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THE FELIX EXPERIMENTS AND COMPUTATIONAL NEEDS FOR EDDY CURRENT ANALYSIS OF FUSION REACTORS*

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1. INTRODUCTION

In a fusion reactor, changing magnetic fields are closely coupled to the electrically-conducting metal structure. This coupling is particularly pronounced in a tokamak reactor, as shown in Fig. 1, in which magnetic fields are used to confine, stabilize, drive, and heat the plasma. Electromagnetic effects in future fusion reactors will have far-reaching implications in the configuration, operation, and maintenance of the reactors. This paper describes the impact of eddy-current effects on future reactors, the requirements of computer codes for analyzing those effects, and the FELIX experiments which will provide needed data for code validation.

2. EDDY CURRENT EFFECTS IN FUTURE REACTORS

Two of the major electromagnetic issues for future tokamak reactors are:

1) The penetration of poloidal field into the plasma region from the superconducting equilibrium field (EF) and ohmic heating (OH) coils, shown in Fig. 1.

2) The forces and torques induced into conducting components by the rapid disruption of the plasma current.

The field from the EF coils and flux from the OH coils must penetrate into the plasma region without undue delay or distortion. In existing fusion experiments, the major encumbrance to field penetration is the thin and high-resistance first wall, deliberately designed to have a short L/R time constant (0.5 ms in JET, 3 ms for TFTR) in order to minimize electromagnetic delay.

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However, in future fusion reactors, the major encumbrance to field penetration will be the thick blanket and shield sectors, truly three-dimensional (3-D) bodies, with large thickness relative to the skin depth and long L/R time constants (100 - 300 ms for INTOR and STARFIRE). Moreover, the gaps between sectors will be small and convoluted to prevent neutron streaming. The computation of such a 3-D system is beyond existing capability.

In a tokamak plasma disruption, a current of megamperes decays in a time of milliseconds, as shown[1] in Fig. 2. Such a disruption induces large current and forces in the first wall, blanket, and shield (FWBS) components surrounding the plasma region.

Most existing fusion experiments, TFTR and JET in particular, have bellows or thin segments to provide continuous but high resistance first wall current paths. The high resistance bellows decrease the L/R time constant of the first wall, facilitate magnetic flux penetration, and tend to limit the induced current flowing in the first wall; but to first order they do not change or constrict the current path. Induced currents flow toroidally, do not interact with the toroidal field, and can to fair approximation be modelled by a relatively small number of coaxial current loops.

By contrast, future fusion reactors will have segmented FWBS components to permit remote maintenance and rapid replacement of FWBS sectors. Induced currents in the first wall will flow from sector to sector at a limited number of electrical connectors. Current paths will not be strictly toroidal; there will be poloidal current components where the current constricts near the connectors. Whereas toroidal currents interact only with the poloidal field, the radial and poloidal currents will interact with the toroidal field, typically ten times stronger, and produce a severe and complex distribution of forces and torques.

3. STATUS OF EDDY CURRENT COMPUTER CODES

Computer codes capable of calculating these electromagnetic effects are just coming into use. Existing codes can handle no more than: (1) several interacting systems, all with axisymmetry; or (2) a single system of thin, segmented pieces; or (3) a single thick piece. None of the existing codes can handle systems with narrow gaps.

Today's codes deal best with thin shells carrying axisymmetric currents, a somewhat adequate characterization of the present generation of tokamak vacuum vessels. Only now are we beginning to develop codes which are useful in modelling future tokamaks with thick, segmented FWBS systems and three-dimensional eddy currents. Network codes can crudely represent a single system, including its segmentation. Codes with coupled coaxial current loops can crudely represent the electromagnetic interactions of several systems, but only under the assumption of axisymmetry. Codes which can include both segmentation and interaction between systems do not exist.

Following is a description of the kinds of eddy current codes which are of some use in electromagnetic analysis of fusion reactors. Many of these are described in the proceedings of the last two COMPUMAG Conferences.[2,3] For a more complete survey of codes, see reference 4. No distinction is made here between finite difference, finite-element, or integral-equation formulations or between field or network conceptualizations since all have achieved roughly the same level of development.

Axisymmetric Codes

Many two-dimensional (2-D) codes can also model axisymmetric systems with toroidal current and radial and poloidal fields. They can model some fusion applications, but it is intrinsic in their 2-D nature that they cannot handle breaks in the toroidal current path. Hence they do not predict the large, complex distribution of forces and torques that result from interaction between eddy currents and the toroidal field.

Coupled Coaxial Current Loops

An axisymmetric system is modeled by up to a hundred coaxial current loops. The resistance and self- and mutual-inductances are assigned. The passive loops respond to each other and to a number of loops with specified currents as a function of time, representing the plasma and PF coils. Again by their 2-D nature, these codes cannot handle segmentation or the interaction between eddy currents and the toroidal field.

Coupled Coaxial Current Loops, Single Break

If in one of the above codes one or more subsets of the passive loops is constrained to have zero net current, that code can treat axisymmetric systems with a single current break. However, a single break is a poor model of segmentation, and these codes can err by an order of magnitude in the size and time variation of eddy current forces and torques.

Plates and Shells

Some codes can model eddy currents in plates and shells if the plate thickness is less than the skin depth and the current density is uniform across the plate or shell, although there are still open questions about the solution of what is an intrinsically 3-D problem with 2-D codes. These codes can also model systems of plates and shells.

Three-Dimensional Codes

Three-dimensional (3-D) codes, allowing current in all three dimensions, suffer from two problems, one conceptual and the other practical. The conceptual problem is finding a formulation in which the variable is uniquely determined and the boundary conditions, especially the boundary conditions between conducting and non-conducting regions, are well defined in terms of the variable. There has been much progress in solving this problem in recent years. The practical problem is the choice of a mesh which is sufficiently fine to simulate the physical system yet coarse enough that computation can be performed with acceptable cost and existing computers. Some 3-D codes[5,6,7] have reached the degree of development that a simple 3-D geometry (brick, finite cylinder, sphere) can be solved. But, systems of such shapes, with narrow gaps between them, are still beyond the capability of these codes and existing computers. These codes require much development and testing.

3-D and 2-D Codes

The need for 3-D codes cannot be overstated. The geometry of the FWBS and other reactor systems is intrinsically 3-D, with fields, currents, forces, and torques in all directions. However, existing 3-D codes are not yet capable of tokamak analysis. Even when they are, the expense in computer time and in data preparation will mean that only a few design concepts and parameter options can be explored via 3-D computation. Like it or not, we must continue to analyze 3-D tokamak geometries with 2-D codes.

To be useful for fusion reactor analysis, both 2-D and 3-D codes must treat transient problems, as in a fusion reactor, all electromagnetic effects are transient. In addition they must treat the whole range of eddy current problems from resistance-dominated (low Magnetic Reynolds Number) to inductance-dominated (high Magnetic Reynolds Number).

4. THE FELIX EXPERIMENTS

Experimental data are needed in validating the emerging 3-D codes and, equally important, in determining the range of validity to modelling 3-D geometries with 2-D codes. A combined program of code development and experiments will provide the capability to solve design problems before 3-D codes become available, and screen a large number of design concepts, choosing only a few for 3-D analysis. Among the 3-D geometries which can to some degree be simulated with 2-D codes augmented by the experiments are:

1. Modelling a thick shell with a thin, high-conductivity shell.
2. Systems with $2\pi/n$ symmetry. In some cases these can be modelled by axisymmetric systems.
3. Misaligned axisymmetric systems. Differences between reuslts of two axisymmetric computations can sometimes predict the results of asymmetry.
4. Segmented but otherwise axisymmetric systems. It would be highly useful to know if <u>any</u> electromagnetic effects of these systems could be modeled by an axisymmetric system with modified properties.

The question can only be answered experimentally.

FELIX Facility Description

FELIX[8,9] is an experimental test facility that has been constructed at Argonne National Laboratory for the study of electromagnetic effects relevant to fusion reactors. It provides in a test volume of 0.76 m^3 within a vertical pulsed dipole field of 0.5 T (with rate of change above 30 T/s) perpendicular to a steady 1 T solenoid field.

The facility occupies an area 12 m x 13 m in a 2,100 m^2 building which has 35 ton and 10 ton cranes, electric utilities of 16 MVA ranging up to 2.4 kV 3-phase 60 Hz, cooling water, heating, ventilation, purging alarm, and fire protection. The major components of FELIX are identified in Fig. 3. Figure 4 shows a front view of the FELIX facility with a plate experiment in place. Control and experimental data handling equipment is located in a nearby metal enclosed room.

A series of experiments has recently been carried out on FELIX, to provide data for validating 2-D and 3-D eddy current computer codes. The solenoid field was not used. The dipole field was raised slowly to levels up to

0.4 T, held to ensure all eddy currents died out, then discharged with a time constant of 16 ms.

Plate Experiments

Four aluminum plate test pieces 1.0 m x 0.8 m and 1.0 cm thick were used. Each was located in the center of the experimental volume, perpendicular to the pulsed dipole field, as shown in Fig. 5. One plate was solid; two had slits, and one had rectangular holes, as shown in Fig. 6. The magnetic field at selected points was measured as a function of time with Hall probes; temperature, with thermistors; and strain, with wire strain gauges. Temperature distributions in the plates, resulting from eddy current distributions, were recorded by infrared (IR) scanning. The instrumentation is described elsewhere.[9]

As expected,[10] the peak temperatures in the solid plate were observed at the center of the edges of the plate. The plates with slits exhibited circularly-symmetric temperature patterns centered on the tip of the slits. These temperature patterns remained virtually unchanged for tens of milliseconds. The plate with rectangular holes exhibited hot spots at the corners of the holes nearest to and fartherest from the center of the plate. In contrast to the temperature pattern from the slits, the temperature at these hot spots rose and fell over a time scale of less than 10 ms. The quantitative analysis of these plate experiments is continuing.

Brick Experiment

As a simple 3-D experiment, a solid aluminum brick 8.1 cm by 10.2 cm by 15.2 cm mounted on a nylon rod of 1.9 cm diameter through its center and parallel to the long dimension. The rod was held at each end in a nylon fork so that the brick was free to rotate about its horizontal axis. The brick was positioned with the 15.2 cm by 10.2 cm and 15.2 cm by 8.1 cm faces at 45° to the vertical pulsed field direction, as shown in Fig. 7. The dipole field was raised slowly, held constant,and then discharged with a 16 ms time constant. The resulting angle of rotation of the brick was observed.

Full-height slits were then cut into the brick 2.54 cm deep from each end, as shown in Fig. 7, and the experiments repeated. Finally the depth of the slits was increased to 5.72 cm, and the experiment repeated. A long pole could be inserted into holes in the brick and fork to prevent the brick from rotating during the ramp-up; the pole was removed during the flat-top to permit the brick to rotate freely in response to the field decay.

The brick without slits rotated to a position + 5% when the field was ramped up to 0.34 T and then to a position -85° after discharge. The sign convection used is that a rotation of +45° (clockwise in Fig. 7) makes the 8.1 cm x 15.2 cm faces horizontal. With the 2.54 cm slits, the brick was not observed to move during ramp-up and rotated to -5° following discharge.

With the 5.72 cm slit, the direction of rotation was reversed. The brick rotated to -30° during ramp-up and to +255° after discharge. If it was held during ramp-up and released during the flat-top, it rotated a full +360° from discharge.

For a field 11% higher, the torque should have been 23% higher. The rotation was found to increase 17%; the 360° increased to 420°.

These experimental results: an average torque of one sign for no slit, of the opposite sign and strong for 5.72 cm slits, and about zero for 2.54 cm slits, can serve as a simple test for 3-D eddy current codes. The plate experiments can be modelled by 2-D codes. Future experiments will explore segmented geometries and the modelling of 3-D geometries with 2-D codes.

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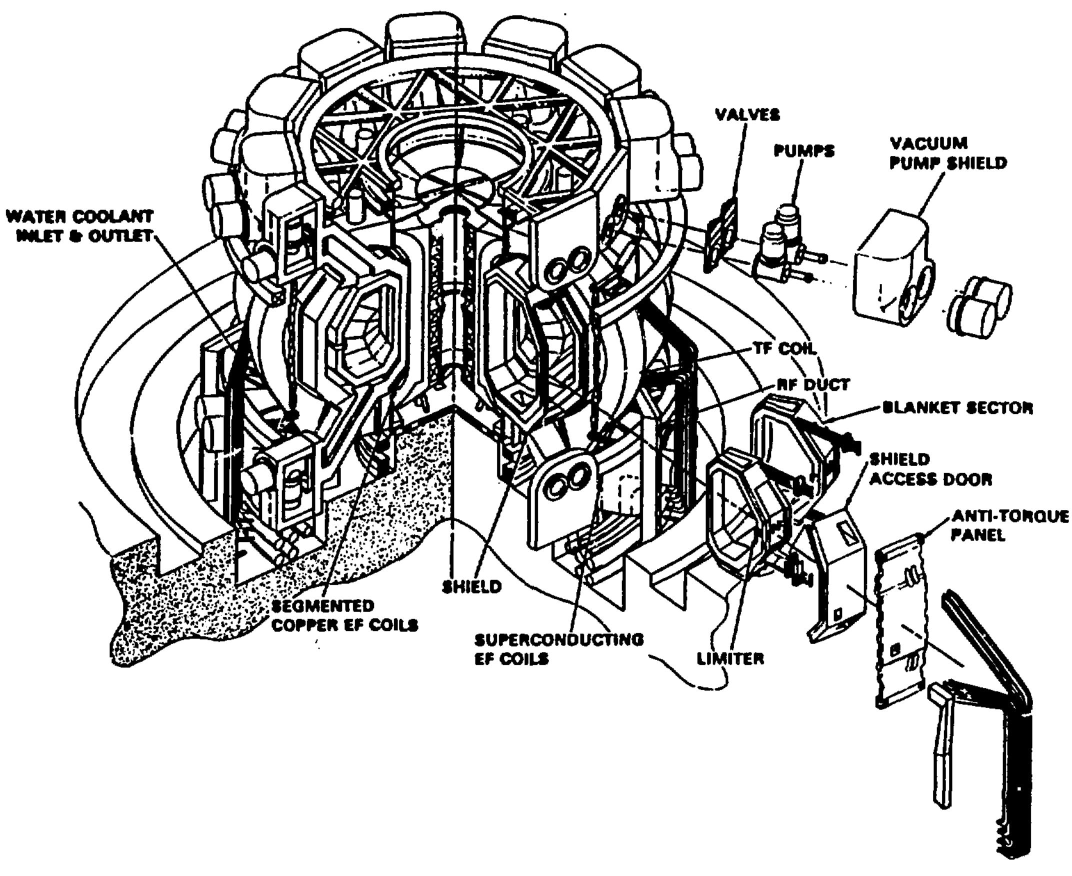


Figure 1. STARFIRE: A tokamak reactor design. Pulsed magnetic fields from the plasma, EF coils, and OH coils induce eddy currents in all metal components. The eddy currents interact with those magnetic fields plus the static field of the TF coils.

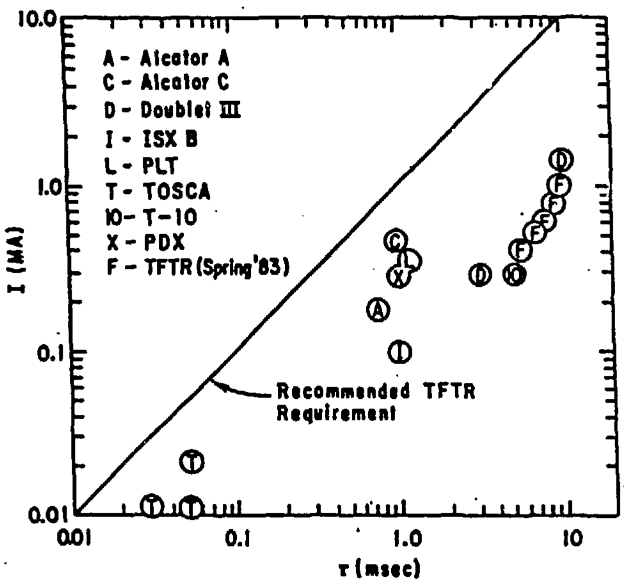


Figure 2. Experimentally observed plasma currents and current disruption times for tokamaks.(1) TFTR was designed to withstand the effects of a plasma disruption with 1. ms/MA, conservative by a factor of two on the basis of the data then available. More recent observations (10, D, and F in the figure) suggest that the time is more like 10 ms/MA. JET was observed to have τ = 35 ms at I = 2.2 MA.

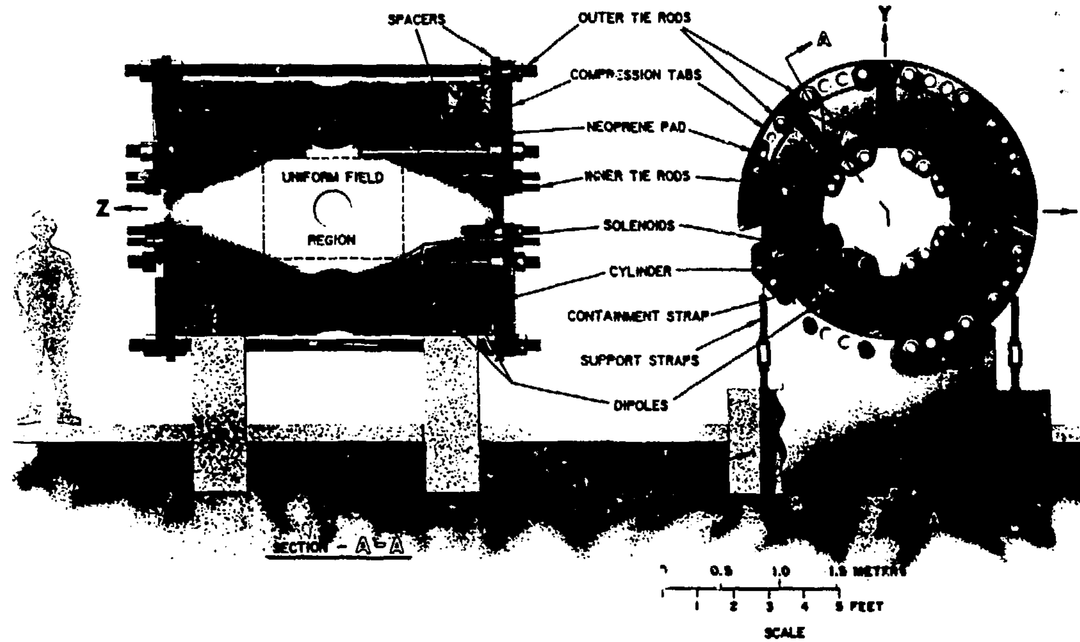
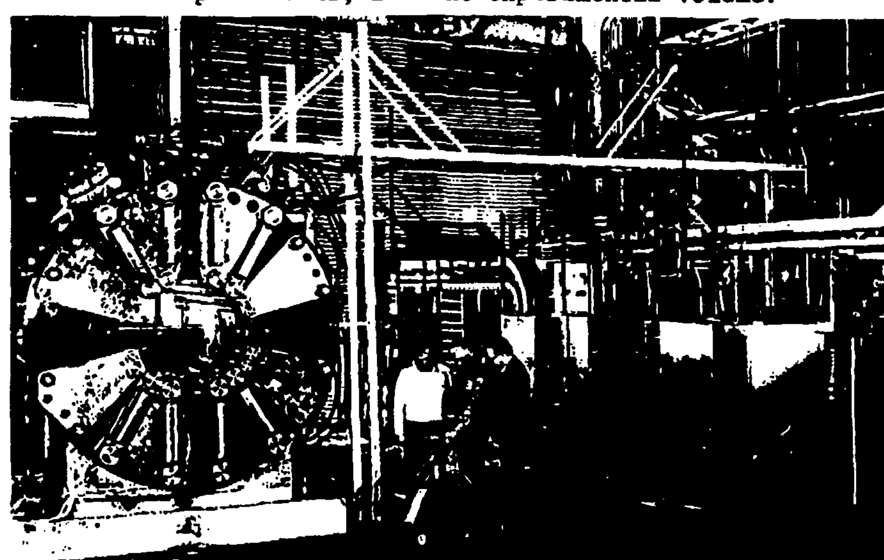


Figure 3. Elevation view of FELIX showing the solenoid coils, the dipole coils, and the experimental volume.



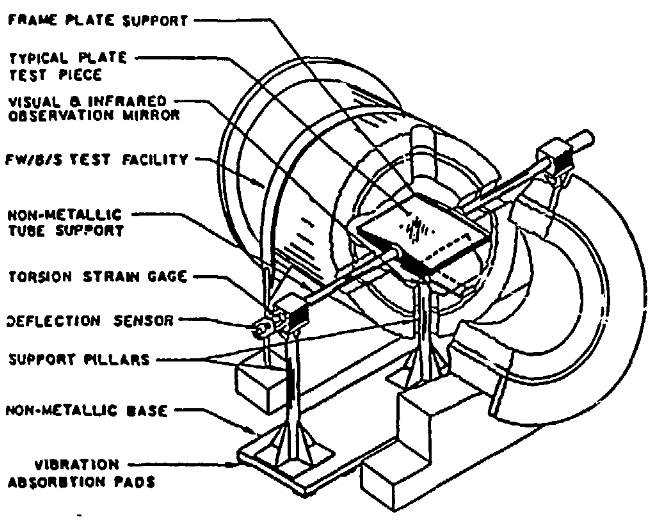


Figure 5. A flat-plate test piece held as a rigid body free to oscillate about an axis perpendicular to both the pulsed (vertical) field and the steady (axial) field.

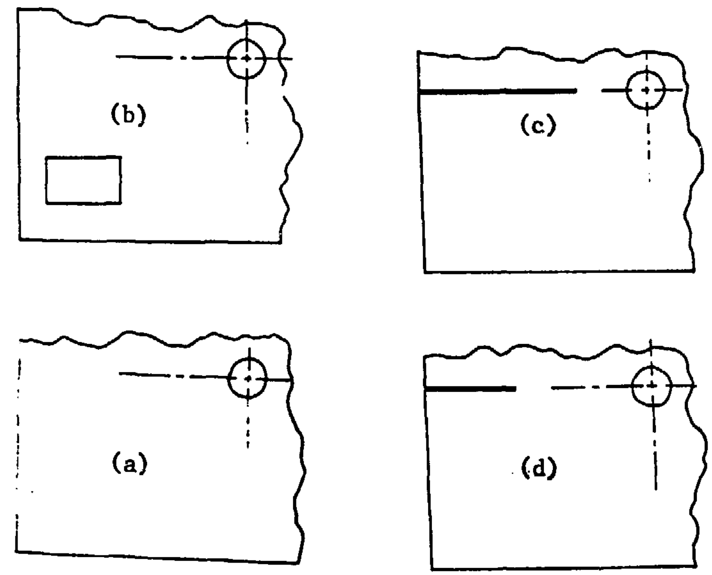


Figure 6. FELIX aluminum flat-plate test pieces. (a) solid plate, (b) plate with rectangular hole in each corner, (c) and (d) plates with slits.

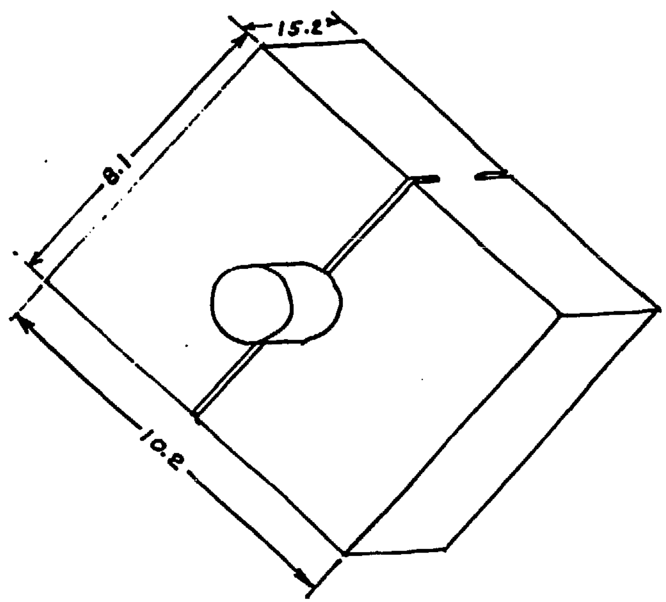


Figure 7. FELIX aluminum brick test piece. Dimensions