CLM - P 460

CLM - P 460

UKAEA RESEARCH GROUP

Preprint

L

THE INTERACTIVE DESIGN OF MAGNETIC FIELDS FOR CONTROLLED THERMONUCLEAR RESEARCH

T J MARTIN

CULHAM LABORATORY
Abingdon Oxfordshire

1976

CLM-P 460

THE INTERACTIVE DESIGN OF MAGNETIC FIELDS FOR CONTROLLED THERMONUCLEAR RESEARCH

T J Martin
Culham Laboratory, Abingdon, Oxon OX14 3DB, UK
(Euratom/UKAEA Fusion Association)

Abstract

An interactive computer program is described which provides a powerful facility for physicists and engineers to design magnetic field configurations for the efficient containment of hot plasma for fusion research. Extensive use is made of on-line graphics to present results.

(Paper presented at COMPUMAG Conference, Oxford,
31 March - 2 April 1976)

June 1976

1. INTRODUCTION

The controlled release of energy from nuclear fusion depends on the ability to heat and contain an ionised gas (plasma) of deuterium and tritium for sufficient lengths of time, which may be of the order of seconds. Since the particles are charged, a natural choice for the containment system is one based on magnetic fields. Many such experimental systems have been proposed and built to contribute to the understanding of the problems involved in plasma physics.

In the first instance, the magnetic field topology must satisfy certain constraints and much optimisation must take place before an experiment is eventually built. The cost of these devices demands that extensive calculations and evaluations are made at the design stage thus providing the motivation for the development of the computer program MAGINT described in this paper.

It will be appreciated that many physicists and engineers engaged in the design of magnetic containment systems are not interested in programming for its own sake and are understandably reticent about using computer programs which require complex procedures for setting up data and producing results. A good user image is essential therefore, if manpower (and computing power) is to be utilised in the most efficient and productive manner. To this end, the interactive, magnetic field design program MAGINT offers comprehensive facilities for the optimisation and evaluation of possible conductor configurations, the results where possible being presented in readily assimilated graphical form.

The vacuum magnetic field is regarded as a superposition of one or more elementary, pre-defined analytic fields (e.g. uniform fields) together with any combination of components produced by the following sets of conductor types:

i. Circular filamentary loops
ii. Rectangular filamentary loops

iii. Linear filaments

iv. Finite, rectangular cross-section solenoids with constant current density distribution

and v. General curvilinear filaments represented by sets of spatial coordinates joined by straight segments.

A whole range of operations are provided to manipulate and calculate these fields within a versatile and easy-to-use framework.

The program is written almost wholly in standard FORTRAN and runs on the Culham ICL 4-70 computer operating under the MULTIJOB regime which provides a fully interactive working environment. Data input to the program is primarily through a conventional teletype and on-line graphical output (generated by the GHOST[1] package) is directed to a COSSOR CSD1000 refresh display. The total store size required by MAGINT is 120 Kbytes and typical runs consume about a minute of processor time.

Section 2 of this paper introduces the philosophy adopted during the initial design and development stage of the program while section 3 describes the facilities in detail. The numerical methods used for field calculations and for following fieldlines are briefly mentioned and in section 5 some examples in the uses of MAGINT are given.

2. PROGRAM DESIGN AND STRUCTURED DEVELOPMENT

For this program we prefer the interactive mode of operation, rather than batch mode, for not only is the user's train of thought uninterrupted, but he will possess specialised knowledge and/or experience which completes the 'iteration loop' in a manual optimisation[2]. Additional benefits are that errors in data input and incorrect usage of the program are picked up immediately, resulting in faster turnround and minimisation of computer time. Disadvantages with the interactive mode are normally restrictions on the size of the program and the complexity of the problem to be analysed, the first being obviated by suitable segmentation of the program. Again by careful programming and selection of optimal numerical methods, it is our experience that useful calculations can be performed on-line for this type of problem. This question is raised again at the end of this section.

During the initial development stage of the program, the following precepts were kept firmly in mind :

i. The program must be easy to use by both inexperienced and expert computer users.

ii. The data input should be kept to an absolute minimum.

iii. The facilities should reflect current requirements and be easily extensible to accommodate growing needs.

iv. Good protection must be provided against misuse of the program.

v. Printed output should be minimal unless specifically requested - immediate graphical output being a more efficient vehicle for the transmission of information.

The strategy adopted for data input consistent with the first requirement is that of a command structure. Every program action is invoked by a four-letter mnemonic keyword and an associated parameter. Any additional information required by the program is requested by issuing a prompt at the terminal. After the action has been carried out, the program returns to the command mode in readiness for the next task. As an example, the following command generates sixteen circular loops equispaced around a given torus (hereinafter, all user-typed information will be underlined):-

```
CMND? TOR 16
RMAJ,RMIN,CURRENT?
? 1.0 0.15 1.27E6
16 TYPE 1 TOROIDAL COILS ADDED
CMND?
```

For the user who is familiar with the program, a facility is provided to switch off the prompts so that faster interaction is made possible. At present about sixty commands are available and are described in more detail in section 3. This form of data input has two main advantages; firstly it is easy to learn and use, and secondly it serves to document particular runs of the program.

The minimisation of information typed by the user is achieved in several ways. All program parameters such as contouring matrix size, accuracy criteria etc. are given sensible default values, commands being provided to change them if necessary. In the same vein, to avoid identifying the type of conductor each time some geometric manipulation is performed, the program assumes a "Currently Active Conductor" type with provision for selecting the alternatives. To avoid repeated input of the same configuration each time the program is executed, sequences are included for storing the geometric details in a magnetic disc file. Finally, specialised commands have been written to take into account any particular configuration symmetry.

The third precept implies a modular program structure so that new facilities can be simply 'plugged in' - an additional advantage being that selected pieces of code may be easily incorporated into other programs.

The final two points are largely self-explanatory; a comprehensive set of diagnostic and error messages being provided to guide the unwary user.

Fig. 1 shows a schematic diagram illustrating the program in its operating environment, the arrows indicating all possible directions of information flow between MAGINT and its hardware peripherals and file storage.

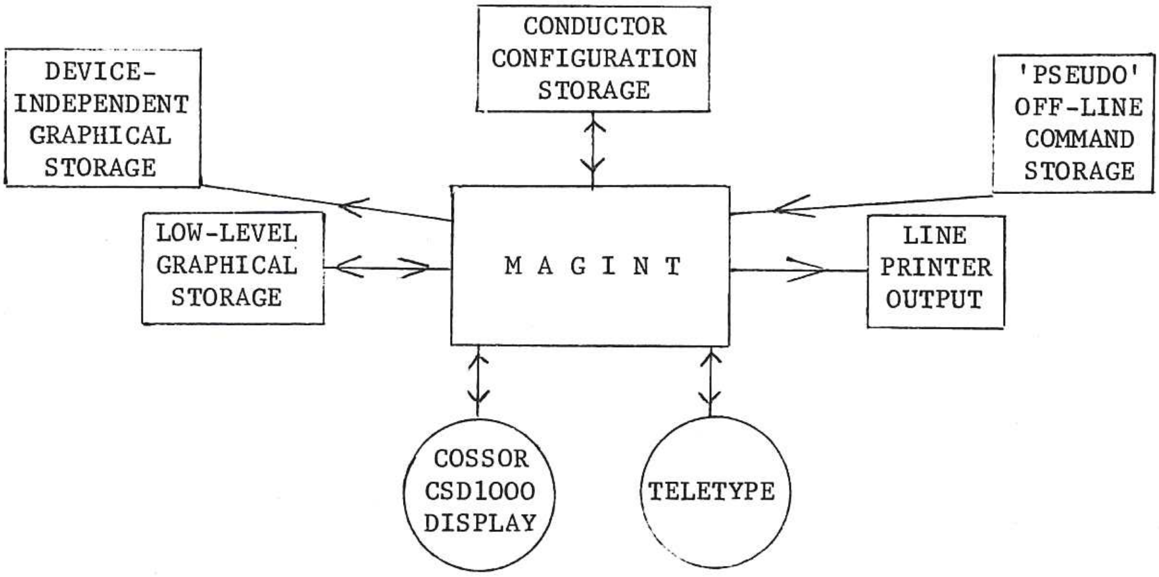

Fig. 1 : Information routes between MAGINT and peripherals

There are of course some aspects of containment system design which require complicated and prolonged calculations such as magnetic surface generation, charged particle and guiding centre trajectory plots. However, MAGINT can be used to set up and verify the configuration before embarking on long (and expensive) batch program runs. A subset of the MAGINT commands that handle conductor manipulation have been incorporated into a separate input package shared by all the Culham magnetic field programs, thereby creating a completely compatible and uniform user image - a very desirable feature.

3. PROGRAM FACILITIES

All but one of the commands can be classified into five logical subsets, each of which are described in detail below. The exception is the 'USER' command. Provision has been made for executing program actions tailored to suit individual user's requirements. Generally these operations are only of interest to particular people and therefore do not warrant a place in the overall command structure - nevertheless they play an important rôle in ensuring that the designer can perform precisely the operation he has in mind. This facility is introduced by the simple expediency of supplying a FORTRAN subroutine with a pre-defined framework.

3.1 Conductor Manipulation Commands

All of these commands act on the pre-selected conductor type and form a powerful basis with which to speedily assemble the desired configuration. Conductors can be introduced into the system by several means. The 'ADD' command requires a complete geometric specification - for example, if a single solenoid is required centred at the origin with its axis at 45° to the x and y axes, the following would be used:-

```
CMND? ADD 1
XS,YS,ZS,AL,AM,AN,RI,RO,W,CUR?
? 0.0 0.0 0.0 1.0 1.0 0.0 0.5 0.7 0.1 2.75E5
CMND?
```

Right hand screw conventions are used throughout in defining the direction of positive current. Taking symmetries into account, coaxial and toroidal coils can be conveniently distributed by the 'COAX' and 'TOR' commands. For stellarator experiments, 'THLX' is available for generating the toroidal helical windings. It is also possible to interact with the refresh display to draw arbitrarily shaped planar conductors using a tracker cross and ball.

Having established the basic conductor set, commands are provided to perform mirror reflections in any of the three principal planes and to spatially translate and rotate all or specified conductors together with the option of retaining the originals.

A group of commands to alter specific geometric properties of the conductors is also available, thereby saving a user the task of retyping the complete specification. Centres of coils and their orientation together with currents and individual points on curvilinear conductors may be quickly changed.

Finally, the ability to delete all or selected conductors is introduced through the 'DEL' command, the conductors being uniquely identified by a number assigned at generation time.

The use of these commands is demonstrated in section 5 and it can be seen that a particular construction may be performed in many different ways, the user choosing the one which is most convenient.

3.2 Parameter Setting Commands

On entry to the program, certain common variables used throughout the various sections are given sensibly selected values in order to avoid repeated specification. For example, circular filamentary loops are assumed to be the currently active conductor type, others being invoked by use of the commands 'RECT', 'LINE', 'SLND' or 'CURV'. The user can also set up his own limits for graphs (the default being automatic limits); he can specify the relative accuracy at which the solenoid routines operate or select the type of three-dimensional projection for viewing the conductor configuration. Suppression of data prompts (for experienced users) and altering the matrix size containing the magnetic field components are effected through the 'MSG', 'MU' and 'MV' commands.

Commonly used, predefined analytic magnetic fields are selected by 'ANAL' e.g. an I/R toroidal field being established by the sequence

```
CMND? ANAL 4
TOROIDAL CURRENT?
? 2.96E6
CMND?
```

giving the field

$$B\varphi = \frac{2.96 \times 10^{6}\ \mu_o}{2\pi\ R} .$$

3.3 Graphics Commands

Picture information can be handled at two levels; in low-level hardware form using the special instructions related to the COSSOR display or at high, device independent level enabling selected pictures to be processed onto any locally available plotter. 'PSTR' controls whether picture information is retained in a file on disc or only shown once and subsequently lost. In this way picture files can be built up that only contain frames of interest. Commands are available for reshowing, combining and overwriting stored pictures and converting all or selected frames into the device-independent format.

Before any field calculation takes place, it is reassuring for the user to 'VIEW' the conductor configuration in some three-dimensional projection to establish its correctness. (see figs. 2, 3, 4, 5, 6, 7 and 8)

After the magnetic field has been evaluated over some plane, selected quantities can either be contoured (see fig. 10) or three-dimensional, isometric developments of the surfaces can be plotted by the command 'PLTM' (see fig. 11). The matrices of field components are not destroyed, enabling the maximum amount of information to be derived from the relatively costly field evaluations. In addition, the 'BDRN' command plots scaled arrows representing the projected direction and magnitude of the field at each of the matrix grid points giving an overall picture of the field without resorting to expensive fieldline calculations.

3.4 Field Evaluation Commands

This important class of commands uses the Culham magnetic field subroutine library to perform the various operations. 'FLDP' and 'FLDL' respectively calculate the cartesian components of the field and its strength at specified points and along an arbitrary line in space, the latter producing a graph of the four quantities together with an optional table printout. 'FLDC' allows the field to be found around a given plotting circle, the results being presented graphically in either a global or natural local coordinate system (see fig. 9). Again, detailed printout may be obtained if required. The user can also specify an arbitrary, rectangular plane over which the field components are evaluated by the 'FLDM' command, graphical interpretation of the results being performed by 'PLTM' as described in 3.3.

Detailed information about the fieldline structure is obtained from 'FLIN'. The ordinary differential equations of the fieldline

$$\frac{d\underset{\sim}{r}}{ds} = \frac{\underset{\sim}{B}}{|B|}$$

are integrated from a given starting point in both directions until certain stopping criteria operate, the points so obtained being projected onto a given plane and displayed. These pictures can be superimposed on $|\underset{\sim}{B}|$ plots to give a comprehensive idea of the field characteristics (see fig. 10).

Fieldlines for the axisymmetric experiments such as the superconducting Levitron are cheaply generated by the 'RAFI' facility where contours of the quantity $R.A\varphi$ (where $A\varphi$ is the azimuthal component of the vector potential) can be plotted.

3.5 Housekeeping Commands

All or part of the conductor configuration geometry can be directed to the teletype or display by using 'LIST' while the contents of the field component matrices and associated quantities can be sent to an output file which is processed on a line-printer at job termination.

Conductors can be stored and retrieved from a disc file using the 'FILE' and 'READ' options. This facility not only reduces the data input when analysing the same configuration over several runs of the program but also offers additional security against possible system/program failures.

The normal input channel to MAGINT is a teletype, but it is possible, through the 'OBEY' command, to redirect this channel to read commands from a disc file. If any errors are encountered, the program immediately returns to interactive mode for corrective action. In its simplest application, the user might require the same sequence of commands for several different runs of the program.

Finally, provisions are made for adding titles to graphs, obtaining summaries of the assembled configuration and parameter values and for correctly terminating the program.

4. NUMERICAL METHODS

Closed, algebraic forms derived from the Biot-Savart law for the field due to linear and circular filamentary conductors (the latter involving elliptic integrals of the first and second kind) are well known and are not reproduced here. The rectangular loops and general curvilinear conductors both use the linear segment approximation. Fields due to finite, rectangular cross-section solenoids are calculated from a method by Snow[3]. Essentially, an infinite series representation of the field is generated for a solid, semi-infinite cylinder, four of which are superimposed to form the solenoid, the current directions being arranged in such a manner as to cancel except in the region of interest.

The method used for integrating the fieldline equations is an eighth order hybrid multistep/Runge-Kutta process described by Butcher[4]. To advance the integration from one point to the next, derivatives and function values are used from the previous three steps together with intermediate values calculated within the new step. Large steps can be taken with this method whilst maintaining a high degree of accuracy - in fact the step can prove too coarse for some plotting purposes. This is overcome by fitting a seventh order Hermite polynomial to the last four function values and associated derivatives enabling accurate interpolation within the current integration interval.

5. EXAMPLES OF USE

To illustrate the use of MAGINT, we reproduce below the commands which could be used to construct and view the superconducting Levitron configuration shown in fig. 2.

PROGRAM RESPONSES	COMMENTARY
CMND? COAX 3	Input 3 circular loops coaxial with the z-axis
AXIS 1,2 OR 3?	
? 3	
HT,RAD,CUR?	
? 0.0 0.3 0.5E5	Superconducting ring
? 0.23 0.158 -0.4E5	Inner vertical field coil

PROGRAM RESPONSES (continued)	COMMENTARY (continued)
? 0.237 0.6 -0.125E5	Outer vertical field coil
3 TYPE 1 COAXIAL COILS ADDED	Confirmatory message
CMND? TRAN -2	Generates remaining B_v coils in upper plane by the save and translate method
COND NO,DX,DY,DZ?	
? 2 0.0 0.0 0.048	Create 2nd inner B_v coil
COND NO,DX,DY,DZ?	
? 3 0.0 0.0 -0.044	Create 2nd outer B_v coil
CMND? RFLT 3	Reflect the four coils in the x-y plane (N.B. Coils in the reflection plane are not duplicated)
4 TYPE 1 CONDUCTORS REFLECTED	
CMND? RECT 1	Select rectangular, filamentary loops
CMND? TOR 12	Generate 12 toroidal B_φ coils
RMAJ,A,B,C?	
? 0.5325 1.2 0.935 0.83333E5	
12 TYPE 2 TOROIDAL COILS ADDED	Confirmatory message
CMND? PROJ 2	Select conical projection
CMND? VIEW 6	Look at complete configuration (fig.2)
XC,YC,ZC,XE,YE,ZE,RI?	
? 0.0 0.0 0.0 90.0 100.0 100.0 1.5	Specify centre of interest, position of eye and the radius of the sphere of interest
CMND?	

A further example demonstrating the power of MAGINT is in the design of a poloidal field coil assembly for the proposed Joint European Torus experiment (JET). We sought to quantify the magnitude of the perturbations in the field caused by the physical connections to the windings and to find the optimum positions such that the perturbations were minimized. Each connection was represented by a five point general conductor and the final distribution is shown in fig. 8 and the corresponding field perturbations around a plotting circle in fig. 9. This calculation would have been prohibitively tedious to perform without the sophisticated conductor manipulations provided by the program.

6. CONCLUSIONS

The computer program described in this paper was developed in collaboration with those people most closely associated with the design of magnetic containment systems and forms the foundation on which future computational aids will be built.

It was pointed out in the introduction that the program is extensible and new facilities are being added all the time as the need arises. Currently, sections to calculate forces on conductors are being implemented and in the future it is hoped to include the effects of magnetic materials.

7. ACKNOWLEDGEMENTS

The author would like to thank his colleagues at Culham Laboratory, particularly C.M. Wilson and C.J.H. Watson, for their helpful comments and criticisms which have greatly contributed to the shaping of the program as it now exists.

8. REFERENCES

[1] Prior, W.A.J., "The GHOST graphical output system user manual" Culham Report CLM-PDN 8/71, Issue 2, 1973.

[2] Martin, T.J. Sykes, A. 'Applications of interactive computing in a scientific environment', ONLINE72, Brunel University, Uxbridge, England, 4 - 7 Sept. 1972.

[3] Snow, Chester 'Magnetic fields of cylindrical and annular coils', U.S. Dept. of Commerce, N.B.S. App. Maths. Series 38, Dec. 1953.

[4] Butcher, J.C. 'A multistep generalisation of Runge-Kutta methods with 4 or 5 stages', J.A.C.M. Vol. 14, no. 1, Jan. 1967, pp. 34 - 99.

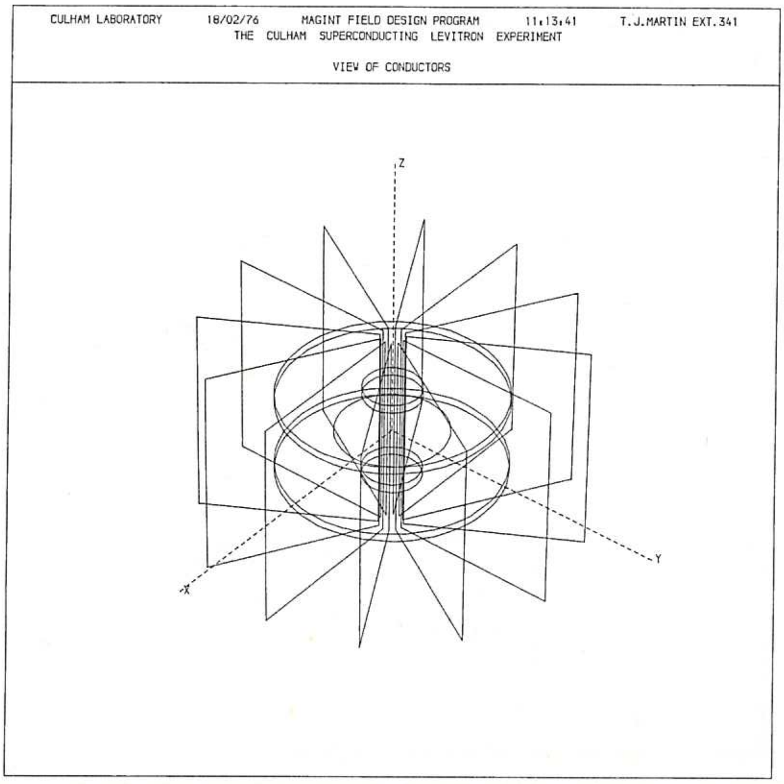

Fig.2 The Culham Superconducting Levitron assembly.

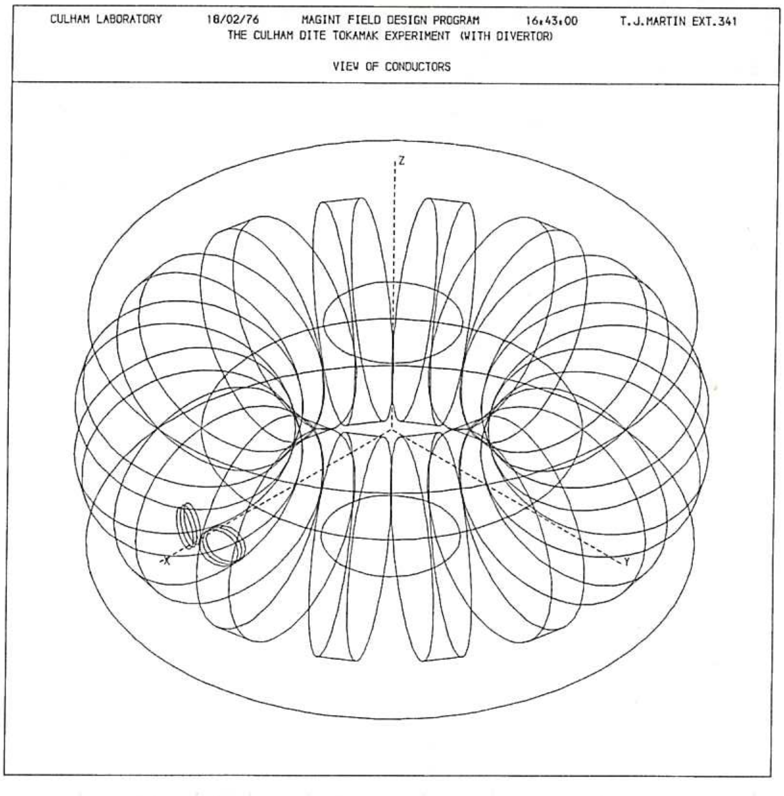

Fig.3 The Culham Dite tokamak experiment with divertor.

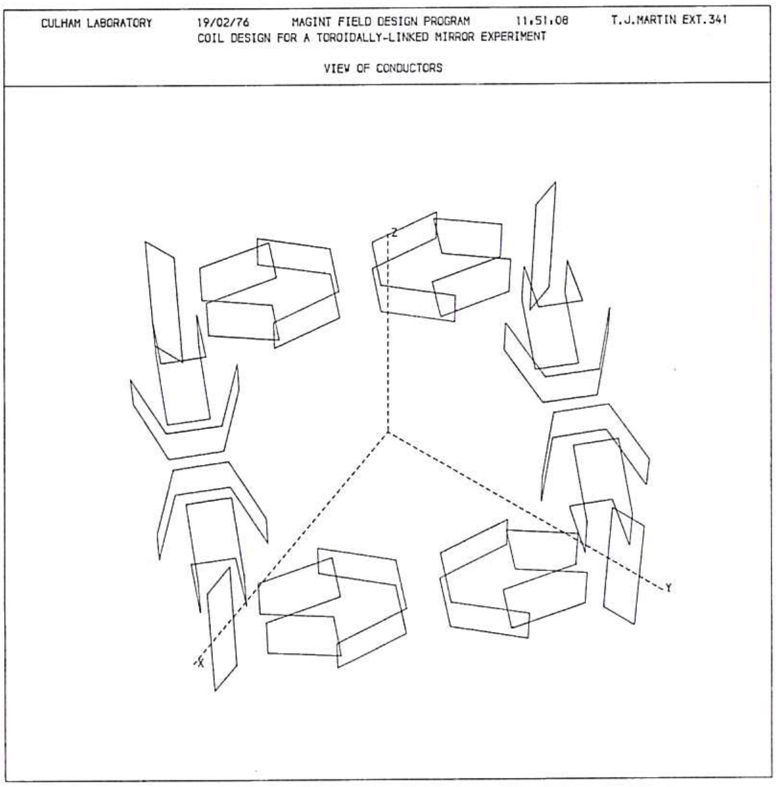

Fig.4 **A proposed, toroidally-linked mirror experiment using Yin-Yang coils.**

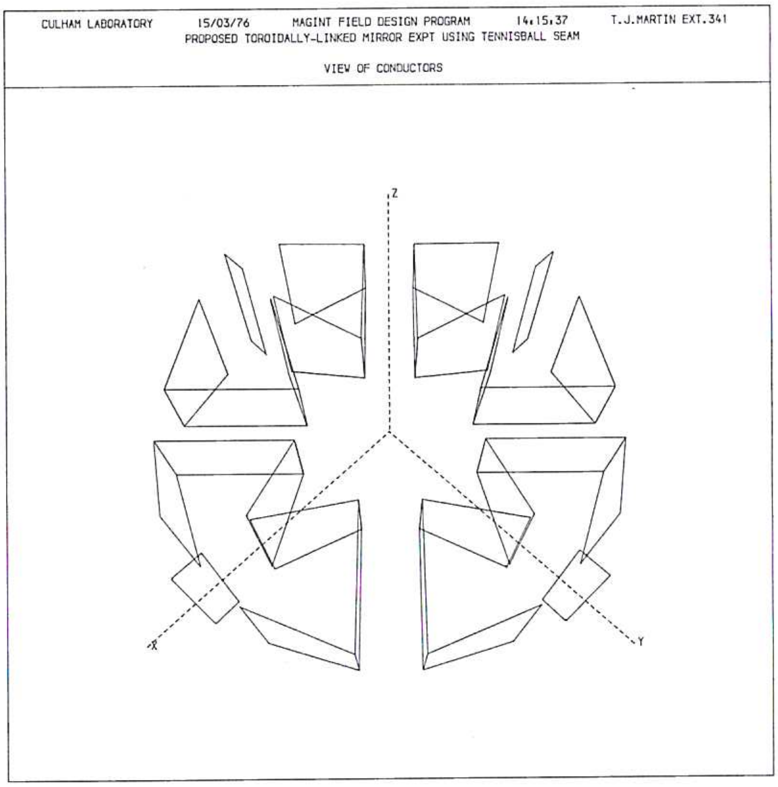

Fig.5 **A proposed, toroidally-linked mirror experiment using tennis ball seam conductors.**

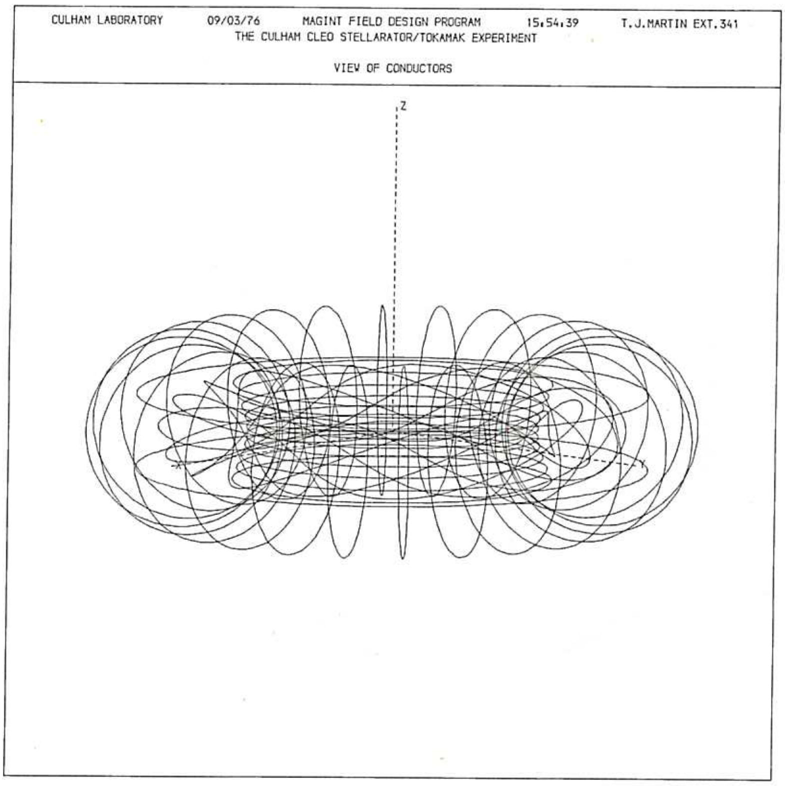

Fig.6 The Culham Cleo Stellarator/Tokamak experiment (general view).

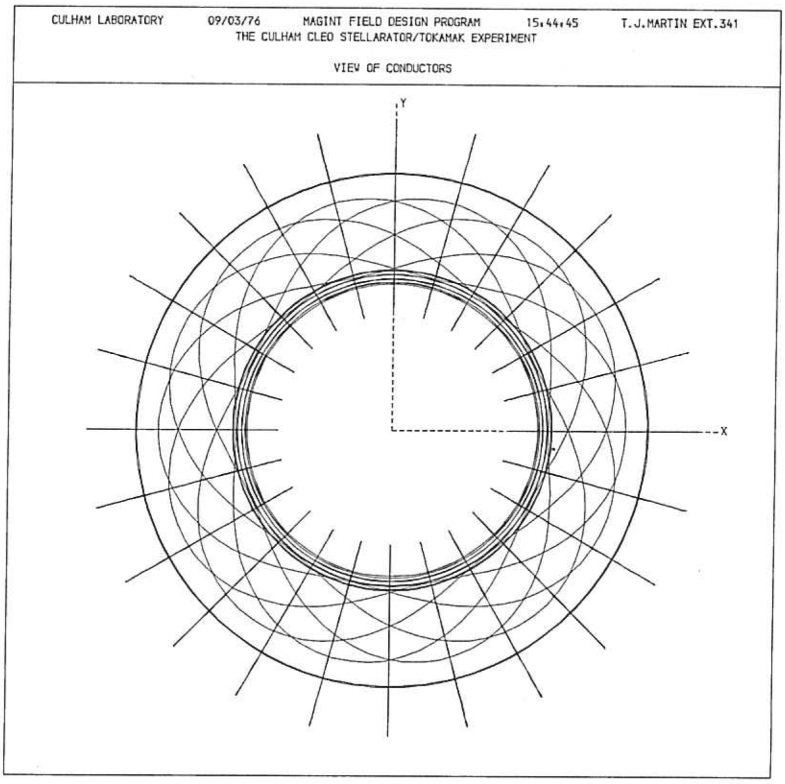

Fig.7 The Culham Cleo Stellarator/Tokamak experiment (plan view).

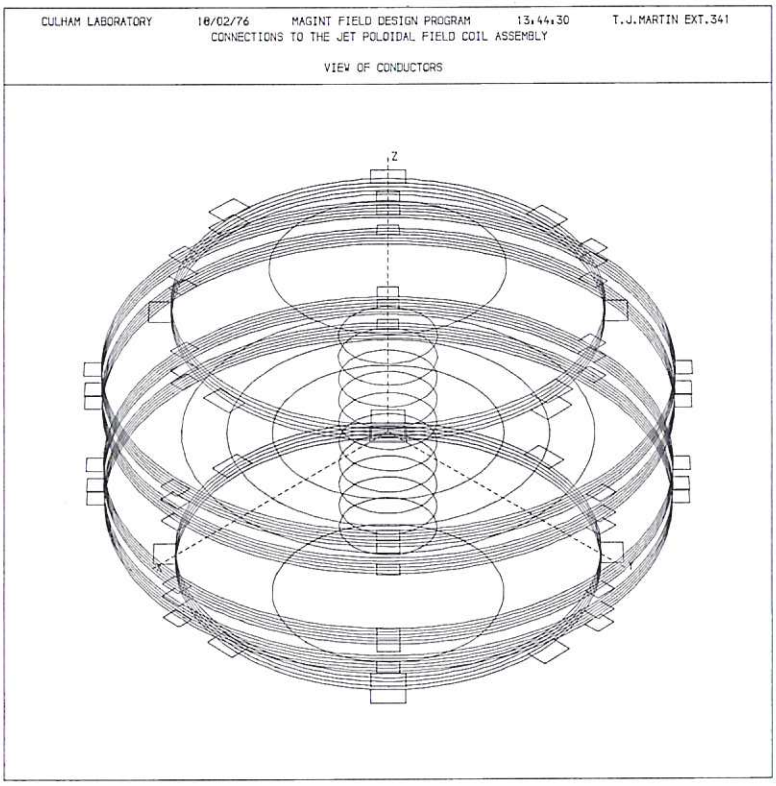

Fig.8 Connections to the poloidal field coils of the proposed JET experiment.

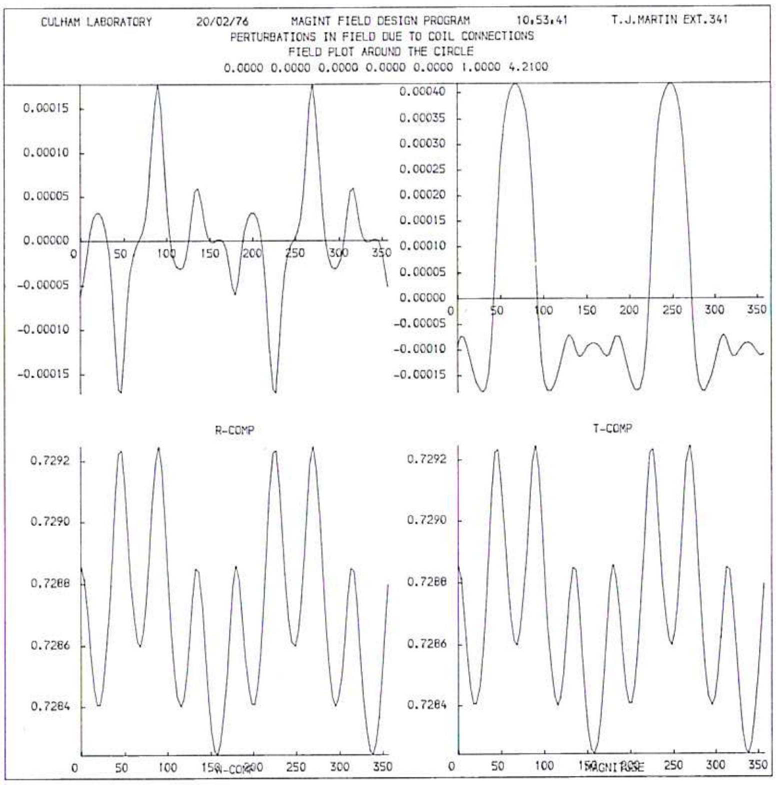

Fig.9 Perturbations in field caused by coil connections (see above).

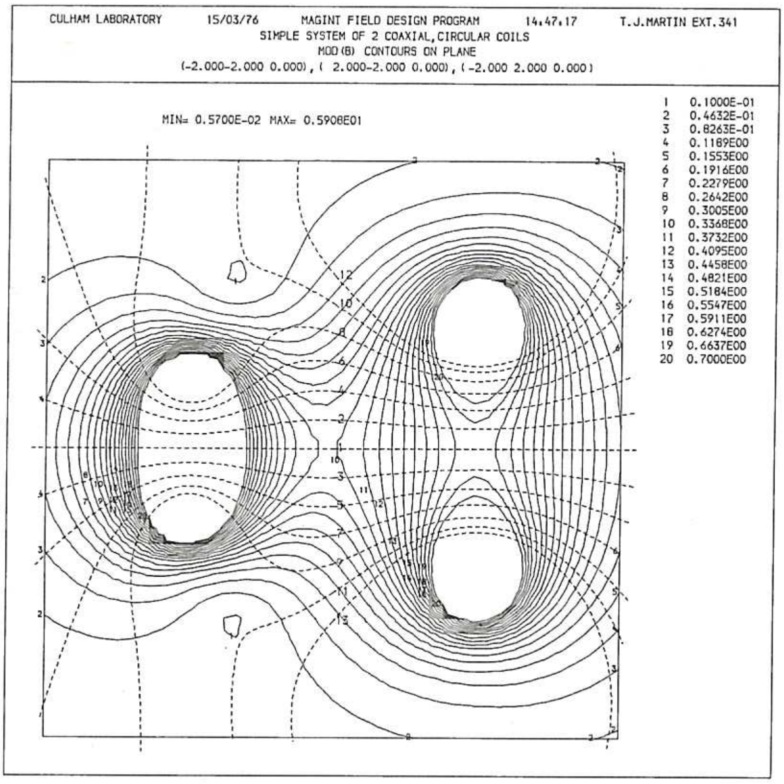

Fig.10 Field lines and $|\underset{\sim}{B}|$ contours for a simple 2 coil system.

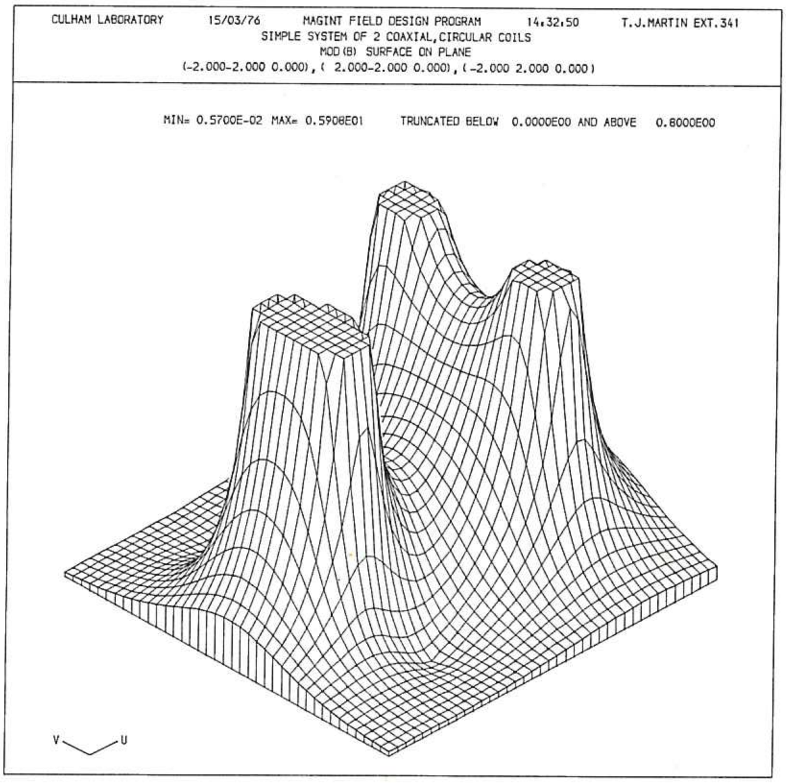

Fig.11 $|\underset{\sim}{B}|$ surface for a simple 2 coil system.