RADIATION RESISTANT MAGNET COILS FROM HARD ANODIZED ALUMINUM CONDUCTOR

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Summary. An extracted beam current of ~ 25 μA of ~ 575 MeV protons from the modified Nevis Synchrocyclotron[1] will strike two meson producing targets before coming to rest in a beam stop. The quadrupole and dipole transport magnets viewing the targets at close range might absorb 10^{10}-10^{11} rad/yr. or more. Conventional coil insulating techniques employing epoxy, fiberglass, alumina filled matrices can withstand, at best, a total absorbed dose of a few times 10^{10} rads. Therefore, a coil fabrication and insulating method depending entirely upon inorganic materials was developed. The coils are fabricated from hollow aluminum conductor which is wound, hard anodized, and assembled. Hard anodized aluminum sheets serve as additional layer to layer and ground insulation and inorganically bound mica mat* is used between turns.

Introduction

The advent of meson facilities at LAMPF, TRIUMF, SIN, and Nevis, capable of producing tens to hundreds of microamperes of 500-800 MeV protons, present new and difficult radiation damage problems. The protons are typically used in conjunction with production targets to produce high intensity pion, muon, and scattered proton beams. The transport magnet coils nearest a production target at Nevis will probably absorb in less than one year the total lifetime dose (~ 10^{10} rads) allowed for insulations composed of the best epoxy, fiberglass, alumina filled construction.[2] Since shielding of the coils is made impossible by tight geometrical constraints, coils insulated entirely with inorganic materials have been developed. At LAMPF and SIN, magnet coils wound with mineral insulated conductor (MgO sanwiched between a copper conductor and an outer copper sheath) have been successfully built and operated.[3] At R.H.E.L., magnet coils insulated with a ceramic strip and Portland cement matrix have been built and operated with success.[4+]

However, the advantages of making coils from aluminum conductor and hard anodizing the surfaces for insulation are very attractive. Several papers[5,6] advocating the use of aluminum rather than copper conductor in ordinary coil construction have been published. Among the advantages are:

1. Aluminum can be extruded in continuous lengths, thereby avoiding costly and possibly undependable splice joints.
2. The keystoning effect is much less in aluminum.
3. The aluminum conductor is extruded fully annealed.
4. The low density of aluminum contributes to the ease of handling. (see Fig. 4)
5. The residual activity is primarily Na^{24} ($\tau_{\frac{1}{2}}$ = 15 hrs.) and decays much more rapidly than that in copper.[7]
6. The cost of aluminum conductor per unit conductance is only $\frac{1}{4}$ that of copper.
7. Optimized magnet systems (including the cost of iron cores, magnet coils, cooling water systems and power supply capital and operating costs) made with aluminum conductor are 10-15% cheaper to build and operate.

One possible disadvantage to using aluminum for the construction of ordinary coils (assuming that the lower conductivity can be compensated with larger conductor cross sections) is the corrosion properties. Aluminum is subject to bimetallic corrosion and may require special piping. However, corrosion and damage caused by electrolysis can be essentially eliminated[8] by maintenance of high resistivity water (> 1 MΩ-cm) utilizing conventional de-oxidizing and de-ionizing water treatment methods.

At Nevis, a combination of precautions has been taken to reduce galvanic and electolytic corrosion. The Al and Cu magnet cooling water systems are independent. The Al systems are composed entirely of stainless steel or aluminum and the number of stainless to aluminum joints has been minimized. In addition, high purity (≥ 1 MΩ-cm) water is maintained by employing a mixed bed deionizing system and a nitrogen blanket over storage and surge tank water reservoirs.

Anodizing and Hard Anodizing of Aluminum

A. Anodizing

The topic of anodizing and other surface treatments of aluminum is extensive, complex, and incompletely understood. Reference 9 is probably the most complete and authoratative treatment of the subject available. We will only give a general discussion of the processes and make a few pertinent remarks as to our own experiences in later sections.

Anodizing is an anodic process utilizing the aluminum as an anode and a vat containing typically chromic, sulphuric or oxalic acid(s) as an electrolyte. Voltage applied between the anode and the vat walls causes current to flow in the forms of ions. Negatively charged anions (including O^{2-}) migrate to the aluminum anode and chemically unite, forming Al_2O_3. The characteristics of the coating formed are dependent on many factors including the nature of the electrolyte and such operating conditions as forming voltage, bath temperature, and treatment time. In addition, the alloy of aluminum and its impurities influences the results.

In industrial anodizing processes, the Al_2O_3 film growth is accompanied by dissolution of the film at the surface in contact with the electrolyte. Pores are formed which are large enough to allow continuous access of the ions to the metal. As the film thickness grows, the electrical resistance increases until the rate of dissolution of the film equals the rate of growth. There after, the film thickness remains constant. The maximum film thickness varies with the electrolyte and operating conditions.

* General Electric Mica Mat 78303
\+ This reference is a good review of the state of magnet coil construction using inorganic materials.

especially the electrolyte temperature, which affects the rate of dissolution of the film.

The anodic coating is composed of two layers: 1) a porous, thick outer layer (O.L.) and 2) a thin, dense, non-porous inner layer or barrier layer (B.L.). The B.L. is formed first and its thickness varies directly with the forming voltage. If no dissolution occurs because of the electrolyte, a maximum B.L. thickness of 14 Å/volt‡ is obtained. In typical commercial processes, however, solvent action of the electrolyte causes the final B.L. thickness to be reduced by an amount depending on the electrolyte. The B.L. thickness per volt is related to the operating conditions of the anodized process in the following ways:

Operating Condition	Influence On Unit Thickness
1 type of electrolyte	slight
2 temperature and voltage	negligible
3 current density	negligible
4 electrolytic concentration	unit thickness decreases, in general, with increases in concentration.

B. Hard Anodizing

The maximum film thickness obtainable for a given electrolyte increases with an increase in current density, voltage, or solution concentration and decreases with an increase in electrolytic temperature. Processes which employ low temperatures electrlytes (~ 0-5°c) at 30-50 amp/sq ft. current density, thus producing coatings 2-10 mils thick, are known as "hard anodizing" processes. Most commercial hard anodizing is done with 5-15% (vol.) concentrations of sulphuric acid with vigorous agitation of the electrolyte to prevent local heating. Masking of surfaces not to be coated is easily accomplished with wax, p.v.c. or laquer, and rubber or hardwood corks can be used to plug holes.

The surface of the material must be prepared carefully prior to anodizing. The surface must be chemically clean i.e. free of oil films and particulate matter and smooth, preferably equivalent to a machined finish of tens of microinches.

The designer of items to be anodized must always be cognizant of the "corner defect" effect. Hard coating does not form satisfactorily at corners since the corner cannot expand in three dimensions and a void develops. To avoid this problem the following minimum radii have been established for 1, 2 and 3 mil coats thicknesses, respectively: 1/32 in., 1/16 in., 1/8 in.

In general, the purest alloys of aluminum produce the best anodic coatings. These same alloys have the highest conductivity with respect to copper, i.e. between 55-62%. We have successfully hard anodized EC, 6061, 6063, and 1100 grades of aluminum. The EC grade has the highest conductance, but is difficult to handle or machine because of its softness.

The basic properties of hard coats are discussed briefly below:

1) Wear resistance - the abrasion resistance can compare favorably with hard tool steel. The hardness can be increased by decreasing the temperature and acid concentration of the electrolyte, and by increasing the current density and the homogeneity of the alloy. It has been observed that abrasion resistance deteriorates somewhat after six months of atmospheric exposure, probably due to hydration with the moisture in the air.

2) Heat resistance - quite good. The coating can stand short exposures to 2000°C.

3) Electrical properties - a) Resistance - increased by polishing the surfaces prior to anodizing and decreases with applied voltage and air humidity. However, moisture does not increase the conductance to the extent of other porous materials e.g. porcelain. Also the resistance is not seriously affected by crazing since voids are filled with air. A comparison of specific resistances of various materials is given in Table I.

TABLE I

Specific Resistances at 20°C (Ω/cm)

Material	Specific Resistance
Slate	10^8
Glass	$10^{11} - 10^{13}$
Porcelain	10^{14}
Dry Anodic Film (2 mils)	10^{15}
Hard Rubber	10^{15}

b) Breakdown Voltage - rises with film thickness and occurs sometime after the voltage is applied. It increases with anodizing time, current density, and bath concentration up to a maximum of 30% (vol.) H_2SO_4. Typical breakdown voltages range between 200-400 volts/mil.

4) Flexibility - poor for very hard coats. Flexibility can be increased with additives to the electrolyte but abrasion resistance is significantly decreased. Bending tests indicate that the coat crazes but adheres on the tension side and cracks and flakes on the compression side.

Fabrication Technique

The coils for use at Nevis are wound from EC-OT grade, hollow aluminum conductor (conductivity ≈ 60-62% Cu). The coil must be completely wound prior to anodizing since the anodic coating is inflexible. Therefore the coil is designed such that it can be disassembled, anodized, and reassembled with minimal distortion. In Fig. 1, Section AA, the two layers nearest the pole iron forming 16 turns, the two inner layers forming 28 turns, and the outer layer forming 14 turns are separable.

In general, each section must be spread slightly and hand polished with stainless steel wool. This is to remove gouges, knicks, burrs, and other surface damage caused by handling, shipping, and winding. The surface damages easily because it is soft but polishes easily also. Conductor should be protectively wrapped by the manufacturer immediately after extrusion to minimize surface damage.

Each section is jigged in a manner that exposes all surfaces. Areas to be used for electrical contact and for water connections are masked. The ends where electrical connections are eventually made are

‡ 1 Å = 10^{-10}m = 4 x 10^{-6} mils

used for electrical contact during anodizing. Each section is degreased and cleaned in a detergent bath and smoothed by removing 2-5 mils of material in an etching bath. Film deposits left by the etching process are removed in a sulphuric-chromic deoxidizing bath and the sections are finally anodized in a sulphuric acid bath. Interspersed are a number of hot and cold water rinses. Fig. 2 depicts the three sections of one coil after anodizing and prior to assembly.

The assembly method is indicated in Fig. 1. Because of the unusual shape of the cross section of the coil (see Section AA, Fig. 1), and the proximity of the pole iron, the inner two and the outer three layers are assembled separately and bound in the straight sections of the coil with stainless steel strips. Hard anodizing sheets of Al (32 mils) are placed between layers and around the coil exterior for additional layer and ground insulation respectively. Strips of 6 mil mica mat are placed between turns to protect against microscopic imperfections in the coating. However, the high quality of the coatings, that we are getting, indicates that the strips are probably superfluous. The two sections are assembled and strapped together at both ends of the coil as shown in Fig. 1. Additional insulation and filler pieces are used as indicated in the figure. Note from Fig. 1 that the bends are made on a constant radius. This causes air gaps to be formed between layers in the turns and eliminates the need for additional layer insulation here.

Figs. 3 and 4 show a completed coil ready for installation in a magnet. The ends of the coil have an alumina filled epoxy-fiberglass ground wrap or "cocoon", whose purpose is to exclude moisture and the atmosphere. No dependence for mechanical strength and electrical insulation is placed on this outer shell. For further protection against the ingress of moisture, the cooling water system is temperature regulated so that, under normal operation, the temperature remains above 90°F. Also, where practical, the water lead joints are placed behind shields that would prevent spraying the coils in the event of a joint failure.

At present we have two coils completely assembled, tested, and ready for installation in the iron cores. Our present plan is to grout the coils in place with White Portland or White Aluminous Cement, though this is subject to change after further tests. We have no experience, as yet, in operating completed magnets.

Electrical Test Results

A. Resistance Tests

A number of tests were performed on samples of EC, 6061, 6063, and 1100 alloys of aluminum that were hard coated to a nominal 2 mils. The samples were exposed to humid atmospheric conditions for many months. Typical values of resistivities measured as a function of voltage are listed below.

TABLE II

Resistivity as a Function of Voltage

V(volts)	Resistivity (Ω-cm)
100	1.6×10^{11}
200	1.6×10^{11}
300	1.0×10^{11}
400	0.3×10^{11}
500	0.08×10^{11}

These values are comparable to materials such as glass, hard rubber, and mica.

B. Breakdown Voltage

The samples above were tested with 500 volts across one coat and 700 volts across two coats without breakdown. The coil shown in Fig. 3 was impulse tested at 17 volts/turn and 1,000 volts from the conductor to the stainless steel strip (across 3 coats) without breakdown.

Final ground tests will be performed after the coils are installed in the iron cores.

Cost Considerations

In these days of very tight budgets, economical considerations were given high prioity in choosing between the alternative methods of producing radiation resistant coils. No cost figures are availabe for the concrete magnet design but a coil similar in size and shape could be made from the standard size, 0.53 in. square hollow m.i. cable.[3] Therefore, we will give our absolute costs and, in addition, compare the total cost of two systems of magnets of identical size, shape, field strength, and ampere-turns, one made of m.i. cable and one of the hard anodized construction indicated in Fig. 1. A coil manufacturer experienced in both coil constuction techniques indicates that the cost of winding the conductor onto a winding form or mandrel is equal (about \$1.00/ft.) for both conductors of equal cross section. Therefore the difference in cost arises primarily from the cost of the m.i. cable compared to the cost of all the handling and processing procedures outlined earlier plus the extra cost of additional insulation. We will ignore problems of ceramic water connections to the coils since they are approximately equal in complexity and cost. The cost of 18,000 ft. of the hollow, 0.53 in. square m.i. cable (enough to make 32 coils similar to the one shown in Fig. 1) is approximately \$3.50/ft.

Our costs are as follows, assuming a 0.52 in. x 0.50 in. cross section hollow aluminum conductor (EC grade) with the same size cooling hole and based on the manufacture of 32 (16 left and 16 right) coils. We have taken into consideration the space occupied by turn to turn and layer to layer insulation.

Category	Cost/Coil	Cost/Ft. of Coil	% of Total Cost
1. Aluminum conductor including material, tooling charges, and shipping	$100.00	$0.22	9
2. Hard anodizing of coils including tooling	510.00	1.13	47
3. Sheet insulation including material, labor, and anodizing	175.00	0.39	16
4. Assembly cost including labor, mica material, and cocooning	300.00	0.67	28
TOTALS	$1085.00	$2.41	100

Thus, this particular design for the coil costs about 30% less than a comparable coil constructed with m.i. cable. One will note from the above figures that 16% of the cost goes into additional insulation. This is primarily because of the limitations on the anodizing equipment which is voltage limited at 50 V d.c. Higher voltages would permit the deposition of 6-8 mils of coating instead of our typical 2-3 mil values, thus eliminating the need for other insulation.

Forty seven per cent of the cost arises from anodizing the coils. This figure could vary considerably depending upon the geographical location of the firm, and upon the size and complexity of the coils.

The resistance of aluminum conductor is 70% of the resistance of the m.i. cable. That is, for the same number of amp-turns, the ohmic power loss of the aluminum coil is 70% less. Thus, comparable savings are realized with the power and cooling systems.

Conclusions

Hard anodized aluminum conductor coils have been successfully built and tested, but have not been operated in assembled magnets, as yet. Coils exposed to normal operating conditions have been electrically tested at values 10-40 times normal operating values. However, coils of this type are not suitable for voltage applications which exceed several thousand volts unless precautions are taken.

A comparison with identical m.i. cable type coils yields the following results:

1. Items 2,3,4, and 5 from page 1 apply.
2. Each conductor type costs about the same to wind.
3. Each can be extruded in very long lengths, obviating the need for splice joints.
4. The cost of identical magnet systems (including iron core, coils, water system and power supply capital and operating costs) made with Al are 25 % cheaper to build and operate. Operating costs are based on 10 yrs. service at todays' New York City area power costs. Initial costs might be reduced by process and design improvements.

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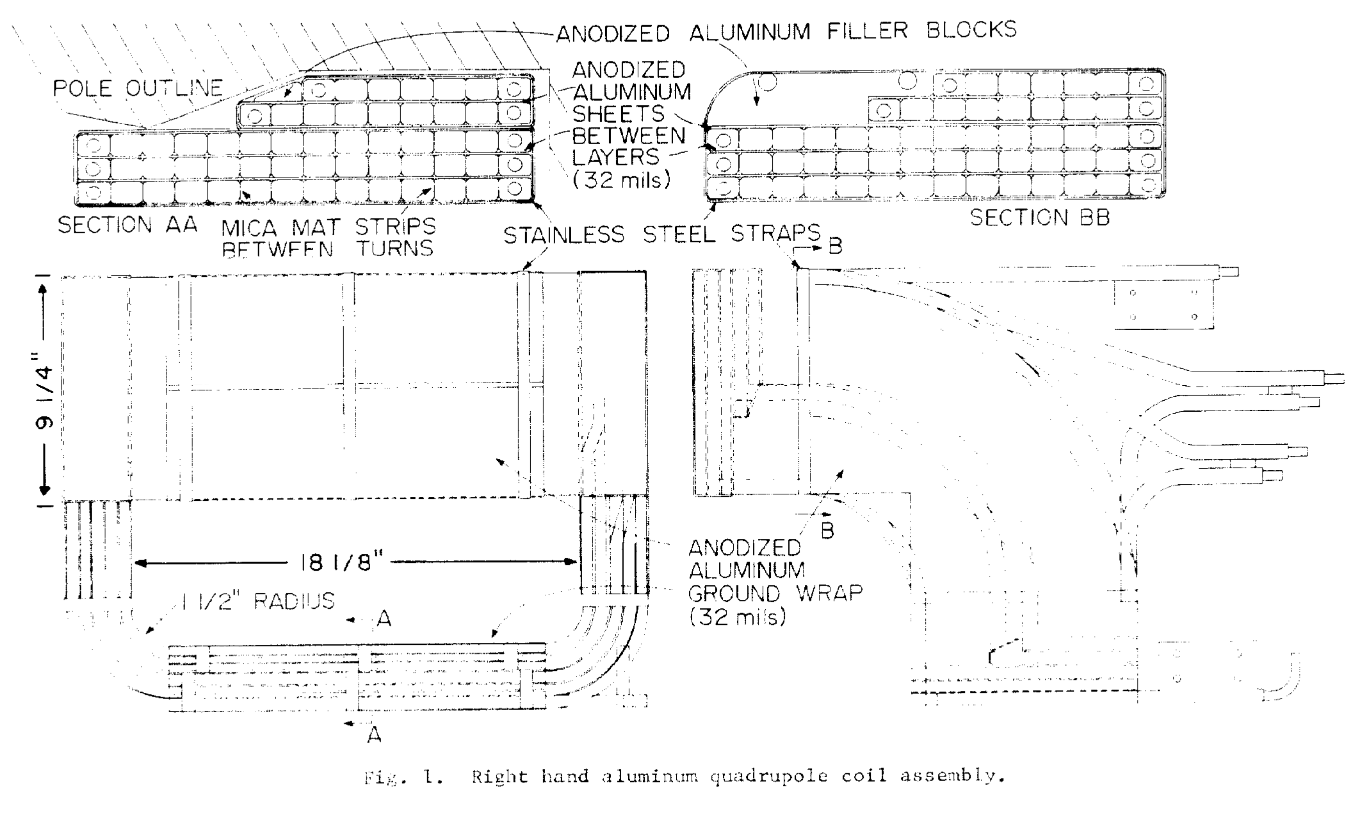

Fig. 1. Right hand aluminum quadrupole coil assembly.

City, N.Y., in developing these coils, and to Prof. Martin Rickey, of the University of Indiana for several helpful discussions.

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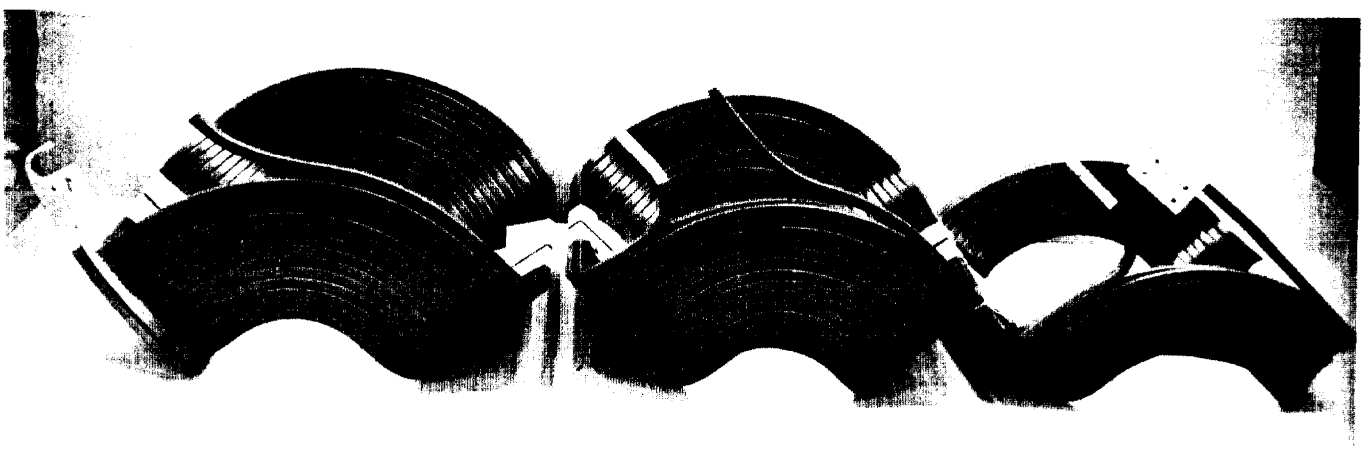

Fig. 2 Hard Anodized Quadrupole Coil Sections Ready for Assembly

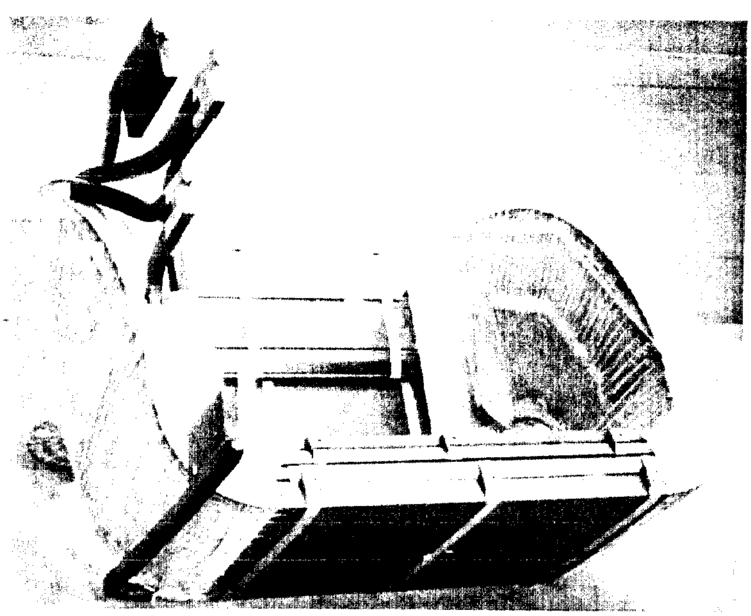

Fig. 3 Hard Anodized Quadrupole Completely Assembled Including "Cocoon".

Fig. 4 Completed Coil Weighs Less Than 150 lbs.