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Author
Colonias, John S.

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LAWRENCE RADIATION LABORATORY
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John S. Colonias

Lawrence Radiation Laboratory
University of California
Berkeley, California

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ABSTRACT

This paper describes the application of computer graphics in the design of beam transport systems. We introduce a computer program called TRACE which allows the user to design beam transport systems interactively with a computer through a display console, light pen, and teletype. We describe briefly the computer environment and its relation to program TRACE. We conclude with a discussion on the operation of the program through an example.

THE TRACE PROGRAM

One of the major activities of nuclear research centers is to carry out experiments in low- and high-energy physics. Such experiments necessitate the design of beam transport systems to carry the beam from the device to the experimental area. Although there are many computer programs available to aid the experimenter in his design, they all suffer from generality and lack of convenience. TRACE provides a vehicle on which man and machine can cooperatively make up for each other's deficiencies in problem-solving capacity, maximizing at the same time the advantages peculiar to each. Although the sensory, intellectual, and motor faculties of humans permit reaction to a wide range of stimuli, their ability to rapidly analyze large quantities of data is severely limited. In program TRACE, we have taken advantage of man's unique ability to interpret information subjectively and, at the same time, present the data to a computer in a form that the computer can digest. Thus, the experimenter is provided with the means that place him inside the processing loop by giving him a "conversational" mode of operation.

Basically, program TRACE is the outgrowth of program TRANSPORT, originally written in Balgol by Butler et al. [1]), and implemented for various machines by many people in the field. Briefly, program TRACE provides means for describing an injected beam and a magnet system.

The beam is specified by a six-dimensional ellipsoid. The magnet system includes the following types of beam elements:

1. Drift spaces
2. Bending magnets: with arbitary angles of entry and exit
3. Quadrupole magnets
4. Sextupoles
5. Solenoids
6. Slits, etc.

The manner by which TRACE produces a solution for a beam transport design is not described here. It is sufficient to say that the program is versatile, to allow for a variety of constraints to be applied to the system. Parameter fitting is also possible with TRACE. This allows the experimenter to specify the parameters he wants to adjust, such as lengths, gradients, or apertures, and the program computes the first-order correction by a least-squares method.

Ray trace ability has been provided, and up to ten vectors may be displayed at the same time. Phase-space ellipses are calculated at any point in the trajectory and the projections on the coordinate axes are displayed. (Any plane may be chosen.)

COMPUTER ENVIRONMENT

Program TRACE is operational under the Chippewa Operating System for the CDC 6600 Computer System using a 252 Model Display Console with an 8K buffer, character and vector generator, light pen, and teletype (fig. 1).

The program is written in Fortran IV. A typical session using TRACE on the CDC 6600 requires approximately 100 K_8 words of main storage, and it lasts for about one-half hour. Since the CDC 6600 is a multiprocessing computer system, the program occupies a control point for the duration of the session; however, the CPU (Central Processor Unit) is released to other programs when not in use. Thus, the total CPU time is, at most, 5% of the total session time. Figure 2 shows a flow chart of program TRACE.

PROGRAM OPERATION

The session begins with the user viewing part of the input data as shown in fig. 3. The data correspond to a Bevatron secondary beam No. 5D, the characteristics of which appear in table 1 and the beam layout in Fig. 4.

The source of this beam is in front of the first magnet (30-deg bending magnet) followed by a quadrupole doublet, the first element of which is vertically focusing. We request a parallel beam in the long straight section. The next quadrupole section has its first element horizontally focusing, followed by a 47.7-deg bending magnet. We request a waist after the fixed-gradient quadrupole. The beam then passes through a quadrupole, to a 55-deg bending magnet, through a doublet, and to the target, where we expect a horizontal and vertical focus.

The data displayed on the screen correspond to the input needed to calculate the first-order optical properties of the Bevatron 5D secondary beam used in this example, and consist of the appropriate parameters of length and field for each constituent element. The formatting of this input is almost identical to that of program TRANSPORT[1, 2].

At this point, the user may exercise any of the options listed in the bottom of the screen. The functions of these options are listed below:

OPTION	FUNCTION
ALTER	Alter data. The alteration is performed by entering the appropriate address in the DATA array. This number is shown on the left column of fig. 1; for example, to change the first drift length to 15 inches, we type 22, 15. $\frac{C}{R}$ (carriage return).
DLINE	Delete one line of input. In other words, delete one element of the beam system.

OPTION	FUNCTION
ALINE	Add one line of input. This option allows the user to enter all his input via teletype, or to add a new element in the beam system.
SNAPB	Record this display on microfilm. (This option is used to record the beam envelope.)
SNAPD	Record this display on microfilm. (This option is used to record the data displayed.)
MDATA	This option (presenting an additional frame) allows the user to view more data; in many instances, one frame is not enough to display all data.
GO	Execute the data (without application of constraints).
ITER	Execute data, applying constraints
FIN	End of session.
VECT	Perform changes on the vectors displayed. This option allows the user to alter vector parameters to enter new vectors or to remove those already specified.
RAYS	This option provides for the display of all rays specified, or individual rays may be displayed at will.
BEAM	This option allows the user to review a beam already calculated.
SCALE	Scaling of both horizontal and vertical beams. The user enters via teletype the region he wants to scale and the scaling factor.
MATRX	This option allows the user to specify the location where he wants to observe the phase-space ellipse and the RC and SI matrices.

OPTION	FUNCTION
(continued) MATRX	(Later paragraphs describe these matrices in more detail.) The user initiates this option by teletype, enters the location where the ellipse is desired, and specifies the planes of the projections of ellipse (x, θ, y, ϕ, etc.)

NOTE: If a teletype is used to initiate any of these options, only the letters underlined need be specified. If a light pen is used, it is pointed at the option desired and, by depressing the microswitch on the light pen, the interrupt is initiated.

This list of options by no means exhausts the multitude of other options that the user might want to incorporate. The modularity of program TRACE allows such expansions, as is mentioned later.

Now--returning to our example: upon initiation of the option "ITER," the executive program of TRACE decodes the action, and signals the beginning of execution, resulting in fig. 5, which displays the beam envelope. Program TRACE again waits (releases CPU) for the user to resume an interaction cycle based on the information displayed.

The user may decide to observe the phase-space ellipse at some location along the beam line; to do so, he points the light pen at the function MATRX. Next, the light pen is pointed at the location on the beam line where the phase-space ellipse is desired, and also specifies the planes on which the phase space ellipse is to be projected. Upon initiation of the interrupt, fig. 6 results. Here, the user has a wealth of information at his disposal. At first the beam envelope is shown, which is defined as the plot of beam size versus position along the system. Interpretation of the trace is fairly obvious. A rectangle is drawn to represent a magnet; the size of the rectangle reflects the magnet length and aperture. The beam size is interpolated linearly in drift spaces.

Both the horizontal and vertical planes are displayed, as shown, along with the cumulative beam length (on top of fig. 6).

Below the beam envelope, the RC matrix (cumulative transfer matrix) is displayed along with the SI matrix (beam matrix).

The RC matrix represents the transfer matrix of the beam transport system up to the point at which it was requested.

The beam transfer matrix (SI) includes the projections of the ellipse upon the coordinate axes. The physical significance of each element of the SI matrix is derived briefly as follows:

Since n coordinates are necessary to describe a particle, it can be shown that the distribution of a group of particles can be approximated by an n-dimensional ellipsoid of the form

$$a_{11} x^2 + a_{22}\theta^2 + a_{33} y^2 + \cdots = 1 \qquad (1)$$

in the principal coordinate system. If the coordinates are rotated as shown in fig. 7, the equation involves off-diagonal terms which measure the rotation of the ellipse.

In general, the equation of a tilted ellipse in n-dimension is

$$\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_i x_j = 1. \qquad (2)$$

We define a matrix of coefficients a_{ij} as

$$\sigma^{-1} = \begin{bmatrix} a_{11} & a_{12} & \cdots \\ a_{21} & & \\ \cdot & & \\ \cdot & & \\ \cdot & & \end{bmatrix} \tag{3}$$

or

$$\sigma^{-1} = a_{ij}. \tag{4}$$

Now, as a particle V passes through a system of magnets, it undergoes transformations described by a matrix M as

$$V_1 = M\,V, \tag{5}$$

and the equation defining the ellipsoid may be written

$$V^T \sigma^{-1} V = 1. \tag{6}$$

Since

$$[x, \theta, y] \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x \\ \theta \\ y \end{bmatrix} = 1, \tag{7}$$

if we employ the identity

$$MM^{-1} = 1, \tag{8}$$

the equation for the ellipsoid (eq. 6) may be written

$$\begin{aligned} V^T(MM^{-1})^T \sigma^{-1}(MM^{-1})V &= 1, \\ (MV)^T(M\sigma M^T)^{-1}(MV) &= 1. \end{aligned} \tag{9}$$

Thus, the same ellipsoid, after having the coordinate transformation

$$V_1 = MV, \tag{10}$$

has become

$$V_1^T \sigma_1^{-1} V_1 = 1, \tag{11}$$

where

$$\sigma_1^{-1} = (M\sigma M^T)^{-1}. \tag{12}$$

Equation (12) may be interpreted as follows: Given a beam, σ, entering a magnet system, and a transformation matrix of the system, the beam σ_1 leaving the system can be calculated from eq. (12).

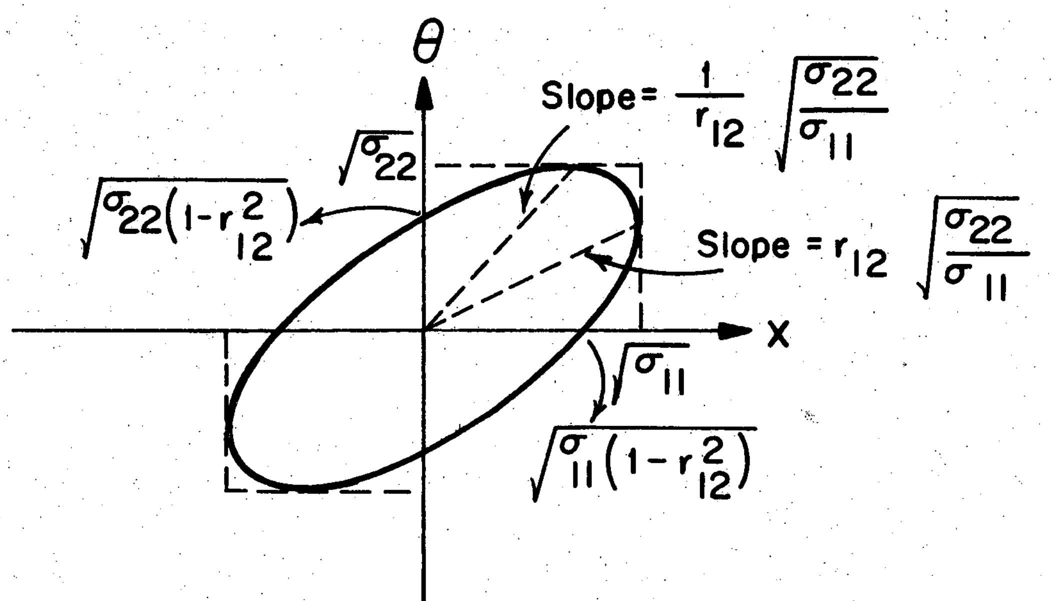
If we consider such an arbitrary beam defined by

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix}, \tag{13}$$

it can be shown that the equation of the ellipsoid can be written as

$$x^2\sigma_{22} + 2\,x\theta\,\sigma_{12} + \theta^2\sigma_{11} = \sigma_{11}\sigma_{22}\,\sigma_{12}^2. \tag{14}$$

The coefficients of the ellipse can be given an interpretation with the aid of fig. 7. The square root of the diagonal elements gives the projection of the ellipse on the coordinate axes.



XBL694-2500

Fig. 7. Projections of ellipse on coordinate axes.

In fig. 6, the SI matrix shown is arranged so that the diagonal elements occupy the first column as shown below:

$$\begin{array}{l} \sqrt{\sigma_{11}}\ \mathrm{CM} \\ \sqrt{\sigma_{22}}\ \mathrm{MR}\ r_{21} \\ \sqrt{\sigma_{33}}\ \mathrm{CM}\ r_{31}\ r_{32} \\ \sqrt{\sigma_{44}}\ \mathrm{MR}\ r_{41}\ r_{42}\ r_{43} \\ \sqrt{\sigma_{55}}\ \mathrm{CM}\ r_{51}\ r_{52}\ r_{53}\ r_{54} \\ \sqrt{\sigma_{66}}\ \mathrm{PC}\ r_{61}\ r_{62}\ r_{63}\ r_{64}\ r_{65}. \end{array} \qquad (15)$$

Since $\sigma_{ij} = \sigma_{ji}$, we have $r_{ij} = r_{ji}$. The off-diagonal elements of this matrix represents various quantities such as dispersion, tilt, etc.

At this point, the user has the option of returning to the display of input data, ALTER, some parameter, and execute (ITER) again, or he may request to view the phase space at a different location on the beam line.

Figures 8 and 9 show the phase-space ellipses at various points along the trajectory; figs. 10 and 11 show a ray trace of six particles and one particle, respectively; fig. 12 shows an enlarged section of the first quadrupole doublet.

Once the computational loop has been completed, the user may repeat the same loop again, or new problems may be brought to the screen by exercising the option NCASE.

At all times, the experimenter may use the options SNAPD or SNAPB to take microfilms of whatever is displayed on the screen. This microfilm is later developed to a hard copy for permanent record.

Thus, by showing the results in an interacting way, the operator can quickly examine the overall characteristics of the system and take immediate action. Errors are detected easily, and time loss because of erroneous data is effectively minimized. During the course of the session, warning messages are available to guide the operator to avoid invalid conditions. In general, a program like the one described could be used effectively both as a design tool and as a teaching tool.

CONCLUSION

On-line program TRACE enables the user to control, interact with, and display a beam-transport system on the 252 display console. Specific mathematical techniques for generating transfer matrices are discussed elsewhere (Refs. 1-4), but it should be mentioned here that the major contribution of TRACE is in the interacting area, by providing a vehicle on which scientists and engineers can design beams with a computer program that requires little knowledge of data processing. Rather than passively accepting preplanned input, program TRACE interacts with and guides the user through the design of his system.

The present version of TRACE is operational on the CDC 6600 Computer system, but major extensions are planned to increase the flexibility of the program. Some of these extensions include the ability to segment a long beam and process and optimize each section separately; to be able to display aperture-constrained polygons; and to include second-order calculations.

ACKNOWLEDGMENTS

The author is indebted to Dr. Arthur Paul of the Lawrence Radiation Laboratory, Berkeley, for translating program TRANSPORT from Balgol and for his continuing encouragement, and to Steven Sackett for writing a substantial portion of the CRT display routines.

REFERENCES

1. C. H. Moore et al., TRANSPORT: A Computer Program for Designing Beam TRANSPORT Systems (unpublished).
2. Karl L. Brown, A First- and Second-Order Matrix Theory for the the Design of Beam Transport Systems and Charged Particle Spectrometers, Stanford Linear Accelerator Center Report SLAC-75, July 1967.
3. B. A. Norman and W. H. Moore, Theory and Design of Beam Transport Systems, Brookhaven National Laboratory report AGSCD-26, September 1, 1967.
4. A. C. Paul, UCRL TRANSPORT, January 5, 1969 (unpublished).

Table 1. Beam No. 5B.

General description	500-MeV/c K^+ or K^-, separated
Physicists responsible	T. Elioff (LRL)
Installation date[a]	June 1967
Target location	External beam-Channel 1 - 2nd focus
Target material	Uranium
Target size	1/8 in. vertically, 3/8 in. horizontally, 1.5 in. in length
Momentum range	≈ 0.2 to 0.60 BeV/c (positive or negative)
Momentum width	4%
Solid angle	≈ 6 millisteradians
Production angle	24 deg
Type of separator	Electrostatic Mark V (10 ft long) 4-in. Gap
Separation factor	Pion rejection $\tilde{>}$ 50 at 550 kV (capable of 600 kV)
Emittance	0.02 radian in. (horizontal); 0.017 radian in. (vertical)
Flux transmitted	≈ 4000 K^+ (500 MeV/c) per 5×10^{11} EPB protons; K^+/all positives ≅ 1/20
Other information	1. Mass split is at first focus with submomentum recombination
	2. At first focus, vertical magnification = 1.5; horizontal magnification = 0.95; $K - \pi$ vertical separation = 0.5 in.
	3. At final focus, vertical magnification ≈ 4.5; horizontal magnification = 0.5. For stopping K^+ in 5 grams of CH, the rate is ≈ 1200 $K^+/5\times10^{11}$ p^+ (EPB). Approximately 60% of K^+ pass through a 3/8×3/8-in. cross section at the final focus.
	4. Target is not mounted in either EPB or secondary-beam vacuum, and is easily accessible.

a. Beam 5B is equivalent to previous Beam 5 (dismantled January 1967) with minor modifications.

FIGURE CAPTIONS

Fig. 1. Control Data display console 252.

Fig. 2. TRACE flow chart.

Fig. 3. Computer display of input data for 5D beam.

Fig. 4. Bevatron secondary beam 5D.

Fig. 5. Beam envelope.

Fig. 6. Beam envelope, displaying phase space at location 32.

Fig. 7. Ellipse in paper.

Fig. 8. Beam envelope, displaying phase space at location 70.

Fig. 9. Beam envelope, displaying phase space at location 84.

Fig. 10. Beam envelope with the dispersion vector shown.

Fig. 11. Ray trace, showing six unit vectors.

Fig. 12. Enlarged section of first doublet (locations 32–48).

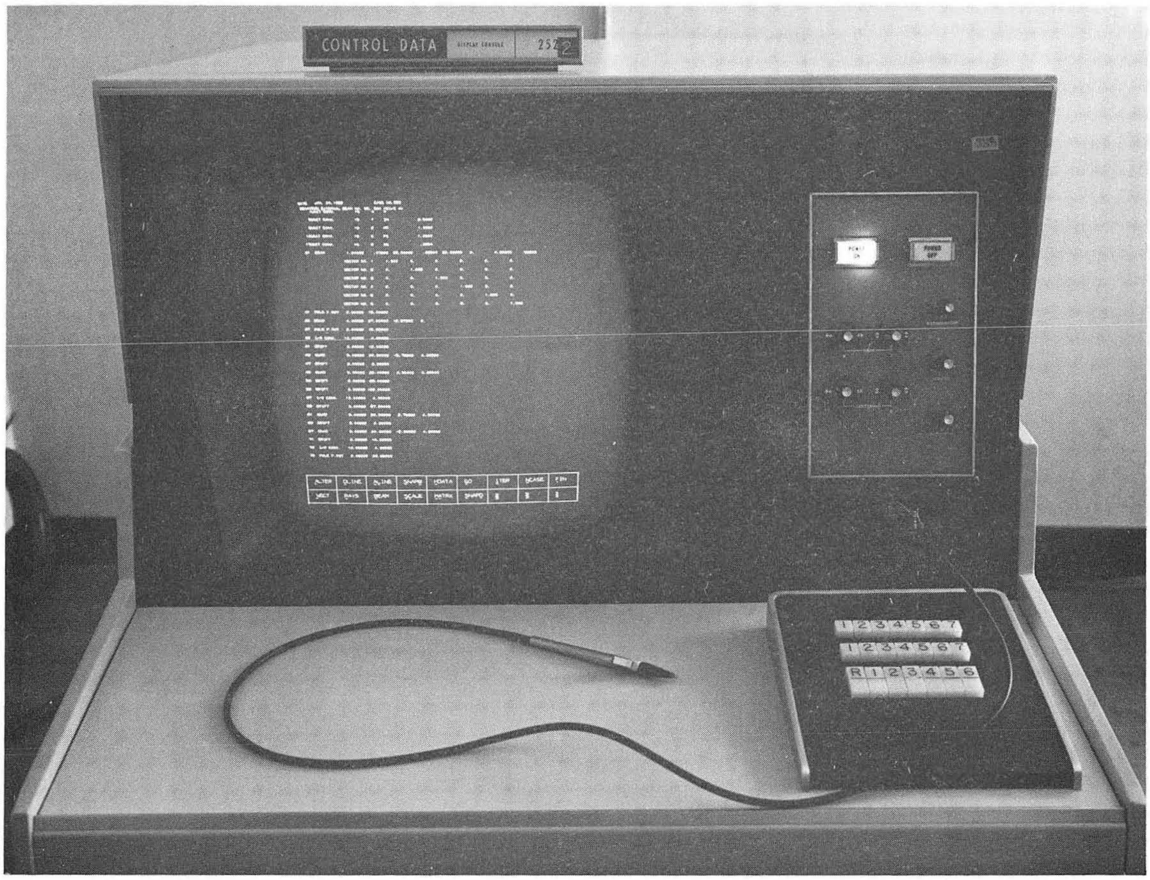


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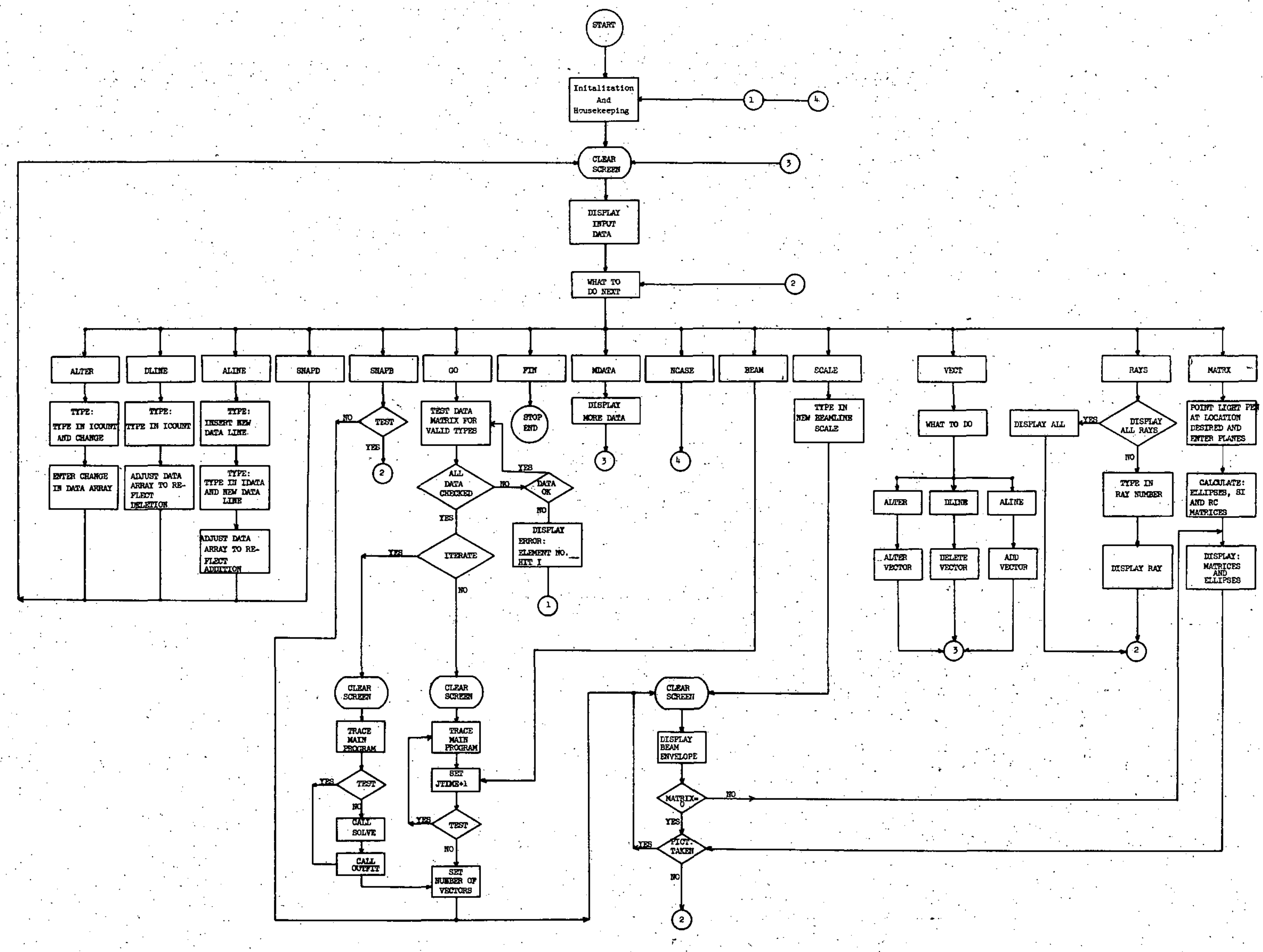
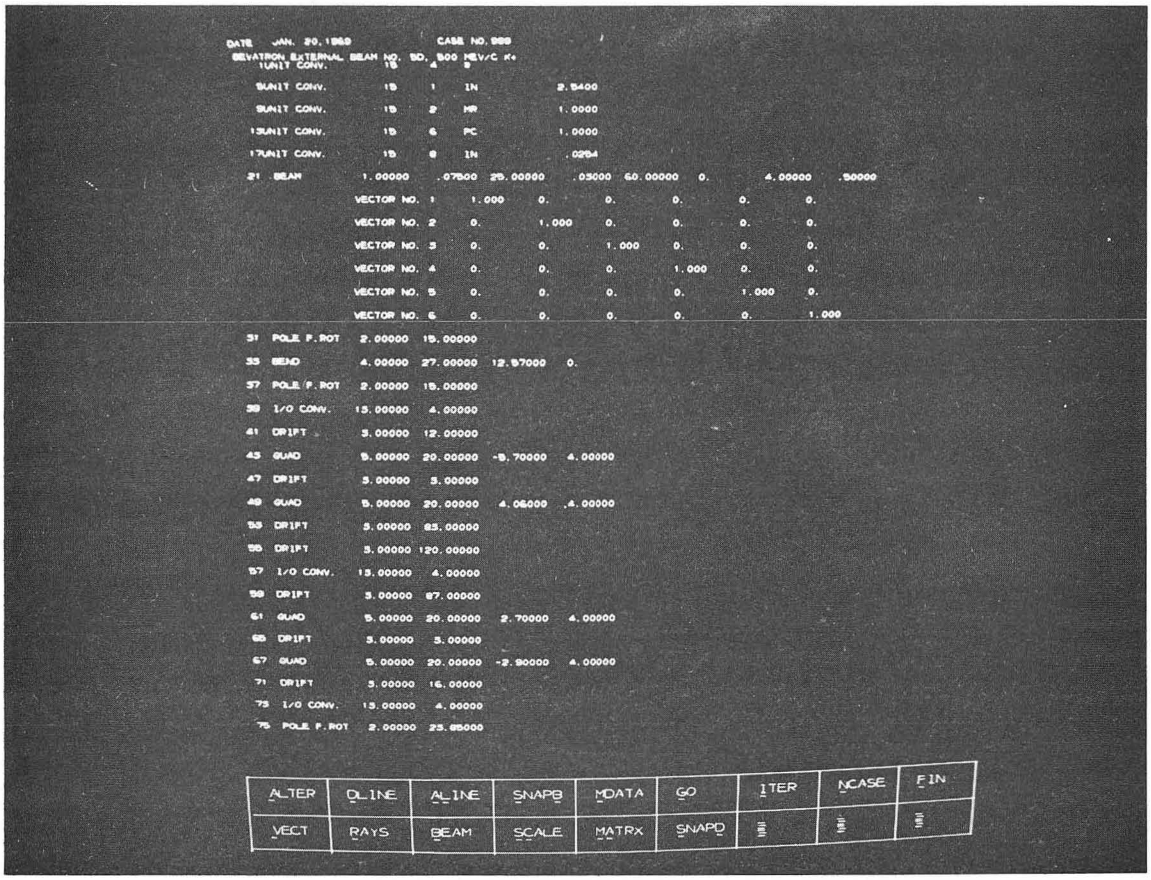
Fig. 1



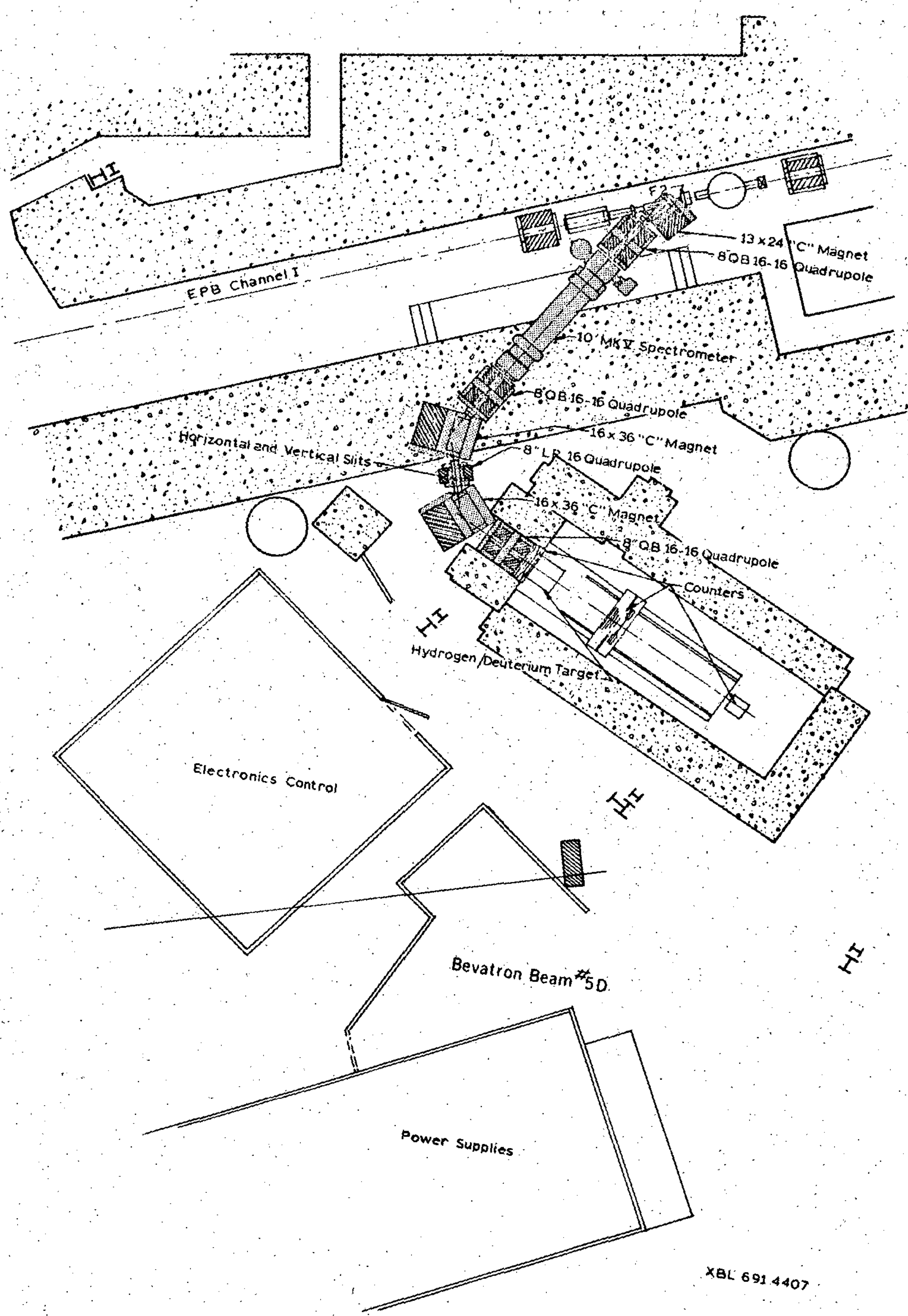
XBL 694-369

Fig. 2



XBB 694-2243

Fig. 3



F2
13 x 24 "C" Magnet
8"QB 16-16 Quadrupole
EPB Channel I
10' MK V Spectrometer
8"QB 16-16 Quadrupole
16 x 36 "C" Magnet
8" LR 16 Quadrupole
Horizontal and Vertical Slits
16 x 36 "C" Magnet
8" QB 16-16 Quadrupole
Counters
Hydrogen/Deuterium Target
Electronics Control
Bevatron Beam #5D
Power Supplies
XBL 691 4407

Fig. 4

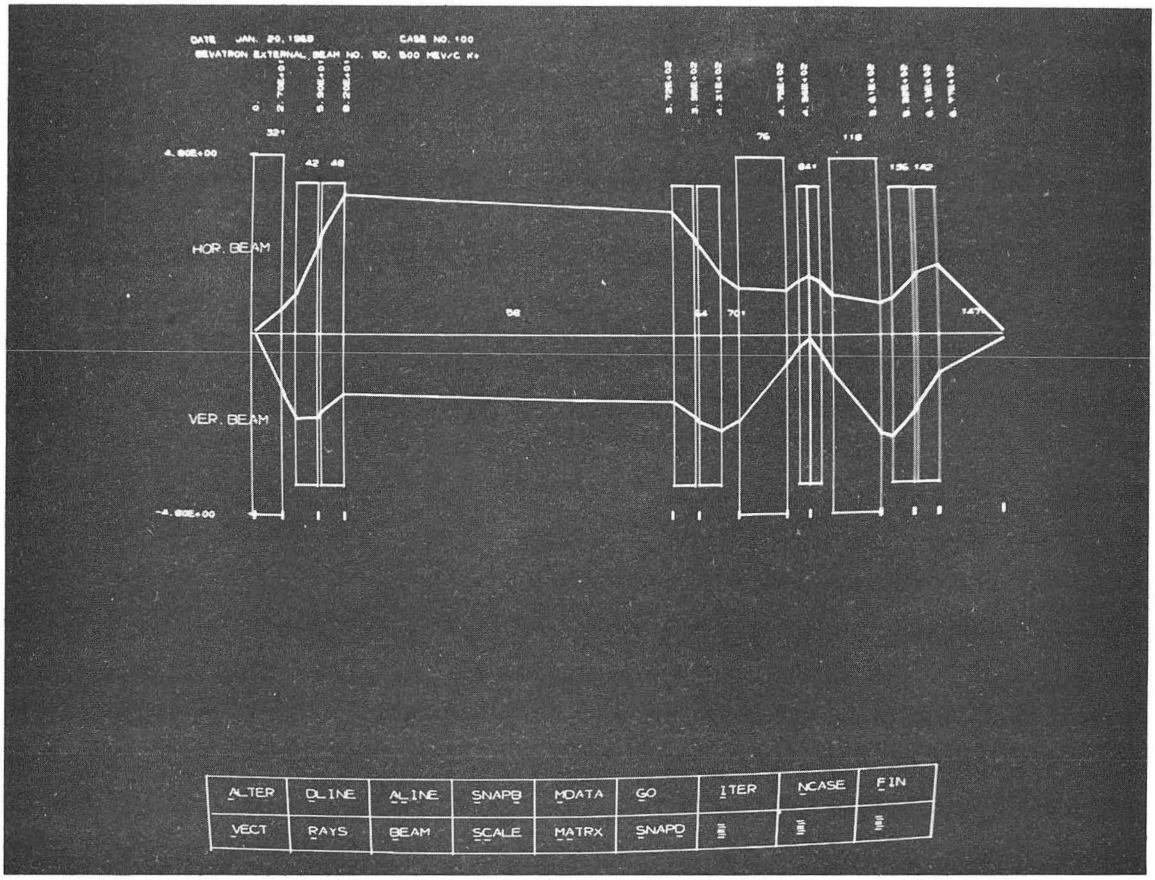


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Fig. 5

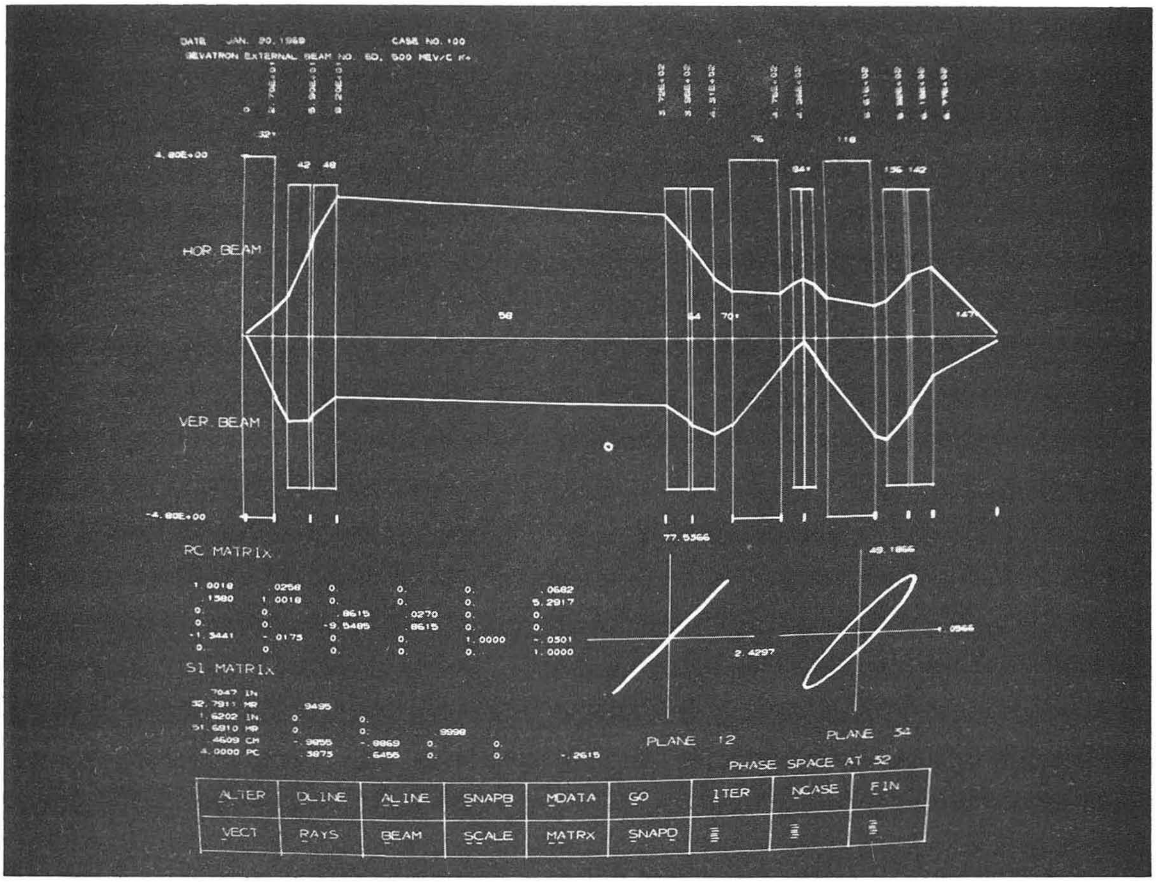

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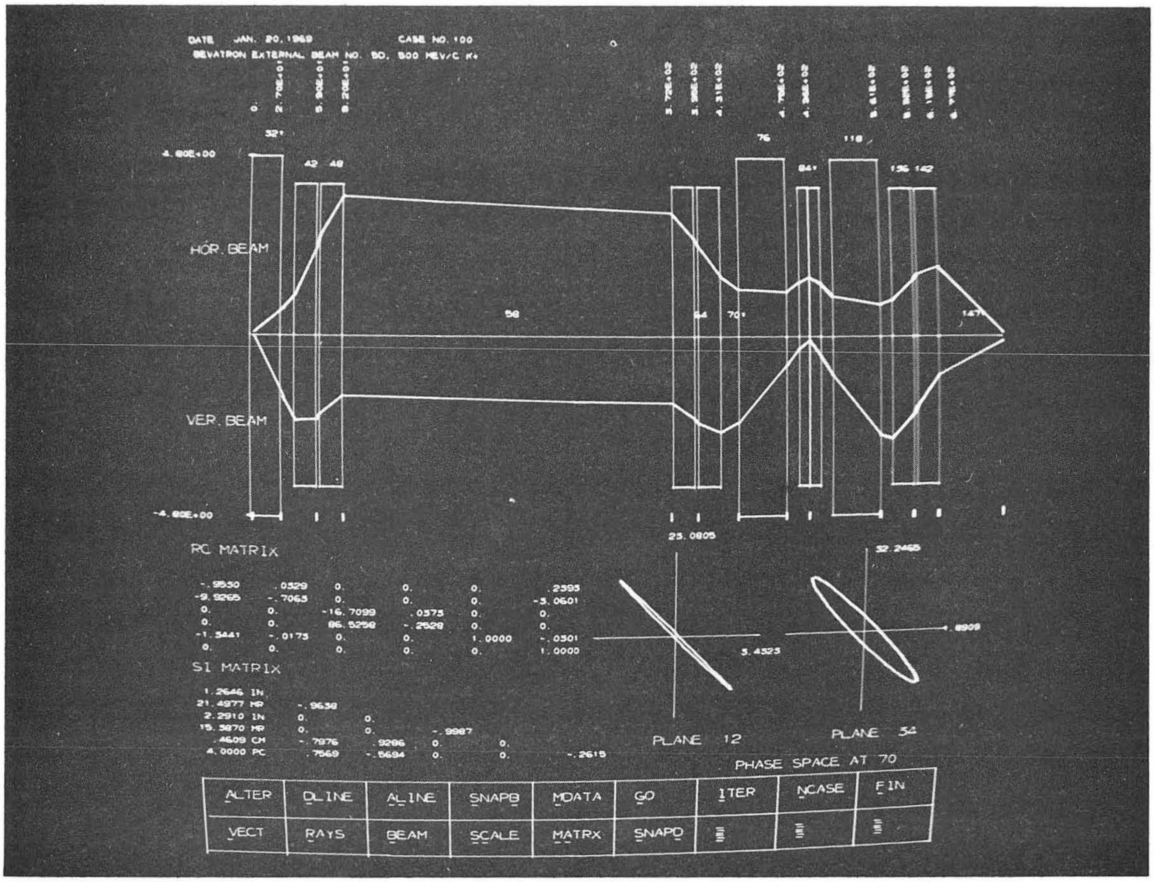
Fig. 6



XBB 694-2241

Fig. 8

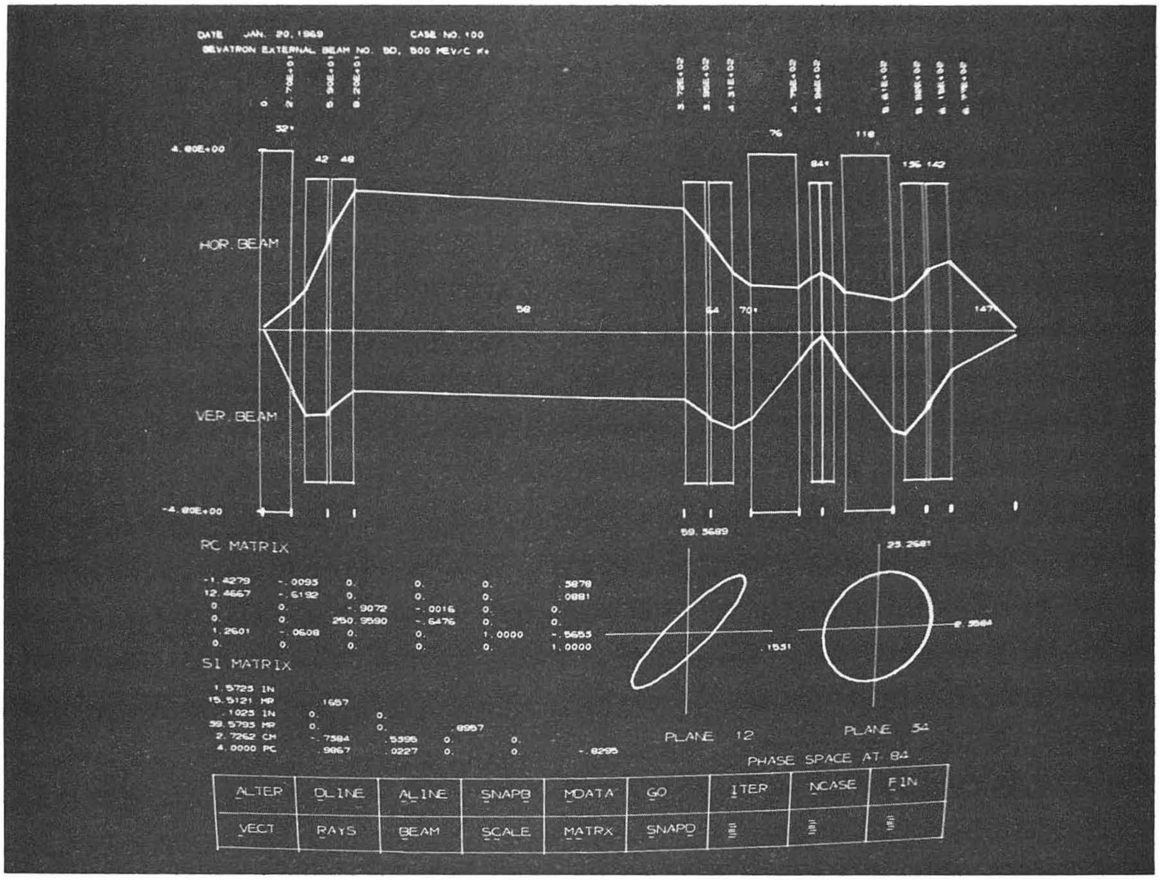


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Fig. 9

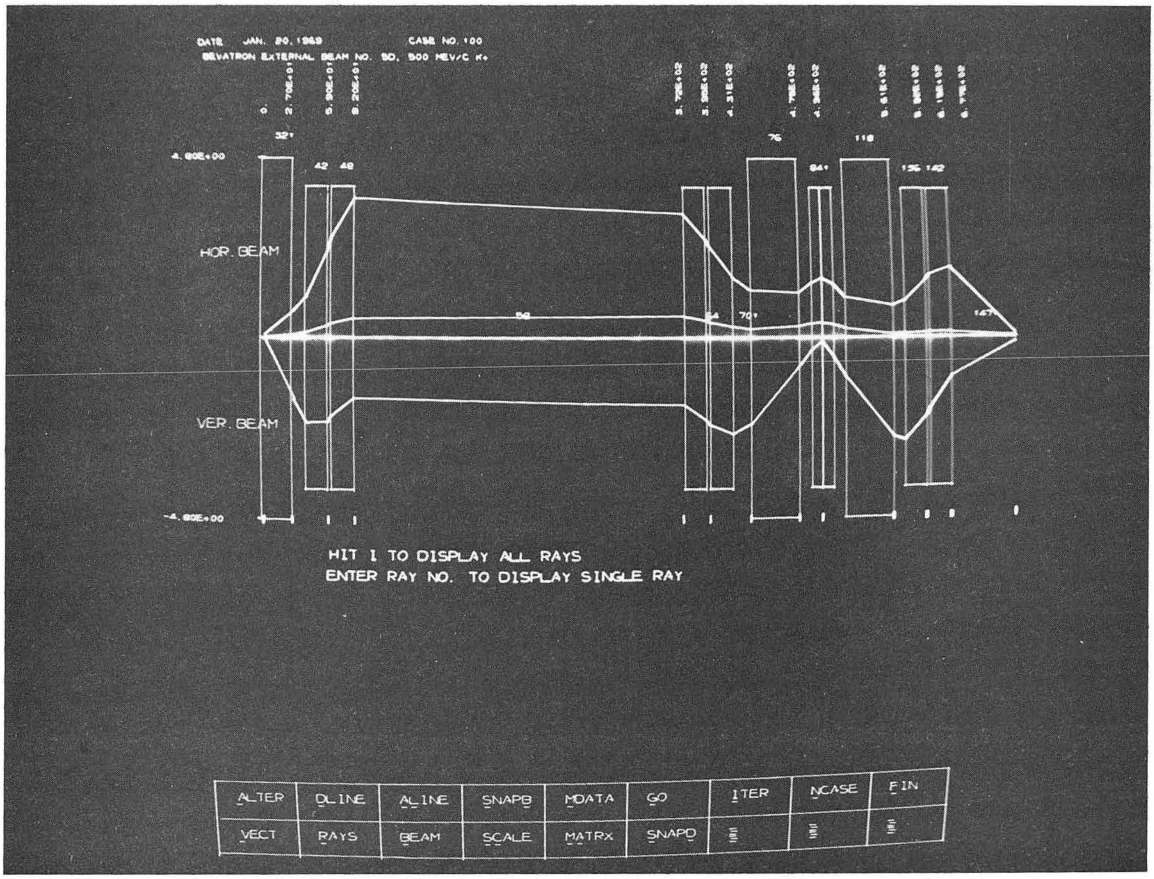

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Fig. 10

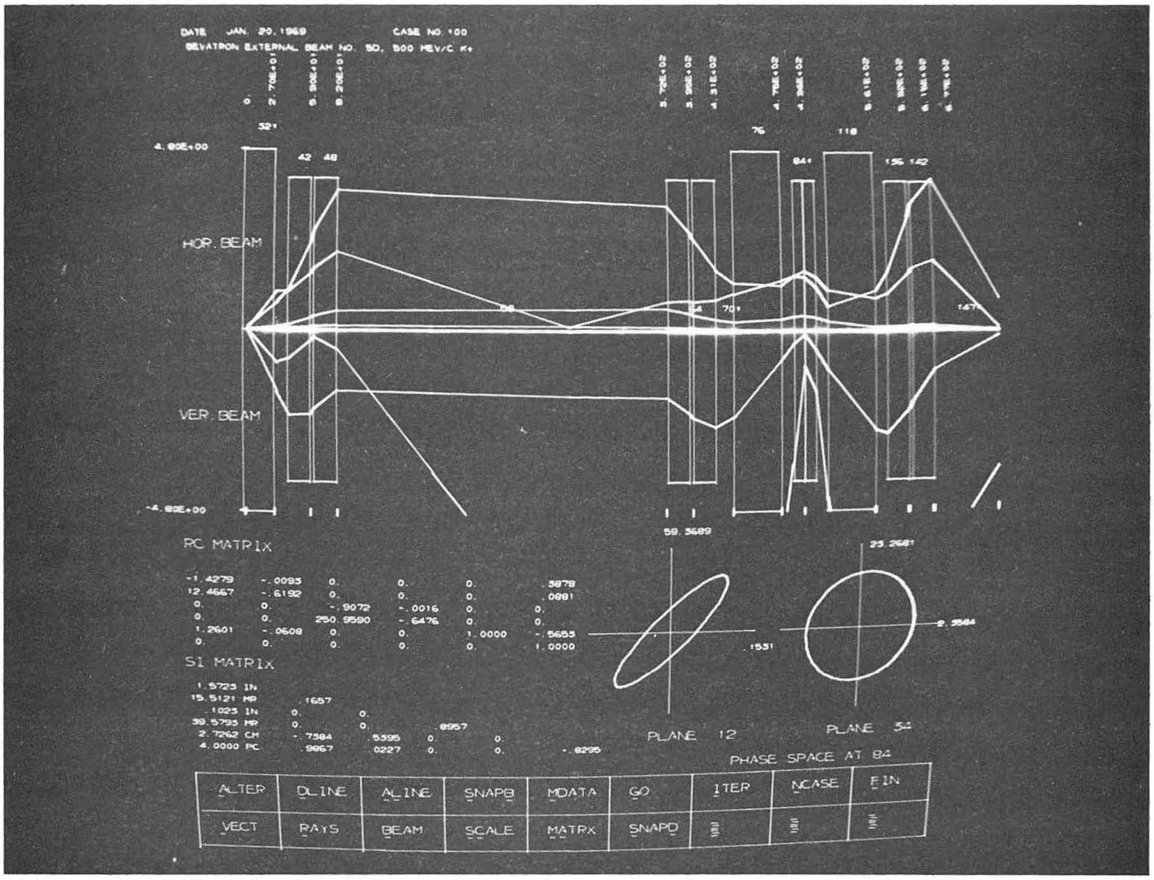

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Fig. 11

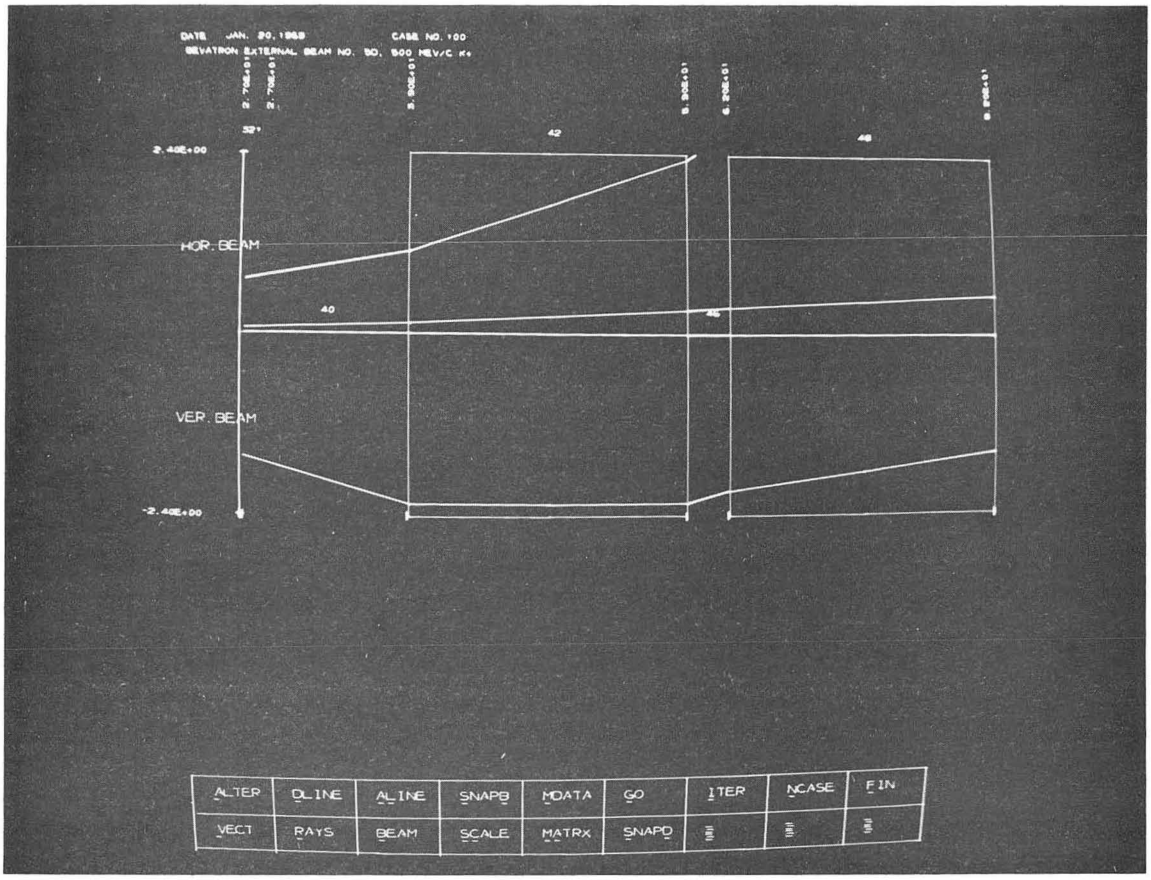

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Fig. 12

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