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EDGE COOLED TAPE MAGNET COILS FOR HIGH CURRENT DENSITY APPLICATIONS*

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Abstract

The LBL HILAC group has had seven years experience in the design, fabrication, and use of magnets using edge cooled tape coils. The high packing factor (90%) achievable with these coils is obviously advantageous, with the problem of producing reliable and long-lived cooling plate-coil thermal bonds as the major detraction. Fabrication techniques for the solution of this problem have been developed, and fully tested.

Designs specifically applicable to the use of tape coils have been developed for quadrupoles, circular, beam bending and beam distribution magnets. These magnets are considerably smaller, lighter, and require less power than magnets using conventional hollow conductor coils. In addition, the coolant circuitry, current terminals and the coil retaining mechanisms are extremely simple. In this paper the design criteria, and cost analysis are developed and details of the design and fabrication techniques are discussed. Limitations to the applicability are also indicated.

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The SuperHILAC[1] accelerator system consists of two injectors (for ions of different charge-to-mass ratio), a prestripper Alvarez linac, a stripping area which is to contain a magnetic charge-state analyzer, and the multiple cavity post-stripper linac. The system replaces the original HILAC, within the same building, but is about twice as long. In addition, the rigidity of the ultra-heavy ion beams, both at the entrance and exit of the linacs, is increased by about a factor of two from the HILAC beams, to 26 kG-m. The longer accelerator encroached upon the area available within the building for experimental caves, and the higher rigidity beam required the redesign of all of the beam transport systems for the accelerator, and in the experimental area.

The extreme limitation on available space necessitated the use of high field and high gradient transport elements and, in addition required that these elements be as small and light weight as possible.

For instance, the primary beam distribution area of the experimental cave system is approximately 5 x 5 meters, and must contain the equipment necessary for the distribution of the beam into eleven separate lines, leading to 17 separate experimental stations. The equipment within this area will consist of nine one-meter focal length quadrupole doublets, five singlet quadrupoles, one ±16° distribution, two multiple port distribution magnets with ±45° maximum, two 45° bending magnets, and three 55° bending magnets which constitute a 180° spectrometer. These latter bending and distribution magnets have bending radii of approximately 1.6 meter. Also included within the area are the necessary pumping stations, and various beam monitoring and emittance measuring devices.

Similar space restrictions exist in the twin injector lines and in the stripper charge-state analyzer system.

Numerous analyses of the cost of beam transport elements have been carried out, and design guidelines exist in the literature. However, except in the case of synchrotron guide magnet systems, these analyses have considered only the magnet (current density in the coil), the power supply and the power costs. Major items in the over-all costs of the transport system are ignored in these analyses. For instance, if the transport system must be shielded for radiation, the costs of providing the shielded area must be included in the analysis. These costs, including shielding, shielded access doors, utility installation costs, protective interlock systems, etc., constitute a major fraction of the total cost of the system. The cost of the installation of the magnetic element, including current and control cabling, coolant piping and hoses, etc., are routinely underestimated and rarely included in the element cost optimization. The costs of heat exchangers, coolant pumps, and primary piping are never considered in this context.

Generally, accelerator experimental areas are not planned in detail. The accelerator is constructed, and only a minimum transport system provided to accommodate the initial limited research program. Subsequent growth is on an ad hoc basis. For the SuperHILAC, however, space limitations forced the development of extremely compact, high field transport elements. The research programs were continuations of those existing on the original HILAC, and were fairly well defined, requiring a complex beam transport system. The combination of limited space, limited primary power and heat exchanger capacity, and the extremely complex transport system led to an analysis of the magnetic transport system costs, including all of the items indicated above.

As with all such costs analyses, the results are clouded by uncertainties in the estimation of the various component costs. However, through the clouds, the general design requirements of the magnetic elements can be discerned. Of paramount importance is the development of the small, compact element, even when space restrictions are not as severe as on the SuperHILAC. All of the elements

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of the system should be operated at as high field levels as is possible, consistent with the maintenance of specified field configuration and quality, and with the beam optics requirements. The power of individually controlled elements should not exceed 25 kW, if possible. Electric potentials in excess of 100 volts require that the cabling be placed in conduits, and should be avoided. Currents in excess of 250 amp require inordinant cable cross-section, and should be avoided. These current, voltage, and power limitations are consistent with minimum power supply, cabling and coolant installation, and operational costs. They require, however, the operation of the magnet coil at current densities considerably less than usual. The development of coils with a high-packing factor is, therefore necessary, if current densities are to be decreased without an inordinant increase in the coil cross-section, and consequent increase in the magnet size.

These considerations have led us to the development of the compact. low power magnets described here, using tape coils with edge cooling.

Tape Coils

The magnets described here are operated at power levels requiring water cooling. For these systems, maximum allowable temperatures are determined by the strength of the epoxy system, and by acceptable coil resistance increase with temperature. High temperature differentials within the coils must be limited to avoid thermal stressing.

The maximum temperature of such a system is due to the coolant temperature rise, the film temperature rise between the water passage surface and the main body of flowing coolant, temperature rises due to bonds between the coil and the coolant tube, and temperature rise in the coil material.

In the design of the system, the flow should be adjusted to provide an acceptable coolant temperature rise. The coolant film rise is a function of the velocity of the coolant in the passage and is proportional to the power density on the surface. The coolant passage cross section should therefore be adjusted so that, with maximum power and the flow adjusted to limit the coolant temperature rise, the velocity of the coolant is sufficient to limit the film drop to an acceptable value.

With modest flow velocities (3 m/sec) circular tubes are capable of removing 15-20 watt/cm^2 with a film temperature rise of less than 10° C. For commonly available hollow copper conductor, at normal operating current densities and coolant flows, power densities of about 0.2 watt/cm^2 are encountered and film temperature rises are negligible. This extremely inefficient use of the cooled surface results in the necessity for high hydraulic pressures to maintain the flow necessary for even modest lengths of tube at reasonable current densities. The designer must resort to the use of high water pressure, or to hydraulically parallel-electrical series coil configuration. Neither of these solutions is desirable, the former necessitating special high pressure coolant systems, and the latter resulting in a maze of hosing and flow protection devices on the paralleled circuits.

The adjustment of the coil electrical resistance is also difficult with the hollow tubing. In addition, for the size and type of magnet discussed here, about 0.6 cm square tubing is generally used and, with this small tube, packing factors are normally less than 50%.

These problems with hollow conductors have long been apparent to the designers of magnets, and the advantages of tape coils equally apparent. However, hollow conductor coils are extremely rugged and reliable, and can tolerate extreme abuse. Inherent in the design of the edge cooled tape coils is the necessity of removing the heat through a thermally conducting bond between the edge of the coil and a cooling plate. This bond must provide electrical strength adequate for the total coil voltage and, to be effective, must be capable of conducting power densities on the order of 4-5 watt/cm^2 with a temperature rise on the order of 10° C. The bond must be rugged, and capable of tolerating the mechanical working due to the differential thermal expansion of the plate and coil.

The advantages of the coil, however, are significant. Packing factors of up to 90% can be achieved. The cooling plate can be designed to produce the desired properties (flow, pressure drop, and coolant velocity) exactly, and the coolant fittings and protective devices are simple and compact. Bussing to the coil is extremely simple and compact.

The solution to the problem of reliable electrically insulating, but thermally conducting, bonds between the coolant plate and the coil is described below. This solution, however, places some restriction on the design of the steel configuration. The cooling plate must be compressed against the coil, requiring a firm clamping structure over the entire surface of the plate. Unless the cooling plate is thick enough to withstand the water pressure (5 atm) without flexing, the coil retaining structure must be capable of supporting this pressure distributed over its entire edge surface. If the turn-to-turn shear strength of the coil is adequate, it can be supported by a simple retainer at the pole edge, otherwise the entire coil must be retained. For circular coils, adequate shear strength can be achieved, so that the simple retainer is possible, but for irregular shaped coils the entire coil must be supported.

For these later magnets, which include beam distribution and bending magnets, we have resorted to a design in which a single coil is used, spanning the entire gap between the two yokes. The yokes are made to cover the entire coil, and serve as the cooling plate clamp structure and coil retainer.

The equations describing the tape coil are similar to those for hollow conductor coils:

$NI = 0.8\ BG/\epsilon_m$

$P = (NI)^2 \rho L/A\epsilon_p$

$\quad = 0.64\ (BG/\epsilon_m)^2\ \rho L/WH\epsilon_p$

$P_d = P/nLW\epsilon_p$

$N = W/(t+i) = W\epsilon_p/t$

$I = NI/N = 0.8\ BG/N\epsilon_m$

$V = P/I$

$R = V/I = \rho LN/tH$

B = maximum field - Gauss

G = magnet gap - cm

ϵ_m = magnetic efficiency

P = total power - watts

L = mean coil length - cm

A = coil cross section area

= WH - cm^2

ρ = conductor resistivity ohm-cm

W = coil width - cm

H = coil height - cm

ϵ_p = coil packing factor

n = number of cooled surfaces

P_d = power density on plate - $watts/cm^2$

N = number of turns

t = conductor thickness - cm

i = insulator thickness - cm

I = current - amps

The resistance of the coil can be varied over a range of about 3, by varying the conductor thickness from about 0.4 to 1.2 mm. The insulation thickness remains constant at about 0.07 mm, so that the coil packing factor varies from 0.84 to 0.94 for these values.

A limitation on the size of the coil arises through the acceptable temperature rise across the cooling plate bond and within the coil (about 10° C for both). For the cooling plates described below, this limit restricts the power density on the cooled edge to 1.1 $cal/sec/cm^2 = 4.5\ watt/cm^2$. Assuming the coil is cooled on two edges, the bond thus limits the current densities (i) within the coil to about $2000/H^{1/2}\ amp/cm^2$ and the allowable temperature rise in the copper to $9500/H\ amp/cm^2$. For the SuperHILAC magnets, the power and power supplies costs normally limit the current density to a maximum of about 300 A/cm^2, and neither of the limitations indicated above have been restrictive in the design of the magnets described here.

In cases where the restrictions apply, however, the aspect ratio (W/H) of the coil can be determined by these current density limits through the required excitation

$$NI = iWH\epsilon_p \quad .$$

Coil Winding

The coils consist of a continuous tape of conductor with turn-to-turn insulation provided with an epoxy impregnated paper. The paper used for the coils described here is Nomex 410 (Dupont nylon) or Fibermat (3M dacron). The epoxy used is either Hysol C-35 or Furane 202. The latter epoxy produces superior bonds to copper at room temperature, but can be operated only to about 70° C. Hysol C-35 has been operated to temperatures in excess of 150° C in this application without apparent detrimental effects.

The production of good epoxy bonds to the conductor is imperative, not only for coil strength, but also to prevent seepage of the etchant (see below) into the turn-to-turn space. Good epoxy bonds to aluminum tape require no special care of the surface, other than normal cleanliness. Bonds to copper, however, are difficult and, without proper pre-treatment and care of the surface, can be erratic in performance. The use of oils in the copper rolling, which can diffuse into the surface, are particularly troublesome. Some lubricants used in copper rolling can leave residues within the copper which cannot be removed by any reasonable subsequent surface treatment. Several copper processing firms are now using kerosene in the rolling, which leaves no residue. Subsequent to the rolling, the copper is heated to drive off the lubricant, and the resulting surface is adequate to produce consistently good epoxy bonds without further processing.

The epoxy bond strength and its integrity is a function of the thickness of the epoxy layer, decreasing drastically for thicknesses of less than 0.03 mm. Since the epoxy provides adequate electrical strength, the insulation paper is necessary only to provide turn-to-turn spacing before the epoxy is cured. A paper with perforations, or with a lace structure, that provides about 0.07 mm spacing, allows a thick epoxy layer with the bond directly copper-to-copper and results in the strongest, most stable, bond. Using materials of this type the bonds are consistently strong and reliable.

The winding can be made either wet or dry. With the dry wind, the coils are vacuum impregnated with epoxy and, since complete penetration into the narrow turn-to-turn space is necessary, this process can be used successfully only for relatively short coils. The size of available impregnating chambers has restricted this technique to relatively small coils.

In the wet winding the insulating paper is saturated with epoxy and an excess of epoxy is provided to assure complete filling of the space between layers. During cure, when its viscosity decreased, the excess epoxy exudes from the edge of the coil leaving a voidless bond. Prior to curing, however, the conductor tape floats on epoxy, with a minimal friction, and has no turn-to-turn shear strength. The coil must, therefore, be supported by some other means during the winding and cure to assure that the tape does not drift.

In the winding, the insulation paper must be of sufficient width so that it extends beyond the conductor and good insulation across the entire tape is provided. Subsequent to the winding, the excess paper is trimmed and, after curing, the coil edge is machined to produce a flat surface to accept the cooling plate.

In the winding of these coils it is necessary that sufficient tension be maintained to stretch the tape during the entire winding process. Generally, the tape is stretched beyond its elastic limit, which results in a work-hardening of the material; for wet winds, the residual elasticity is adequate to maintain tension during the loss of excess epoxy on cure.

The winding system, Fig. 1, must be capable of producing tensions of up to 1000 kG, and the feed and wind reels must be supported on axles of adequate strength. The feed reel must have a braking system that can maintain an adequate and constant tension. We have found that a relatively inexpensive truck rear-axle and brake drum (using a regulated air pressurized cylinder to maintain constant pressure on the hydraulic brake) will provide this constant tension.

Even under constant tension, the stretching is not constant or uniform across the tape during the winding process, and the tape has a tendency to creep perpendicular to the wind direction, resulting in uneven edges. To compensate for this tendency, which requires an inordinate amount of machining to produce a flat edge, the feed reel is capable of motion perpendicular to its axis. The motion of this reel is controlled by a sensor at the wind reel, to maintain the tape edge at a uniform height during the winding. Using this system, the coil edge run-out can be held to less than 0.5 mm during the winding, even for the largest coils.

Power is applied through a standard 1948 Ford transmission and a chain drive to the winding reel. Through combinations of the chain gear-wheel ratio and the transmission, speeds of 0.25 to 2 rpm are possible. Generally the winding is carried out with speeds of about 1 rpm.

The spacing between the feed reels and the winding reel on this system is adequate to accommodate coils of approximately 1.6 m diameter (or length).

The larger coils are generally wound wet, on special wooden mandrels cut to the shape of the magnet pole tip. For circular magnets, the coil can be wound directly on the pole. "C" shaped coils are produced by winding the tape directly on the outer arc of the "C", and stright across a chord of the inner arc. A spacer at the end of the coil is provided so that the tape in this region is long enough to provide for the inner arc. Subsequent to the winding, the end spacers are removed and a wooden clamp, arched to the calculated final coil outer turn configuration, is placed against the inner straight section, and the coil forced back so that its inner turn conforms with the pole shape (Fig. 2). The clamp is maintained in position during the curing, which is accomplished by resistance heating of the coil.

The drift of the tape for these wet wound coils, during the winding and curing, can be eliminated by stretching the tape over a mandrel which is slightly arched in a direction perpendicular to the wind. With adequate tension, the arch persists throughout the entire coil, and an arch with a crown of about 1 mm is adequate to prevent drift in a 200 mm high coil. The arch also significantly increases the turn-to-turn shear strength of the final cured coil.

The winding system shown in Fig. 1, was developed to produce the 230 drift-tube quadrupole magnets for the SuperHILAC linacs. The tape quadrupole is produced using two simultaneously wound tapes, each of which have four 1.5 mm wide slots per turn on the tape edge and extending into the space which is to be cut out to receive the poles. The slots are located at 90° on alternate sides of the tape, and off-set by 90° between the two tapes. The winder has been provided with automatic punches to produce these slots, controlled to position the slots on each tape, taking into account the increasing coil diameter during the wind. These coils are short and small, so that dry winding with subsequent vacuum epoxy impregnation was used.

Coil Machining

After the epoxy has been cured, the coil forms an extremely strong monolithic structure that can be sawn, drilled, milled, or turned. For the aluminum coils, reasonably careful machining of the exposed tape edges generally results in a short-free surface. For copper, however, almost any machining process results in the dragging of the copper across the insulation, with consequent turn-to-turn shorts. These surfaces can be rendered short-free by etching the conductor away from the insulation (using ammonium persulfate for copper and sodium hydroxide for aluminum). In this process, the thin material dragged across the insulation in the machining is the first to be removed. After etching, the insulation extends beyond the conductor, and provides a high turn-to-turn insulation strength.

The coil is etched and rinsed, first in a neutralizer then with water, and heated to remove moisture from the surfaces. The exposed edges are then sealed with a thin coating of epoxy (Furane 212).

For the surfaces that are not to be cooled, a deep etch is used, with the conductor etched back from the insulation by about 0.5 mm. After application of the epoxy sealer and a glass-epoxy mechanical shield, these surfaces have insulation strengths in excess of 1000 volts. All beam tube holes, current bus holes, etc., are treated in this manner.

The surfaces which are to receive the cooling plates must be machined flat (milled with a fly-cutter in the case of large irregular shaped coils, or turned in the case of smaller circular quadrupole and solenoid coils). As noted below the efficient heat transfer to the coolant plate requires that only a light etch be used. The machining must therefore be carried out with very fine cuts so that minimum dragging of the material is encountered. All of the machining operations on the coil must be carried out without the use of lubricants.

For bending magnets using the yoke to contain the coils and cooling plate, the beam vacuum chamber within the gap usually consists of a stainless steel tube, bent on a radius to conform with the beam trajectory, and flattened to provide a horizontal aperture wider than the vertical. Magnets of this design built for the SuperHILAC have a vertical aperture of about 35 mm, and a 1.5 mm wall tube is adequate to withstand vacuum pressures with horizontal apertures up to 140 mm. The tube is flattened to a vertical height somewhat greater than the magnet gap, and is compressed into its final configuration on assembly of the poles. To contain this tube, eliptical holes are milled into the ends of the coil, and the exposed tape edge surface etched and provided with a mechanical shield. The beam tube is slipped through the coil and the vacuum flanges are heliarc welded to it after complete assembly of the magnet.

Some of these bending magnets contain a "straight through" beam port, which requires the drilling of a hole through the outer curved side of the coil, on the entrance beam axis. These holes are circular, and require the use of a long rifle drill. For this type of port, the circular straight-through beam pipe is heliarc welded to the flattened and bent tube within the pole gap region, before the assembly of the pole-yoke (Fig. 3).

For the quadrupole coils, the holes for the poles are either sawn or milled. The holes to contain the tapered poles must be machined, and this is accomplished with a tape controlled milling machine, with the coil chilled with liquid nitrogen during the milling. The cooling reduces the copper dragging during milling, and the resulting surface is normally short free, and can be made precisely so that the surfaces can provide keying for the symmetrical positioning of the poles. This precise machining also provides a maximum copper volume between the poles, and allows the quadrupoles to be operated at extremely high magnetic gradients, with a minimum outer diameter.

For the quadrupoles, the current is applied to the pair of outer turns, and bussing is accomplished by soldering terminals to these turns, with appropriate access through the yoke. For the dipoles, current is applied to the inner and the outer turn; bussing to the inner turn is made with a copper stud, extending through a hole drilled in the coil, and soldered to the copper tape (or heliarc welded to aluminum). The drilled hole is etched, protected with an insulating sleeve, and the stud epoxyed in place. The resulting terminal is extremely strong, and a single nut on the stud serves to clamp one power cable-lug to a pad soldered on the outer turn, and the other cable-lug to the stud. Figures 4 and 5 show finished coils for a quadrupole and dipole respectively.

All of the machining operations necessary for the production of these coils are simple and straight forward. The success of the operation, however, depends critically on a strong, reliable turn-to-turn bond. In addition, adequate backing must be provided where the machining tool cuts perpendicular to the tape on the inner or outer turns. Without this backing, even the strongest bond will separate, allowing the etching reagent to penetrate between turns, resulting in a low turn-to-turn insulation strength.

Except for the surfaces to be cooled, rough machined and sawn surfaces are adequate, since heavy etching can be used in the clean up of resulting burrs or sharp edges. Since the coils are, in some cases, large and heavy, and the holes necessary for beam passage are at odd angles, the set-up can be time consuming. In addition, all feed rates must be slow, to avoid separation of the epoxy-conductor bond.

Cooling Plates

The cooled edges of the coils consist of layers of copper, 0.5 to 0.75 mm in thickness, interleafed with insulation (Nomex paper and epoxy) of about 0.075 mm thickness. The surface is milled or turned flat and the copper etched back from the insulation about 0.075 mm. After the application of the epoxy sealer to this surfact, the turn-to-turn electrical strength is 200-250 volts. Turn-to-turn voltages are approximately 0.3 volts for dipoles and a maximum of 25 volts for quadrupoles. The bare surface is, however, extremely delicate, and the etchant leaves the surface somewhat hygroscopic. The cooling plate must, therefore, be designed so as to protect the surface from abrasion and from moisture.

Generally, good electrical insulating, but thermally conducting, bonding materials have thermal conductivities of $2\text{-}3 \times 10^{-3}$ cal/sec-cm^2/°C/cm. Bonds for the conduction of power densities of 4-5 watts/cm^2 (1 cal/cm^2-sec) thus require 0.2 mm equivalent thickness in order to produce acceptable temperature drops of 10° C. For larger coils, using a single cooling plate covering the entire surface, thermal expansion of the coil results in a continually changing stress on the bond and, if the shear strength of the bonding material is greater than that of the bond, the bond will fail due to the thermal working. Since the thermal conductivity of the joint is dependent on intimate bonding to both the cooling plate and the coil, the failure of either bond reduces the joint conductivity drastically. This mode of failure is catastrophic in that the coil temperature in the locality of the bond failure increases, resulting in greater stress on the residual bond and the eventual failure of the entire surface.

To circumvent this type of failure, we have resorted to the use of bonding material with no shear strength (thermally conducting greases). With this material, the thermal working of the coil, continually forces the grease from the joint, and thus, produces increasingly better conductivity of the joint with time.

Although the thermally conducting grease produces an excellent, non-destructible bond, it cannot provide spacing between the electrically conducting cooling plate and the coil. We have investigated numerous techniques to maintain proper spacing, (including grease loaded with dispersed spacers, hard anodized aluminum, etc.). Our present technique is the plasma spraying of the cooling plate with aluminum oxide to a thickness of about 0.075 mm. This coating, when saturated with silicone grease provides a bond with an electrical insulation strength in excess of 1.5 kV. The coating is extremely strong and resistant to chipping under flexing of the cooling plate, and has proven entirely satisfactory in service.

The bond joints produced by this technique can be made to be equal that calculated using the thermal conductivities of the various materials, (i.e., 2-3° C/cal/cm^2-sec) however, the achievement of this quality of bond requires a very thin coating of grease and that the cooling plate be applied to the coil under vacuum, to exclude air pockets in the joint. In practice, air is included and the resultant bonds have conductivities 3-4 times less than calculated.

The cooling plate is constructed of stainless steel sheet, spaced to provide the proper water passage, and heliarc welded along the inner and outer edges. The plates are generally single pass, without channeling, so that the inner passage includes only a barrier between the coolant inlet and outlet fittings, which are placed on a tab extending over the edge of the coil. The coolant plates are made to the exact pattern of the coil edge. The general design of the magnet is such that the yoke structure provides backing for the cooling plate, and the cooling plate walls are made deliberately thin, so that the coolant pressure expands the plate and compresses it against the coil, thus maintaining good thermal contact. For the captured coil dipole, two cooling plates on either edge of the coil are used and, in operation, the coil floats between the two due to the water pressure in the plates.

The thickness of the water passage is adjusted so that the coolant velocity is high enough, at the designed flow, to maintain a temperature rise across the coolant film consistent with other thermal characteristics of the system (generally, $\Delta T_{film} \cong \Delta T_{coolant} \cong \Delta T_{bond}$). These passages are on the order of 1.5 mm thick, and the total plate thickness is about 3.5 mm. Due to the single pass coolant circuit, pressure drops are low, on the order of 1/2 atm.

Figure 5 shows a cooling plate for a 90° bending magnet with R = 300 mm. The plates are designed for a maximum power density of 1 cal/sec-cm^2 (5 watt/cm^2) with a water flow of 14 ℓ/min and a coolant velocity of 2.5 m/sec. The packing density of the coil (including the cooling plate) for this magnet is 82%.

Coolant plates for small solenoids, or for the quadrupole lenses, consist of aluminum discs, with an appropriate thin coolant passage. The plates are single pass; a radial barrier separates inlet and outlet. Coolant enters through a large (compared to the coolant passage) hole drilled radially to the center of the plate, and is distributed uniformly over the coolant passage entrance, flows azimuthally around the plate and exits through a similar outlet. A cooling plate of this type is shown in Fig. 4.

Dipoles

Over the past few years, as the understanding of beam optics has increased, the demand for magnets with specific and highly accurate, field configurations has increased. Generally, these magnets must operate over a wide range in field, with the steel permeabilities varying by up to two orders of magnitude. The maintenance of uniform fields under these conditions is difficult, and is usually solved by a combination of Purcell gaps at the pole root, to maintain vertical fields in this region, and pole tips considerably wider than the anticipated usable aperture, to allow for variations in the edge fringing fields at different field levels.

Neither of these solutions is desirable, the former due to the additional excitation required to drive the Purcell gap, and the latter due to the additional unusable flux in the gap.

With regard to the size and steel weight of a magnet, the figure of merit of the pole and pole tip design is the ratio of the usable magnetic flux (appearing in the usable beam aperture) to the total flux that must be carried by the steel return path. The requirement for field uniformity within the aperture necessitates an extension of the steel aperture beyond the beam aperture. Steel must be provided to the return path to carry this excess flux and unfortunately, appears at the outer periphery of the yoke-leg structure. A small increase in the pole width, therefore, results in an inordinate increase in the steel weight to carry the excess flux. In the design of a compact magnet, therefore, of primary consideration is the achievement of uniform fields with the minimum possible pole width.

For a long dipole of the "H" configuration, due to symmetry, only odd field harmonics can exist in the gap (the first being the sextupole component). However, for a bending magnet where the pole follows the beam trajectory, it is impossible to provide equal reluctance paths on both sides of the pole over the entire range of operational permeabilities. At high fields the magnet becomes asymmetrical, resulting in even field harmonics, the first of which is the quadrupole.

Generally, beam transport systems contain adequate quadrupole focusing elements to compensate for quadrupole fields produced in the bending magnet due to the asymmetries in the design of the magnet. It is necessary to consider only the sextupole component in the requirement for field homogeneity. This relaxation of the field uniformity requirement allows concentration of effort on the design of the pole tip contour, with only minor consideration being given to the yoke-leg return path design, other than the maintenance of acceptable magnetic efficiency at the maximum field levels.

The use of presently available two dimensional field computer programs (Refs. 2 and 3) has greatly facilitated magnet design. These programs, which can accommodate variable permeability of the steel and which include various optimization routines, are capable of designing pole tip contours that produce the greatest region of uniform field for a given pole width.

In using the programs, information of the rough pole tip contour, position of the conductors, dimensions of the return path, etc., are specified. In the optimization the computer adjusts the pole contour to minimize the undesirable field harmonics, for both low and high field conditions. The specified optimum configuration generally results in a sextupole field at both the low and high fields, but of opposite sign. In addition, the program computes the field at all points in the magnet, so that it is possible to adjust the return path to accommodate the actual flux, providing minimum safety factor. The actual magnetic efficiency of the steel circuit is also calculated at the highest operational field, providing information necessary for the design of the coil, the power supply, and the coolant circuitry. Figure 6 is a flux plot for the magnet shown in Fig. 3 as calculated by the computer.

The achievement of a high figure of merit for the pole design, is critically dependent on the positioning of the conductors. The design of the coils described here for the "H" magnets, with the coil spanning the gap, is highly advantageous in this respect.

Most of the "H" magnets constructed for the SuperHILAC transport system have gaps of about 4 cm, with poles about 5 cm high, so that the coil height, including the cooling plates, is about 14 cm.

With this design and using a straight-sided pole, the achievement of a calculated field uniformity of $1:10^4$ over a beam aperture A, requires a pole width, $w = (A + G)$. For this configuration, the figure of merit is $1/(1 + 1.57\ G/A)$. For a magnet with $G/A = 0.33$, 68% of the flux is within the usable aperture. At a gap field of 15 kG the pole root is at 19 kG and, with the yoke-leg thickness adjusted to operate at 16 kG, the magnetic efficiency is 95%.

For these magnets, the poles are constructed of a single plate, milled to the proper configuration as described by the computer analysis, on a tape controlled milling machine. The coils are wound to fit snugly around the pole with minimum clearance, and the return path legs flame-cut to conform with the outer coil edge. The two yokes are flame cut to cover the entire coil and legs.

The two legs are simultaneously Blanchard ground to an identical height, and the yokes ground to produce flat inner surfaces, with the outer surface cleaned only. The magnet is assembled using precision spacers to assure a uniform gap, with appropriate shimming between the yoke and leg surface. A rubber pad between the yoke and one of the cooling plates assures compression of the cooling plates to the coil and the proper positioning of the coil. No other retainer is provided for the coil.

A typical cross section of one of these magnets is shown as Fig. 7.

The measured field uniformity of these magnets varies from 2 to $3:10^4$, consistent with the steel uniformity and the fabrication and assembly techniques used.

Quadrupoles

Multipole tape wound coils have been previously described in detail.[4] The coils are produced by winding two strips of tape simultaneously, with appropriate slots in the tape edge at alternate poles. The slots allow current flow only across one end of each pole, alternately, on adjacent poles. The two tapes are connected at the center turn, and current flows inward on one tape, in alternate directions between adjacent poles, across alternate pole ends (due to the slots), then outward on the other tape, in the same direction between each pole, but across opposite ends of each pole. The current thus produces a complete loop around each pole with adjacent poles energized in the opposite sense, as required for a multipole field. The technique is applicable for all 2N multipoles, but has been primarily applied to the quadrupole.

The coils are made so that a large fraction of the area between poles is filled with copper ($\cong$85% packing factor). Unfortunately, with this design, only half of the copper at the ends of the poles is active, so that this portion of the coil has a packing factor of about 44%. A further disadvantage of the design is the fact that the tape width between poles decreases with radius, so that the coils have a higher current density at the inner radius.

The total power dissipated by these coils is the sum of that in the area between poles (where the packing factor is high) and across the pole ends, where the packing factor is low. However, the overhang of the coil beyond the pole, can be adjusted at will to minimize the losses in this portion of the coil.

The turn-to-turn insulation effectively restricts radial thermal conduction, so that all of the power must be removed at the coil ends. Although some power is conducted through the poles from the inner turns to the cool outer turns, the effective limitation on excitation is the temperature rise of the center turn, at the longitudinal center of the pole. The temperature rise on this turn is calculated as

$$\Delta T = \Delta T_{bond} + 6 \times 10^{-8} (IQ/A)^2$$

where I is the current, Q is the pole length in cm, and $A = tw$ cm^2, where t is the tape thickness (which is constant with radius), and w its width in cm (which varies with radius).

For a given strength quadrupole element, the product of magnetic gradient and effective pole length (L_{eff}) must be maintained constant. For hollow conductor construction, the total power required increases less than linearly with the pole length, but as the square of the magnetic gradient. For the tape coils, however, the temperature rise at the center turn is limiting, also increasing as the square of the magnetic gradient but somewhat stronger than the square of the element length.

The emphasis in design of these magnets, therefore, is the achievement of high magnetic gradients, with minimum excitation.

The excitation necessary to produce a given magnetic gradient increases as the square of the steel aperture and the temperature rise on the center turn as the fourth power. Important in the deisgn of these magnets, therefore, is the production of high quality, usable fields throughout the entire steel aperture, and fabrication techniques to allow the beam to occupy the full aperture. Since the width of the inner turn is dependent on the width of the pole tip, this high quality field must be produced with a minimum width pole.

A coincidental objective in the design of these magnets is a high figure of merit in the steel return path configuration. As with the dipole, the figure of merit is calculated as the ratio of the usable flux appearing in the beam aperture to total flux which must be carried in the steel return path. In the quadrupole, the leakage flux appears from pole-to-pole outside the beam aperture, both within the magnet and in the fringe fields at the pole ends. The total usable flux in the quadrupole is calculated to be

$$4\, B' R_a^2 L_{eff} \quad ,$$

with B' the magnetic gradient kG/cm^2, and R_a and L_{eff} the aperture radius and effective pole length in cm.

The pole root and yoke steel thickness, therefore, are dependent on the aperture in the same manner as the excitation, i.e., increasing as the square of the radius. The high current turn near the steel aperture assists in the achievement of high quality fields with narrow pole tips and, in addition, reduces the flux leakage from pole-to-pole outside the steel aperture. The design leading to the highest possible excitation, is therefore, compatible with the production of the highest figure of merit in steel use.

Halbach[5] has made an analysis of the effects of fabrication errors on the field harmonics in a multipole configuration. These effects can be divided into two categories; those produced by asymmetries in the fabrication and/or assembly of the poles and coils, and those produced by improper pole tip contour. The former can lead to harmonics of all N, whereas the latter, through the fourfold symmetry of the quadrupole, produce only harmonics with $N = 2(2n + 1)$. The analysis provides information of the fabrication and assembly tolerance necessary to maintain acceptable harmonic content and, in addition, assists in the design of pole contours to reduce the symmetric harmonics.

The design of the pole tip configuration starts with the generation of the optimum pole tip (with regard to width) as determined by the two dimensional computer program described above. Since the two dimensional description is inadequate for the fringing fields at the pole ends, correction of the pole contour must be made to compensate for the objectionable harmonics produced in this region. The pole contour is adjusted so that the integrals of the unwanted harmonics is minimized.

The HILAC quadrupole pole tips are designed with steps (see Fig. 4) rather than with a smooth contour. Adjustment of the width and height of two of these steps provides four parameters with which to minimize the symmetric harmonics through $N = 14$.

The integrated harmonic content of the field is measured using a long, parallel sided coil system, extending through the magnet and its fringe fields, and rotated about an axis parallel to the longitudinal axis of the magnet.[6] The harmonic analysis of the output of this coil indicates the harmonic content of the integrated field of the magnet. With the aid of Halbach's analysis, indicating the effect of steel removal at various azimuthal positions on the pole tip, usually one (and not more than two) adjustment of the pole step parameters, is adequate to produce pure quadrupole fields (B_N/B_2 of less than 0.5% at 95% of the steel aperture).

The fabrication and assembly techniques adopted are those necessary to maintain objectionable harmonics produced by asymmetries, to less than 0.2% of the quadrupole field at 95% of the steel aperture.

With this design, the entire steel aperture of the magnet is usable for beam, and the excitation necessary to achieve a given lens strength, is minimal. The method of design also leads to the production of pure quadrupole fields with a minimum width pole tip, as necessary with the tape coils.

The design studies for the HILAC quadrupoles have led to a minimum pole width (W) of 1.1 R_s which, in turn, produces a maximum coil inner turn width of 0.4 R_s. For the square-end poles with $R_s/Q < 0.5$ the effective length of the element is approximately $L_{eff} = (Q + 0.9\ R_s)$ and, for optimum design, the pole root flux is approximately 2.6 $B'R_sWQ$. The figure of merit for this configuration (assuming full use of the available steel aperture, R_s) is given by:

$$4\ B'R_s^2(Q + 0.9\ R_s)/4 \times 2.6\ B'R_sWQ$$

$$= 0.35(1 + 0.9\ R_s/Q) \quad .$$

Thus, for a quadrupole with $R_s/Q = 0.2$ and using the full steel aperture for beam, 45% of the total flux in the return steel appears as quadrupole field in the usable aperture.

For the parallel sided pole, the root field as indicated above, $B_{root} = 2.6\ B'R_s$, effectively limits the pole tip field ($B'R_s$) to about 7 kG when using normal low carbon steels with this design. An increase in pole tip fields requires the use of special steels and/or tapered poles. The HILAC prestripper linac drift tube quadrupoles (Fig. 9) employs both to achieve pole tip fields of 11.5 kG, and an integrated quadrupole field of 60 kG, with Q = 3.3 cm, and R_s = 0.7 cm.

Generally, for the HILAC design, using edge cooling on the coils, the yoke is made to cover the entire coil and cooling plate. The necessary thickness of the yoke can be calculated from the total flux indicated above, with yoke fields limited to 16-17 kG. The resulting magnet operates with magnetic efficiencies of about 95%, if the yoke and pole root fields are limited to this maximum in type 1015 low carbon steel.

The quadrupole yokes are low carbon seamless steel mechanical tubing, annealed and machined to be circular on the inside diameter. The poles (except for the high gradient drift-tube quadrupoles) are low carbon steel machined as a single bar, with a circular root to fit the yoke inside diameter, and with the pole tip steps milled with a symmetrical ganged-cutter. The poles are cut to length, slipped through the coil holes and positioned with their center steps into keyways precisely positioned at 90° on a mandrel of the proper radius. The coil-pole system is then slipped into the yoke, and the entire structure vacuum epoxy potted.

The cooling plates are bonded to the coil end with thermally conducting grease, and clamped in place, either with the bore tube vacuum flanges, or with a special clamping plate attached to the yoke end.

Costs

Pertinent dimensions and operational parameters of some of the magnets that have been built for the SuperHILAC over the past four years are shown on Tables I and II.

All of the magnets were constructed by the Lawrence Berkeley Laboratory mechanical shops, and relatively complete cost accounting was maintained. These costs, however, include the development effort involved in new designs and fabrication techniques, which were attempted with each new magnet. The 55° bending magnets were the only units using proven designs and fabrication techniques. Material cost for each of these units was $2,400, half of which was for the copper tape and the coil insulation materials. The total effort was 600 man-hours, half of which was expended in the set-up of the winder, coil winding, machining, etching and installation of bussing, and in the fabrication of the cooling plates.

These costs are approximately the same as for similar magnets of conventional design using square hollow tube coils. Significant savings are realized, however, in the installation of the element, the power supplies, and in operational costs.

Table I. Quadrupoles

	2.5"Q	2"Q	Post Gr 2	Pre Gr 1
Aperture diameter (cm)	6.4	5.0	4.2	1.4
Gradient (kG/cm)	2.0	1.9	1.8	15.4
Pole length (cm)	15.2	5.1	11.7	3.4
Effective strength (kG)	45	14	25	60
Power (kW)	5.2	1.4	0.4	1.2
Harmonic Content*	4×10^{-3}	10^{-2}	10^{-2}	5×10^{-3}
Coil wt (lbs)	70	11	45	13
Steel wt (lbs)	160	20	40	28
Magnet length (cm)	25.4	14.2	15.8**	4.3**
Magnet outer diameter (cm)	30.5	17.3	19.8	25.4

* $|B_n|/B_2$ at 0.95% aperture.

**No cooling plates or end plates.

Table II. Bending magnets.

	Ion source magnet	Fannie	Sandy	Candy	Bernie Jr.
Bending angle (degrees)	---	±60	45	55	90
Bending radius (cm)	---	85	79.2	156.	28.2
B_{max} (kG)	6	18	16	16	12
Gap (cm)	10.2	4.4	4.4	3.8	2.5
Aperture width (cm)	12.7	---	8.1	10.2	5.1
Field uniformity	10^{-2}	10^{-3}	10^{-2}	$3x10^{-4}$	$5x10^{-4}$
Power (kW)	3.6	28	13.5	20	3.4
Coil wt (lbs)	670	900	350	800	180
Steel wt (lbs)	1700	9100	1400	4500	650

Acknowledgments

The magnet designs and fabrication techniques described here have evolved over a period of several years, and contributions have been made by the entire HILAC mechanical engineering and technical staff.

Notable are Physicist D. Spence, Engineers R. Holsinger, J. Haughian, and T. Scalise, and Technicians G. Newell, M. Morrison, and P. Kennedy.

K. Halbach developed most of the analytical techniques used in the steel designs, and the computer programs were written by R. Yourd, R. Holsinger, and S. Magary, under his direction.

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Figure Captions

Fig. 1. Coil winder set-up for quadrupole coils.

Fig. 2. 55° magnet coil forming operation.

Fig. 3. 55° magnet subassembly.

Fig. 4. Quadrupole components.

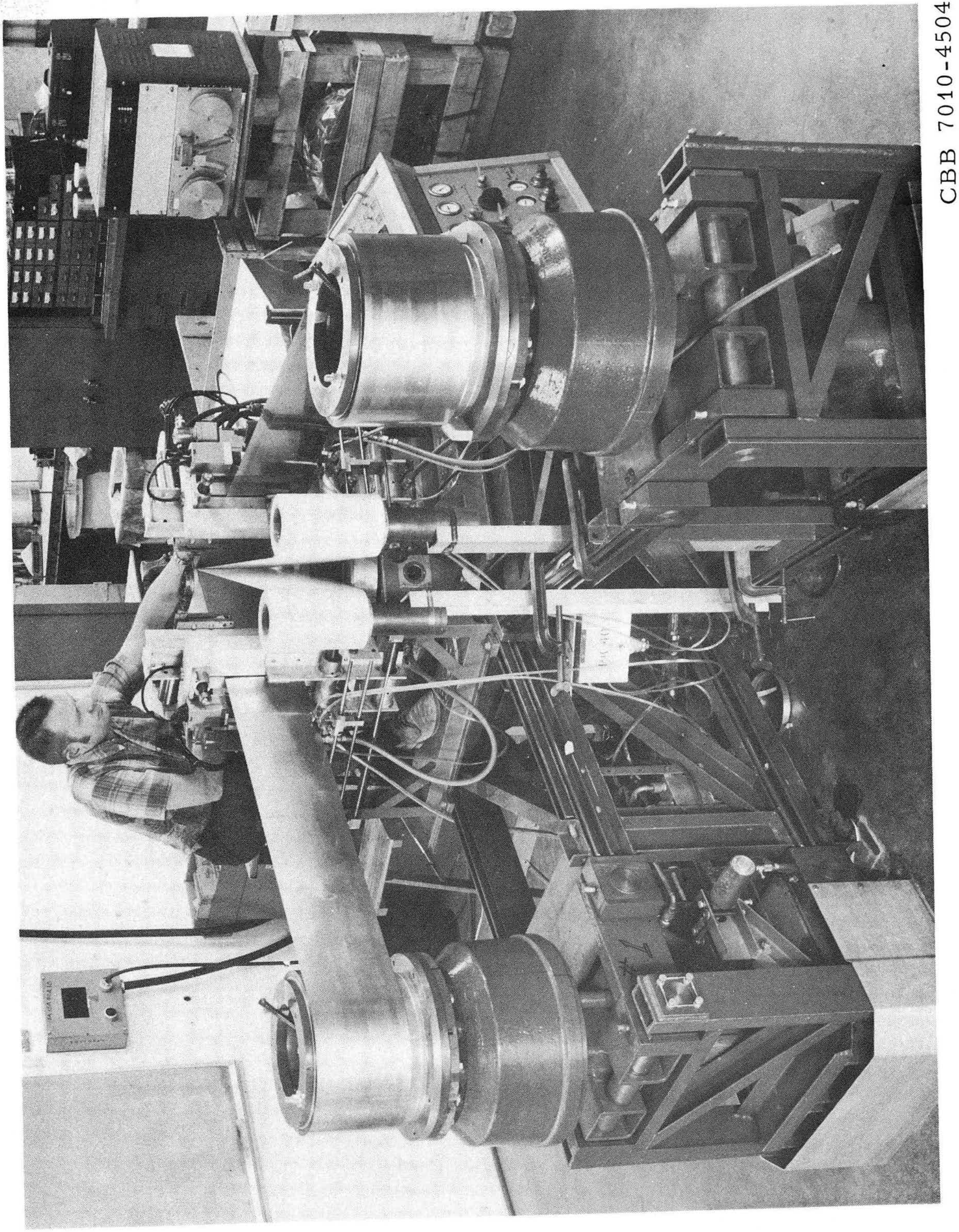
Fig. 5. 90° magnet components.

Fig. 6. 55° magnet flux plot.

Fig. 7. Typical magnet cross section.

Fig. 8. ±60° beam distribution magnet components.

Fig. 9. Drift tube quadrupole magnet.



CBB 7010-4504

Fig. 1

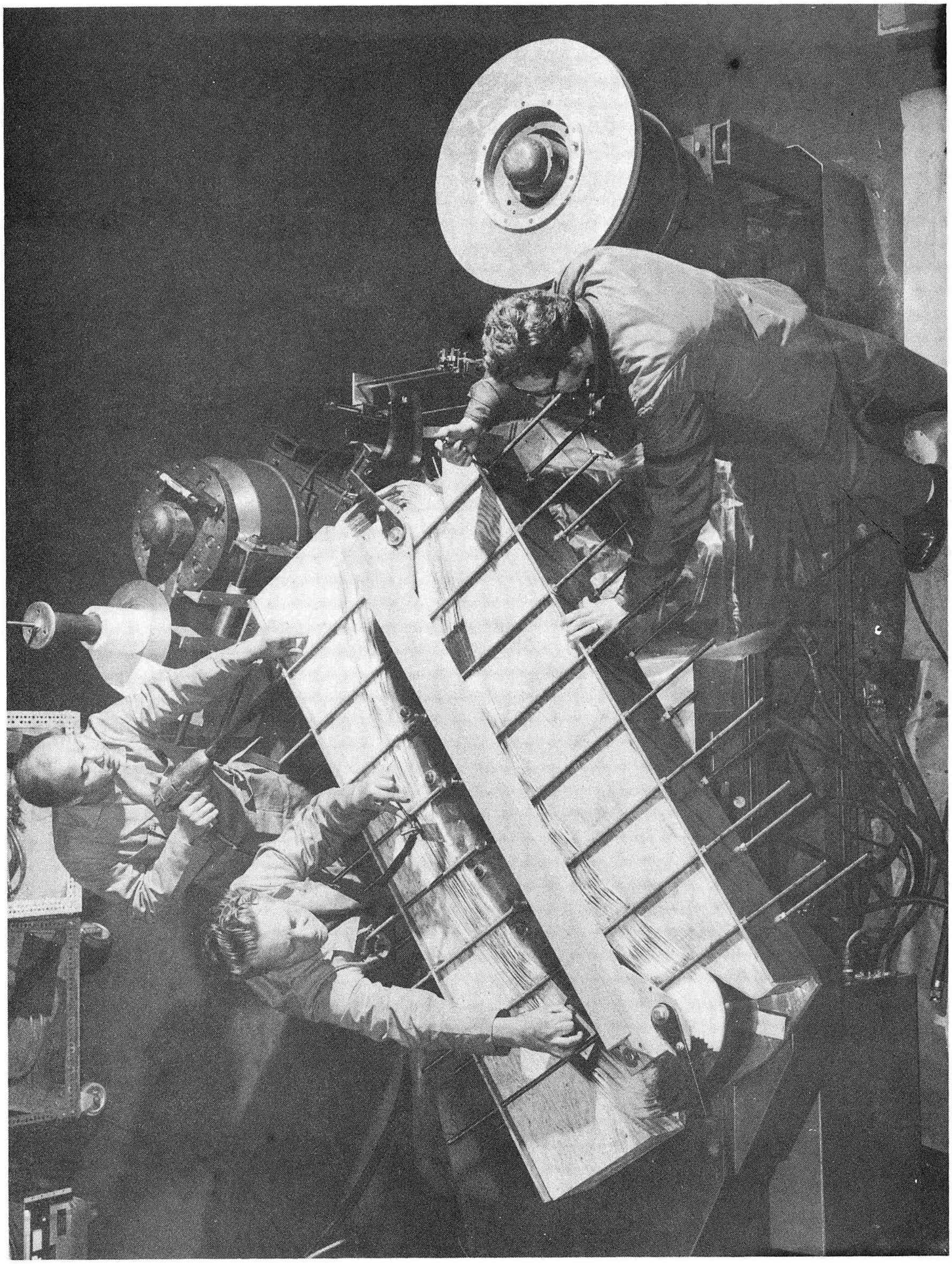


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Fig. 2

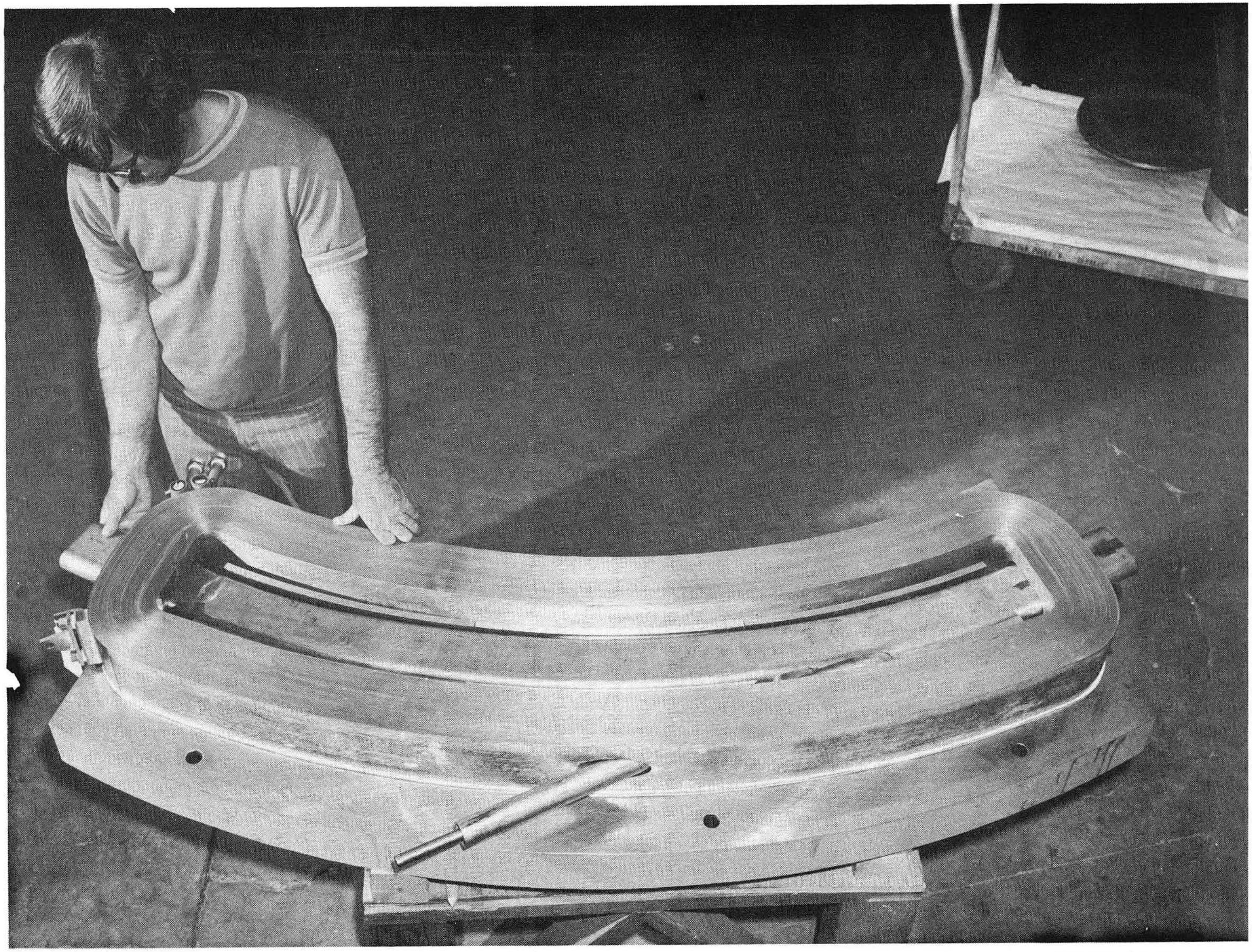

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Fig. 3

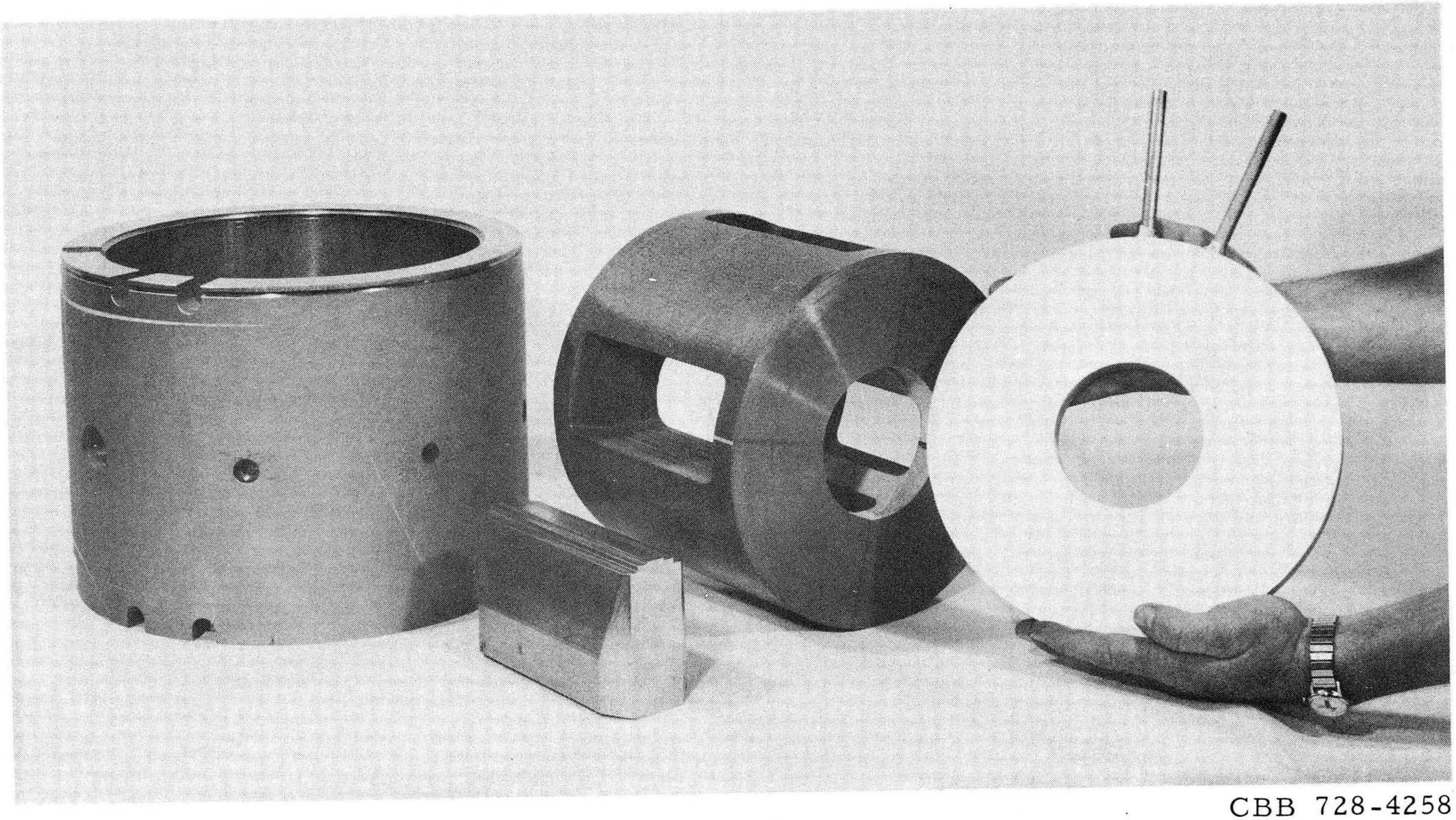

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Fig. 4

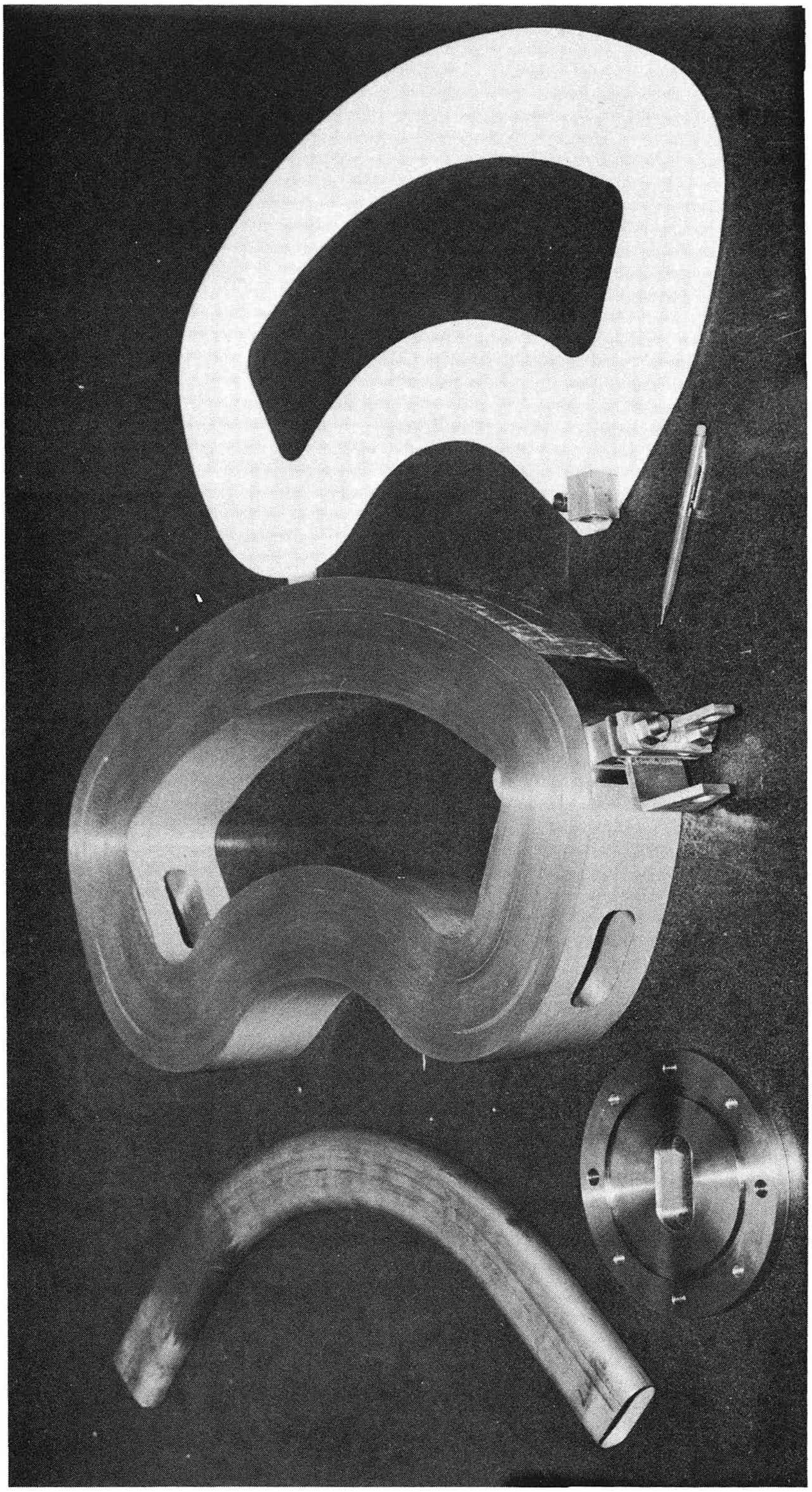

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Fig. 5

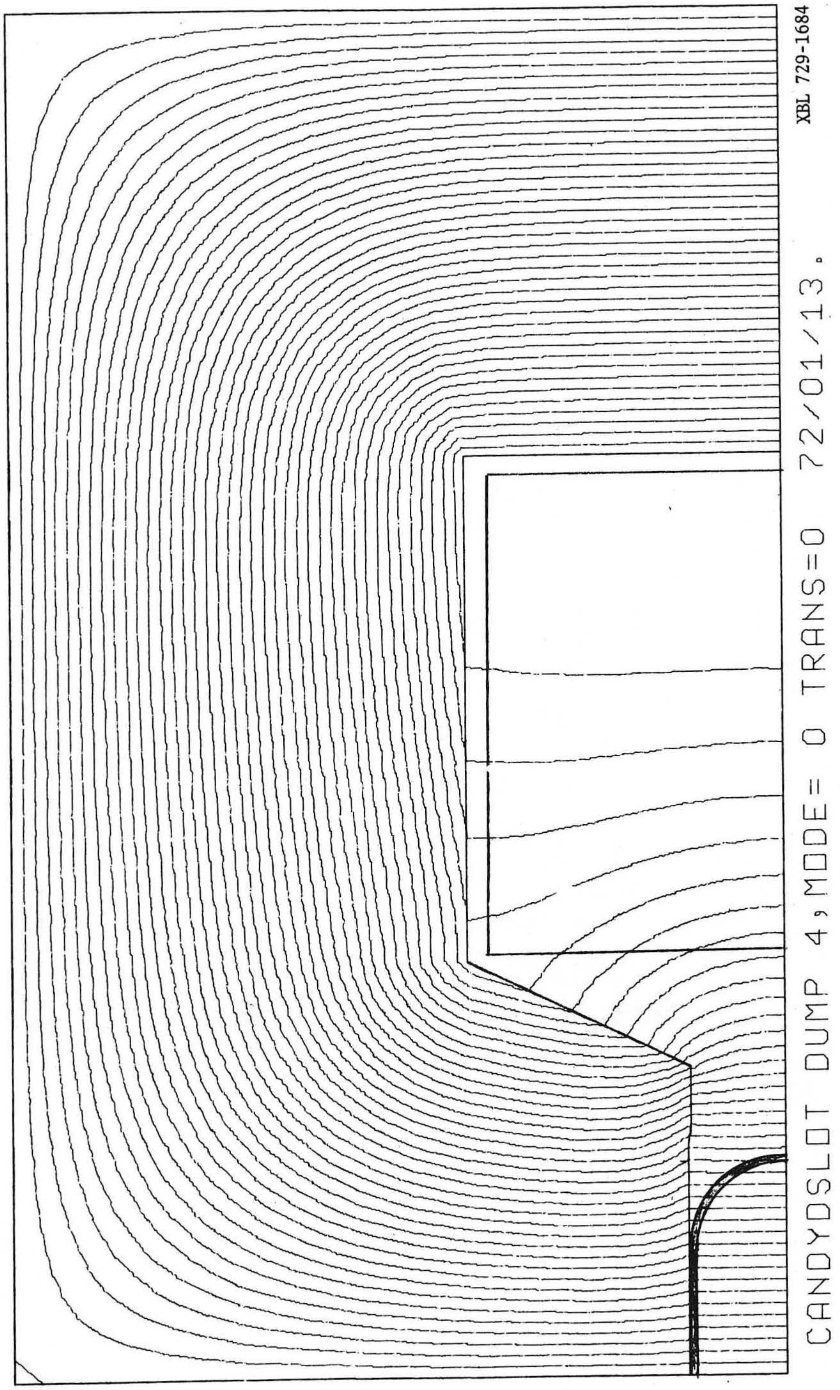

Fig. 6

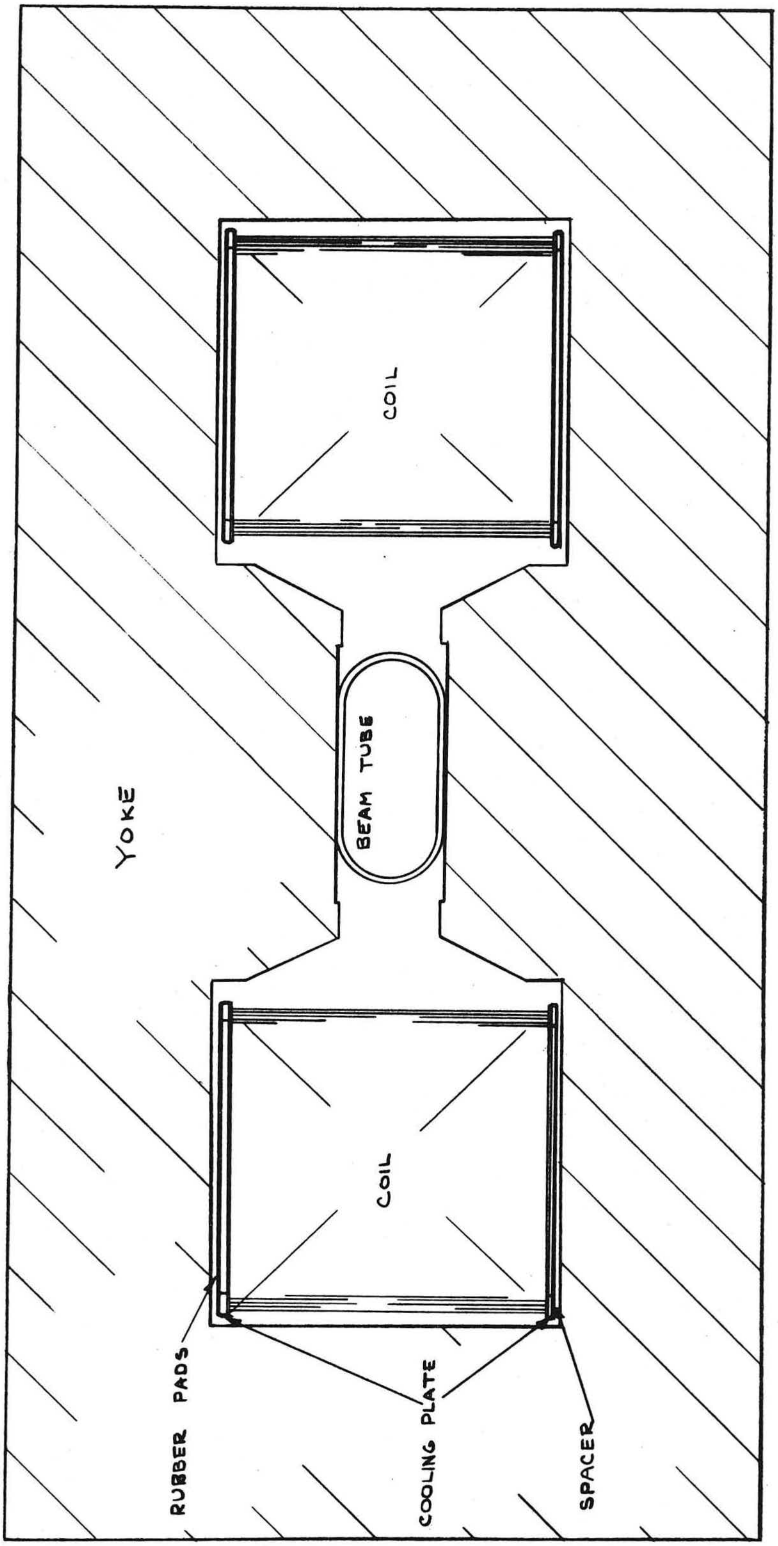

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Fig. 7

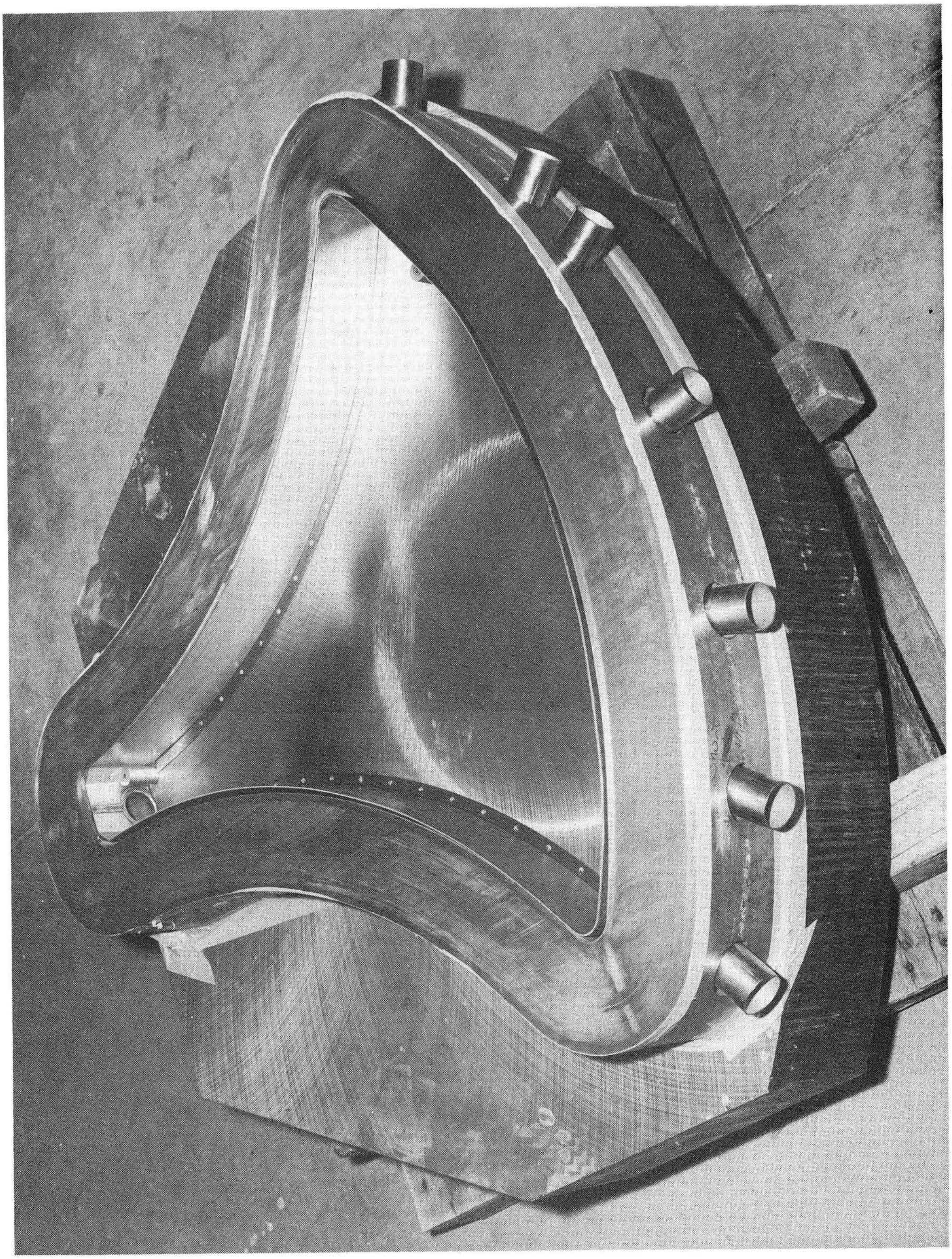

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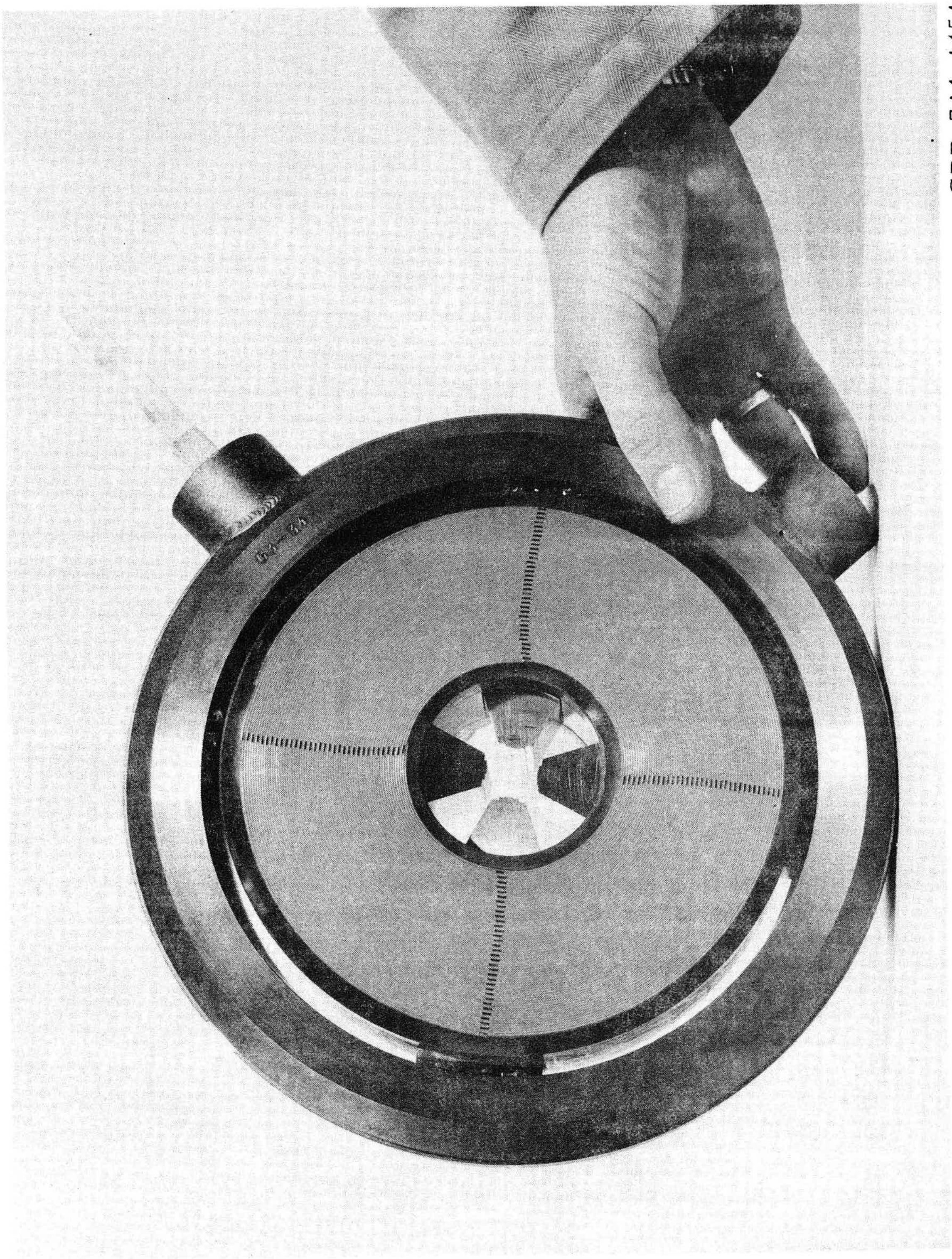
Fig. 8



CBB 714-1451

Fig. 9

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