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FELIX CONSTRUCTION STATUS AND EXPERIMENTAL PROGRAM*

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FELIX CONSTRUCTION STATUS AND EXPERIMENTAL PROGRAM*

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ABSTRACT

FELIX (Fusion Electromagnetic Induction eXperiment) is an experimental test facility being constructed at Argonne National Laboratory (ANL) for the study of electromagnetic effects in the first wall/blanket/shield (FWBS) systems of fusion reactors. The facility design, construction status, experimental program, instrumentation, and associated computer-code comparisons are described.

INTRODUCTION

The design of a fusion reactor must prevent harmful electromagnetic effects without compromising other needs such as

neutron shielding and remote maintenance. FELIX is an experimental test facility being constructed at ANL for the study of electromagnetic effects in the first wall/blanket/shield (FWBS) systems of fusion reactors. The FELIX program is part of the FWBS Engineering Technology Program, administered by ANL. FELIX will provide a steady horizontal magnetic field of 1.0 T and a pulsed vertical field of 0.5 T over an experimental volume of 0.76 m^3 . The pulsed field decays at rates up to 50 T/s. Several aspects of the FELIX facility are now different from the preliminary design.¹ This paper reports on the construction of FELIX, which will soon be complete, and the program of upcoming experiments.

Fig. 1 The FELIX Facility, Showing the Solenoid and Dipole Coils and the Experimental Volume

* Work Supported by the U.S. Dept. of Energy

FACILITY DESIGN

Figure 1 shows elevation views of FELIX. Coil reoptimization has reduced the size of the coils and has reduced the energy stored in the solenoid and dipole fields by 36% and 32%, respectively. The six large solenoid coils have been replaced by 24 two-layer pancake coils. The cross section of the dipole coils has been reduced by 25%. A large axial spacing of 30.5 cm between the solenoid pancakes at the center permits access to the experimental volume through ports at the top, bottom, and two sides, in addition to the full-diameter access at the two ends. The ports at the two sides are used for support of the test piece, and the one at the bottom is used to support a mirror for visual and infrared observation of the test piece, as shown in Fig. 2.

Fig. 2 Support for the Test Piece and the 45° Mirror

This spacing of the solenoid pancakes limits the solenoid field uniformity to $\pm 15\%$ over the entire (0.9 m diameter by 1.2 m axially) experimental volume. Over a reduced volume (0.6 m diameter by 1.2 m axially) the field uniformity is $\pm 5\%$.

The vertical pulsed magnetic field of 0.5 T is produced by two pairs of nested dipole coils. The coil positions were chosen to approximate a $\cos \theta$ distribution of current; the field uniformity over the entire experimental volume is $\pm 8\%$.

The FELIX magnets are now mounted closer to the floor to give greater experimental access at a reduced cost. The number of support pillars has been reduced from four to two. The pillars are concrete, with footings below floor level. Axial tie rods across the coils and spacers are prestressed to withstand the internal forces and moments from the coil reactions. With a central field of 1.0 T axially and 0.5 T vertically, the leakage field outside of FELIX is about .080 T at 2 m, .010 T at 4 m and .001 T at 8 m.

CONSTRUCTION STATUS

FELIX is scheduled for completion in July 1983. The solenoid coils and dipole saddle coils are being wound and potted and will be assembled in May 1983, with testing in June 1983.

Figure 3 shows a solenoid pancake being electrically tested prior to vacuum impregnation with epoxy. Figure 4 is the large dipole saddle coil as it rests on the mount surface of its impregnation support fixture. The coil consists of four separate coils, each a two-tier pancake. The four pairs of coil leads are visible along the side of the impregnation fixture.

All major components for the solenoid and dipole magnet power supplies have been received and assembled; the main rectifier transformers, transferred to FELIX from other, completed ANL programs, are in place. Electrical connection of the transformers to the incoming 13.2 kV, 60 Hz line and to the rectifier bridges will be followed by testing into a dummy load, scheduled for early May 1983. In the experimental hall, installation of the cubicles containing switchgear, rectifier bridges, filters and the 13 kA, 13 kV dipole switch is near completion. In late May, the magnets, power supplies, and rapid-discharge dipole switch unit will be interconnected.

EXPERIMENTAL PROGRAM

As a typical test piece will experience no net force and a net torque only about an axis perpendicular to both the dipole and solenoid fields, the test pieces will be supported on non-metallic tubes along that axis. The tubes will pass through two horizontal holes in the facility. Torques are measured by strain gauges on the tube, located outside the high magnetic fields. The support system is shown in Fig. 2.

Two-Dimensional Experiments

Fig. 3 Electrical Test of a Solenoid Pancake

Fig. 4 Dipole Saddle Coil on the Impregnation Fixture

The first series of experiments to be performed when the facility is completed will study eddy-current effects in flat plates. These two-dimensional (2D) geometries will be the easiest to instrument and to simulate with computer codes. Some of the objectives of the 2D experiments will be to study the 2D eddy-current pattern and the resulting fields, forces, torques, stresses, and heating; to study the perturbing effects of slits, holes, and other geometrical features; and to evaluate 2D codes. The test piece consists of a rectangular aluminum plate 1 m by 0.8 m and 1 cm thick perpendicular to the dipole field.

The currents, fields, temperatures, forces, and torques to be expected in the plate have been computed with the code EDDYNET.² Figure 5 shows the net force components acting on one quadrant of the plate for pulsed and steady fields of 0.5 T and 1.0 T respectively. The z component, which arises from the interaction of the eddy currents with the time-independent solenoid field, reaches its peak later than the x and y components, which arise from the interaction of the eddy currents with the decaying dipole field. The insert sketches in Fig. 5 show the signs of the force components in all four quadrants of the plate. In the uniform magnetic fields, there is no net magnetic force, but a net torque peaking at 76 kNm and 15 ms is predicted. In carrying out the experiment, a solenoid field of 0.1 T will be used to make the torque more manageable; the full solenoid field will be needed in later experiments with smaller or segmented test pieces.

Fig. 5 Forces Acting on One Quadrant of Flat Plate Test Piece

Fig. 6 Temperature Distribution Over One Quadrant of Plate

The temperature profile over the test piece is probably the most direct means available of determining the overall current flow pattern in the test piece; temperature measurements will be made globally with infrared viewing and locally with thermistors. Contour plots of temperature rise in the plate as a function of time were also calculated with EDDYNET; the plot at 160 ms is shown in Fig. 6. At all times the highest temperature is in the center of the long edge; the peak temperature is 5.1°C above ambient and occurs 140 ms after the start of the pulse.

In later experiments, the plate will be tilted, i.e., rotated about an axis (y axis) perpendicular to both the pulsed field (z axis) and solenoid field (x axis). In such an orientation, the plate will experience a torque about the y axis even when there is no solenoid field, with a time behavior quite different from that produced by the solenoid field.

Experiments with plates containing slits and holes are important and logical successors to those with the solid plate. Some computer codes can handle round holes more easily, others can handle square holes; both should be included in the experiments.

Among the expected output of the 2-D experiments will be:

1. Experimental information (current and temperature distributions, torque and field perturbation as functions of time) for flat plates. Flat plates are a first-order model of many FWBS component segments.
2. Qualitative and, in many cases, quantitative information about the effects of slits and holes. Even for this simple plate geometry, it may be years before the codes could provide this information, which is immediately applicable to estimating electromagnetic effects around penetrations of the FWBS system.

Three-Dimensional Experiments

Subsequent experiments will deal with three-dimensional (3D) geometrical effects. Test pieces will include a hollow conducting cylinder and an array of conducting bricks. The effects of segmentation and the separation between segments will be studied. Objectives of the 3D experiments include studying the eddy-current shielding by continuous and slit hollow cylinders; studying the current patterns, heating, and forces in such cylinders and bricks; and evaluating 3D codes.

The aluminum alloy cylinder is 120 cm long, 40 cm in outside diameter, and 0.5 cm thick. It is supported by, but electrically insulated from, a ring at its midplane. The ring is attached to the same support structure as the plate in the previous experiment. The cylinder has two full-length slits and can be rotated so that the slits are at any angular position. Different positions will produce different eddy current patterns.

The most important measurements are those of the field at different points along the axis, to determine how the field penetrates the cylinder with time. The cylinder dimensions were chosen with the expectation that end effects would be small near the center of the cylinder axis.

An array of aluminum bricks will be used in the segmentation experiment. The most important measurements are the fields in the spaces between bricks, as a function of time. Overall torque measurement is also important for comparison with code predictions. Complete analysis of these experiments requires a 3D computer code, and thus cannot be accomplished until a 3D code is available; but there are immediate results that justify doing them early. For example, a cavity can be left in the center of a

symmetrical stack of bricks, and changes in the field in the cavity measured as bricks are removed or the separation between bricks is changed.

The force acting on a brick in a stack can be found by connecting all the other bricks of the stack together and then measuring the force between the stack and the remaining brick. The bricks will be bolted together, through insulated holes in each brick; the insulation separation between bricks is thereby easily varied.

Among the expected output of the 3-D experiments will be:

1. Detailed results on field shielding by a cylindrical shell, with appropriate scaling rules, for use by reactor designers. Results with the shell have immediate applications to field and flux penetration through the FWBS system.
2. Detailed results on segmentation effects, with appropriate scaling rules, for use by reactor designers. The segmentation effects have immediate impact on the configuration of a FWBS or limiter system for any device.
3. Shielding of a cavity in a symmetrical stack of rectangular blocks, with scaling for block size and gap between blocks. Knowing the effect of gap size will have high impact on blanket and shield design because of the conflicting requirements for flux and field penetration and for avoiding neutron streaming.

Later Experiments

Later experiments will include component concepts, component models, and, finally, component prototypes. Other studies may deal with arcing, electrical contacts between FWBS sectors, melt layer behavior, and growth or welding of a crack in a thin plate. As the melt layer effects are completely unknown, the first experimental aim should be to exhibit the phenomena, using any convenient molten metal. Experiments with liquid metal flow and ferritic stainless steel component concepts are also under consideration.

INSTRUMENTATION AND CONTROL

Sensors to be used in the experimental program were evaluated with respect to four general requirements: they must produce the desired signal transformation with usable

accuracy and range; they should exhibit as much immunity to signal interference as possible; they should have the necessary dynamic characteristics; and they must be available at a reasonable cost. Of these requirements, noise immunity to the expected 50 T/s field changes was the most difficult to satisfy.

Strain Sensors

The measurement of strain is involved in three aspects of the FELIX program: to monitor the structural integrity of the magnet system; to measure surface strains on the test pieces; and to measure test-piece torques. The sensor chosen is a two layer foil strain gauge developed for use on Tokamak Fusion Test Reactor (TFTR) structures. It consists of two identical foil patterns superimposed and series connected so as to cancel the signal induced by magnetic field impulses. The lead wire connections are made to minimize their noise contribution. Various signal wire protection techniques will be tested including special inter-twisted, two pair cable known as inter-8 weave. AC excitation with 20 KHz carrier-demodulators will be used to avoid susceptibility to the local fields, which are limited to frequency components below 200 Hz.

Temperature Sensors

The dependence of temperature rise on current density allows the inference of eddy current density from point measurement and full field two dimensional scanning of temperature. Point measurements will be made with low mass thermistors, the only temperature sensor which can track the temperature transients predicted by computer codes to be about 4°C in 40 ms. Thermocouples will be used to calibrate the nonlinear and poorly stabilized thermistors.

Full field two-dimensional heat patterns will be obtained with infrared (IR) scanning. These systems use mechanically scanned mirrors and lenses to focus a point of the thermal scene onto a cryogenically cooled sensor chosen for the expected infrared wavelength. The scene is reconstructed in a video format and can be digitally stored and processed by computer. The IR system chosen will provide a full scene scan in 30 ms or a series of linear scans at 8 KHz to capture transient temperature patterns. The initial flat plate objects will be viewed through the open end of FELIX along the solenoid axis using a front surface mirror mounted at 45° under the plate, as shown in Fig. 2.

Magnetic Field Sensors

Magnetic field mapping will be required in measuring both the field patterns from the coils alone and the disturbances to these patterns caused by eddy currents in the test objects. Hall probes will be used. They are excited with 5 KHz currents and should be able to provide transient field data well beyond the frequency range expected. Their lead wires should also be relatively immune to local electromagnetic interference. Search coil pairs will also be tested for eddy current sensing and gauged sets may be used to map current densities directly.

Signal Processing

The instrumentation and control system will include a minicomputer, mass storage system, and operator interaction devices. The control functions include the setting of current and timing limits for the power supplies, the timing control of the data-taking system, the monitoring of various system parameters for safe operating limits, and the triggering of the shot itself, including the timing of repetitive cycles. The same computer system will gather data from the various sensors, perform preliminary computations such as averaging, linearizing, and conversion to more useful formats, and store the data for archival and early processing purposes.

Since it is desired to correlate data from the various sensors and since the number of data channels can be as high as 20-30 for simple configurations, it has been decided to digitize the data during the shot. In this way the number of channels can be increased easily and early reduction and immediate display can be programmed to occur after each shot.

The computer system will be able to store, retrieve, process, and present infrared images using a video frame memory and a grey scale video scan converter. It will also be able to transmit data sets to ANL central computers for further processing.

COMPUTER CODE COMPARISON

Two eddy current computer codes are being installed on the IBM computers at ANL, in

preparation of a comparison of the codes in solving problems relevant to FWBS concerns. NMLMAP³ is a general purpose, finite element code for calculating magnetic fields. It treats axisymmetric or 2D geometries. In axisymmetric problems, it calculates axial and radial components of fields and toroidal eddy currents in response to a specified toroidal, time-varying distribution of driving currents. TRIDIF⁴ is a finite difference code, treating the same geometry. A third, proprietary computer code, PE2D⁵ can be used for similar problems. The codes will be compared on the basis of results, computer space and time requirements, and ease of use.

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