AN INTERACTIVE BEAM DESIGN PROGRAM WITH MONTECARLO CAPABILITIES†

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The paper presents the development of an interactive program for beam design. The desirable features of an interactive program are discussed and the capabilities of this program are compared with programs for batch processing. The program, as implemented, provides Montecarlo capability as well as ray tracing, optimization, and phase plane mapping, while accepting up to 333 elements. The program has been used in the design of a number of beams at Argonne.

1. INTRODUCTION

Computer simulations of beam transport systems have been found useful by high energy physicists in beam design. Numerous batch processed programs are available and have been used to simulate the various properties of beam transport systems. However, if many changes are required in the initial beam design, the designer may spend much of his time waiting for his job to be scheduled, run, and finally printed. He may then find he has numerous pages of data describing an unworkable beam. An interactive program working with a time-sharing computer can eliminate these inconveniences. This report describes such a program.

DAOPTIC is derived from the program OPTIK[1] and incorporates several other capabilities. As with OPTIK, each source particle is represented by a six-dimensional vector. The beam line is made up of an arrangement of the four element types; drift length, bending magnet, quadrupole, and separator. Each element is represented by a six-by-six transfer matrix which describes its action on the particle vector. A product matrix, the transfer matrix from the source to the end of the element, is computed and stored for each element.

After the beam has been loaded into the active file, other commands allow the manipulation of the beam elements and the optimization of quadrupole gradients to meet requested conditions. Whenever desired any parameters for any or all of the beam elements can be displayed. Particle vectors can be tracked and displayed either as a list or graphically.

Other commands will track phase-space ellipses or generate a number of random particles, track them down the beam line, and plot the requested results. After a final design has been reached, the current parameters can be listed at the terminal. The beam can then be stored on a disk file or punched onto paper tape for future use, freeing the active disk area for a new beam.

The program was written in Fortran IV and developed on the TYMSHARE[2] system using a Com Data series 33 terminal and model 301A acoustic data set to couple to the telephone line. The formats of the graphic displays fill the 27 line display area of the Hazeltine 2000 CRT terminal which allows operation at 30 characters per second. In order to provide an alternative commercial timeshare system, the program was adopted to run on the CYPHERNETICS[3] system. Preliminary tests have indicated that this revised version is somewhat more efficient. The program is divided into five parts, each less than 8000 characters long. Only one part is in core at a given time. Thus, the program can be easily adopted to any timesharing system that allows a file size of about 8000 characters with an overlay system to transfer the program parts into and out of core as they are needed.

2. ELEMENT ALGORITHMS

2.1. *The Six-Dimensional Vector Space*

Each particle emitted by the target is defined at the entrance plane of the beam line by a vector $(X, X', Y, Y', DP/P, M)$ where X is the horizontal displacement from the equilibrium orbit, X' is the horizontal angle with respect to the equilibrium

orbit, Y and Y' are the corresponding quantities in the vertical direction, $DP/P = (P1 - P)/P$ where P is the design momentum and P1 is the true momentum of the particle under consideration, and M is the projection operator which accounts for particles of different mass. M is used directly only by the separator(s). $M = 0$ for the undeflected particle; $M = 1$ for the deflected particle. The operation of each element on the particle vector is represented as a six-by-six transfer matrix:

$$[T] = \begin{bmatrix} M_{11} & M_{12} & 0 & 0 & M_{15} & 0 \\ M_{21} & M_{22} & 0 & 0 & M_{25} & 0 \\ 0 & 0 & M_{33} & M_{34} & 0 & M_{36} \\ 0 & 0 & M_{43} & M_{44} & 0 & M_{46} \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

For the beam elements handled by this program, two-thirds of the matrix elements are always zero (or one) as shown. The matrix multiplication routine used in this program takes advantage of this to reduce the operation required and increase the speed.

2.2. Source

The source is a rectangular solid from which the particles originate (see Fig. 1). The source parameters are:
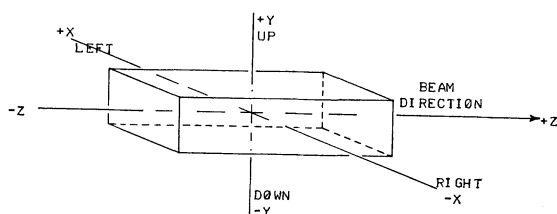

FIG. 1. The source.

P = Design momentum.
XTARG = The horizontal displacement of the center of the target from the axis of the beam line.
WIDTH = The horizontal thickness of the target.
YTARG = The vertical displacement of the center of the target from the Z axis of the beam line.

HEIGHT = The vertical thickness of the target.
ZTARG = The distance downstream from the center of the target to the entrance to the first element.
TLEN = The target length.
HANG = The horizontal angle; the projection, in the horizontal plane, of the angle between the Z axis of the beam line and the average path of the particles emitted by the source.
HRANG = The range of angles, in the horizontal plane, of the source particle trajectories.
VANG = The vertical angle; the projection, in the vertical plane, of the angle between the Z axis of the beam line and the average path of the particles emitted by the source.
VRANG = The range of angles, in the vertical plane, of the source particle trajectories.
PMIN = The minimum momentum.
PMAX = The maximum momentum.

The full set of parameters is needed only by the MONTECARLO routines which generate a set of particles having a uniform distribution of position, within the dimensions of the source, angles within the range defined by the four angular terms, and momentum over the range PMIN to PMAX. In calculating the target phase space intercepts, only the X and Y dimensions are needed. In the ray tracking and other operations, the source parameters are not used. If the source is replaced after the beam has been loaded, the element transfer matrices for the quadrupoles and bending magnets are automatically recomputed at the new design momentum.

2.3. Drift Length

A drift length contains no deflecting fields and is completely defined by its length, L. Its matrix is as follows:

$$[T] = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

A drift length, like each of the other three element types, has limits to maximum allowable X and Y displacements of the particles. These apertures are specified when the element file is created. The apertures are used by the LOSS and MONTE-CARLO routines to determine whether or not a particle is lost within an element. The apertures are also reflected back to the source for calculating the limiting lines in the target phase planes.

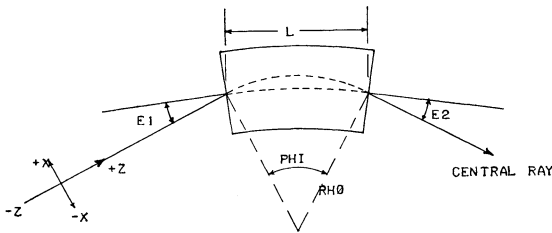### 2.4. *Bending Magnet* (see Fig. 2)

FIG. 2. The bending magnet.

This is a region in which the field is parallel to the Y axis and is constant along the X axis. There are two types, ID = 4 and ID = 11. In the first type, the field is constant along the Z axis and falls abruptly to zero at the ends of the magnet. In the second type, the field is maximum at the center of the magnet and decreases symmetrically with increasing distance from the center along the Z axis, finally reaching zero at some distance outside the magnet. The first is defined by the parameters L, E1, E2, and PHI where:

    L = Length of magnet.

    E1 = The angle between the central ray and the normal to the entrance face of the magnet.

    E2 = The angle between the central ray and the normal to the exit face of the magnet.

    PHI = The total bend angle, the angle between the central ray at the entrance, and the central ray at the exit.

From these values the program will compute the radius of curvature and the magnetic field required to produce the given bend angle. For the second type it is necessary to specify also the Z variation of the field. DZ and B(I) must be specified where DZ is the distance between readings taken along the Z axis beginning where the field is zero or near zero and ending at the center of the magnet. B(I),

I = 1, N is the set of field values where B is in kilogauss. Both algorithms are valid for small bend angles, but for larger bend angles the vertical focussing contributed by the gradient along the Z axis becomes significant.

The matrix elements for the type 4 bending magnets are described in the reference for OPTIK.[1] The algorithm for the type 11 bending magnet was obtained from the program TRAMP.[4]

2.5. *Quadrupoles*

This is a region of quadrupole magnetic field. The quadrupole is defined by P, L, and DB/DR where:

    P = Design momentum.

    L = Quadrupole length.

    DB/DR = Quadrupole field gradient.

The quadrupole matrix elements were obtained from program OPTIK.[1]

2.6. *Crossed Field Separator*

The separator is a region of uniform electric field perpendicular to a uniform magnetic field both perpendicular to the beam axis giving no deflection to the particle of mass MU but giving a vertical deflection to a particle of mass MD. It is defined by L, D, V, MU, and MD where:

    L = Length.

    D = Vertical gap.

    V = Electric field.

    MU = Mass of the undeflected particle.

    MD = Mass of the deflected particle.

The program computes the magnetic field needed to give zero deflection to the undeflected particle. The separator transfer matrix is:

$$[T] = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & L*S \\ 0 & 0 & 0 & 1 & 0 & S \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where S is defined in the OPTIK[1] report.

3. CREATION AND MANAGEMENT OF BEAM FILES

The nine commands used for this purpose are INPUT, SAVE, PUNCH, LOAD, TAPE, APPEND, DIRECTORY, SCRATCH, and QUIT.

3.1. *Input*

INPUT allows the user to enter the element parameters at the terminal, and is usually used when the beam is created. The program will prompt for each value as it is needed, requesting first the source parameters. The source is referred to as element zero and has an identification number, ID, of 1. After the source parameters have been read and stored in the appropriate files, the program will prompt for the ID and aperture limits for the first element of the beam line (NEL = 1). See Table I for a list of ID numbers for the element

TABLE I

ID	Element Types
0	End of Beam
1	Source
2	Drift Length
3	Quadrupole Doublet
4	Bending Magnet
5	Crossed Field Separator
7	Quadrupole Symmetric Triplet
8	Precomputed Matrix
9	Horizontally Converging Quadrupole
10	Horizontally Diverging Quadrupole
11	Bending Magnet with Soft Edge Vertical Focussing

types. When these values have been read, the program will request the remaining parameters needed according to the element type. Next, the element transfer matrix and product matrix are computed and written in their respective files. The program will then ask for the ID of the second element. After all the desired elements have been loaded, the end of the beam is indicated by typing an ID of zero.

3.2. *Save, Punch*

After completing the desired work on the active beam, the command 'SAVE, NAME' can be used to save the beam on an inactive file to prevent its being written over and lost. The file must be named to identify it for loading at a later time.

If a beam is to be stored for a long period of time, it may be economically advantageous to store it on paper tape rather than a disk file. This is accomplished with the command 'PUNCH'. More time is required to punch the tape than to execute the SAVE command, but there is a corresponding saving on the storage charge for disk space.

3.3. *Load, Tape, Append*

A beam that was saved with the SAVE command is loaded into the active field with the command 'LOAD, NAME'. NAME is the name that was assigned with the SAVE command. The product matrices are not stored with the SAVE command; therefore, after loading the beam with the LOAD command, the product matrices must be recomputed. This is done with the command 'COMPUTE, 0'.

The command 'TAPE' is used to read a beam from paper tape. The tape may have been created by the PUNCH command or by copying an OPTIK input data deck.

At some time it may be desired to add several elements to the end of the beam. For this the command 'APPEND, NEL' is used. This command acts exactly as the INPUT command except that input begins at element NEL. The new elements will replace the old element NEL and any later elements in the stored beam.

3.4. *Directory, Scratch, Quit*

DIRECTORY is used to maintain a record of saved beams and to locate lost files. DIRECTORY causes the system to type a list of all files written on the disk.

When a beam stored on the disk is no longer wanted, the command 'SCRATCH, NAME' is used to erase the file from storage.

When a session at the terminal is finished, the QUIT command is used to leave the program and perform the required log-out procedure.

4. OPTIMIZATION OF BEAM PARAMETERS

There are seven commands for the optimization of the beam. These commands are: DELETE, INTERCHANGE, INSERT, REPLACE, COMPUTE, OPT1, and OPT2. The first four are used to move the beam elements. After each operation is finished, the program asks whether to compute the new product matrices at this time. If several changes are to be made, time is saved if the product matrices are not corrected after each change. After all the changes have been made, the COMPUTE command should be used.

'DELETE, NEL' deletes element NEL from the

beam line. 'INTERCHANGE, NF, NL' interchanges the pair of elements NF and NL. 'INSERT, NEL' inserts a new element immediately after element NEL. 'REPLACE, NEL' inserts a new element in place of element NEL. 'COMPUTE, NEL' recomputes the product matrices for elements NEL through the end of the beam. The new element parameters required for the INSERT and REPLACE commands are the same as those required by INPUT. After a DELETE or INSERT command, the elements are renumbered to retain a set of sequential integers.

The last two commands, OPT1 and OPT2 are used to optimize quadrupole gradients. OPT1 uses an iterative procedure to find the gradient necessary to give a specified value to a product matrix element. OPT2 tunes two gradients to satisfy two conditions not necessarily in the same product matrix.

5. DISPLAY OF BEAM PARAMETERS

After loading a beam or making changes in it, the operator may want to display some of the beam parameters. For this purpose there are seven commands. These commands are: APERTURE, ELEMENT, EME, LIST, PRODUCT, PME, and SOURCE.

5.1. *Aperture, NF, NL*

The element aperture is the inside dimension of the element which limits the maximum displacement of the particle. This command lists the apertures for elements NF through NL. To speed the display of data, negative apertures are displayed only when they differ from the positive apertures.

5.2. *Element, NF, NL*

This command displays the entire transfer matrix for each element NF through NL. If after display of the first few values of the matrix, the operator decides that the remaining elements are not wanted, the escape key can be used to terminate the command. If only one beam element matrix is desired, NL is set equal to NF.

5.3. *EME, I, J, NEL*

This command is used to display a single matrix element. It will display matrix element (I, J) for

beam element NEL. EME writes in a free format and is therefore useful when a matrix element is too large to be displayed within the format used by the ELEMENT command.

5.4. *List, NF, NL*

This displays the beam element parameters for elements NF through NL.

5.5. *Product, NF, NL*

This command displays the product matrices for elements NF through NL.

5.6. *PME, I, J, NEL*

This command is used to display a single product matrix element (I, J) for beam element NEL. PME writes in a free format and is, therefore, useful when a matrix element is too large to be displayed within the format used by the PRODUCT command.

5.7. *Source*

This command is used to list the source parameters.

6. PHASE-SPACE ELLIPSES

Phase-space limits can be studied by propagating element apertures back to the target phase plane or by defining ellipses at the source and propagating them down the beam line.

6.1. *Limits, Minimum*

The command 'LIMITS, NF, NL' is used to compute and display the limiting lines in phase space at the source. This is done by propagating element apertures back to the source to determine where they intersect the axes in the $X-X'$ and $Y-Y'$ phase planes. The results are displayed for elements NF through NL. 'MINIMUM' finds and displays the element at which each of the above limits is at a minimum.

6.2. *Target, TMIN*

The command 'TARGET, NF, NL' computes and displays the values of X', Y', and Y' deflected at the points where the $X-X'$, $Y-Y'$, or $Y-Y'$ deflected limiting lines intersect the X or Y limit of the target in the phase planes. The set is

displayed for each of elements NF through NL. 'TMIN' finds and displays the elements at which each of these limits is a minimum.

6.3. *Ellipse, T, V1, V2, Z, NF, NL*

This is an adaptation of a routine from program TRAMP.[4,5] Phase space ellipses are displayed at the ends of elements NF through NL. T = H for horizontal plane. T = V for vertical. The initial ellipse is upright with semi-axes V1 and V2 at a distance Z upstream from the entrance to the first element.

7. TRACKING OF PARTICLES

Two methods are available. First, a set of up to nine vectors can be loaded using V and V2 commands and displayed with the commands DR, LOSS, XPLOT, XPPLOT, YPLOT, YPPLOT. Second, a set of random particles can be generated and tracked with the MONTECARLO command.

7.1. *V2, V, DR, LOSS*

'V2' is used to enter the on axis, 2 per cent off momentum vector [0, 0, 0, 0, .02, 0]. 'V, X, X', Y, Y', DP/P, M' is used to enter any other vector. The DP/P term affects the bending magnet divergence but not the chromatic aberration of the quadrupoles. A maximum of nine vectors can be entered as a set. The execution of any command other than V or V2 will close the vector set so that the next execution of V or V2 will erase the old set and begin with the first vector of a new set. 'DR, NF, NL' displays the set of emerging vectors at the ends of elements NF through NL. 'LOSS, NV' tracks vector number NV of the set of vectors from source to end of beam. At the first element at which the X or Y position of the particle exceeds the entrance or exit aperture, the element number and the vector are printed. If no apertures are exceeded, the message 'END of BEAM, NO LIMITS EXCEEDED' is printed.

7.2. *The Plotting Routines*

There are four plotting routines which can be used with the vector set.

'XPLOT, NV, NF, NL' Plots X versus element.
'XPPLOT, NV, NF, NL' Plots X' versus element.
'YPLOT, NV, NF, NL' Plots Y versus element.

'YPPLOT, NV, NF, NL' Plots Y' versus element.

In each case the ordinate is adjusted according to the maximum excursion to best fill the display area. NV identifies which vector of the set is to be used. If only a few elements are included in the plot, the elements NF through NL are spread out to cover at least half of the width of the page.

7.3. *Montecarlo Routines*

These are adapted from program LLURCH.[6] There are three types of MONTECARLO displays and a SETRAND command. 'SETRAND, IX' can be used, if desired, to set the random number generator for the MONTECARLO runs. If IX is positive or zero, the sequence will begin with a number determined by IX. If IX is negative, the sequence will begin with a number set by reading the internal clock of the computer in milliseconds.

The MONTECARLO routine generates particles of random position, angles, and momentum within the dimensions of the source. The DP/P term of the particle vector affects only the bending magnet divergence; it does not include the chromatic aberration of the quadrupoles. The particles are tested at the entrance and exit aperture of each element and tracked through the beam line until lost by striking an element. After NTRY, particles have been tracked, the results are displayed. The flux continues to accumulate and print after every NTRY particles until interrupted with the escape key. Then a new value of NTRY is requested.

'MONTECARLO, 0' displays a list of flux versus element.

'MONTECARLO, 1' plots particle flux versus one particle dimension.

'MONTECARLO, 2' plots one particle dimension against another and shows the flux in each bin.

The parameters requested by each command are shown below:

'MONTECARLO, 0' MASS, NTRY.

'MONTECARLO, 1' MASS, REF, HVAR, HPLOT, HMIN, HMAX, NTRY.

'MONTECARLO, 2' MASS, REF, HVAR, HPLOT, HMIN, HMAX, VVAR, VPLOT, VMIN, VMAX, NTRY.

MASS = 0 for undeflected particles.

MASS = 1 for deflected particles.

NTRY = number of particles tracked before displaying results.

HVAR = 1 to plot X.

HVAR = 2 to plot X'.

HVAR = 3 to plot Y.

HVAR = 4 to plot Y'.

HVAR = 5 to plot DP/P.

HPLOT = Element number at which horizontal plot data is wanted.

HMIN = Minimum value to be plotted horizontally.

HMAX = Maximum value to be plotted horizontally.

VVAR, VPLOT, VMIN, and VMAX are vertical counterparts of HVAR, HPLOT, HMIN, and HMAX.

REF = Element number of reference element.

8. SAMPLE BEAM DESIGN

To demonstrate the capabilities of the program, a sample beam design is presented. Figures 3 through 10 are the teletype output produced during this problem. The user input has been underlined to distinguish it from the computer output.

The initial beam is loaded with the INPUT command, see Fig. 3, and consists of a point source of 1000 MeV/c particles, a drift length, a horizontally converging quadrupole, and several more drift lengths. After the initial beam has been loaded, the APPEND command can be used to add more elements to the end of the beam. In our example a bending magnet and a drift length are added. To keep the total beam the same length, element 3 is replaced with a shorter drift length to compensate for the vertically converging quadrupole

```
TYPE COMMAND: INPUT

DO YOU WISH TO DISPLAY ELEMENT PARAMETERS ? NO
ELEMENT MATRICES ? N
PRODUCT MATRICES ? N
NEL=  0
 ID=  1
  P=1000, XTARG=0, WIDTH=0, YTARG=0, HEIGHT=0, ZTARG=0, LENGTH=0
  HANG=0, HRANG=0, VANG=0, VRANG=0, PMIN=1000, PMAX=1000
NEL=  1
 ID=2, LIMITS:5,-5,5,-5, L=131.5
NEL=  2
 ID=9, LIMITS:2,-2,2,-2, L=37.5
 GRAD=500
NEL=  3
 ID=2, LIMITS:5,-5,5,-5, L=329.5
NEL=  4
 ID=2, LIMITS:4,-4,4,-4, L=35.6
NEL=  5
 ID=2, LIMITS:3,-3,3,-3, L=15.8
NEL=  6
 ID=2, LIMITS:4,-4,4,-4, L=35.6
NEL=  7
 ID=2, LIMITS:4,-4,4,-4, L=297
NEL=  8
 ID=0
END OF BEAM, TOTAL ELEMENTS =    7
TYPE COMMAND: APPEND,8
DO YOU WISH TO DISPLAY ELEMENT PARAMETERS ? N
ELEMENT MATRICES ? N
PRODUCT MATRICES ? N
NEL=  8
 ID=4, LIMITS:4,-4,2,-2, LEFF=38, E1=5.5, E2=5.5, PHI=11
NEL=  9
 ID=2, LIMITS:4,-4,4,-4, L=400
NEL= 10
 ID=0
END OF BEAM, TOTAL ELEMENTS =    9
TYPE COMMAND: REPLACE,3
 NEW ID=2, LIMITS: 5,-5,5,-5, L=281.5
COMPUTE PRODUCTS ? N
TYPE COMMAND: INSERT,1
 NEW ID=2, LIMITS: 2,-2,2,-2, L=10.5
COMPUTE PRODUCTS ? N
TYPE COMMAND: INSE,1
 NEW ID=10, LIMITS: 2,-2,2,-2, L=37.6, GRAD=500,COMPUTE PRODUCTS ? Y
END OF BEAM, TOTAL ELEMENTS =   11
TYPE COMMAND:
```

FIG. 3. Entering the beam elements.

```
TYPE COMMAND: OPT2
ELEMENT NUMBERS OF QUADRUPOLES ARE 2,4
CONDITIONS TO BE SPECIFIED AT THE ENDS OF ELEMENTS NUMBERED 11,11
AT THE END OF ELEMENT     11   ,SPECIFY THE MATRIX ELEMENT
AND ITS DESIRED VALUE. 1,2,0
AT THE END OF ELEMENT     11   ,SPECIFY THE MATRIX ELEMENT
AND ITS DESIRED VALUE. 3,4,0
TRIAL VALUES FOR ITERATION     1
COND1=  -482.73333   THETA1=  .78368123
COND2=   606.34533   THETA2=  .71013913
OPTIC HAS DONE IT AGAIN. A SOLUTION HAS BEEN REACHED.
THETA2=  .71312682   GRADIENT2=   474.89968
THETA1=  .80543556   GRADIENT1=   602.58287
TYPE COMMAND: PROD,11,11
PRODUCT    11
   -3.356175     .000000      0           0         80.673365      0
    -.004698    -.297958      0           0           .192578      0
        0           0      -9.678072    -.000000        0        0.000000
        0           0        -.004038   -.103326        0        0.000000
        0           0         0           0            1          0
        0           0         0           0            0          1
TYPE COMMAND: LIST,1,11
NEL ID    R1          R2          R3          R4        R5         R6
  1  2 131.50000
  2 10  37.60000     .80544    602.58287
  3  2  10.50000
  4  9  37.50000     .71313    474.89968
  5  2 281.50000
  6  2  35.60000
  7  2  15.80000
  8  2  35.60000
  9  2 297.00000
 10  4  38.00000    5.50000      5.50000    11.00000  198.23521   6.62007
 11  2 400.00000
TYPE COMMAND: APER,1,11
NEL     X          Y          -X         -Y
  1   5.000      5.000
  2   2.000      2.000
  3   2.000      2.000
  4   2.000      2.000
  5   5.000      5.000
  6   4.000      4.000
  7   3.000      3.000
  8   4.000      4.000
  9   4.000      4.000
 10   4.000      2.000
 11   4.000      4.000
TYPE COMMAND:
```

FIG. 4. Quadrupole optimization and parameter list.

```
TYPE COMMAND: LIMIT,1,11
NEL     X          X'          Y          Y'       Y (DEFL) Y'
  1   5.000      38.02      5.000      38.02
  1
  2   1.490       9.16      2.887      16.03
  2
  3   1.296       7.73      3.769      18.06
  3
  4   1.094       6.08     47.975      23.39
  4
  5   9.904      20.42     -1.534      73.35
  5
  6  11.849      17.07     -1.088      60.63
  6
  7  11.392      13.07      -.777      46.15
  7
  8  41.625      18.27      -.935      63.69
  8
  9  -3.079      30.66      -.515      89.89
  9
 10  -2.708      33.56      -.248      48.39
 10
 11  -1.192   10000.00      -.413   10000.00
 11   1.192   10000.00       .413   10000.00
TYPE COMMAND: MINI
NEL=    2    +Y' MIN=       16.029838
NEL=    2    -Y' MIN=      -16.029838
NEL=    2    +Y' DEFL MIN=   16.029838
NEL=    2    -Y' DEFL MIN=  -16.029838
NEL=    4    +X MIN=     1.0944868
NEL=    4    -X MIN=    -1.0944868
NEL=    4    +X' MIN=     6.0837458
NEL=    4    -X' MIN=    -6.0837458
NEL=   10    +Y MIN=    -.2480459
NEL=   10    -Y MIN=     .2480459
NEL=   10    +Y DEFL MIN=   -.2480459
NEL=   10    -Y DEFL MIN=    .2480459
TYPE COMMAND:
```

FIG. 5. The limiting lines in phase space.

and drift length to be added with the INSERT command. The two quadrupoles will form a doublet and allow specification of conditions in both the horizontal and vertical planes.

In Fig. 4, with the command OPT2, the program is instructed to adjust the two quadrupole gradients until images are formed in both planes at the end of element 11, the end of the beam. After the beam has been optimized, the commands PRODUCT, LIST, and APERTURE can be used to list some of the beam parameters. The LIMITS command, see Fig. 5, lists the limiting lines in the target phase plane for the specified range of elements. Often only the minimum values are wanted from this list. The MINIMUM command can then be used to find and print the minimum value from each column.

The last phase of the beam design is the propagation of particles down the beam line. This can be done specifically by using sets of particle vectors or statistically by using large quantities of randomly generated particle vectors. In Fig. 6 a set of 3 vectors is loaded with the V2 and V commands. The DR command is then used to display the resulting vectors at the end of each element of the beam. Alternately, one term of a vector may be plotted as a function of element number. In Fig. 7, the horizontal position of the second vector of the set of 3 is plotted for elements 1 through 11. A variation on the vector trajectory is provided with the ELLIPSE command. In Fig. 8 of the example, a horizontal phase-space ellipse with initial semi-axes of 0.1 inches and 10 mrad is tracked through the beam line. The statistical analysis is provided by the 3 MONTECARLO commands. The SOURCE command displays the current source parameters. Since the source was initially given zero dimensions, it must be changed before the MONTECARLO routines will have any value. The source is changed by replacing element number zero. The first routine, MONTECARLO, 0,

```
TYPE COMMAND:  V2

TYPE COMMAND:  V,-.3,10,0,0,0,0

TYPE COMMAND:  V,0,10,0,10,0,0

TYPE COMMAND:  DR,1,11
NEL      X              X'              Y            Y'
  1
       1.015000      10.000000
       1.315000      10.000000     1.315000     10.000000
  2
       1.780409      32.890791
       2.183094      38.644871     1.247673    -13.385481
  3
       2.125762      32.890791
       2.588865      38.644871     1.107126    -13.385481
  4
       2.739246      -1.570157
       3.287448      -2.979583      .855179     -.616363
  5
       2.297247      -1.570157
       2.448696      -2.979583      .681673     -.616363
  6
       2.241349      -1.570157
       2.342623      -2.979583      .659730     -.616363
  7
       2.216541      -1.570157
       2.295545      -2.979583      .649992     -.616363
  8
       2.160643      -1.570157
       2.189472      -2.979583      .628049     -.616363
  9
       1.694307      -1.570157
       1.304536      -2.979583      .444989     -.616363
 10    .072843       3.851561
       1.634915      -1.570157
       1.191833      -2.979583      .413305    -1.033264
 11    1.613467      3.851561
       1.006852      -1.570157
        .000000      -2.979583     -.000000    -1.033264
TYPE COMMAND:
```

FIG. 6. Entering and displaying propagated vectors.

```
TYPE COMMAND: XPLOT,2,1,11
      .
      .
      .
    5----------------------------------------------------------------
      .
      .
      .
      .
      .                      *     *
      .            *     *              *     *     *
      .      *                                            *     *
      .                                                            *
    0----------------------------------------------------------------
      .
      .
      .
      .
      .
      .
      .
      .
    5----------------------------------------------------------------
      .
TYPE COMMAND:
```

FIG. 7. Plot of particle trajectory.

```
TYPE COMMAND: ELLIPSE,H,,1,10,0,1,11
  NEL    SEMIAXIS     ANGLE          PROFILES
         INCHES       DEGREES     INCHES     MILLIRADIANS
   1     1.6540       37.1503     1.3188     10.0000
   2     4.4446       60.5222     2.1872     38.6924
   3     4.6580       56.1675     2.5935     38.6924
   4      .0302       84.7916     3.2925      3.0164
   5      .0405       83.0410     2.4492      3.0164
   6      .0423       82.7343     2.3429      3.0164
   7      .0432       82.5896     2.2957      3.0164
   8      .0453       82.2420     2.1895      3.0164
   9      .0745       77.4109     1.3110      3.0164
  10      .0809       76.3684     1.2009      3.0164
  11      .3478       27.7628      .3356      3.0164
TYPE COMMAND: SOURCE
XTARG=     0     WIDTH=      0
YTARG=     0     HEIGHT=     0
ZTARG=     0     LENGTH=     0
HANG=      0     HRANG=      0
VANG=      0     VRANG=      0
P=      1000     PMIN=      1000     PMAX=      1000
TYPE COMMAND: REPL,0
ID=1
  P=1000, XTARG=0, WIDTH=.2, YTARG=0, HEIGHT=.2, ZTARG=0, LENGTH=.5
  HANG=0, HRANG=20, VANG=0, VRANG=20, PMIN=980, PMAX=1020
END OF BEAM, TOTAL ELEMENTS =     11
TYPE COMMAND: MONTECARLO,0,MASS=0,NTRY=10
START=     10
       10     9     8     7     7     7     7     7     7     7
        7
START=     20
       20    17    15    12    12    12    12    12    12    12
       12
START=     30
   NTRY=200
START=     243
      243   227   190   139   139   139   139   139   139   139
      139
NTRY=0
TYPE COMMAND:
```

FIG. 8. Ellipse, source and Montecarlo, 0 commands.

```
TYPE COMMAND: MONT, 1, MASS=0, VAR.  TYPE=1, PLOT=11, REFERENCE=11
MIN.=-4, MAX.=4, NTRY=500

  VAR. TYPE= 1   PART.TYPE= 0   PLOT EL.=  11   REF. EL.=  11
  MIN.=   -4    MAX.=     4    BIN SIZE=    .16
  START=   500  PLOT=    321   OVERFLOW=   0   UNDERFLOW=    0
  MEAN X=      7.0506391E-02
                                       *
                        *   ** *       *
                        *   ** *       *
                        *   ** *       *
                        **  ** *  * *  ** *
                        **  ** *  * *  ** *
                        **  *** *****  ** *
                       * ** *********  ****
                       **** ********* ****
                       ***** ********* ****
                       ***** ********* ****
                       *******************
                       *******************
                       ****************** *
                       ****************** *
                       ************************
                       ***********************
                       ************************
                      * *11111*111121111*1111***
                       21513296949930464699636573
---- ----X----+----X----+----X----+----X----+----X----+----X
NTRY=0
TYPE COMMAND:
```

FIG. 9. The Montecarlo, 1 command.

```
TYPE COMMAND: MONT, 2, MASS=0, REF. EL.=11, X VAR.=1, X PLOT=11
X MIN.=-2, X MAX.=2, Y VAR.=5, Y PLOT=11, Y MIN.=-.02, Y MAX.=.02
NTRY=1000

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 2 3 5 6 3 4 PRI/SEC    0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 4 5 2 3 3 2 1 REF. EL.  11
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 3 5 0 3 3 2 2 3 1 START    1000
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 3 1 5 4 3 0 2 1 0 PLOT      50?
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 1 1 7 4 5 6 3 3 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 2 3 4 4 2 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 6 8 4 5 2 4 1 0 0 0 0 0 ACROSS:
0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 6 4 2 3 0 3 0 0 0 0 0 0 0 TYPE       1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 3 3 2 3 2 1 0 0 0 0 0 0 0 EL. NO.   11
0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 2 4 6 1 3 1 1 0 0 0 0 0 0 0 MAX.   2.000
0 0 0 0 0 0 0 0 0 0 0 0 4 2 2 6 4 4 1 4 2 0 0 0 0 0 0 0 0 MIN.  -2.000
0 0 0 0 0 0 0 0 0 0 0 2 3 2 2 5 5 4 1 1 0 0 0 0 0 0 0 0 0 BIN     .133
0 0 0 0 0 0 0 0 0 0 1 2 0 3 4 4 2 1 2 0 0 0 0 0 0 0 0 0 0 OVERFLO    2
0 0 0 0 0 0 0 0 0 1 0 2 4 5 4 2 0 3 0 0 0 0 0 0 0 0 0 0 0 UNDERFL    2
0 0 0 0 0 0 0 0 0 3 4 3 5 6 4 4 0 0 0 0 0 0 0 0 0 0 0 0 0 MEAN    .000
0 0 0 0 0 0 0 0 0 5 6 4 1 3 0 2 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1 7 0 3 3 6 3 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 1 1 4 4 3 5 4 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 UPWARDS:
0 0 0 0 0 1 1 1 3 2 2 0 4 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 TYPE       5
0 0 0 0 1 1 2 1 3 3 0 1 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 EL. NO.   11
0 0 0 0 5 0 3 2 5 4 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 MAX.    .020
0 0 0 1 3 1 6 6 3 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 MIN.   -.020
0 0 3 0 5 5 5 4 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 BIN     .002
0 1 2 2 4 1 3 2 3 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 OVERFLO    0
2 1 4 4 8 6 4 3 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 UNDERFL    0
1 2 5 6 2 4 3 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 MEAN   -.000
NTRY=0
TYPE COMMAND: SAVE, EM1A

 NEW FILE NEW FILETHE STORED BEAM CONTAINS   11   ELEMENTS.
P=     1000   DELP=    2E-02
TYPE COMMAND: QUIT


CPU TIME: 226 SECS.
TERMINAL TIME: 0:13:14

PLEASE LOG IN:
```

FIG. 10. The two-dimensional Montecarlo plot.

prints a list of the number of surviving particles at the end of each beam element. When interrupted with the escape key, the program requests a new value of NTRY. The user can respond with a new increment or a zero to terminate the command. The command MONTECARLO, 1, produces a graph of particle flux versus one element of the particle vector. Figure 9 is a plot of particle flux versus horizontal position. As with the first routine, an interruption with the escape key causes the system to request a new value of NTRY. MONTECARLO, 2, operates like the first two routines but produces a two-dimensional plot. In Fig. 10, X is plotted horizontally and DP is plotted vertically. Each number printed is the flux in that bin. Finally, the beam was named BM1A and stored with the SAVE command, then the program was terminated with QUIT.

9. SUMMARY

In the TYMSHARE system the compiled program requires about 173K characters of disk storage and the maximum number of elements in a beam is limited by file size to 333. The CYPHERNETICS system, since only the load module need be stored, requires only 93K of disk storage; the file size is unlimited. However, the X and Y plotting routines are limited by paper size and can plot only 69 of the elements on a single graph. The MONTECARLO routines are limited by file size and the dimension statements to the first 100 elements of the beam. In the CYPHERNETICS system this could be very easily increased by changing the dimension statements.

The sample problem of Figs. 3 through 10 provides a good indication of the cost of using this program in terms of both time and money. The Cyphernetics Corporation charges for their services at the rate of $10.00 per hour for terminal connect time plus $0.02 per page-second of CPU time. This problem used a total of 40 minutes plus 390 page-seconds for a cost of $14.50. Of this time, entering the beam elements, Fig. 3 used about $6\frac{1}{2}$ minutes and 26 page-seconds. Optimization of the two quadrupoles, Fig. 4, used 1 minute and 12 page-seconds. The MONTECARLO, 0 routine used 2 minutes and 18 page-seconds to track 243 particles. The MONTECARLO, 2 routine used 15 minutes and 134 page-seconds to track 1000 particles.

Earlier work[7,8] has been oriented toward interactive beam design programs which allow the user to interact, usually on a graphic display console, with a CPU (Central Processing Unit). This program has the advantage of offering complete versatility, while requiring only a timeshare terminal on the part of the beam designer. The program has been implemented on two commercial timeshare systems, and can be implemented on any system which supports Fortran IV.

REFERENCES

1. T. J. Devlin, Lawrence Radiation Laboratory Report, UCRL-9727, 'OPTIK: An IBM 709 Computer Program for the Optics of High Energy Particle Beams' (1961).
2. TYMSHARE: A time-shared computer service based in Palo Alto, California.
3. CYPHERNETICS: A time-shared computer service based in Ann Arbor, Michigan.
4. G. S. Keyes, Argonne National Laboratory Internal Report, 'TRAMP CDC 3600 Version' (1965).
5. J. W. Gardner and D. Whitesides, Rutherford High Energy Laboratory, NIRL/M/W21, 'TRAMP' (1961).
6. J. Lloyd, University of Oxford Nuclear Physics Laboratory, private communication, Nov. 17, 1967.
7. J. S. Colonias, *Nucl. Instr. and Methods*, **76**, 13 (1969).
8. G. A. Concaildi, R. D. George and S. M. Marcowitz, Argonne National Laboratory Internal Report, 'MAYPO, An On-Line, Real-Time Beam Optics Program' (1971).