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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

PLASMA DISRUPTION FORCES:
A PROGRAM FOR THE
HP 9845 B AND 9872 B PLOTTER

by

Martyn H. Foss

Fusion Power Program

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ABSTRACT

A computer program is described for the calculation of currents, forces, torques, and voltages in the conducting first wall and limiter of a tokamak reactor experiencing a plasma quench. Instructions are given for running the program on a HP 9845 B desk-top computer with a 9872 B plotter. The first wall and limiter have been modelled by 44 coaxial loops. The inductance matrix among the loops is calculated, and the currents in them are calculated step-by-step over time, driven by the flux from the decaying plasma current and subject to the field from the plasma, from the poloidal field coils, and from all current loops. An insulating break in the limiter or first wall can be modelled by imposing a back voltage which causes all the currents in the limiter or first wall to sum to zero. This potential is related to the voltage between segments of a segmented limiter or first wall.

INTRODUCTION

A disruption is represented by a plasma current which decreases linearly with time but does not change position. The limiter and first wall are represented by a set of wires. The poloidal field coils carry a fixed current which must be supplied by a current regulated source. The toroidal field is assumed to be inversely proportional to radius.

As an option, the sum of the currents in the limiter can be made zero by introducing a bucking voltage. This approximates a limiter with a single cut.

The limiter design is based on drawings from H. C. Mantz, McDonnell Douglas Astronautics Co., Bldg. 107, St. Louis, MO 63166, sent to Rich Mattas, Argonne National Laboratory. Positions on these drawings were digitized using the cursor on the 9872 B plotter. The resulting numbers were used to decompose the drawing into lines and arcs. The routines used have been removed to recover the space. (The "next time" this program should be segmented. Blocks could be linked as required. This of course could be invisible to the user except for the time required to link the next program segment.)

The poloidal coil positions and currents are from a printout supplied by D. J. Strickler, Oak Ridge National Laboratory Fusion Energy Design Center, 04/05/82. The listing also gives the plasma parameters. The radial position of the plasma was shifted slightly to make the flux tangent to the limiter with the plasma represented by a single current loop.

The first wall is a simple set of arcs and lines which enclose the flux line tangent to the top of the limiter.

The limiter and first wall conductors are divided up into sections. This division was intended to give the desired results with few sections. No parametric study was made to determine the effect of the division on the results.

Each section is represented by a wire which is at the center of gravity of the section. The self inductance of each wire is determined from the maximum dimension of the section. This is rather poor.

The change in current in each wire in a small time interval is calculated from the voltage equations. An average IR drop is used for each wire and each time. The equations are stable for small time intervals. The method of averaging IR was chosen to make the equations stable for larger time steps.

To represent a discontinuous limiter, a common voltage was added to each limiter wire to make the sum of the limiter currents vanish.

STARTUP

The tape containing the program has a file in the last record on the first side named "T..#16". If this tape is loaded with the autoset key depressed then the program and SFK's will be loaded, then, the name of the program will appear, followed by instructions. To change the name press EXECUTE, make the change, press STORE, then press CONT. If no change is desired press CONT. Page 1 of the SFK definitions will appear. This is somewhat like Fig. 1. When a KEY is pressed a row of asterisks is displayed under the key definition as is shown under PAGE. In this case pressing KEY 15 causes PAGE 2 to be presented, see Fig. 2, and pressing 15 again causes PAGE 3 to be presented, see Fig. 3.

SFK'S

The program has a section which assists the user by defining the Special Function Keys, or SFK's, on the monitor. There are 3 pages of definitions. Page 3 for example has SFK's for operating the cursor, labeling drawings, etc. After an SFK is pressed, further information, as required, is requested on the monitor.

- 3 -

PAGE 1

0	1	2	3	4	5	6	7
TIMES?	PR.TIME	CURRENTS	PR.AMP	Pol. B×I	Tor. B×I		PLASMA
8	9	10	11	12	13	14	15
DIVIDE	PR.WIRE	PR. DET.	PR. MAT.	PR.Pol.C	EDITLINE		PAGE

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PAGE 2

0	1	2	3	4	5	6	7
DRAW LMTR	DRAW WIRE	DRAW AMPS	FLUX-LINE		DR.FORCE	TITLE	GR CLEAR
8	9	10	11	12	13	14	15
WIRES ?		B,A,FLUX	L	M & V	EDITLINE		PAGE
			.				*****

PAGE 3

0	1	2	3	4	5	6	7
SET	PEN	LINE TYPE	ENHANCE	LABEL	VIEW GR	DUMP GR	GR CLEAR
8	9	10	11	12	13	14	15
CURSOR	PRINT-CUR	PLOT-CUR	SAV PROG	LOCATE	EDITLINE	LIST	PAGE *****

The letter K is reserved for starting variable names and labels in this section. SET is also used for some labels. The variable K was inadvertently used for the elliptic integral in the remainder of the program but this seems to cause no trouble.

Any operation may be terminated by pressing STOP then CONT (if the monitor contains graphics some other key must also be depressed to return to TEXT). DO NOT PRESS RUN as all results will be lost.

EXAMPLE

If KEY 1 on PAGE 1 is pressed then a table of the times used in the calculations is printed. This is illustrated in Fig. 4. The SFK definitions are presented on the monitor. When KEY 1 is pressed asterisks are printed under PR.TIME and the table is printed. The printer may be the screen or the thermal printer, (see SEf on PAGE 3). The title block is printed followed by a list of times at which the currents will be calculated. These times are established in the subroutine "TIMES:" and are arbitrary. They are contained in the vector "TIME," TIME (0) = 0.

Following each time is a character "P", "*", or " ". These are taken from TO\$ and control printing, plotting, and some calculation. The characters shown are not the default values but have been given new values by using KEY 0, TIMES? After the printing is complete PAGE 1 SFK definitions are again presented on the monitor.

CALCULATION OF FORCES

The operations used to calculate forces are on PAGE 1. These are DIVIDE, CURRENTS, Pol. BxI, and Tor.BxI.

DIVIDE divides the conductors into wires. The conductors may be any combination of limiter, first wall, and limiter cooling pipes. Having the cooling pipes separate has two useful functions: the system can be checked out

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PAGE 1

0	1	2	3	4	5	6	7
TIMES?	PR.TIME *****	CURRENTS	PR.AMP	Pol. BxI	Tor. BxI		PLASMA
8	9	10	11	12	13	14	15
DIVIDE	PR.WIRE	PR. DET.	PR. MAT.	PR.Pol.C	EDITLINE		PAGE

PLASMA DISRUPTION FORCES (Program=limitv on T..#16 M.FOSS ANL 9/20/82)
DISCONTINUOUS WATER PIPES
PLASMA: I=6.473(MA), R=5.26(m), Z=.092165(m), DECAY=20(ms);
F.W.T. CONST.=100(ms), TOR. B Rho=27.8(Tm) LIMITER RES.=17.32(nOhm m)

TIMES USED IN CALCULATIONS (ms.)

.25	P	10	*	20	P	29.5	
.5	P	10.5		20.25	P	30	P
1	P	11		20.5	P	30.5	
1.5	P	11.5		21	P	31	*
2	P	12		21.5	P	31.5	
2.5	P	12.5		22	P	32	P
3	P	13		22.5		32.5	
3.5	P	13.5		23	*	33	*
4	P	14	*	23.5		33.5	
4.5	P	14.5	*	24	P	34	P
5	P	15	*	24.5		34.5	
5.5	*	15.5	*	25	*	35	*
6	*	16	*	25.5		35.5	
6.5	*	16.5	*	26	P	36	P
7	*	17	*	26.5		36.5	
7.5	*	17.5	*	27	*	37	
8	*	18	P	27.5		37.5	P
8.5	*	18.5	P	28	P		
9	*	19	P	28.5			
9.5	*	19.5	P	29	*		

PAGE 1

0	1	2	3	4	5	6	7
TIMES?	PR.TIME	CURRENTS	PR.AMP	Pol. BxI	Tor. BxI		PLASMA
8	9	10	11	12	13	14	15
DIVIDE	PR.WIRE	PR. DET.	PR. MAT.	PR.Pol.C	EDITLINE		PAGE

rapidly with only two wires, and the effect of leaving the pipes out (e.g. stainless pipes in a copper limiter) can be observed. Leaving the first wall out gives the effect of a first wall with a very short time constant.

After the division is complete the computer BEEPS. The program then calculates the mutual inductance matrix, the field at one wire due to current in another, the field at each wire due to the plasma, and the field at each wire due to the poloidal field coils. Finally the mutual inductance matrix is inverted.

CURRENTS calculates the current in each wire at each time given in the vector "TIME."

Pol. BxI calculates, prints, and tabulates for plotting effects of the poloidal fields.

Tor. BxI calculates the vertical force at the end of discontinuous limiter due to the toroidal field.

INSTRUCTIONS PAGE 1

KEY 0: TIMES?

This key allows TO\$ to be changed. The routines are written so that the characters in "P", "*", and " " produce predictable results. These characters control times for printing and plotting. "P" causes detailed printing, "*" gives only summary results, and " " causes the corresponding time to be skipped. Non blank causes summary results to be stored for plotting. Results are plotted for times corresponding to non blank characters. When TO\$ is satisfactory press STOP, CONT.

KEY 1: PR.TIME

Prints a table of the time in the vector "TIME" and the characters from TO\$.

KEY 2: CURRENTS

Calculates the current in each wire at each value of "TIME." Currents can be calculated for a continuous or discontinuous LIMITER. DIVIDE (KEY 8) must be executed first.

KEY 3: PR.AMP

Values of the currents are printed for selected times (see KEY 0, PAGE 1) and selected wires (see KEY 8, PAGE 2).

KEY 4: POL BxI

After (KEY 2, CURRENTS), this key will calculate and print forces due to the poloidal fields at selected times, and also for selected wires if PRINT WIRE CURRENTS is selected (KEY 0, P1 & KEY 8, P2).

KEY 5: TOR. BxI

After (KEY 2, CURRENTS), this key will calculate the vertical force at the radial cut in the limiter at selected times (KEY 0).

KEY 7:. PLASMA

After (KEY 8, DIVIDE) several factors may be changed, e.g. plasma position, limiter resistivity, and first wall time constant. The options are:.

INPUT NEW VALUES:. permits modification of old values

USE CURSOR VALUES:. uses cursor (0) values for plasma position

USE DEFAULT VALUES:. restores values to default

In any case the values can be modified.

KEY 8:. DIVIDE

This routine establishes the geometry. The options are to include any or all of the

1. LIMITER
2. FIRST WALL
3. LIMITER COOLING PIPES

KEY 9:. PR.WIRE

Prints a table of the wires in the limiter and first wall.

KEY 10:. PR.DET.

Prints the determinate of the mutual inductance matrix.

KEY 11:. PR.MAT

Prints arrays:.

1. Mutual inductance matrix
2. Its inverse
3. $B(x)$ in one wire due to current in another
4. $B(y)$ in one wire due to current in another

Only 3 characters are printed for each value; it is therefore important to scale the values. A suggested scale factor (or the previous factor) is presented for modification. Finally, the arrays may be so big that they are presented half at a time.

KEY 12:. PR.Pol.C

Prints a table of the poloidal field coils and the plasma.

INSTRUCTIONS PAGE 2

KEY 0:. DRAW LMTR

Draws the limiter and first wall. The first option is the area to show. The second option is the part to be drawn.

1. Limiter surface
2. Limiter conductor
3. First wall surface

Figure 5 shows the limiter surface, first wall, poloidal coils and plasma, the area of the circles is proportional to the current. Figure 6 shows a portion of the limiter surface and the tangent flux line due to the plasma and poloidal coils. Figures 7 & 8 show the limiter surface and some limiter wires over plots of the sum of the currents in these wires.

KEY 1:. DRAW WIRE

Draws the wires selected with KEY 8 if they are in the area shown. The wires may be labeled with their numbers. The size of the numbers, etc. can be changed by ENHANCE (KEY 3, PAGE 3). Examples are in Figures 5, 7, and 8. The radius of first wall and limiter wires is that used to calculate the self inductance.

KEY 2:. DRAW AMPS

The first option is to determine the time and current scales. The second option is to plot each current separately, or to plot the sum of all the currents selected. The wires are selected with WIRES? (KEY 8). Figures 7 & 8 show the sums of currents in selected wires.

KEY 3:. DRAW FLUX

The first option is the area to show. The next is to put in the starting point, $R_1 Z$), the step size, and the line type. If the line type is negative the line will start in one direction, and if positive in the other. The

Fig. 5 Limiter Surface, First Wall, Poloidal Field Coils and Plasma

PLASMA:

$R = 5.26 \text{ m.}$

$Z = .092165 \text{ m.}$

Fig. 7 Limiter, Some of the Wires Representing the Limiter, and the Sum of the Currents in These Wires Vs. Time

Fig. 8 Similar to Fig. 7 But Different Wires

routine draws chords so the line is rough if the step size is too large. If the cursor is used for the starting point, it may also be used with B,A,FLUX (KEY 10) to get the value of the flux. Figure 6 shows a flux line. Pressing CONT stops the flux line. If the negative (line type) direction is drawn first then reusing the numbers will draw the positive direction.

KEY 5:. DR.FORCE

The first option is the scale. Next is the force to be plotted vs. time.

1. Radial per meter of circumference
2. Vertical per meter due to poloidal field
3. Torque per meter
4. Vertical force at limiter cut due to toroidal field

See Fig. 9 for an example.

KEY 6:. TITLE

Title block in the lower left hand corner.

KEY 7:. GR CLEAR

Clears graphics.

KEY 8:. WIRES?

This permits selection of wires for printing and plotting.

The first option is the number of wires.

1. All
2. Previous set

When this selection is made the designated number is displayed under the control of the editor. This can be changed to the desired number. Then press CONT. A list of wire numbers is displayed under control of the editor. If there are too many numbers a second line is displayed. Edit to desired values.

Fig. 9 Forces Vs. Time

KEY 10:. B,A,FLUX

First input position of loop R and Z

Select the source of the field

1. Plasma
2. Poloidal coils
3. Both

The position of the wire B_1 , B_2 , A, and Flux are printed on the current printer. (The position of the plasma is also printed.)

KEY 11:. L

Input loop radius and wire radius. Prints self inductance.

KEY 12:. M & V

Input position of loop R and Z. Prints mutual inductance between plasma and loop and voltage in loop due to decaying plasma.

INSTRUCTIONS PAGE 3

KEY 0:. SET

The options presented are:.

1.	Printer	2.	Screen
3.	Plotter	4.	Graphics
5.	Overlap	6.	Serial

The conditions can be odd or even. (Default even.) Overlap makes some functions faster but weakens error control.

KEY 1:. PEN

Select pen on 9872 B plotter. Also a negative number erases graphics. I often keep the target in slot 4 for use with the cursor.

KEY 2:. LINE TYPE

Default values are presented under control of the editor. After each plot-off order the line type is returned to the default values.

KEY 3:. ENHANCE

The options are

1. Character size

The default values of SIZE, WIDTH/HEIGHT, & SLANT are presented under control of the editor.

2. Label origin

A table showing the options is presented.

3. Label direction

Such expressions as $\pi/2$ are allowed.

KEY 4:. LABEL

Use for writing on figures.

The first option is

1. Label at cursor position
2. Label at next line

If 1 is selected then the option

WHICH CURSOR NUMBER

is presented. (See KEY 8, CURSOR)

After the position is selected a prompt, *, is displayed. The desired label is typed in after the *.

KEY 8: CURSOR

The options are:

1. Cursor
2. Give cursor position
3. Pop cursor stack

If 1 is selected the cursor is presented on the screen or placed under control of the plotter. After it is positioned press CONT for graphics or ENTER on the mechanical plotter. The cursor coordinates are entered into position 0 of the cursor stack and previous positions are pushed down.

If 2 is entered the desired position is requested. The cursor moves to this position. The operation proceeds as in 1.

If 3 is entered the values in position 0 are removed and the other values are moved up, position 1 to position 0, etc.

KEY 9: PRINT-CUR

Prints the desired number of CURSOR positions from the stack.

KEY 10: PLOT-CUR

This plots a + at the cursor position.

The first option is Which Cursor Number to plot. The second option is the length and line type.

KEY 11:. SAV PROG

RE-SAVE's and RE-STORE's the program and rewinds the tape.

KEY 12:. LOCATE

The options are:.

1. New location
2. Restore default
3. Manual

This marks out the portion of the screen or plotter platten to be used for a drawing. One might put two drawings on the same sheet of paper or use a vertical display instead of a horizontal.

MISCELLANEOUS

It would be nice to have an axis drawing routine.

This program uses a large fraction of the memory. Because the computer stores temporary numbers, the memory can be used up if the housekeeping is not good. This results in very strange printout and/or errors. This can be cured by pressing STOP, CONT.

The program lends itself to being segmented, with large sections linked as required.