HIGH FIELD IRON MAGNETS FOR OPERATION AT CRYOGENIC TEMPERATURES*

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I. Introduction

This paper will describe results of testing high field iron magnets with excitation coils at cryogenic temperatures.

In various papers by Danby, Allinger, and Jackson1-5 on the properties of a separated function lattice for a large synchrotron it was pointed out that in addition to its advantages in optics and economy it had potential for a specific future improvement using iron core magnets with cryogenic superconducting coils. The design of room temperature window frame dipoles is dominated by the problem of attaining sufficiently high current densities. The replacement of the exciting coil by a much smaller area high current density cryogenic superconducting or pure metal coil would permit increasing the peak field to about 30 kG with controllable lattice aberration, thus easily obtaining 50% increase in particle energy.

This work was continued and using pulsed models immersed in liquid nitrogen (for testing convenience) it was shown that much higher fields are practical with configurations that are suitable for high energy machines. For example, Fig. 1 shows the relative saturation as a function of field for a window frame dipole, with vertical aperture as a parameter. In all cases the horizontal aperture is two inches and the coil horizontal dimension is one inch. The coil height in all cases equals the vertical aperture.

The aberration on the horizontal midplane, as a function of excitation, is shown in Fig. 2 and is almost all sextupole component.

The aberration at 41 kG, partially corrected by a pole face current, is illustrated in Fig. 3.

The coil dimensions chosen for the models are not critical since the variation in saturation and aberrations with exciting coil thickness are moderately flat functions in the domain where both the coil and the aperture are roughly square in cross section and of equal area.

Pulsing was carried to 50 kG and various methods of reducing the sextupole aberration were investigated. Correction current windings, pole face shaping and crenelations can be used to reduce aberrations resulting from the simple window frame geometry, at least partly passive or self-induced correction is attractive. It should be noted that auxiliary correction sextupoles distributed in each half cell of a large synchrotron can compensate fairly easily for 1 or 2 percent sextupole aberration as well as serving other useful tuning functions.

The current density requirements for small aperture magnets of this type can be considerably less than for equivalent air core magnets. This is true even with the iron near the pole surfaces highly saturated. For example, a 2 in. x 2 in. aperture magnet with a 2 in. x 2 in. cross-section coil has about 25% saturation at 40 kG. The same coil without iron requires about 3.2 times more current at all excitations. With the iron circuit, current elements farther from the aperture can still be efficiently coupled to the aperture region. For a given practical current density higher fields can be achieved with the iron circuit. This makes the use of high purity aluminum excitation coils at cryogenic temperatures a quite attractive possibility.

About a year ago it became known that very high purity aluminum (14,000 resistivity ratio from 300K to 4.2K) was obtainable from the Consolidated Mining and Smelting Co., Electronics Division, Spokane, Washington, in relatively large quantities. We are indebted to V. Arp and his colleagues at the National Bureau of Standards, Boulder, Colorado, for most of our information on the subject of pure aluminum.6,7

Preliminary studies indicated that cryogenic aluminum exciting coils could be competitive with superconductor excitation for a pulsed synchrotron and appeared to have many practical advantages.6

Tests have been conducted with high purity aluminum coils in a 2.5 in. vertical aperture dipole magnet model in the Brookhaven 30-inch bubble chamber. A smaller 1.25 in. vertical aperture model has been tested in both liquid H2 and liquid He.

Work on the dipole magnetic circuits as well as on cryogenic temperature iron core quadrupoles and sextupoles has continued. However, as pointed out in Ref. 6, for a very large synchrotron such as we have been interested in studying (2000 GeV/c) the scaling is such that the quadrupole tip field can be significantly less than the dipole field and still provide the necessary focusing with quadrupole length, which is only a few percent of the length of a deflection half cell.

The remainder of this paper will be devoted primarily to preliminary test results of high field dipoles in liquid H2 and liquid He.

II. Dipole Models

An approximately full-scale model (in cross section) of a dipole magnet was constructed which with refinements could be suitable for an accelerator (Fig. 4). The laminated core block with a 2.5 in. vertical aperture was rectangular in cross section and was constructed from 0.060 in. low

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carbon steel sheets. The inside dimensions were 2.3 in. x 6 in. and the outer dimensions were 11.5 in. x 15 in., i.e., 45 inches of iron surrounded the aperture and coil package. The two excitation coils were each approximately 1 in. x 2 in. in cross section. Each coil was made from 90 turns of 0.015 in. x 1 in. aluminum ribbon. One coil was made from 69 aluminum with a 14,000 resistivity ratio at 4.2°K. The other coil was made from 59 aluminum with a resistivity ratio of ~2500 at 4.2°K. Both coils were wound with 0.005 in. x 1 in. B-staged polyester tape as insulation and bonding agent. The high purity aluminum after extrusion was cold rolled to the ribbon dimensions by the supplier (Cominco). The material was not annealed for this model other than being heated for one hour at 300°F in an oven to cure the polyester tape.

The top and bottom coils were separated by 0.010 in. of Kapton H-film on the horizontal median plane and no edge cooling occurred on this surface.

No real attempt to provide gas vents in the iron core block was made in this model although this can be done quite easily. A coolant passage existed on the top and bottom faces of the coil assembly, but any substantial outflow of gas precluded the entrance of liquid hydrogen.

Except at very low power levels edge cooling of the conductor occurred only at the ends of the coils outside the core block which is adequate for low repetition rates.

Each of the two exciting coils had a voltage measuring lead attached at both ends as well as a lead attached to its center.

For a given current the voltage could be read across the outer half of a coil, the total coil, or the inner half of a coil. These see, to first order, a magnetic field of respectively 1/4, 2/4, and 3/4 of the aperture field which is parallel to the ribbon surface. The magnetoresistance for the various coil parts can, therefore, be observed as a function of their respective average fields.

The expected zero field resistivity as a function of resistivity ratio and temperature is shown in Fig. 5. The ideal lattice resistivity $\rho_l$ is plotted from data supplied by V. Arp (private communication). The practical working curves represent simply a temperature independent constant resistivity $\rho_0$, added to the ideal curve. This is due to impurity and strain and is essentially the resistivity measured at 4.2°K.

A second model dipole magnet was made which is essentially a half-scale copy of the magnet cross section illustrated in Fig. 4. The core length of this model is 7 1/2 in. This model can be inserted in a 9 in. diameter commercial liquid helium Dewar, as well as in an available liquid hydrogen Dewar.

Excitation is by means of a single coil consisting of 51 turns of the 0.015 in. x 1 in. 14,000 resistivity ratio aluminum ribbon. This single coil has voltage connections at both ends and at its center. The conductor surface cleaning consisted of an ultrasonic degreasing bath only. The coil was wound with 0.005 in. x 1 in. Kapton H-film. The entire wound coil was annealed in air at 600°F for one hour and cooled over a period of several hours.

### III. Test Results

The 30-inch Brookhaven bubble chamber was pressed into use for a limited time to provide a quick test of the full-scale model magnet. The time available permitted only a brief survey of the over-all resistivity and pulsed behavior of the magnet. The correctness of the superposition of properties of aluminum coils (as taken from established literature) and the magnetic circuit behavior could thus be tested.

For the 59 aluminum coil the zero field resistivity ratio was 835 in the bubble chamber. This gives, using $\rho = 2.64 \times 10^{-6}$ Ω-cm at room temperature $\rho = 3.15 \times 10^{-9}$ Ω-cm.

For the 69 aluminum coil the zero field resistivity ratio was 1630, giving $\rho = 1.85 \times 10^{-9}$ Ω-cm. These results were obtained at a temperature of 21°K. Referring to Fig. 5, this gives an ideal lattice resistivity of 0.75 x 10^{-9} Ω-cm. The size effect, at zero field, for this resistivity would contribute approximately 8% to the 69 aluminum resistivity and ~8% to the 59 aluminum resistivity. (At higher fields the cyclotron radius of the electrons overcomes this resistance due to surface scattering.)

69 $\rho_c$ corrected = 1.7 x 10^{-9} Ω-cm
69 $\rho_p$ corrected = 3.0 x 10^{-9} Ω-cm
59 $\rho_c = (1.7 - 0.75) \times 10^{-9} = 0.95 \times 10^{-9}$ Ω-cm
59 $\rho_p = (3.0 - 0.75) \times 10^{-9} = 2.25 \times 10^{-9}$ Ω-cm.

It is clear that this cold rolled ribbon is highly strained in rolling and is only partially annealed at 300°F. Furthermore, each aluminum conductor is sufficiently pure that the increase in resistivity due to strain and the relationship of stress to strain are roughly about the same. If it is assumed that they both received similar stress in rolling, both will have roughly the same contribution due to this cause. The difference in the resistivity then, i.e., 1.3 x 10^{-9} Ω-cm, would be due to the relative purity. Observing Fig. 5, the difference in $\rho_0$ is about 0.9 x 10^{-9} for 14,000 varin and 2500 varin material. Considering the fact that strain resistivity is the dominant contribution to the 69 aluminum and about half of the 59 aluminum, this agreement is not bad.

It is certainly clear that even in the largely unannealed state the 69 material has about half the resistivity of the 59 material. Assuming $\Delta \rho = -0.8 \times 10^{-9}$ Ω-cm is due to strain, this corresponds to a strain of ~1.3% which could be produced by a stress of ~7000 psi. This is very reasonable for the residual condition considering the history of this ribbon.

For various parts of the two coils the
magnetoresistance was measured as a function of excitation. A Kohler plot of the results is shown in Fig. 6 which gives the increase in resistivity due to magnetic field normalized to the zero field resistivity [i.e., \( \frac{\rho_B - \rho_0}{\rho_0} \)] plotted versus the product of the average magnetic field times the zero field resistivity ratio. These data are in fair agreement for the various coil segments, and also in agreement with published data which indicates saturation at \( \sim 1.8 \). This means that for high fields the resistance is \( \sim 2.8 \) times the zero field value.4,5

The magnetic circuit design is such that under pulsed load the dissipation is essentially the resistive dissipation in the coils.6 Eddy current dissipation and core hysteresis losses should be small by comparison.

Various cycles with rise and fall times in the range of 30 to 100 kG/sec and peak fields varying from 8 to 43 kG were used. Indeed, not only were secondary pulsed losses low, as expected, but the total dissipation as given by the flow rate of the warm gas boil-off from the bubble chamber seemed to be anomalously below the predicted coil dissipation. The coil dissipation was calculated by using 2.0 times the zero field resistance. This effective coil resistance was multiplied by the time integral of the square of the current for repetitive cycles.

Since the over-all dissipation was observed to be encouragingly low for pulsed cycles of interest in the brief bubble chamber test, the quantitative measurement of various contributions to the losses is now being studied in other models.

The half-scale model dipole (described in Section II) was tested in liquid hydrogen at 20.8°K and gave a resistance ratio of 1760 at low fields. This corresponds to \( \rho = 1.35 \times 10^{-9} \) \( \Omega \)-cm. With a size effect correction of 10%, \( \rho = 1.35 \times 10^{-9} \) \( \Omega \)-cm. With \( \rho_1 = 0.75 \times 10^{-9} \) \( \Omega \)-cm at 20.8°K, this leaves a residual \( \rho_0 = 0.6 \times 10^{-9} \) \( \Omega \)-cm. Assuming \( 0.2 \times 10^{-9} \) \( \Omega \)-cm impurity resistance for the 14,000 material, this gives a \( \Delta \rho \) strain of \( \sim 0.4 \times 10^{-9} \) \( \Omega \)-cm. This strain is half that of the coils in the full-scale model which were annealed at 300°F. A test of a sample ribbon with no anneal at all indicated that the 300°F strain resistivity was roughly midway between the 600°F case and no anneal.

A partial Kohler plot of the resistance of the coil parts is also included in Fig. 6 and agrees fairly well with the data on the larger model.

A suitable power supply for high power excitation was not available at the location of the liquid hydrogen Dewar and it was decided to continue the tests in liquid helium.

The coil was annealed at 750°F for one hour which approach the fully annealed aluminum properties (V. Arp, private communication).7 This assumes that the lack of surface chemical etching prior to anneal and the presence of coil insulation and coil form during the annealing cycle have not added impurities.

A plot of the resistance in liquid helium of the inner and outer half of the coil versus the average field over the entire coil (i.e., half the aperture field) is shown in Fig. 7. This plot indicates a resistance ratio of approximately 6500 at zero field. However, the size effect at low fields is 30-40% for ribbon this thin which indicates a coil resistance ratio of about 9000.

Since the large size effect in the ribbon at 4.2°K would require quite a correction to the lower field points, Fig. 7 is used in lieu of a Kohler plot. However, the saturated resistance ratio is \( \sim 8000 \).

A subsequent coil specimen was made of strips cut from the aluminum ribbon with a paper cutter, degreased, and annealed at 750°F. The strips were then wound with Kapton H-film for turn insulation and tested at 4.2°K. This coil gave a resistivity ratio of 3300 at higher magnetic fields than those in Fig. 7. This higher ratio should not at this stage be interpreted as indicating a better technique, but it does show that the modest strain induced in winding after annealing was not a problem.

In summary, actual working coils with preliminary techniques, gave resistance ratios of \( \sim 10,000 \). This corresponds to \( \rho = 0.25 \times 10^{-9} \) \( \Omega \)-cm. The material gives nominally 14,000 short sample ratio,* indicating the stress resistivity is no more than \( 0.1 \times 10^{-9} \) \( \Omega \)-cm.

These coils were wound in a flat racetrack form but are very short, in fact one-third of the ribbon is in the coil ends, so that cooldown stress is severe. With these results from 4.2°K tests one should get \( \rho = 1.0 \times 10^{-9} \) \( \Omega \)-cm at 20.38°K. Further study and long-term usage is necessary for temperature optimization, but it is clear that calculations based on operation at 20.38°K are quite conservative and practical operation at \( \sim 15°K \) is indicated.

IV. Quadrupole Model Magnet

An iron quadrupole model magnet with a 2.5 in. pole tip aperture has been tested (Fig. 8). The current density is higher than in small aperture room temperature magnets which results in a much smaller magnet. The total cross section of conductors in each slot is 1.2 in. \( \times \) 0.75 in. The coil extent in the radial direction is chosen arbitrarily, and can be varied depending on the desired optimization of size, current density and highest field of operation, etc.

This model has 24 turns per pole of 1/8 in. \( \times \) 1/8 in. copper wire and has been tested in liquid nitrogen. Preliminary harmonic analyses show a change in the 60 aberration of \( \sim 1/3 \) from low fields to 24 kG pole tip field. The measurement radius was 1/16 in. from the pole. Other aberrations appear

* The short sample, acid etched and annealed at 400°C, were measured by the NBS Group who collaborated with Cominco in the development of this material.
At the coil ends the NbTi and aluminum were soldered together. (The direction of coil winding was alternated in assembly so that connections between coils were very short.) The coil connections were, for convenience, vertical stubs of NbTi ribbon contained inside copper clips and soldered to the NbTi ends of each coil. Continuity was completely dependent on these junctions between the almost completely unstabilized ribbon. This was far from an ideal arrangement but was easiest for a first trial.

By very slowly increasing the current it was possible to obtain a maximum current of 270 A in a short sample of the NbTi ribbon. The hybrid coil magnet was tested and remained superconducting to a current of about 190 A which is equivalent to a current density of ~ 35,000 A/cm² in the NbTi. Above this current the excess switched into the aluminum to a total current of 400 A which was the maximum current used in the test.

Because of the limited coil area, the ratio of current density to field was high since only a few kilogauss were developed (200 A = ~ 5 kG average field in the coil).

These initial tests again demonstrated, as expected, that the superconducting coil could be stabilized by winding in high purity aluminum strip. The power supply involved was a regular unit used for AGS beam transport magnets and develops appreciable noise and ripple. Magnet performance was insensitive to relatively rapid changes in current.

In these preliminary tests the hybrid magnet was also pulsed several times to various field intensities, up to a maximum of 51 kG.

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References

Fig. 1. Saturation effects for various magnet geometries.

Fig. 2. Aberrations in 2.4 in. model.

Fig. 3. Sextupole aberration partially corrected by pole face windings.

Fig. 4. Schematic assembly drawing of 2.5 in. x 2.0 in. x 2.0 in. model magnet.
Fig. 5. Aluminum resistivity and resistance ratio as a function of temperature.

Fig. 7. Resistance of aluminum coils in 1.25 in. x 1.0 in. x 1.0 in. model as a function of the average field across the coil.

Fig. 6. Kohler plot giving transverse magneto-resistance of model magnet coils at liquid H_2 temperature.

Fig. 8. Schematic drawing of 2.5 in. diameter quadrupole magnet.