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TRACE - AN INTERACTIVE BEAM TRANSPORT PROGRAM FOR UNBUNCHED BEAMS

K. Crandall *)

I. INTRODUCTION

TRACE is a four-dimensional beam-transport program written for use on the Linac PDP 11/45. It is patterned after a program of the same name written by the author at Los Alamos [1]. TRACE provides an on-line, interactive capability for doing beam transport calculations.

In principle, one could make an emittance measurement and then immediately calculate the beam characteristics throughout the transport system. If the beam does not have the proper characteristics, then one may use TRACE to see the effects of changes in any of the parameters of the transport system. One may also specify a condition to be satisfied, specify which parameters are variables, and then ask TRACE to seek a solution.

One communicates with TRACE via various devices in the Linac control system : the touch panel is used for issuing commands to the program ; the alphanumeric keyboard and scope is used for entering parameters and the storage scope is used for displaying the results of the beam-transport calculations.

*) Scientific Associate, on leave from LAMPF, Los Alamos, New Mex., USA.

The purpose of this report is to provide a user's manual for TRACE. (The details of the beam dynamics calculations are not being given, since these are fairly standard and can be found in Ref. 1. The results of TRACE have been found to be in agreement with the results of a beam-transport program written at CERN.) The way of specifying a transport system is described, followed by a description of the options and capabilities of TRACE. Finally, the actual mechanics of running the program are given as they exist at this writing.

II. SPECIFICATION OF THE TRANSPORT SYSTEM

A transport system consists of a sequence of elements, each specified by five or fewer parameters. The type of each element is specified by an alphabetic character. The permissible elements and their parameters are given in Table I.

T A B L E I

Transport elements

Element	Type Code	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
Drift	D	ℓ				
Quad	Q	G	ℓ			
Doublet	L	G	ℓ	s		
Triplet	T	G_{out}	ℓ_{out}	s	G_{in}	ℓ_{in}
Bend	B	α	ρ	$\beta 1$	$\beta 2$	

Definition of Parameters

1. Drift : ℓ is the drift length
2. Quad : G is the gradient, and ℓ is the effective length
3. Doublet : G is the gradient of the first quad, and $-G$ is the gradient of the second quad ; ℓ is the effective length of each quad ; s is the drift length ebetween the two quads (the total length of the doublet is 2ℓ +s).

4. Triplet : G_{out} is the gradient of the outer quads ; ℓ_{out} is the effective lengths of the outer quads ; G_{in} and ℓ_{in} are these same quantities for the inner quad ; s is the drift length between the quads (the total length of the triplet is $2(\ell_{out}+s) + \ell_{in}$).

5. Bending magnet : α is the angle of bend ; ρ is the radius of curvature ; β_1 and β_2 are the entrance and exit edge angles, respectively, measured from the normal to the central trajectory of the beam.

6. Units : lengths and displacements in mm, quad gradients are in T/m, bending and edge angles are in degrees and divergences are in mrad. A quad with a positive gradient is focusing in the horizontal plane.

The transport system specification is created using the PDP text editor [2]. An example is shown in Fig. 1, which specified the LEBT from the output of the column to the entrance of the buncher. The character specifying the type of element is typed in the first column, followed by a blank column. The parameters are typed in free format, with a comma and a blank space following each parameter (except for the last parameter). Decimal points must be typed. An "F" typed in the first column indicates that the specification is finished.

Notice that the drift spaces following the second and third triplets are each broken into two parts. When the beam dynamics are calculated, one always follows the beam from the input (or output) of one element to the output (or input) of another element. Consequently, it is necessary to arrange the drift spaces so that one can supply input or obtain output at convenient locations, such as at emittance measuring stations.

III. CAPABILITIES

Data Storage

In addition to the specification of the transport system, TRACE also requires a number of other parameters, such as the current, energy, emittance ellipse parameters, display parameters, etc. All of the necessary parameters including the transport system parameters, are stored in a COMMON block in the program. After any parameter is changed, and after every dynamics run, the entire COMMON block is stored as the first record (one block of information) in a binary file on the disk. Conversely, each time that TRACE is used, and before each dynamics run, the information in the first record is read into the COMMON block. This seemingly wasteful work has several useful purposes.

Firstly, it eliminates the necessity of redefining all of the parameters each time that TRACE is used. The initial information is that which was last used by TRACE.

Secondly, it makes TRACE insensitive to computer crashes. Very little, if any, information is lost due to a computer crash. Although crashes may be rare, their effects may be serious if the data is unrecoverable.

Thirdly, it provides a possible interaction mechanism with other programs. For example, a program may be written to read the present settings of the triplets in the LEBT, and to store these values in the proper places in this record. TRACE could then be told to "GO", and the dynamics would be calculated using the present settings of the triplets.

In addition to this first record, which always contains the information last used by TRACE, the binary file consists of 19 other records (numbered from 2 to 20). The purpose of these records is to allow the user to store and retrieve different situations or intermediate results. However, there are no restrictions that would prevent any user from storing information in any of these records. Consequently, it is up to the user to keep track of where he stores his information, and to co-ordinate with other users so that useful information is not lost.

Graphical output

The results of the dynamics calculations are displayed on the storage scope, an example of which is shown in Fig. 2. The dynamics are calculated between two specified points in the transport system. The horizontal and vertical transverse phase plane ellipses at the end points of the calculation are shown in the upper portion of the display. The numbers labelled A and B, written on the background of each phase plane, are the ellipse parameters α and β, respectively. The numbers below the lower right phase plane are the values assigned to the graph boundaries. In the example shown in Fig. 2, each phase plane covers the range of 20mm by 40 mrad.

On the lower part of the display, the horizontal (the upper curve) and vertical (lower curve) profiles are shown plotted against longitudinal position along the transport system. The rectangles along the axis represent the quadrupoles in the system. The motion of the beam is from left to right, but of course the calculations can proceed in either direction. (In the phase planes above, the ones on the left represent the beam at the upstream end of the calculation, and the ones on the right represent the beam at the downstream end.) The numerical value near the top of the left boundary of the profile display shows the scale of the profile graph.

Entering data via the keyboard

The many parameters required by TRACE can all be specified or modified via the keyboard. The parameters are broken into several small groups, and, using the touch panel, one tells TRACE which group he wishes to modify. Then, each parameter in that group will appear, one at a time, on the keyboard scope. If the user wants to keep the present value of any parameter, then he may simply press the "return" key. He will then be shown the next parameter, if any, in the group. For any parameter that he wants to change, he simply types in the new value and then presses the "return" key.

Touch-panel options

The touch-panel display, through which one issues commands to TRACE, is shown in Fig. 3. The description of each command is given below.

BUTTON 1. GET TRANSPORT FILE.

This button tells TRACE that the user wants to read in a new transport system specification which has already been created using the text editor. The message "ENTER FILE NAME" will then appear on the keyboard scope, and the user must type in the name of the file containing the transport system specification. The file will then be read by TRACE. If button 1 is touched by mistake and the user does not want to read in a new system, then he may simply press the "return" key and the command will be ignored.

BUTTON 2. GET TRACE RECORD.

This button is used for retrieving information that has previously been stored in one of the 20 binary records provided. The message "GET TRACE RECORD NUMBER" will appear on the scope, and the user must type in the record number that he desires. The information in the specified record will then be read into the COMMON block of TRACE, and then written onto the first record. Consequently, if button 2 is pushed by mistake, then the user could specify record 1 and nothing would be changed. If a number outside the range from 1 to 20 is entered, then the message "RECORD NUMBER MUST BE BETWEEN 1 AND 20" will appear on the scope, and TRACE will await another <u>touch panel</u> command.

BUTTON 3. PRINT TRANSPORT SYSTEM

When this button is pushed, the present specification of the transport system is written on the storage scope. Each line of the output contains the sequence number of the element, the character defining the type of element, and the associated parameters. The sequence number will be referred to throughout this writing as the element number. An example of the output obtained when this button is pushed is shown in Fig. 4.

BUTTON 4. SAVE TRACE RECORD. The button is used for transferring information from the COMMON block in TRACE to one of the 20 binary records provided. This button is the inverse operation of button 2. The message "SAVE DATA ON TRACE RECORD NO." is written on the scope, and the user must enter the record number desired.

BUTTON 5. ENTER PARAMETER SET 1.

This button allows the user to change any or all of the following parameters :

1. the rest mass of the beam particles, in MeV ;
2. the charge to mass ratio, relative to the proton ;
3. the kinetic energy, in MeV ;
4. $\Delta p/p$, the momentum deviation from the above kinetic energy, in per cent
5. the displacement associated with the right boundaries of the transverse phase space graphs, in mm ;
6. the angular divergence associated with the top boundaries of the transverse phase space graphs in mrad ;
7. the displacement associated with the top of the profile graph, in mm.

BUTTON 6. ENTER PARAMETER SET 2.

This button allows the user to change any or all of the following parameters :

1. the starting element number, N1 ;
2. the ending element number, N2 ;
3. the beam current, in mA ;
4. SMAX, the maximum calculational step size, in mm.

If $N1 \leqslant N2$, then the dynamics calculations proceed in the forward, or downstream, direction starting at the upstream edge of element N1 and ending at the downstream edge of element N2. If $N1 > N2$, then the beam is followed in the backward direction, starting at the downstream edge of element N1 and ending at the upstream edge of element N2. The calculations are made at discrete intervals, with the step size being determined as follows : if the length of an element is shorter than SMAX, then, the transformation of the beam through that element is done in one step ; otherwise, the element is subdivided into an integral number of equal steps SMAX. Except during a matching procedure, the beam profiles are plotted on the storage scope at each computational step. Consequently, a smaller value for SMAX will produce a smoother profile curve. The space charge calculations should also be more accurate with smaller step sizes. However, the time required for a complete computation is directly proportional to the number of steps taken, so one must strike a satisfactory compromise.

BUTTON 7. ERASE.

Pressing this button puts TRACE in the "erase" mode, which means that each time that a calculation is started (via button 11), the storage scope is erased and a new background will be drawn. TRACE is initially in the erase mode.

BUTTON 8. DO NOT ERASE.

After this button is pressed, the storage scope will not be erased at the beginning of subsequent dynamics runs. Rather, the profiles and the output ellipses will be superimposed on the display that already is on the scope.

BUTTON 9. INPUT BEAM ELLIPSE.

This button allows the user to specify the ellipse parameters (α, β and E/π) in the horizontal and vertical phase planes at the starting edge of element N1. The present values will appear on the scope, one at a time, and may be modified if desired.

BUTTON 10. ENTER MATCHING CRITERIA.

This button allows the user to specify a condition that he wants the beam to satisfy at the exit of element number N2. Four options are available. The message "MATCHING TYPE n" appears on the scope, when n is an integer between 1 and 4 and indicates the matching type previously specified. If the user wants a different matching type, then he must enter the type number. He will then be prompted, via the scope, to enter several conditions, depending on which matching type was selected.

TYPE 1.

The user specifies the ellipse parameters, α and β, for both horizontal and vertical phase planes.

TYPE 2.

The user specifies the divergences at the horizontal and vertical edges of the beam (x' at x_{max}, and y' at y_{max}).

TYPE 3.

The user specifies the beam size (x_{max} and y_{max}).

TYPE 4.

The user specifies the boundaries of the phase space ellipses (x_{max}, x'_{max}, y_{max} and y'_{max}).

BUTTON 11. GO.

This button tells the program to calculate the dynamics of the beam from the beginning edge of element N1 to the ending edge of element N2. If the program is in the "erase" mode, then before the calculations are started the storage scope is erased, a new background is constructed, and the initial phase space ellipses are drawn. The horizontal and vertical profiles are drawn on the scope as the beam is followed from element N1 to element N2. At the end of the calculation, the final phase space ellipses are drawn.

BUTTON 12. DROP.

This button is used for "dropping" the program from the computer memory. TRACE occupies a significant amount of memory, so one should drop it as soon as one finished with it. Also, in order to not damage the display surface of the storage scope, PLEASE ERASE THE STORAGE SCOPE when you are through with the display.

BUTTON 13. MODIFY ANY ELEMENT.

This button allows the user to modify any or all parameters of any element number, including the type of element. In fact, this button provides the user with an alternate means of creating a transport system specification. When this button is pushed, the message "SPECIFY WHICH ELEMENT TO MODIFY" will appear on the scope, and the user should type the number of the element that he wants to modify. (If the button was pushed by mistake, then pressing the "return" key without entering an element number will cause the command to be ignored.) The character defining the type of the element will appear on the scope and the user has the opportunity to change it. The user is then shown, one-by-one, the present values of the parameters belonging to that element, and may change any or all (or none) of these parameters.

BUTTON 14. SPECIFY VARIABLES.

There are usually a few parameters, such as quad strengths, that the user will want to change more often than he does other parameters, such as drift lengths. This button allows the user to specify up to 10 parameters as being the so-called "variables". The user is asked to first specify the number of variables, and then is asked to specify the variables by typing the element number and the parameter number, separated by a comma, for each of the variables. The parameters thus defined as variables are also the parameters that will be treated as the variables during a matching process (via button 16).

BUTTON 15. MODIFY VARIABLES.

This button allows the user to conveniently change any or all of the parameters that have been defined to be variables via button 14. The message "MODIFY VARIABLE PARAMETERS" will appear on the scope followed by (for each variable) the element number, the parameter number, and the present value of the parameter. The user may change any, all, or none of the parameters specified as variables, but he cannot change the element number or the parameter number.

BUTTON 16. START-STOP MATCHING.

This button is used for starting a matching procedure, or for stopping a matching procedure that is in progress. Prior to matching, the user must have specified, via button 10, the matching criteria (the condition to be satisfied by the beam at the exit of element N2). He must also have specified, via button 14, which parameters are to be considered as variables in the matching procedure. If the user has specified type 1 or type 4 matching, then he must have specified 4 variables since 4 conditions must be satisfied. Likewise, if type 2 or type 3 matching have been specified, then two variables must have been specified. However, two things should be mentioned in this connection :

1. the program does not check on the legitimacy of any variable ; and
2. any variable having an initial value of zero will never be changed.

These two facts permit the user to specify one or more "dummy" variables. For example, suppose that one wishes to do type 1 matching in a portion of a transport system beginning at element 3 and ending at element 5. Further, assume that elements 3 and 5 are drift lengths, that element 4 is a triplet, and that the real variables are the quad strengths of the triplet. In this case the user could specify his two dummy variables as being the second parameter of element 3, and then set the value of this parameter to zero (via button 15). Since element 3 is a drift length, its second parameter is not used and cannot affect the transport calculation. In this example, it is unlikely that an exact solution would be found ; however, an improvement over the initial situation might be found.

In the matching procedure, the program attempts to find the simultaneous solution of n equations with n variables. The user supplies the initial "guess" at the solution (via button 15, for example). Using the random number generator, the program generates n more guesses in the neighbourhood of the initial guess. For each guess, the n equations are evaluated, along with a convergence estimate. The convergence estimate and the values of the n variables are written on the scope each time that a new guess is tried, but nothing is displayed on the storage scope. After evaluating the n equations for each of the n+1 guess, the program makes an educated guess of the solution. The program continues to revise its guess until convergence is achieved (the convergence estimate is less than 0.01) or until 10 tries have been made. After ten tries (without having obtained convergence) the program keeps the "best" solution found thus far (the one having the minimum convergence estimate), generates n more random guesses in its neighbourhood, and continues as before. This continues until either convergence is achieved or the user stops the process by pushing button 16. If the user stops the process, then the variables will be given the values that gave the smallest convergence estimate thus far.

Whether the matching procedure converges on a solution or not, nothing is written on the storage scope during matching. If the user wants to see the results displayed (which is recommended), he must push "GO" after the matching procedure has been stopped.

IV. OPERATING PROCEDURE

Since TRACE requires a touch panel and a storage scope, it must be run on either console 2 or console 3. One starts TRACE running by typing on the keyboard either

```
SET /UIC =[210,210]
RUN DK1:TRACE
```

or

```
RUN DK1:[210,210]TRACE/UIC=[210,210]
```

In the above sequence, UIC stands for the User Identification Code, which consists of a group number and a user number.

The program TRACE is associated with the group number and user number [210,210]. DK1 is the name of the physical device unit on which TRACE resides, in this case disk 1. At this writing, DK1 is a general users disk shared by several people. From time to time the disk gets full and unusable for new programs. Consequently, the users have been warned to keep a back-up tape containing the files that they cherish, so that the files on DK1 can be purged when necessary. Therefore, if one tries to run TRACE and it is not on DK1, then he must read it onto disk from tape using the PDP-11 file transfer program [2), FLX, by typing

```
FLX
FLX DK1:=DTØ:TRACE.TSK/RT
```

assuming that he has mounted the proper type on DTØ.

When the program starts running, the message

```
CONSOLE NUMBER = 3
```

will appear on the scope. If the user is sitting at console 3, then he should just push the "return" key ; if he is at console 2, he should type in a 2 and then push the return key. On the touch panel screen at the specified console will then appear the TRACE panel, as shown in Fig. 3. The program will then wait to receive a command via the touch panel.

When the user has finished with TRACE, he should drop the program via button 12 and <u>erase the storage scope</u>.

ACKNOWLEDGEMENT

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R E F E R E N C E S

1) K. Crandall, TRACE : An interactive beam-transport program, LA-5332, Los Alamos Scientific Laboratory, 1973.

2) RSX-11M : Utilities Procedure Manual, DEC-11-OMUPA-A-D.

```
D 79.5
T 7.3, 79.6, 17., -7.7, 138.
D 1327.
T -3.06, 129., 24., 3.11, 227.
D 190.5
D 626.5
T 3.12, 129., 24., -3.06, 227.
D 343.5
D 623.5
T -2.82, 129., 24., 2.84, 227.
D 389.5
F
```

Figure 1 EXAMPLE OF TRANSPORT SYSTEM SPECIFICATION

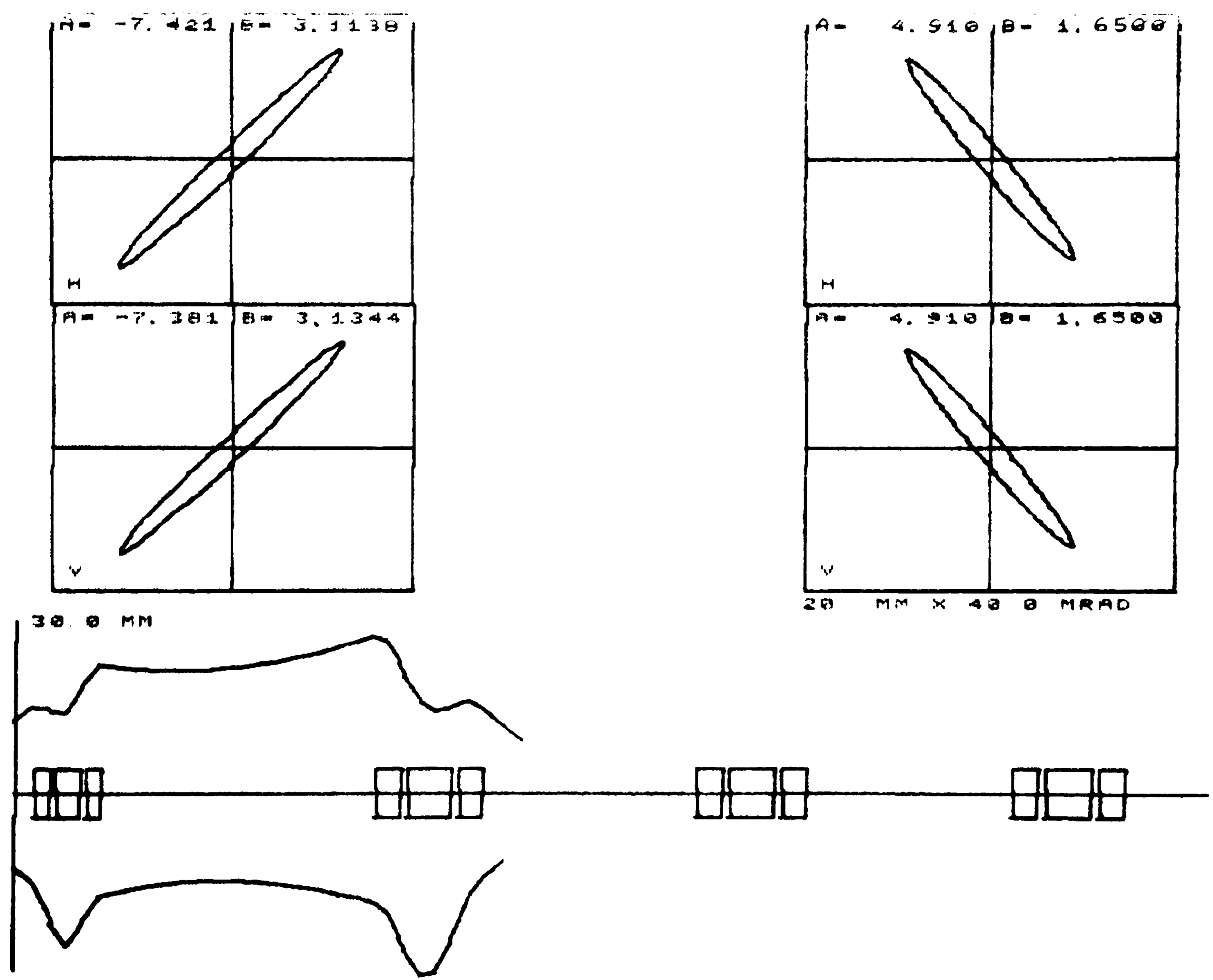

Figure 2 EXAMPLE OF STORAGE SCOPE DISPLAY

GET TRANSPORT FILE	GET TRACE RECORD	PRINT TRACE RECORD	SAVE TRACE RECORD
ENTER BEAM PARAM	ENTER CONTROL PARAM	--------- ERASE ---------	DO NOT --------- ERASE
INPUT BEAM ELLIPSE	MATCHED BEAM ELLIPSE	--------- GO ---------	--------- DROP ---------
MODIFY ANY ELEMENT	SPECIFY VARIABLE PARAM	MODIFY VARIABLE PARAM	OPTIMIZE --------- STOP OPT

Figure 3 TOUCH PANEL DISPLAY

	TYPE	PARAMETERS				
1	D	79.40				
2	T	6.82	79.60	17.00	-7.21	132.00
3	D	1327.00				
4	T	3.54	129.00	24.00	-3.53	227.00
5	D	190.50				
6	D	826.50				
7	T	3.12	129.00	24.00	-3.06	227.00
8	D	343.50				
9	D	623.50				
10	T	-2.82	129.00	24.00	2.04	227.00
11	D	389.50				

Figure 4   EXAMPLE PRINT-OUT OF TRANSPORT SYSTEM