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**TORCAPP: Time-Dependent
Cyclotron Orbit Calculation
and Plotting Package**

Linda B. Maddox
Gregory S. McNeilly

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UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY

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Contract No. W-7405 eng 26

Computer Sciences Division

**TORCAPP: Time-Dependent Cyclotron Orbit Calculation
and Plotting Package**

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Work supported by
Holifield Heavy Ion Research Facility, Physics Division

Date Published - November 1979

UNION CARBIDE CORPORATION, NUCLEAR DIVISION
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ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of J. D. Bell in debugging portions of the packet calculation.

The development and documentation of this program were funded by Holifield Heavy Ion Research Facility, Physics Division, under Contract No. W-7405 eng 26.

**TORCAPP: Time-Dependent Cyclotron Orbit Calculation
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ABSTRACT

TORCAPP calculates the motion of charged particles in electromagnetic fields with time as the independent variable, and produces a variety of printed and plotted output of results. Finite-size beam behavior is studied conveniently by following groups of particles which define an appropriate phase space area. Since time is the independent variable, general motion in the near-median-plane region may be followed. This includes, for example, loops not enclosing the origin and strongly radial motions. Thus, TORCAPP is particularly useful for injection studies for isochronous cyclotrons, or other devices with near-median-plane charged particle motion.

1. INTRODUCTION

TORCAPP (Time-dependent cyclotron orbit calculation and plotting package) consists of two programs, one which calculates packets¹ (see also Appendix A) and particle trajectories (CALPAT), and one which accepts data from CALPAT and produces plot data in a DISSPLA compressed format² (PATPLT). The compressed plot data files may be plotted on a CALCOMP plotter or on a TEKTRONIX graphics terminal using program QWKPOP.³ TORCAPP is intended to be especially useful in calculating injection paths in a separated sector cyclotron. Injection usually occurs in a valley with low magnetic field and thus the path is relatively straight and in the radial direction. Looping motion not about the origin may also be followed in TORCAPP. The GOC (General Orbit Code)⁴ employs an angle-dependent integration which is not satisfactory for this type of motion. TORCAPP, with time as the independent variable, can follow any general near-median-plane motion.

TORCAPP is structured to allow straightforward modification of the subroutines which determine the electric and magnetic fields, and thus may be readily adapted to specialized uses such as central region studies, or acceleration calculations with unusual dee geometries.

2. CAPABILITIES AND FUNCTIONS

Calculations Performed in CALPAT

CALPAT calculates the paths of one or more particles from an initial time to a final time.

CALPAT allows any particle (as specified by its initial conditions: position, velocity, charge and mass) to be followed through time in a magnetic field. The code has provisions for using an isochronized field; i.e., a field may be input along with isochronizing factors (calculated by GOC) for that particular field and particle.

The user may initially specify the approximate distance the particle covers in one integration step. Internally, this quantity is converted to the time it takes to cover that distance for the initial velocity. The user may also specify at which times (i.e., at which integration steps) the particle position and velocity should be printed or written to disk for later plotting.

Initial position and velocity of the particle or particles may be specified in several ways. Initial conditions may be input in x, y and z coordinates or by specifying an initial radius, angle, and direction. Initial conditions for a packet of particles may be calculated from the given initial conditions of the central particle. Optionally, coordinates for up to nine particles may be input directly instead of being calculated.

The present version of CALPAT determines the magnetic field along the path, given field values in a median plane polar mesh. Subroutines BRECT, etc., described below, return the field components based on this situation. Any arbitrary magnetic field configuration may be allowed by modifying these routines.

Printed Output from CALPAT and PATPLT

Depending on input parameters, the following types of printout may be obtained.

- 1) A columnar listing, one particle at a time, of time, position, velocity, field value, radius, and angle at each time step requested.
- 2) A listing showing the position and velocity of all particles at one time, then another time, etc.

- 3) A listing of the transverse displacements and momenta, with respect to particle 1, will be generated when packet plots are requested. The time of each packet is printed, along with the position and velocity of particle 1.

Plots Generated from PATPLT

Plotting in PATPLT is accomplished by using a very versatile plotting package called DISSPLA.² This package is installed on the various computer systems in Oak Ridge, and is generally available at other DOE laboratories, and many university centers. It can be accessed by linking in the appropriate libraries as shown in the sample JCL. PATPLT produces a compressed plot data file which may be plotted on the CALCOMP plotter or routed to the user's PDP-10 disk area and plotted on a TEKTRONIX graphics terminal.

Depending on input parameters, the following types of plots may be generated.

- 1) Individual particle trajectories, either one per plot, or all particles on one plot.
- 2) Particle trajectories by time ranges, i.e., all particles at one time range on one plot, or each particle at each time range on a separate plot.
- 3) Plots of transverse displacement and transverse momenta relative to particle 1 (packet plots) -- either R-packets or Z-packets with either one per page or four per page.

3. GENERAL EQUATIONS IMPLEMENTED

Equations of Motion in an Electromagnetic Field (defined in subroutine EQUA)

The equations of motion consist of the derivatives of position and velocity, each one broken down into its x, y, and z components. The Lorentz relation is used.

$$\vec{F} = m\vec{a} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

where $\vec{F}$ = total force

m = mass

$\vec{a}$ = acceleration

q = charge

$\vec{E}$ = electrical field

$\vec{v}$ = velocity

$\vec{B}$ = magnetic field.

Thus, the six equations of motion, derivatives with respect to time, are:

$$\frac{dx}{dt} = v_x \quad (2.a)$$

$$\frac{dy}{dt} = v_y \quad (2.b)$$

$$\frac{dz}{dt} = v_z \quad (2.c)$$

and, since $\vec{a} = \frac{d\vec{v}}{dt}$, then

$$\frac{dv_x}{dt} = \frac{q}{m} (E_x + v_y B_z - v_z B_y) \quad (2.d)$$

$$\frac{dv_y}{dt} = \frac{q}{m} (E_y + v_z B_x - v_x B_z) \quad (2.e)$$

$$\frac{dv_z}{dt} = \frac{q}{m} (E_z + v_x B_y - v_y B_x) \quad (2.f)$$

Determination of x, y, and z Components of the Magnetic Field

(Defined in subroutine BRECF)

Using a first-order Taylor expansion out of the median plane (i.e., $z=0$), the field components can be written as

$$B_x(x,y,z) = B_x(x,y,0) + z \frac{\partial}{\partial z} B_x(x,y,0) \quad (3.a)$$

$$B_y(x,y,z) = B_y(x,y,0) + z \frac{\partial}{\partial z} B_y(x,y,0) \quad (3.b)$$

$$B_z(x,y,z) = B_z(x,y,0) + z \frac{\partial}{\partial z} B_z(x,y,0) \quad (3.c)$$

We assume, from median plane symmetry,

$$B_x(x,y,0) = 0 \quad (4.a)$$

$$B_y(x,y,0) = 0 \quad (4.b)$$

$$\frac{\partial}{\partial z} B_z(x,y,0) = 0 \quad (4.c)$$

This leaves as unknowns:

$$B_z(x,y,0) \quad (\text{Field data, input to calculation}) \quad (5.a)$$

$$\frac{\partial B_x}{\partial z}(x,y,0) \quad (5.b)$$

$$\frac{\partial B_y}{\partial z}(x,y,0) \quad (5.c)$$

Interpolation to get Field Value at the Desired Point $B_z(x,y,0)$

(Defined in subroutine BINTRP)

The x and y values of the desired point are converted to a radius and angle since the median plane magnetic field values are input as an (r,θ) mesh. A three-point statement function TRELAG is used twice to perform the two-variable Lagrangian interpolation.

Two-Point Central Differencing used in Calculating Partial Derivatives of the Magnetic Field (defined in subroutine BPRIME)

Using the fact that the curl $\vec{B} = 0$, we know that

$$\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x} \quad (6.a)$$

$$\frac{\partial B_y}{\partial z} = \frac{\partial B_z}{\partial y} \quad (6.b)$$

Then to find the field derivatives at the central point with respect to x and y, four points are selected relative to the central point, one each in the positive and negative x-direction and the positive and negative y-direction. The following equations are used:

$$\frac{\partial B_z}{\partial x} = (B_2 - B_4)/(2. * XH) \quad (7.a)$$

$$\frac{\partial B_z}{\partial y} = (B_3 - B_5)/(2. * YH) \quad (7.b)$$

with

B_2, B_4 = field values of points in positive and negative
x-direction

B_3, B_5 = field values of points in positive and negative
y-direction

XH = x-distance from central point to B_2, B_4

YH = y-distance from central point to B_3, B_5 .

Calculation of Transverse Distances and Momenta for Packet Plots

(Defined in subroutine PLTPAK)

R-packets and Z-packets are treated separately, with the R-packet ignoring all Z-motion. Appendix A defines a packet.

For R-packets, transverse distances and momenta are calculated relative to a line perpendicular to the momentum of particle 1 (transverse momentum line). To obtain the position and momentum of particle j at its intersection with the transverse momentum line, the approximation is made that the particle is traveling in a circular path. (See Fig. A.2 in Appendix A.) The intersection of the circular path and the transverse momentum line is obtained. The distance (displacement) between the point of intersection and the point (x_1, y_1) is calculated. The sign of the displacement is conventionally chosen to be positive for positions to the right of particle one in the median plane, as viewed along the path of particle one.

To find the transverse momentum displacement, one determines the new components of P after the momentum vector has been moved along the circle to the point of intersection. Then,

$$P_{x_j} = P \cos \phi_2 \quad \text{and} \quad (8.a)$$

$$P_{y_j} = P \sin \phi_2, \quad \text{where} \quad (8.b)$$

$$\phi_2 = \phi_1 + \phi, \quad \text{with} \quad (3.c)$$

ϕ_1 being the original momentum angle, and ϕ is the angle of rotation along the circular path. The transverse momentum is found by differencing

$$\theta_j = \tan^{-1} (P_{y_j} / P_{x_j}) \quad (9.a)$$

and

$$\theta_1 = \tan^{-1} (P_{y_1} / P_{x_1}) \quad (9.b)$$

For Z-packets the transverse distance is just z_j . The transverse momentum is $\tan^{-1} (P_{z_j} / P)$.

For both type packets, transverse momentum is scaled to milliradians and transverse displacement is scaled to millimeters.

[Note: The FORTRAN function ATAN2 was used in finding $\tan^{-1}$.]

Runge-Kutta Integration

The equations of motion described earlier are integrated over time with subroutine DE.⁵ This Runge-Kutta routine uses a self-adjusting step size. The accuracy parameters RELERR and ABSERR should be adjusted for satisfactory numerical behavior for any particular problem.

4. DESCRIPTION OF SUBROUTINES

CALPAT1) MAIN

Initializes variables

Reads option type variables

Calls INPUTF

Calls INPUTP

Calls PARTCL

2) INPUTF

Reads in field characteristics and data

Multiplies field by isochronizing factors

Converts field to negative tesla

3) INPUTP

Reads in particle defining information

Reads beginning, ending times and integration step size

Converts all variables to MKS units

Calls PACKET

4) PACKET

Converts R, NTI and TI into position and velocity in x,y, and z coordinates.

Calculates a nine-particle elliptical packet in r or z and returns position and velocity to calling routine.

Calls FPHI.

5) FPHI

Finds angle that subtends equal segments of an arc on an ellipse.

Calls function SQUANK⁶ to integrate function EL2.

6) PARTCL

Loops over NP (number of particles) times.

Decides at which time steps position and velocity information should be saved.

Calls DE⁵ to integrate equations of motion.

Writes position, momentum, and time out to scratch disk.

Prints time, position, velocity, field value if PRTOPT > 0.

- 7) DE
Calls EQUA to define equations to be integrated.
Integrates equations over time.
- 8) EQUA
Defines equations to be integrated.
Calls BRECT to find field components in x, y, and z directions.
- 9) BRECT
Sets up points around central point that will be needed in calculating field derivative.
Calls BINTRP to interpolate to find field value at central point and those around it.
Calls BPRIME to calculate partial field derivatives.
Defines equations determining field components in x-, y- and z-directions.
- 10) BINTRP
Loops over number of points to be interpolated.
Finds R and θ of field position to be interpolated.
Determines subset of field array needed for interpolation.
Calls statement function TRELAG to perform two-variable Lagrangian interpolation.
- 11) BPRIME
Defines equations that calculate partial field derivatives using 3-pt Lagrangian differencing.

PATPLT

- 1) MAIN
Read in position, velocity, and time data that was calculated and saved by CALPAT.
Depending on type of plotting specified, one of the following three calls is made:
CALL PLOT1P
CALL PLTPAK
CALL PLOTNP

If PRTOPT < 0, a table is printed showing position and velocity of all particles at one time, then another time, etc.

2) PLOTNP*

This subroutine is called when more than one particle trajectory is calculated and a packet plot is not desired. A variety of plot combinations may be achieved depending on the number of time ranges and number of particles per plot.

Call COMPRS to cause plot data to be stored in a compressed file.

Determine number of plots to be generated.

Loop over number of plots.

CALL BGNPL

Determine x, y, and z minimum and maximum values

Call TITLE or TITL3D

Call GRAF or GRAF3D

Call CURVE or CURV3D

Call ENDPL

Call DONEPL.

3) PLOTIF

This subroutine is called when only one particle trajectory is calculated.

Call COMPRS.

Determine number of plots to be generated, depending on number of time ranges specified.

Loop over number of plots.

Determines x, y, and z minimum and maximum values.

Call BGNPL

Call TITLE or TITL3D

Call GRAF or GRAF3D

Call CURVE or CURV3D

Label plot with particle number, time, mass, charge, and energy

Call ENDPL.

Call DONEPL.

*The fundamental modules in the plotting program are in DISSPLA.²

4) PLTPAK

This subroutine is called when a packet plot is desired.

Loop over time steps

Pick out position and momentum for this plot out of large data array.

Calculate transverse displacement and transverse momentum.

Call COMPRS

Determine number of plots to generate

Set up origins for plots

Loop over number of plots

Call BGNPL

Call PHYSOR

Call TITLE

Call CROSS

Call RLINT to put particle numbers on their packet locations

Label plot

Call ENDPL

Call DONEPL.

5. DATA INPUT GUIDE

CALPAT - Unit 5

1. Plotting variables Format (6I5)

PLTOPT	PRTOPT	IDIM	NPRPLT	IBEOPT	MRKPLT	
5	10	15	20	25	30	

2. Calculation type variables Format (3I5)

IPAK	IOPT	IPRNTB	
5	10	15	

3. Field size variables Format (4I5)

NR	NT	NXT	IFTYPE	
5	10	15	20	

4. Field step sizes and accuracy parameters Format (4F10.0)

DR	DT	RELERR	ABSERR	
10	20	30	40	

5. Field format Format (18A4)

Note: This character string would be something like '(9F8.1)'.

FMT(1)	FMT(2)	FMT(3)	FMT(4)	...	FMT(18)
4	8	12	16	...	72

6. Isochronizing factors Format (8F10.0)

7. Packet widths and phase space areas Format (4E10.5)

Note: This group is read only if IPAK $\neq$ 0.

8. Particle and integration variables Format (6E10.5)

9. Time - plotting variables Format (E15.6, 15, E15.6)

Note: This group read only if IBEOPT $\neq$ 0. This group must consist of 10 lines, even if there are not 10 ranges specified.

10. Number of particles and interpolation mesh-size adjustor Format (I5,F10.0)

NP	FUDGE	
5	15	

11. Particle position variables Format (F10.2, I5, F10.2, 2E15.6)

Note: This group read only if IOPT $\neq$ 1. If IPAK $\neq$ 0, this group is read for particle 1 only. If IPAK = 0, this group is read for NP particles.

R(1)	NTI(1)	TI(1)	S(3,1)	V(3,1)
10	15	25	40	55

⋮

R'(NP)	NTI(NP)	TI(NP)	S(3NP)	V(3,NP)
10	15	25	40	55

12. Particle position variables Format (3E15.6/3E15.6)

Note: This group read only if IOPT = 1. If IPAK $\neq$ 0, this group is read for particle 1 only. If IPAK = 0, this group is read for NP particles.

S(1,1)	S(2,1)	S(3,1)	...
15	30	45	80

⋮

S(1,NP)	S(2,NP)	S(3,NP)	...
15	30	45	80

V(1,1)	V(2,1)	V(3,1)	...
15	30	45	80

V(1,NP)	V(2,NP)	V(3,NP)	...
15	30	45	80

CALPAT - Unit 10

1. Field data

Format [72x/(FMT)]

Note: This format is valid only if IFTYPE = 0. If IFTYPE = 1, there are no blank cards before each radius and field is read with format FMT only.

blank	B(1,1)	B(1,2) . .	...		B(1,NT)
:					
blank	B(NR,1)	B(NR,2) . .			B(NR,NT)

PATPLT - Unit 11

Note: Input to PATPLT is normally read in from disk after being written by CALPAT and the user need not alter the input. However, if the user wishes to use the same particle position and velocity data more than once, plotting the data in various ways, he may do so by substituting his input for input to unit #11.

1. Plotting variables

Format (8I5, 3F5.0)

PLTOPT	PRTOPT	NP	IDIM	NPEPLT	MRKPLT
5	10	15	20	25	30

IBDIM	IPAK	ESAV	FMSAV	QSAV
35	40	45	50	55

Note: IBDIM, ESAV, FMSAV, and QSAV should not be altered; therefore they do not appear in the input definitions.

2. Plotting variables

Format (15I5)

Note: ITSTOP and ITIMPP should not be altered since they deal with the way the position and velocity data was written and the data must be read just as it was written.

ITSTOP(1)	ITSTOP(2)	... ITSTOP(9)	ITIMPP(1)	... ITIMPP(6)
5	10	45	50	75

ITIMPP(7)	ITIMPP(8)	ITIMPP(9)	ITIMPP(10)	
5	10	15	20	

Input Variable Definitions

Abbreviations Used:

Subroutine Names

IF - INPUTF
IP - INPUTP
M - MAIN for CAL/AT

Data Units:

AMU - atomic mass units
C - control variable
CM - centimeter
DEG - degrees
EU - electron units
G - gauss
MEV - million electron volts
MM - millimeter
MRAD - milliradian
S - second

Variable Name	Input Group Number	Subroutine Read In	Data Units	Definitions
ABSERR	4	IF	C	Accuracy parameter for subroutine DE ⁵ . Absolute error test.
B(100,150)	1/Unit 10	IF	C	B-field array. First index is azimuthal, second index is radial. If a partial field is input, i.e., only one sector, the program assumes the field is symmetric.
BEG (10)	9	IP	S	Array of beginning times at which plots are produced. Used with END and INC arrays. Maximum of 10 time ranges may be requested.
DR	4	IF	IN	Radial step size of B-field array.
DT	4	IF	DPC	Azimuthal step size of B-field array.
E	8	IP	MEV	Energy of particle or particles to be tracked.
END	9	IP	S	Array of ending times at which plots are produced. BEG(I), END(I), and INC(I) form a time range at which plots are desired.
FMASS	8	IP	AMU	Mass of particle to be tracked.
FMT	5	IF	C	Format in which field array is read in. This is a literal string, such as '(9F8.1)'.
FUDGE	10	IP	C	Factor to adjust step size in x and y for partial derivatives determined in subroutine BPRIME. FUDGE = 1.0 is recommended, with small adjustment about 1.0 to test numerical behavior.
IBEOPT	1	M	C	= 0 implies BEG, END, INC arrays will not be read in, i.e., plots are produced from TINT to TMAX. = 1 implies time ranges (BEG, END, INC) will be read in.
IDIM	1	M	C	= 2 implies two-dimensional plot generated. = 3 implies three-dimensional plot generated.

Variable Name	Input Group Number	Subroutine Read In	Data Units	Definitions
II*TYPE	3	IF	C	<p>= 0 implies field to be read is from ORIC measured data, i.e., a blank card before each radius, with the initial azimuth of the field measured at 63°.</p> <p>= 1 implies no blank card will be read before each radius and the first azimuth is taken to be at 0°.</p>
INC (10)	9	IP	C	An array used with BEG and END--used to indicate how often time steps in a certain range will be printed or plotted. Ex.: If INC(I) = 5, every fifth time step from time BEG(I) to time END(I) will be saved for printing or plotting.
IOPT	2	M	C	<p>= 0 implies particle coordinates are input as initial radius (R), initial angle (NTI), and direction (TI).</p> <p>= 1 implies initial particle position is defined by x, y, and z coordinates.</p>
IPAK	2	M	C	<p>= 0 implies no packet to be calculated, i.e., coordinates are input for NP particles.</p> <p>= 1 implies R packet will be calculated.</p> <p>= 2 implies Z packet will be calculated.</p> <p>= 3 implies both R and Z packets will be calculated.</p>
IPRNTB	2	M	C	<p>= 0 implies field data and isochronizing factors will not be printed.</p> <p>= 1 implies field data and isochronizing factors will be printed.</p>
ISOFAC(NR)	6	IF	C	An array of factors, one for each radius, by which data is multiplied to adjust the field to an isochronous or other desired radial variation.

Variable Name	Input Group Number	Subroutine Read In	Data Units	Definitions
MRKPLT	1	M	C	<p>= 0 implies single-particle plot will not be marked.</p> <p>= 1 implies single-particle plot will be marked at same timesteps as a corresponding packet plot.</p>
NP	10	IP	C	Number of particle trajectories to be integrated.
NPRPLT	1	M	C	<p>Effects of NPRPLT depend also on PLTOPT and NP.</p> <p>If PLTOPT < 1, NP = 9.</p> <p>NPRPLT = 1 implies one packet per plot. = 4 implies four individual packets per plot.</p> <p>If PLTOPT > 1, NP > 1.</p> <p>NPRPLT = NP implies all particles at one time range will be shown on one plot.</p> <p>= 1 implies each particle and each time range on a separate plot.</p>
NR	3	IF	C	Number of radial points in the field data to be input for each angle.
NT	3	IF	C	Number of angular data points input for each radius.
NTI	11	IP	DEG	NTI is the initial angle of particle 1, directed toward the center of the machine. For example, NTI = 0 is a particle at zero degrees directed along the x-axis toward the origin.
NXT	3	IP	C	Number of extra theta values to add to each end of a sector of symmetric field data to allow for interpolation. NXT should be at least large enough to allow interpolation at the end points of the field array. NXT = 1 is sufficient for TRELAG.
PLTOPT	1	M	C	<p>> 1 means plot one particle at a time through each time step requested.</p> <p>< 1 means plot packets.</p>

Variable Name	Input Group Number	Subroutine Read In	Data Units	Descriptions
PRTOPT	1	M	C	<p>> 1 means printout will consist of all time steps requested for one particle, then another particle, etc.</p> <p>< 1 means printout will consist of position and velocity of all particles at one time step, then another time step, etc.</p>
PSPACE(2)	7	IP	MM-MR/D	Phase space area of packet to be calculated. PSPACE(1) is for R-packet, PSPACE(2) is for Z-packet.
PWIDTH(2)	7	IP	MM	Packet width. PWIDTH(1) is for R-packet, PWIDTH(2) is for Z-packet.
Q	8	IP	EU	Charge of particle in electron units.
R	11	IP	CM	Radius of particle at initial position.
RELERR	4	IF	C	Accuracy parameter for subroutine DE ⁵ . Relative error test.
S(3,9)	12	IP	CM	<p>Particle position in x,y,z coordinates.</p> <p>First subscript = 1 implies x = 2 implies y = 3 implies z</p> <p>Second subscript is particle number.</p>
TI	11	IP	DEG	Implies direction of packet. Positive TI is measured counterclockwise from radial NTI line. TI = 0 assumes packet is directed toward center along NTI line.
TINT	8	IP	SEC	Initial time at which integration begins.
TMAX	8	IP	SEC	Final time at which integration ends.
V(3,9)	12	IP	CM/SEC	Particle velocity in x, y, and z coordinates. Subscripts are used the same as for S.

6. PLOTTING PROCEDURE

1. Once a compressed plot data set is generated in PATPLT, a post-processor program must be executed to plot the data. The data set may be postprocessed on a CALCOMP plotter or a TEKTRONIX graphics terminal. JCL to execute the CALCOMP postprocessor may be seen on page 2).
2. To postprocess on a TEKTRONIX terminal at ORNL, a compressed file must have been sent to the user's PDP-10 disk area. The JCL described for sending compressed data to the PDP-10 would cause a file to be sent to the disk area [6137,67] and it would be named LBML.PCH. The following sequence of commands would cause the file to be plotted. (The notation <CR> means carriage return.)

```
RENAME FOR24.POP = LBML.PCH <CR>
```

```
ASSIGN TTY LPT <CR>
```

```
R QWKPOP <CR>
```

(At this point the program asks for plotting commands.

To plot all plots in the file, respond with <CR> <CR>.)

Other postprocessor commands may be used to change the size of the plots, etc.

After one plot has been drawn and the user is ready to see the next plot, simply type a <CR> and plotting will proceed.

7. EXAMPLE JCL

SAMPLE JCL FOR EXECUTING CALPAT

```

//LEMIN1 JOB (14163),'SAVE6137,67 XCSDA214'
//*SOLO CPU1
//*CLASS CPU91=ZOS,IO=1.5
//*ROUTE PUNCH REMOTE5
//*ROUTE PRINT LOCAL
//*
//* THIS STEP DELETES FILES IF THERE ARE ANY OF THE SAME NAME AS THOSE
//* TO BE CREATED
//*
//STEP0 EXEC SPDASCH
//SYSIN DD *
  1.LBM04163.IN1.FT11 1.LBM04163.IN1.FT12
/*
//RUN EXEC FORTQCCLG,LIB=LAB,
// PARM.GO='DUMP=1,EU=-1',REGION.GO=270K
//*
//*
//* OBJ CONTAINS INCPY.F4[6137,30],CALPAT.DE, DE,
//* AND PACKET.F4
//*
//LKED.OBJ DD DSN=1.LBM04163.CALPAT.ALL,DISP=SHR
//LKED.SYSIN DD *
  INCLUDE OBJ
/*

```

(continued on next page)

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```

/*
/* FT11 IS ITSTOP ARRAY AND ITIMPP ARRAY TO BE PASSED TO PATPL1
/*
//GO.FT11FOO1 DD DCB=(RECFM=FB,LRECL=80,BLKSIZE=3520),
// DSN=T.LEMO4163.IN1.FT11,UNIT=SPDA,
// DISP=(NEW,CATLG),SPACE=(TRK,(10,5),RLSE)
/*
/* FT12 IS POSITION AND VELOCITY DATA AT EACH INTEGRATION STEP TO
/* BE PASSED TO PATPL1
/*
//GO.FT12FOO1 DD DCB=(RECFM=FB,LRECL=80,BLKSIZE=3520),
// DSN=T.LEMO4163.IN1.FT12,UNIT=SPDA,
// DISP=(NEW,CATLG),SPACE=(TRK,(10,5),RLSE)
/*
/* FT10 IS BFIELD DATA THAT IS INPUT TO CALPAT
/*
//GO.FT10FOO1 DD *
=BFIELD.DAT
/*
/* FT04 IS INPUT DATA TO CALPAT THAT IS READ IN BY SUBROUTINE
/* INCOPY, PRINTED, AND WRITTEN TO A TEMPORARY DISK TO
/* BE READ IN AS NORMAL FROM INPUT UNIT 15
/*
//FT15FOO1 DD UNIT=SYSDA,DCB=(RECFM=FB,LRECL=80,BLKSIZE=2000),
// SPACE=(2000,(10,10),RLSE)
//GO.FT04FOO1 DD *
=INPUT.DAT
/*
//
ENDINPUT

```

SAMPLE JCL TO EXECUTE CALCOMP POSTPROCESSOR

```

//LEMCPOP JOE (14163), 'XCSD-PADDGX-A214'
//*CLASS CPU91=20S,IG=4
/*ROUTE PRINT LOCAL
/*
/* PROGRAM POPD92 IS CALCOMP POSTPROCESSOR
/*
//STEP4 EXEC PGM=POPD92,REGION=110K
//STEPLIB DD DSN=SYS2.DISSPOP,DISP=SHR
//F105F001 DD *
DRAW=1-END
/*
//F106F001 DD SYSOUT=A
/*
/* COMPIN IS COMPRESSED DATA SET THAT IS INPUT TO THE POSTPROCESSOR
/*
//COMPIN DD DSN=T.LEM04163.PLTIN1,DISP=SHR
/*
/* F149 AND PLOTSUBS ARE NECESSARY FOR DISK PLOTTING
/*
//F149F001 DD UNIT=IN2002,DISP=(NEW,KEEP),
// SPACE=(3200,(10,10),RLSE),DSN=C925600.TIMIN1.PL11,
// LCB=SYS2.DISKDCB
//PLOTSUBS DD DSN=SYS2.JGSPLGTH,DISP=(SHR,PASS)
//
ENDINPUT

```

SAMPLE JCL TO SEND COMPRESSED DATA TO
PDP-10 DISK AREA

```
//LEH1POP JOB (14163),'SAVE6137,07H BIN M'
//*CLASS CPU91=10S,10=2
/*ROUTE PRINT LOCAL
/*ROUTE PUNCH REMOTE5
/*
/* THIS STEP TRANSFERS COMPRESSED DATA SET ON IBM360 DISK
/* TO USER'S PDP-10 DISK AREA FOR TEKTRONIX POSTPROCESSING
/*
//STEP4 EXEC PGM=IEBGENER
//SYSIN DD DUMMY
//SYSPRINT DD SYSOUT=*
//SYSUT1 DD DSN=T.LEM04163.PLT1N1,DISP=(OLD,KEEP),
// DCB=(RECFM=FB,LRECL=60,BLKSIZE=4000)
//SYSUT2 DD SYSOUT=B,DCB=(RECFM=FB,BLKSIZE=60,LRECL=60)
//
ENDINPUT
```

SAMPLE JCL FOR EXECUTING PATPLT

```

//LEMINIP JOB (14163),'SAVE6137,67 XCSDA214'
//*SOLE CPU1
//*CLASS CPU91=405,10=3
/*ROUTE PRINT LOCAL
/*ROUTE PUNCH REMOTE5
// EXEC SPDASCH
//SYSIN DD *
  1.LEM04163.PLTIN1
/*
//PLOT EXEC FORTQCLG,PARM.FOR1='XREF',
// PARM.GO='DUMP=1',REGION.GO=270K
//FOR1.SYSIN DD *
=PATPLT.F4
/*
//LKED.SYSLIE DD
// DD
// DD DSN=SYS2.DISSPLA,DISP=SHR
//GO.FT11F001 DD DCE=(RECFM=FB,LRECL=80,BLKSIZE=3520),
// DSN=1.LEM04163.IN1.FT11,DISP=(OLD,KEEP)
//GO.FT12F001 DD DCE=(RECFM=FB,LRECL=80,BLKSIZE=3520),
// DSN=1.LEM04163.IN1.FT12,UNIT=SPDA,DISP=(OLD,KEEP)
/*
/** FT13 IS NEEDED WHEN RUNNING A SINGLE PARTICLE. IT
/** PROVIDES A WAY OF MARKING A SINGLE TRAJECTORY AT THE SAME
/** TIME STEPS THAT ARE SHOWN ON A COMPARISON PACKET PLOT
/** FT13 SHOULD BE THE DSN OF THE FT11 DATA SET FROM A PACKET
/** RUN
/**
//GO.FT13F001 DD DCE=(RECFM=FB,LRECL=80,BLKSIZE=3520),
// DSN=1.LEM04163.IN1.FT11,UNIT=SPDA,DISP=(OLD,KEEP)
/*
/** COMPUT IS DISSPLA COMPRESSED DATA SET THAT IS WRITTEN TO DISK
/** TO BE POSTPROCESSED IN LATER JOB STEP
/**
//GO.COMPUT DD DISP=(NEW,CATLG),
// UNIT=SPDA,SPACE=(4000,(30,6),RLSE),
// DSN=1.LEM04163.PLTIN1
//
ENDINPUT

```

8. EXAMPLE CALCULATIONS

Example 1:

The input data set (Fig. 8.1) will calculate an injection trajectory for a particle in an ORIC magnetic field. The particle used is 75 MeV $^{12}\text{C}^{+2}$ with the path followed from time zero to 0.6×10^{-7} seconds. The particle is initially positioned at 135° at a radius of approximately 28 cm. These initial conditions were those of an equilibrium orbit calculated by GOC⁴. Figure 8.2 was produced by program PATPLT, with input from program CALPAT using the data set in Fig. 8.1. Note: To simulate an injection path from an equilibrium orbit in which the particle tracks backwards from the foil, the signs of P_x and P_y should be reversed and either the signs of the isochronizing factors reversed or the charge made negative (implying a sign change for the field).

Example 2:

The input data set (Fig. 8.3) in CALPAT will calculate the trajectories of a nine-particle packet. The central particle has the same initial conditions as the particle in Example 1. Initial positions and velocities of the other eight particles are calculated in the program.

Figure 8.4 shows the packet position at eight different times during the trajectory. The x and y coordinates of particle 1 are printed in order to show the absolute position of the whole packet.

Example 3:

The input data set (Fig. 8.5) in CALPAT calculates a trajectory of a particle injected along the edge of a hill and with a charge that would result from pre-injection stripping. The magnetic field is that of a K=440 separated sector machine with four-fold symmetry. The particle used is 225 MeV $^{127}\text{I}^{+34}$. It is injected at an angle of 28° .

Stripping before injection would allow a form of precessional injection. This approach has been used in the past as a means to transport beams from an external ion source to the cyclotron central region.⁶ Here the principle is the same, except the ions have an energy of 225 MeV. The trajectory shown in Fig. 8.6 illustrates the general nature of the code, which allows integration of any arbitrary (near median plane) motion as a function of time.

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Fig. 8.1. INPUT DATA SET FOR SINGLE PARTICLE INJECTION

Fig. 8.2. SINGLE PARTICLE INJECTION

Fig. 8.4. NINE PARTICLE PACKET INJECTION

Fig. 8.4. NINE PARTICLE PACKET INJECTION (cont.)

1	1	2	1	0	0	PLTOPT, PRTOPT, IDIM, NPRPLT, IBEOPT, MRKPLT		
0	0	0				_PAK, IOPT, IPRNTB		
51	90	5	1			NR, NT, NXT, IFTYPE		
2.832900		1.		1.E-6	1.E-6	DR, DT, RELERR, ABSERR		
(9F8.1)						FMT		
1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000
1.0000000	1.0000000	1.0836519	1.0364774	1.0405780	1.0388015	1.0327975	1.0276940	
1.0252323	1.0224559	1.0194546	1.0174705	1.0150536	1.0128902	1.0122326	1.0122510	
1.0120196	1.0124696	1.0131135	1.0137726	1.0146785	1.0155321	1.0168803	1.0183607	
1.0197806	1.0216779	1.0239473	1.0258356	1.0278560	1.0308065	1.0336033	1.0350608	
1.0385285	1.0420404	1.0455367	1.0493717	1.0533241	1.0574711	1.0616465	1.0641517	
1.0662621	1.0683744	1.0704885						
					ISOFACT			
225.0	127.	34.	5.	0..49000D-06	E, FMASS, Q			
1	.0		NP, FUDGE					
340.	28	0.0	0.0	0.0	R, NTI, TI, S, V			

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Fig. 8.5. INPUT DATA SET FOR PRECESSIONAL INJECTION

Fig. 8.6. PRECESSIONAL INJECTION

9. UNITS INFORMATION

All internal calculations use MKS equations of motion and metric quantities; however, quantities are input in more "user preferred" units.

Input Variable	Input Units	Internal Units
B	gauss	negative tesla
BEG	seconds	seconds
DR	inches	meters
DT	degrees	radians
E	MeV	joules
END	seconds	seconds
FMASS	amu	kilograms
NTI	degrees	radians
PSPACE	millimeters	millimeters
PWIDTH	mm-mrad	mm-mrad
Q	electron units	Coulombs
R	cm	meters
S	cm	meters
STPSIZ	cm	meters
TI	degrees	radians
TINT	seconds	seconds
TMAX	seconds	seconds
V	cm/sec	meters/sec

APPENDIX A

Finite-beam properties may be studied by following the trajectories of a group of particles which outline the perimeter of an appropriate volume of phase space. Such a group of particles is shown in Fig. A.1, and is referred to as a "packet". Particle 1 defines the center of the beam, and the remaining eight particles are distributed in the transverse-plane to particle 1 in either spatial or angular displacement.

Since the initial conditions differ for the particles in the packet, at some later time $T \neq T_1$, the particles will no longer lie on the transverse-plane to particle 1, but will appear as in Fig. A.2. (Note that the displacement from the transverse-plane is exaggerated for clarity.) In order to display the transverse-plane phase space packet, particles 2 through 9 must be transformed to the transverse-plane. This is accomplished by assuming the magnetic field to be constant within the volume of the packet, which implies the particles follow circular trajectories to the transverse-plane, as indicated in Fig. A.2.

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Fig. A.1. PHASE SPACE PACKET

FIG. A.2. TRANSFORMATION TO TRANSVERSE PLANE

REFERENCES

1. For a definition of a packet, see GIP: An Interactive General Orbit Code Input Program, ORNL/CSD/TM-14 (1976).
2. DISSPLA is a software plotting package (Integrated Software Systems Corp.) locally implemented on the IBM-360's and the PDP-10. Documentation is available from the Computer Sciences Division librarian at ORNL.
3. QWKPOP is a DISSPLA program. See plotting procedure for brief description of its use.
4. GOC is documented in ORNL/CSD/TM-53 (1979).
5. L. F. Shampine and M. K. Gordon, Computer Solution of Ordinary Differential Equations, W. H. Freeman and Co., San Francisco, (1975).
6. G. W. Westley and J. A. Watts, Editors, The Computing Technology Center Numerical Analysis Library. CTC-39, (1970).
7. W. A. van Kampen and J. Liedorp, "Precession Injection in the Delft Isochronous Cyclotron," in Proceedings of the Seventh International Conference on Cyclotrons and their Applications, Birkhäuser Verlag, Basel and Stuttgart (1975), p. 254.

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