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# THE MAGNETIC AND THERMAL STABILITY OF SUPERCONDUCTING ACCELERATOR MAGNETS*

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Summary. The two model superconducting storage ring magnets ISA I and II[1] have been subjected to extensive magnetic and thermal cycling to determine the effect of long term operation on their field distribution. The magnets were pulsed using the cycle proposed for ISABELLE (i.e. 100 sec rise, 100 sec fall) but substituting a 10 sec flat top so that a large number of pulses could be run in a relatively short time. The harmonic content of the magnets was measured periodically during the test. No significant changes were observed after a total of 5500 pulses. During the test, which lasted approximately six months the magnets were allowed to warm up to 150 K several times for refrigerator maintenance. They were also cycled to room temperature (300 K) twice after the pulsing test. Again no change in the harmonic coefficients was observed.

## I. Introduction

In recent years improvements in materials and design techniques have made the construction of very high energy accelerators and storage rings using superconducting magnets technically feasible. However, very little is known about the long-term effects of the cyclic magnetic forces and thermal stresses that will be experienced by these magnets in day-to-day operation. Magnets whose field configuration changes with time would considerably complicate machine design, perhaps even making it impossible. The object of the ISA model magnet program is to demonstrate that superconducting magnets of accelerator quality can be built with the required reproducibility at reasonable cost and that such magnets can withstand the forces encountered during operation for the expected lifetime of an accelerating storage ring structure such as ISABELLE. A secondary objective was to gain experience in operating such magnets and their associated cryogenic hardware over an extended period under simulated accelerator conditions.

## II. Magnet Design

The ISA model magnets are dipoles of the cos θ type; wound from a single layer of wide braided superconductor. They are approximately 1 m long and have an aperture of 8 cm. The construction details have been presented elsewhere.[1] The coil halves are pressure molded at elevated temperature to form a monolithic structure which is then clamped around the beam tube which contains sextupole and decapole correction windings. A photograph of a coil end is shown in Fig. 1. The complete coil assembly is cooled in liquid $N_2$ and then inserted in a warm iron core to insure that the conductors are under compression at all temperatures. This method of construction is thought to be largely responsible for the exceptionally small amount of training experienced with these magnets.

## III. Magnet Performance

Both magnets were initially tested individually while vertically positioned in an open mouth dewar at 4.18 K. The magnets were quenched several times to check for possible training and extensive magnetic measurements were made. After these tests had been completed the magnets were mounted in a horizontal cryostat and connected in series. Figure 2 shows both magnets just prior to insertion in the dewar. The cryostat is fitted with a room temperature aperture containing two sets of magnetic measuring coils on a common shaft. The magnetic and thermal cycling tests were performed in this configuration.

Fig. 1. End configuration of ISA dipole. The [illegible] 5θ correction windings are built into the [illegible]

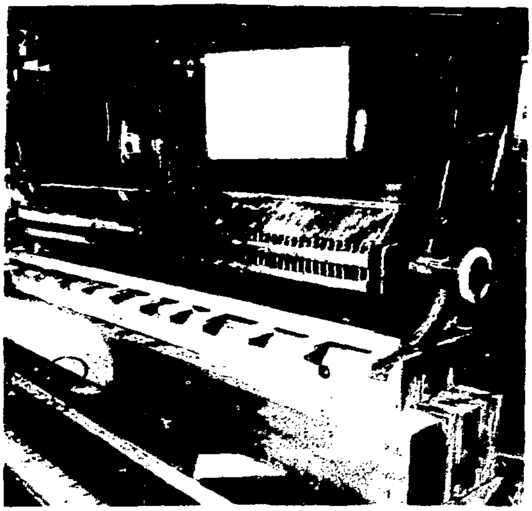

Fig. 2. ISA I and II just before insertion in horizontal cryostat.

### 1. Training

Remarkably little training was observed in either magnets. In Fig. 3 the load line for the magnets is shown on a current vs field plot for the conductor used and the first seven quench points are marked for ISA I. The two curves indicate the maximum and minimum currents observed in the wires used to make the braided conductor. I($10^{-12}$ Ω-cm) is the current at which the effective overall resistivity is $10^{-12}$ Ω-cm and is generally taken as the highest practical operating current for conductors

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containing very small filaments. Even the first quench exceeded the design current (3450 A) and subsequent quenches resulted in about 10% higher current. The field plotted in Fig. 3 is the central field and no allowance has been made for the fact that the peak field is about 5% higher at some positions in the coils. The quench history of both magnets is shown in Fig. 4.

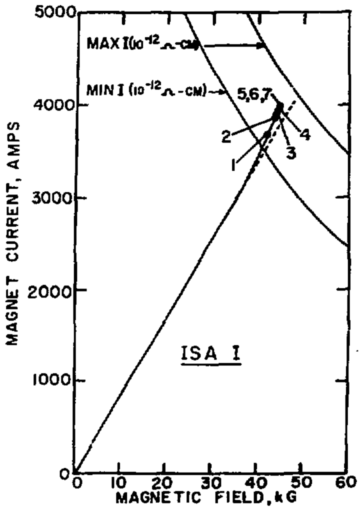

Fig. 3. Current vs field curves for the conductor in ISA I the maximum and minimum values for the individual wires used in the braid are shown for an effective overall resistivity of $10^{-12}$ Ω-cm. The number points are the first seven quenches.

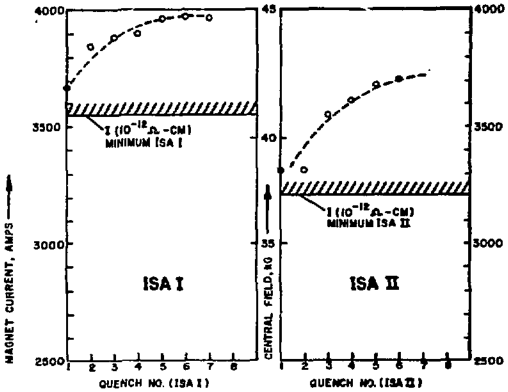

Fig. 4. The quench history of ISA I and II at 4.2 K. The horizontal line indicates the minimum current at $10^{-12}$ Ω-cm for the wires used to make the braids in each magnet.

The conductor used for ISA II is not quite as good as that used for ISA I resulting in a somewhat lower field. After warm-up the magnets reached their highest previous current on the first energizing.

## 2. Current Density

The performance of the two model magnets is even more remarkable when the high current density required in this design is taken into account. The total radial winding thickness is only 1.9 cm and the overall current density at 40 kG on the median plane is 30 kA/cm$^2$. This corresponds to 60 kA/cm$^2$ in the wires used to form the braid and 130 kA/cm$^2$ in the superconductor itself.

## 3. Temperature Dependence

When mounted in the horizontal cryostat the magnets are at a somewhat higher temperature than in the vertical test dewar because of refrigerator back pressure. The temperature can be as low as 4.25 K when the system is free of impurities. The dewar pressure increases with time as impurities collect in the return line until a temperature of 4.9 K is reached at which time the system is usually warmed for cleaning. It takes approximately three weeks for the system to collect enough impurities to require warm-up, and the clean-up process itself requires about 24 hours. Because the magnets are in series the quench current is set by ISA II, which has the lowest quench current. Figure 5 shows some quench points obtained at different temperatures and compares them with the expected values based on an extrapolation of the 4.18 K value (the dashed line). The scatter in these points is probably due to the fact that we have used the dewar pressure as a temperature monitor rather than the actual magnet temperature.

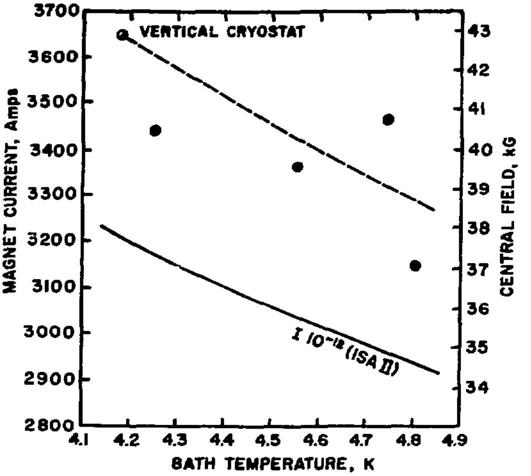

Fig. 5. Maximum current as a function of temperature for the two magnets in series with the closed loop refrigeration system. The dashed curve is the expected performance based on the results obtained at 4.18 K.

## IV. Magnetic Measurements

During the vertical test, magnetic measurements were made using a set of Morgan[2] coils of 6.9 cm diameter. This set contained dipole, quadrupole, sextupole, decapole, 14-pole and 18-pole windings. The results are shown in Table I for 6 kG (injection), 24 kG and at a high field, 40 kG, where the effect of iron saturation is evident. Calculated values for the harmonic coefficients are also given in Table I. These calculated values take into account the actual dimensions of the wedges used and the differential contraction of the coils on cooldown and represent the built-in or "construction" harmonics. Only the in-phase ($b_n$) terms are affected by these symmetric construction displacements of the current blocks. The calculated values for the out-of-phase ($a_n$) terms are based on a random error in block placement of 50 µm. The $b_n$ terms are also subject to random errors. Since the calculated values do not include the effect of superconductor magnetization or iron saturation they are only valid at medium fields where the magnetization is small and iron saturation is not important. In general, the measured values fall within the range allowed by the assumed error. The quadrupole component (2θ) is sensitive to coil centering in the iron shield and shows considerably more variation from magnet to magnet.

**Table I. Harmonic Coefficients for ISA I and II**

ISA I

| Harmonics | Measured 6 kG | | Measured 24 kG | | Measured 40 kG | | Calculated 24 kG | | Units |
|---|---|---|---|---|---|---|---|---|---|
| | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | |
| 3θ | - 3.1 | - 0.2 | - 2.7 | - 0.1 | + 2.8 | - 0.1 | - 2.6 | ± 0.3 | $10^{-4}/cm^2$ |
| 5θ | - 3.1 | - 0.5 | - 3.4 | - 0.5 | - 8.7 | - 1.4 | - 1.4 | ± 2.6 | $10^{-6}/cm^4$ |
| 7θ | 11 | 7 | 7 | 7 | 4 | 4 | 11 | ± 19 | $10^{-8}/cm^6$ |
| 9θ | - 230 | < 1 | - 170 | < 1 | - 120 | < 1 | - 300 | ± 170 | $10^{-10}/cm^8$ |
| 2θ | 0.9 | 3.5 | 1.1 | 3.7 | 0.7 | 5.4 | ± 1.1* | ± 1.1 | $10^{-4}/cm$ |

ISA II

| Harmonics | Measured 6 kG | | Measured 24 kG | | Measured 40 kG | | Calculated 24 kG | | Units |
|---|---|---|---|---|---|---|---|---|---|
| | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | |
| 3θ | - 3.6 | - 0.1 | - 3.3 | - 0.1 | + 2.2 | 0.0 | - 2.8 | ± 0.3 | $10^{-4}/cm^2$ |
| 5θ | - 5.1 | - 0.4 | - 4.6 | - 0.4 | - 9.4 | - 0.8 | - 1.9 | ± 2.6 | $10^{-6}/cm^4$ |
| 7θ | 7 | 11 | 7 | 4 | - 4 | - 4 | 8 | ± 19 | $10^{-8}/cm^6$ |
| 9θ | - 400 | < 1 | - 350 | < 1 | - 290 | < 1 | - 350 | ± 170 | $10^{-10}/cm^8$ |
| 2θ | 2.7 | 0.9 | 2.2 | 2.0 | 2.5 | 0.2 | ± 1.1* | ± 1.1 | $10^{-4}/cm$ |

*No allowance made in the calculation for noncentering of coil in iron core.

In the horizontal test configuration two sets of Morgan coils were used in the warm bore. These coils were mounted on a common shaft and centered in each magnet. Only dipole, quadrupole, sextupole and decapole (10θ) coils were used because of the small diameter available. The shaft was driven by a stepping motor under the control of a small computer (HP 9100B) which also read the signals and computed the harmonics. The system is completely automatic and is shown schematically in Fig. 6. The sextupole component of ISA I is shown as a function of dipole field in Fig. 7 for a cycle to 40 kG and back to 1 kG. From Fig. 7 it can be seen that the sextupole component returns to the original increasing field curve at approximately injection field. This curve is for dc excitation; under pulsed conditions the harmonics are altered considerably by currents induced between wires in the braid. It is expected that newer conductor types with faster dynamic response will eliminate this problem in the model magnets now under construction. An electronic scheme for automatic control of the harmonics is also under development.

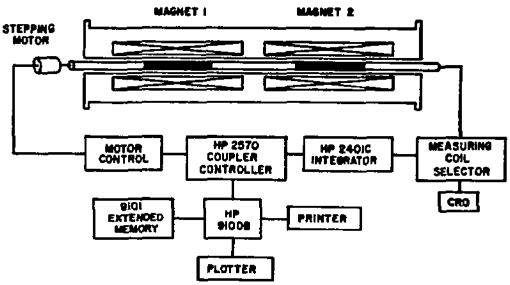

Fig. 6. Block diagram of automatic harmonic analysis apparatus.

A fixed frequency NMR set-up has been used to compare the two magnets. This device has two probes so that one can be mounted in each magnet and small differences in the fields observed directly. Since the magnets are in series, it is possible to compare them directly to a few parts in $10^5$ despite the difficulty of determining the absolute current to much better than a part in $10^3$. The measured magnetic constant for both magnets at the aluminum resonance field (20.72 kG) was

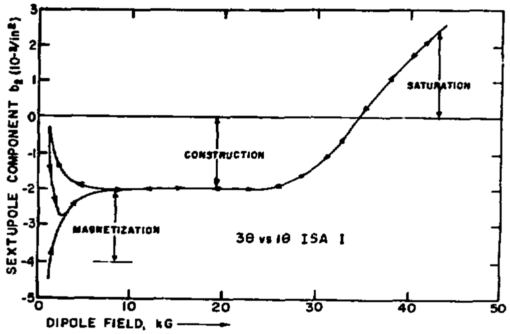

Fig. 7. Dependence of sextupole coefficient on dipole field for increasing and decreasing dc fields; ISA I.

11.73 gauss/A. The calculated value using the program MAGFLD is 11.762. The difference between these two values is less than the uncertainty in current determination.

## V. Magnetic Cycling

The magnets were cycled using a 100 sec current rise and fall and a 10 sec flat top and dead time. The idealized waveforms for the current and voltage are shown in Fig. 8 (a) and (b) and the actual waveforms are shown in Fig. 8 (c) and (d). A total of 5500 pulses were run to simulate the lifetime of an accelerating storage ring such as ISABELLE. Almost all of these pulses were to approximately 35 kG which was the highest field at which the magnets would operate for long periods without quenching due to low liquid level or high dewar temperature. The operation was completely automatic and proceeded with remarkably little difficulty. The harmonic coefficients were checked periodically during the run. No changes were observed within the accuracy of the measurement. The resolution possible from the measuring setup is $1 \times 10^{-5}/\text{cm}^2$ for the sextupole component and $5 \times 10^{-7}/\text{cm}^4$ for the decapole component. Considerable care must be taken in making the measurements since the dynamic effects can easily give differences of this magnitude if a precise measuring sequence is not followed.

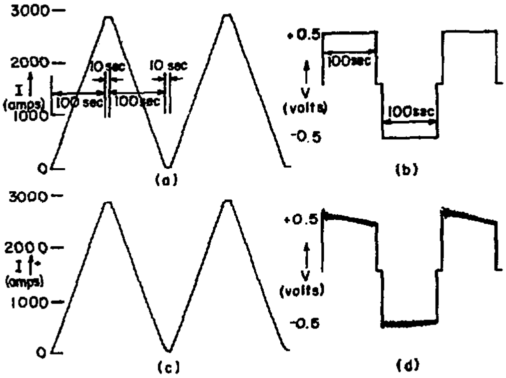

Fig. 8. Ideal and observed current and voltage waveforms for pulsing test.

## VI. Thermal Cycling

As mentioned previously, the magnets were warmed up periodically for refrigerator maintenance. The maximum temperature reached during these periods varied from 50 K to 150 K. The system would reach a temperature of 150 K if allowed to warm unattended for one week. After completion of the pulsing test the magnets were purposely warmed to room temperature by circulating helium gas and then recooled. Again no appreciable changes in the harmonic coefficients were observed during this thermal cycling. Quenching of the magnets produces a rapid temperature rise in the coils and considerable thermal shock, but this did not effect the field distribution either.

## VII. Conclusions

Both magnets performed well throughout the test. They exhibited very little training and could be operated successfully in series. The reproducibility from magnet to magnet was quite good and indicates that mass produced magnets of this type would meet the tolerances required for storage ring applications. The magnetic and thermal cycling tests indicate that no significant changes in field quality or magnet performance would be encountered during the life of a machine like ISABELLE.

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