

MECHANICAL PROPERTIES OF ISABELLE SUPERCONDUCTING COILS\*

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Summary

As a part of the manufacturing processes, several mechanical measurements are made on ISABELLE dipoles. These are done both to control the process and to provide information for the evaluation of the behavior of the completed magnets. This paper discusses the Young's Modulus ( $E = 1-3 \times 10^6$  psi), the thermal contraction of the coil assembly ( $\Delta L/L = -290 \pm 17 \times 10^{-5}$  at 77°K), and the loss of applied prestress with time (~20% for times 20 days).

Introduction

The ISABELLE dipole coils are wound with a cosine theta current distribution<sup>1</sup>, have a mean radius of 5.8", and are composed of a composite of braided Cu(Nb-Ti) conductor, epoxy impregnated fiberglass and a copper pole piece. The assembled coil structure is inserted into a cylindrical iron yoke. The Lorentz forces at full field produce 8.8 Kpsi compression at the midplane of the magnet. These forces can produce motion which is significant both for effect on field quality and as a disturbance source for quenches. Figure 1 shows these forces as calculated by the FBNML Magnet Technology Group.<sup>2</sup> Also shown is the motion of the coil if it has an effective modulus of  $2 \times 10^6$  psi. A simple model of static friction produces an estimate of the energy released when a portion of the coil which has been held to its equilibrium position.

$$\Delta \epsilon = \frac{(\mu_s F_{\perp})^2 L}{2EA}$$

where  $\mu_s$  = static coefficient of friction,  $F_{\perp}$  is the perpendicular force, L the unsupported length, E the Young's modulus and A the cross-sectional area of the portion of the coil which moves. For magnets running near the conductor critical current, the energy necessary to produce a quench (10-100mJ) is comparable to this release. Maximizing E thus should reduce the energy available to initiate a quench.

The required field quality can be qualitatively translated into a limit<sup>3</sup> of 0.002" magnet-to-magnet difference in the coil locations, which is small compared to the unconstrained motions. It is attractive to reduce these motions by preloading the coil. Figure 1 shows the reduction in motion produced by optimum preloading. The magnet coils are operated at 3.8-4.8°K after insertion into the iron yoke; the preload is achieved by forcing the diameter of the coil in the operating condition to be smaller than its unloaded diameter. To determine the preload thus requires a knowledge of the coil thermal contraction and its modulus, together with any inelastic deformation produced by relaxation or creep.

Two mechanical types of magnets have been constructed: "soft banded" in which the coils are 50% enclosed in fiberglass and then inserted in the yoke with a 4°K interference of 0.04% and "aluminum banded" in which the coils are inserted (with 0.4% interference) in aluminum tubing, before insertion in the iron

yoke. The overall coil compression for the second type is 0.2%. The tangential preloads produced by these two models are ~0.5 Kpsi and ~4 Kpsi. The latter is intended to preload the magnet enough to minimize motion.

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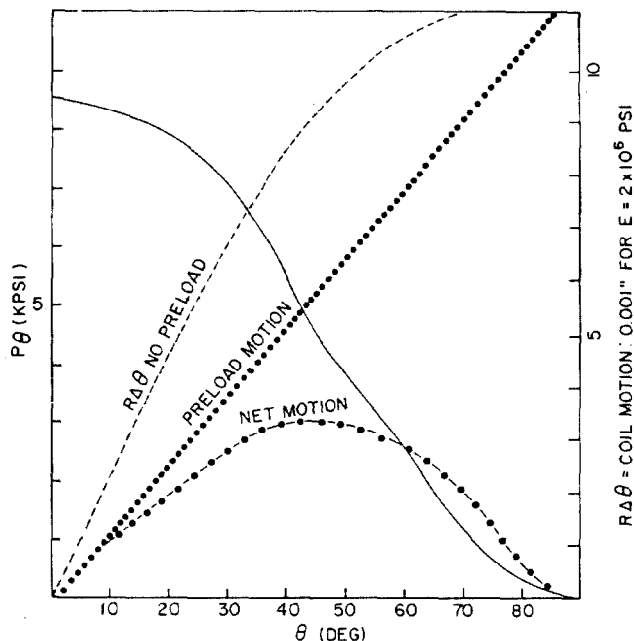


Fig. 1. The accumulated pressure from the Lorentz Force (solid curve) for the ISABELLE Dipole design. Also shown is the coil motion with no preload (dashed curve), and with optimum preload (dot-dash curve).

The ISABELLE quadrupoles which have been built have mechanical properties rather similar to the dipoles but the predicted coil motions are less by a factor of 5. They are not discussed in this paper.

Young's Modulus Data

As part of the assembly process, split rings (clamps) are bolted around the circumference of the coils. The bolts are repeatedly tightened and loosened and the diameter recorded at each step. From the measured torque and the empirical equation  $F = aT$  ( $a = 100 + 20 \text{ ft}^{-1}$ ), and the diameter measurements one determines an effective modulus. The diameter normally decreases with these repetitive cycles; this change ("walkover") is presumably due to compaction of the structure and localized yielding. At the end of this procedure the diameter is the molded diameter less the "walkover" and the elastic compression. Figure 2 shows the final diameters and moduli for recent ISABELLE dipoles. Most of the magnets cluster about  $E = 2 \times 10^6$  and a final diameter of -0.1%. The outlying magnets are of some interest: MK 23 was molded oversize, and MK 34/MK 35 were "high porosity" (very little epoxy used) magnets. Figure 3 shows the "walkover" plotted against modulus; here the only anomalies are the two "high porosity" magnets. It appears that one can build these magnets with a

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modulus of  $2 \times 10^6$  psi and controllable final diameter. Higher values of the modulus would be desirable in limiting the motion. Significantly lower values would probably generate motion unacceptable from the field shape criterion. They also generate manufacturing problems.

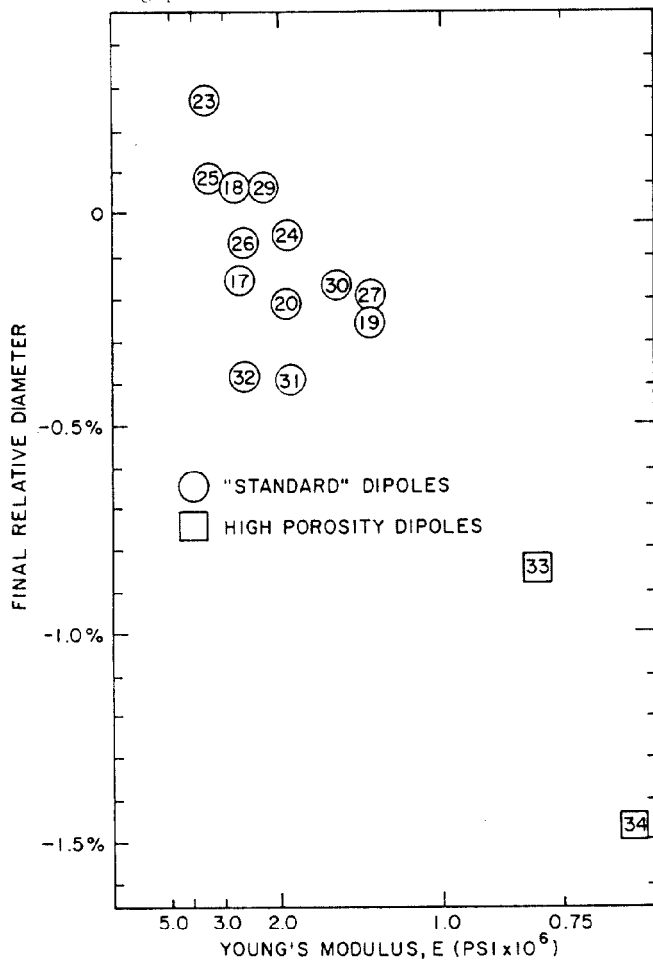


Fig. 2. Plot of final relative diameter vs. Young's Modulus for recent ISABELLE dipoles. The zero for the diameter scale is somewhat arbitrary.

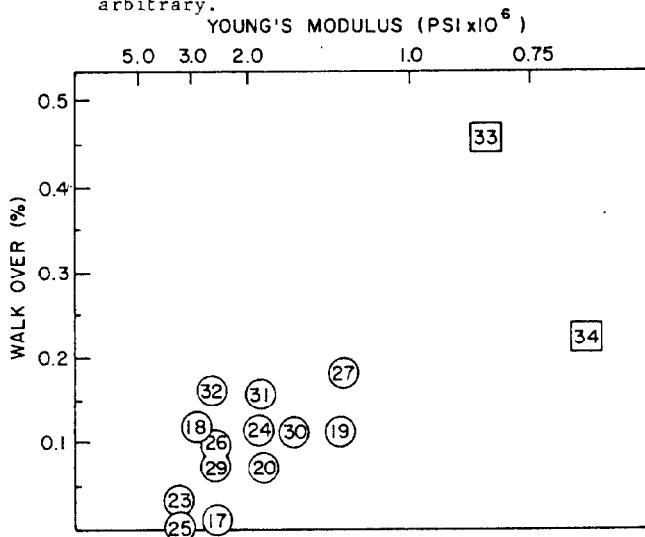


Fig. 3. "Walkover" (change in diameter with repeated mechanical cycling) vs. Young's Modulus. This data is the difference between the diameters (at full compression) for the 1st and 3rd cycles.

Four recent dipoles have been assembled with aluminum banding. As part of this assembly procedure, by measuring the stretch of the aluminum, it is possible to make an independent measurement of the modulus of the coil.

Table I: Comparison of Modulus Measurements

Magnet	E From Clamping	E From Al Stretch
MK 18	$2.6 \pm 0.5$	$2.1 \pm 0.5 \times 10^6$ psi
measurement	at 77°K	$2.4 \pm 0.5 \times 10^6$ psi
MK 24	$1.7 \pm 0.4$	$1.8 \pm 0.5 \times 10^6$ psi
measurement	at 77°K	$2.0 \pm 0.5 \times 10^6$ psi
MK 31	$2.3 \pm 0.5$	$4 \times 10^6$ psi
MK 30	$1.7 \pm 0.4$	$14 \times 10^6$ psi

The large disagreement for the latter two magnets is thought to be due to problems with the aluminum banding procedure.

#### Thermal Contraction

The difficulty of making accurate measurements on a 16 foot long object at 77°K are considerable. Figure 4 shows the contraction measured from room temperature to 77°K. A reasonable summary is  $290 \pm 17 \times 10^{-5}$ . This is 15% more than a simple weighted average of the coefficients of Cu and Nb-Ti. No measurements have yet been made at 4°K on the completed coil assemblies. It is estimated that the contraction at 4°K is 1.05 times that at 77°K. Not shown is the fact that the midplane diameter of the magnet tends to contract by  $25 \pm 10 \times 10^{-5}$  more than the above number. This decreases the clearances during assembly.

#### Relaxation Measurements

Due to the differential contraction of the yoke and coil, the stresses on the magnet are highest when stored at room temperature. Because relaxation is a strong function of temperature, it is necessary to determine what inelastic changes will take place in a magnet stored for a period of the order of a year under these conditions. Figure 5 shows the relative change in strain gauge readings for a magnet stored in an iron yoke. The strain gauges are mounted on the copper pole pieces of the magnet. The data shown are typical in that there are three distinct slopes (decreasing in magnitude) and a total decrease of 20%. Table II tabulates similar data for this and other magnets. The data for the other magnets was obtained while they were compressed by the temporary bolted clamps. The present data suggest that the magnets will not deteriorate during storage but long term measurements (~1 yr) have not yet been made.

Table II

Magnet	S <sub>1</sub>	S <sub>2</sub>	S <sub>3</sub>	D
MK 20	-14	-6	...	-7%
MK 26	-8	-2	+0.5	-20%
MK 30	-10	-2	...	-20%
MK 31	-12	-2	0	-30%
MK 32	-1	0.3	...	-13%

S<sub>1</sub>, S<sub>2</sub> and S<sub>3</sub> are the short (less than 1 day), medium (~5 days), and long term (> 10 days) slopes; the units are %/day. D is the total change. The uncertainties are  $\pm 30\%$  of the stated numbers plus  $\pm 1\%$ .

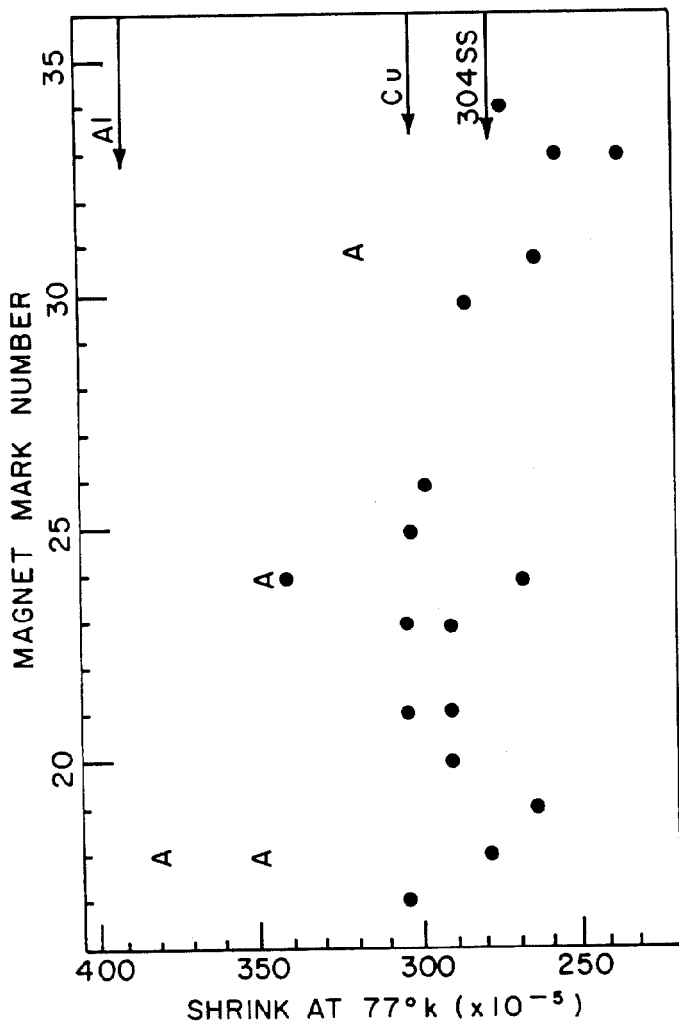


Fig. 4. Measurement of the fractional thermal contraction of the outside diameter of ISABELLE dipoles from 300°K to 77°K. Arrows to the right indicate contraction of representative metals.

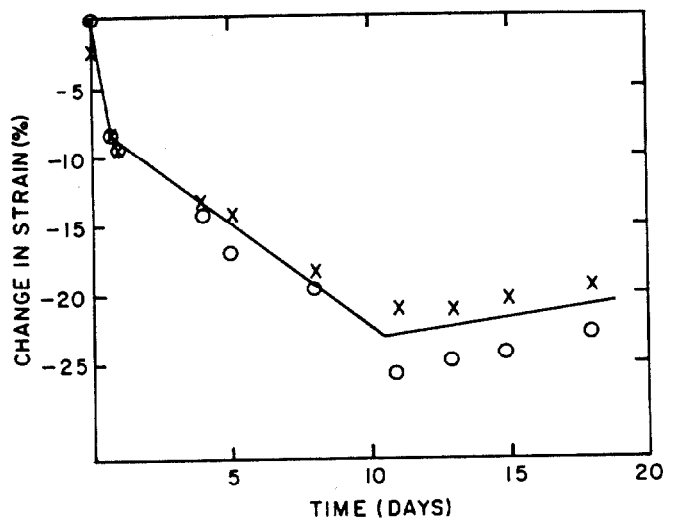


Fig. 5. Relaxation of prestress in MK 26. The prestress is measured by strain gauges placed in the pole piece. The measurement was made at 300°K with a preload of ~5 Kpsi.

#### Longitudinal Forces

The rest of this paper discussed only the two dimensional cross section of the magnet. The forces on the ends are outwards and average 4.5 Kpsi. Preliminary measurements indicate a preload of 0.8 Kpsi in this direction. Friction is significant in constraining this motion, and a detailed analysis has not been attempted.

#### References

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