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MAGIC: A ONE-DIMENSIONAL MAGNETO-INDUCTIVE PARTICLE CODE

MASTER

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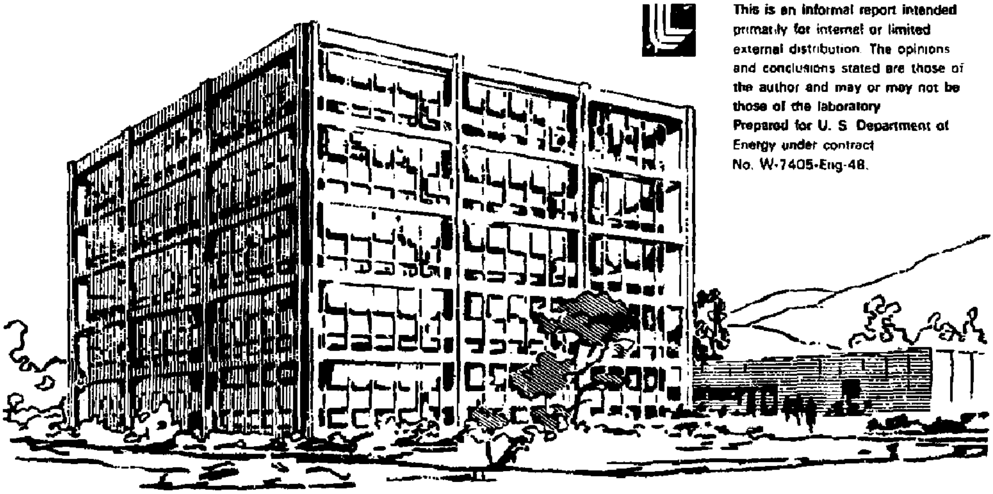

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MAGIC: A ONE-DIMENSIONAL MAGNETO-INDUCTIVE PARTICLE CODE

ABSTRACT

MAGIC, a new one-dimensional particle code, simulates magneto-inductive phenomena in a cylindrically-symmetric magnetized plasma. We describe the physical model and the computational algorithm used for the code. A user's guide to and a listing of MAGIC are also included.

INTRODUCTION

A one-dimensional particle code, MAGIC, simulates magneto-inductive phenomena in a cylindrically-symmetric magnetized plasma. We present the physical model and the computational algorithm and contrast them with those of LMR, a one-dimensional version of SUPERLAYER. The results of the two codes are very close, despite their differences in physics and algorithms.

The MAGIC I code solves for the vector potential from the accumulated currents; MAGIC II solves for the magnetic flux. With MAGIC, the user can have either a uniform-density (warm or cold) background plasma and can use one of several injection modes (pulsed, constant, or linearly increasing rates).

A user's guide (see Appendix A) to MAGIC I and II is also included. It briefly provides the information needed to execute MAGIC. We have also included the Fortran listing of the code (see Appendix B).

DESCRIPTION OF THE PHYSICAL MODEL

MAGIC is one-dimensional, magneto-inductive particle code. It simulates an infinitely long, cylindrically-symmetric magnetized plasma. The physical model describes magneto-inductive phenomena and is a radial version of the r-z codes used by Dickman, Morse, and Nielson,[1] and Byers.[2] In our model, MAGIC I solves the following vector potential equation from the accumulated currents:

$$\left(\frac{1}{r}\frac{\partial}{\partial r}\, r\, \frac{\partial}{\partial r} - \frac{1}{r^2}\right) A_\theta = -4\pi J_\theta/c. \qquad (1)$$

MAGIC II solves this equivalent equation for the magnetic flux rA_θ, and

$$B_z = \frac{1}{r}\frac{\partial}{\partial r}\,(rA_\theta), \qquad E_\theta = -\partial A_\theta / c\partial t. \tag{2}$$

Radiation and electrostatic fields are legislated out of the model because the longitudinal and transverse displacement currents are absent on the r. h. s. of Eq. (1). The model of the magnetic field is self-consistent and the code can move two ion species in the self-consistent fields. We assume implicitly that electrons completely neutralize the charge of the ions, but do *not* contribute to the currents. We assume the plasma is surrounded by a cylindrical conductor.

Maxwell's equations and the equations of motion are finite-differenced and integrated in the following manner:

$$\begin{aligned}\left(\frac{1}{r}\frac{\partial}{\partial r}\, r\, \frac{\partial}{\partial r} - \frac{1}{r^2}\right) A_\theta^n &= \frac{A_{\theta j+1}^n - 2A_{\theta j}^n + A_{\theta j-1}^n}{\Delta r^2} \\ &\quad + \frac{1}{2r_j\Delta r}\left(A_{\theta j+1}^n - A_{\theta j-1}^n\right) - \frac{A_{\theta j}^n}{r_j^2} = 4\pi c^{-1} J_{\theta j}^n \\ &= -4\pi c^{-1} \sum_i \left\{\frac{e}{mr_i}\, S\left(r_i^n - r_j\right)\left[P_{\theta i} - \frac{e}{c}\sum_{j} r_i S\left(r_i^n - r_{j'}\right) A_{\theta j'}^n\right]\right\},\end{aligned} \tag{3}$$

$$B_{zj}^n = \frac{A_{\theta j+1}^n - A_{\theta j-1}^n}{2\Delta r} + \frac{A_{\theta j}^n}{r_j}, \quad \frac{1}{2}\left(E_{\theta j}^n + E_{\theta j}^{n-1}\right) = \frac{-(A_\theta^n - A_\theta^{n-1})}{c\Delta t}, \tag{4}$$

where $P_{\theta i}$ ≡ canonical angular momentum, S ≡ linear interpolation factor, i ≡ super-particle index, j, j' ≡ grid indexes, and n ≡ time level. E_θ and A_θ vanish at $r = 0$, and at $r = a$ on the surface of a perfect conductor. A_θ has a smooth first derivative at $r = 0$, and $A_\theta = 0$ for $r \geq a$.

The super particles, advanced with a Boris mover,[3] can be represented formally by:

$$(v_r,v_\theta)^{n+1/2} = (v_r,v_\theta)_i^{n-1/2} + \Delta t\,(e/m)\left\{\sum_j S(r_i^n - r_j)\,E^n_{\theta j}\,\hat{e}_\theta + \left(\frac{1}{2c}\right)\left[(v_r,v_\theta)^{n+1/2} + (v_r,v_\theta)^{n-1/2}\right]\sum_j S(r_i^n - r_j)\,B_{zj}\,\hat{e}_z\right\} \qquad (5)$$

and

$$r_i^{n+1} = \left[\left(r^n + v_r^{n+1/2}\,\Delta t\right)^2 + \left(v_\theta^{n+1/2}\,\Delta t\right)^2\right]_i^{1/2} . \qquad (6)$$

We chose a system of nondimensional units internal to the code:

$$r^* = r/c\Delta t,\ v^*_{r,\theta} = v_{r,\theta}/c,\ \Delta t^* = \omega^0_{ci}\,\Delta t,$$

$$B^*_z = \left(B_z/B_0\right)\Delta t^*,\quad E^*_\theta = \left(E_\theta/B_0\right)\Delta t^*,\quad \text{and } A^*_\theta = \left(\omega^0_{ci}/c\right)\left(A_\theta/B_0\right),$$

where ω^0_{ci} is the ion cyclotron frequency of the principal ion species in the applied magnetic field B_0, and Δt is the time step. These are the input quantities. The input and output are in physical units (Gaussian cgs).

The uniform-density background plasma can either be a warm Maxwellian or cold. There are three injection modes: pulsed, constant, and linearly, increasing rates. Slow particles ($v_r \lesssim a/\Delta t$) are elastically reflected by the conductor. Fast particles ($v_r \gtrsim a/\Delta t$) are inelastically reflected at a random angle with the thermal velocity of the wall (which is specified by the user).

The computational scheme is explicit after taking the A_θ dependence of Eq. (3) to the l.h.s. It is also perfectly time-centered and yields the following linear dispersion relation[4,5] describing the propagation of compressional Alfvén waves across an applied magnetic field in a cold plasma:

$$\lim_{k\Delta r\to 0}\ \tan^2(\omega\Delta t/2) = \frac{k^2 v_a^2 \Delta t^2/4}{1 + (\omega_{ci}\Delta t/2)^2 + k^2 v_a^2/\omega_{ci}^2}\ , \qquad (7)$$

where k is the effective radial wave number $k = \chi_n a^{-1}$, $J_1(\chi_n) = 0$, and $v_A = (\omega_{ci}/\omega_{pi})\,c$ the Alfvén wave velocity. Thus as $kv_a/\omega_{ci} \to \infty$, $\omega \to \omega_{ci}$, if $\omega_{ci}\Delta t/2 \ll 1$. There is no Courant condition, and the magnetosonic waves are stable at all wave numbers. Numerical stability of a cyclotron orbit in a warm plasma requires $\omega_{ci}\Delta t/2 < 1$. Figure 1 displays results of simulations that verify the linear dispersion relation given by Eq. (7).

The MAGIC code is reversible because of the perfect time-centering, and there is no numerical damping. Pulsed injection necessarily excites normal modes at all frequencies, and in particular at the highest (Nyquist) frequency of the simulation, $\omega = \pi/\Delta t$. The lack of numerical damping permits these high frequency oscillations to persist, i.e., the system rings! Byers' code SUPERLAYER uses the pulsed injection mode, but numerically damps high frequency oscillations.[6] We recommend against using the pulsed-injection mode in MAGIC, since the ringing is physical but the finite time-step distortion is not.

Figures 2-5 display simulation results obtained using MAGIC and LMR, a one-dimensional version of SUPERLAYER. LMR conserves canonical angular momentum exactly. These four simulations use injection of energetic deuterium to drive the magnetic field to a null inside an injected ring. MAGIC injected one super particle per time step for 1024 time steps. Using a constant rate of injection: 800 A at an energy of 20 keV and a radius of 5.8 cm. LMR injected a nearly equivalent amount of current, but with the canonical angular momentum of each newly injected ion *not* self-consistent with the plasma self-magnetic field. The results are obviously quite similar despite the differences in algorithms and physics.

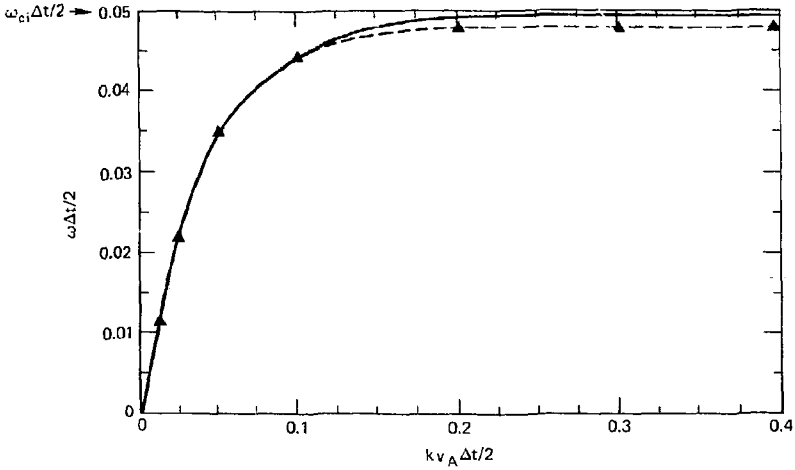

Fig. 1. Linear dispersion relation for compressional Alfvén waves.

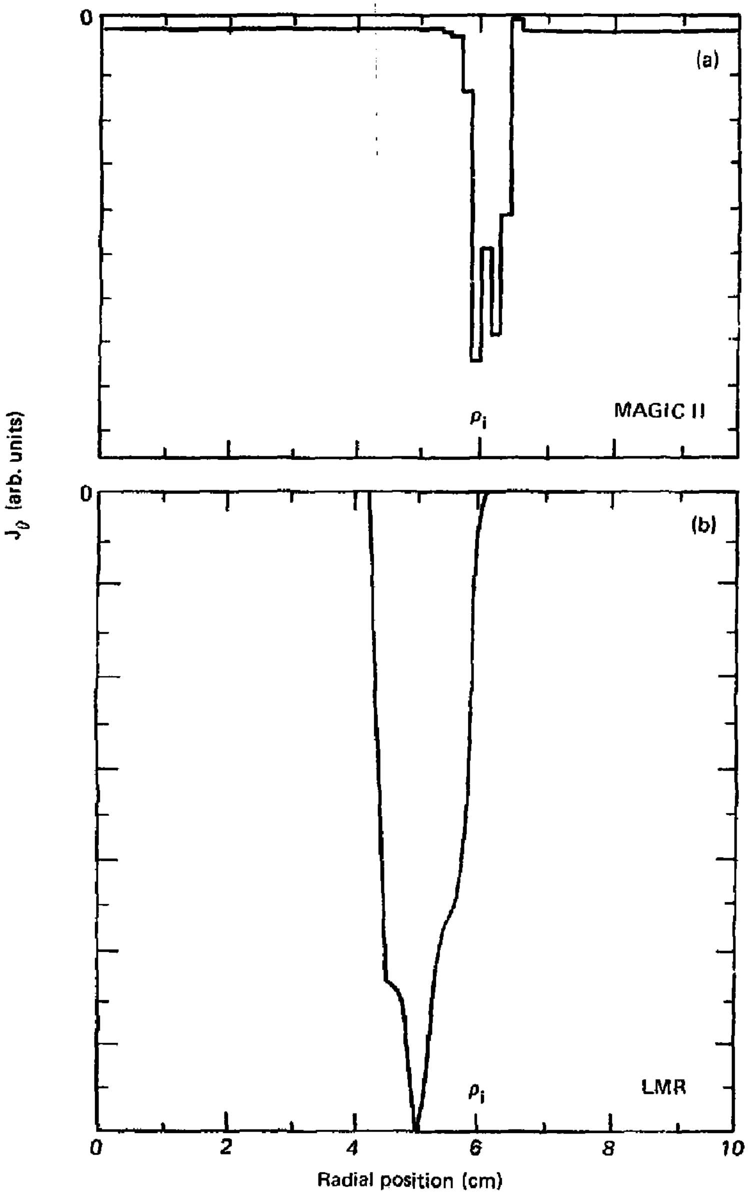

Fig. 2. Simulation results from a ring-like injection for MAGIC II (a) and LMR (b). The ion Larmar radius ρ_i in the applied magnetic field is noted for reference.

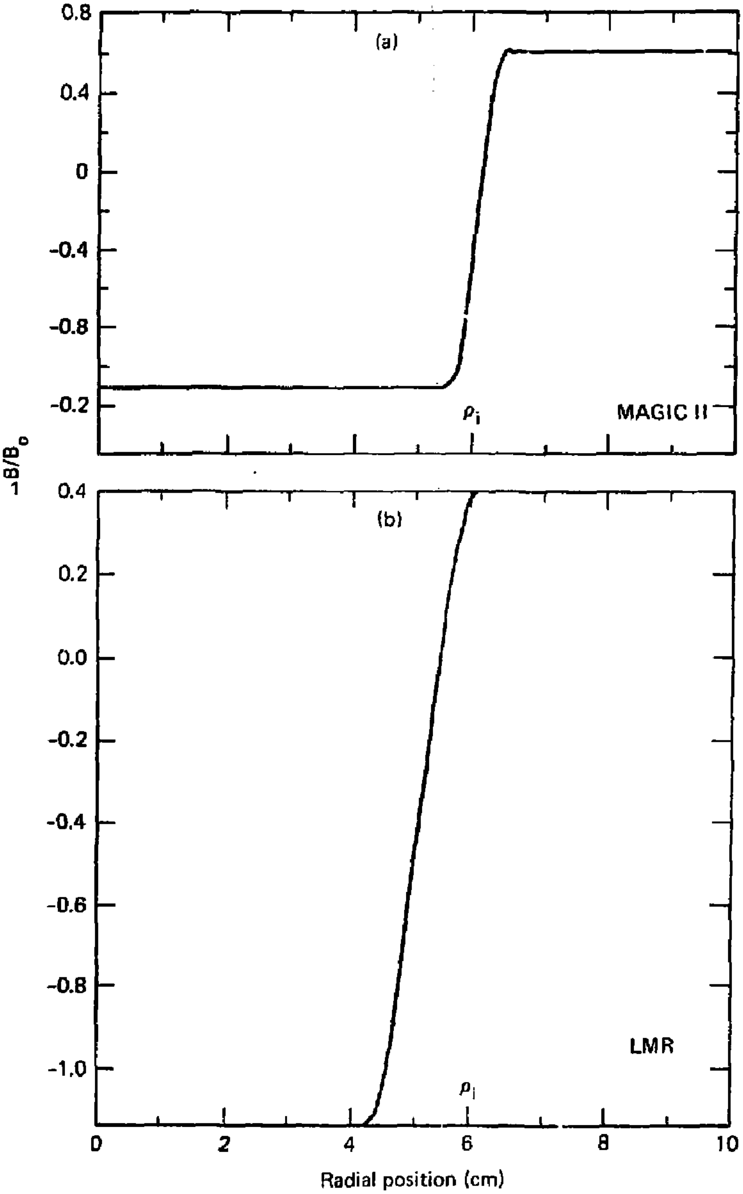

Fig. 3. Simulation results from a ring-like injection for MAGIC II (a) and LMR (b). Note the reversal of the magnetic field inside the ring.

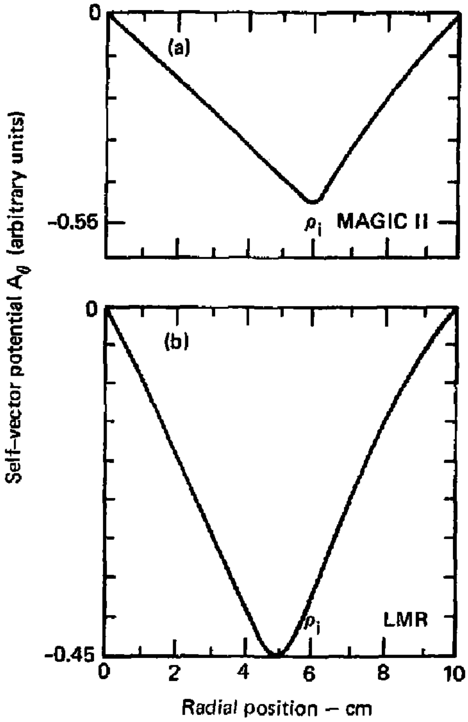

Fig. 4. Simulation results from a ring-like injection for MAGIC II (a) and LMR (b).

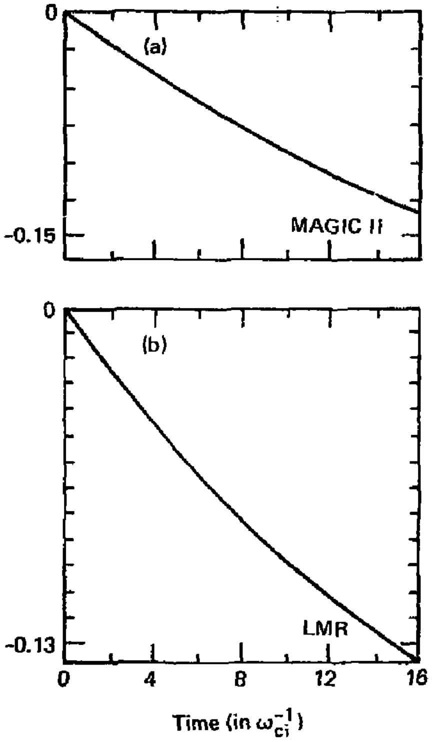

Fig. 5. Simulation results at $r \sim 1/3\,\rho_i$ from a ring-like injection for MAGIC II (a) and LMR (b).

REFERENCES

1. D. O. Dickman, R. L. Morse, and C. W. Nielson, *Phys. Fluids* 12 1708 (1969).
2. J. A. Byers, *Phys. Rev. Lett.* 39 1476 (1977).
3. J. P. Boris, "Relativistic Plasma Simulation — Optimization of a Hybrid Code," in *Proc. of the Fourth Conf. on Numerical Similation of Plasmas*, J. P. Boris and R. Shanny, Eds. (U.S. Government Printing Office, Washington, D.C., 1970) p. 3.
4. B. I. Cohen, "A New Particle Pusher and a Time-Centered Field Solve for SUPERLAYER," MFC/TC/78-110 (March 14, 1978).
5. J. A. Byers, B. I. Cohen, W. C. Condit, and J. D. Hanson, *Hybrid Simulations of Quasineutral Phenomena in Magnetized Plasma*, Lawrence Livermore Laboratory, Rept., UCRL-79437 (1977).
6. R. P. Freis and B. I. Cohen, Lawrence Livermore Laboratory, private communication (May 1978).

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APPENDIX A: USER'S GUIDE TO MAGIC I AND II

MAGIC I and II are one-dimensional, magneto-inductive particle simulation codes written in FORTRAN, and designed to run on the DEC 10 computer. There is one major difference between the two codes. MAGIC I has a field solver that solves for the vector potential from the accumulated currents; MAGIC II solves for the magnetic flux from the currents. MAGIC II also has some additional convenience features, particularly in the plotting of output data.

MAGIC allows either uniform-density or injection runs, or combination of the two. The user can also launch cold magnetosonic waves, for which he supplies the wave number and amplitude.

This Guide briefly provides the user with the information needed to execute MAGIC. It describes the input file and output plot formats and gives an example of the input file. This Appendix, in somewhat altered form, is also available online. See the section on Source File Availability for details.

Input File Format

MAGIC reads all of the necessary input data (in Gaussian cgs) from a NAMELIST input file. An example of an input file that tests the constant rate injection in MAGIC II looks like (where the parameters are defined in the next section):

```
THIS IS A RUN FOR BETA OF ONE.

  $INPUT

CURR=8E+2
EINJ=20.
ITRMAX=1024
ITRPLT=64, INJMOD=1

NGYRO=1
GYRRAN=0.
RINJ=5.84
NINJ=1
WINJ=.1
DELTS=.1
```

The first dollar sign must appear in column 2. Data items can be separated by commas. Comments can appear before the $INPUT line. The second dollar sign (in column 1) is a required delimiter.

Input Parameters. The NAMELIST parameters that can be set in the data file are:

AWAVE	Amplitude for launching a magnetosonic wave in volts.
BO	Background magnetic field in gauss.
CURR	Injection current to be reached at the end of the injection in amperes.
DELTS	Ion cyclotron frequency times the time step.
DENSI	Initial uniform density in particles per cubic centimetre.
EINJ	Energy of the injected particles in hiloelectron volts.
GYRRAN	Range of gyrophase angles, from -GYRRAN to +GYRRAN, in radians.
IATHS	Logical switch for the self-vector potential versus the radial position plot.
IBZS	Logical switch for the self-magnetic field versus the radial position plot.
IDENS	Logical switch for the particle density versus the radial position plot.
IETHS	Logical switch for the self-magnetic field versus the radial position plot.
IJTH	Logical switch for the theta current versus the radial position plot.
INJMOD	Injection mode: 0. pulsed injection (T = 0). 1. constant-rate injection. 2. linearly-increasing-rate injection.
IPT1 IPT2 IPT3 IPT4	Grid cell numbers for sampling self-vector potential versus time.
ITEK	Switch to turn on plotting for the Tektronix terminal.
ITRMAX	Number of time steps to the end of the run.
ITRPLT	Number of time steps between the phase space and field quarters plots.
IVRR	Logical switch for the radial velocity versus the radial position plot.

IVTHVR	Logical switch for the theta velocity versus the radial velocity plot.
KWAVE	Wave number for launching a magnetosonic wave.
NGYRO	Number of gyrophase angles per injection point.
NINJ	Number of particles to be injected per time step per gyrophase angle.
NUS	Drag coefficient, ν_{ie}/ω_{ci}^{0}.
RINJ	Radius of the center of the injection profile in centimetres.
RMAX	Outer radius of system in centimetres.
TEMPO	Energy of the uniform background particles in electron volts (Maxwellian-loaded).
TWALL	Energy given to the fast particles that are absorbed by the wall and then re-emitted.
WINJ	Width of the injection profile in centimeters.

Running the Code

To run the code, type:

```
RU MAGIC2 [30,3057]
```

Follow this line with a carriage return. Then enter the name of the input file when the code requests it, and again follow this line with a carriage return. When the run is completed, the DD80 output file, called MAGC2.DD8, can be processed by GRAF10 and then plotted on the Versatec printer. The file can also be looked at with TEK10. GRAF10 and TEK10 are available from the magnetic Fusion Energy Network's Computer Center.

The user should not set the ITEK parameter to 1 when his terminal is not a Tektronix; if he does so, he receives a vast amount of useless, printed binary output.

Output Plot Format

Output plots, in the form of DD80 files, are packed four to a page. The output consists of:

- A heading page. This page contains:
  - (a) The date and time of the run.
  - (b) The name of the input data file.
  - (c) A complete printout of the contents of the data file.

(d) A list of the run parameters calculated by the code.

(e) A list of the current values, including defaulted ones, of all the NAMELIST parameters.

- Phase space and field quantity plots, taken at preset intervals. The plots included in this group are:
  - (a) Radial velocity versus radial position.
  - (b) Theta velocity versus radial velocity.
  - (c) Particle density versus radial position.
  - (d) Self-vector potential versus radial position.
  - (e) Self-magnetic field (ΔB/B0) versus radial position.
  - (f) Self-electric field versus radial position.
  - (g) Theta current versus radial position.
- History plots. The plots included in this group are:
  - (a) Self-vector potential versus time. This is plotted for four different radial locations.
  - (b) Injected and calculated energy versus time.
  - (c) Energy error (fluctuation) versus time.
  - (d) Maximum beta versus time.
  - (e) Average beta versus time.

MAGIC is designed so that any of the phase space-field quantity plots can be switched off by a NAMELIST parameter. (See the parameter descriptions in the preceding section that begin, "Logical switch....") MAGIC then repacks the plots four to a page.

Source File Availability

These seven MAGIC files are available publicly on the M Division DEC 10 from user number [30,3057] through the PIP program. The files are:

MAGIC1.STR and MAGIC2.STR	(contain the common blocks),
MAGIC1.FOR and MAGIC2.FOR	(contain the main routine),
MAGIC1.LIB and MAGIC2. LIB	(contain the subroutines),
MAGIC2.SWP	(online copy of the user's guide).

APPENDIX B: MAGIC LISTING

```
C       THIS IS THE STORAGE BLOCK FOR MAGIC2
C       FOR DESCRIPTION OF VARIABLES, SEE MAGDOC IN MAGIC2.LIB

        IMPLICIT DOUBLE PRECISION (A-H,O-Z)

        PARAMETER NP=1000,NG=64,NT=200
        PARAMETER NGROUP=2

        DOUBLE PRECISION JI,M,KWAVE,NUMER,NUS
        DOUBLE PRECISION JTHETA

        COMMON /INDATA/ BO,DELT,RMAX,DENSI,NUS,CURR,ITRMAX,ITRPLT
     1                 ,NINJ,RINJ,WINJ,INJMOD,EINJ,NGYRO,GYRRAN
     1                 ,TEMPO,TWALL,ITH

        COMMON /RDATA/ ITER,NIN,NLAST
     1                 ,VINJS,RINJS,WINJS
     1                 ,ENRTOT,NHOT,NCOLD,VTHERM,VWALL

        COMMON /PRTCLS/ R(NP),VR(NP),PTHETA(NP),VTHETA(NP)

        COMMON /GRID/ FLUX(NG),JTHETA(NG),BZ(NG),ETHETA(NG)
     1                 ,CM(NG),CZ(NG),CP(NG),TV1(NG),TV2(NG)

        COMMON /CONST/ PI,C,DELTS,DELR,DELRS,E,M,WCI

        COMMON /SWITCH/ IVRR,IVTHR,IVTHVR,IDENS,IBZS,IFLXS,IETHS
     1                 ,IJTH,IATHS

        COMMON /PLOTS/ JPLOT,XOFF,YOFF,FNAME,KSAMPL,ISAMPL,KMAX

        COMMON /HISTRY/ XTIME(NT),BAVG(NT),BMAX(NT),TENERC(NT)
     1                 ,TENERI(NT),ATTIME(4,NT)
     1                 ,IPT1,IPT2,IPT3,IPT4

        COMMON /GROUP/ NMIN(NGROUP),NMAX(NGROUP),BETA(NGROUP)
     1                 ,SUPN(NGROUP)

        COMMON /WAVES/ WPI,WALF,VALF,KWAVE,AWAVE,WWAVE,AMP
```

```
C       MAGIC2 :
C                           TIME CENTERED
C                           DOUBLE PRECISION
C                           MAGNETO - INDUCTIVE
C                           IONS - ONLY
C                           CODE

C       ALGORITHMS BY BRUCE COHEN
C       CODING BY TOM BRENGLE

C       CURRENT VERSION -   19-APR-78

        INCLUDE 'MAGIC2.STR'

C       SET UP PLOT FILE
        CALL KEEP80 (5HMAGC2,2)
        CALL DD80ID (6HMAGIC2,1)

C       GET INPUT DATA FROM INPUT FILE
        CALL INPUT

C       SET UP CONSTANTS AND CALCULATE RUN PARAMETERS
        CALL SETCON

C       PRINT OUT THE HEADING PAGE
        CALL HEADER

C       IF ITEK IS ONE, TURN ON TEKTRONICS SCREEN
        IF (ITEK .EQ. 1) CALL TEKID

        ITER = 0

C       ZERO OUT GRID ARRAYS, CALCULATE ENERGY DUE TO BACKGROUND
C       MAGNETIC FIELD, AND IF A WAVE IS TO BE LAUNCHED,
C       SET ETHETA FOR T=0.
        CALL INITLZ

C       FOR COLD PARTICLES (GROUP 1) SET UP VR, VTHETA, PTHETA AND R
C       (USING MAXWELLIAN IF TEMP0 IS NOT ZERO). ALSO ACCUMULATE
C       JTHETA AND ENERGY FOR T=0. IF A WAVE IS TO BE LAUNCHED,
C       SET UP VR FOR T=0.
        CALL MAXLOD

C       BEGIN TIME LOOP
101     CONTINUE

C       LOOP THROUGH UNTIL TIME TO PLOT
        DO 100 I = 1,ITRPLT

C       INJECT NEW PARTICLES AND ACCUMULATE JTHETA AND ENERGY FOR THEM
        CALL INJECT

C       SOLVE FOR NEW SELF FIELDS
        CALL FIELDS

C       MOVE NEW PARTICLES BACKWARD BY DELT/2 AND THEN MOVE
C       ALL PARTICLES AHEAD BY DELT
C       CALL BORIS MOVER
```

```
      CALL BORMOV

C     IF APPROPRIATE, SAMPLE FOR TIME PLOTS
      IF (ITER .GE. ISAMPL * (KSAMPL - 1)) CALL SPLOT

      ITER = ITER + 1
100   CONTINUE

C     DIAGNOSTICS (FIELD QUANTITY AND PHASE SPACE PLOTS)
C     PLOT VR VS. R
      IF (IVRR .EQ. 1) CALL VRR
C     PLOT VTHETA VS. VR
      IF (IVTHVR .EQ. 1) CALL VTHVR
C     PLOT DENSITY VS. R
      IF (IDENS .EQ. 1) CALL DENSR
C     PLOT ATHETA VS. R
      IF (IATHS .EQ. 1) CALL ATHSR
C     PLOT BZSELF VS. R
      IF (IBZS .EQ. 1) CALL BZSR
C     PLOT ETHETA VS. R
      IF (IETHS .EQ. 1) CALL ETHSR
C     PLOT JTHETA VS. R
      IF (IJTH .EQ. 1) CALL JTHR

C     PUT NEXT SET OF PLOTS TO START ON NEW PAGE
      JPLOT = 5
      CALL IPLOT
      JPLOT = 1

C     IF NOT FINISHED, REPEAT TIME LOOP
      IF (ITER .LT. ITRMAX) GO TO 101

C     IF FINISHED, TAKE LAST TIME SAMPLE
      CALL SPLOT

C     TIME DIAGNOSTICS (PLOTS VS. TIME)

C     PLOT ATHETA VS. TIME AT IPT?
      CALL ATHT(1)
      CALL ATHT(2)
      CALL ATHT(3)
      CALL ATHT(4)
C     PLOT ENERGY INJECTED AND ENERGY CALCULATED VS. TIME
      CALL EICT
C     PLOT ENERGY ERROR (FLUCTUATION) VS. TIME
      CALL EFLT
C     PLOT MAXIMUM BETA VS. TIME
      CALL BMAXT
C     PLOT AVERAGE BETA VS. TIME
      CALL BAVGT

C     FINISH CURRENT PAGE
      JPLOT = 5
      CALL IPLOT

C     ALL DONE
      CALL EXIT

      END
```

```
        SUBROUTINE ATHSR
        INCLUDE 'MAGIC2.STR'
C.......................................................................

C       THIS PLOTS SELF ATHETA VERSUS R

        CALL IPLOT

        CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
        CALL SETLCH (0.,.07,1,0,0,1)
        WRITE (100,1300)
 1300   FORMAT ('SELF VECTOR POTENTIAL : THETA')
        CALL SETLCH (.217,-.055,1,0,0,0)
        WRITE (100,1301)
 1301   FORMAT ('RADIAL POSITION (CM)')

        TV1(1) = 0.
        TV2(1) = 0.

        DO 1302 I = 2,NG
        TV1(I) = (I - 1) * DELR
        TV2(I) = FLUX(I) / ((I - 1) * DELRS)
 1302   CONTINUE

        TS1 = 0.
        TS2 = 0.

        CALL CARTMM (NG,TS1,TS2,TV2,2)
        YMIN = 1.3*AMIN1(SNGL(TS1),0.)
        YMAX = 1.3*AMAX1(0.,SNGL(TS2))
        CALL MAPS (0.,RMAX,(B0*C/WC1)*YMIN,(B0*C/WC1)*YMAX,
     1                  XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
        CALL MAP (0.,RMAX,YMIN,YMAX,
     1                  XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
        CALL TRACE (TV1,TV2,NG,2,2)

C.......................................................................

        RETURN
        END

        SUBROUTINE ATHT(J)
        INCLUDE 'MAGIC2.STR'
C ......................................................................

C       THIS PLOTS ATHETA AS A FUNCTION OF TIME
C       FOR SEVERAL DIFFERENT POINTS

        CALL IPLOT

        CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
        CALL SETLCH (0.,.09,1,0,0,1)
        WRITE (100,200) J
 200    FORMAT (';THETA VS. TIME AT IPT',I1)
        CALL SETLCH (.217,-.055,1,0,0,0)
        WRITE (100,250)
 250    FORMAT ('TIME')

        TS1 = 0.
```

```
      TS2 = 0.

      CALL CARTMM (KMAX,TS1,TS2,ATTIME(J,1),8)
      YMIN = AMIN1(1.2 * SNGL(TS1) , SNGL(TS1) / 1.2)
      YMAX = AMAX1(1.3 * SNGL(TS2) , SNGL(TS2) / 1.3)
      IF (YMIN .NE. 0. .OR. YMAX .NE. 0.) GO TO 300
      YMIN = -1.E-4
      YMAX =  1.E-4
300   CALL MAPS (XTIME(1),XTIME(KMAX),(B0*C/WC1)*YMIN,(B0*C/WC1)*YMAX,
     1               XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL MAP (XTIME(1),XTIME(KMAX),YMIN,YMAX,
     1               XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL TRACE (XTIME,ATTIME(J,1),KMAX,2,8)

C.................................................................

      RETURN
      END


      SUBROUTINE BAVGT
      INCLUDE 'MAGIC2.STR'
C.................................................................

C     THIS PLOTS THE AVERAGE BETA

      CALL IPLOT

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.09,1,0,0,1)
      WRITE (100,100)
100   FORMAT ('AVERAGE BETA')
      CALL SETLCH (.217,-.055,1,0,0,0)
      WRITE (100,200)
200   FORMAT ('TIME')

      CALL CARTMM (KMAX,TS1,TS2,BAVG,2)
      CALL MAPS (XTIME(1),XTIME(KMAX),TS1/1.2,1.3*TS2,
     1               XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL TRACE (XTIME,BAVG,KMAX,2,2)

C.................................................................

      RETURN
      END

      SUBROUTINE BMAXT
      INCLUDE 'MAGIC2.STR'
C.................................................................

C     THIS PLOTS THE MAXIMUM VALUE OF BETA

      CALL IPLOT

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.09,1,0,0,1)
      WRITE (100,100)
100   FORMAT ('MAXIMUM BETA')
      CALL SETLCH (.217,-.055,1,0,0,0)
      WRITE (100,200)
```

```
200     FORMAT ('TIME')

        CALL CARTMM (KMAX,TS1,TS2,BMAX,2)
        TS1=TS1/1.2
        TS2=1.3*TS2
        CALL MAPS (XTIME(1),XTIME(KMAX),TS1,TS2,
     1                   XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
        CALL TRACE (XTIME,BMAX,KMAX,2,2)

C.......................................................................

        RETURN
        END


        SUBROUTINE BORMOV
        INCLUDE 'MAGIC2.STR'
C.......................................................................

C       THIS IS THE 2D BORIS MOVER IN POLAR COORDINATES

C       FIRST ROTATE AND ACCELERATE NEWLY INJECTED SUPERPARTICLES
C       BACKWARD BY DELT/2.

        DELRSI = 1. / DELRS

        IF (NLAST .EQ. NMAX(2)) GO TO 350
C       NOTE THAT ON FIRST TIMESTEP (ITER=0) , NLAST=0
C       SINCE NMAX(2) IS ALWAYS THE INDEX OF THE LAST SUPERPARTICLE,
C       EVEN IF THERE ARE NO HOT SUPERPARTICLES, ALL SUPERPARTICLES IN
C       THE SYSTEM AT THE FIRST TIMESTEP ARE MOVED THE HALF STEP.

        DO 300 I = NLAST+1,NMAX(2)
        RPGC = R(I) * DELRSI
        J = RPGC
        DR = RPGC - J
        DRC = 1. - DR
        BZP = DRC*BZ(J+1)+DR*BZ(J+2)+DELTS
        ETHP = DRC*ETHETA(J+1)+DR*ETHETA(J+2)
C       ALPHA=-B(CODE,Z)/4
        A  = .25*BZP
        A2 = A*A
        T  = 1.+A2*(.333333+A2*.133333)
        F2 = -.25*T
C       TAN(ALPHA)=
        T  = T*A

        VT2 = VTHETA(I)+F2*ETHP

        VR2 = VR(I)-VT2*T
        S   = (T+T)/(1.+T*T)
        VT2 = VT2+VR2*S
        VR(I) = VR2-VT2*T

        VTHETA(I) = VT2+F2*ETHP

300     CONTINUE

C       NOW MOVE ALL SUPERPARTICLES IN SYSTEM AHEAD BY DELT.
C       THIS TIME ACCUMULATE C'S, JTHETA, AND ENERGY.
```

```
C         THE C'S ARE THE LINEARLY WEIGHTED COEFFS OF FLUX
C         WHICH ARISE FROM THE IMPLICIT CALCULATION OF JTHETA
350       DO 390 IGROUP = 1,NGROUP
          IF (NMAX(IGROUP) .LT. NMIN(IGROUP)) GO TO 390

          DO 400 I = NMIN(IGROUP),NMAX(IGROUP)
          RPGC = R(I) * DELRSI
          J = RPGC
          DR = RPGC - J
          DRC = 1. - DR
          BZP = DRC*BZ(J+1)+DR*BZ(J+2)+DELTS
          ETHP = DRC*ETHETA(J+1)+DR*ETHETA(J+2)
C         ALPHA=-B(CODE.Z)/2
          A  = -.5*BZP
          A2 = A*A
          T  = 1.+A2*(.333333+A2*.133333)
          F2 = .5*T
C         TAN(ALPHA)=
          T  = T*A

          VT2 = VTHETA(I)+F2*ETHP - VTHETA(I) * NUS * DELTS
          VR2 = VR(I) - VR(I) * NUS * DELTS

          VR2 = VR2-VT2*T
          S   = (T+T)/(1.+T*T)
          VT2 = VT2+VR2*S
          VR2 = VR2-VT2*T

          VT3  = VT2+F2*ETHP - VT2 * NUS * DELTS
          VR2 = VR2 - VR2 * NUS * DELTS

          R2  = R(I)+VR2
          R(I) = DSQRT(R2**2+VT3**2)
          PTHETA(I) = PTHETA(I) - 2. * R(I) * VTHETA(I) * NUS

          RPGC = R(I) * DELRSI
          J = RPGC
          DR = RPGC - J
          DRC = 1. - DR

          IF (R(I)) 4071,4072,4071
4071      RI = 1. / R(I)
          RISQ = RI ** 2
          CA = R2*RI
          SA = VT3*RI

          CM(J+2) = CM(J+2) - BETA(IGROUP) * DRC * DR * RISQ
          CZ(J+1) = CZ(J+1) - BETA(IGROUP) * DR * DR * RISQ
          CZ(J+2) = CZ(J+2) - BETA(IGROUP) * DRC * DRC * RISQ
          CP(J+1) = CM(J+2)

          GO TO 407
4072      CA = 1.
          SA = 0.

407       VR(I) = VR2*CA+VT3*SA
          VTHETA(I) = -VR2*SA+VT3*CA

          RMAXS = FLOAT(NG - 1) * DELRS
          IF (R(I) .LT. RMAXS) GO TO 408
```

```
C       SLOW SUPERPARTICLES HITTING WALL BOUNCE BACK
        R(I) = 2. * RMAXS - R(I)
        VR(I) = - VR(I)
        IF (R(I) .GT. 0.) GO TO 408
C       FAST SUPERPARTICLES ARE ABSORBED, RE-EMITTED AT VWALL,
C       RANDOM ANGLE.
        R(I) = RMAXS
        EKIN = SUPN(IGROUP) * (M / 2.) * (C ** 2)
     1                   * (VTHETA(I) ** 2 + VR(I) ** 2)
        ENRTOT = ENRTOT - EKIN
        THETA = PI * (.5 - RAN(-1))
        VR(I) = - VWALL * COS(THETA)
        VTHETA(I) = VWALL * SIN(THETA)
        PTHETA(I) = R(I) * (VTHETA(I) / DELTS + R(I) / 2.)
        EKIN = SUPN(IGROUP) * (M / 2.) * (C ** 2)
     1                   * (VTHETA(I) ** 2 + VR(I) ** 2)
        ENRTOT = ENRTOT + EKIN

408     JTHETA(J+1) = JTHETA(J+1) + BETA(IGROUP) * DRC *
     1                          ( -.5 + PTHETA(I) / (R(I) ** 2))
        JTHETA(J+2) = JTHETA(J+2) + BETA(IGROUP) * DR *
     1                          ( -.5 + PTHETA(I) / (R(I) ** 2))

400     CONTINUE

390     CONTINUE

C.............................................................

        RETURN
        END


        SUBROUTINE BZSR
        INCLUDE 'MAGIC2 STR'
C.............................................................

C       THIS PLOTS SELF BZ VERSUS R

        CALL IPLOT

        CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
        CALL SETLCH (0.,.09,1,0,0,1)
        WRITE (100,1300)
1300    FORMAT ('DELTA B / B0 : Z')
        CALL SETLCH (.217,-.055,1,0,0,0)
        WRITE (100,1301)
1301    FORMAT ('RADIAL POSITION (CM)')

        CONST = RMAX / (NG - 1)

        DO 1302 I = 1,NG
        TVI(I) = (I - 1) * CONST
1302    CONTINUE

        TS1 = 0.
        TS2 = 0.
```

```
      CALL CARTMM (NG,TS1,TS2,BZ,2)
      YMIN = 1.3*AMIN1(SNGL(TS1),0.)
      YMAX = 1.3*AMAX1(0.,SNGL(TS2))
      CALL MAPS (0.,RMAX,YMIN/DELTS,YMAX/DELTS,
     1                   XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL MAP (0.,RMAX,YMIN,YMAX,
     1                   XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL TRACE (TV1,BZ,NG,2,2)

C.................................................................

      RETURN
      END



      SUBROUTINE DENSR
      INCLUDE 'MAGIC2.STR'
C.................................................................

C     THIS PLOTS DENSITY VERSUS R

      CALL IPLOT

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.1,1,0,0,1)
      WRITE (100,502)
502   FORMAT ('DENSITY OF PARTICLES')
      CALL SETLCH (.217,-.055,1,0,0,0)
      WRITE (100,503)
503   FORMAT ('RADIAL POSITION (CM)')

      CONST = RMAX / (NG - 1)

      DO 500 I = 1,NG
      TV1(I) = 0.
      TV2(I) = (I - 1) * CONST
500   CONTINUE

      DO 504 IGROUP = 1,NGROUP
      IF (NMAX(IGROUP) .LT. NMIN(IGROUP)) GO TO 504

      DO 501 I = NMIN(IGROUP),NMAX(IGROUP)
      RPGC = R(I)/DELRS
      J = INT(RPGC)
      TV1(J+1) = TV1(J+1) + SUPN(IGROUP) /
     1                        (PI * ((J + 1) ** 2 - J ** 2)
     1                                 * DELR ** 2)
501   CONTINUE

504   CONTINUE

      TV1(NG) = 0.

      CALL CARTMM (NG,YMIN,YMAX,TV1,2)
      CALL MAPS (0.,RMAX,0.,1.3*YMAX,
     1                   XOFF+.055,XOFF+.49,YOFF,YOFF+.3)

      R1 = 0.
```

```
      DO 505 I = 1,NG-1
      R2 = I * DELR
      CALL LINE(R1,TV1(I),R2,TV1(I))
      CALL LINE(R2,TV1(I),R2,TV1(I+1))
      R1 = R2
505   CONTINUE

C..........................................................................

      RETURN
      END

      SUBROUTINE EFLT
      INCLUDE 'MAGIC2.STR'
C..........................................................................

C     THIS PLOTS THE ENERGY CONSERVATION ERROR

      CALL IPLOT

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.09,1,0,0,1)
      WRITE (100,100)
100   FORMAT ('ENERGY ERROR')
      CALL SETLCH (.217,-.055,1,0,0,0)
      WRITE (100,200)
200   FORMAT ('TIME')

      DO 300 I = 1,KMAX
      TENERI(I) = TENERI(I) - TENERC(I)
300   CONTINUE

      CALL CARTMM (KMAX,TS1,TS2,TENERI,2)
      YMIN = AMIN1(1.2*SNGL(TS1),SNGL(TS1)/1.2)
      YMAX = AMAX1(1.3*SNGL(TS2),SNGL(TS2)/1.3)
      IF (YMIN .NE. 0. .OR. YMAX .NE. 0.) GO TO 302
      YMIN = -1.E-4
      YMAX =  1.E-4
302   CALL MAPS (XTIME(1),XTIME(KMAX),YMIN,YMAX,
     1                 XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL TRACE (XTIME,TENERI,KMAX,2,2)

C..........................................................................

      RETURN
      END

      SUBROUTINE EICT
      INCLUDE 'MAGIC2.STR'
C..........................................................................

C     THIS PLOT INJECTED ENERGY AND CALCULATED ENERGY
C     AS A FUNCTION OF TIME

      CALL IPLOT

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.09,1,0,0,1)
      WRITE (100,400)
400   FORMAT ('ENERGY')
```

```
      CALL SETLCH (.217,-.055,1.0,0,0)
      WRITE (100,401)
401   FORMAT ('TIME')

      CALL CARTMM (KMAX,TS1,TS2,TENERI,2)
      CALL CARTMM (KMAX,TS3,TS4,TENERC,2)
      TS5 = AMIN1(SNGL(TS1),SNGL(TS3))
      TS6 = AMAX1(SNGL(TS2),SNGL(TS4))
      YMIN = .9999 * TS5 - .1 * (TS6 - TS5)
      YMAX = 1.0001 * TS6 + .1 * (TS6 - TS5)
      IF (YMIN .NE. YMAX) GO TO 402
      YMIN = .99 * YMIN
      YMAX = 1.01 * YMAX
402   CALL MAPS (XTIME(1),XTIME(KMAX),YMIN,YMAX,
     1                XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL SETPCH (1,1,1,0,100)
      CALL TRACEC (IHC,XTIME,TENERC,KMAX,2,2)
      CALL TRACEC (IHI,XTIME,TENERI,KMAX,2,2)

C.......................................................................

      RETURN
      END

      SUBROUTINE ETHSR
      INCLUDE 'MAGIC2.STR'
C.......................................................................

C     THIS PLOTS SELF ETHETA VERSUS R

      CALL IPLOT

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.076,1,0,0,1)
      WRITE (100,1300)
1300  FORMAT ('SELF ELECTRIC FIELD : THETA')
      CALL SETLCH (.217,-.055,1.0,0,0)
      WRITE (100,1301)
1301  FORMAT ('RADIAL POSITION (CM)')

      CONST = RMAX / (NG - 1)

      DO 1302 I = 1,NG
      TV1(I) = (I - 1) * CONST
1302  CONTINUE

      TS1 = 0.
      TS2 = 0.

      CALL CARTMM (NG,TS1,TS2,ETHETA,2)
      YMIN = 1.3*AMIN1(SNGL(TS1),0.)
      YMAX = 1.3*AMAX1(0.,SNGL(TS2))
      CALL MAPS (0.,RMAX,(B0/DELTS)*YMIN,(B0/DELTS)*YMAX,
     1                XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL MAP (0.,RMAX,YMIN,YMAX,
     1                XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL TRACE (TV1,ETHETA,NG,2,2)

C.......................................................................
```

```
        RETURN
        END
        SUBROUTINE FIELDS
        INCLUDE 'MAGIC2.STR'
        DIMENSION ALPHAS(NG),BETAS(NG),GAMMAS(NG),DELTAS(NG)
        DIMENSION ES(NG),FS(NG)
        EQUIVALENCE (CM,GAMMAS),(CZ,BETAS)
        EQUIVALENCE (CP,ALPHAS,ES),(TV1,DELTAS,FS)
C.......................................................................

C       THIS IS THE 1D FIELD SOLVER FOR THE RADIAL DIRECTION

        IF (KWAVE .NE. 0. .AND. ITER .EQ. 0) GO TO 517

        JTHETA(1) = 0.
        JTHETA(NG) = 0.


C       DO TRIDIAGONAL SOLVE FOR FLUX AS FUNCTION OF R FROM THE
C       JTHETA AND C'S THAT HAVE BEEN ACCUMULATED
        DO 504 I = 2,NG-1
        RG = FLOAT (I - 1) * DELRS
        RSQRD = RG ** 2
        ALPHAS(I) = - (RG / DELRS ** 2 - 1. / (2. * DELRS)
     1                                  + RSQRD * CP(I))
        BETAS(I)   =   (- 2. * RG / DELRS ** 2 + RSQRD * CZ(I))
        GAMMAS(I) = - (RG / DELRS ** 2 + 1. / (2. * DELRS)
     1                                  + RSQRD * CM(I))
        DELTAS(I) = - RSQRD * DELTS * JTHETA(I)
504     CONTINUE

        ALPHAS(1) = 0.
        BETAS(1) = 1.
        GAMMAS(1) = 0.
        DELTAS(1) = 0.
        ALPHAS(NG) = 0.
        BETAS(NG) = 1.
        GAMMAS(NG) = 0.
        DELTAS(NG) = 0.

        ES(1) = - ALPHAS(1) / BETAS(1)
        FS(1) = DELTAS(1) / BETAS(1)

        DO 506 I = 2,NG
        DENOMI = 1. / (BETAS(I) + GAMMAS(I) * ES(I-1))
        ES(I) = - ALPHAS(I) * DENOMI
        FS(I) = (DELTAS(I) + GAMMAS(I) * FS(I-1)) * DENOMI
506     CONTINUE

        DO 507 J = 1,NG-1
        I = NG - J
        FS(I) = FS(I) - ES(I) * FS(I+1)
507     CONTINUE

C       FS NOW CONTAINS THE NEW FLUX
C       USE IT TO GET THE NEW BZ
        DO 508 I = 2,NG-1
        BZ(I) = (FS(I+1) - FS(I-1)) / (2. * (I - 1) * DELRS ** 2)
508     CONTINUE
```

```
          BZ(1) = 2. * FS(2) / (DELRS ** 2)
          BZ(NG) = - FS(NG-1) / ((NG - 1) * DELRS ** 2)

          ETHETA(1) = 0.

C         NOW USE FS AND OLD FLUX TO GET A TIME CENTERED ETHETA
          DO 509 I = 2,NG
          ETHETA(I) = - 2. * (FS(I) - FLUX(I)) / ((I - 1) * DELRS)
     1                                 - ETHETA(I)
509       CONTINUE

C         SAVE NEW FLUX
          DO 510 I = 1,NG
          FLUX(I) = FS(I)
510       CONTINUE

C         ZERO ARRAYS TO BEGIN NEW ACCUMULATIONS
517       DO 511 I = 1,NG
          JTHETA(I) = 0.
          CM(I) = 0.
          CZ(I) = 0.
          CP(I) = 0.
511       CONTINUE

          IF (KWAVE .NE. 0.) RETURN

C         IF NO WAVE HAS BEEN LAUNCHED, TRY TO START ETHETA UP
C         SMOOTHLY
          IF (ITER - 1) 512,514,516

512       DO 513 I = 1,NG
          ETHETA(I) = 0.
513       CONTINUE

          RETURN

514       DO 515 I = 1,NG
          ETHETA(I) = ETHETA(I) / 2.
515       CONTINUE

          RETURN

C.......... ...... ..................................................

516       RETURN
          END

          SUBROUTINE HEADER
          INCLUDE 'MAGIC2.STR'
          DIMENSION BUFF(15)
C...................................................................

C         THIS PLOTS THE OUTPUT HEADING PAGE

          CALL SETCH (2.,60.,1,0,0,0)
          WRITE (100,1500)
1500      FORMAT('MAGIC2 - NO ELECTRON PHYSICS')
          CALL DATE (DATE1)
          CALL TIME (TIME1)
          WRITE (5,1501) DATE1,TIME1
```

```
        WRITE (100,1501) DATE1,TIME1
1501    FORMAT(X,A10,A5)

        WRITE (100,1502) FNAME
1502    FORMAT('INPUT FROM FILE: ',2A5)

        OPEN (UNIT=20,ACCESS='SEQIN',FILE=FNAME)
        WRITE (100,1503)
1503    FORMAT('INPUT FILE FOLLOWS:')
        WRITE (100,1504)
1505    READ (20,1504,END=1506) BUFF
1504    FORMAT(15A5)
        WRITE (100,1504) BUFF
        GO TO 1505
1506    CLOSE (UNIT=20)

        CALL SETCH (70.,60.,1,0,0,0)

        WRITE (100,1545) NHOT,NCOLD,SUPN,BETA
1545    FORMAT('NHOT = ',I6,
     1          /'NCOLD = ',I6,
     1          /'SUPN(1) = ',E12.3,
     1          /'SUPN(2) = ',E12.3,
     1          /'BETA(1) = ',E12.3,
     1          /'BETA(2) = ',E12.3)

        WRITE (100,1550) B0,DELTS,RMAX,DENSI,CURR,NUS,ITRMAX,
     1                          ITRPLT
1550    FORMAT (/'B0 = ',F15.2,
     1          /'DELTS = ',F12.2,
     1          /'RMAX = ',F12.1,
     1          /'DENSI = ',E11.1,
     1          /'CURR = ',E12.1,
     1          /'NUS = ',E12.3,
     1          /'ITRMAX = ',I9,
     1          /'ITRPLT = ',I9)

        WRITE (100,1551) IVRR,IVTHR,IVTHVR,IDENS,IBZS,IATHS,IETHS,IJTH
1551    FORMAT ('IVRR = ',I11,
     1          /'IVTHR = ',I10,
     1          /'IVTHVR = ',I9,
     1          /'IDENS = ',I10,
     1          /'IBZS = ',I11,
     1          /'IATHS = ',I10,
     1          /'IETHS = ',I10,
     1          /'IJTH = ',I11)

        WRITE (100,1552) INJMOD,NINJ,RINJ,WINJ,EINJ
1552    FORMAT ('INJMOD = ',I9,
     1          /'NINJ = ',I11,
     1          /'RINJ = ',F13.2,
     1          /'WINJ = ',F13.2,
     1          /'EINJ = ',E13.2)

        WRITE (100,1553) NGYRO,GYRRAN,TEMPO
1553    FORMAT ('NGYRO = ',I9,
     1          /'GYRRAN = ',F12.3,
     1          /'TEMPO = ',E12.2)

        WRITE (100,1554) WCI,WALF,VALF,WPI,WWAVE
```

```
1554    FORMAT (/'HCI = ',E13.3,
     1          /'HALF = ',E13.3,
     1          /'VALF = ',E13.3,
     1          /'WPI = ',E13.3,
     1          /'WWAVE = ',E13.3)

        CALL FRAME

C.......................................................................

        RETURN
        END


        SUBROUTINE INITLZ
        INCLUDE 'MAGIC2.STR'
C.......................................................................

C       THIS INITIALIZES THE FIELDS

C       ZERO GRID ARRAYS
        DO 600 I = 1,NG
        CM(I) = 0.
        CZ(I) = 0.
        CP(I) = 0.
        BZ(I) = 0.
        ETHETA(I) = 0.
        FLUX(I) = 0.
        JTHETA(I) = 0.
600     CONTINUE

        ENRTOT = 0.
        R1 = 0.

C       CALCULATE ENERGY DUE TO BACKGROUND MAGNETIC FIELD
        CONST = DELRS * C * DELT

        DO 601 I = 1,NG-1
        R2 = FLOAT(I) * CONST
        ENRTOT = ENRTOT + ((B0 ** 2) / 8.) * (R2 ** 2 - R1 ** 2)
        R1 = R2
601     CONTINUE

        IF (KWAVE .EQ. 0.) RETURN

C       IF A WAVE IS TO BE LAUNCHED, SET UP ETHETA.
        DO 602 I = 1,NG
        RAD = (I - 1) * DELR
        ETHETA(I) = AWAVE * J1(KWAVE * RAD)
602     CONTINUE
C.......................................................................

        RETURN
        END


        SUBROUTINE INJECT
        INCLUDE 'MAGIC2.STR'
C.......................................................................
```

```
C     THIS DOES THE SUPERPARTICLE INJECTION

      NLAST = NMAX(2)
      NIN = 0

C     SELECT INJECTION MODE, AND CALCULATE HOW MANY SUPERPARTICLES
C     ARE TO BE INJECTED
C     INJMOD = 0 : ALL INJECTION AT T = 0.
C            = 1 , CONSTANT RATE
C            = 2 , LINEARLY INCREASING RATE
      IF (INJMOD .EQ. 0 .AND. ITER .EQ. 0) NIN = NINJ
      IF (INJMOD .EQ. 1) NIN = NINJ
      IF (INJMOD .EQ. 2) NIN = NINJ * ITER
C     IF NO SUPERPARTICLES ARE TO BE INJECTED, THEN RETURN
      IF (NIN .EQ. 0) RETURN

C     SET UP PARAMETERS TO GIVE PARABOLIC INJECTION PROFILE
      RI = RINJS - WINJS / 2.
      TS1 = RINJS / WINJS
      TS2 = 2. / NIN

C     INJECTION LOOP
      DO 700 I = NMAX(2)+1,NMAX(2)+(NGYRO*NIN),NGYRO

C     CALCULATE RADIUS FOR NEXT SUPERPARTICLES FROM PARABOLIC PROFILE
      TS3 = RI / WINJS
      TS4 = TS3 * TS3
      TS5 = TS3 * TS4
      TS4 = TS1*(3.-4.*TS1*(TS1-3.*TS3)-12.*TS4)+4.*TS5-3.*TS3-TS2
      IF (TS4 .LT. -1.) TS4 = -1.
      TS6 = RINJS+WINJS*COS((4.*PI+ACOS(SNGL(TS4)))/3.)
      TS3 = (R1+TS6)/2.
C     TS3 IS THE RADIUS FOR THE NEXT BATCH OF SUPERPARTICLES

C     NOW INJECT NGYRO OF SUPERPARTICLES AT THIS RADIUS WITH NGYRO
C     DIFFERENT GYROPHASE ANGLES AS DISTRIBUTED UNIFORMLY
C     BETWEEN -GYRRAN AND +GYRRAN
      DO 701 K = 0,NGYRO-1

C     CALCULATE THE GYROPHASE ANGLE FOR THE NEXT SUPERPARTICLE
      IF (NGYRO .GT. 1) THETA = - GYRRAN
     1                 + (2. * FLOAT(K) * GYRRAN / (NGYRO - 1))
      IF (NGYRO .EQ. 1) THETA = 0.

C     GIVE IT THE PROPER RADIUS, VR, AND VTHETA
      R(I+K) = TS3
      VR(I+K) = VINJS * SIN(THETA)
      VTHETA(I+K) = VINJS * COS(THETA)

C     GET THE LINEAR WEIGHTING FACTORS TO CALCULATE PTHETA
      RPGC = R(I+K)/DELRS
      J = INT(RPGC)
      DR = RPGC - FLOAT(J)
      DRC = 1. - DR
      PTHETA(I+K) = R(I+K) * VTHETA(I+K) / DELTS
     1                  + (DRC * FLUX(J+1) + DR * FLUX(J+2)) / DELTS
     1                           + (R(I)** 2) / 2.

C     GET THE C'S FOR THE FIELD SOLVER
```

```
          RISQ = 1. / (R(I+K) ** 2)

          CM(J+2) = CM(J+2) - BETA(2) * DRC * DR * RISQ
          CZ(J+1) = CZ(J+1) - BETA(2) * DR * DR * RISQ
          CZ(J+2) = CZ(J+2) - BETA(2) * DRC * DRC * RISQ
          CP(J+1) = CM(J+2)

C         ADD ON THE JTHETA DUE TO THIS NEW SUPERPARTICLE,
C         EVEN THOUGH THE VELOCITIES ARE OFF BY HALF TIME STEP
          JTHETA(J+1) = JTHETA(J+1) + BETA(2) * DRC *
     1                                ( -.5 + PTHETA(I+K) * RISQ)
          JTHETA(J+2) = JTHETA(J+2) + BETA(2) * DR *
     1                                ( -.5 + PTHETA(I+K) * RISQ)

C         ADD ON THE KINETIC ENERGY DUE TO THIS SUPERPARTICLE
          EKIN = SUPN(2) * (M / 2.) * (C ** 2)
     1                    * (VTHETA(I+K) ** 2 + VR(I+K) ** 2)
          ENRTOT = ENRTOT + EKIN
701       CONTINUE

          R1 = TS6
700       CONTINUE

C         MOVE UP NMAX(2) BY THE NUMBER OF SUPERPARTICLES
C         INJECTED THIS TIME
          NMAX(2) = NMAX(2) + NGYRO * NIN

C.....................................................................

          RETURN
          END


          SUBROUTINE INPUT
          INCLUDE 'MAGIC2.STR'
C.....................................................................

C         THIS INPUTS THE RUN DATA

          DIMENSION INAME(15)

          NAMELIST /INPUT/ B0,DELTS,RMAX,DENSI,CURR,NUS,ITRMAX,ITRPLT
     1                   ,IVRR,IVTHR,IVTHVR,IDENS,IBZS,IFLXS,IETHS
     1                   ,IJTH,IATHS
     1                   ,INJMOD,NINJ,RINJ,WINJ,EINJ,GYRRAN,NGYRO
     1                   ,TEMPO,TWALL,ITEK
     1                   ,KWAVE,AWAVE
     1                   ,IPT1,IPT2,IPT3,IPT4

          DATA     B0/7000./,DELTS/.2/,RMAX/10./,DENSI/0./,NUS/0./
     1             ,CURR/1.E+3/,ITRMAX/10/,ITRPLT/1/
     1             ,IVRR/1/,IVTHR/0/,IVTHVR/1/,IDENS/1/,IBZS/1/,IFLXS/1/
     1             ,IETHS/1/,IJTH/1/,IATHS/1/
     1             ,INJMOD/0/,NINJ/5/,RINJ/5./,WINJ/8./
     1             ,EINJ/40./,NGYRO/8/,GYRRAN/1.57/
     1             ,TEMPO/.20/,TWALL/10./,ITEK/0/
     1             ,KWAVE/0./,AWAVE/0./
     1             ,IPT1/10/,IPT2/20/,IPT3/30/,IPT4/40/

          DATA     INAME/15*1H /,IDOT/1H./
```

```
        WRITE (5,800)
800     FORMAT (X,'INPUT FILE: ' $)
        READ (5,801) INAME
801     FORMAT (15A1)

        IFLAG = 0

C       THIS LOOP CHECKS TO SEE IF THE DOT WAS LEFT OFF THE FILENAME
C       IF IT WAS, IT IS PUT BACK IN
        DO 803 I = 1,15
        IF (INAME(I) .EQ. IDOT) IFLAG=1
        IF (INAME(I) .NE. 1H ) GO TO 803
        IF (IFLAG .EQ. 0) INAME(I)=IDOT
        GO TO 804
803     CONTINUE

804     ENCODE (10,805,FNAME) (INAME(I),I=1,10
805     FORMAT (10A1)

        OPEN (UNIT=20,ACCESS='SEQIN',FILE=FNAME)

        READ (20,INPUT)

        CLOSE (UNIT=20)

C.................................................................

        RETURN
        END


        SUBROUTINE IPLOT
        INCLUDE 'MAGIC2.STR'
C.................................................................

C       THIS MANAGES THE PLOT OUTPUT
C       BY INCREMENTING THE JPLOT COUNTER, CALLING THIS SUBROUTINE
C       GENERATES THE DIFFERENT OFFSETS NECESSARY TO GET FOUR PLOTS
C       PER PAGE

        DATA JPLOT/1/

        GOTO (1,2,3,4,5), JPLOT

1       XOFF = 0.
        YOFF = .7
        GO TO 6
2       XOFF = 0.
        YOFF = .32
        GO TO 6
3       XOFF = .51
        YOFF = .7
        GO TO 6
4       XOFF = .51
        YOFF = .32
        GO TO 6
5       CALL SETCH(20.,8.,1,0,2,0)
        TIME = FLOAT(ITER) * DELT
        WRITE (100,7) ITER,TIME
```

```
7       FORMAT ('ITER = ',I4,5X,'TIME = ',1PE12.2)
        CALL FRAME
        JPLOT = 1
        GO TO 1
6       JPLOT = JPLOT + 1

C.......................................................................

        RETURN
        END

        DOUBLE PRECISION FUNCTION J1(RAD)
        IMPLICIT DOUBLE PRECISION (A-Z)

C.......................................................................

C       BESSEL FUNCTION FOR GENERATING WAVES

        IF (RAD .GT. 3.) GO TO 450

        RAD3 = (RAD / 3.) ** 2

        J1 = .5 - .56249985 * RAD3      + .21093573 * RAD3 ** 2
     1          - .03954289 * RAD3 ** 3 + .00443319 * RAD3 ** 4
     1          - .00031761 * RAD3 ** 5 + .00001109 * RAD3 ** 6

        J1 = RAD * J1

        RETURN

450     RAD3 = 3. / RAD

        F1 =    .79788456               + .00000156 * RAD3
     1     + .01659667 * RAD3 ** 2 + .00017105 * RAD3 ** 3
     1     - .00249511 * RAD3 ** 4 + .00113653 * RAD3 ** 5
     1     - .00020033 * RAD3 ** 6

        T1 = -2.35619449               + .12499612 * RAD3
     1     + .00005650 * RAD3 ** 2 - .00637879 * RAD3 ** 3
     1     + .00074348 * RAD3 ** 4 + .00079824 * RAD3 ** 5
     1     - .00029166 * RAD3 ** 6

        T1 = RAD + T1

        J1 = F1 * COS(T1) / SQRT(RAD)

C.......... ............................................................

        RETURN
        END

        SUBROUTINE JTHR
        INCLUDE 'MAGIC2.STR'
C.......................................................................

C       THIS PLOTS JTHETA VERSUS R

        CALL IPLOT

        CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
```

```
        CALL SETLCH (0.,.13,1,0,0,1)
        WRITE (100,502)
502     FORMAT ('THETA CURRENT')
        CALL SETLCH (.217,-.055,1,0,0,0)
        WRITE (100,503)
503     FORMAT ('RADIAL POSITION (CM)')

        CONST = - 80 / (4. * PI * WCI * DELT ** 2)

        DO 500 I = 2,NG-1
        RG = (I - 1) * DELRS
        TV1(I) = (FLUX(I+1) - 2. * FLUX(I) + FLUX(I-1))
     1                         / (RG * DELRS ** 2)
     1                 - (FLUX(I+1) - FLUX(I-1))
     1                         / (2. * RG ** 2 * DELRS)
        TV1(I) = TV1(I) * CONST
        TV2(I) = (I - 1) * DELR
500     CONTINUE

        TV1(1) = 0.
        TV1(NG) = 0.
        TV2(1) = 0.
        TV2(NG) = RMAX

        CALL CARTMM (NG,YMIN,YMAX,TV1,2)
        YMIN = 1.3*AMIN1(SNGL(YMIN),0.)
        YMAX = 1.3*AMAX1(0.,SNGL(YMAX))
        CALL MAPS (0.,RMAX,YMIN,YMAX,
     1                XOFF+.055,XOFF+.49,YOFF,YOFF+.3)

        DO 504 I = 1,NG-1
        CALL LINE(TV2(I),TV1(I),TV2(I+1),TV1(I))
        CALL LINE(TV2(I+1),TV1(I),TV2(I+1),TV1(I+1))
504     CONTINUE

C.......................................................................

        RETURN
        END

        SUBROUTINE MAXLOD
        INCLUDE 'MAGIC2.STR'
C.......................................................................

C       THIS LOADS A MAXWELLIAN BACKGROUND

C       IF NO COLD SUPERPARTICLES ARE TO BE PUT IN, THEN RETURN
        IF (NCOLD .EQ. 0) RETURN

C       THIS LOOP INITIALIZES THE RANDOM NUMBER GENERATOR
        CALL TIME(J,N)
        N = (N .AND. ¤3777700000) / ¤100000
        DO 200 J = 1,N
        B = RAN(-1)
200     CONTINUE

C       CALCULATE THE RADII FOR THE COLD SUPERPARTICLES
        RHO = 2. * FLOAT(NCOLD) / (((FLOAT(NG) - 1) ** 2) * DELR ** 2)
        I = 1
```

```
      DO 210 N = 1,NG-1

C     FIGURE OUT HOW MANY COLD SUPERPARTICLES GO IN THIS GRID CELL
      NPCELL = .5 + RHO * (FLOAT(N) - .5) * DELR ** 2

      DO 215 J = 1,NPCELL

C     GIVE EACH SUPERPARTICLE A RANDOM RADIUS WITHIN THE CELL
      R(I) = DELRS * (FLOAT(N) - RAN(-1))
      I = I + 1
215   CONTINUE

210   CONTINUE

      IF (TEMPO .EQ. 0.) GO TO 250

C     IF TEMPO <> 0, THEN RANDOMLY INTERCHANGE RADII
      DO 220 I = 1,NCOLD
      NSWP = 1 + INT((NCOLD - 1) * RAN(-1))
      SWP = R(I)
      R(I) = R(NSWP)
      R(NSWP) = SWP
220   CONTINUE

C     PUT IN VTHETA AND VR FOR EACH SUPERPARTICLE FROM MAXWELLIAN
      NBINS = 10 * NCOLD
      CONST = 4. * PI * FLOAT(NCOLD)
     1                   * (DSQRT(1. / (PI * VTHERM ** 2))) ** 3
      DELV = 4. * VTHERM / FLOAT(NBINS)
      I = 1
      VOLD = 0.
      VNEW = 0.
      VRTOT = 0.
      VTTOT = 0.
      FOLD = 0.
      FNEW = 0.

C     INTEGRATE THE MAXWELLIAN UNTIL TIME TO PUT IN
C     ANOTHER SUPERPARTICLE
      DO 230 K = 1,NBINS
      VNEW = VNEW + DELV
      FNEW = FNEW + CONST * (VNEW ** 2) *
     1            EXP(- (VNEW ** 2) / (VTHERM ** 2)) * DELV
      IF ((FNEW - FOLD) .LT. 1.) GO TO 230
      VAVG = .5 * (VOLD + VNEW)
      VI = VAVG * (1. + .10 * RAN(-1))

C     GIVE SUPERPARTICLE RANDOM PITCH ANGLE
      THETA = 2. * PI * RAN(-1)
      VR(I) = VI * COS(THETA)
      VRTOT = VRTOT + VR(I)
      VTHETA(I) = VI * SIN(THETA)
      VTTOT = VTTOT + VTHETA(I)
      EKIN = SUPN(I) * (M / 2.) * (C ** 2)
     1                  * (VTHETA(I) ** 2 + VR(I) ** 2)
      ENRTOT = ENRTOT + EKIN
      I = I + 1
      VOLD = VNEW
      FOLD = FOLD + 1.
230   CONTINUE
```

```
C         CALCULATE THE AVERAGE VELOCITIES
          VRAVG = VRTOT / (I - 1)
          VTAVG = VTTOT / (I - 1)

          DO 240 I = 1,NCOLD

C         SUBTRACT OFF THE AVERAGE VELOCITIES SO THAT THE
C         NEW AVERAGE VELOCITIES WILL BE ZERO.
          VR(I) = VR(I) - VRAVG
          VTHETA(I) = VTHETA(I) - VTAVG

C         CALCULATE LINEAR WEIGHTING FACTORS TO GET PTHETA
          RPGC = R(I)/DELRS
          J = INT(RPGC)
          DR = RPGC - FLOAT(J)
          DRC = 1. - DR
          PTHETA(I) = R(I) * VTHETA(I) / DELTS
     1                  + (DRC * FLUX(J+1) + DR * FLUX(J+2)) / DELTS
     1                            + (R(I) ** 2) / 2.

C         CALCULATE THE C'S FOR THE FIELD SOLVER
          RISQ = 1. / (R(I)) ** 2)

          CM(J+2) = CM(J+2) - BETA(I) * DRC * DR * RISQ
          CZ(J+1) = CZ(J+1) - BETA(I) * DR * DR * RISQ
          CZ(J+2) = CZ(J+2) - BETA(I) * DRC * DRC * RISQ
          CP(J+1) = CM(J+2)

C         ADD ON JTHETA FOR NEW SUPERPARTICLE
          JTHETA(J+1) = JTHETA(J+1) + BETA(I) * DRC *
     1                            ( -.5 + PTHETA(I) * RISQ)
          JTHETA(J+2) = JTHETA(J+2) + BETA(I) * DR *
     1                            ( -.5 + PTHETA(I) * RISQ)

240       CONTINUE

          RETURN

C         DO THIS LOOP IF THE SUPERPARTICLES ARE ALL COLD
250       DO 260 I = 1,NCOLD
          VR(I) = 0.
          VTHETA(I) = 0.

C         CALCULATE LINEAR WEIGHTING FACTORS TO GET PTHETA
          RPGC = R(I)/DELRS
          J = INT(RPGC)
          DR = RPGC - FLOAT(J)
          DRC = 1. - DR
          PTHETA(I) = (DRC * FLUX(J+1) + DR * FLUX(J+2)) / DELTS
     1                            + (R(I) ** 2) / 2.

C         CALCULATE C'S FOR FIELD SOLVER
          RISQ = 1. / (R(I) ** 2)

          CM(J + 2) = CM(J+2) - BETA(I)  *  DRC * DR * RISQ
          CZ(J+1) = CZ(J+1) - BETA(I) * DR * DR * RISQ
          CZ(J+2) = CZ(J+2) - BETA(I) * DRC * DRC * RISQ
          CP(J+1) = CM(J+2)
```

```
C       ADD ON JTHETA FOR NEW SUPERPARTICLE
        JTHETA(J+1) = JTHETA(J+1) + BETA(I) * DRC *
     1                            ( -.5 + PTHETA(I) * RISQ)
        JTHETA(J+2) = JTHETA(J+2) + BETA(I) * DR *
     1                            ( -.5 + PTHETA(I) * RISQ)

260     CONTINUE

        IF (KWAVE .EQ. 0.) RETURN

C       IF A WAVE IS TO BE LAUNCHED, THEN SET UP VR AND ACCUMULATE
C       EKIN FOR ALL THE COLD SUPERPARTICLES
        DO 270 I = 1,NCOLD
        RAD = R(I) * C * DELT
        VR(I) = AMP * J1(KWAVE * RAD)
        EKIN = SUPN(I) * (M / 2.) * (C ** 2)
     1                            * (VR(I) ** 2)
        ENRTOT = ENRTOT + EKIN
270     CONTINUE

C...............................................................
        RETURN
        END

        SUBROUTINE SETCON
        INCLUDE 'MAGIC2 STR'

C...............................................................

C       THIS SUBROUTINE SETS THE VALUES OF CONSTANTS

C       SET UP CONSTANTS
        PI = 3.1415
        C = 3E+10
        E = 4.803E-10
        M = 3.343E-24
        WCI = E*B0/(M*C)
        DELT = DELTS / WCI
        DELR = RMAX / (NG - 1)
        DELRS = DELR / (C * DELT)
        NUS = NUS / 2.
        RINJS = RINJ/(C*DELT)
        WINJS = WINJ/(C*DELT)
        VINJS = - DSQRT(6.4E-9*EINJ/M)/C
        VTHERM = DSQRT(3.2E-9*TEMP0/M)/C
        VWALL = DSQRT(3.2E-12*TWALL/M)/C
        AWAVE = AWAVE * DELTS / B0
        IF (DENSI .EQ. 0.) GO TO 505
        RHO = M * DENSI
        VALF = B0 / DSQRT(4. * PI * RHO)
        WPI = DSQRT(4. * PI * DENSI * (E ** 2) / M)
        WALF = KWAVE * VALF
        S = (DSIN(KWAVE * DELR / 2.) / (KWAVE * DELR / 2.)) ** 2
        DENOM = 1. + (WCI * DELT / 2.) ** 2 + (KWAVE * C / WPI) ** 2 / S
        NUMER = (WALF * DELT / 2) ** 2 / S
        WWAVE = (2. / DELT) * DATAN(DSQRT(NUMER / DENOM))

        DENOM = (WCI * DELT / 2.) ** 2 -
     1          (DSIN(WWAVE * DELT / 2.) / DCOS(WWAVE * DELT / 2.)) ** 2
        NUMER = (WCI * DELT / 2.) ** 2 / DCOS(WWAVE * DELT / 2.)
```

```
          AMP = AWAVE * (S / DELTS) * (NUMER / DENOM)

505       NLAST = 0

          IF (CURR .EQ. 0.) GO TO 514

C         CONVERT CURR TO CGS FROM MKS (AMPS TO ESU / SEC)
          CURR = CURR * (E / 1.602E-19)

C         SELECT DESIRED INJECTION MODE
          GO TO (510,520,530) , INJMOD + 1

C         CALCULATE THE NUMBER OF SUPERPARTICLES TO BE INJECTED
C         AND THE CHARGE PER SUPERPARTICLE
510       NHOT = NINJ * NGYRO
          ESUP = CURR * DELT / (NINJ * NGYRO)
          GO TO 550

520       NHOT = ITRMAX * NINJ * NGYRO
          ESUP = CURR * DELT / (NINJ * NGYRO)
          GO TO 550

530       NHOT = (ITRMAX * (ITRMAX + 1) / 2.) * NINJ * NGYRO
          ESUP = CURR * DELT / (ITRMAX * NINJ * NGYRO)

C         CALCULATE THE NUMBER OF PARTICLES PER SUPERPARTICLE
550       SUPN(2) = ESUP / E
          QPP = ESUP / (2. * PI * DELR)
C         CALCULATE THE BETA FOR THE FIELD SOLVER
          BETA(2) = 4. * PI * QPP * DELTS / B0

          IF (NHOT .LE. NP) GO TO 560
          WRITE (5,1000) NHOT
1000      FORMAT(' NHOT = ',I5,' IS TOO LARGE.')
          CALL EXIT

C         SET UP COLD SUPERPARTICLES
560       IF (DENSI .NE. 0.) GO TO 570
          NCOLD = 0
          NMIN(1) = 0
          NMAX(1) = -1
          NMIN(2) = 1
          NMAX(2) = 0
          GO TO 513

570       NCOLD = 100 * INT((NP - NHOT) / 100.)
          IF (NCOLD .NE. 0) GO TO 571
          WRITE (5,572)
572       FORMAT(' NO PARTICLES LEFT FOR COLD PLASMA.')
          CALL EXIT
571       SUPN(1) = (DENSI * PI * RMAX ** 2) / NCOLD
          QPP = SUPN(1) * E / (2. * PI * DELR)
          BETA(1) = (4. * PI * QPP * DELTS) / B0
          NMIN(1) = 1
          NMAX(1) = NCOLD
          NMIN(2) = NCOLD + 1
          NMAX(2) = NCOLD
          GO TO 513

514       NCOLD = 100 * INT(NP / 100.)
```

```
          SUPN(1) = (DENSI * PI * RMAX ** 2) / NCOLD
          QPP = SUPN(1) * E / (2. * PI * DELR)
          BETA(1) = (4. * PI * QPP * DELTS) / B0
          NMIN(1) = 1
          NMAX(1) = NCOLD
          NMIN(2) = NCOLD + 1
          NMAX(2) = NCOLD

513       WRITE(5,512) NHOT,NCOLD,SUPN
512       FORMAT(' NHOT = ',I6/' NCOLD = ',I6/
     1              ' QCOLD = ',E12.3/' QHOT =  ',E12.3)
          ENRTOT = 0.
          KSAMPL = 1
          ISAMPL = 1
          KMAX = NT
          IF (ITRMAX .LT. (NT - 1)) KMAX = ITRMAX + 1
          IF (ITRMAX .GT. (NT - 1)) ISAMPL = 1 + ITRMAX / (NT - 1)
          IF (ITRMAX .GT. (NT - 1)) KMAX = 1 + ITRMAX / ISAMPL

C...............................................................

          RETURN
          END


          SUBROUTINE SPLOT
          INCLUDE 'MAGIC2.STR'
C...............................................................

C         THIS DOES THE TIME SAMPLING

          DO 100 I = 1,NG
          TV1(I) = 0.
          TV2(I) = 0.
100       CONTINUE

C         ACCUMULATE TOTAL KINETIC ENERGY FOR EACH GRID CELL
          DO 200 IGROUP = 1,NGROUP
          IF (NMAX(IGROUP)  .LT. NMIN(IGROUP)) GO TO 200

          DO 201 I = NMIN(IGROUP),NMAX(IGROUP)
          J = 1. + R(I) / DELRS
          TV1(J) = TV1(J) + (M / 2.) * (C ** 2) * SUPN(IGROUP)
     1                            * (VR(I) ** 2 + VTHETA(I) ** 2)
201       CONTINUE

200       CONTINUE

          R1 = 0.
          ENER = 0.

C         CALCULATE THE BETA OF EACH GRID CELL AND THE TOTAL ENERGY
          DO 300 I = 1,NG-1
          R2 = FLOAT(I) * DELRS * C * DELT
          TV2(I) = TV1(I) / (PI * (R2 ** 2 - R1 ** 2))
          TV2(I) = TV2(I) / ((B0 ** 2) / (8. * PI))
          BINT = B0 + (B0 / DELTS) * .5 * (BZ(I) + BZ(I+1))
          ENER = ENER + TV1(I) + ((BINT ** 2) / 8.)
     1                 * (R2 ** 2 - R1 ** 2)
```

```
        R1 = R2
300     CONTINUE

C       GET THE MAXIMUM BETA VALUE ON THE GRID
        CALL CARTMM (NG,TS1,TS2,TV2,2)
        BMAX(KSAMPL) = TS2

        TS1 = 0.

C       CALCULATE THE AVERAGE BETA ON THE GRID
        DO 400 I = 1,NG
        TS1 = TS1 + TV2(I)
400     CONTINUE

        BAVG(KSAMPL) = TS1 / NG

C       SAVE THE ENERGY SAMPLES
        TENERC(KSAMPL) = ENER
        TENERI(KSAMPL) = ENRTOT

C       SAMPLE ATHETA AT IPT?
        ATTIME(1,KSAMPL) = FLUX(IPT1) / ((IPT1 - 1) * DELRS)
        ATTIME(2,KSAMPL) = FLUX(IPT2) / ((IPT2 - 1) * DELRS)
        ATTIME(3,KSAMPL) = FLUX(IPT3) / ((IPT3 - 1) * DELRS)
        ATTIME(4,KSAMPL) = FLUX(IPT4) / ((IPT4 - 1) * DELRS)

C       SAVE THE TIME AT WHICH THIS SAMPLE WAS TAKEN
        XTIME(KSAMPL) = FLOAT(ITER) * DELT
        KSAMPL = KSAMPL + 1

C............................................................

        RETURN
        END

        SUBROUTINE VRR
        INCLUDE 'MAGIC2.STR'
C............................................................

C       THIS PLOTS VR VERSUS R

        COMMON /CRTVLS/ CPL(36)

        CALL IPLOT

        TS1 = 0.
        TS2 = 0.

        CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
        CALL SETLCH (0.,.084,1,0,0,1)
        WRITE (100,1100)
1100    FORMAT ('RADIAL VELOCITY (CM/SEC)')
        CALL SETLCH (.217,-.055,1,0,0,0)
        WRITE (100,1101)
1101    FORMAT ('RADIAL POSITION (CM)')

        TS1 = 1.E+25
        TS2 = -1.E+25

        DO 1105 IGROUP = 1,NGROUP
```

```
      IF (NMAX(IGROUP) .LT. NMIN(IGROUP)) GO TO 1105

      DO 1106 I = NMIN(IGROUP),NMAX(IGROUP)
      IF (VR(I) .GT. TS2) TS2 = VR(I)
      IF (VR(I) .LT. TS1) TS1 = VR(I)
1106  CONTINUE

1105  CONTINUE

      YMIN = 1.3*AMIN1(SNGL(TS1),0.)
      YMAX = 1.3*AMAX1(0.,SNGL(TS2))
      CALL MAPS (0.,RMAX,C*YMIN,C*YMAX,
     1                 XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL MAP (0.,RMAX/(C*DELT),YMIN,YMAX,
     1                 XOFF+.055,XOFF+.49,YOFF,YOFF+.3)

      DO 1110 IGROUP = 1,NGROUP
      IF (NMAX(IGROUP) .LT. NMIN(IGROUP)) GO TO 1110

      DO 1111 I = NMIN(IGROUP),NMAX(IGROUP)
      CALL POINT (R(I),VR(I))
1111  CONTINUE

1110  CONTINUE

C.....................................................................

      RETURN
      END


      SUBROUTINE VTHVR
      INCLUDE 'MAGIC2.STR'
C.....................................................................

C     THIS PLOTS VTHETA VERSUS VR

      CALL IPLOT

      TS1 = 0.
      TS2 = 0.
      TS3 = 0.
      TS4 = 0.

      CALL MAP (0.,.5,0.,.3,XOFF,XOFF+.5,YOFF,YOFF+.3)
      CALL SETLCH (0.,.075,1,0,0,1)
      WRITE (100,1200)
1200  FORMAT ('THETA VELOCITY (CM/SEC)')
      CALL SETLCH (.205,-.055,1,0,0,0)
      WRITE (100,1201)
1201  FORMAT ('RADIAL VELOCITY (CM/SEC)')

      TS1 = 1.E+25
      TS2 = -1.E+25
      TS3 = 1.E+25
      TS4 = -1.E+25

      DO 1210 IGROUP = 1,NGROUP
      IF (NMAX(IGROUP) .LT. NMIN(IGROUP)) GO TO 1210
```

```
      DO 1211 I = NMIN(IGROUP),NMAX(IGROUP)
      IF (VR(I) .GT. TS2) TS2 = VR(I)
      IF (VR(I) .LT. TS1) TS1 = VR(I)
      IF (VTHETA(I) .GT. TS4) TS4 = VTHETA(I)
      IF (VTHETA(I) .LT. TS3) TS3 = VTHETA(I)
1211  CONTINUE

1210  CONTINUE

      XMAX = 1.3*AMAX1(ABS(SNGL(TS1)),ABS(SNGL(TS2)))
      YMAX = 1.3*AMAX1(ABS(SNGL(TS3)),ABS(SNGL(TS4)))
      CALL MAPS (-C*XMAX,C*XMAX,-C*YMAX,C*YMAX,
     1            XOFF+.055,XOFF+.49,YOFF,YOFF+.3)
      CALL MAP(-XMAX,XMAX,-YMAX,YMAX,
     1            XOFF+.055,XOFF+.49,YOFF,YOFF+.3)

      DO 1215 IGROUP = 1,NGROUP
      IF (NMAX(IGROUP) .LT. NMIN(IGROUP)) GO TO 1215

      DO 1216 I = NMIN(IGROUP),NMAX(IGROUP)
      CALL POINT (VR(I),VTHETA(I))
1216  CONTINUE

1215  CONTINUE

C.................................................................

      RETURN
      END


      SUBROUTINE MAGDOC
C     GLOSSARY OF VARIABLE NAMES
C.................................................................


C     VARIABLES IN COMMON BLOCKS IN FILE MAGIC2.STR

C     PARAMETERS
C     NP      MAXIMUM NUMBER OF PARTICLES ALLOWED
C     NG      NUMBER OF GRID POINTS TO BE USED
C     NT      MAXIMUM NUMBER OF TIME SAMPLES ALLOWED

C     NG      NUMBER OF GROUPS OF PARTICLES
C                  ( PRESENTLY 2, FOR HOT AND COLD )

C     /INDATA/
C     B0      VACUUM MAGNETIC FIELD IN Z DIRECTION IN GAUSS
C     DELT    TIME STEP IN SECONDS
C     RMAX    RADIUS OF SYSTEM IN CENTIMETERS
C     DENSI   INITIAL DENSITY OF COLD PLASMA IN PARTICLES
C                  PER CUBIC CENTIMETER
C     CURR    CURRENT TO BE INJECTED IN AMPERES
C     NUS     DRAG COEFFICIENT
C     ITRMAX  NUMBER OF TIME STEPS TO BE DONE
C     ITRPLT  NUMBER OF TIME STEPS BETWEEN PLOTTING
C     NINJ    NUMBER OF PARTICLES TO BE INJECTED PER TIME STEP,
C                  PER INJECTION POINT, PER GYRO PHASE ANGLE
C     RINJ    RADIUS OF CENTER OF INJECTION IN CENTIMETERS
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C        WINJ    WIDTH OF PARABOLIC INJECTION PROFILE IN CENTIMETERS
C        INJMOD  INJECTION MODE - 0. PULSE AT T = 0
C                                 1. CONSTANT CURRENT INJECTION
C                                 2. LINEAR RAMP CURRENT INJECTION
C        EINJ    ENERGY PER INJECTED PARTICLE IN KEV
C        NGYRO   NUMBER OF GYRO PHASE ANGLES PER INJECTION POINT
C        GYRRAN  RANGE OF GYRO PHASE ANGLES, FROM -GYRRAN TO +GYRRAN,
C                        GIVEN IN RADIANS
C        TEMPO   ENERGY PER COLD PARTICLE IN EV
C        TWALL   ENERGY GIVEN TO FAST PARTICLES WHICH ARE ABSORBED
C                        AND THEN RE-EMITTED BY THE WALL
C        ITEK    SWITCH WHICH TURNS ON PLOTTING OF OUTPUT TO
C                        TEKTRONICS TERMINAL

C        /RDATA/
C        ITER    NUMBER OF TIME STEPS COMPLETED
C        NIN     NUMBER OF PARTICLES PER INJECTION POINT, PER
C                        GYRO PHASE ANGLE FOR THIS STEP
C        NLAST   TOTAL NUMBER OF PARTICLES UP TO THIS INJECTION
C        VINJS   VELOCITY OF INJECTED PARTICLE IN CODE UNITS
C        RINJS   RADIUS OF CENTER OF INJECTION PROFILE IN CODE UNITS
C        WINJS   WIDTH OF INJECTION PROFILE IN CODE UNITS
C        ENRTOT  ACCUMULATED ( OVER TIME ) TOTAL ENERGY IN ERGS
C        NHOT    TOTAL NUMBER OF HOT PARTICLES TO BE INJECTED
C        NCOLD   TOTAL NUMBER OF COLD PARTICLES TO BE PRESENT AT STARTUP
C        VTHERM  THERMAL VELOCITY OF COLD PARTICLES IN CODE UNITS
C        VWALL   VELOCITY OF FAST PARTICLE RE-EMITTED FROM WALL

C        /PRTCLS/
C        R       RADII OF PARTICLES IN CODE UNITS
C        VR      RADIAL VELOCITIES OF PARTICLES IN CODE UNITS
C        PTHETA  CANONICAL ANGULAR MOMENTUM OF PARTICLES IN CODE UNITS
C        VTHETA  THETA COMPONENT OF VELOCITIES OF PARTICLES IN CODE UNITS

C        /GRID/
C        FLUX    THETA COMPONENT OF SELF MAGNETIC FLUX AS FUNCTION OF
C                        RADIUS IN CODE UNITS
C        JTHETA  THETA COMPONENT OF CURRENT AS FUNCTION OF RADIUS
C                        IN CODE UNITS
C        BZ      Z COMPONENT OF SELF MAGNETIC FIELD IN CODE UNITS
C        ETHETA  THETA COMPONENT OF SELF ELECTRIC FIELD IN CODE UNITS
C        CM
C        CZ      GEOMETRICAL FACTORS USED IN ACCUMULATION OF JTHETA
C        CP
C        TV1
C        TV2     TEMPORARY VECTORS USED IN GRID CALCULATIONS


C        /CONST/
C        PI      3.1415
C        C       SPEED OF LIGHT - 3E+10
C        DELTS   TIME STEP IN CODE UNITS
C        DELR    GRID POINT SPACING IN CENTIMETERS
C        DELRS   GRID POINT SPACING IN CODE UNITS
C        E       ELECTRONIC CHARGE - 4.803E-10
C        M       PROTON MASS - 3.343E-24
C        WCI     ION CYCLOTRON FREQUENCY

C        /SWITCH/
C        IVRR    TURNS ON AND OFF VR VS. R PLOT
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C         IVTHR      "      "   "    "  VTHETA VS. R PLOT
C         IVTHVR     "      "   "    "  VTHETA VS. VR PLOT
C         IDENS      "      "   "    "  DENSITY VS. R PLOT
C         IBZS       "      "   "    "  SELF B FIELD - Z COMPONENT VS. R PLOT
C         IATHS      "      "   "    "  SELF VECTOR POTENTIAL - THETA COMPONENT
C                                                VS. R PLOT
C         IETHS      "      "   "    "  SELF ELECTRIC FIELD - THETA COMPONENT
C                                                VS. R PLOT
C         IJTH       "      "   "    "  CURRENT - THETA COMPONENT VS. R PLOT

C         /PLOTS/
C         JPLOT    KEEPS TRACK OF WHERE TO PUT THE PLOTS ON A PAGE
C         XOFF     HORIZONTAL OFFSET TO BE USED FOR CURRENT PLOT
C         YOFF     VERTICAL OFFSET TO BE USED WITH CURRENT PLOT
C         FNAME    NAME OF INPUT DATA FILE
C         KSAMPL   NUMBER OF TIME SAMPLES THAT HAVE BEEN TAKEN SO FAR
C         ISAMPL   NUMBER OF TIME STEPS PER TIME SAMPLE
C         KMAX     MAXIMUM NUMBER OF TIME SAMPLES THAT WILL BE TAKEN

C         /HISTRY/
C         XTIME    TIME VALUES FOR X - AXIS OF TIME PLOTS
C         BAVG     AVERAGE BETA VERSUS TIME VALUES
C         BMAX     MAXIMUM BETA VERSUS TIME VALUES
C         TENERC   CALCULATED TOTAL ENERGY VERSUS TIME VALUES
C         TENERI   TOTAL INJECTED ENERGY VERSUS TIME VALUES
C         ATTIME   SELF VECTOR POTENTIAL VERSUS TIME VALUES FOR 4
C                          DIFFERENT RADII
C         IPT1
C         IPT2
C         IPT3     GRID POINT NUMBERS FOR ATTIME SAMPLING
C         IPT4

C         /GROUP/
C         NMIN     KEEPS VALUE OF PARTICLE ARRAY INDEX FOR FIRST PARTICLE
C                          OF EACH GROUP
C         NMAX     KEEPS VALUE OF PARTICLE ARRAY INDEX FOR LAST PARTICLE
C                          OF EACH GROUP
C         BETA     KEEPS CURRENT WEIGHTING FACTOR FOR FIELD SOLVER FOR
C                          EACH PARTICLE
C         SUPN     NUMBER OF PARTICLES PER SUPERPARTICLE

C         /WAVES/
C         WALF     ALFVEN FREQUENCY
C         KWAVE    MAGNETOSONIC WAVE NUMBER
C         AWAVE    MAGNETOSONIC WAVE AMPLITUDE FOR SELF ELECTRIC
C                          FIELD IN VOLTS

C...........................................................................

          END
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