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INFORMAL REPORT

Radiation-Hardened Magnets Using Mineral-Insulated Conductors

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by

A. Harvey

This report is based on a paper published in the Proceedings of the Fourth International Conference on Magnet Technology, Brookhaven, September 1972. It has minor revisions and has been updated.

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ABSTRACT

A unique feature of the LAMPF high-intensity linac experimental area is the extensive use of inorganic magnet coils to withstand the high radiation doses expected.

In a large number of these magnets the coil insulation is compacted magnesium oxide powder ("mineral insulation," m.i.) and pre-insulated cable is wound into the required coil configuration. Although the cable itself is expensive compared to bare copper conductor, the finished coil cost is comparable to a conventional coil, since no insulation application is required of the coil winder.

Two conductor formats are used at LAMPF: solid conductor, externally cooled, using soft solder to improve the heat transfer within the coil; and directly cooled, hollow conductor m.i. cable. At LAMPF both conductor types are conservatively rated. Indirectly cooled coils are used exclusively in the switchyard magnets, where low field strengths and high quality are required. Higher-power magnets for target-to-target transport and secondary beam lines use direct cooling. Methods of making terminations on the cable are described.

Measured operating parameters for all these magnets are tabulated. Pole-shaping techniques for the bending magnets and quadrupoles are examined and the results given.

I. INTRODUCTION

One of the dominant problems facing the designers of the LAMPF experimental area was the anticipated high radiation dose arising from the high intensity of the beam. The 1 mA average current of 800 MeV protons impinging on a target such as graphite or molybdenum is expected to produce radiation doses in the target cells of 10^{11} - 10^{12} rad/yr. "Conventional" magnet insulations (e.g., epoxy-fiberglass, with a radiation tolerance of 10^{10} rad max) were ruled out, and after some consideration, "mineral-insulation" was decided on for the main beam line and some secondaries.

"Mineral-insulation" is a term from the wire and cable industry, used to describe an electrical insulation of metal oxide (usually magnesium oxide). The oxide is in the form of a powder, generally held around the copper conductor by a copper sheath (see Fig. 1). Although multiple conductor formats are

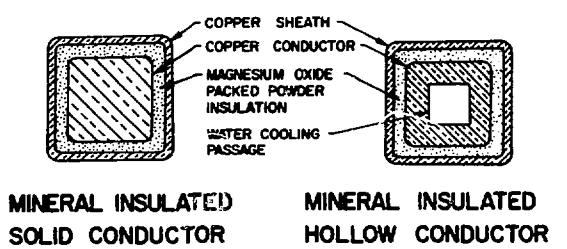


FIG. I

common in the industry, only one conductor is required for magnet coil fabrication. The development needed was to make the cable square, to improve packing in a coil, and to provide direct conductor cooling for higher current densities.

This paper illustrates the successful achievement of these objectives. It should be noted that at present there are only two plants in North America with the capability of producing the cables described here: Pyrotenax of Canada Ltd., in Trenton, Ontario, Canada, and General Cable Corp., in Perth Amboy, N.J. All of the m.i. cable used at LAMPF has been produced by Pyrotenax of Canada Ltd.

II. CABLE

Formats

Two formats of mineral-insulated cable are used at LAMPF. The solid conductor cable is a single-conductor cable of conventional construction, formed square outside, and used with external cooling (indirect cooling).

Hollow conductor cable has a hole in the center of the conductor to allow direct water cooling, and hence, higher current densities (Fig. 1). This is a rather significant change in the usual manufacturing process for mineral-insulated cable, but has been done before.[1]

Manufacture

General

Two manufacturing methods are currently employed to produce m.i. cable commercially. In the first method, short tubular preforms of magnesium oxide are pressed and baked, and then loaded into the annulus between the conductor rod and sheath tube. In this case the reduction in cross section by drawing is generally not great (about 50% on diameter in several draws). Each one or two draws is followed by an annealing cycle to soften the copper.

The second method fills the annulus between the conductor rod and sheath tube (the latter about 2" o.d.) with MgO powder, tamped firmly in an assembly up to 30 ft long. This then is reduced to the required size (with anneals as necessary between draws). In either method square cable is produced by using square dies instead of the usual circular ones for the final draws.

The maximum length of cable that can be manufactured is set generally by the length of the assembly at the start, and the annealing furnace used when the cable cannot be coiled, since later draws use a bull-block, coiling up the cable, and so are capable of handling any length of cable. Current technology gives the edge on length to the powder-fill method, and Table 1 lists the lengths now available.

TABLE 1.
Maximum Available Lengths
for Mineral-Insulated Cable

Solid		Hollow	
Nominal Size	Maximum Length	Nominal Size	Maximum Length
0.25" sq	1,950 ft	0.375" sq	550 ft
0.375" sq	820 ft	0.53" sq	220 ft
0.412" sq	650 ft	0.75" sq	220 ft
0.53" sq	410 ft		

Solid Conductor

Solid conductor m.i. cable for magnet use is basically a standard round, single-conductor, mineral-insulated cable, formed square in cross section. However, the insulation thickness required by the conservative electrical licensing authorities for use in 600V rated power wiring is more than a magnet designer needs, since it reduces his packing factor and the magnet voltage generally does not exceed 200V. To date we have succeeded in providing minimal insulation thickness only in the 0.25" sq size (see Table 1). Given sufficient inducement there is no doubt the manufacturer could do the same in the other sizes.

Specifications for the three sizes of solid-conductor m.i. cables used at LAMPF are given in Tables 2 through 4. The pertinent comment here is that the 0.412" square and 0.53" square sizes are standard circular, single-conductor m.i. cables drawn square. However, the 0.25" sq size requires a special manufacturing process (note the packing factor for this size is 32%, quite good for such a small conductor).

TABLE 2.

Mineral Insulated Solid
Conductor Cable, 0.25" Sq.

Specification: Overall size: 0.25" sq + 0.000" - 0.010"
Corner radius 0.050" max
Conductor size: 0.157" nominal square outside
Insulation thickness: 0.015" minimum
0.020" nominal
Sheath thickness: 0.020" + 0.005" - 0.00"
Materials: Conductor: copper, 100% I.A.C.S.
Max. resistance at 25°C: 0.4 Ω/1000 ft
Insulation: compacted magnesium oxide
Sheath: copper, commercial anneal. Free of burrs, nicks and scratches.
Tests: Insulation resistance, inner conductor to outer sheath > 5,000 MΩ/1000 ft at 25°C, 100V dc
Dielectric strength, > 1,250V rms inner conductor to sheath, 1 min.
Immersion of coiled cable (except ends) in warm water for 30 min. to produce no change in insulation resistance.
Weight: 180 lb/1,000 ft
Nominal current rating: 125A
Shipping: Coiled to minimum diameter of 2 ft. All ends of insulation sealed against moisture.

TABLE 3.
Mineral Insulated Solid
Conductor Cable 0.412" Sq.

Specification: Overall size: 0.412" sq + 0.000" - 0.010"
Corner radius 0.032" max
Conductor size: 0.238" nominal square outside
Insulation thickness: 0.030" minimum
0.060" nominal
Sheath thickness: 0.027" ± 0.005"
Materials: Conductor: copper 100% I.A.C.S.
Resistance: 0.159 Ω/1000 ft nominal
0.169 Ω/1000 ft maximum
Insulation: compacted magnesium oxide
Sheath: copper, commercial anneal, free of nicks, scratches and burrs
Tests: Insulation resistance, inner conductor to outer sheath > 5,000 MΩ/1000 ft at 25°C, 100V dc
Dielectric strength >1,500V rms inner conductor to sheath, 1 min.
Immersion of coiled cable (except ends) in warm water for 30 min to produce no change in insulation resistance
Weight: 425 lb/1000 ft
Nominal current rating: 180A
Shipping: Coiled to a minimum diameter of 3 ft. All ends of insulation sealed against moisture.

TABLE 4.

Mineral Insulated Solid
Conductor Cable 0.53" Sq.

Specification: Overall size: 0.53" sq + 0.000" - 0.010"
Corner radius 0.032" max
Conductor size: 0.350" nominal square outside
Insulation thickness: 0.030" minimum
0.060" nominal
Sheath thickness: 0.030" ± 0.005"
Materials: Conductor: copper 100% I.A.C.S.
Resistance: 0.0795 Ω/1000 ft nominal
0.0844 Ω/1000 ft maximum
Insulation: compacted magnesium oxide
Sheath: copper, commercial anneal, free from nicks, scratches and burr
Tests: Insulation resistance, inner conductor to outer sheath > 5,000 MΩ/1000 ft at 25°C, 100V dc
Dielectric strength > 1,500V rms inner conductor to sheath, 1 min.
Immersion of coiled cable (except ends) in warm water for 30 min to produce no change in insulation resistance
Weight: 726 lb/1000 ft
Nominal current rating: 300A
Shipping: Coiled to minimum diameter of 4 ft. All ends of insulation sealed against moisture.

Hollow Conductor

To enable direct water-cooling of the conductor, a hole is required in the center of the conductor. Again, two methods are available to produce this: using a die in the bore (either fixed or floating), or filling the bore of the conductor to prevent its collapse during drawing. This latter method requires the filling to be easily removable for annealing and final use. Again, lengths available are listed in Table 1. Specifications for two sizes are given in Tables 5 and 6.

Tests

Electrical. The electrical characteristics of the cable are of paramount importance, and in fact, because of the inherently irregular configuration of the conductor, are specified in preference to mechanical dimensions. It should be clear that the outside dimensions of the cable, being produced by drawing, can be held to close tolerances. However, the conductor itself is formed by the intermediate MgO layer, and the outside and inside of the conductor are difficult to define in dimensional terms.

TABLE 5.

Mineral Insulated Hollow Conductor Cable 0.53" Sq.

Specification: Overall size: 0.530" sq + 0.000" - 0.010"
Corner radius 0.063" maximum
Conductor size: 0.36" nominal square outside
0.18" nominal square inside
0.050" minimum wall thickness
Insulation thickness: 0.020" minimum
0.055" nominal
Sheath thickness: 0.030" ± 0.005"
Materials: Conductor, copper, 100% I.A.C.S.
Max resistance at 25°C: 0.091 Ω/1000 ft
Insulation, compacted magnesium oxide
Sheath: copper, commercial anneal
Tests: Insulation resistance, inner conductor to outer sheath > 5,000 MΩ/1000 ft at 25°C, 100V dc

Dielectric strength, > 1,500V rms inner conductor to sheath, 1 min
Water tests: 300 psi water in central hole to produce no change in insulation resistance
Immersion of coiled cable (except ends) in warm water for 30 min to produce no change in insulation resistance
Water flow: 0.5 USGPM, with max pressure drop 1.0 psi/ft
Weight: 0.6 lb/ft
Nominal current rating: 750A
Shipping: Coiled to minimum diameter of 4 ft. All ends of insulation sealed against moisture. Tube ends plugged.

TABLE 6.

Mineral Insulated Hollow Conductor Cable 0.75" Sq.

Specification: Overall size: 0.75" sq + 0.00" - 0.01"
Corner radius: 0.08" max
0.04" min
Conductor size: 0.57" nominal square outside
0.26" nominal square inside
0.09" min wall thickness
Insulation thickness: 0.05" nominal
0.03" minimum
Sheath thickness: 0.035" ± 0.005"
Materials: Conductor: copper 100% I.A.C.S.
Max resistance at 25°C: 0.035 Ω/1000 ft
Insulation: compacted magnesium oxide
Sheath: copper, commercial anneal
Tests: Insulation resistance, inner to outer > 5,000 MΩ/1000 ft at 25°C, 100V dc
Dielectric strength, > 1,500V rms inner conductor to sheath, 1 min
Water test: 400 psi water in central hole to produce no change in insulation resistance
Water flow: 2.5 USGPM, with max pressure drop 200 psi/180 ft
Weight: 1.4 lb/ft
Nominal current rating: 1800A
Shipping: Coiled to minimum dia of 4 ft. All ends of insulation sealed against moisture. Tube ends plugged.

It is more reasonable, then, to define (1) a conductor maximum resistance (which controls both the cross-sectional area and the copper quality), (2) an insulation resistance between conductor and sheath, which controls the quality (mainly dryness) of the magnesium oxide insulation, and (3) a high-potential test, which controls the minimum insulation thickness. Tables 2 - 6 give examples of such specifications.

Mechanical. Arguments similar to those above lead to very few mechanical parameters being specified. The outside dimensions are given, with low-side tolerances only, for convenience. A corner radius is desirable to reduce the tendency to crack at bends.

Conductor lengths are chosen to suit the particular design: the maxima for various sizes are listed in Table 1.

Hydraulic. The hydraulic tests serve two purposes: to insure adequate cooling flow, and to insure the integrity of the sheath and conductor wall.

The water-flow test specifies a maximum pressure drop for the flow required to maintain cooling at the rated current, and controls the cross section of the cooling passage. It may be noted that, again, this hole may be irregular; the common practice of blowing a ball through the cooling passage is not recommended with m.i. cable.

Two tests check the integrity of the copper enclosing the MgO insulation. An immersion in water tries the outer sheath, while pressurizing the cooling passage with water checks the conductor wall. Measuring insulation resistance after these tests determines if there has been any water penetration into the MgO. This test is extremely sensitive, since the loss of insulation resistance caused by moisture is catastrophic.

III. COILS

General

The manufacture of coils from m.i. cable is generally similar to conventional techniques, with the main difference being that no insulation application is required. Coil forms are standard, and tension is applied in the usual way. The relatively long lengths in which m.i. cable is available makes joining generally unnecessary: LASL practice has been to make terminations and external joints when the lengths are not adequate. An advantage of this system is that, in case of insulation problems for instance, individual sections can be isolated and tested.

A parameter of interest in coil design and fabrication is the minimum bending radius. There are two criteria which can be used: the first, within a coil, is the amount of "keystoning" which is produced; and the second (on leads, for example) is simply the smallest radius which will not damage the cable sheath. Both criteria are listed in Table 7.

TABLE 7.

Cable Size	In-coil Min. Radius	Keystoning	Out-of-Coil Min. Radius
0.25" sq	0.9"	0.010"	0.6"
0.375" sq	1.1"	0.012"	0.75"
0.412" sq	1.25"	0.010"	1"
0.53" sq	1.75"	0.02"	1.5"
0.75" sq	2.5"	0.02"	2"

It must be stressed that, in bending the conductor outside a coil, particularly to minimum radius, a mandrel and bending fixture are necessary. The copper sheath is soft and less than 0.04" thick, and can be damaged by local pressure. Moreover, the cable, particularly in the larger sizes, 0.75" sq., does not take kindly to being re-bent. A single bending operation to the final configuration is essential in this size.

Indirectly-Cooled Coils

For magnets requiring low power densities (at LAMPF, the switchyard magnets, where fields generally do not exceed 4 kG because of the H^- beam) it is feasible to use a solid-conductor cable, cooled externally, to wind coils. As has been pointed out previously[2], soft-soldering can be used to effect the heat transfer from conductor to cooling channels. This still seems the most economical way to provide the requisite metallic path for heat conduction: the quality of the soldering required is dependent on the heat transfer efficiency (and so, power density) required. One requirement we have found necessary is to insure that no corrosive flux remains in the final soldered assembly. We also require pre-tinning of the cable.

Since heat from the conductor traverses insulation only once before being transferred by the matrix of copper sheaths and solder to the cooling channels, relatively high current densities may be used. Table 8 gives, in addition to recommended current densities already published,[3] limiting current densities which will cause solder melting in

TABLE 8.

Cond. Size	Recommended Current Density	Current	Maximum Current Density	"Solidus" Current
0.25" sq	5100 A/in^2	125A	11,800 A/in^2	290A
0.412" sq	3200 A/in^2	180A	6,575 A/in^2	370A†
0.53" sq	2450 A/in^2	300A	5,720 A/in^2	700A*

* 8-layer coil: would be less in a 10-layer coil.

† Cast coil: We have seen melting as low as 205A in a poorly soldered coil.

10-layer test coils, water-cooled on one side. Both these ratings depend on the quality of the soldering (i.e., the voids left in the coil).

Note that the temperature rise in the cooling water of such coils is small, and by having the cooling coils on the outside of the coil, adjacent to the iron, temperature changes in the iron are minimized. This was a factor in the design of the LAMPF switchyard magnets, where high field quality was required (see Fig. 2).

Soldering. There are a number of ways to solder the cable and cooling-coil assembly together. We outline three methods here, with their relative advantages and disadvantages, but three features are common to them all. 1) Tinning the cable before (or during) winding is the only way to insure that solder wets the sheath inside the coil. 2) The coil dimensions have to be maintained during soldering. Steel banding straps will hold the coil cross section, and are easily removed after soldering, as the strap is not wet by solder. 3) Any corrosive flux must be excluded from the finished coil assembly. Since removal is difficult, the safest course is to solder the pre-tinned parts without using flux. This is quite practical if care is taken to avoid excessive oxidation of the tinning.

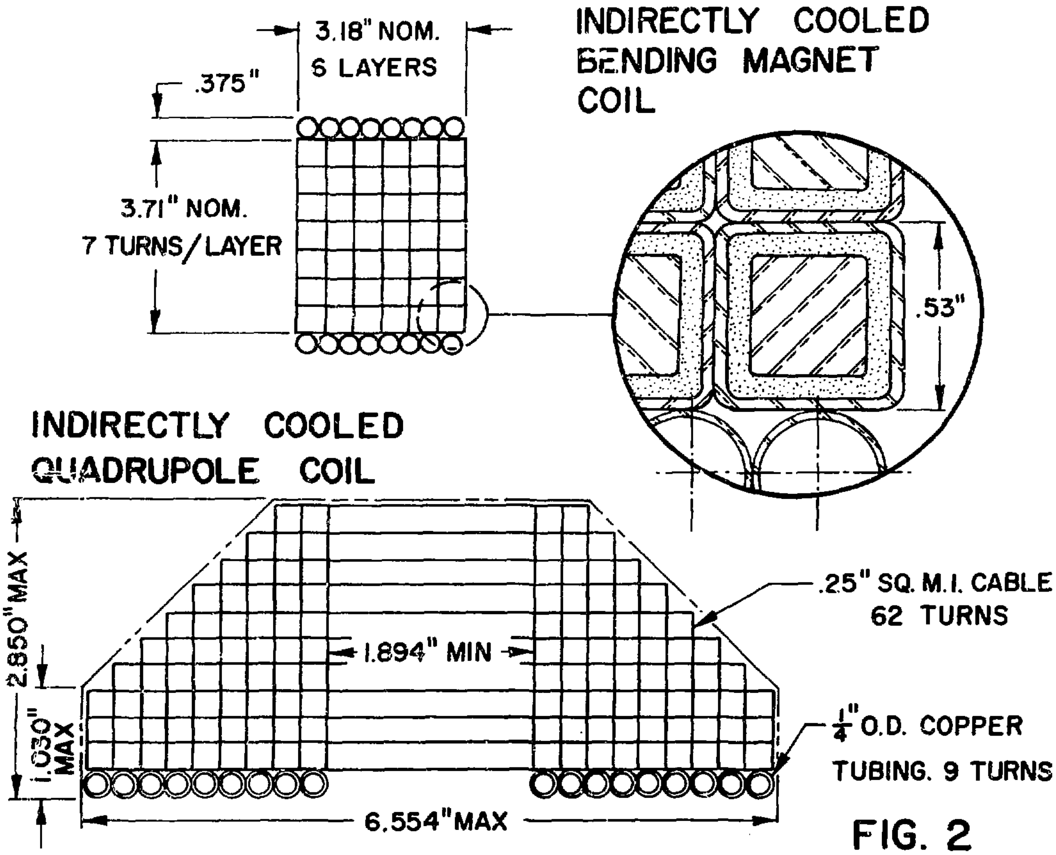


FIG. 2

A. Dip Soldering. This requires a solder bath larger than the coil assembly to be soldered, so is probably the most expensive method of the three. Further, it is necessary to remove the coil from the bath at a temperature as close to the solidus point as possible, otherwise most of the solder simply runs out of the coil. It is difficult to provide void-free construction this way.

B. Casting. Here the coil assembly is placed in a mold and molten solder is poured in. Preheating of the coil seems desirable to insure penetration to the inside of the coil, but if this is done, this method produces the best filling of the coil, hence the maximum heat transfer. This method has been used in-house, evacuating the mold and coil before casting, or simply furnace-heating both.

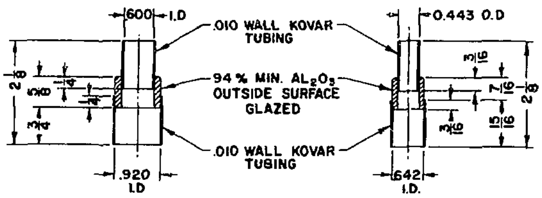
C. Resistance Heating. The coil may be heated electrically (using the conductor) and solder applied from the outside, usually with the assistance of local torch (flame) heating. A chill plate on the bottom of the coil prevents excessive loss of solder (a cooling coil may be used as the chill plate). This is probably the cheapest method of soldering the coil, as no special equipment is required, but the quality of the job depends on the care which is taken, and some judgment is required of how much solder to add to the coil to fill most of the internal voids. However, for conservative ratings, such as are used at LAMPF, the results are perfectly satisfactory.

Terminations. The sealing of the MgO insulation (to keep moisture out) is a problem common to solid and hollow conductor m.i. cables. Since the radiation environment dictates the use of an inorganic insulation in the cable, non-organic seals are used at LAMPF. A fairly standard ceramic-to-metal seal (see Fig. 3) is squared at the larger end to fit the cable sheath. Nickel ends form

NOTES

1. Silver brazed, vacuum tested by helium leak detector

2. Metal ends copper plated 0.0001 to 0.0005 th'k. × 1/2 lg. min.



0.75 SQ. M.I. CABLE   0.53 SQ. M.I. CABLE

FIG. 3

CERAMIC SEALS

relatively easy; Kovar may be formed if pressure is applied to all four sides simultaneously. The conductor is machined to a more circular cross section (by a hollow mill in a hand drill) and the seal is soldered in place. Two soldering techniques are used, both intended to keep flux from reaching the MgO insulation, which seriously and permanently degrades its insulation resistance. Note that the copper plating is essential for both methods.

1. Soft-Soldering

   a) Tin the ends of the ceramic-to-metal seal with 50-50 solder (flux permitted), wash in hot water and dry. Check insulation resistance and leak tightness.

   b) Cut back the cable sheath to the required distance, clean copper slivers and dust from the MgO surfaces, and thoroughly clean the copper (wire brush).

   c) Put a temporary epoxy seal in the end of the MgO. We suggest Hysol 615 or Astrodyne Thermal-Bond 312.*

   d) Mill the conductor section exposed, and check that the seal fits.

   e) Tin an inch or two of cable sheath and adjacent conductor with 50-50 solder (flux permitted), wash and dry.

   f) Remove temporary epoxy seal completely and check cable insulation resistance. Dry out if necessary.

   g) Put seal in place and solder using no flux and a reducing torch flame. Build up a substantial layer of solder at both joints.

   h) Recheck cable insulation resistance and follow for a day or two for signs of moisture penetration.

2. Hard-Soldering

   a) Cut back the cable sheath to the required distance, clean copper slivers and dust from the MgO surface, and thoroughly clean the copper (wire brush).

   b) Put a temporary epoxy seal in the end of the MgO. We suggest Hysol 615 or Astrodyne Thermal-Bond 312.*

   c) Mill the conductor section exposed and check that the seal fits. Note that in this case the epoxy seal serves largely to avoid losing MgO powder from the annulus during this operation.

   d) Remove the epoxy seal completely and check the cable insulation resistance. Dry out if necessary.

   e) Put seal in place and braze ends to copper using AWS BCuP-5 (Silfos) using no flux.

   f) Recheck cable insulation resistance and follow for a day or two for signs of moisture penetration.

Although the second technique has fewer steps, it requires more skill of the operator since the higher melting point of the solder increases the risk of damaging the ceramic-to-metal seal. It is now the preferred method at this laboratory.

The seals used at LAMPF are of simple, inexpensive design. They are available from a number of ceramic-to-metal seal manufacturers.* If high conductor temperatures or rapid changes in current

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*The Hysol epoxy is fast-setting (3-5 min) but will not tolerate a warm cable. If the cable has been warmed (to drive out moisture) the Astrodyne epoxy can be applied satisfactorily: its drying time then is ½-6 hours depending on the temperature.

*Alberox, Ceramaseal, Latronics, R & W Products are anticipated, which might cause relative movement between conductor and sheath, seals can be made with a flexible metal disc incorporated in the end, to minimize the strain on the ceramic.

There may also be situations where radiation-hardening of the seal is not necessary. Then an epoxy seal (similar to the pot seals provided by m.i. cable manufacturers for circular power cable) may be used. Removal of the MgO for 1/8" from the end, and filling this space with epoxy well bonded to the conductor and sheath provides a seal of good strength. A piece of 1" i.d. copper tubing, an inch long, can be squared for 1/2" and used as a pot on the 0.75 in. sq cable.

All seals require that care be taken in subsequent handling or manipulation of the cable end to avoid mechanical damage. At LASL seal installation is an in-house operation, and one of the last to be performed on the magnet.

Directly-Cooled Coils

Winding. Techniques for winding hollow m.i. cable are again quite conventional apart from insulation application. It is desirable to keep the conductor bore sealed to prevent foreign material entering the coolant passage, and, as with all operations on m.i. cable, the MgO should be sealed.

Cooling Connections. Directly-cooled conductors require insulating connections to water headers and to replace the rubber or synthetic hoses used in conventional magnets, we install ceramic water insulators. Figure 4 shows two sizes. These are designed to provide a long water path of minimal cross section to keep the leakage current through the water low (a radiation environment will decrease the water resistivity even though a high initial value -- 1 MΩ-cm at LAMPF -- is maintained). There is reason to believe that deposition of contaminants inside the insulator (generally copper oxide) is more dependent on the total voltage across the insulator than on the voltage gradient,[4] so the short lengths of these ceramic tubes compared to hoses may not be a great disadvantage. Maintaining a low oxygen content in the water also helps.

To evaluate the possible problems in a radiation environment an assembly of two of these insulators (3" long x 1/4" i.d. Al_2O_3 tube in Fig. 4) was irradiated in LASL's Omega West Reactor. Each insulator was in a 300 psi water circuit with 100V dc across it. After a total radiation dose of 5×10^{11} rad the insulation resistance of these insulators had dropped from > 5TΩ to 0.7 and 1.7GΩ respectively. There was some internal deposit on

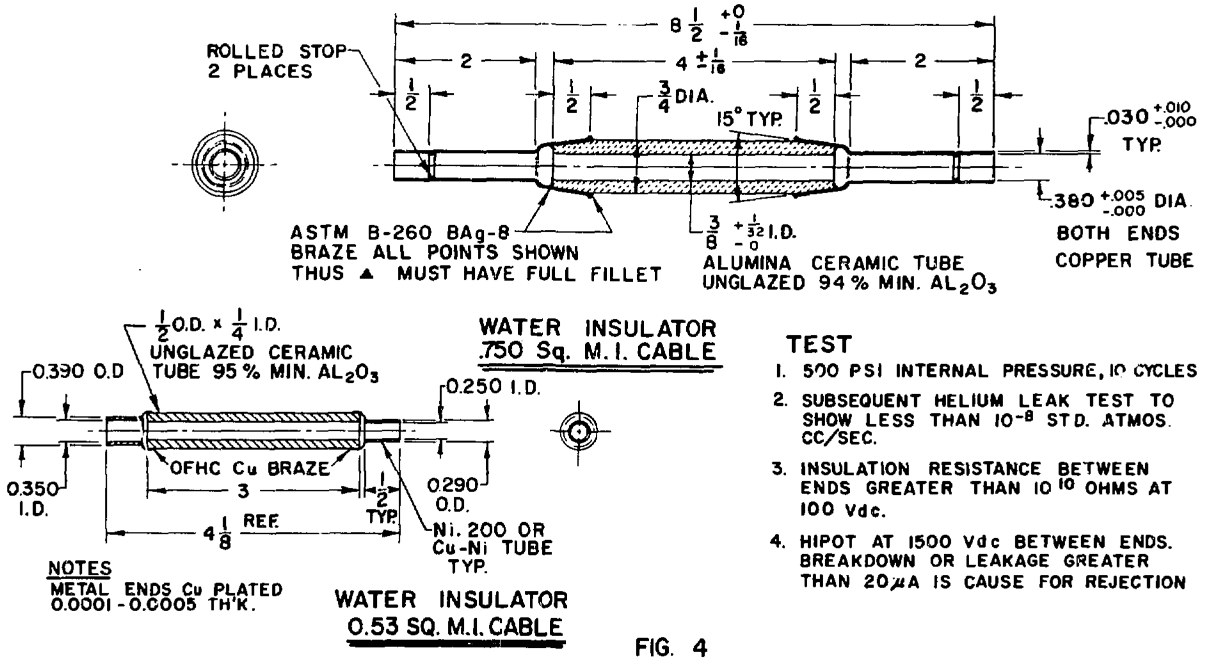


FIG. 4

the ceramic tube, but obviously they were still adequate insulators.

The connections from conductor to insulator, and insulator to manifold, are made with annealed copper tubing. Two bends in orthogonal planes provide adequate strain relief for the ceramic tube, but we also put a tube fitting at each end of the insulator assembly to facilitate replacement. Figure 5 is a photograph of an 8" quadrupole with these insulators installed.

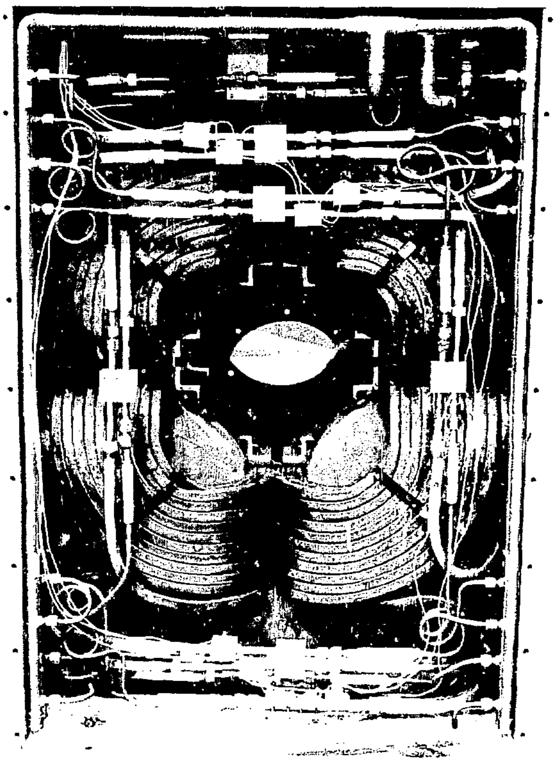


Fig. 5. 8" bore narrow quadrupole (8QN16M/7) with ceramic seals, water insulators and temperature switch interlocks installed. Connections at top.

Joints in the water systems are made using 95Sn-5Sb solder, a higher-strength soft-solder because of the relatively high pressure (300 psi) cooling water.

Repairs

Since damage to coils in fabrication or assembly seems inevitable, it is worthwhile to say something of repair techniques. Any penetration of the outer copper sheath allows ingress of atmospheric moisture, and the insulation resistance of the cable drops. Note that the moisture penetration into the MgO is slow, because of the tight packing, and is limited by the conversion of MgO to $Mg(OH)_2$, with an increase in volume. This limits the moisture penetration from any exposed insulation to a foot or so. However, if the exposure to moisture has been long enough to form magnesium hydroxide, the cable has to be heated to 350°C minimum to drive off the water.

Diagnostics. A hole in the cable sheath can be found, if the cable insulation resistance is reasonably high, say over 10MΩ, by wetting the sheath locally. A wet cloth or spray bottle is convenient. A continuously-reading megohmmeter* on the cable will show a marked decrease in I.R. when the water enters the hole -- and the effect is immediate.

However, probably a better test is to use a medium-sized oxy-acetylene torch flame, because this will provide an indication on the megohmmeter whatever the initial I.R. is (in fact, if it is below the megohm range, an ohmmeter may be used). The cable requires to be warmed only slightly, and an indication will be noted on the meter when the flame is directed at a moist patch in the cable.

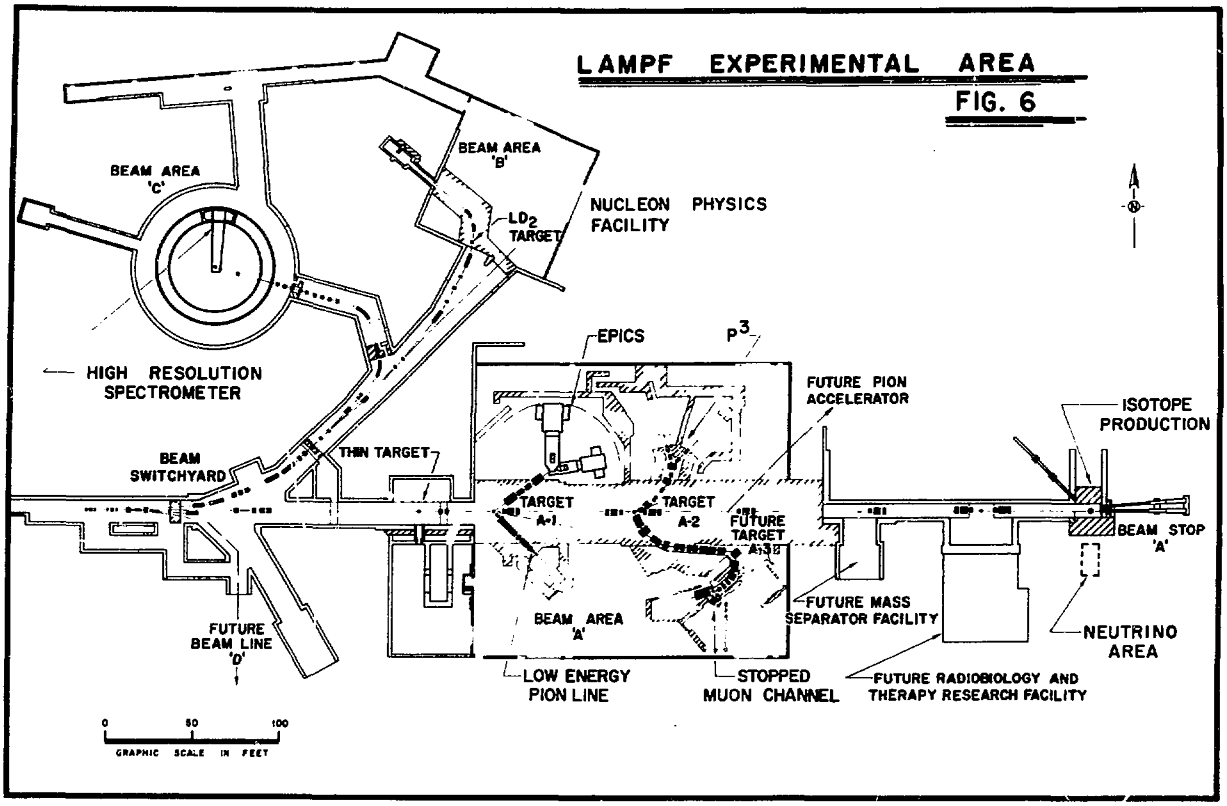
Repair. Faced with a hole in the sheath, there are two possible courses of action. For a small hole less than 1/16" in any direction, it may be sealed using AWS BCuP-5 (Silfos) with no flux. This may be filed to give a flush surface. But larger holes require a patch of copper foil, again brazed on without flux. Trying to cover a large hole directly with Silfos generally results in the torch flame blowing MgO from the cable, so that the braze metal either contacts, or is very close to, the conductor, and no dielectric remains. In contrast, the space behind a patch may be packed with dry MgO powder and the final cable properties are unaffected. The outside dimensions, however, are increased.

Similar techniques are used to produce cable splices as illustrated in Ref. 2. In every case the vital point is to avoid contaminating the MgO insulation.

Specifications

It has been LASL practice to specify the wound coil tests as follows:

* General Radio Type 1863, 1864 or 1644.



LAMPF EXPERIMENTAL AREA
FIG. 6

1. Insulation Resistance. A value 1/10 of the cable "as supplied" resistance. For a typical 200 ft piece of cable, the cable manufacturer's specification calls for 25GΩ, so the coil winder is required to maintain 2½GΩ in the finished section. Note that in a magnet with 16 coil sections, this will give a completed magnet ground resistance of 156MΩ minimum, which is generally more than sufficient for any leakage or regulation requirements. LASL experience has been that much higher readings are obtained (1 to 10GΩ). If that level can be maintained for a week, this provides a good indication that all the seals are hermetic, and the insulation resistance will then remain constant. Beware of lowered resistance readings caused by moisture or dirt on the outside of seals, or high-conductivity water inside insulators.

2. Hipot Test. The coil high-potential test is specified as 1500V dc, giving an applied voltage 0.7 times that used for the cable.

3. Water Flow. The same maximum pressure drop for the required water flow rate is specified for the coil as for the cable. Since the cables made so far are able to meet the pressure drop requirement comfortably, we have not encountered any problem in requiring the same flow admittance in the coil, despite some quite complex geometries (see next section).

IV. MAGNETS

Figure 6 shows the general layout of the LAMPF switchyard and experimental areas.

LAMPF Switchyard

The magnets for the LAMPF switchyard have been briefly described.[5] These magnets have been in operation since June 1972, and Fig. 7 shows some of the switchyard.

LAMPF Experimental Area

Higher power magnets are required in the experimental area, although the medium-energy operation

Fig. 7. LAMPF switchyard looking upstream. "Straight-through" beam line A on left; beam line X (to areas B and C) on right.

TABLE 9.

Magnet Designations Used at LAMPF

The following system is used to designate bending magnets and quadrupoles in this report. Inch units are used for dimensions:

Bending Magnets

Prefix	Width	Gap Height	Iron Length	Suffix	Field
C: C-magnet H: H-magnet P: Picture-frame S: Septum W: Wedge R: Radiussed end(s)	in., Arabic, usable width	in., Roman nearest integer	in., Arabic	M: mineral-insulated R: rad-hard Conventional insulation if omitted	kilogauss

Example: HW20VI30R/15 is interpreted as a wedge H-magnet, 20" usable width, 6" gap, 30" iron length (on centerline), rad-hardened insulation, 15 kG design flux density.

Quadrupoles

Diameter	Q	Affix	Iron Length	Suffix	Field
in., Arabic		E: elliptical beam tube N: narrow P: Panofsky S: slim	in., Arabic	M: mineral-insulated R: rad-hard Conventional insulation if omitted	kilogauss at pole tip

Example: 8QN20M/5 is interpreted as an 8" bore narrow quadrupole, 20" iron length, with mineral-insulated coils, 5kG at pole tip.

"Narrow" quadrupoles have overall width = 3 x bore diameter.

"Slim" quadrupoles have overall width = 2 x bore diameter.

places the emphasis on field quality rather than high field strength. Bending magnets generally are 15-16 kG, and quadrupoles up to 9 kG at the pole tip. The radiation environment for magnets in the target cells is estimated at 10^{11} - 10^{12} rad/yr.

Bending Magnets. Most experimental area bending magnets use 0.75" sq hollow m.i. cable (Table 6) rated at 1800A in lengths up to 220 ft, or at 2000A in lengths up to 100 ft. The LAMPF cooling water system is 300 psi, an important factor in allowing the use of long cable lengths.

These magnets vary in complexity: Fig. 8 shows a PR24VI37M/15* with adjustable shoes on the field clamp to trim the effective field boundary to the required radius. The saddle coils have one concave and one convex end, which require care in winding to avoid twisting the cable at the bends.

Pole shaping is used on the C7II132M/16* (Fig. 9) to improve field uniformity. See Section V. The packing factor in these coils (defined as nominal copper cross-section divided by total coil space in the magnet) is 44% -- the same as is achieved in cement-potted coils[6] at LASL. From the limited information available,[7] it appears that other forms of cement potting could give packing factors of about 50%.

*See Table 9.

Quadrupoles. Quadrupoles use the 0.53" sq hollow m.i. cable (Table 5). Their mechanical design depends heavily on the LBL design of narrow quadrupoles.[8] Provided that the basic pole blocks for these magnets are made rectangular initially (Blanchard grinding is recommended) the magnet assembly requires little adjustment to produce symmetry and so a low sextupole component.

Pole shaping for these quadrupoles was done at LASL (see Section V), and the pole-end chamfering to reduce duodecapole to an acceptable level was performed at LASL as described in Ref. 9. The measured values obtained for two sizes of quadrupoles are given in Table 10.

TABLE 10.

Magnet	Current A	Pole Tip Field kG	Integrated Harmonics as % of n = 2: n = 3	n = 6	n = 10
8QN16M/7	750	6.7	0.033	< 0.1	0.026
11QN22M/9	750	9.1	0.022	0.07	0.01

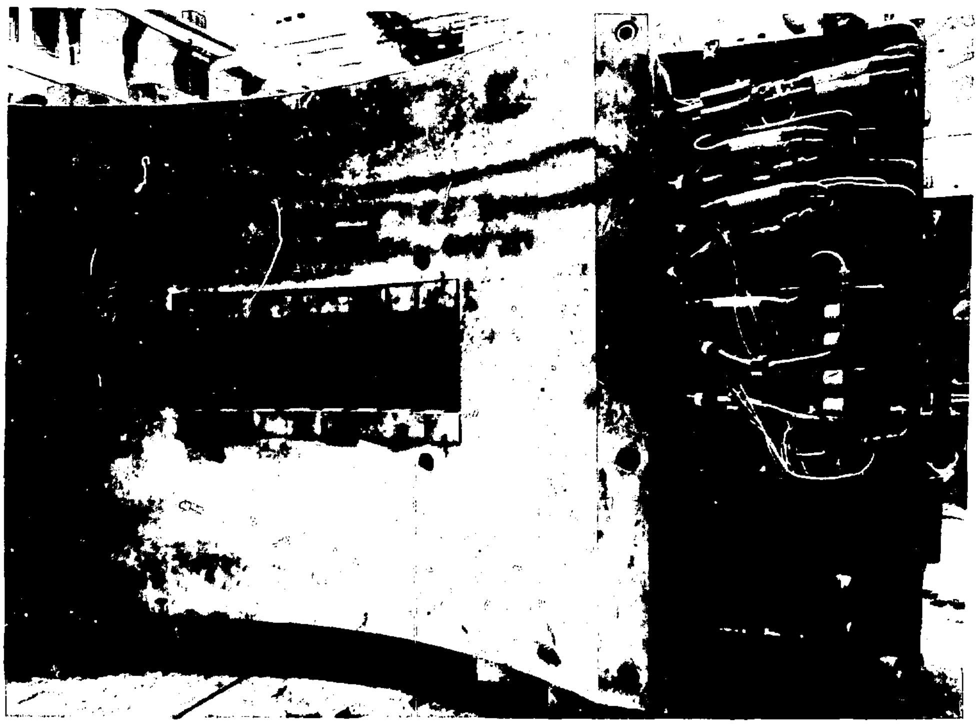


Fig. 8. PR24VI37M/15 bending magnet with radiussed ends and adjustable field clamp. Wound with 0.75 in. sq. m.i. cable.

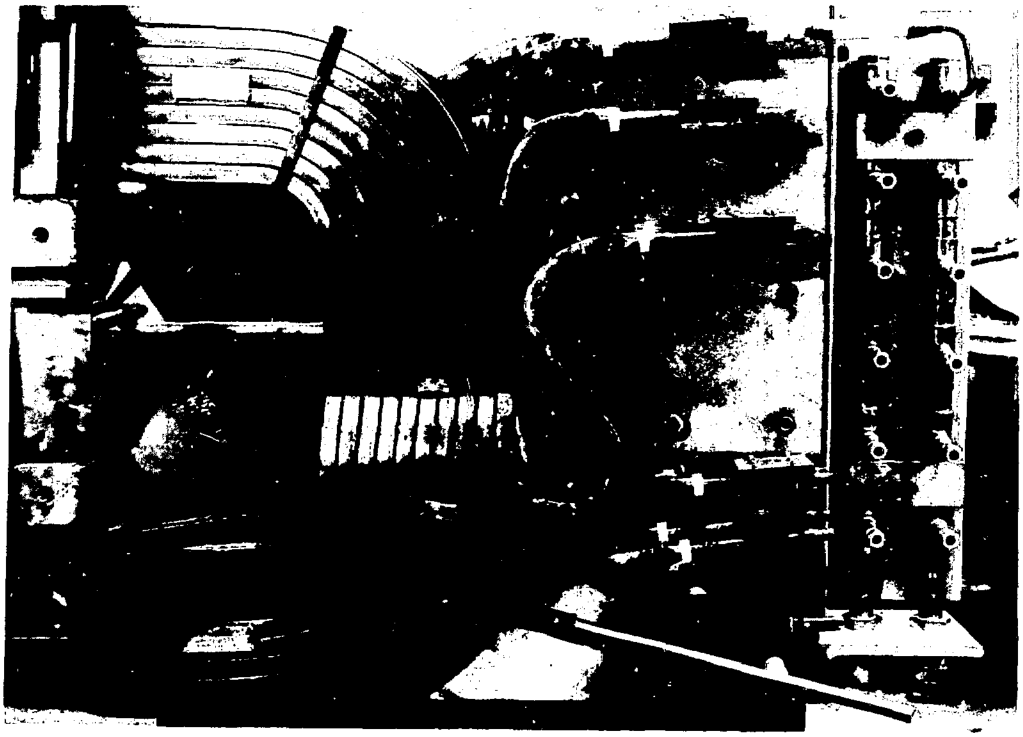


Fig. 9. C7III32M/16 bending magnet, partly completed. This photo shows clearly that a bend in the 0.75" sq. m.i. cable made on the coil form is smooth, but an unsupported bend of the same radius made in the leads produces wrinkles in the sheath.

Costs. To illustrate the contention that the overall cost of a mineral-insulated magnet is not very different from a conventional one, we list in Table 11 the costs of magnets procured for LAMPF. Magnets with an M before the slash are mineral-insulated; those without generally have epoxy-fiberglass insulated coils. Note, however, that the cost of applying seals and insulators to the mineral-insulated coils is not included in these costs. LASL experience to date indicates that an average of about a man-month of labor is required in addition to the hardware, making this operation cost about $2,000 per magnet, for directly-cooled magnets. Magnets in the table are listed in order of increasing weight, but there is no indication of the quality of the magnetic field, an important factor.

Magnet Characteristics. Two features of m.i. cable wound magnets are worth mentioning. First, the sheath surrounding the conductor acts as a transformer secondary of low impedance, so that ripple voltage from a power supply will cause ripple current to flow in the coil to an extent not seen in conventional coils. The power supply designer has to be prepared for this low inductance. However, the balancing sheath current suppresses the ripple in the magnetic field to the same level as in a conventional magnet. See Ref. 10.

The sheath also serves as a shield for electrical noise (if an SCR power supply is used, for instance). This can be a decided advantage if counting equipment is in the vicinity: obviously, the magnet leads have to be shielded as well, and at LAMPF many of these are also m.i. cable. This helps to maintain a low-noise environment for experimenters.

V. POLE SHAPING

General

Two techniques have been used to determine pole shapes for the magnets described here. Shims for low-field bending magnets were derived by experiment, and the same shims were conformally transformed to produce poles for the 2" quadrupoles.

Alternatively, the magnetostatic design program POISSON was used in an inversion program, MIRT,[11]

MAGNET PROCUREMENT COSTS

TABLE 11.

May 1973

Magnet	Designation	No.	Weight (lb)	Cost($)	Notes	$/lb
1° Bend., Line C	H5II9R/4	5	400	2,618		6.55
Inj. 2.5" Triplet	Alpha	1	600	3,650	†	6.08
805 2" Quad. Doublets	Spectro	110	712	3,355	†	4.71
Inj. 3" Triplets	Alpha	2	950	3,285	†	3.46
Line B 4" Quads	ICI 405957	6	957	2,950	†	3.08
Test Channel Quads	4Q12/5	2	1,000	2,920		2.92
Inj. ± 30° Bend	Alpha	1	1,150	4,550	†	3.96
Inj. 3" Quadruplets	Alpha	2	1,150	3,795	†	3.30
Inj. 45° - 20° Bend.	Alpha	1	1,340	6,105	†	4.555
Swyd. 2" Doublet	2Q19M/6	2	1,500	9,525	ϕ	6.35
Inj. ± 45° Bend.	Alpha	1	1,500	5,755	†	3.84
Swyd. 2" Triplet	2Q9-19M/6	2	1,530	11,470	ϕ	7.50
4° Bend., Line C	H5II38R/4	2	1,955	5,843		2.99
Line C Elliptical Quad	8QE18/3	1	2,900	10,521		3.63
Swyd. 2° Bend.	H16III17M/4	5	3,500	6,982	*§	1.99
Swyd. 6" Quad.	6Q22M/5	7	3,900	12,928	§	3.31
Trans. 45° Bend.	Spectro	1	4,000	13,900	†	3.48
8" Narrow Quad., (LEP,P³)	8QN16M/7	4	4,020	11,279	ψ§	2.80
Line C 6" Quad.	6Q29R/7	9	4,030	8,350		2.07
8" Narrow Quad. (P³)	8QN16M/10	2	4,580	11,636	ψ§	2.54
12" Danby Quads. (Muon)	12Q15	12	6,200	12,676		2.04
HRS Quads.	10QE27/9	1	6,700	17,337		2.59
Swyd. 8° Bends.	H4III69M/4	3	7,100	13,805	*§	1.94
Expt. 99 Spectrometer	PW9IV37/18	2	10,000	16,785		1.68
Biomed Triplet	11QN15M/9	3	10,000	18,134	§ψ	1.81
Biomed Quads.	14QE11/7.5	5	10,500	18,138		1.73
EPICS Spectrometer Quads.	12QE18/12	3	11,000	19,300		1.75
Swyd. 12° Bends.	H7III99M/4	3	13,700	16,837	*§	1.23
11" Narrow Quads. (LEP)	11QN22M/9	2	13,800	21,087	ψ§	1.53
Muon Channel Quads.	12QW20/7	9	15,500	22,397	ψ	1.44
Biomed Bend.	HW25VII14/15	1	16,000	19,208	*ψϕ	1.20
Biomed Bends. (built together)	HW24VI20M/8.4 HW16IV8M/8.4	1	18,000	24,310		1.35
Muon "C" Bends.	C30XI32/7	3	20,000	30,739	ψ	1.54
Muon Cement Quads.	14QE22R/7.5	2	20,500	26,222	ψϕ	1.28
LEP Epoxy Bends.	PR20VI37/15	2	23,000	29,518		1.28
Muon Cement C-Bend.	C32XI18R/7	1	25,520	24,651	ψϕ	0.97
P³ Bend	C12VI34M/15	1	28,800	33,575	§	1.17
EPICS Model	H18III21/20	1	29,000	29,167	*†τ	1.005
57° Bends., Line C	H10II130/16	2	30,000	103,627	τ	3.45
Target Cell Triplets	8 & 11QN-M/7&9	9	30,800	53,542	ψ§	1.74
LEP m.i. Bends.	PR24VI37M/15	2	40,000	49,147	ψ§	1.22
EPICS Channel Bends.	H20IV28M/18	2	44,000	40,000	ϕτ§	0.98
EPICS Channel Bends.	H32IV28M/18	2	59,000	60,000	ϕτ§	1.02
EPICS Spectrometer	H44VII54/18	2	180,000	134,122	ϕ	0.75
H.R.S.	H37IV174/19	2	260,000	289,003	ψ*ϕτ	1.11

† includes vendor design

* LASL supplied steel, included in cost

ψ LASL supplied conductor, included in cost

§ does not include terminations and interlocks, applied at LASL

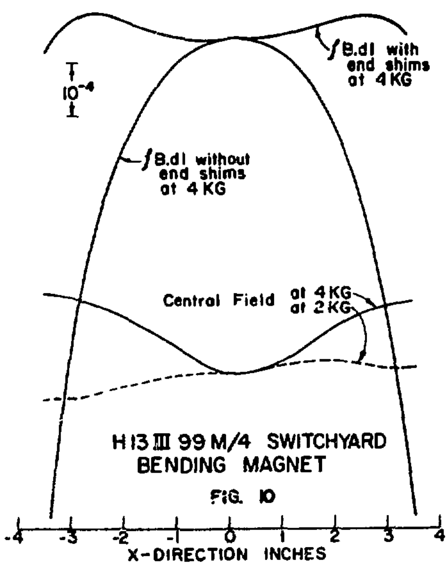
ϕ assembly in-house at LASL

τ has H_T windings (Ref. 13)

to optimize the pole profile in dipole geometry, and then to transform this optimized pole, if required, into quadrupole geometry. Thus, the two methods are basically similar, the first being empirical, while the second, sophisticated, method uses a CDC 6600 or 7600 computer. However, it may be noted in what follows that the first method was used primarily for the low-field switchyard magnets, while the latter was used for the higher-field experimental area magnets. While measurements on the switchyard magnets are now completed, those on the larger magnets are only now under way.

Empiriral Approach

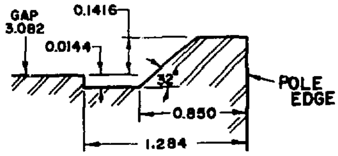
Bending Magnets. Reference 5 gave one experimentally-derived shim-anti-shim combination, which was used on a LAMPF switchyard bending magnet, the H10III69M/4. Figure 10 gives the measured field



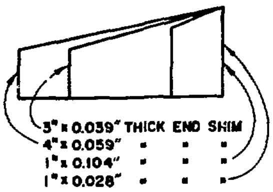
H13 III 99 M/4 SWITCHYARD BENDING MAGNET

FIG. 10

distribution from another pole shape, at roughly 4 kG and 2 kG. Also shown is the adjusted $\int B \cdot d\ell$ scan across the magnet, showing the effect of the end shims used to correct for the fall-off at the corners. These end shims are pieces of low-carbon sheet steel empirically chosen, and fastened to the pole ends. Their thickness varies from 0.028 in. to 0.104 in., and length (i.e., across the magnet width) from 1 in. to 6 in. Their outer sides are aligned with the pole edge, and the side nearest the gap tapers away from the pole face to give some smoothing of the effect from stacked shims. Figure 11 shows a typical shim stack and the pole contour. It



SHIM-ANTISHIM, H13 III 99 M/4



POLE SHIMS

FIG. 11

may be noted here that shimming as illustrated here, can only be done with low-field magnets. At higher fields the shim corners saturate, changing the field distribution. Even at low fields some change of effectiveness as a function of field strength can be observed.

Quadrupoles. Quadrupole poles may be derived from bending magnet poles by conformal transformation, and Fig. 12 shows a pole shape for a 2" bore quadrupole, 2Q19M/6 designed by the $x = X^2$ transformation from the H10III69M/4 bending magnet shim.[5]

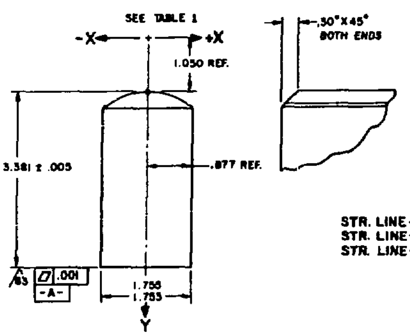


TABLE 1	
COORDINATES TO BE WITHIN ± .002	
-X & +X	Y
0.000	1.050
0.071	1.052
0.142	1.060
0.233	1.075
0.318	1.097
0.438	1.139
0.513	1.169
0.583	1.201
0.648	1.234
STR. LINE 0.738	1.282
STR. LINE 0.796	1.324
STR. LINE 0.843	1.324
0.877	1.345

NOTES

ALL FOUR POLE FACES FOR ANY MAGNET SHALL BE MACHINED TOGETHER, AND THE UPSTREAM END OF ALL POLES SHALL BE IMPRESSION STAMPED FOR IDENTIFICATION.

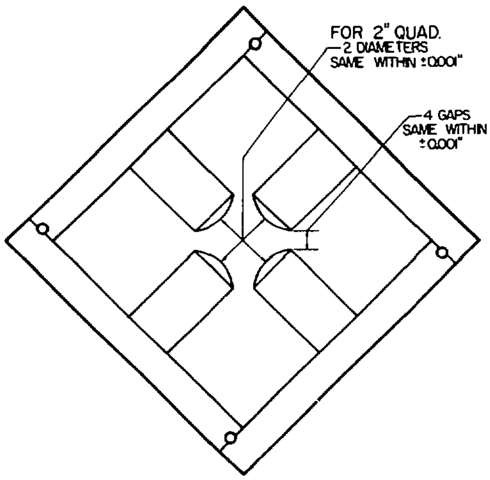
FIG. 12
2Q19 M/6
POLE

Table 12 gives the measured harmonics for this quadrupole with a 0.3 in. x 45° chamfer at the pole ends.

TABLE 12.

Magnet	Current A	Pole Tip Field kG	Integrated Harmonics as % of n=2 n=3	n=6	n=10
2Q19M/6	100	5.2	0.025	0.019	0.242
	50	2.7	0.01	0.03	0.239

Figure 13 shows the "adjustable box" construction used in the switchyard quadrupoles to achieve close symmetry tolerances: 0.004 in. on bore diameters and 0.002 in. between adjacent poles in the



QUADRUPOLE SECTION

FIG. 13

6" bore quadrupole, and 0.001 in. (as shown in Fig. 13) for both measures in the 2" bore quadrupoles.

A number of methods have been used to produce the shaped poles required: template-following planing, shaped milling cutters and planing with a variety of shaped tools to match a template. All seem to be satisfactory for the specified ±0.002 in. tolerance on the pole tip contour.

Beam Tubes. All beam tubes in the LAMPF switchyard quadrupole magnets are seamless austenitic stainless steel; in the bending magnets, the rectangular beam tubes have the welds well away from the "good field" region. We have measured field perturbations of over 2 in 10^4 due to welds in 304 stainless steel made with no filler. If a filler rod is used, the perturbaton is larger.

MIRT

More sophisticated pole shaping may be done with the help of computer-based magnetostatic programs. TRIM[12] and POISSON solve the 2-dimensional field equations for arbitrarily-shaped iron boundaries, and can accommodate not only the conductors, but also differing permeabilities in sections of the magnet. These programs have the advantage over the techniques in the previous section that smooth-contour shims can be incorporated, making saturation less of a problem. The inversion program[11] incorporated in MIRT is set up to allow the designer to vary the pole contour in designated areas to achieve the field uniformity required. The 3" gap, 16 kG, C-magnet (C7III32M/16) has a calculated field uniformity of 0.5G over the 2 in. beam trajectory; the measured uniformity is 29G over 2" width, at 16kG, but the discrepancy between calculation and measurement is less at lower fields, suggesting that saturation is not properly modeled in the computer program. Figure 9 is a photograph of this magnet nearing completion. Table 13 is the coordinate table for an 11 in. bore quadrupole, 11QN22M/9, with negligible n = 6(duodecapole).

TABLE 13.

Coordinate Table, 11QN22M/9
(Tolerance = ±0.002)

X	Y	X	Y
2.140	7.000	3.305	5.294
2.224	6.830	3.180	5.052
2.417	6.633	3.363	4.778
2.620	6.325		
2.684	6.004	3.568	4.503
		3.800	4.227
2.782	5.774	4.008	4.008
2.904	5.532	Pole Centerline	

VI. ACKNOWLEDGMENTS

Many of the handling and terminating techniques for m.i. cables described here are the result of joint efforts and discussions at Pyrotenax of Canada Ltd., and at LASL. The development work

on producing hollow m.i. cable owes a great deal to the efforts of Mr. Sid Walker, plant manager of Pyrotenax. Group CMB-6 at LASL also helped in the early development work, and recently solder-cast some indirectly-cooled coils. The seal application has been developed and implemented by LASL technicians under the capable direction of Ted Montoya.

The MIRT computations were made by Ron Yourd, now of LBL, while at LASL. Finally, the measurements reported here were taken by the LAMPF section formerly directed by Wm. Hassenzahl.

Magnets made using these techniques have been fabricated by a number of vendors in American industry: their skill has contributed to the success of this program.

I am also indebted to my colleagues at LAMPF who have provided cost data on the magnets for which they were responsible.

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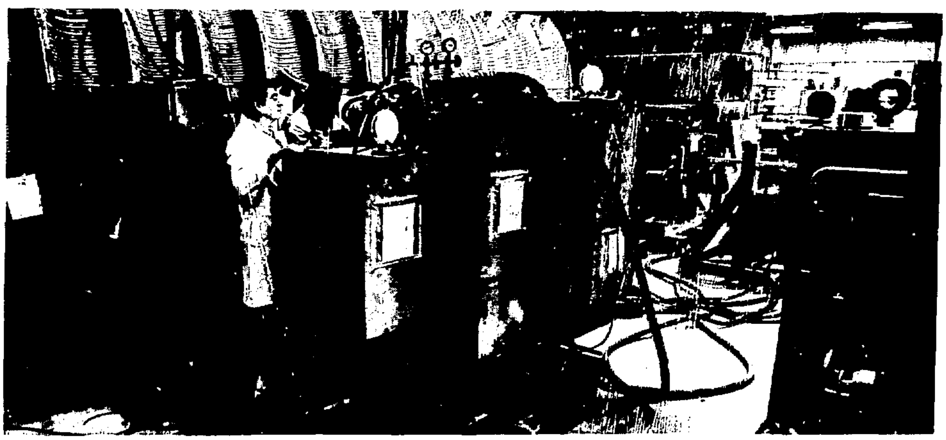

A target cell triplet quadrupole being set up for test in the experimental area at LAMPF by Lon Martinez and Ted Montoya. This entirely inorganic magnet (8QN16M/7 - 11QN32M/9 - 11QN15M/9) is arranged for remote handling -- note the electrical and water connections on top, and the locating pins on the base.