HIGH GRADIENT MAGNETIC DRIFT TUBE QUADRUPOLES *

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INTRODUCTION

The Berkeley heavy ion accelerator (Hilac) pre-stripper system consists of 550kV Cockroft-Walton injector and a 15 ft. long grid-focused Alvarez linac operating at 70MHz with a maximum electric gradient of 500 kV/ft. This system accelerates particles with a minimum charge-to-mass ratio (ϵ) of 0.140 to an energy of 1 MeV/nucleon. At this energy the particles are stripped to a minimum ϵ of 0.30 and accelerated to a maximum of 10 MeV/nucleon in a 90 ft. long magnetic quadrupole focussed Alvarez linac (post-stripper cavity) at the same frequency and maximum electric gradient. The system operates with pulse rates varying from 0 to 40 per second and pulse widths 1 to 20 msec. The maximum duty factor, limited by power dissipation of the rf cavities, varies from 15% for the heavy ions (argon, $M=40$) to 80% for the light ions.

Limitations on the mass of the ion which can be presently accelerated in usable intensities are primarily those of the ion source. Krypton-84 ions in the +12 charge state ($\epsilon=0.143$) can be produced in intensities of approximately 10^{11} per second and subsequent losses due to duty factor, pre-stripper acceptance, grid attenuation and stripping reduce this by about a factor of 1000. The beam from the ion source consists, predominately, of the lower charge states; for example, Krypton +8's are approximately 200 times more abundant than +12's. The production of usable beams of these heavy ions, therefore, requires the modification of the pre-stripper system to accept particles of a lower charge-to-mass ratio and the use of quadrupole focusing to reduce the acceptance losses and grid attenuation in the rf cavity. Intense beams of light ions at low charge states will also be available from the source, and sputtering of the grids by these beams would be a severe problem. This fact dictates the use of quadrupole focusing throughout the system.

In the design of the improvements, limitation of funds required that as much as possible of the existing equipment be used in the modified system: the modified pre-stripper cavity was designed to be compatible with existing vacuum and rf equipment; the post-stripper cavity could neither be moved nor substantially modified (both the frequency and the 1 MeV/nucleon stripping energy must be maintained). Similarily, modifications to the building to gain additional space were ruled out. The severely restricted existing space must be judiciously distributed between the injector terminal, the dc accelerating column, space for bunching and beam handling, the linac, and space for the stripper. With space the controlling factor, the injector potential should be as low as possible, consistent with achievable magnetic quadrupole gradients within the early drift tubes and with electric fields within the early gaps.

Experience with the present pre-stripper rf cavity indicates that, with a slight increase in gap spacing at the entrance, the system will operate with a maximum electric gradient of 650kV/ft. Space is available to increase the cavity length to 20 ft. and, with an injection potential of 750kV (the maximum deemed feasible), the minimum charge-to-mass ratio that can be accepted is 0.095, ($\beta=0.0123$). The cavity will contain 48 drift tubes, varying in length from 1.59 to 5.83 inches. With NNSS configuration the required magnetic gradients vary from 37 kG/inch (14.5 kG/cm) at the entrance to 15.8 kG/inch (6.25 kG/cm) at the exit. These requirements are appreciably more stringent than those normally encountered in proton accelerators, and have led to considerable effort expended in the development of small high-gradient dc quadrupoles. The following is a description of these quadrupoles and a discussion of the fabrication techniques.

TAPE COILS

The coils consist of two copper tapes insulated from each other, except at the inner turn, wound together on a circular mandrel.[1] Holes are cut into the coil for the poles, and slots in the tape at the ends of the poles provide a current path which alternates around opposite ends of adjacent poles. Figure 1 shows the tapes as they would appear if the coil were unwound, with the current path indicated. Each turn of each tape provides one half turn to each of the four poles, the other half turn being provided by the other tape.

With this type of coil, the slot between poles can be completely filled with copper (approximately 90% packing factor) independent of the width of the coil over-hang. Complete freedom is allowed in the adjustment of the ratio of coil length to pole length. In the early drift tubes, where space is severely restricted, the entire drift tube can be filled with coil. It should be noted, however, that only half of the copper across the ends of the poles is active, so that the packing density for this portion of the coil is about 45%. The design of a magnet with minimum pole width is, therefore, of considerable importance, particularly in the early drift tubes where 75% of the total power is dissipated across the pole ends.

The coils are intrinsicially symmetric so that the inner turn can be positioned close to the pole tip without concern for possible degradation of quadrupole quality due to winding assymetries. The fraction of the total flux that appears in the aperture is thus increased, the pole base width can be decreased, resulting in decreased power requirements, as noted above.

With the exception of variation on packing factor, the power required is independent of the tape thickness, allowing considerable latitude in the adjustment of the coil impedance. The Hilac quadrupoles have been designed to operate at about 4500 ampere-turn per pole, provided by 225 amperes flowing through 40 turns of 0.032-in. copper tape insulated with 0.006 in. epoxy-nylon paper (each turn provides on-half turn per pole). Apertures and quadrupole lengths are varied to maintain this current approximately constant along the length of the accelerator. Power requirements vary from 0.8 to 1.1 kilowats per magnet (not including busing), depending on the space available in the drift tube for coil overhang beyond the pole.

COIL FABRICATION

The coil fabrication method described here, although involving numerous steps, is simple and, except for the double feed winding machine (and the equipment designed to facilitate quantity production), requires no special tooling.

To achieve symmetry, it is necessary that the poles (and the slots in the tape at the ends of the poles) be located accurately with respect to both the inner and the outer ends of the tape. This keying is provided by 1/4 x 1/2 x 1 inch long bars soldered to the inner end of each tape. In winding, the bars protrude through slots in a 1/4 inch wall bakelite mandrel into key-ways in a solid steel winding mandrel (Fig. 2a). Subsequently, the bars serve as reference keys in for the slotting and sawing operations.

The method of producing the slots at the ends of the poles requires the winding of two separate coils. Each of the coils is wound with two tapes separated by insulation, under a tension of about 30 pounds per inch of tape width. After winding, the coil is secured with a hose clamp and the pole end slots cut with a band saw, completely across its face, the cut on one end perpendicular to that on the other. The second coil is similarily slotted, with the slots oriented 90 degrees from those of the first coil (using the keys as reference). The slots of both coils are then etched with nitric acid to remove the sharp edges produced by the saw cut.

When the clamps are removed, the released coils unwind sufficiently that the tapes can be separated and the insulation spacer removed. The tapes are etched all over to provide a good surface for the subsequent epoxy bonding.

The coils are then reassembled with the two inner tapes interchanged between the two coils. Insulation material (two layers of Nomex nylon paper)(Fig. 2b) of the same thickness as used in the original winding are placed between the tapes and the coils rewound, (Fig. 2c) similar to the winding of a clockspring. When the coils are wound tight, the slots line up along the diameter of the original saw cut, i.e., the slots of one tape are to be perpendicular to those in the other. This method produces two coils with the pole windings in the opposite sense.

The rewound coils are secured with a hose clamp, vacuum-pressure impregnated with Hysol-C35 epoxy and cured at progressively higher temperature for 12 hours, with a final cure at 135°C.

Radial holes are then drilled through the coil to accept the band saw blade used to cut the holes for the poles. The holes are sawed with a circular spiral tooth blade capable of cutting in any direction. This blade, although slow, (0.050 in per minute with a 5 in. deep cut) produces a cut that can be controlled to within about 0.005 in. For the straight sided poles the blade is threaded completely through the coil and the two opposing holes are sawed simultaneously. To produce the 60 coils necessary for the Hilac, we have motorized an X-Y table so that after the welding of the saw blade, the complete cut (two poles) is made automatically without attention (Fig. 2e). Sawing of the four holes requires approximately 3 hours.

For the sawing, the coil is mounted on an index head and, after the completion of one saw cut, the coil is rotated 90° for the second cut. The resulting holes are perpendicular and can be accurately positioned with respect to the center of the coil to within about 0.010". The close fit of the poles to the holes assures the symmetric positioning of the coil in the assembly of the magnet. The saw cut is sufficiently smooth so that no subsequent surfacing is required, except for etching to reduce the level of the copper below the insulation. The sawing operation also removes the bakelite mandrel and the mandrel keys, which are no longer required for indexing.

To this point in the fabrication, the two tapes are isolated from each other so that continual checking for turn to turn shorts can be made. After a final check for shorts the tapes are soldered together at the inner radius and the outer busing provided. The quality of the coil is then checked by a harmonic analysis of the central fields produced by the coil without steel.

Approximately 8 hours labor per coil are required for the complete fabrication when the coils are produced in quantity.

YOKE-POLE DESIGN

The yoke-pole configurations are designed with the assistance of the computer program MIRT, which combines a magnetostatic analysis program TRIM[2] with a program for the inversion of system analysis PISA.[3] TRIM is a two dimensional program that is capable of including the effects non-uniform current distribution and of finite permeability materials. PISA is a weighted least squares optimization program incorporating a linearization and iteration procedure that allows the optimization of non-linear systems.

In MIRT the field distribution of a specified pole geometry, and alterations of this distribution due to suitably chosen modifications to the geometry, are calculated by TRIM. This information is used by PISA to find the modifications for optimum performance of the magnet (least square fit any desired field distribution). Figure 3 is a Calcomp plot of a MIRT-designed/ 1 inch aperture quadrupole of infinite length with the current distribution as in a tape coil. The pole tip contour consists of a hyperpola (originally specified) with superimposed parabolas matched in slope at their intersecting points, and optimized to produce minimum deviation from a constant gradient on the transverse axis. The program also indicates the field distribution at all points including the steel, assisting in the optimum (minimum steel) design of the yoke-pole structure.

Since the end effects in the Hilac quadrupoles are of considerable importance, the contours generated by MIRT can be used only as an approximation. The poles are fabricated with the MIRT contour approximated by a series of three steps giving six free parameters which can be used to produce the desired field configuration. A harmonic analysis of the complete magnet, including fringe regions, is made for each arbitrary modification of three of these six parameters. PISA uses this information, (similar to that provided by TRIM, above) to calculate the modifications to the original contour necessary to produce the optimum magnet, in this case minimum higher harmonic content. This general procedure has been previously described,[4] however, the use of PISA considerably reduces the number of pole modifications necessary to achieve the desired field configuration.

In order to confine the fields to the region of the pole, the pole ends are not contoured. The integrated higher harmonics are thus minimized only for a limited operating range, and the correction must be made at operating gradients.

YOKE-POLE FABRICATION

The effects of misalignments of the magnets on the beam has been investigated using the 4P computer program.[5] This program is similar to PARMILA, indicating the phase space characteristics of the beam at various points along the accelerator, but also includes the effects of various lens aberations as well as those due to arbitrary misalignments of the elements. The criterion used in the establishment of allowable misalignments of the magnet system are those which produce a 20% increase in the phase area at the exit of the accelerator. These displacements are:

Longitudinal Axis	0.010 in rms
Transverse Axis	0.002 Radian rms

The location of the longitudinal magnetic axis with respect to the drift tube presents no problem. The positioning of the transverse axis to the required accuracy and the achievement of the symmetry necessary for the elimination of odd order harmonics requires considerable care in the fabrication and assembly of the magnets. The method of fabrication we have developed takes advantages of the stepped pole tip described by Danby and Jackson.[4]

The bore tube is a heavy walled cylinder into which four key slots are milled using a precision indexing head. (See Fig. 4). One end of the tube is machined to accept the bore of the drift tube face. The other end is machined with a land to position the pole tips axially and a taper extending beyond the pole tips. The keyed-taper serves as radial and azimuthal reference in subsequent assembly operations. After welding of the completely assembled magnet to the stems, the azimuthal reference is transtered to one stem, and the tapered end of the bore tube machined to accept the drift tube face.

The poles are machined to the contour derived as described above and the steps, when fitted into the precision keyed bore tube, serve to position the tip both radially and azimuthally.

Both the pole base and the matching cylindrical yoke are machined with a slight axial taper. On assembly, (Fig. 5), the four poles are wrapped with a layer of paper, pushed through the holes in the coils and positioned on the keyed bore tube. The yoke is then placed over the poles; the matched taper forces the poles radially inward to fit snuggly against the bore tube and at the same time eliminates the possibility of non-uniform gaps at the base of the pole. A small hole is match-drilled through the yoke into each pole and reamed to accept a taper pin. The entire structure is then vacuum potted and the faces machined to the proper length. In this machining operation they keyed-taper end of the bore tube is used to position the entire magnet structure.

An analysis of the errors involved in the fabrication of the jigging and in the magnet assembly leads us to expect variations of the magnetic radial and transverse axis from those indicated by the keyed-taper of about 0.0004 in. and 0.0008 radian, respectively.

DRIFT TUBE DESIGN

The Hilac drift tubes are approximately 10" diameter and are supported by two 60 in. long, 1.25 in. od by 0.5 in. id stems at 90 deg. At operating gradients an unbalanced magnetic force between quadrupoles of about 4 pounds would produce axial drift tube deflections of approximately 0.060 in. if shielding were not provided. The inclusion of this shielding presents a considerable mechanical problem and, in addition results in a substantial decrease of the effective length of the quadrupole. Figure 5, a section of the drift tube, shows our solution to the problem of shielding. The face is 0.050 in. magnetic stainless steel (type 430), copper plated on the outer surface to a thickness of 0.015 in. The stainless steel provides the required magnetic shielding and can withstand the internal water pressures (about 19 psi maximum) without excessive balloning of the faces.

With the exception of varying bore diameter, all of the drift tube faces are identical pressings, and require only minimum machining at the bore and outer edge.

In assembly, the stems are welded to the magnet yoke, and the keyed taper at the end of the bore tube removed. The drift tube faces are positioned on the bore tube and are then spot-welded to the magnet yoke (which extend about 0.060" beyond the coil), providing additional stiffening to the drift tube face. The seams at the outer edge of the drift tube and at the bore are then soldered with low-temperature high-conductivity solder with local heating.

Water enters the drift tube through one stem, (Fig. 6) is channeled through slots in the end of the yoke radially inward between one end of the coil and the drift tube face, axially along the bore tube, radially outward on the opposite end of the coil, and leaves the drift tube through the other stem. Maximum heating load, both magnet and rf, will be about 2.5 kilowatts, requiring a water flow of about 1.5 gallon per minute. A closed water circuit will be provided and operated so as to reduce the internal pressure in the drift tube to about 10 psia when providing a 10 psi drop across the system.

MAGNET PERFORMANCE

The Hilac magnet system will consist of fifty quadrupoles operating in the NNSS configuration. Three separate sets of magnets will be constructed. The first eight will have vanadium-permendur poles varying in length from 0.85 to 1.1 inch with a 0.7 inch diameter aperture. Quadrupoles 9 throgh 16 will have straight sided vanadium-permendur poles, 1.4 inches long with a 0.875 inch diameter aperture. The remaining magnets will have straight sides, low carbon steel poles 2.0"long with a 1.0 inch diameter aperture.

The apertures and lengths of the magnets have been chosen to maintain the required excitation (4500 ampere turns per pole) approximately constant along the accelerator. This excitation will be provided by identical coils (except for length) with inner and outer diameters of 2.0 and 5.5 inches.

During the development of the coil fabrication techniques several coils have been constructed and tested. Power distribution in these coils, and total power, differ only slightly from those calculated assuming current densities inversely proportional to tape widths at various points in the coil.

Using 0.006 inch double layer insulation, we have had no problem with turn-to-turn shorts or current leakage. Turn-to-turn electrical strength exceeds 1000 volts, with ultimate failure on the machined face. Similar coils have operated for long periods immersed in low conductivity water, with no apparent degradation in performance. To increase the electrical strength and to inhibit corrosion, however, the Hilac coil faces will be coated with a thin (0.002 inch) layer of epoxy.

Preliminary measurements of pole tips designed with the assistance of the Pisa computer program indicate that, with as few as four modifications of the pole, the amplitudes of the 6th, 10th and 14th harmonics can be reduced to a few tenths percent of the quadrupole harmonic at 0.9 aperture radius. This will allow the use of almost the entire magnet for beam.

REFERENCES

*This work was done under the auspices of the U.S. Atomic Energy Commission.

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4. G. T. Dangy and J. W. Jackson, IEEE Trans. Nuc. Sci., June 1967, p. 414.
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DISCUSSION

(R. M. Main)

BLEWETT, BNL: When you quote 0.3% of the 6th harmonic, is this measured at the limiting radius of the aperture?

MAIN, LRL: This is at about 0.9 of the aperture radius, as close as we can get with the pick-up coil. I think that we could do better than this if we wanted to; however, this is good enough for the Hilac quadrupoles.

FEATHERSTONE, CERN: Could you tell us what is the practical range of voltage and current?

MAIN, LRL: With these coils you can adjust the impedance to anything you want by changing the tape thickness. Except for slight changes in the packing density of the coil, the power is the same for a given number of ampere-turns per pole. In general, the tape should be made as thick as possible, consistent with allowable lead losses. Our choice of 225 amperes is mostly based on what we consider acceptable losses in about 14 feet of magnet leads necessary to get out of the system.

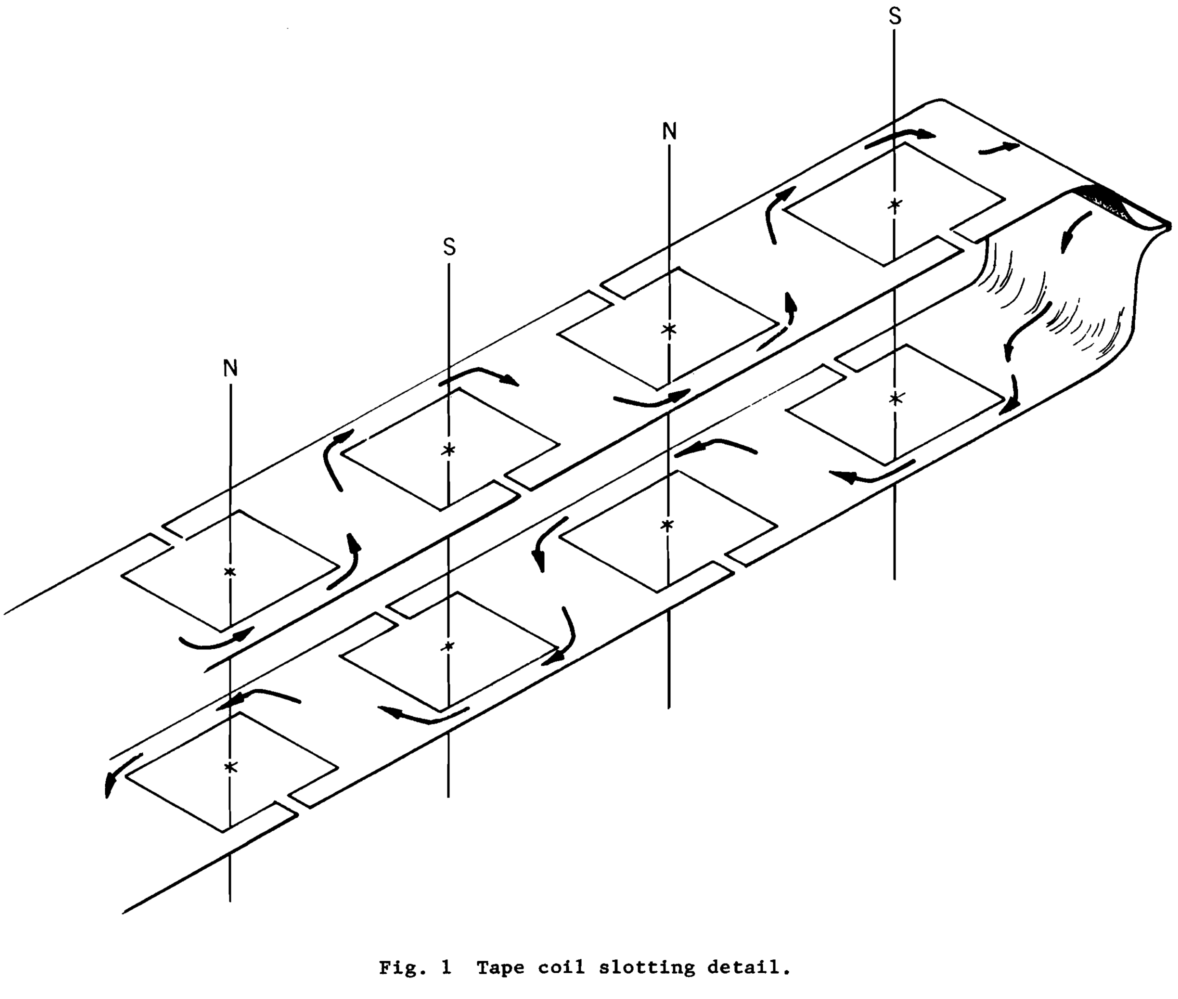

Fig. 1 Tape coil slotting detail.

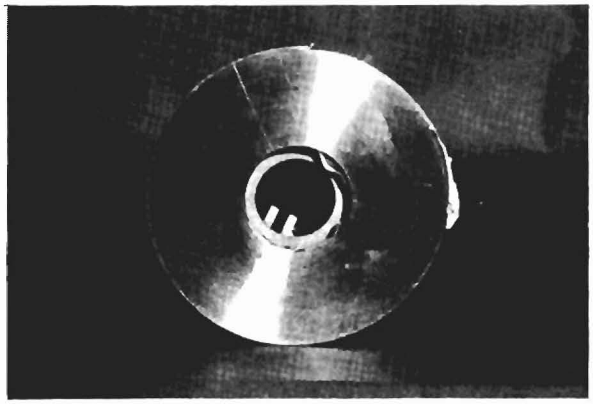

Fig.2a Tape coil fabrication.

Fig.2b Tape coil fabrication.

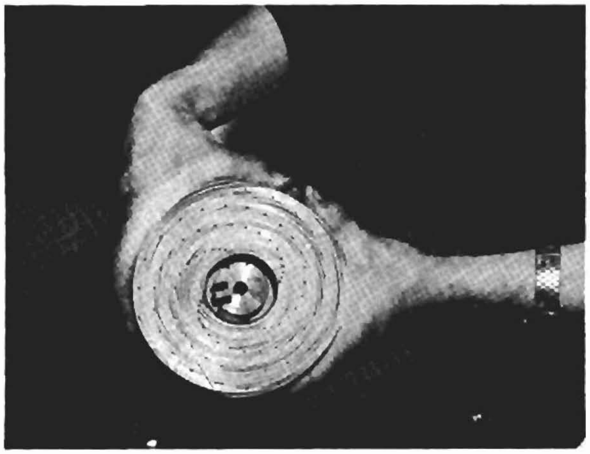

Fig.2c Tape coil fabrication.

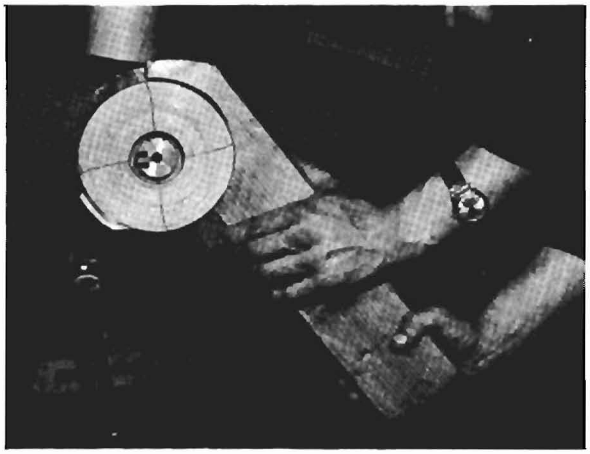

Fig.2d Tape coil fabrication.

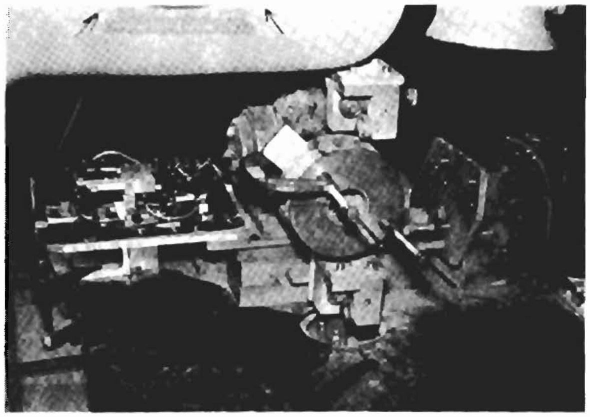

Fig.2e Tape coil fabrication.

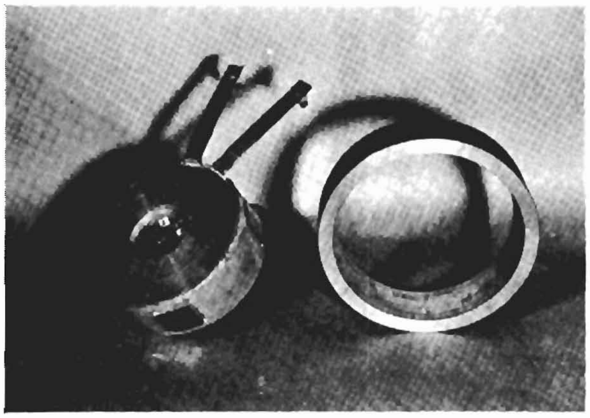

Fig.2f Tape coil fabrication.

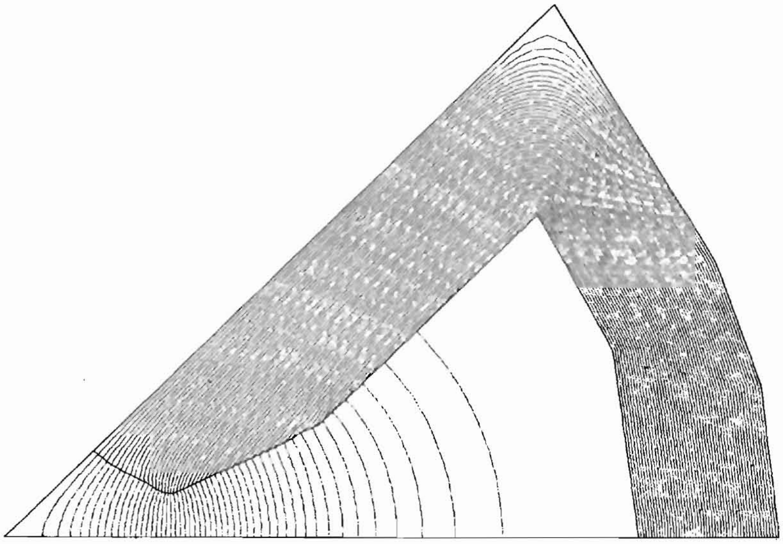

Fig. 3 MIRT designed quadrupole type 1010 low carbon steel 12.5 kG/inch, 1-inch aperture.

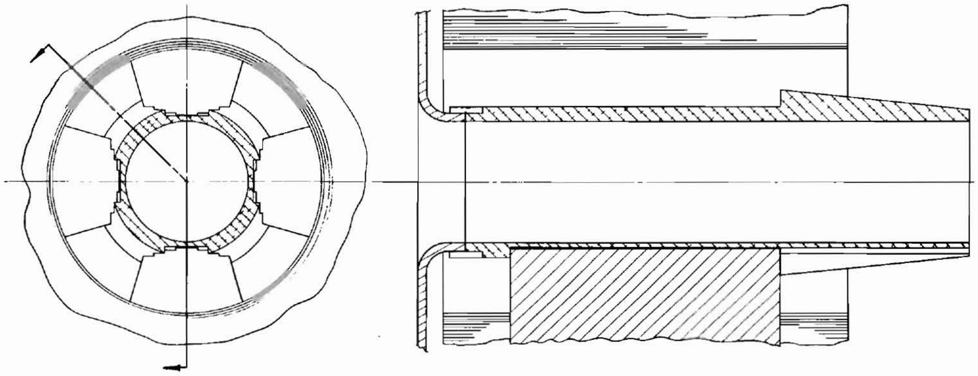

Fig. 4 Drift tube bore cylinder pole tip positioning jig.

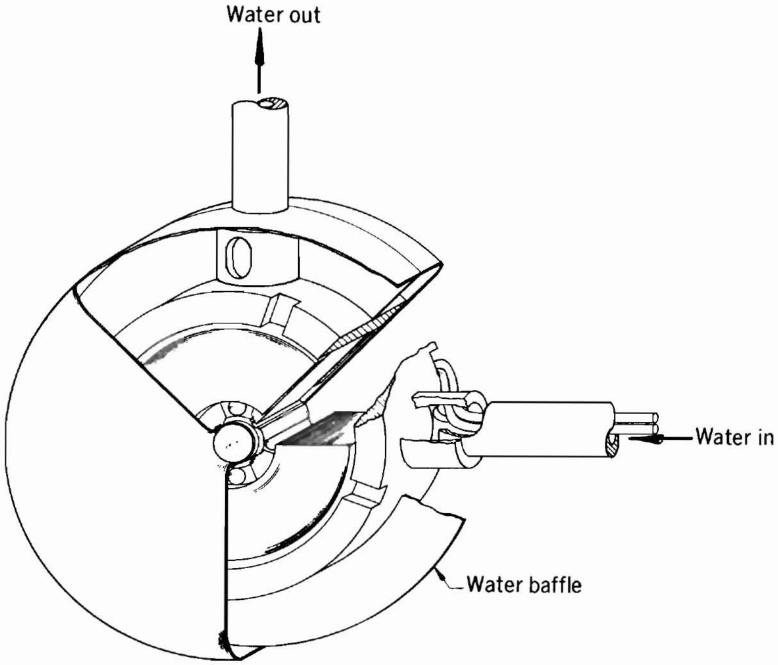

Fig. 5 Drift tube assembly cut-out.

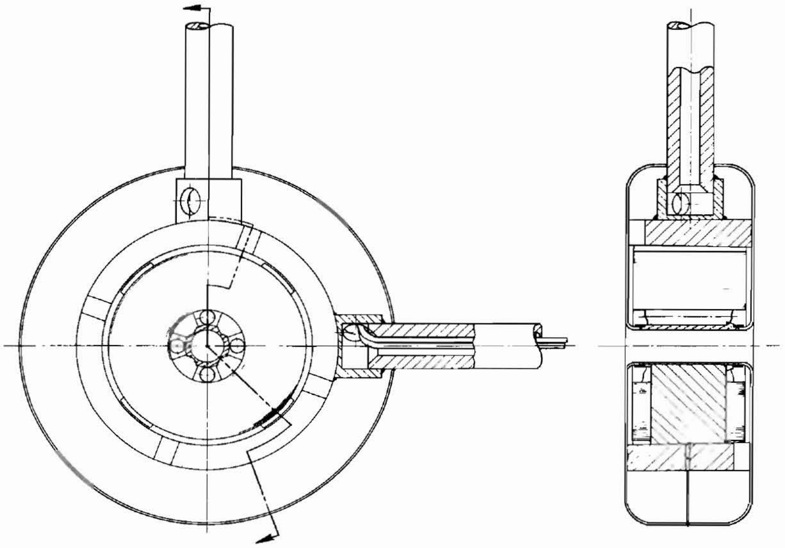

Fig. 6 Drift tube assembly.