A PRESTRESSED-CORE HOLLOW-STRAP-COIL TEST MAGNET FOR THE OMNITRON*

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Summary

Design, fabrication, and preliminary testing of a test prototype gradient magnet for the Omnitron incorporating several novel design features is reported.

The laminated magnet core achieves structural integrity with prestressed tension rods which hold the 0.014-in.-thick M-19 steel laminations with an average interlamination pressure of 200 psi. Some advantages of such a system are: elimination of strong backs for support of individual laminations, a higher steel packing factor than for glued laminations, and easy disassembly of the magnet to make changes during test and development.

Simplicity in coil design is achieved using a continuous 9/32- by 3-in. hollow-strap** aluminum conductor wound in a single layer. The high section modulus of the strap eliminates the need for coil clamps at the ends of the magnet. Furthermore, this coil design avoids multiple cooling connections between "pancakes" and saddle-shaped coil ends, because notches can be machined into the coils after they are wound.

Introduction

The Omnitron is a multipurpose accelerator facility currently being designed at the Lawrence Radiation Laboratory in Berkeley, California.[1] Current layout of the accelerator includes a synchrotron whose 64 focusing and defocusing gradient magnets have a 60 c/s peak guide field of 10 kG. External to the synchrotron is a storage ring with also 64 gradient magnets requiring a fixed guide field of 10 kG. The first prototype magnet has been built to test basic concepts of both the synchrotron and storage-ring gradient magnets. Mechanical design, fabrication, and preliminary testing of this test prototype gradient magnet is reported.

Mechanical Design

Many sets of magnet parameters can satisfy the beam dynamics and magnetic-field requirements. Both C- and H-magnet geometries have been considered for the Omnitron; the H selected for its greater compactness, its smaller stray fields, its larger contribution to radiation shielding, and its economy. For both the synchrotron and storage ring, a split H-magnet has been selected over a one-piece H-magnet. A test magnet lamination is shown in Fig. 1. The split H has a number of advantages over a one-piece H-magnet for the Omnitron; it allows for the assembly of larger cross-sectional coils, easier assembly and disassembly of the magnet, and a simpler vacuum-chamber design.

Magnet Core

For the synchrotron the magnet core material tentatively selected is AISI M-19 electrical steel sheet, 0.014-in.-thick, fully processed, non-grainoriented, with AISI Core Plate C-5 surface insulation. Other steels, such as Trancor A6, used in several existing accelerators, were also considered. For the synchrotron frequency and peak field, the improvement in saturation properties, as measured by reduced errors in the profile parameter k, of M-19 over A6, more than offset the slight increase in core loss. The storage-ring magnet cores will use a low-carbon low-silicon steel.

Basic magnet core design for the synchrotron and storage ring will be similar except for the type of steel. Here, mechanical test results of the test magnet, patterned for the synchrotron magnets, will be also applicable to the storage-ring magnets.

Whether to use hot-rolled or cold-rolled M-19 electrical steel sheet is not easily answered since mechanical and magnetic property information provided by the steel manufacturers is not easily assessed without experimentation. Since a choke is required for the test magnet, two identical test magnets have been fabricated, one with a hot-rolled M-19 core and the other with a cold-rolled M-19 core. Thus, testing both magnets will give a comparison of mechanical and magnetic properties of hot- and cold-rolled M-19.

The test magnet, having a nominal 28-in. length, requires about 2000 0.014-in.-thick laminations per split H-magnet core. A simple system has been devised to hold the 2000 laminations; namely holding them together with prestressed tension rods. Figure 2, displaying the test magnet assembly, shows two split H-magnet cores

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**A "strap" conductor is one with a cross-sectional aspect ratio of at least 10:1.

assembled. The prestressing rods exert a load on the end plates which in turn are transferred to the laminations. The prestressing rods with a combination of Belleville washers offer the advantages of eliminating the progressive "core-slackness" problem[2] due to creep after assembly and of providing an integral magnet structure that is amply strong to resist torsional and bending stresses and strains. An average interlamination pressure of 200 psi was selected which provides an adequate safety factor over the 20-psi interlamination pressure required to resist structural stresses from the shear and torsional loads imposed on the laminations through the end plates to which magnet supports are attached.

This structural design avoids the need for supporting individual laminations with a strong-back, attains a slightly higher packing factor than for glued laminations, avoids warpage due to welding, and obviously permits easy assembly and disassembly of the magnet to make changes during the test and development period.

Magnet Coil

Cost-optimization studies, using computer program MAGHYP[3], indicated that costs for magnets with aluminum coils do not differ significantly from those with copper coils. Aluminum, EC grade, was selected as the coil conductor material for the test magnet because it was readily available and easily extruded to a special hollow-strap shape. With the hollow-strap aluminum conductor (9/32-in. by 3-in. with an internal water passage 1/8-in. by 7/16-in. centered in the conductor cross section), a simple 11-turn single-layer coil has been developed. Such coils are shown in Fig. 3. A coil is wound from a single conductor length of 85 feet, thus eliminating the need for internal joints. Further, the conductor is made from a single billet, eliminating welding of multiple billets in the extrusion process, thus avoiding a potential source of leaks.

This strap conductor design does offer advantages over the square hollow design, namely, a higher coil packing factor, elimination of multiple "pancake" coil cooling connections, elimination of coil end clamps, and elimination of saddle-shaped coil ends for clearance purposes. This latter advantage is very important for the storage-ring magnets where it is planned to bring the coils down to the magnet midplane. This is shown in Fig. 4. With the strap coils, clearance for the vacuum chamber is achieved by machining notches in the coil ends after the strap conductor is wound into a coil. This machining after winding, that is possible with a strap conductor, also facilitates the fabrication of a variety of coil cross-sections, for example the chamfered edge shown in Fig. 3.

The coil insulation system selected, based on preliminary electrical and mechanical tests, uses 12-mil "Fairhope" contour knitted fiberglass, Volan treated, for turn-to-turn spacing and Hysol C-35 epoxy insulation, vacuum potted. The contour knitted fiberglass is a more open weave material than square-woven fiberglass which allows for better epoxy penetration and fewer voids in vacuum potting. Currently, a number of insulation systems are under study with electrical life tests planned for an equivalent of 10 years operation at 60 c/s.

Magnet Assembly

The split H-magnet cores are positioned, mirror imaged, with two rows of 3-in.-long glass dowels that mesh with the semicircular slots in the core laminations (see Fig. 1). One row of dowels has a close fit with the core laminations; clearance is less than ±0.0006 in. The other row allows for an accuracy of better than ±0.0006 in. in the vertical direction with an acceptable horizontal motion of ±0.0016 in.

The magnet cores are held together with side clamp bars, engaging the core dove-tails. To prevent the coils from vibrating, they are preloaded with rubber springs when the cores are clamped.

Fabrication

Magnet Core

The split H-magnet laminations are fabricated in a two-step punching process. First the steel is blanked to the approximate shape of the split H with about a quarter of an inch overlap from the final shape left on all edges for the final punching. This prepunching is necessary to obtain better dimensional uniformity of the finished laminations. Final punching produces the split H-magnet shown in Fig. 1. A dimensional check of finished laminations stamped from both cold- and hot-rolled M-19 revealed better dimensional precision with the hot-rolled material, based on the measurements of three hot-rolled laminations and two cold-rolled laminations. For example, the dimensional precision of the nominal 21.7500-in. dimension between the two semicircular indentation centerlines, was measured with ±0.0005-in. variation for the hot-rolled material compared to ±0.0016 in. for the cold-rolled material. Assuming the variations are due to internally locked stresses in the raw material, they are of a greater magnitude in the cold-rolled material.

In order to assemble the laminations into cores, a stacking fixture is necessary. The fixture is essentially a husky framework for positioning laminations with provisions for prestressing. Positioning is with two steel dowels aligned along their entire length to within ±0.0005 in. in two planes.

Magnet core assembly consists of first inserting an end plate into the stacking fixture. Next, stacks of laminations are weighed and inserted into the fixture. To insure that laminations are accurately positioned in the fixture, a small metal bar is used to tap the laminations into place. This process is continued until the required magnet weight is achieved. Then the other end plate is inserted. Prestressing rods are inserted through their respective holes in the end plates. On one end of the rods are placed Belleville washers and Allenuts and on the other end ceramic washers and Allenuts. Next, jacks are attached to the prestressing rods and pressurized such that the magnet laminations receive an average interlamination pressure of 200 psi. To eliminate initial core creep, it has been found desirable to load the core first to approximately 400-psi interlamination pressure and then reduce the load to 200 psi. Relieving the jack pressure transfers the load to the tightened nuts and core assembly is complete with removal of the core from the fixture.

Coil

Fabrication of the hollow-strap coils followed three basic steps: conductor winding, application of turn-to-turn spacer material, and vacuum potting of insulation. Conductor winding includes: internal lead fabrication, conductor winding around a mandrel with a cardboard spacer which is subsequently removed, external lead fabrication, and welding of conductor ends. After a leak tightness test with air pressure, the water passage is coated with a thin layer of Böhmite by circulating saturated steam to inhibit possible subsequent corrosion.[4] With the conductor fabrication complete, the coil is thoroughly cleaned.

The spacing between turns is provided by 12-mil contour knitted fiberglass tape which protrudes from either side of the conductor. After inserting the turn-to-turn spacer, the ground plane insulation is started by wrapping, half lapped, contour knitted fiberglass tape around the coil until about a 1/8 of an inch thickness is obtained.

The insulation system is completed by vacuum potting of the coil with Hysol C-35.

Assembly

Magnet assembly is simple. A half core is positioned such that its pole tip is facing upward. The first coil is placed in the core, with rubber protectors and electrical leads in a downward direction. On top of the coil are placed Bakelite spacers along with rubber springs. Then comes the second coil with rubber protectors and its leads in an upward direction. The glass aligning dowels are laid into the lower core and the upper core is lowered into position. Assembly is completed with the mounting and tightening of the side clamps.

Preliminary Testing

Initial mechanical tests indicate that the "prestressed-core hollow-strap-coil" design provides an excellent solution for storage-ring gradient magnets. Machining of chamfers in the coils after they had been wound and potted followed by etching with a standard sodium hydroxide solution was successful. Five-hundred-fifty volts was subsequently held between adjacent turns, spaced a minimum of 0.040 in., without breakdown. Since the storage ring guide field is steady and only a few volts per coil are required, coil notching for the vacuum tank clearance by machining after winding should present no difficulties.

The type of conductor for the synchrotron coils has not yet been selected. Preliminary data for strap coils tested in the magnet at 60 c/s ac excitation give a ratio of eddy current heating to normal ohmic heating of 5:1. This ratio was decreased to 3:1 by slightly chamfering the coils near the pole tip. Chamfering resulted in a 10% reduction in coil cross-sectional area which reduced the total coil heating (eddy current heating plus normal ohmic heating) by 1/3. Tests are proceeding to compare coils constructed of square hollow and stranded conductors for synchrotron operation.

Core performance under synchrotron operation has not been evaluated at full power, but at reduced levels (2/3 ac excitation) the core is quiet and cool with the exception of the magnet ends where the transition sections have yet to be added.

Test data on the mechanical characteristics of the magnet core indicate that the basic design concepts are quite satisfactory. The measured mechanical characteristics are as follow:

1. Elastic modulus of the laminated core. Figure 5 shows interlamination pressure as a function of core length deflection for both cold-rolled and hot-rolled steel. These curves indicate that the elastic modulus (slope) is not constant but increases rapidly with pressure. The elastic modulus of the hot-rolled laminated steel core is 1.5×10^5 psi for a 200-psi interlamination pressure and increases to about 10^6 psi for a 400-psi interlamination pressure.

2. Gravitational deflection of magnet with simple supports at ends. The magnet "sag" cannot be calculated without measurements of the elastic modulus. Using the elastic modulus data of Fig. 5, the calculated sag (.0027 in.) agrees closely with the measurements. The measured "sag" in the middle of the magnet simply supported at the ends (with an average interlamination pressure of 200 psi) was:

.0021 in. average for a half-magnet with pole tip pointing down
.0026 in. average for a half-magnet with pole tip pointing up
.0030 in. maximum for the assembled magnet

Variations of ±0.003 in. were obtained in the half-magnet core "sag" measurements. Since the sag is inversely proportioned to the elastic modulus, the sag decreases if the laminations are prestressed to 400 psi.

3. Crown buildup of hot-rolled vs. cold-rolled steel laminations. The rolling process produces

a "crown" which means that the thickness of the steel laminations is not absolutely uniform. Both the hot- and cold-rolled steel laminations were received from the factory, in blank form, with the thicker edge oriented such that the punched laminations would have their thicker edge on the pole-tip side. With the 2000 laminations stacked and preloaded, the hot-rolled material was about 0.040-in. thicker in the median plane corresponding to 0.00002-in. buildup per lamination. For the cold-rolled material the buildup was about ten times greater: 0.470 in. for the core corresponding to 0.00023-in. per lamination. Thus the cold-rolled magnet required many partial shims whereas none was required for the hot-rolled magnet.

4. Steel packing factor for the magnet core. At 200-psi interlamination pressure the magnet cores had a 95% packing factor for the hot-rolled material and a 97% packing factor for the cold-rolled material.

5. Dimensional precision of the assembled magnet. The measured straightness of the magnet was within ±.0005 in. in the horizontal direction. The core twist is 0.63 milliradians over the entire length. The magnet gap variation is within ±0.0005 in. in 27-in. length and within ±.001 in. over its entire length.

As indicated in the introduction, this paper reports mechanical test data for the first prototype magnet built to test the basic concepts of both the synchrotron and storage-ring gradient magnets. It is planned to build other prototype magnets each more nearly resembling the production magnets during the next year.

References

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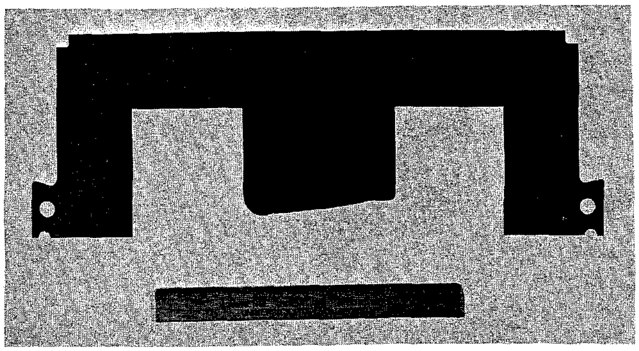

Fig. 1. Test Magnet No. 1 Core Lamination.

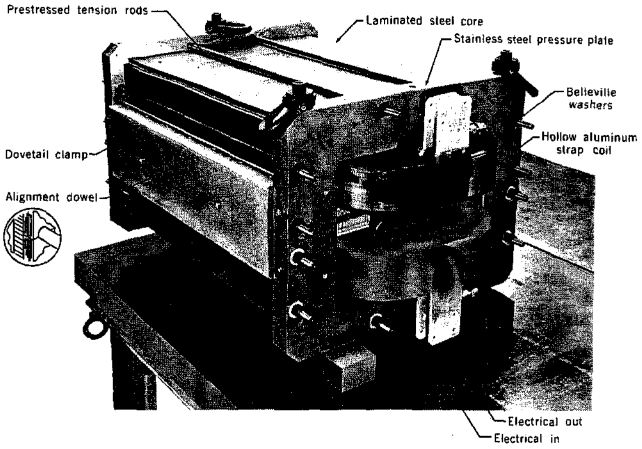

Fig. 2. Test Magnet No. 1 Assembly.

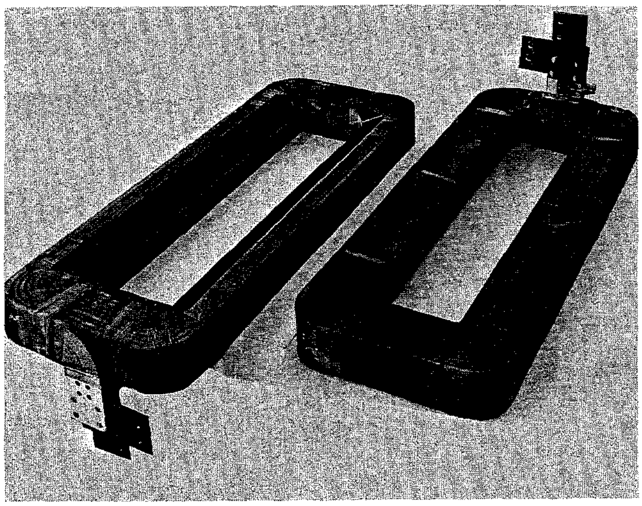

Fig. 3. Chamfered Hollow Strap Aluminum Conductor Coils.

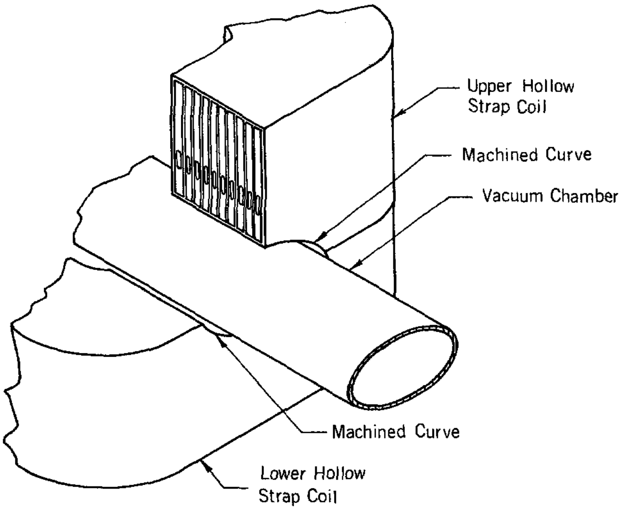

Fig. 4. Storage-Ring Coil End Detail.

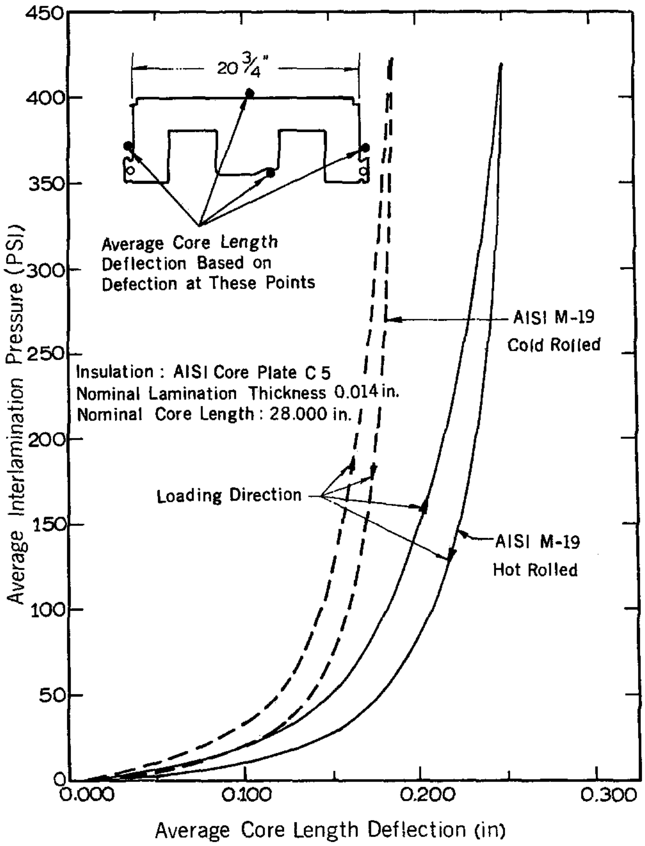

Fig. 5. Average Interlamination Pressure as a Function of Average Core Length Deflection for AISI M-19 Electrical Steel Sheet.