C00-2780-3

Lateral Buckling and Vibrations of
Superconducting Magnets for Magnetic
Fusion Reactors*

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May 1977

Progress Report to ERDA for the Period
October 1976 - May 1977

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* Supported by grants from the National Science Foundation (ENG-76-23527)
and the Energy Research and Development Administration (EY-76-S-02-2780)

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Introduction

It is not suprizing that with the advent of a new technologies, such as magnetic fusion and superconductivity, new forms of elastic instabilities might appear. The combination of magnetically stressed magnet coils and the need to minimize thermal paths into the cryogenially cooled coils can lead to magnetoelastic instability without proper constraints between the coils. This instability was first suggested in two theoretical papers and has recently been observed in experiments on different combinations of flexible superconducting coils. Buckling in three coil and five coil partial torii were reported. It was found that the lateral modes of deformation of the coils were unstable about a critical buckling current, while the in-plane modes were stable [4]. Further it was found from these experiments that when the experimental values of the buckling currents were compared with theoretical calculations, corrections due to the in-plane tension were required.

While experiments on a partial torus have demonstrated the instability phenomena, it was thought that in a full torus the combined tensioning effect of fields of all the coils might provide sufficient lateral stiffening to overcome the instabilities. The experiments reported here show that this is not the case. There is a raising of the buckling current above that predicted by the simple model, but excessive lateral deflections were observed below the normal-superconducting transition current.

Accomplishments and Progress on the Present Grant, 1976-77

Our main results center around experimental buckling results obtained in a 16 coil superconducting torus. (Figure 1) This device is a 1/75th model of an early Argonne National Lab experimental power reactor design.

The coils in the experimental torus were designed to buckle below the normal transition current level. Up to 130 KAMP-turns were placed in the torus during these tests.

Description of Apparatus

The 16 coils in the torus were designed with sufficient flexibility so that the buckling currents for the cantilevered, single pin and double pin and double pin modes were within the range of the 250 A power supply in our laboratory. Two sets of eight coils were wound from 40 turns of 0.36 mm diameter NbTi wire (180 filaments, 1.8 copper/superconductor ratio) and potted in a filled epoxy. The first set were used in an eight coil torus experiment in which buckling was observed for the cantilevered mode. These coils were each made from two 20 turn epoxy potted pancakes which were bonded together with epoxy. This method at first produced flat undistorted coils. However in trying to wind another set of eight coils, pronounced twist resulted after potting. (Though the same wire material was used, a different spool was ordered.) After many attempts at again winding flat untwisted coils we changed the method and wound the second set of eight in one pancake of 40 turns. Thus while the overall geometry and number of turns were the same for the two sets of coils, they had slightly different stiffnesses, due to the different arrangement of wires in the cross section. Thus while magnetically they were the same the mechanical stiffness of the two sets were somewhat different.

The "D" shaped coils were scaled to those of the Argonne Tokamak reference design. The model to full scale ratio was about 1:75. The height of the coils was 17.5 cm, and the total outside diameter of the torus was 30 cm. The coils were clamped along the straight part of

the "D" shape with lexan wedges. These fit together in a pie like fashion.

The straight part of the "D" coils were clamped to a 5 cm. diameter center post of lexan.

I. Experimental Results and Discussion

Buckling of Toroidal Coils

In the previous grant an eight coil torus was tested and exhibited lateral buckling of toroidal coils at a critical value of the current. These tests showed pairing of the coils during below the buckling current (Figure 2). In addition, Southwell plots for five of the coils showed almost identical values of the buckling currents, Figure 3. Similar behavior was observed in the 16 coil torus for three different constraint conditions. In addition, pairing of the coils during buckling was observed. A 16 mm movie of the buckling was taken in the dewar as well as photographs (Figure 4).

As current was placed in the torus, the combined elastic and magnetic stiffness of the coils was observed to decrease as evidenced by the decrease in natural bending frequencies (Figures 5-7). The zero frequency intercept on these graphs provide an experimental definition of the buckling current. The experimental and theoretical buckling currents based on the principal investigator's earlier work agree when corrections are added to the stiffness for the in-plane tension in the coils. Table I.

II. Buckling of Poloidal Coils

In the 1976 final report it was reported that the poloidal coils might exhibit a helical elastic instability when in the presence of the toroidal field. One of the major objectives of this year's program was to obtain

experimental evidence for this instability. This evidence has been obtained for a rigid coil in a toroidal field. A 12 turn coil was wound parallel to the toroidal field direction inside the 16 coil torus. This superconducting coil was connected in series with the 16 coils of the torus. The coil was attached to four elastic springs. At a critical value of the applied current, large pitching deflections and lateral deflections of the coil were observed (Figures 8, 9). Photographic evidence was also obtained. Experiments will also be performed in an attempt to measure the elastic deformation of a poloidal coil (Figure 10).

These results support a theoretical analysis for poloidal coil buckling which gives the proper number of structural constraints on the coil to avoid this type of structural instability.

III. Dynamic Interaction of Poloidal and Toroidal Coils

The 16 coil torus has also been used to simulate the dynamic interaction between poloidal and toroidal coils. Two, rigid, superconducting poloidal coils were attached to the torus (Figure 1) and transient pulses of 600 Amps were put through the coils. This current places an overturning torque on the toroidal coils. Oscilloscope traces of these events are shown in Figure 11. Dynamic overshoot in the bending strain both during application of the current and removal of the current can be seen.

Additional tests of pulsed fields near the toroidal coils have shown that the magnetically coupled coils can propagate mechanical bending waves around the torus. The waves propagate due to magnetic coupling of the coils in different vibration modes. Some of these vibration modes have been observed in vibration experiments on the torus (Figure 12).

IV. Bending and Torsional Stiffness of Pancake Coils

While much of the experiments were directed toward verifying the magnetic forces in a torus, two tests were performed to measure the bending and torsional stiffness of pancake type coils. A number of designs for magnet coils envision winding separate pancake-like rings, stacking them and surrounding the pancakes with a stainless steel case. To determine the stresses due to lateral bending, the bending and torsional second moment of area must be used. Tests on solid and pancake-like square rods showed that as the number of pancakes increased, the stiffness was carried almost entirely by the surrounding shell. These results are shown in Figure 13 for bending, and Figure 14 for torsion. This reduction of stiffness is believed due to the inability of the multi pancake structure to effectively carry shear. The effect of the reduced stiffness is to decrease the buckling currents compared to that for a solid cross-section.

Communication of Research Results

Lectures

Brookhaven National Laboratory	September 1976
National Science Foundation	May 10, 1977
Oak Ridge National Laboratory	May 12, 1977
ERDA - Germantown, Maryland	May 13, 1977

Attendance at Symposia on Fusion

American Society of Mechanical Engineers, New York December, 1976
American Nuclear Society, Niagra-Finger Lakes Section, Ithaca, New York
May, 1977

Reports and Research Papers

Research Report to ERDA - October, 1976

1. "Elastic Stability and Vibrations of Superconducting Magnets for Magnetic Fusion Reactors"
2. "Experiments on Buckling and Vibration of Superconducting Coils," F. C. Moon and C. Swanson. J. Applied Mechanics, to appear.
3. "Buckling and Vibrations in a Five Coil Superconducting Partial Torus," C. Swanson and F. C. Moon. J. Applied Physics, to appear.
4. "An Eight Coil Superconducting Torus for Elastic Buckling Studies," F. C. Moon, C. Swanson, S. King. Cryogenics, to appear.

TABLE I

Comparison of Theoretical and Experimental Buckling Currents in a 16
Coil Superconducting Torus

Mode	Experimental Static			Values Dynamic		Theoretical Values		
						$I^2 = \frac{m \omega^2}{4M_I}$		
				Amps/Turn		With Tension Correction		
1	Coil#3 41.8	Coil#4 42.4		#3 44.8	#4 43.5	#3 46.2	#4 46.9	
2	#4 102 149	#7 213	#9 125 169	#8 154	#4,#3 117.	103.9	#4 117	#8 138
3	#7,8 214	#9 248	#10 291	#9-10 328		194.8	259	

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Figure 1. Photograph of 16 coil superconducting torus for buckling studies;
130 KILOAMP-TURNS MAXIMUM TOTAL CURRENT.

Figure 2

Figure 3.

TOP VIEW
OF
TORUS
←
PAIR
BUCKLING
OF
TOROIDAL
COILS

Figure 4. Photograph of pairwise buckling of superconducting coils in liquid helium.

Figure 6 .

Figure 7

Figure 8. COMBINED TRANSLATION-PITCH INSTABILITY
OF A POLOIDAL COIL IN A TOROIDAL
MAGNETIC FIELD

Figure 9.

Figure 10. Helical Buckling Shape of a Poloidal Coil in a Toroidal Magnetic Field B_T .

Figure 11 Dynamic strain records for a toroidal coil near two pulsed poloidal coils. Upper trace - toroidal strain versus time; lower trace - poloidal current versus time.

Figure 11 Dynamic strain records for a toroidal coil near two pulsed poloidal coils. Upper trace - toroidal strain versus time; lower trace - poloidal current versus time.

VIBRATION MODES IN A 16 COIL SUPER CONDUCTING TORUS

Figure 12.

Figure 13. Deflection versus Force for different composite pancake beams.

TORSIONAL
STRAIN
 10^3 RAD/IN

ALUMINUM
SHAFT.

22

20

18

16

14

12

10

8

6

4

2

0

HOLLOW W/4 LAYERS

HOLLOW W/1 LAYER SOLID

HOLLOW

HOLLOW
W/2 LAYERS

TORQUE (in.-lbf)

FIGURE 14.