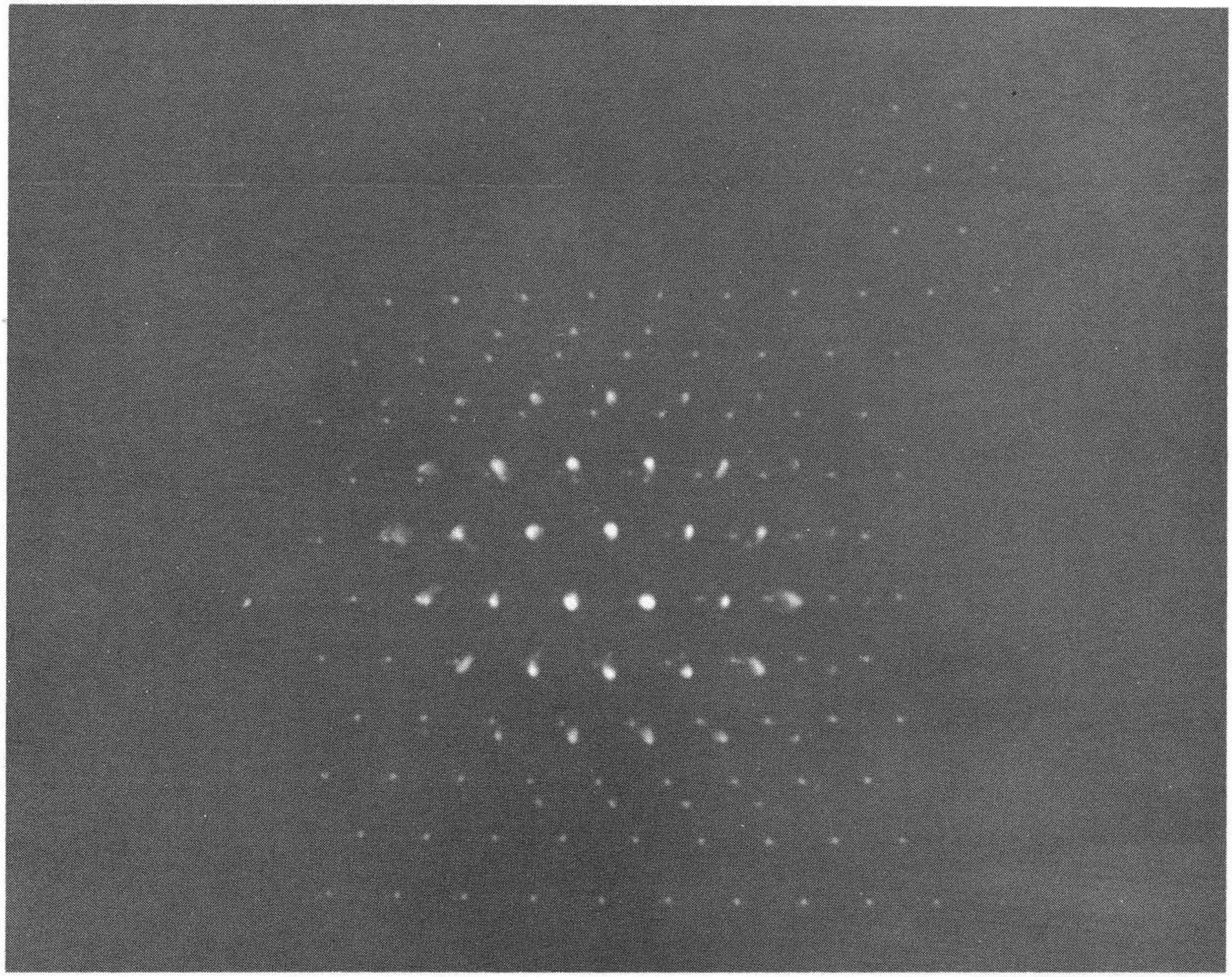
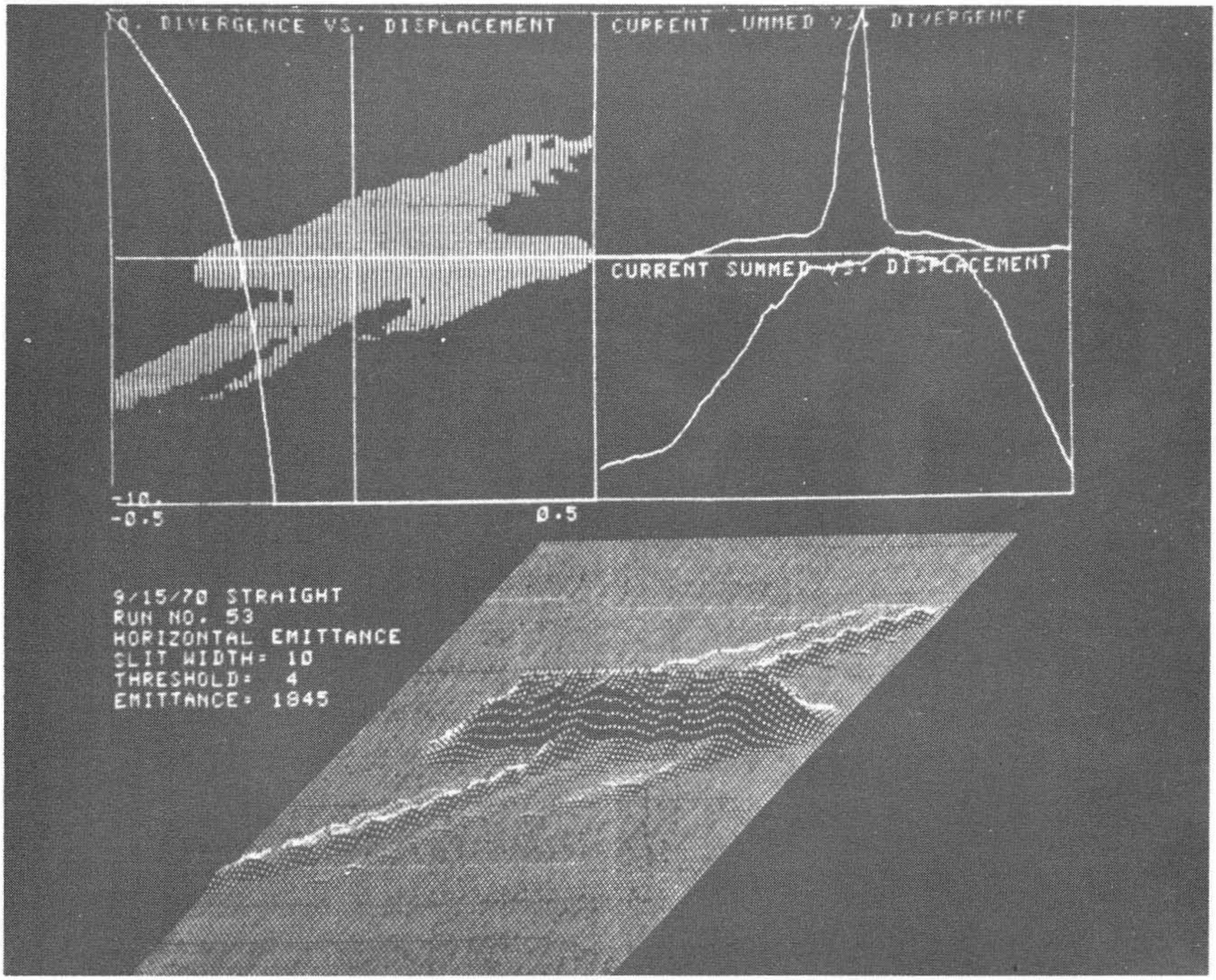


Fig. 7. Pepper-pot emittance pattern showing the action of the initial quadruplet in preferentially focusing the proton fraction of the extracted beam. The proton beam emittance is π cm-mrad.



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RUN NO. 53
HORIZONTAL EMITTANCE
SLIT WIDTH= 10
THRESHOLD=  4
EMITTANCE= 1845
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Fig. 8. Emittance pattern of the horizontal phase space obtained with the electronic emittance scanner of the entrance to the first 95° bending magnet. The proton fraction (25 mA) of the beam in the central region is at a waist and is about 1.9 cm wide.

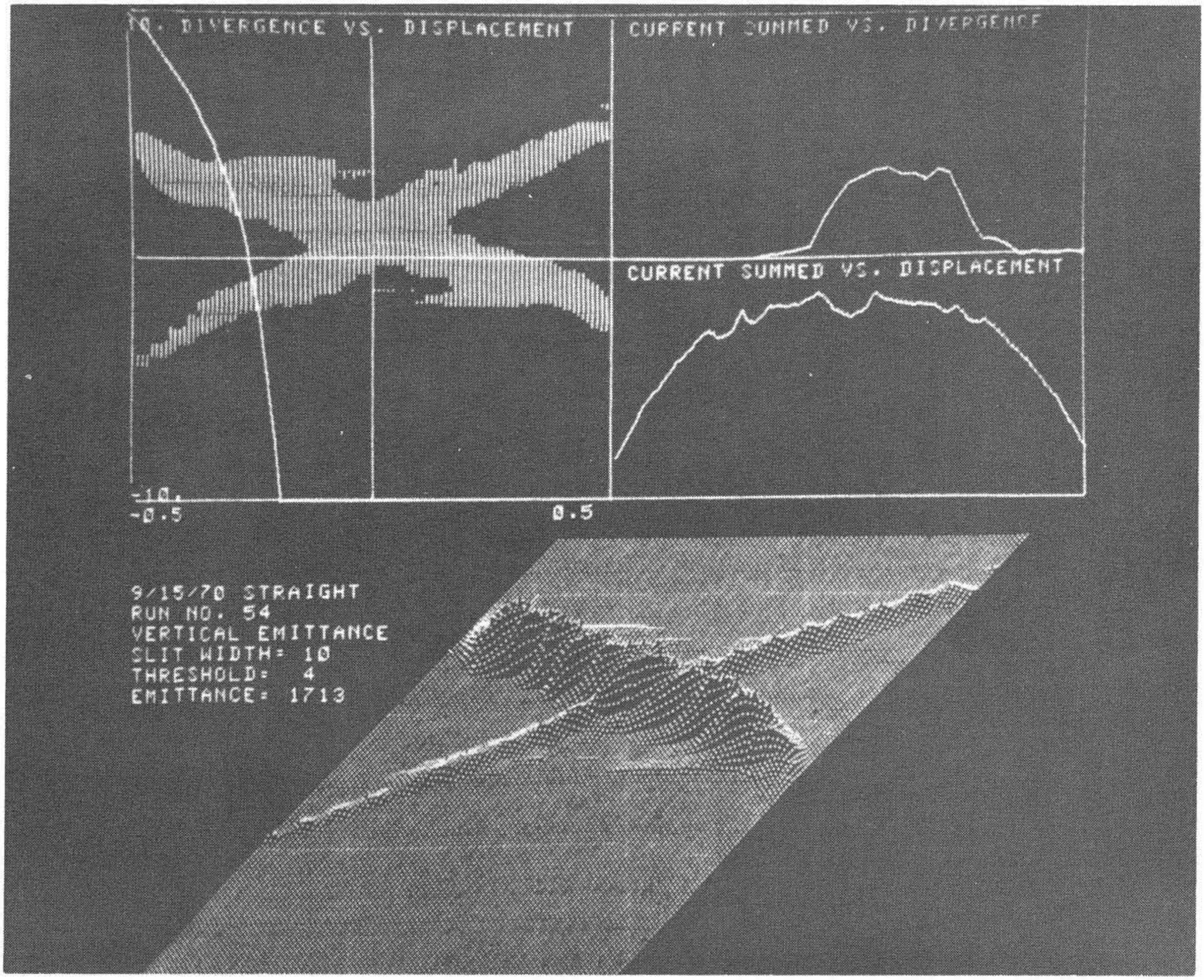


Fig. 9. Emittance pattern of the vertical phase space obtained with the electronic emittance scanner at the entrance to the first 45° bending magnet. The proton fraction (25 mA) of the beam in the central region is slightly converging and is about 2.5 cm wide.

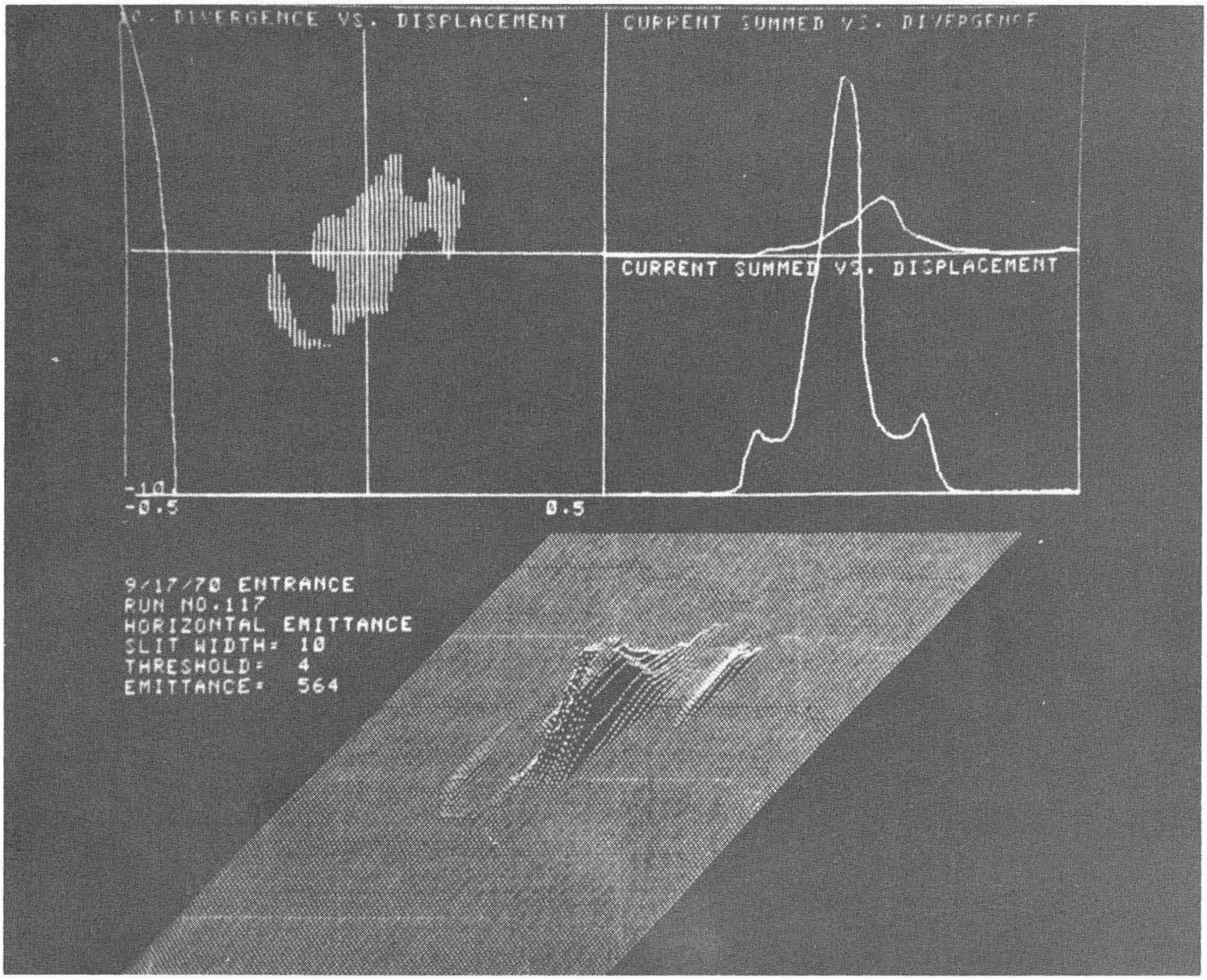


Fig. 10. Emittance pattern of the horizontal phase space obtained with the electronic emittance scanner at the entrance to the first tank of the linac. The beam is at a waist and has an emittance of 1.1 π cm-mrad. The width of the high current central portion is 0.6 cm.

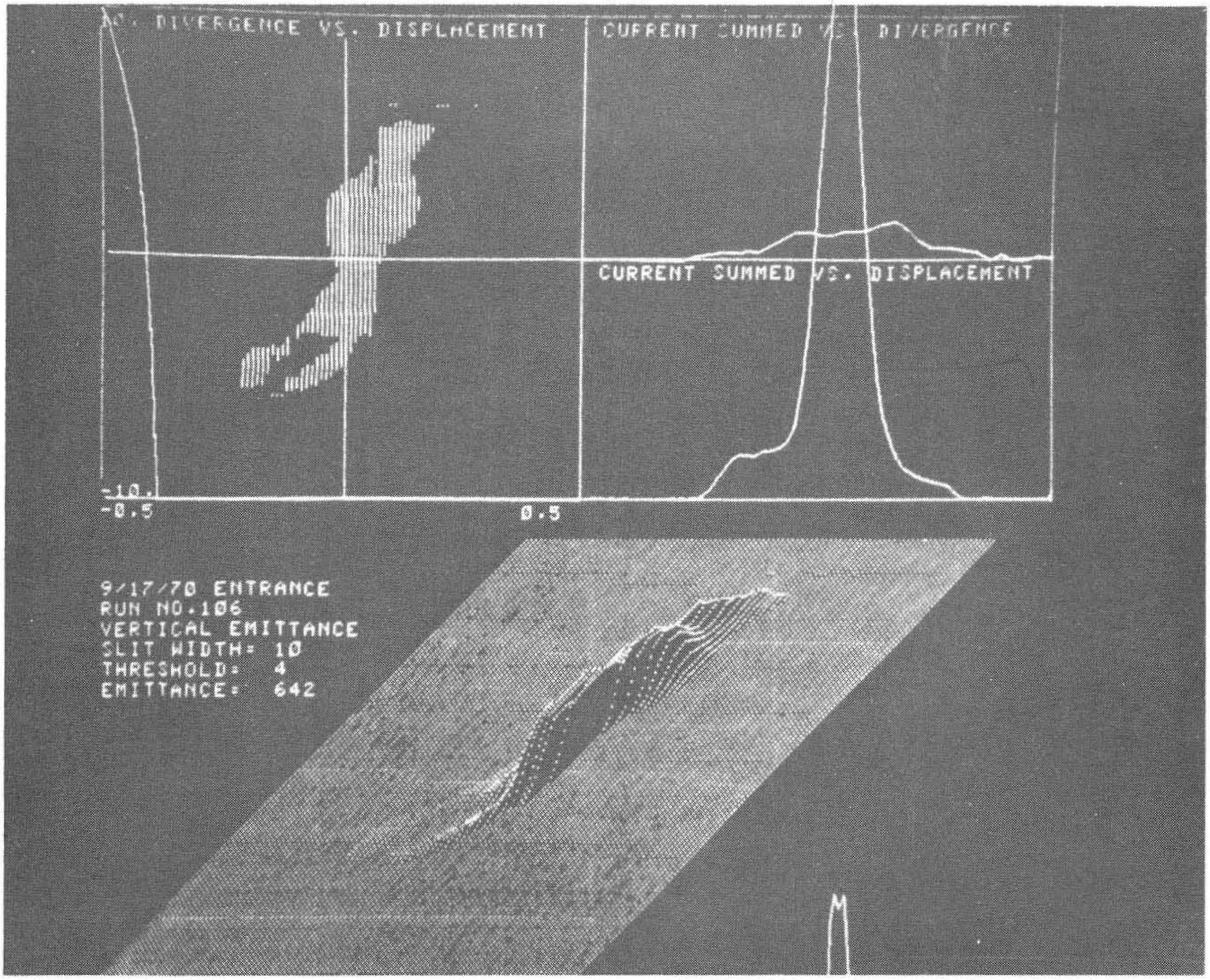


Fig. 11. Emittance pattern of the vertical phase space obtained with the electronic emittance scanner at the entrance to the first tank of the linac. The beam is at a waist and has an emittance of 1.7 π cm-mrad. The width of the high current central portion is 0.5 cm.

DISCUSSION

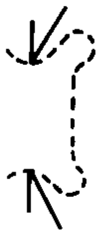
E. Regenstreif (University of Rennes): Is a "waist-to-waist" transfer the equivalent to what we would call at CERN a "turnover quadruplet"?

R. C. Emigh (LASL): A "waist-to-waist" transfer implies, at least in this case, that the beam is at its minimum radius and parallel at that point in that particular dimension, either x or y. A double waist then would be the same conditions on both dimensions, but they don't have to be the same size.

T. J. M. Sluyters (BNL): What does the plasma boundary in the cup look like? You suggested more-or-less earlier that you could trace back to the plasma cup from your emittance results.

R. C. Emigh: When we get a nice emittance pattern with no halos, the boundary probably looks, in our case, something like (a) below. The potential of the cup is about -70 V and by biasing the anode structure, for example, to match this -70V, one trims up the rim. We have found that if we extrapolate these halos back through the system that they come from this rim area. When one doesn't have a bias on the anode, the plasma appears to look like (b) below.

a



b