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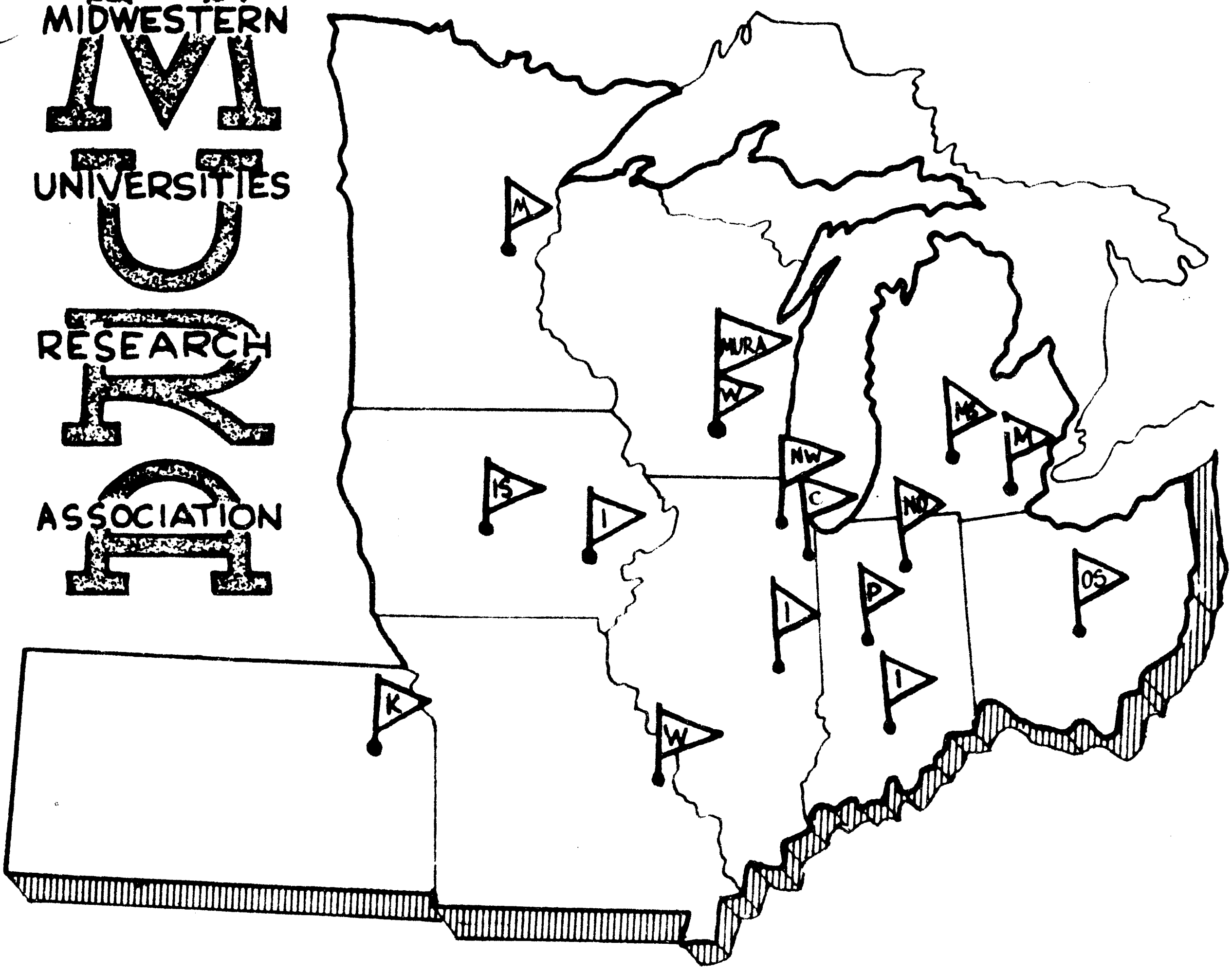

COMPUTER PROGRAM FOR BEAM TRANSPORT PROBLEMS

D. A. Swenson

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2203 University Avenue, Madison, Wisconsin

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July 20, 1962

ABSTRACT

This report describes a computer program, entitled BEAM TRANSPORT, which was written to facilitate the study of beam transport systems. The program was written in Fortran for an IBM 704 computer with a 32K fast memory and at least one tape unit. The program simulates the action of each element of a beam transport system on a group of charged particles representing a beam. The high speed and flexibility of this approach provides a powerful tool for the design of transport systems, as it is practical to evaluate the performance of many "imperfect" systems in the process of adjusting the parameters of the transport system to obtain a more satisfactory one.

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Introduction

Beam transport systems generally consist of bending magnets and magnetic quadrupole lenses which bend, focus, and defocus a beam of charged particles so that it moves in a "satisfactory way" from one piece of apparatus to another.

The action of each element of a beam transport system on a charged particle is simple, at least to the first approximation. However, transport systems often take the form of a complicated array of elements, and the evaluation of the combined action of all the elements on a collection of particles representing a beam is a lengthy calculation.

The computer program, entitled BEAM TRANSPORT, was written to facilitate high speed evaluation of the performance of beam transport systems. The program was written in Fortran for an IBM 704 computer with a 32K fast memory and at least one tape unit. The high speed and flexibility of this approach provides a powerful tool for the design of such systems, as it is practical to evaluate the performance of many imperfect systems in the process of adjusting the parameters of the transport system to obtain a more satisfactory one.

For most beam transport problems, the task of evaluating the performance and adjusting the parameters can be accomplished by a computer subroutine written especially for the particular problem. The addition of an "Adjust" subroutine, greatly enhances the power of this approach to the solution of beam transport problems.

When considering a transport system which is to accommodate a beam of particles of momenta $p \pm \Delta p$, it is convienient to select a trajectory of a particle of momentum p as the axis of the system, and to describe the motion of all other particles with reference to this axis. Let x and y be the transverse displacements of a particle from this axis, and let x' and y' be defined as dx/ds and dy/ds respectively, where s is a coordinate along the axis. Each particle is defined by its four coordinates x, x', y, and y'. The coordinates x and x' form one plane of a transverse phase space, while y and y' form another. It is convienient to employ the concept of these transverse phase planes in the description of the action of a beam transport system on a beam of charged particles.

The computer program described here will simulate the passage of a group of particles through a particular beam transport system. As the program stands, the transformations which simulate the action of the elements of the transport system include only the linear terms and are convieniently recorded in the form of matrices which operate on the column vectors $\begin{bmatrix} x \\ x' \\ \Delta p/p \end{bmatrix}$, and $\begin{bmatrix} y \\ y' \\ \Delta p/p \end{bmatrix}$.

The transformation simulating a drift space of length s is simply the matrix M_s shown in Fig. 1. The transformations describing the action of a quadrupole lens is the matrix M_C for the converging plane, and the matrix M_D for the diverging plane, where L is the length of the lens and k^2 is the gradient of the magnetic field divided by the magnetic rigidity of the particle. The transformation describing the action of a bending magnet is M_p in the plane of the bend, and M_n in the direction normal to the plane of the bend, where α is the angle of the bend, ρ the radius of curvature, and β_1 and β_2 the entrance and exit edge angles respectively.

An excellent review of the considerations leading to these transformations may be found in an article by S. Penner[1] of the National Bureau of Standards.

Particular attention was paid to the ease of input and the ease of interpretation of output. The transport system is described via a deck of IBM cards. Two to four cards are required to describe each element. The drift spaces between the elements are inserted automatically by the program. Any parameter of the entire transport can be changed by a single card. Elements can be added to the transport system, even after the transport has been read into the computer, and likewise, any element may be removed by reading a single card into the card reader.

Only two cards are required to describe the initial x, x', y and y' coordinates of any number of points arranged on any straight line or on almost any ellipse in the x and y phase planes, or a list of coordinates may be entered via a deck a cards.

The entire set of coordinates undergoes a transformation simulating a drift to the entrance plane of the first element. The coordinates then undergo a transformation through the element to its exit plane. Next comes a transformation simulating a drift to the entrance of the second element, etc.

Output may be requested at the entrance and exit planes of any element. Output is provided only where requested, and consists of a list of the coordinates, and a pair of asteric graphs to demonstrate the position of the particles in the x and y phase planes. The asteric graphs are a tremendous aid to the rapid evaluation of the output. (See Fig. 2.)

II. Preparation of Data Cards

All input data should be prepared in the format of the 7 column table given below.

Identification 6 17	Label 19-23	V1 25-38	V2 40-53	N1 56-60	N2 61-65	N3 66-70

Each line of this table should then be punched onto a single IBM card in the columns indicated. The resulting deck of cards, when properly prepared, will define a particular beam transport system and furnish the necessary information for the completion of one run or a series of runs.

The column headed by the word IDENTIFICATION may contain up to twelve alpha-numerical characters, usually in the form of an identifying name such as QUADRUPOLE, MOMENTUM, BEGIN, END...etc. The columns headed by the word LABEL, and the symbols N1, N2, and N3 may contain any integer N where $-9,999 \leq N \leq 99,999$. The columns headed by the symbols V1 and V2 may contain a floating point

$$M_s = \begin{bmatrix} 1 & S & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$M_c = \begin{bmatrix} \cos kL & \frac{1}{k}\sin kL & 0 \\ -k\sin kL & \cos kL & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$M_D = \begin{bmatrix} \cosh kL & \frac{1}{k}\sinh kL & 0 \\ k\sinh kL & \cosh kL & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$M_p = \begin{bmatrix} \frac{\cos(\alpha-\beta_1)}{\cos\beta_1} & \rho\sin\alpha & \rho(1-\cos\alpha) \\ A & \frac{\cos(\alpha-\beta_2)}{\cos\beta_2} & B \\ 0 & 0 & 1 \end{bmatrix}$$

where

$$A = \frac{-(1-\tan\beta_1\tan\beta_2)\sin(\alpha-\beta_1-\beta_2)}{\rho\cos(\beta_1+\beta_2)}$$

$$B = \sin\alpha + (1-\cos\alpha)\tan\beta_2$$

$$M_N = \begin{bmatrix} 1-\alpha\tan\beta_1 & \alpha\rho & 0 \\ C & 1-\alpha\tan\beta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where

$$C = -\frac{1}{\rho}(\tan\beta_1 + \tan\beta_2 - \alpha\tan\beta_1\tan\beta_2)$$

Fig. 1

number. The Fortran format statement by which these cards are read is:

FORMAT (5X, 2A6, 1X, I5, 1X, E14.7, 1X, E14.7, 2X, 3I5).

As a matter of record and convienience, all input data is reproduced on the output in the same Format. (See Fig. 2.)

A. Descriptions of the Transport Systems

The first card of the data deck must contain the word TRANSPORT in the Identification column, and may contain an identifying number in the Label column.

Following this card, the first element of the transport system is described with the aid of 2 to 4 IBM cards. Similiarly the second, third, fourth...etc, elements of the transport are described. As the program stands, it can accept quadrupole lenses, bending magnets, screens and a destination as elements of the transport system. A screen is simply a means of requesting output at locations other than the entrance or exit of a quadrupole lens or bending magnet. A destination is simply a screen which marks the end of the transport system.

The description of a quadrupole lens requires three cards with the information in the following format.

Identification	Label	V1	V2	N1	N2	N3
QUADRUPOLE	N	DISTANCE	STRENGTH	TYPE	OUTPUT	
		LENGTH		ORIENT		
		SCALEH	SCALEV			

where

N is the ordinal number of the element.

DISTANCE is the distance from the center of the previous element (or the starting point if N = 1) to the center of the N^{th}

element. (centimeters),

STRENGTH is the absolute value of the magnetic field gradient (gauss/cm),

TYPE is simply "1",

OUTPUT is "0" if no output is desired, and "1" if output is desired at the N^{th} element.

LENGTH is the length of the quadrupole (centimeters).

ORIENT is the orientation of the quadrupole, and is "+1" for a lens which is focusing in the X plane, and "-1" for a lens which is defocusing in the X plane.

SCALEH is a scale factor for the asteric graphs, and represent the maximum values of X and Y which will be plotted on the graph. (centimeters)

SCALEV is a scale factor representing the maximum value of X' and Y' which will be plotted on the graph. (unitless).

The description of a bending magnet requires four cards with the information in the following format.

BEND	N	DISTANCE	ANGLE	TYPE	OUTPUT	
		RADIUS		ORIENT	PLORMI	
		BETAEN	BETAEX			
		SCALEH	SCALEV			

where

N, DISTANCE, TYPE, OUTPUT, SCALEH, SCALEV, are the same as in the the description of the quadrupole lens. The center of a bending magnet is taken to be the intersection of the axis entering the magnet, with the axis leaving the magnet.

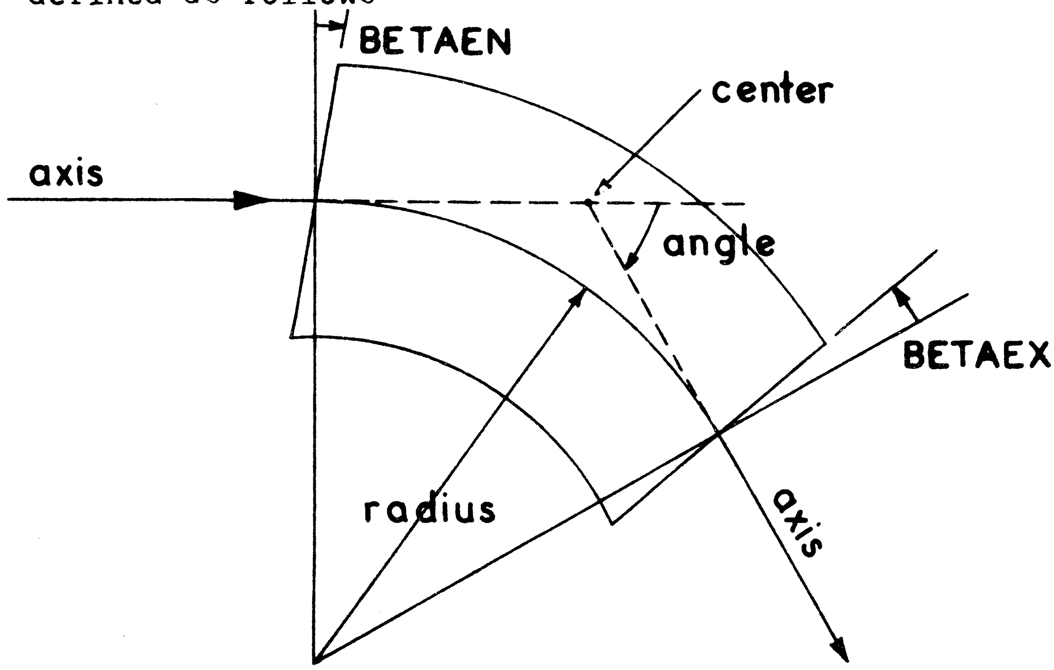
ANGLE is the angle through which the axis is bent (degrees),

RADIUS is the radius of curvature of a particle of momentum p in the magnet (centimeters),

ORIENT is the orientation of the bending magnet, and is "+1" if the bend is in the X plane and "-1" if the bend is in the Y plane.

PLORMI is "+1" if the bend is towards the negative half plane, and "-1" if the bend is towards the positive half plane.

BETAEN and BETAEX are the entrance and exit edge angles of the magnet defined as follows



The description of a screen requires two cards with the information in the following format,

SCREEN	N	DISTANCE		TYPE	OUTPUT	
		SCALEH	SCALEV			

where all quantities are the same as in the description of the quadrupole lens.

The description of a destination is identical with that of a screen, except that the word DESTINATION appears in the first column instead of SCREEN.

This completes the basic description of the beam transport system.

B. Description of Runs

The first card in the description of each of a series of runs must contain the word RUN in the Identification column, and may contain an identifying number in the Label column.

Following the RUN card, the program is prepared to accept cards with the words or letters, INSRTQ, INSRTB, INSRTS, INSRTD, REMOVE, REPLACE, CHANGE, INPUT, OUTPUT, MOMENTUM, DELTAP, AAAA, BBBB, CCCC, DDDD, EEEE, GGGG. Only those cards required by the particular run need to appear in the deck of cards describing the run, and may appear in any order. All of the information supplied via these cards is retained from run to run, thus eliminating the necessity of reentering parameters which are to remain unchanged in a series of runs.

The description of a run is terminated by a card with the word BEGIN in the Identification column. At this point the computer ceases reading the input data cards and begins the calculation required for the run. On completion of the run the computer begins reading cards again, and is prepared to accept a card with the word RUN, TRANSPORT or END in the Identification column. All other cards result in the writing of "cards out of place" on the output, and the reading of the next card.

If and when a RUN card is read the computer is prepared to accept the description of a run as described above.

If and when a TRANSPORT card is read the computer is prepared to accept a new beam transport system.

If and when an END card is read, the computer arrives at a PAUSE 77. The computer may be reactivated by pushing the start button, whereupon it begins searching for a RUN, TRANSPORT or END card again.

A card with the letters INSRTQ in the Identification column allows the <u>insertion</u> of a quadrupole lens into the beam transport system at any specified point. The information is presented in the following format

INSRTQ	N	D				M

where N is an identifying number of the inserted element, and may be any integer ≤ 50 which has not been used as the ordinal number of an element of the transport system. The N^{th} element will be inserted at a distance D following the M^{th} element. The information in the hatched rectangles of the table is identical in format to that used in describing a quadrupole lens.

Cards with the letters INSRTB, INSRTS and INSRTD allow the <u>insertion</u> of bending magnets, screens and destinations respectively. Here again, if N is the identifying number of the inserted elemt, it will be inserted at a distance D following the M^{th} element, and the information is presented in a format identical to that used for specifying the element with the addition of the integer M in the <u>N3</u> column.

The N^{th} element may be removed from the transport system with the following card.

REMOVE	N					

Any element N which has been removed may be replaced with the following card.

REPLACE	N					

Any parameter of the N^{th} element of a beam transport system which is presented in columns V1 or V2 of the data deck may be changed to the value V with a single card

CHANGE	N	V		J		

where J is the "address" of the storage of the parameter, and is given the table below.

J	QUADRUPOLE	BEND	SCREEN OR DESTINATION
1	Distance	Distance	Distance
2	Strength	Angle	
3	Length	Radius	
5		BETAEN	
6		BETAEX	
15	SCALEH	SCALEH	SCALEH
16	SCALEV	SCALEV	SCALEV

Several parameters of the N^{th} element of a beam transport system which are presented in columns N1, N2, and N3 of the data deck may be changed to the value I with a single card

CHANGE	N				K	I

where K is the address of the storage of the parameter. ORIENT information is stored at K = 7, PLORMI is stored at K = 8, and OUTPUT information is stored at K = 9.

The initial sample of coordinates to be transformed through the transport system are supplied on two or more cards in one of the three formats given below.

1. A list of J sets of coordinates (x, x', y, y') may be entered via 2J + 1 cards in the following format.

INPUT	J			1		
		X_1	X_1'			
		Y_1	Y_1'			
		X_2	X_2'			
		Y_2	Y_2'			
		⋮	⋮			

2. A line of J particles may be constructed which extends from (x, x') to (-x, -x') in the x plane, and from (y, y') to (-y, -y') in the y plane by specifying the input in the following format

INPUT	J	X	X'	2		
		Y	Y'			

3. An ellipse of J particles may be constructed having a center at (0, 0) and passing through (x, 0) and (0, x') in the x plane, and through (y, 0) and (0, y') in the y plane. The format is as follows.

INPUT	J	x	x'	3		
		y	y'			
		Lx	Ly			

A transformation simulating a drift of Lx for the x ellipse and a drift of Ly for the y ellipse may be effected by inclusion of the third card of the format above. Ommission of the card eliminates the transformation.

Output instructions may be entered via a card with the word OUTPUT in the Identification column. This information supercedes output instructions appearing along with each element of the beam transport system. Output may be requested or cancelled at the N^{th} element with a card of the following format.

OUTPUT	N	SCALEH	SCALEV	1	K	

where K = +1 if output is requested and k = -1 if output is to be cancelled.

Output may be requested or cancelled at all elements from N through M with a card of the following format.

OUTPUT	N	SCALEH	SCALEV	2	K	M

where K has the same meaning as above.

The design momentum p is presented on a card as follows:

MOMENTUM		p				

where p is expressed in terms of the particles magnetic rigidity B_ρ

BEAM TRANSPORT PROGRAM SWENSON

TRANSPORT		4002	-0.	-0.	-0	-0	-0
BEND	1	1	0.1000000E 03	0.2000000E 02	1	-0	-0
		-0	0.2000000E 03	-0.	1	1	-0
		-0	0.3000000E 02	0.	-0	-0	-0
QUADRUPOLE		2	0.2006250E 03	0.4000000E 03	1	-0	-0
		-0	0.5000000E 02	-0.	1	-0	-0
QUADRUPOLE		3	0.1337500E 03	0.4000000E 03	1	-0	-0
		-0	0.5000000E 02	-0.	-1	-0	-0
QUADRUPOLE		4	0.2006250E 03	0.2000000E 03	1	-0	-0
		-0	0.5000000E 02	-0.	1	-0	-0
QUADRUPOLE		5	0.2006250E 03	0.4000000E 03	1	-0	-0
		-0	0.5000000E 02	-0.	-1	-0	-0
QUADRUPOLE		6	0.1337500E 03	0.4000000E 03	1	-0	-0
		-0	0.5000000E 02	-0.	1	-0	-0
BEND		7	0.2006250E 03	0.2000000E 02	1	-0	-0
		-0	0.2000000E 03	-0.	1	-1	-0
		-0	0.	0.3000000E 02	-0	-0	-0
DESTINATION		8	0.1000000E 03	-0.	1	-0	-0
RUN		23	-0.	-0.	-0	-0	-0
INPUT		73	0.1000000E 01	0.5000000E-03	3	-0	-0
		-0	0.1000000E 01	0.5000000E-03	-0	-0	-0
OUTPUT		1	0.1250000E 01	0.5000000E-02	1	1	-0
MOMENTUM		-0	0.2149600E 07	-0.	-0	-0	-0
DELTAP		-0	0.5000000E-02	-0.	-0	-0	-0
CHANGE		1	0.2745000E 02	-0.	5	-0	-0
CHANGE		2	0.4656610E 03	-0.	2	-0	-0
CHANGE		3	0.3725288E 03	-0.	2	-0	-0
CHANGE		4	0.4207037E 03	-0.	2	-0	-0
CHANGE		5	0.3725288E 03	-0.	2	-0	-0
CHANGE		6	0.4656610E 03	-0.	2	-0	-0
CHANGE		7	0.2745000E 02	-0.	6	-0	-0
BEGIN		-0	-0.	-0.	-0	-0	-0

RESULTS AT EXIT FROM ELEMENT 1

X	1.177665	1.179572	1.172961	1.157882	1.134450	Y	0.818675	0.820930	0.816938	0.806729	0.790379
XP	0.002441	0.002481	0.002515	0.002544	0.002565	YP	-0.002597	-0.002551	-0.002486	-0.002401	-0.002299
X	1.102843	1.063301	1.016126	0.961677	0.900368	Y	0.768015	0.739805	0.705965	0.666753	0.622465
XP	0.002581	0.002590	0.002592	0.002587	0.002576	YP	-0.002178	-0.002042	-0.001889	-0.001723	-0.001543
X	0.832665	0.759085	0.680186	0.596569	0.508872	Y	0.573441	0.520052	0.462706	0.401837	0.337911
XP	0.002558	0.002534	0.002503	0.002466	0.002424	YP	-0.001351	-0.001150	-0.000939	-0.000721	-0.000498
X	0.417760	0.323928	0.228090	0.130975	0.033322	Y	0.271413	0.202849	0.132742	0.061624	-0.009963
XP	0.002376	0.002323	0.002266	0.002204	0.002138	YP	-0.000271	-0.000042	0.000187	0.000415	0.000640
X	-0.064126	-0.160627	-0.255446	-0.347862	-0.437172	Y	-0.081473	-0.152364	-0.222095	-0.290136	-0.355969
XP	0.002069	0.001998	0.001924	0.001849	0.001772	YP	0.000860	0.001073	0.001279	0.001474	0.001658
X	-0.522696	-0.603782	-0.679815	-0.750214	-0.814446	Y	-0.419093	-0.479027	-0.535316	-0.587530	-0.635273
XP	0.001695	0.001619	0.001543	0.001468	0.001395	YP	0.001830	0.001988	0.002130	0.002257	0.002366
X	-0.872019	-0.922497	-0.965496	-1.000687	-1.027804	Y	-0.678181	-0.715928	-0.748226	-0.774830	-0.795536
XP	0.001324	0.001257	0.001192	0.001132	0.001076	YP	0.002457	0.002529	0.002583	0.002616	0.002630
X	-1.046640	-1.057050	-1.058958	-1.052347	-1.037267	Y	-0.810189	-0.818675	-0.820930	-0.816938	-0.806729
XP	0.001025	0.000980	0.000939	0.000905	0.000877	YP	0.002624	0.002597	0.002551	0.002486	0.002401
X	-1.013835	-0.982228	-0.942686	-0.895512	-0.841062	Y	-0.790379	-0.768015	-0.739805	-0.705965	-0.666753
XP	0.000855	0.000839	0.000831	0.000828	0.000833	YP	0.002299	0.002178	0.002042	0.001889	0.001723
X	-0.779753	-0.712051	-0.638470	-0.559571	-0.475955	Y	-0.622465	-0.573441	-0.520052	-0.462706	-0.401837
XP	0.000844	0.000862	0.000887	0.000917	0.000954	YP	0.001543	0.001351	0.001150	0.000939	0.000721
X	-0.388257	-0.297145	-0.203313	-0.107475	-0.010360	Y	-0.337911	-0.271413	-0.202849	-0.132742	-0.061624
XP	0.000996	0.001044	0.001097	0.001155	0.001216	YP	0.000498	0.000271	0.000042	-0.000187	-0.000415
X	0.087293	0.184741	0.281242	0.376061	0.468477	Y	0.009963	0.081473	0.152364	0.222095	0.290136
XP	0.001282	0.001351	0.001422	0.001496	0.001571	YP	-0.000640	-0.000860	-0.001073	-0.001279	-0.001474
X	0.557787	0.643310	0.724397	0.800429	0.870829	Y	0.355969	0.419093	0.479027	0.535316	0.587530
XP	0.001648	0.001725	0.001801	0.001878	0.001952	YP	-0.001658	-0.001830	-0.001988	-0.002130	-0.002257
X	0.935060	0.992634	1.043112	1.086111	1.121302	Y	0.635273	0.678181	0.715928	0.748226	0.774830
XP	0.002025	0.002096	0.002164	0.002228	0.002288	YP	-0.002366	-0.002457	-0.002529	-0.002583	-0.002616
X	1.148419	1.167254	0.060307	0.	0.	Y	0.795536	0.810189	0.	0.	0.
XP	0.002344	0.002395	0.001710	0.	0.	YP	-0.002630	-0.002624	-0.	0.	0.

RESULTS AT EXIT FROM ELEMENT 1

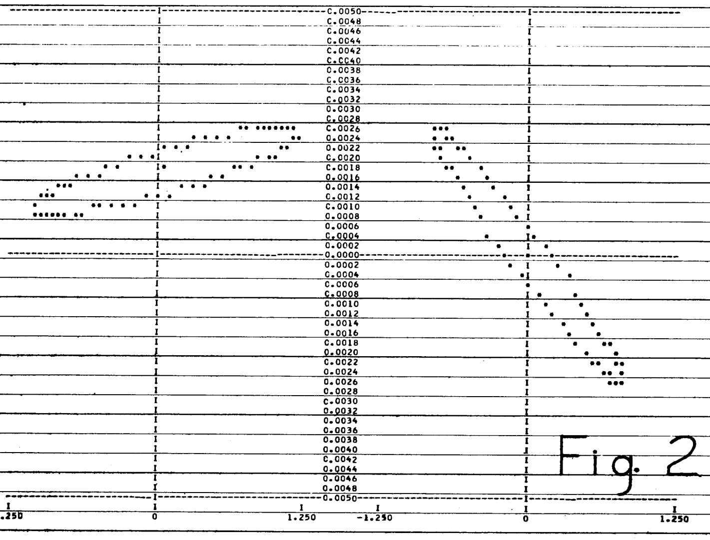
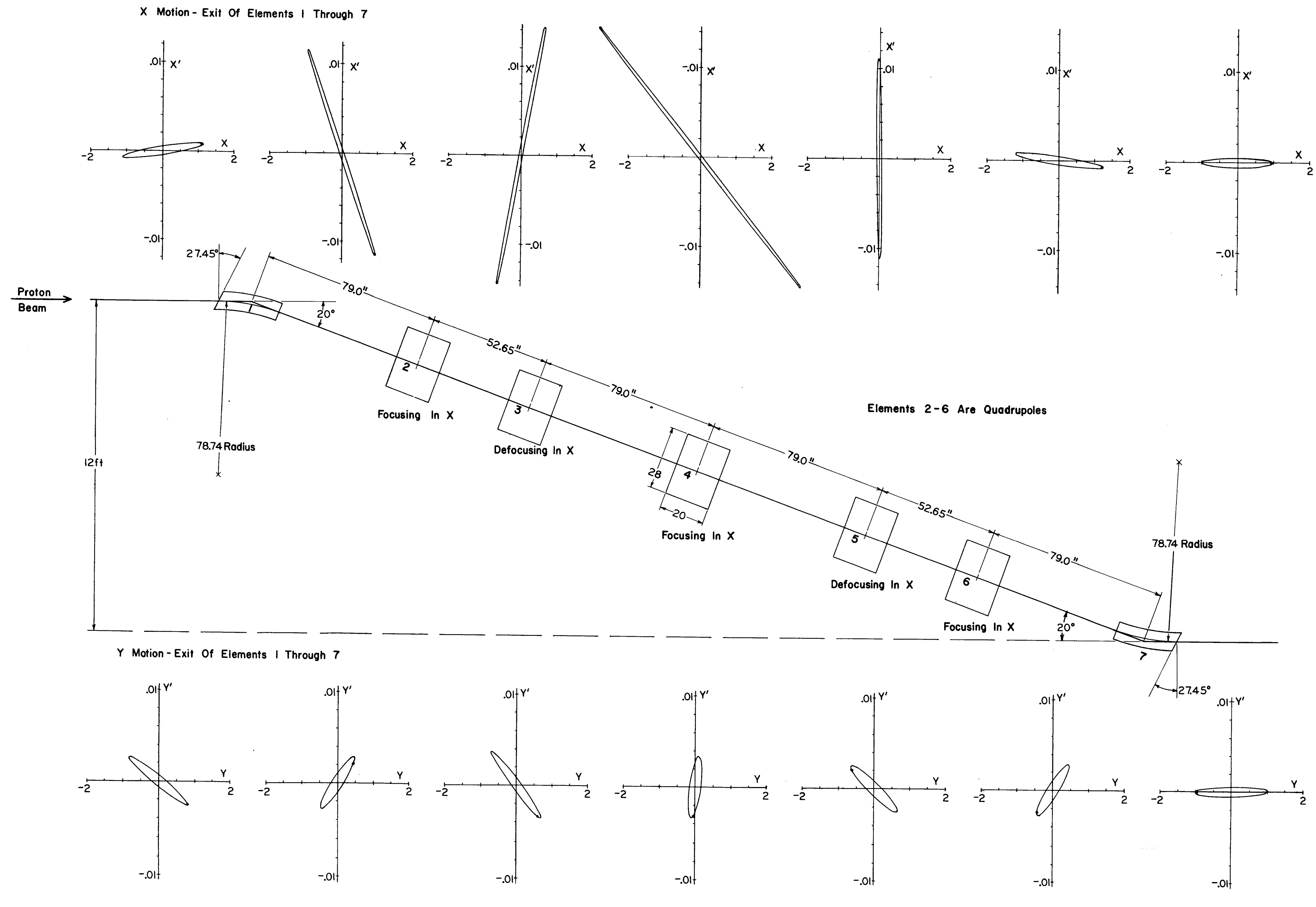


Fig. 2



AN ACHROMATIC TRANSLATION FOR BEAM TRANSPORT SYSTEM (gauss centimeters).

The fractional error in momentum $\Delta p/p$ is presented on a card as follows:

DELTAP		$\Delta p/p$				

Cards with the letters AAAA, BBBB, CCCC, DDDD, EEEE, and GGGG allow entry of constants into the common portion of the computer storage. These constants have been useful for entering information into subroutines written for specific purposes.

A sample of the computer output is shown in Fig. 2. As stated previously, the output contains a reproduction of the input data deck in addition to the list of coordinates and the asteric graphs at all locations in the transport system where output was requested. The transport system described in the sample data is shown in Fig. 3, where the dimensions have been changed from centimeters to inches.

III. Operating Instructions

The program is read into the computer from a deck of binary cards. On ingesting the program, the computer will begin reading the data deck from the card reader.

Output is written in BCD form on tape unit 9.

All sense switches are normally in the up position. Depression of sense switch 2, will cause a portion of the output (the asteric graphs) to be printed on-line, in addition to being written on tape 9. Depression of sense switch 3, will cause the "adjust" subroutine to be called instead of the "output" subroutine at each point, where output was requested.

References 1. S. Penner, RSI 32, 150 (1961)