BEAM DIAGNOSTICS FOR THE NAL 200-MeV LINAC

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ABSTRACT

The NAL Linac group decided, at the beginning of the project, to use the capabilities of the Sigma II control computer for the on-line acquisition, processing, and display of beam-diagnostic information. This decision has affected both the types of measurements which are feasible and design of instrumentation to perform the measurements. Some of the tasks implemented through the computer system include the readout of beam currents, beam-emittance measurements, and beam-profile measurements using both ion-collection and wire-scanning equipment. Using width information from three profile monitors, the emittance of the 10-MeV beam has been calculated and compared with slit-measured emittance values. The results of this comparison indicate that the profile monitor data can be used to determine the emittance at higher energies where destructive techniques are less attractive. The diagnostic equipment, software programs, and operating experience using these systems will be described.

Introduction

A number of diagnostic devices have been built and used to measure properties of the NAL linac and preaccelerator beams. The computer-control system has been implemented and used during each of the operating periods. All of the diagnostic instrumentation has been interfaced with the computer to provide the operator with digital and graphic readout of beam measurements and digital or analog control of variable devices. Using this system, emittance measurements of the preaccelerator beam were made as early as April 1969. A description of the instruments and software is given in the following sections along with examples of typical data.

Hardware

Analog Data Acquisition

In order to make information available in the control computer, all analog signals are interfaced to the computer through an analog multiplexer and analog-to-digital converter. Pulsed analog waveforms are individually sampled-and-held at a point in time selected by the operator. The sample-and-hold circuits are triggered

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simultaneously so that all the digitized data stored in the computer were taken at precisely the same time during the beam pulse. Once a second, the computer collects diagnostic data at an earlier time, which is normally set a few μsec before the beam pulse. This "zero" data can then be subtracted from the beam data to automatically correct for amplifier dc offsets and sample-and-hold circuit pedestals.

The sampling time may be varied by the operator through the computer. This allows the operator to plot the shape of repetitive, pulsed signals using the computer system as a sampling scope. This time plot and other applications involving data sampled from numerous beam pulses require good stability of the linac. The linac stability has been excellent and pulse-to-pulse variations have not been a problem.

Beam-Current Measurements

The magnitude of the linac beam is measured at the entrance and exit of each cavity. Due to space limitations, only one current transformer is used between cavities 1 and 2. The transformer output drives the signal through a terminated RG/108 cable to a signal conditioner located in the equipment area. The sensitivity, S, of a toroid in volts/ampere is given by S = R/N, where R is the load resistance and N is the number of turns on the toroid winding. A sensitivity of 0.5 mV/mA, with a droop of less than 1% per 100 μsec, is obtained by choosing the number of turns equal to twice the cable impedance in ohms. The signal conditioner consists of a gain of 100 differential amplifier, a sample-and-hold circuit interfaced with the computer, and a video output which is connected to the video matrix to make the beam current waveform available to the operator in the control room.

Probe Drive

Some diagnostic devices require a mechanical actuator to position and scan detectors across the beam. To fulfill this requirement, the probe drive shown in Fig. 1 was built and used for emittance measurements, wire scans, and for positioning segmented detectors and slits in the beam. The drive consists of a probe stem, to which the detector is attached, supported and positioned by a pair of precision ball screws. These screws are gear driven for a stepping motor. The gear ratio is a compromise between position resolution and probe speed. The ratio chosen provides probe motion of 0.002 in. per step and traverses a 4-in. scan in 10 seconds. Motion through the vacuum interface is accomplished by using a long-travel bellows. The electronics for driving the motor and the linear potentiometer position signal are interfaced to the computer so that the probe may be positioned and scanned under program control.

Emittance Probe

A display of the beam in two-dimensional phase space provides the operator with useful information about the beam size, density profile, and focal conditions. Therefore, it was decided to use the capabilities of the computer to rapidly collect and display beam emittance. The probe used to obtain this data consists of a single slit, a drift space, and a 20-segment target oriented with the segments parallel to the slit. This assembly is then scanned through the beam. At each position the currents detected by the segments represent the angular distribution of the beam passing through the slit. The dimensions chosen for the 750 keV probe, shown in Fig. 2, are slit width = 0.003 in., slit thickness = 0.002 in., drift space = 4 in., segment width = 0.006 in. on 0.008-in. centers. Each segment corresponds to a 2 milliradian angular width. In operation, the computer reads the value of the current collected on all 20 segments during a single beam pulse and advances the probe to the next location.

During the operation of the 10-MeV section, horizontal and vertical probes were located at the exit from the first triplet in the preaccelerator beam line, before the entrance to the first drift tube in the linac cavity, and in the 10-MeV transport line. Because this is a destructive measurement, signals from these six probes were locally sub-multiplexed under computer control to allow only the active probe signals to be sent to the computer. The software associated with these measurements allows the operator to run any four of these probes in sequence. The data-collection time for the four selected probes is about 70 seconds.

Wire Scanner

At higher energies, the destructive methods for measuring emittance are less attractive. Information about the beam focal conditions can be obtained from beam-profile measurements. These profiles may be obtained from residual gas ion monitors, although these devices are limited in sensitivity and resolution, require several channels of high gain amplifiers near the beam line, and are sensitive to the residual gas pressure.

An extremely simple method of making high resolution profile measurements is shown in Fig. 3. Two 0.001 in. wires are driven across the beam at 45°. During the scan, the current on the two wires is read by the computer. Although this technique is slower than residual gas ion measurements, it offers the advantage of higher resolution with fewer analog data channels. Signal strengths are large enough (a few tens of μA) to allow the current amplifiers to be located outside the radiation area. A typical profile scan taken with this detector is shown in Fig. 4(a). The use of these data for determining the beam emittance is described in a later section. An example of three ion monitor beam-profile measurements is shown in Fig. 4(b). The ellipses are calculated from width measurements using these ion profiles. This type of detector will be used in the 200-MeV area to measure emittance and momentum spread.

Diagnostic Software and Data Analysis

Diagnostic System Operation

All the diagnostic systems are operated from the control room. The linac operator monitors and controls the current operating parameters of the machine through the alphanumeric displays generated by the linac control computer.[1] This control computer is a 32 K, 16 bit computer with a complement of peripherals which includes a magnetic disk, magnetic tape, card reader, high speed printer, an alpha-numeric display and a Tektronix 611 graphical storage scope.[2] Each display is driven by a non-resident foreground program that is brought into the core memory from the disk on command of the operator.[3] Figure 5 shows one of the displays used during the 66-MeV beam studies. The parameter values shown are averaged over 13 accelerator cycles and updated about once per second. The basic parameter displays are "customized" in that the operator may change any line to another parameter merely by typing its call number. Through the alphanumeric display and associated control knob, he can change magnet settings or move probes and observe on-line a graphical display of the variation of any parameter plotted against the parameter being controlled. Simple examples of such plots are beam intensity versus quadrupole current or steering-magnet current. Figure 4(a) was generated by this method. Other display programs are set up for very specific tasks.

Destructive Emittance Programs

The slit emittance device is operated by a display program which issues pulses to the stepping motors driving the probes and uses slit position information from a linear potentiometer readout. A typical emittance measurement display is shown in Fig. 6. The initial position and step size used for a run may be altered for each probe. The program adjusts these parameters so that they correspond to an integral number of stepping motor pulses. Activation of the keyboard interrupt initiates taking up to four data runs in sequence, storing the data on disc and also on magnetic tape. Immediately after each data scan, a phase space contour of the data is displayed on the graphical storage display device along with the emittance area of the contour and percent beam contained within the area.

The operator may obtain further plots of the data via another display program either immediately after collecting the data or at some later time by recalling the data from magnetic tape. An example of the usual emittance data plot is shown in Fig. 7. The most useful section of this display for visualizing the beam intensity distribution in phase space is the isometric plot in the lower left portion. This plot shows the beam in the x, x' plane with beam intensity, above a specified threshold level, plotted in the Z direction. Linear interpolation between probe strip data is used at each slit position to help give the impression of a surface. "Hidden" points are removed by simply refraining from plotting a point which is lower on the display than the previous highest point plotted at that same horizontal position in the display as the plot is generated from the foreground to the background of the picture. The emittance contour for the selected threshold is shown in the upper left. Integrating the data over angle yields the beam position profile at the upper right, while integration over position gives the angular distribution profile at the lower eight. A plot of percent beam within a contour versus emittance contour area is shown in the upper right corner. These data were used in calculating and displaying emittance growth as a function of percent beam through the first linac cavity, before succeeding cavities were in place. The various parameters of the plot, such as threshold level, are shown in Fig. 8. About 15 seconds are required to generate the emittance data multiplot. A scatter plot is available where the plotted point density is proportional to beam intensity. Figure 9 is a scatter plot of 750-keV beam where the multiple mass beams are separated in phase space due to magnetic focusing in the transport.

The angular resolution of the destructive emittance probe is somewhat limited, covering a ± 20 mrad range with 20 segments. Therefore, if the angular spread of the beam at any position is narrow, it will be collected on only one or two segments of the collector. Such operating conditions do not optimize the resolution of the device and result in an overestimate of the emittance area. A simple linear interpolation in angle is used in the calculation that can result in overestimates of area of about 10 percent. A correction to the calculated area is required because of the finite slit width. Since the slit width is 1/3 of a segment width, one needs to subtract 2/3 mrad-cm of area per cm of emittance width from the area calculated. Minimizing the space between neighboring segments insures that the beam is seen even if giving a poor measure of area for these cases. The signal-to-noise ratio is better further into the fringe of the beam than it would be with narrower segments.

Comparison of Wire Scanner and Destructive Emittance Data

During the 66-MeV operating period, 10-MeV beam was drifted through linac cavities 2 and 3. Emittance measurements and wire scans were obtained in the 66-MeV transport line. Direct comparisons between the emittance values measured by the 10-MeV emittance probe and calculated from three beam widths measured by wire scanners were planned. However, the wire data inadvertently failed to get stored on magnetic tape, so the comparison was not possible in most cases. A specialized program is used to scan three wire detectors simultaneously, collect the data, and calculate the emittance ellipse determined from the three widths in both phase planes. An example of data from this on-line measurement is shown in Fig. 10.

The raw data obtained during a destructive emittance measurement is a 20×100 matrix of numbers representing the 2-dimensional beam-intensity distribution in the transverse phase plane. Given this data, it is possible to shift the rows of data relative to one another in such a way that the shifted matrix represents an apparent drift of the beam along the transport line. Then, a summation of the columns of data in this matrix forms the beam profile at the drifted location of the beam. By repeating this process one can obtain the three beam profiles required for calculating emittance from width measurements. This simulated "drift" capability was added to the emittance data plotting routine and typical results are shown in Figs. 11 (a), (b), and (c). During the calculation, the program stores the drifted profile data to make it available for use by the width-emittance routine. Ellipse data from this calculation are shown in Fig. 10(d).

Metzger[4] has shown that optimum results from the width-emittance calculation are obtained for the symmetric case, with a waist at the second width measurement, and for equal drift distances between profile measurements of $\ell = \sqrt{3}L$. Here ℓ is the drift distance and L is the ratio of the ellipse parameters, x/x', at the waist. The data of Fig. 11 nearly satisfy these conditions, although the drift lengths are somewhat shorter. Ninety percent beam widths are determined at the three locations. The three beam widths, drifted to the location of the waist, form the hexagon shown in Fig. 11(d). Although this hexagon is formed from three 90% measurements, some of the specific particles in the excluded 10% are different in the three cases, and therefore the percentage of beam contained within the hexagon must lie between 70% and 90%. An even smaller, and less well known, percentage of beam is contained within the ellipse circumscribed by the hexagon. The optimum configuration described by Metzger tends to minimize the difference in area between the hexagon and the ellipse.

In general, comparison of the destructive and width methods shows the width-ellipse to reproduce adequately the orientation of the beam in phase space. By adjusting the threshold used in the destructive emittance calculation, one can find a value which results in a two-dimensional phase-space contour having the same width as the ellipse obtained from the width method. Compared on this basis, the areas determined by the two methods agree to within about 5%. For the few cases analyzed, the percentage of beam contained within the calculated ellipse (using 90% widths) is about 80 percent.

Three detailed beam-profile measurements contain far more information about the beam distribution in phase space than is required by the width method discussed above. By using the entire profile shape it may be possible to determine the percentage beam contained within a calculated phase-space area. Investigation of methods for making more refined calculations from these data are underway.

Acknowledgments

The efforts of many people have contributed to the work described in this paper. In particular, the authors would like to thank D. E. Young and Phil Livdahl for their constant support and encouragement, C. D. Curtis for his many valuable ideas and suggestions, both in the design of detectors and analysis of the data, and Robert Kocanda who fabricated most of the electronic equipment associated with the detectors.

References

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[3] R. W. Goodwin, NAL Linac Control System Software, Proc. of the 1970 Proton Linear Accelerator Conference, National Accelerator Laboratory, p. 371.

[4] Mesures des Emittances et du Centrage des Faisceau dans la Ligne de Mesure "800 MeV" du PSB, CERN/SI/Int. DL/69-10.

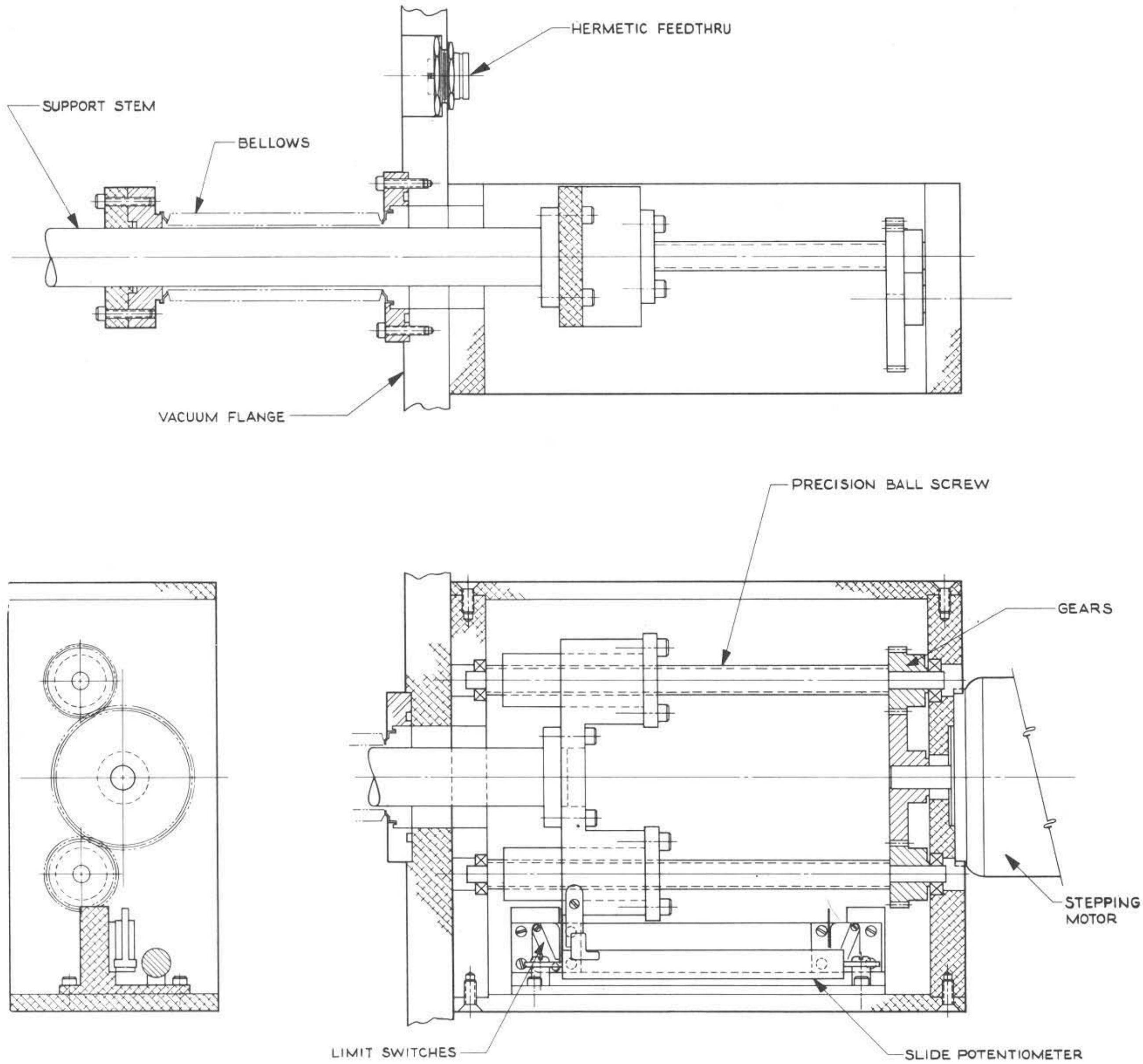


Fig. 1. Assembly drawing of probe drive.

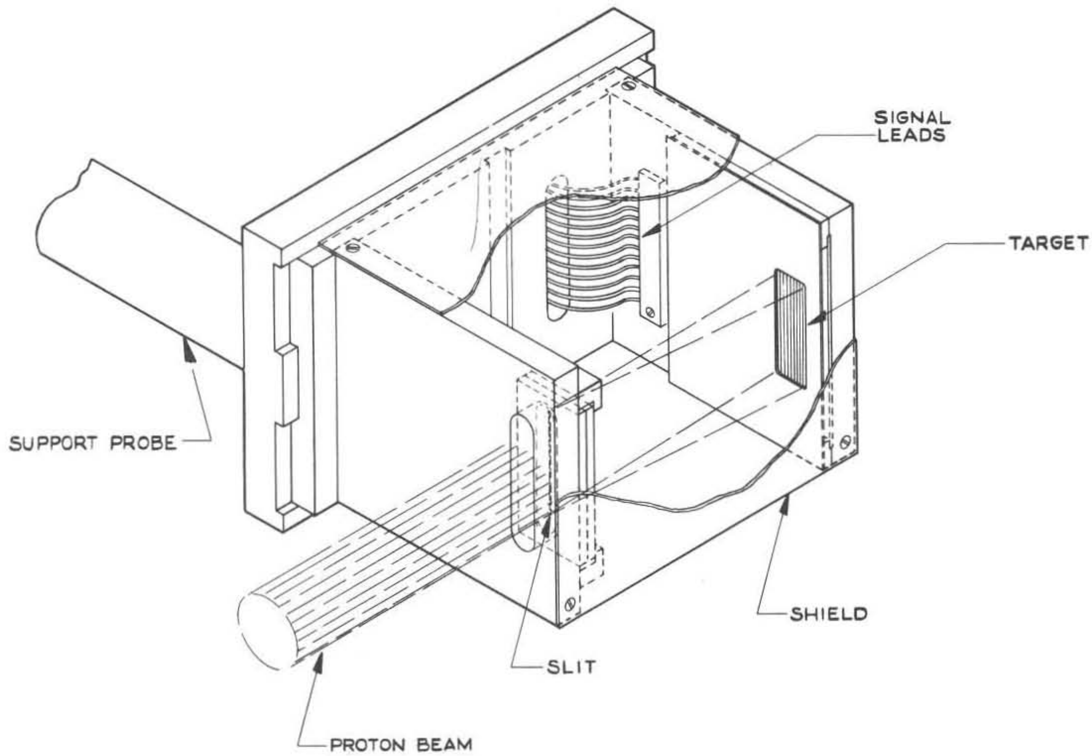


Fig. 2. Destructive emittance probe.

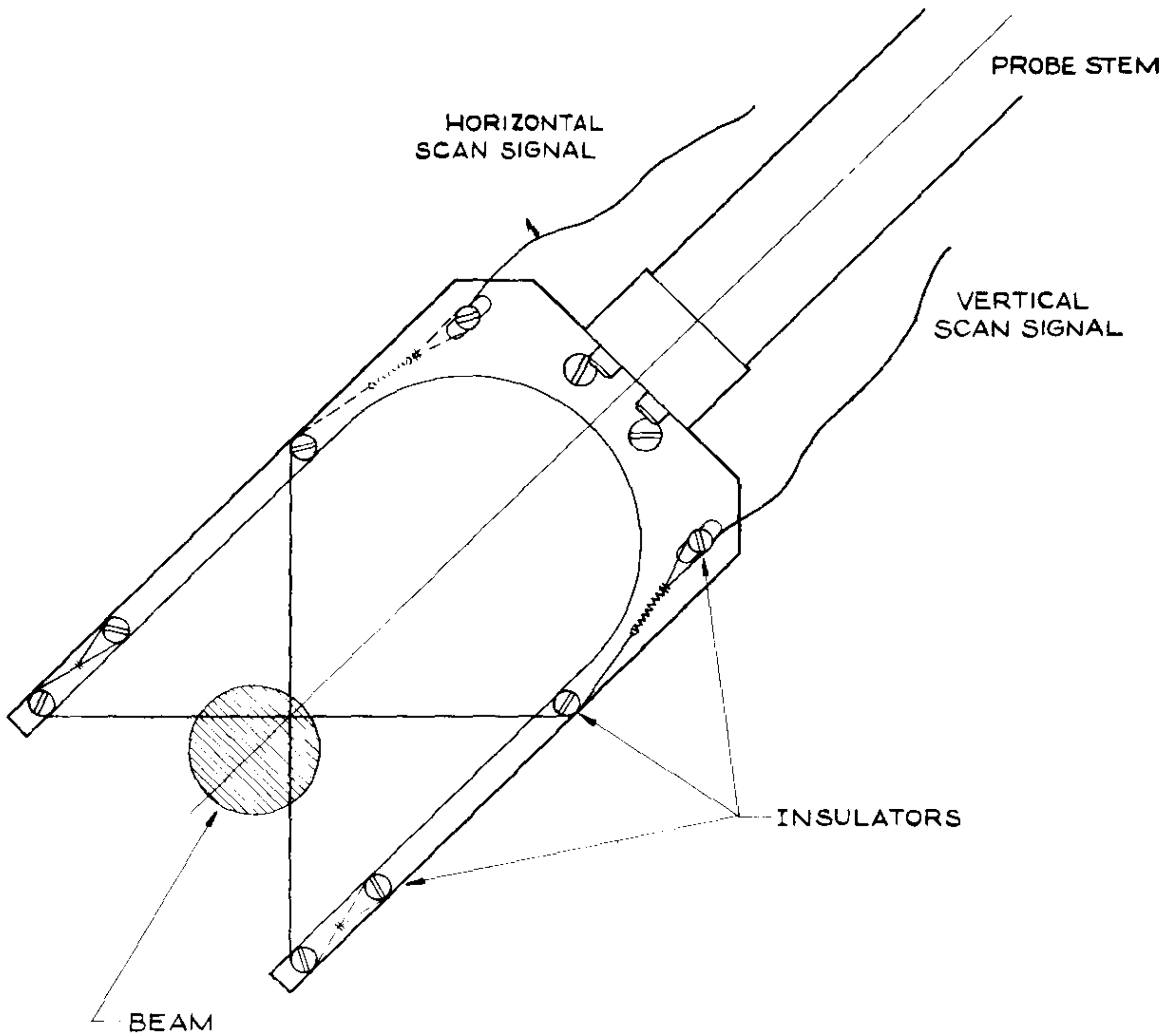
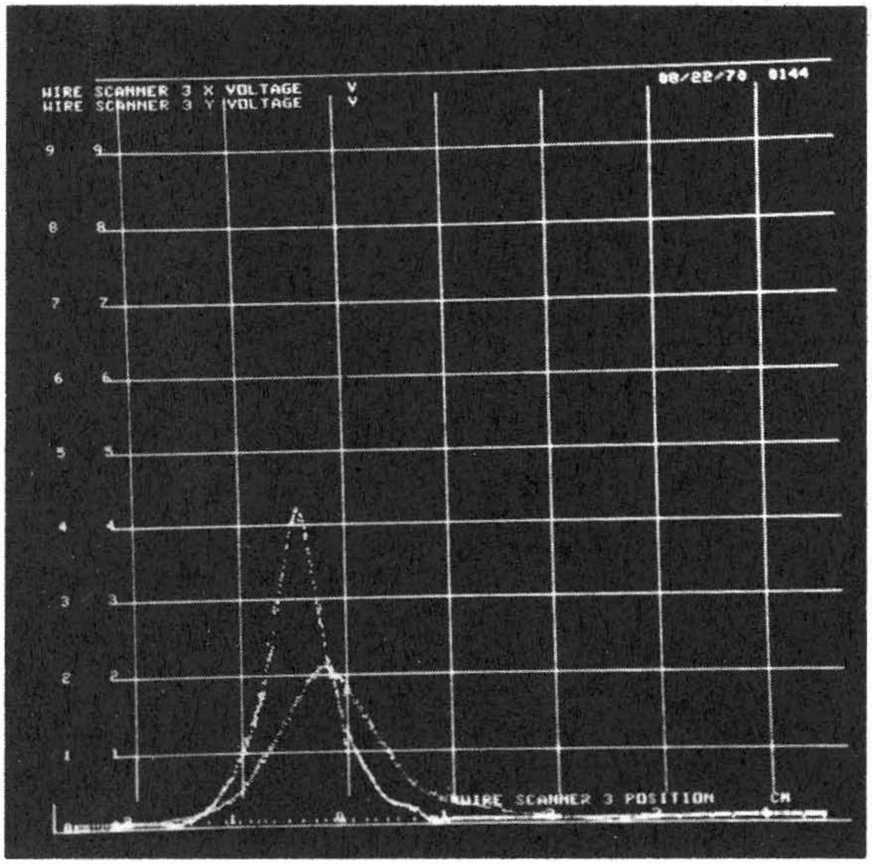
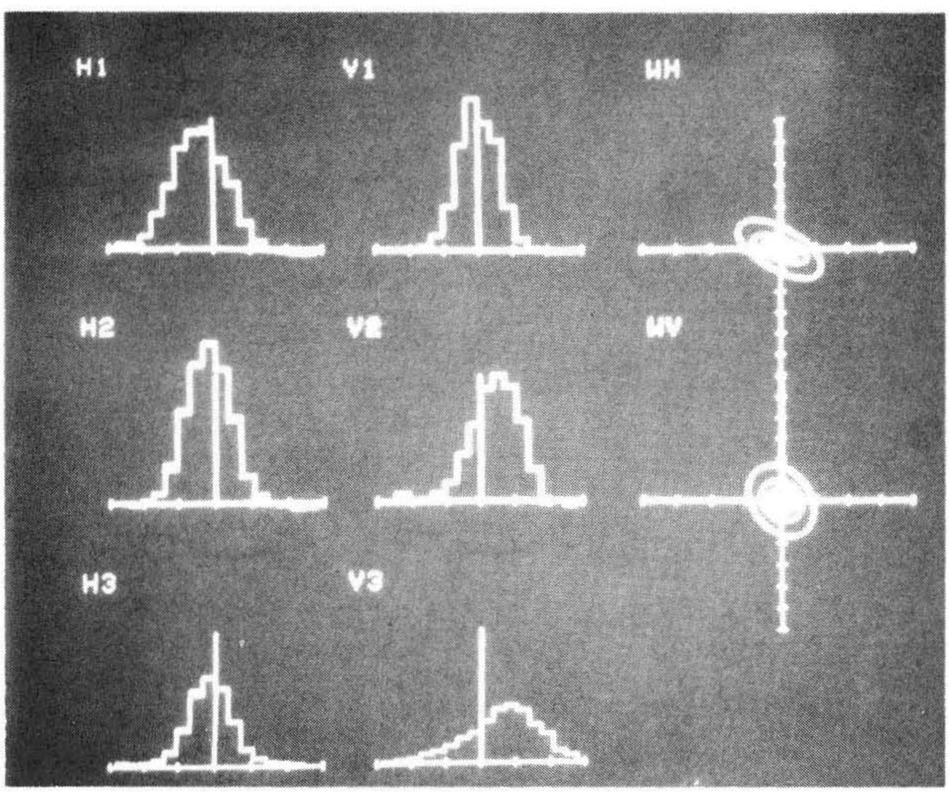


Fig. 3. Wire-scan beam profile probe.



(a)



(b)

Fig. 4. Beam-profile data from (a) the wire-scanner and (b) residual gas ion monitor.

```
    66 MEV XPORT        *PRINT
YCHAN=470  Y2=471       *TIME N= 10     SEC
YG=1     YNORM=            YZERO= 0     V
(1)CH (2)DA (3)NOM (4)TOL
T1 TOROID IN                    96.18 MA
T3 TOROID IN                    29.09 MA
T3 TOROID OUT                   27.62 MA
T3 TRANSMISSION                 95.62 %
T4 TOROID IN                    27.68 MA
T4 TOROID OUT                   26.34 MA
T4 TRANSMISSION                 95.87 %
BEAM DUMP CURRENT (66 MEV)      20.81 MA
T3 QPS #19 QUAD #35             92.83 AMPS
T3 QPS #20 QUAD #36             108.3 AMPS
*STEERING MAGNET  HORIZ        -2.613 AMPS
*STEERING MAGNET  VERT          .013  AMPS
*DOUBLET  QUAD 1                125.6 AMPS
*DOUBLET  QUAD 2                122.9 AMPS
*WIRE SCANNER 1 POSITION        3.136 CM
*WIRE SCANNER 2 POSITION        4.658 CM
*WIRE SCANNER 3 POSITION        2.614 CM
*ENERGY MONITOR POS (66 MEV)    63.51 MEV
```

Fig. 5. 66-MeV transport-line parameters.

```
     EMITTANCE  MEASUREMENT
*  INC 2           >PR*BE PARA 2
*  SLIT INITIAL POSITION.....-  2.0 CM
        PRESENT POSITION.....- 1.72 CM
*       STEP SIZE............  0.05 CM
   BEAM CURRENT PRESENT......   162 MA
                ACCEPTABLE...   160 MA
                TOLERANCE....     5 %
   BEAM PULSES TOTAL NO......    10
               ACCEPTED......     8
*  THRESHOLD LEVEL RECAL.....   .10
*  RUN PROBES................  1234
*  RETRACT PROBES............
*  PRINT.....................
   INTERPOLATION ON LASL.....
   WRITE ON MAG TAPE.........


*READ RUN=            *REW      0
*SRB  *SRF   *LIST    *SFF        1
*WRITE RUN            *EOF      1
```

Fig. 6. Display for controlling the destructive emittance measurement equipment.

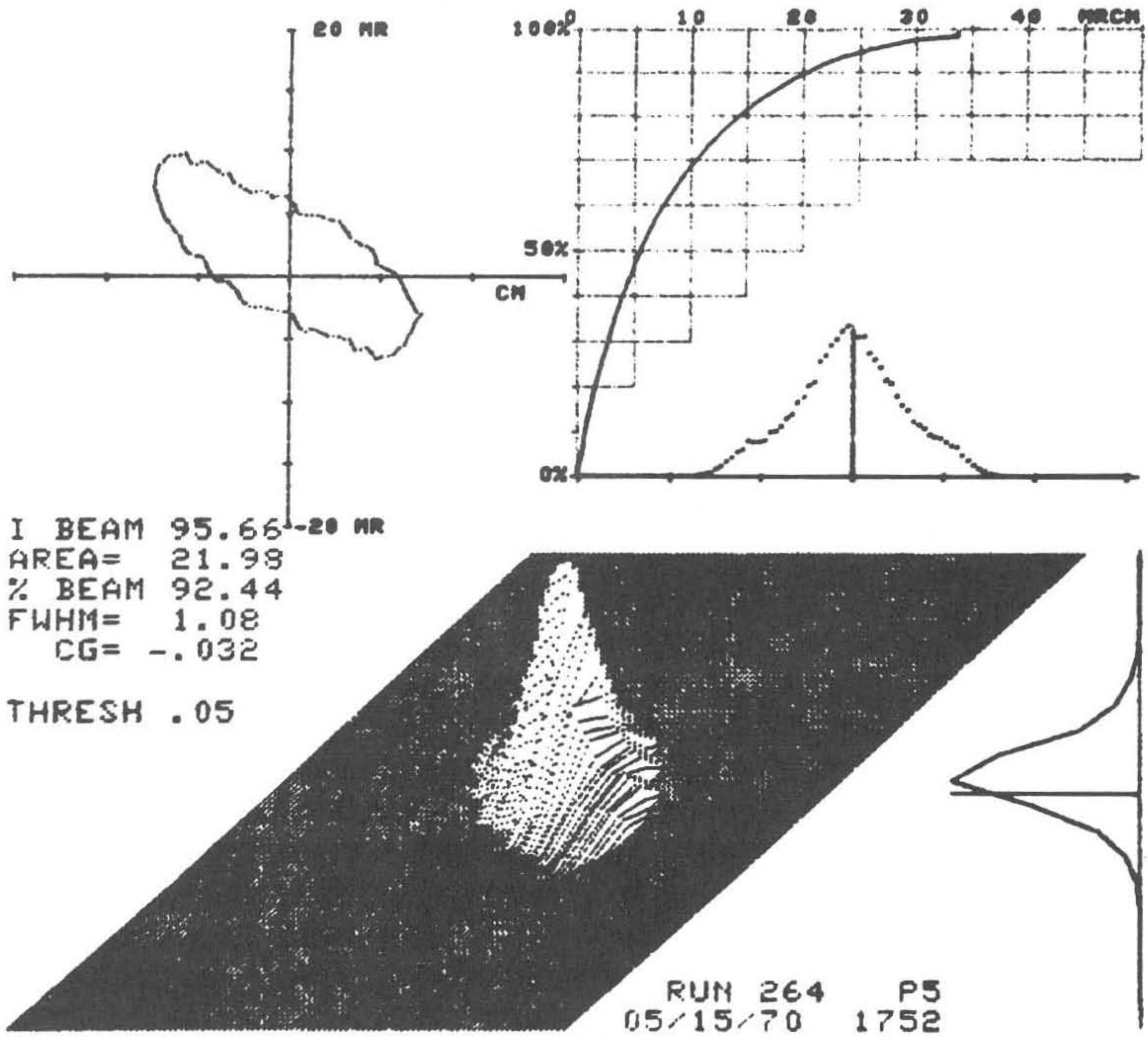


Fig. 7. Graphical display of destructive emittance data.

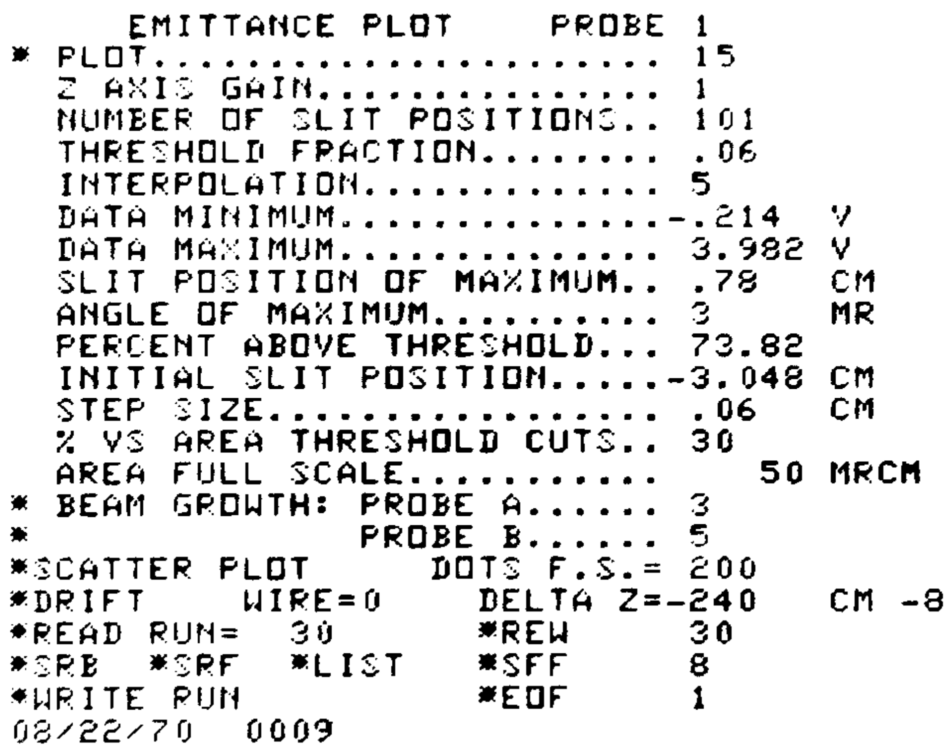


Fig. 8. Display for controlling the emittance data plotting program.

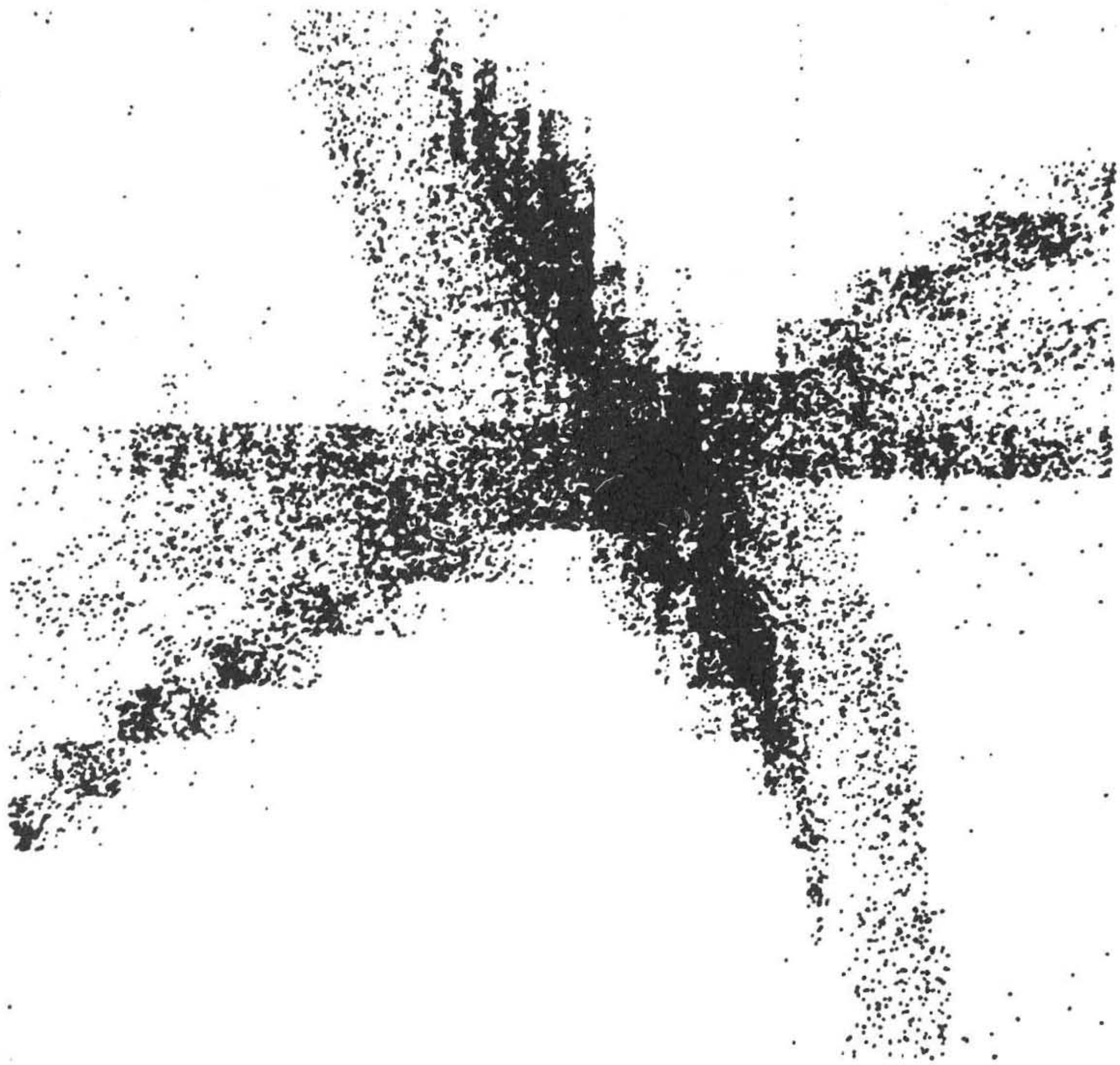


Fig. 9. Scatter plot of a multiple-mass 750-keV beam.

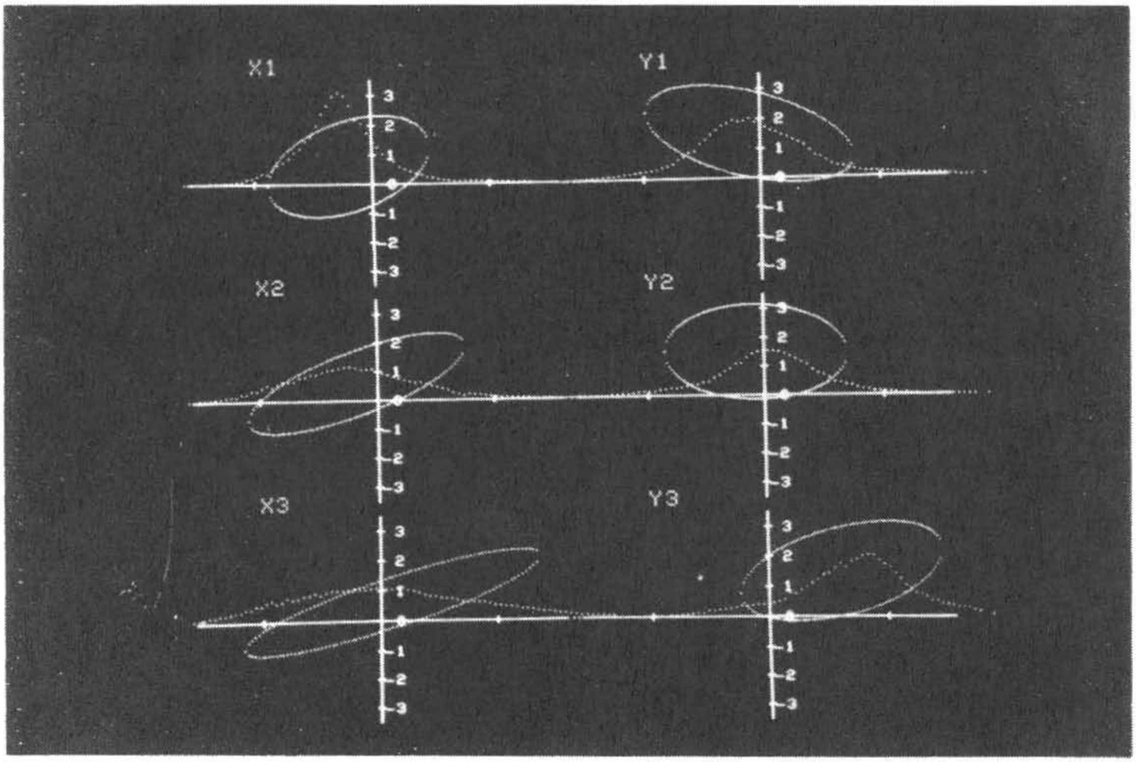


Fig. 10. On-line wire profile emittance measurement.

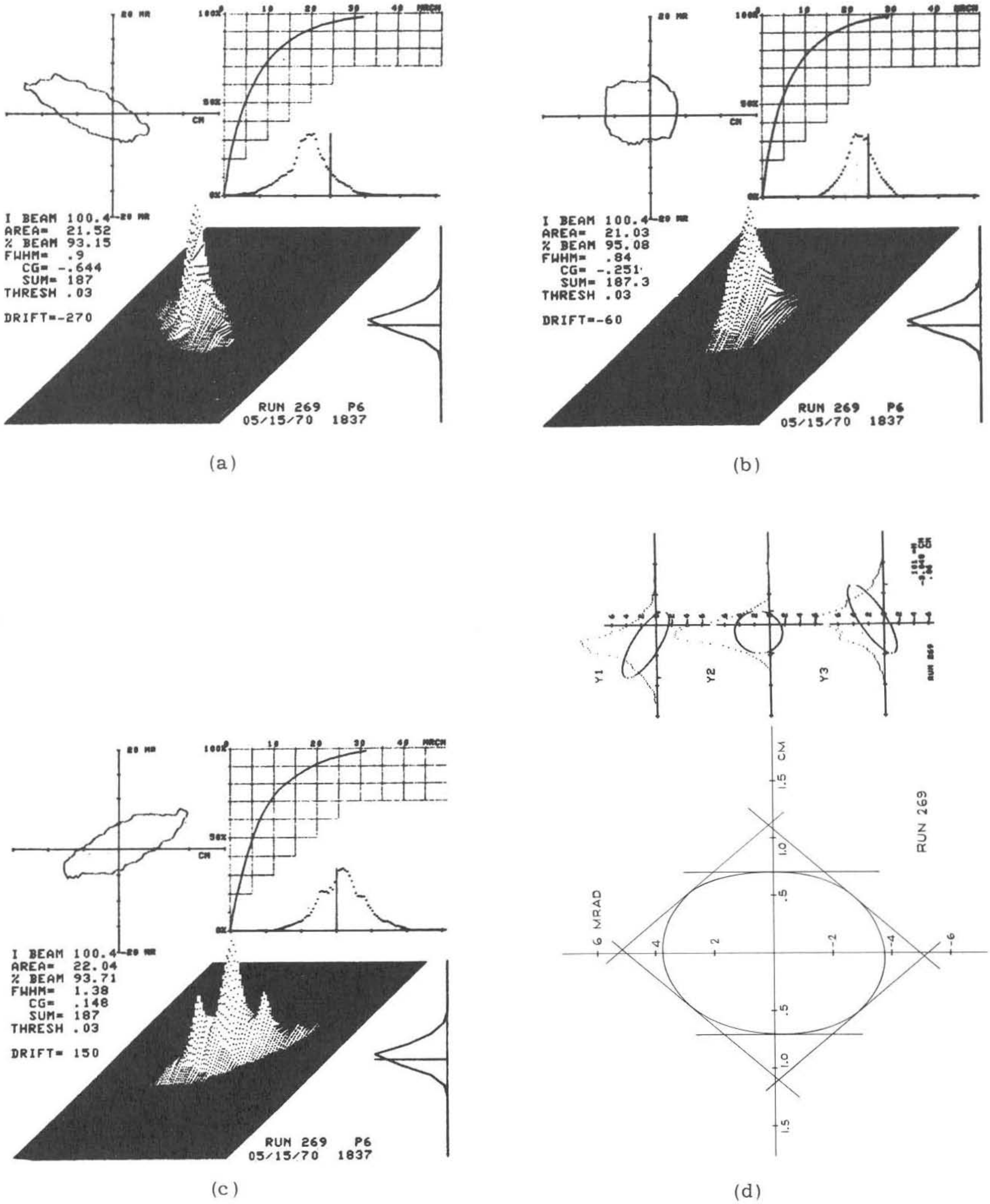


Fig. 11. Destructive emittance data for a 10-MeV beam numerically "drifted" to three locations along the transport line (a-c); (d) results of width-emittance calculation using "drifted" data.

DISCUSSION

D. A. Swenson (LASL): Do you plan to use a wire scan in the 200-MeV transport?

M. F. Shea (NAL): Yes. We have them both in the direct line and in the analysis line.

E. A. Crosbie (ANL): How long does it take to do a wire scan?

M. F. Shea: With the motor speed, it takes 5 or 6 seconds to run across the beam, which corresponds to taking data about every 0.05 cm. If one wants more data, one goes slower, and it takes a little longer. As far as the erosion on these wires, we are worried about that, but on the ones we ran at 10 and 66 MeV, we couldn't find any obvious erosion of the tungsten wire in the period that we ran.