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ABSTRACT

Magnet Design B for the Superconducting Super Collider (SSC) consists of a 5 cm diameter collared coil assembly 12 m long with concentric aluminum thermal shields at 10 K and 80 K, a G-10 post type support system and a minimal iron vacuum vessel located at a large radius from the coil. In order to determine the behavior of such a magnet under both direct current and quenching conditions, a 6 m model was built using Tevatron tooling to produce a 7.6 cm diameter coil. The dc operation demonstrated that the post type suspension has acceptable rigidity. Distortions in the aluminum thermal shield during quench resulted from stresses in the material below the yield values. Temperature increases in the thermal shield due to eddy currents were larger than those calculated using simple assumptions, demonstrating the value of using a model to verify eddy current behavior in complex situations.

INTRODUCTION

As part of the Superconducting Super Collider (SSC) Reference Design Study[1] Fermilab has developed a design for a cosine theta type dipole magnet with minimal iron located at a large radius from the coil. The magnet, Reference Design B, consists of a collared coil assembly, 10 K aluminum thermal shield, 80 K aluminum thermal shield, and a low carbon steel outer vacuum jacket. The cold components are supported on a system of G-10 posts.[2] Because of industrial manufacturing tolerances in the placement of the room temperature steel vacuum jacket relative to the coil assembly, the constant current magnetic forces between the coil assembly and vacuum jacket, due entirely to misalignment of the coil and iron effective centers, are difficult to predict precisely. Because of the complexity of the high electrical conductivity thermal shields, the coil collars, and the steel, the large eddy currents which are induced during quench are not readily calculated. It is therefore necessary to test a model magnet to determine the forces on the coil and shields during both constant current and quenching conditions. A 6 m long model of the Design

B magnet was built and tested. The principle objectives of the program were to:

    .Study fabrication techniques for a coil-cryostat system.
    .Understand cryostat component tolerances.
    .Measure coil assembly deflection due to off-center forces.
    .Measure eddy current induced motions during quench.
    .Determine whether the forces during quench exceed material
     limits.

MODEL DESIGN

    Reference design B specifies a coil diameter of 5 cm with a magnetic field of 5 T. The model employed a 7.6 cm diameter, aluminum-collared coil assembly of 6 m length built using existing Tevatron magnet tooling. The coil-cryostat relation was configured to approximate the response of a 12 m long magnet having an anchor at mid span. An optical target system located in the magnet bore allowed for monitoring of the coil position before and after cooldown and during operation. Electromechanical displacement sensors were employed to provide measurements of the motions of the coil assembly and the 10 K shield during cooldown, constant current operation, and quenching conditions. The anchor support post was equipped with temperature sensors to monitor cooldown and performance of the post. All electrical instrumentation was monitored, recorded, and processed by an online data acquisition system. The model is shown in Figs. 1-3.

TEST OPERATIONS AND RESULTS

    Thermometers were installed on the 80 K and 10 K shields and on the support post assembly. The 10 K shield was actually operated at 4.6 K for all of these tests. All thermometers were read during cooldown. The post temperatures were recorded when cooldown was complete and thermal equilibrium was reached and the thermal performance of the support post assembly was determined.[2] During high rate current extraction from the coil or during a quench, eddy currents are induced in the thermal shields. The currents in the 10 K shield were observed by measuring the temperature rise using carbon resistance thermometers located on the shield in a position indicated in Fig. 3. During a quench from 5300 A (4.5 T) a
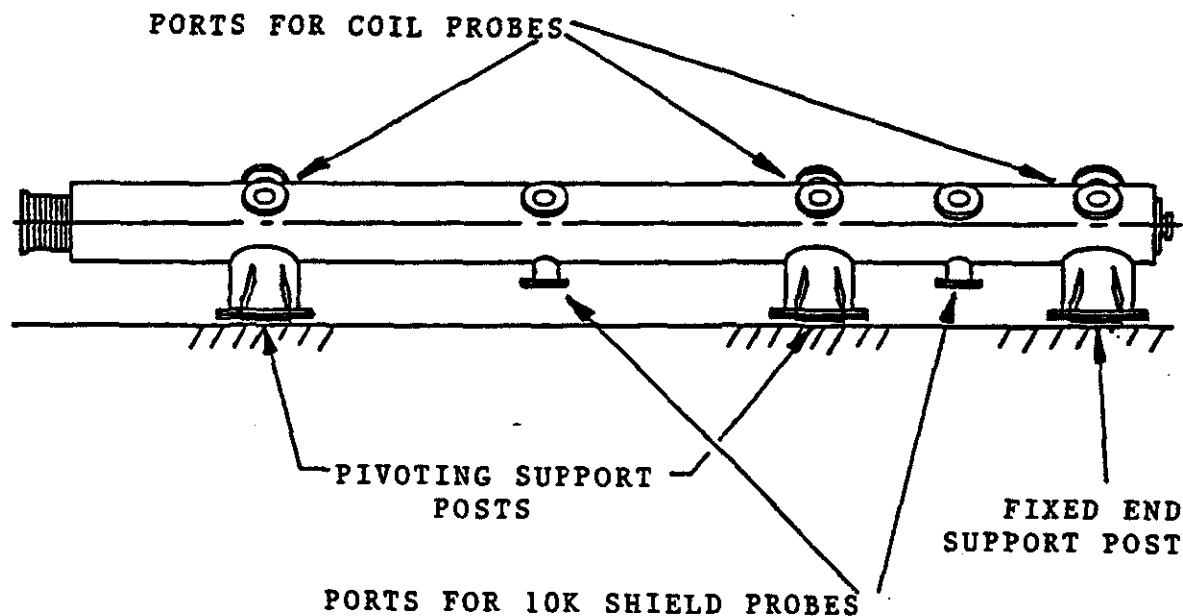

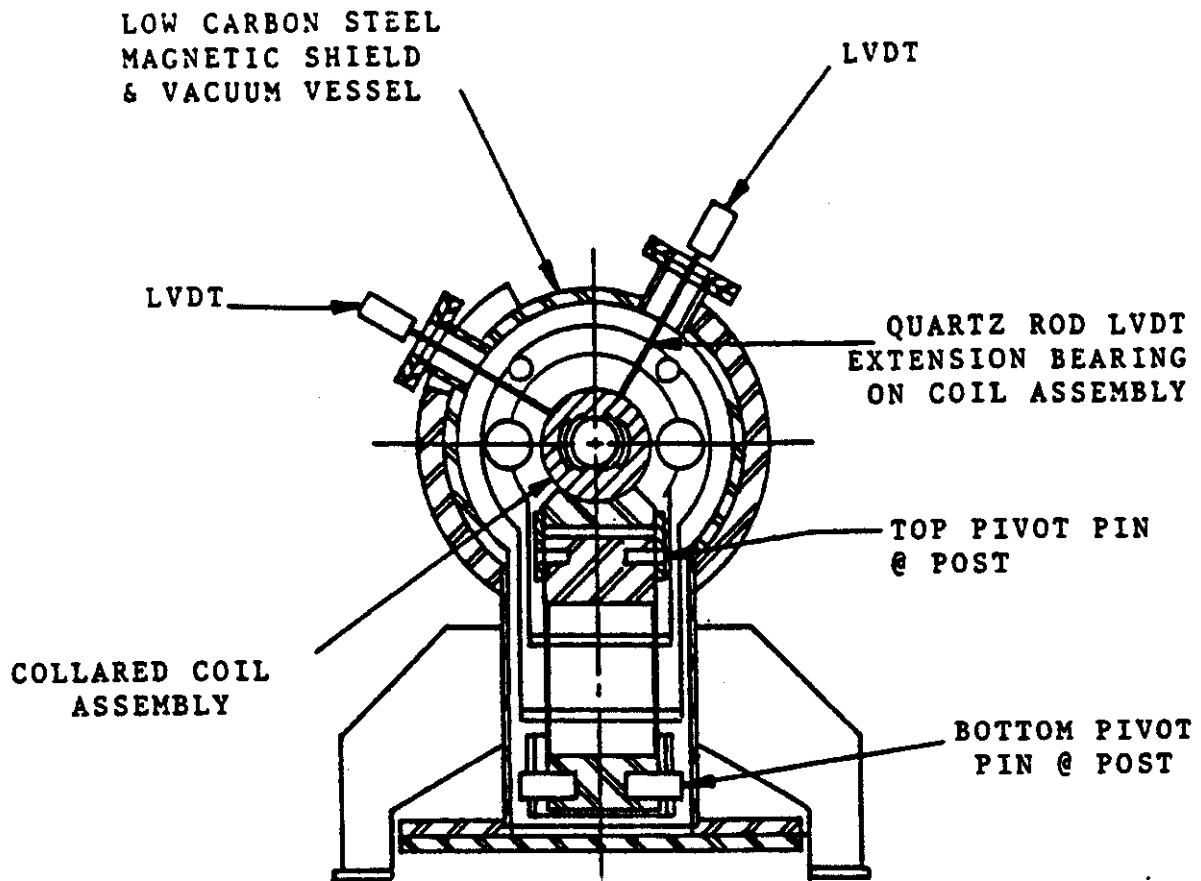Fig. 1. Side view of model magnet cryostat.

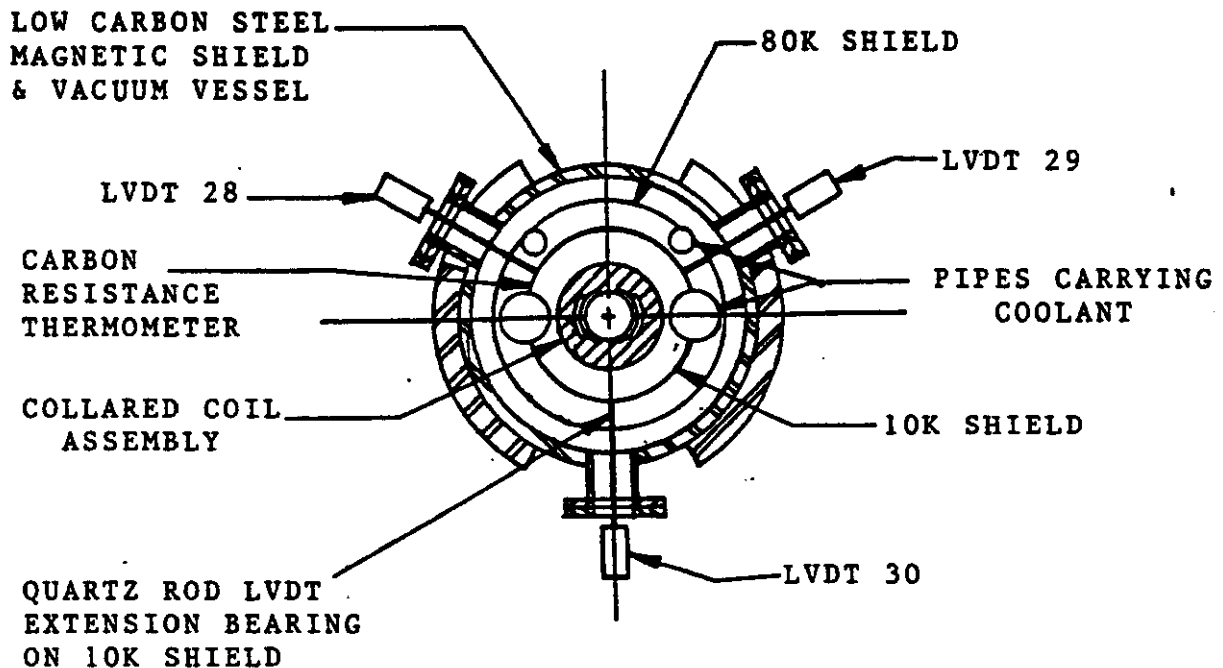Fig. 2. Cross section of model at a support post showing the LVDT position sensors for the coil assembly.

Fig. 3. Cross section of model between supports identifying LVDT and thermometer locations on 10 K shield.

temperature increase from 4.6 K to 39 was observed. This temperature
increase substantially exceeds our estimates, indicating that the eddy
current behavior of the complex geometry involved cannot be calculated
using simple approximations. The observed temperature rise is shown in
Fig. 4. along with a calculated response for a heat input of 40 joules
per centimeter of length of the shield. The heat input calculated for
eddy currents in a cylindrical shell is about one third of the measured
value. That the predicted temperature increase occurs faster than the
observed response may be due to several effects:

1. The response time of the carbon resistors was not taken into
   account.

2. The thermal conductivity of the 6061-T6 aluminum shield material
   is not known and values for 6063-T5 were used.

3. In the calculations the shields and vacuum vessel are represented
   by cylindrical shells, and the predicted eddy currents have
   cosine distributions with maxima at the horizontal midplane. The
   actual distribution of conducting material near this midplane
   includes the liquid cooling pipes (The pipe nearest the
   thermometers was dry during this test.) embedded in the 10 K
   shield, and the effect of this pipe material may be poorly
   represented in the calculation.

Linear variable differential transformers (LVDT's) were used to
monitor the position of the coil and 10 K shield during cooldown, slow
current ramping, and quench. The position of the coil was also monitored
using optical survey targets within the bore of the magnet. The coil
position was monitored at the support post locations whereas the 10 K
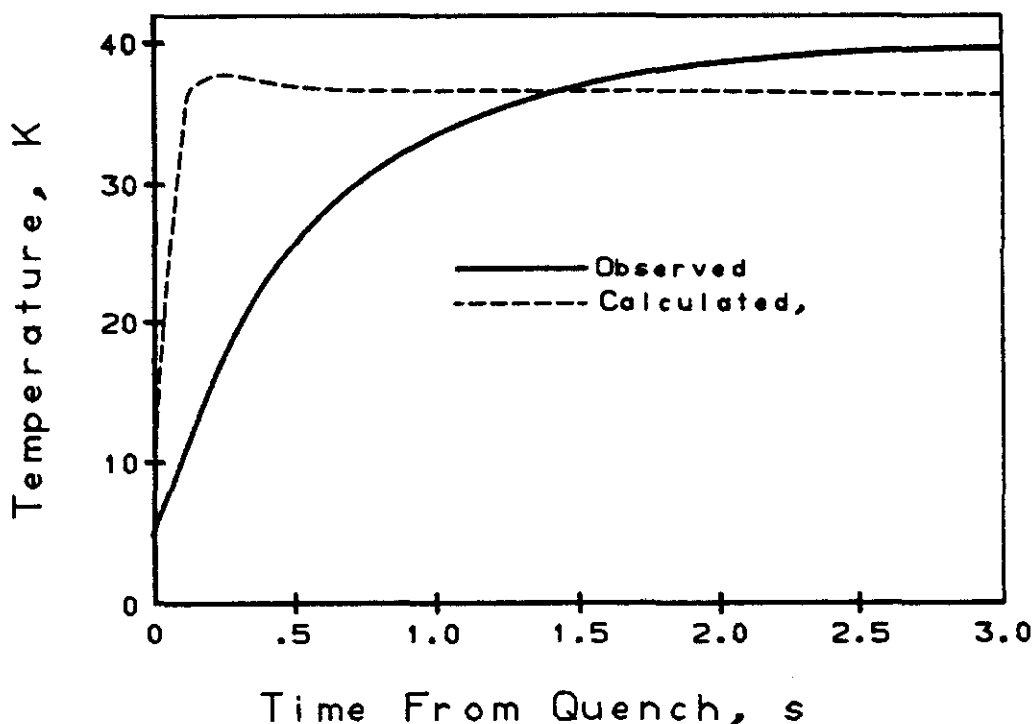shield position was monitored midway between the support posts. The

Fig. 4. Temperature of 10 K shield vs. time from quench for a 5300 A
quench. The calculated curve represents a total heat input of
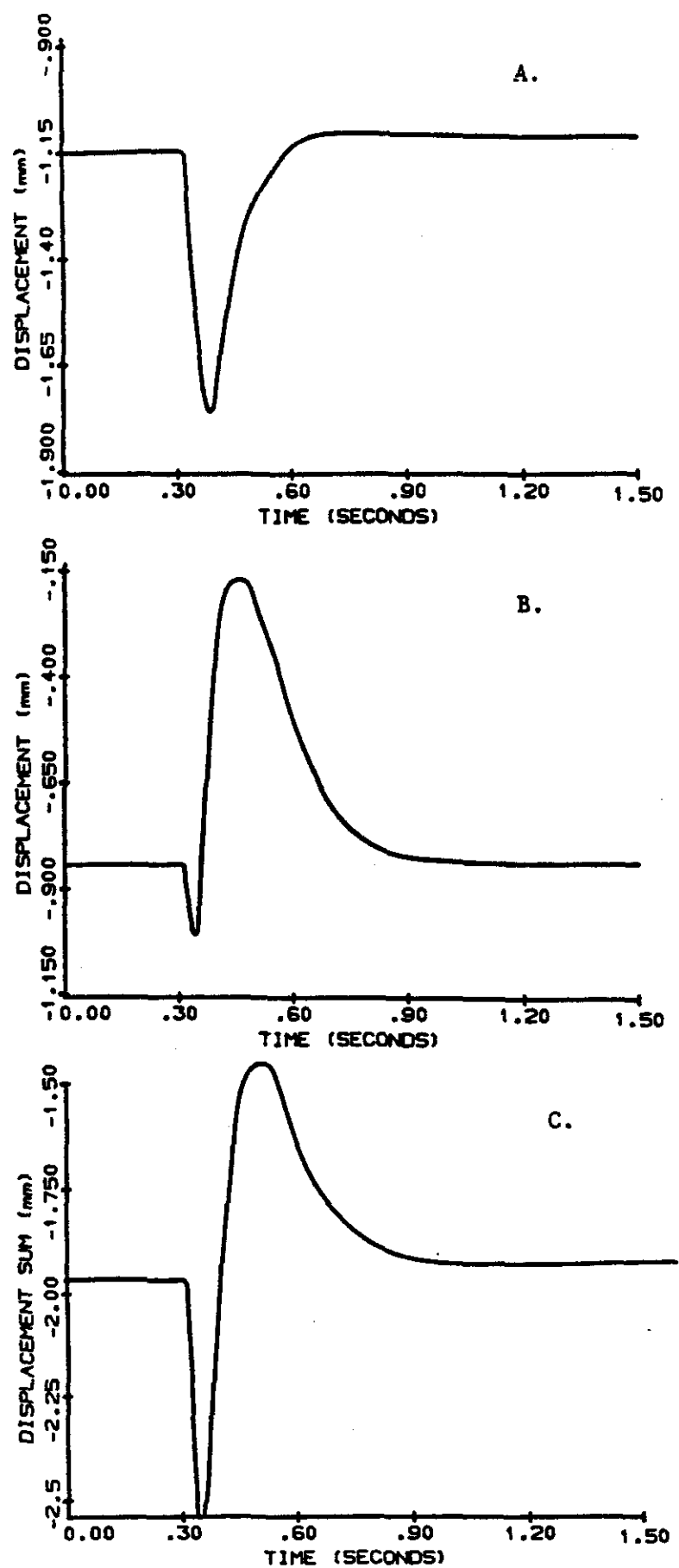40 J/cm.

Fig. 5. Displacement (arbitrary zero) of 10 K shield during quench
vs. time. Quench occurs at 0.3 s. A. LVDT 28, -60° from
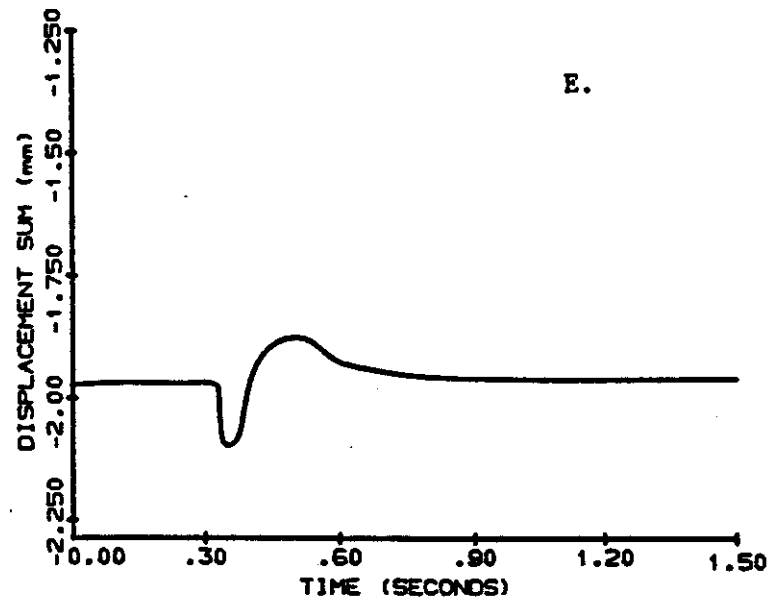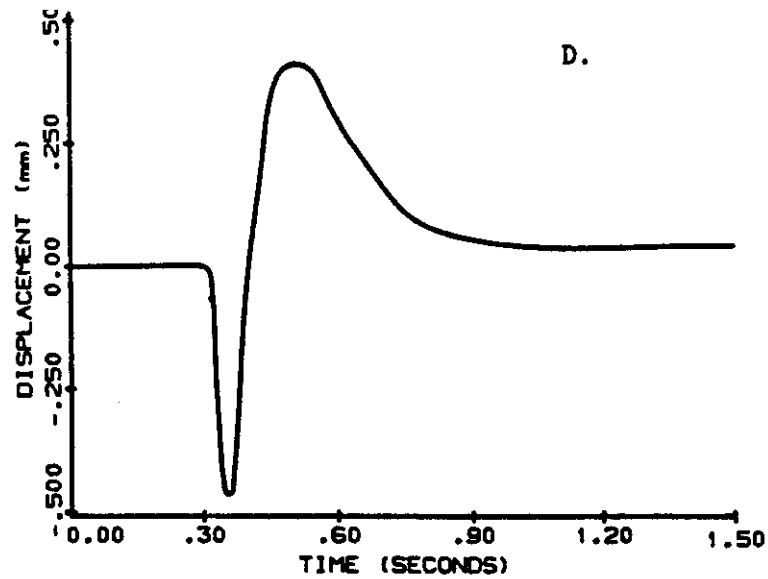vertical. B. LVDT 29, +60° from vertical. C. LVDT 28 + LVDT 29.

Fig. 5. (cont.) D. LVDT 30, bottom. E. LVDT 28 + LVDT 29 - LVDT 30
represents the deviation from the expected ovaling of the shield.
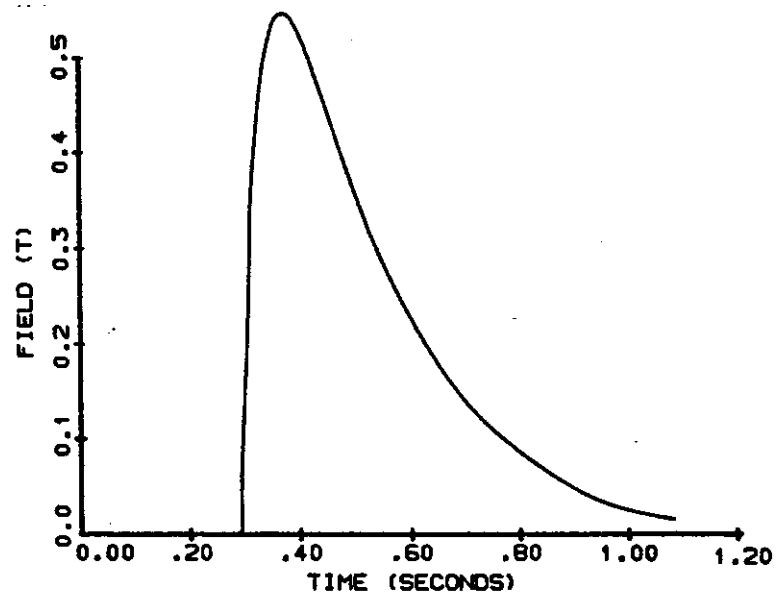

Fig. 6. Magnetic field due to eddy currents after quench vs. time. Quench
occurs at 0.3 s.

magnet was constructed with ordinary industrial techniques and had a typical displacement of the coil axis from the magnetic axis of the steel vacuum vessel of 2 mm. Movement of the coil as the magnet was energized to 5000 A was up to 1 mm and was found to approximately satisfy an equilibrium equation containing the measured spring constants of the support posts and the calculated magnetic forces. The cold mass and coil axis were then further displaced from the steel axis by an additional 4.4 mm to understand the results of extreme manufacturing errors and the coil motion again measured. The maximum observed movement of the coil at any support post increased to 2.2 mm at 5000 A. The equilibrium at these larger displacements was complicated by bowing of the coil assembly between support posts and by mechanical hysteresis of the post assembly.

The shape and position of the 10 K shield were monitored during fast current extraction and quench at a variety of time constants and currents. The eddy currents induced cause the shield to distort and to move horizontally by up to 2.2 mm during a 5100 A quench under the off-center cold mass test condition. The LVDT arrangement at the 10 K shield is shown in Fig. 3. With this geometric arrangement of the LVDT's at 120 degree intervals about the magnet, symmetric distortion (ovaling with a constant shield perimeter) can be separated from translations by adding LVDT's 28 and 29, Fig. 5a,b. Changing the shield width will be indicated by a change in the sum of LVDT's 28 and 29, Fig. 5c., and a corresponding elongation of the shield cross section which is seen by LVDT 30, Fig. 5d. If the ovaling hypothesis is correct, the value of LVDT 28 + LVDT 29 - LVDT 30 should be a measure of asymmetric behavior, Fig. 5e. The small values seen are an indication that the ovaling distortions predominate. While calculations of induced eddy currents and subsequent deformation of the shield are difficult, due to the complicated shape of the shields with their component pipes, the predicted motion is for the shield to stretch vertically while it shrinks horizontally, to return to a circular configuration, and finally to stretch horizontally while shrinking vertically. The first part of the motion just described is caused by the interaction of the decaying magnet current with the induced eddy currents while the later motion is due to the interaction of the eddy currents in the shields and vacuum jacket with each other. A Hall probe monitored the magnetic field within the magnet bore. If the magnetic field calculated from the measured coil current during quench is subtracted from the field measured by the hall probe the result is the field due to the eddy currents. Figure 6 shows the eddy current magnetic field deduced in this way plotted on the same time scale used in Fig. 5. It is clear that the horizontal stretching of the shield is due to the eddy current interactions as expected. Figure 5 is from a 3000 A extraction through a 240 milliohm dump resistor in the on-center geometry and are typical of shapes seen at other currents with other extraction current rates. No evidence of permanent deformation of the shields was found at any test current up to the maximum of 5300 A indicating the eddy current induced stresses in the shield remain below the yield strength of the material.

IMPLICATIONS FOR FUTURE MAGNETS

We may predict the behavior of the newest version of the Design B magnet, Fig. 7., which has a 5 cm diameter coil, 6 T field, and 58.5 cm inside diameter steel vessel, using the results of the measurements on this model. Assuming the fabrication tolerances are correctly represented by the on-center measurements and that the new support posts are no more rigid than those in the model, the maximum coil deflection due to support post bending would be 0.12 mm. The new support post assembly is calculated to be 3.0 times as rigid, resulting in a deflection of only 0.04 mm at full field. Coil bending between support posts will be limited

LOW CARBON STEEL
VACUUM VESSEL &
CLADDING

80K NITROGEN PIPE

10K SHIELD

80K SHIELD

COLLARED COIL
ASSEMBLY

10K HELIUM
PIPE

4.5K HELIUM
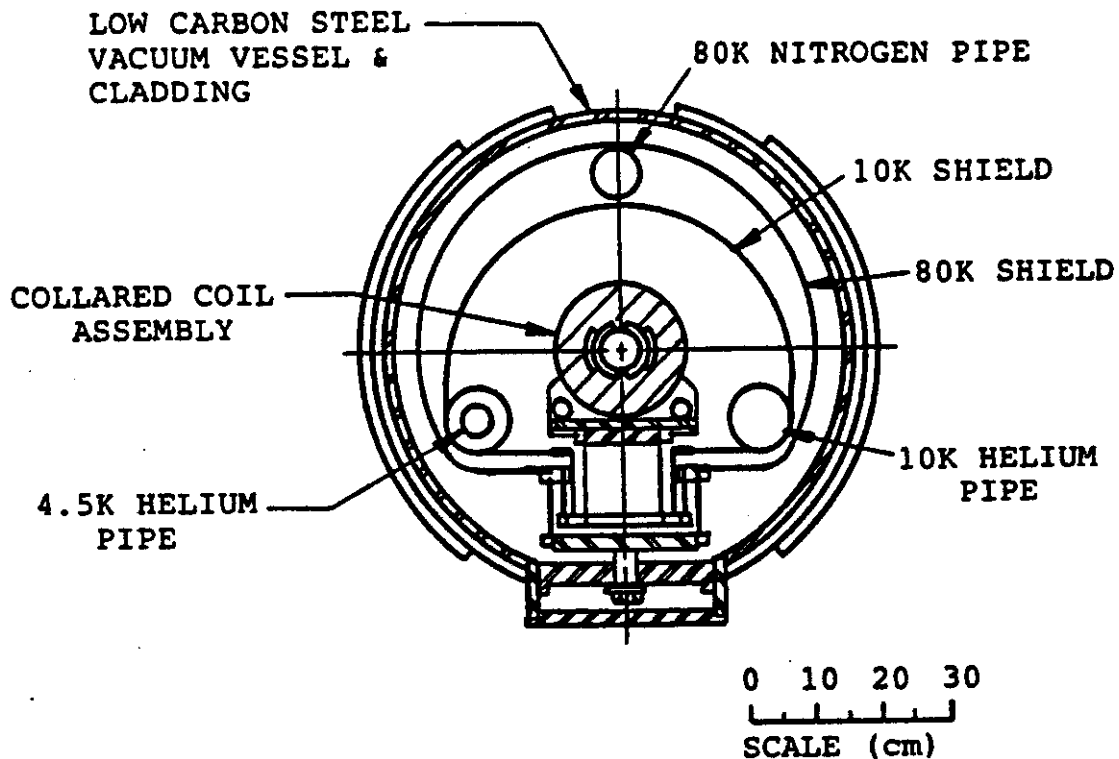PIPE

0 10 20 30

SCALE (cm)

Fig. 7. Cross section of new Design B magnet showing folded post support.

to a deflection of 0.12 mm. The stresses in the 10 K shield will be reduced from the (acceptable) stresses which occurred in the model for the following reasons:

1. The smaller coil diameter and larger effective shield diameter reduce the stresses in the new design. Using the approximation of cylindrical shells, one finds the stresses to be less than in the model by a factor of 8 for the same quench time constant.

2. Moving the piping on the shield away from the midplane will reduce the eddy currents therein to about 60% of those observed in the model. This estimate is based on the temperature rise measurements of the shields during quench. The corresponding further reduction in shield stresses reduces them to only about 7% of the stresses in the model.

The very large safety factor allows a broad choice of alloys for the shields to minimize production costs.

CONCLUSIONS

1. A Design B magnet can be built with existing manufacturing methods to the accuracy required for proper performance.

2. The suspension system tested can provide the necessary rigidity to allow for stable control of the coil assembly position during high current operation and quenching.

3. One piece aluminum thermal shields can withstand quench induced eddy current forces elastically.

REFERENCES

1. "Reference Designs Study Group on the Superconducting Super Collider" (U. S. Department of Energy, May 1984), DOE/ER-0213.

2. R. C. Niemann, et al., Design, Construction and Performance of a Post Type Cryogenic Support, in: "Advances in Cryogenic Engineering," Vol. 31, Plenum Press, New York (to be published).