APPENDIX VI. MAGNET SYSTEM

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A. Introduction

This section describes the mechanical design of the Doubler superconducting-magnet system. This topic includes the magnet-string concept, the dipole, quadrupole and trim-magnet designs, and the magnet-support design.

The foremost system choice was to build a separated-function accelerator with a duplicate lattice to the Main Ring. Our early efforts convinced us that superconducting pure dipoles and quadrupoles would be preferable to combined-function magnets. Inherent in the latter magnet is a large coil-bundle to iron-shield force. In a no-saturation warm-iron design, this force causes excessive heat conduction through the support to helium and excessive deflection-caused field inaccuracy.

We know from our Main-Ring experience that less trim magnet space is required and we believe that we can make a greater-strength quadrupole. These conditions allowed us to lengthen the dipole slightly to 22 ft center-to-center and shorten the quadrupole to 4 ft. (The Main-Ring dipoles are 20 ft 11 in. center-to-center and quads are 7 ft.) The design calls for 778 dipoles and 240 quadrupoles. Most of our effort has been directed towards the dipoles and they will be treated first in this report, with quadrupoles and trim magnets discussed in less detail.

B. Magnet Strings

The remaining over-all system choice was to group the magnets into 48 subsystems each made of 16 dipoles, 4 quadrupoles and trim magnets. All magnets in these strings share a common current (except the trims), common helium supply (one-phase helium and return two-phase helium), common beam and thermal-insulation vacuums, and common 20K-shield helium flow. The magnets are made as identical modules and are connected at their ends in junction boxes to form strings. The strings extend from every tunnel service entrance independently in each direction halfway to the next entrance.

The string choice was made at the project start and follows from the simplifying philosophy of seeking the smallest number of penetrations from room temperature to cold helium. The primary penetrations to minimize were the 4500-A current leads. At least one set per string is required because the power supplies are warm. Our design holds to this minimum. These penetrations are located in the service buildings where there is easy access to the refrigerator and where it is easy to connect to the power supplies.. Calculations to investigate replacing these leads with a superconducting-secondary transformer proved the replacement to be impractical. The transformer is too large at our ramp rate. A superconducting transmission bus inside the helium supply pipe carries the current down to the magnets, which act as their own bus and transfer the current downstream from one magnet to the other. The current handoff to the next independent string halfway in the tunnel is made cold and superconducting. The only remaining active leads are the low current (200-A) trim-magnet leads coming out at the individual magnets. Every dipole and quadrupole has an inactive gas-cooled safety lead.

The remaining features of these strings, such as the liquid-helium coolant and gaseous-helium shield, as well as the vacuum systems, are discussed in Appendices XI and XII.

Connections between magnets take place at junction boxes. Over-pressure relief and magnetic-energy withdrawal safety leads are placed in these and are the major penetrations. Magnets will all be made as standard modules, with the end functions of every system handled entirely within the separate clamp-on end boxes.

C. Dipoles

Coils are the heart of the magnets. They are made of wire that is a twisted and flattened cable (0.300 × 0.050 in.) of twenty-three, 0.027-in. dia. strands. As discussed in Appendix V, the strands are made of 2300 filaments of Niobium Titanium coextruded in a copper matrix with the proportions of one part superconductor to 1.8 parts copper. Once the individual strands met the stability criteria of Appendix V, we selected the number of strands in the cable and hence the operating current by the following reasoning. A coil package of two layers with few turns is easiest to build and has the smallest inductance. The smallest cable to let this geometry reach 45 kG with a small factor of safety is the 23-strand operating at 4500 A. This many strands had never been made up in a flat cable, but working with our vendors, we were finally able to produce it reliably.

The dipole coil package is formed as a top and a bottom coil, each made of

two layers or shells forming saddle-shaped coils. In double-layer winding, the conductor winds out from the center in a flat spiral on one level and after a transition to a second level, out from the center in the opposite-hand spiral. The leads end up conveniently on the outer edges of the coil and no internal splice need be made; the entire double layer can be made of one length of conductor. Thirty-four turns are wrapped into the inner spiral and 21 in the outer. In the top coil, the last half turn in the outer shell is left out to form a lead at the back end of the coil. An additional wire is then placed into the void created and becomes the bus conductor. The coil bundle has a lead set at each end.

Superconducting wire has no resistance to electric current and can be made about one-hundredth the size of a comparable copper conductor. This allows the magnet designer to use almost unlimited current and turns without economic hesitation and allows placing them into a small enough package that high fields can be achieved. An additional construction difference from conventional magnets is that the iron has been removed from the active-field area. In conventional magnets, the contour of the iron pole tip determines the field quality. In superconducting magnets, the sole determinant of field quality is the wire position. This position dependence requires a new precision on the part of coil fabricators, which in the past had only to be concerned with external coil dimensions and not positions of individual turns.

Field calculations to determine the position of these wires are discussed in Appendix III. Manipulating the inner coil edges of our simple geometry allows fields good to one part in 10^4 at 1 in. from the center at the mid-plane.

The insulation system for the coils has several requirements. The conductors have to be isolated turn-to-turn to withstand voltages of the order of 10V. Extreme parts of the coils must withstand thousands of volts to either ground, companion top or bottom coils, or the bus conductor. For turn-to-turn protection, the conductor is covered in a spiral-wrapped overlapped 0.001-in. thick Mylar tape. Before this wrapping, the cable is ultrasonically cleaned in Freon solvent to remove fabrication-induced metallic slivers. No adhesive is used on the tape because of our experience that any adhesive bonded to the cable causes degraded coil characteristics. The cable should have a keystone or trapezoid shape to fit well into the Roman arch-like shell geometry. Since it is actually a rectangle, a layer of 0.003-in. 1/3-width Mylar tape is applied along the outer edge to fill the void. (Experiments are underway to form the cable as a trapezoid.) Over this taped cable

is wrapped a 0.007-in. lightly epoxy-impregnated 0.25-in. wide glass tape. It is wrapped like a barberpole with 1/16-in. gaps to aid helium permeation. When the coil is formed in its mold, there is just enough epoxy to hold the coil together but not enough to drip or seep into the cable itself.

The insulation from inner to outer shells is by intermediate banding. This epoxy-impregnated 1/4-in. wide glass tape, 0.021-in. thick, spaced 3/8-in. apart, is applied in a herringbone pattern down the length of the inner layer or shell. The second shell is then wound on top of this spacer. The gaps form helium convection passages to aid in cooling the outer shell. At the coil ends, the spacer is placed in a chevron pattern to support the coil wraparounds uniformly. Upper-coil to lower-coil insulation is provided by an extra layer of 0.010-in. Kapton at the midplane where they meet. Short-to-ground insulation is provided by a 0.030-in. built-up mat of Dacron-Mylar-Dacron sheet.

It might be noted that cable is available to a size tolerance of ±0.001 in. In 34 turns this can result in a 0.068-in. difference in build-up. We have found that the 0.007-in. glass tape barberpole is mushy enough before curing to take up this difference with ease.

Because the superconducting wire is sensitive to field strength, there should be no regions in the coil where the field is unnecessarily high. This would quench the conductor. Such a weakest-link region exists at the inner hairpin turnarounds of the inner shells. Our design spaces out the inner ten turns with crescent-like spacers. This diffuses the magnetic field to bring it down to the average coil field.

To produce the abrupt transition from layer to layer at the center of these double-layer coils, the twisted cable is untwisted one half pitch. The strands are then parallel and able to be jogged easily between the layers in the 0.75-in. length provided.

The coils can be molded very accurately in a mold after winding, but they will not stay that way without some filler to complete the circular arch. We have designed these fillers or keys into the coil-clamp-collar coil supports to be discussed below. At the half-circular ends of the coils, the coil-clamp collars cannot perform this function. Machined G-10 keys with matched coefficient of thermal expansion fill the gap. They also house the guide and support slot for the layer-to-layer transition mentioned above.

To complete the cylindrical coil package, curved wedge-shaped pieces are

pushed in and clamped against the coil ends. These maintain a definite end geometry and resist the magnetic forces.

In our designs we have concentrated on keeping the wire constrained at all times to prevent frictional heating caused by motion. Through our testing it has become evident that adhesives like epoxy bonding the wire can make coils quench prematurely. When the strong bond cracks, the heat generated by the resultant motion is great enough to cause a quench. When we switched to the present Mylar-covered wire, the magnets performed better, as if the Mylar was also acting as a thermal insulation preventing the cracking epoxy heat from reaching the wire. The epoxy is still necessary to assemble the coil. Associated with this adhesive cracking and frictional heating is the training process. The coils are finally trained and the highest currents achieved when all wires have jockeyed to their lowest-energy positions.

In our past reports we proposed a form of banding to restrain the coils against the 6000-lb/in. outward force. The moment tending to flatten the coil was taken by a stiff bore tube or stiff rings. This system amounted to an internal skeleton. It was successful in that our coils were able to reach 95% of the maximum attainable current, but we found the deflections of the coil bundle to be too large to maintain the proper conductor placement required for field quality.

Our present solution is an external skeleton scheme known as "coil-clamp collars". They are a lamination made of stainless steel. Instead of inserting the coils in a finished yoke, as in a conventional magnet, these non-magnetic laminations are built up around the coil. They are fastened by a combination of a dovetail epoxy lap joint and a series of welds. They have cut the deflection of the coil by a factor of two. They show less training and they have a built-in potential to produce a more accurate coil bundle.

The collar is a single lamination that performs many functions. Two laminations complete the circular wrap around the coil with the keyed joint at a plane 20° to the vertical. The adjoining pairs in the buildup are flipped such that a 40°-wide overlap for an epoxy lap joint is seen by every lamination. The laminations have key surfaces on the inside that butt up against the edge insulation of the two shells. The laminations are registered to each other by notches in the outside circular surface. During assembly, the tooling squeezes the laminations down while registering them with respect to one another as the epoxy cures.

The selection of stainless steel for these clamp collars and for the sur-

rounding cryostat takes some care. Most stainless steels, especially at low temperature, can turn slightly magnetic. This happens when portions of the alloy revert from the austenite phase to the magnetic ferrite phase. Normal iron exhibits this phase change at about 1200°F. Some alloying elements, such as nickel, nitrogen and carbon, eliminate this transformation or force it to lower temperatures. Others, such as chromium, tend to raise it. Too much nickel, as in Inconel and 310, causes magnetic properties stemming from the nickel itself, even though the material never transforms. Many of the "good" elements like carbon and nitrogen are subject to a large manufacturing tolerance. One composition of 304 will transform and another will not.

Another variable is treatment of the material. Cold working tends to raise the transformation temperature. Certain high temperatures can cause the elements to segregate, allowing transformation of some lean crystals. Higher temperatures and a rapid quench cause frozen-in homogeneity and non-magnetic properties. In welding, however, magnetic ferrite is desirable in the weld bead because it aids hot ductility and prevents microcracks. Alloy 310 and 205 do not form this ferrite in the weld bead.

The alloy we have chosen is Armco Nitronic 33. (Its composition percentages are 18 chrome, 3 nickel, 13 manganese and 0.04 nitrogen.) It has the lowest natural permeability of the stainless steels, approximately 1.001. Its cost is the same as that of 304L. It is low in carbon, so weld segregation is minimized. In its natural unworked state, it never transforms to ferrite. Only after fracture does it show any signs of ferrite formation and that only at the fracture point. To prevent weld cracks, it does deposit ferrite at a weld. It has a yield strength of 60,000 psi, double that of 304L. Comparisons of this material to other steels are shown in VI-1 and VI-2. Figure VI-1 shows a comparison at room temperature of the permeabilities of the various stainless steels. Figure VI-2 shows the austenitic stability tolerance for Nitronic 33 and some other common stainless alloys.

The coil bundle ends with an end ring fastened to the laminations squeezing the end fillers into the coil. Three pairs of leads stick out from between the illers, two sets at the lead end, and one set at the return end. One pair at each end is used for the coil terminals. The extra pair at the lead end is lapped and soldered to form the splice between top and bottom coils. The enclosing splice block, which is a copper channel, is mounted against the end plate with suitable helium-ventilated insulation.

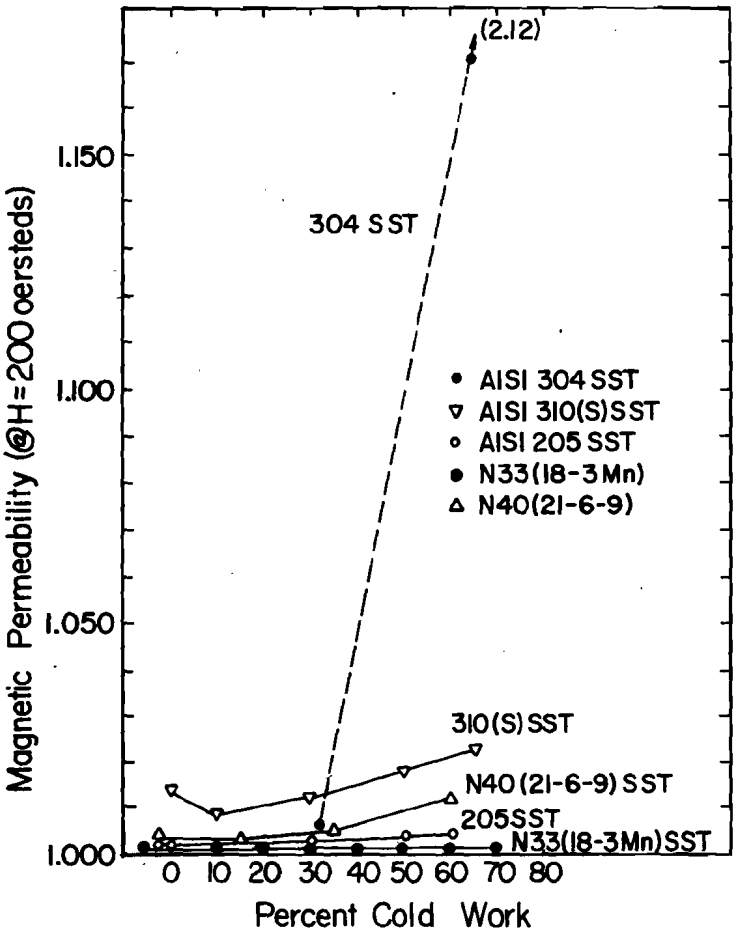

Fig. VI-1. Permeability as a function of cold work.

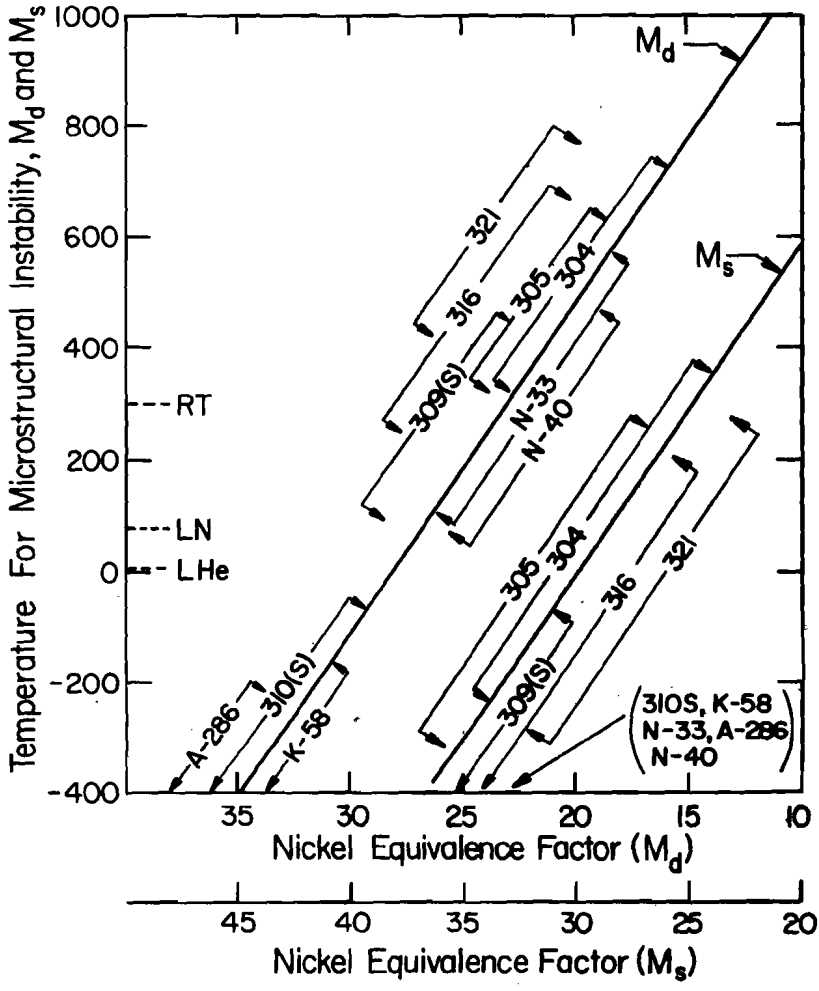

Fig. VI-2. Austenitic stability tolerance of stainless-steel alloys.

The splice mentioned above is the only splice in the dipole. The two double-layer coils are wound with a continuous length of wire. Current flow across a splice between wires cannot be made superconducting, because the superconducting filaments cannot be directly joined. If the copper is etched away to expose the strands, the oxide film that immediately forms on the filaments is more resistive than the original copper. Welding and silver soldering are not possible because the high temperatures destroy the superconducting properties in the joint vicinity. The least-resistive alternative is a soldered lap joint. We make this lap joint by squeezing the wires together during soldering. A heat generated at 5000 A is 0.0325 watts in a 4-in. splice, which can easily be dissipated to the surrounding helium.

Cryostat. Each coil bundle is immersed in one-phase (bubble-free) supply liquid helium contained in an annular cryostat. The inner tube of this annulus allows heat transfer to a second inner annular space filled with the colder, boiling, two-phase return helium. Each triple-tube package with coil is suspended within the thermal-insulating vacuum space by roller suspensions of fiberglass-epoxy composite. A thermal-radiation shield operating at 20K is also suspended in this space. Dimplar multilayer insulation between the shield and room temperature vacuum wall intercepts the bulk of the radiation heat load. The warm-iron magnetic shield is clamped around the outer vessel. The enlarged ends of the vacuum tube called the junction box use a large bellows as an access cover to expose the Conoseal service connections.

The cross-sectional features of the magnet can all be seen in Fig. 2 of the main text. In giving further component detail, the parts will be discussed from inside to out. The beam tube is an approximation to an ellipse with a horizontal major axis of 2.900 in. and a vertical minor axis of 2.0 in. It is made of rolled strip, seam-welded and drawn to shape. The weld is annealed to remove magnetic properties. The inside is Diversy-cleaned for better vacuum properties. The elliptical shape is useful for extraction aperture. Since it is directly in contact with two-phase helium, beam-heating effects are shielded from the coils.

An annular space is formed between the beam tube and the next tube out, the two-phase tube. The space is sized to maintain the two-phase helium in froth flow rather than slug or separated flow. The outside wall of this space, known as the two-phase tube, is again an elliptical approximation and of the same construction as the beam tube. The two tubes are made this thin to minimize eddy-current heat-

ing. Vacuum collapse is prevented by making the tubes into a unit by spot welding them together at their major axis.

The space between the two-phase tube and the coil bundle is used to transmit the bulk of the one-phase flow. It is sized to minimize pressure drop along the string. An insulation strip along the major axis electrically isolates the tube and coil bundle surrounding it.

A thin-wall tube of identical construction sheathes the outside of the coil bundle. Just enough space is left between the coil-clamp collar outer surface and the tube to allow the tube to be slipped on during assembly. The wall is thick enough to withstand the pressures encountered in service but is thin enough to allow the suspension rollers to deform it into contact with the coil collars.

The 20 K shield is the next concentric shell encountered; it is made of five Nitronic 33 tubes. Stand-offs of NEMA G-10 fiberglass-epoxy composite space the shield from the outer cryostat. The shield tube also acts as a mount for the brackets holding the roller suspensions. Cooling is provided by a helically wrapped, flattened stainless tube containing 20 K helium gas. Heat is conducted from the tube to the shield by copper braids soldered to both. A phosphoric-acid based flux is used in the soldering to eliminate any chloride-flux stainless-steel corrosion problems.

Dimplar multilayer insulation fills the gap between the shield and the outer vacuum-vessel wall. It is crinkled, aluminized Mylar insulation. It was chosen over Mylar-and-glass paper because of the good pumping characteristics of its large spacings and because the glass paper tended to shred during handling. Glass-felt buffer material is used at all edges to prevent thermal-radiation entry to the inner layers. Quartz felt is used under weld points to prevent burning the Mylar.

Any displacement error of the coil from the center of the iron shield leads to forces attracting the coil toward the shield. The larger the error, the greater the force. Accordingly, a strong but low heat-loss suspension mechanism must be interposed between the coil bundle and the iron shield. This off-center force is the dominant factor in determining the conductive heat leak from the outside world to the helium vessel.

The rate of force increase with error for the E Series is 1 lb for every inch of length. Our suspensions, spaced every 24 in., are designed to react at 3-1/2 times this rate or 84 lb per 0.001 in. deflection. For example, with an initial error of 0.005 in. in centering, the force per suspension at peak field is

120 lb. This is enough to defelct the suspensions an additional 0.0014 in., at which a force equilibrium is reached at 154 lb and the error from center increased to 0.0064 in. Such errors in placement do not cause significant field-quality problems.

Ideally, the suspensions should be put at the end of the coils to simplify construction, but the coil bundle is not stiff enough and would sag over the 22-ft length. Thus the suspension system must consist of 11 units and must fit within the iron. Each unit consists of four rollers placed at 45° to the horizontal. They are in essence compression pegs that have been converted to rollers to allow 0.75-in. longitudinal shrinkage of the cryostat. They are compressed at room temperature so as to be exactly to size at low temperature when the coil bundle has shrunk across its diameter. The rollers are made stiff enough and are spaced close enough that the total coil off center error is never greater than 0.010 in. One roller is replaced by a NEMA G-10 tube at the magnet center. This tube acts as an anchor to maintain rotational and longitudinal alignment.

The iron shield is made of laminations because they are easily stamped and stacked to the tolerances required. It forms an approximate cosine distribution about a circular bore. It is split into two half yokes along the vertical plane. The laminations are held into a pack by tie angles running along the magnet length at the corners and welded to stiff end plates. The cores are to be impregnated with epoxy that acts as the beam shear web. The cores are stacked curved to a precamber to produce an eventual straight magnet under gravity load. In addition, it is possible to curve the magnet in the horizontal plane to approximate the 1/4-in. sagitta correction to increase the beam aperture.

If the steel shield were to extend over the magnet ends, the highest field applied to the superconducting material would occur in the end region. To counteract this field enhacement, the dipole steel shield stops somewhat short of the coil ends.

In the end junction boxes of the magnet, provision must be made for connection to its neighbor of (i) the beam tube, (ii) the two helium vessels, (iii) the two current leads (the internal bus conductor results in the magnet becoming a four-terminal device), (iv) the outer insulating vacuum chamber, and (v) the intermediate heat-shield cooling tube.

The outer vacuum insulation space is connected from magnet to magnet by an enlarged outer vacuum tube connected by a very flexible bellows and a Marmon type

O-ring flange. Inside at the beam tube, a bellows with an internal cryosorption vacuum pump spans the beam tube. To the aisle side and underneath are the single- and two-phase helium connections using Aeroquip Conoseal joints and bellows for flexibility. The single-phase connection containing the electrical terminals may be flexed back into the vessels to allow the terminal joints to be made. To the top of the beam bellows is the crossover connection of the shield tube. Connecting to one single-phase vessel end is the insulated, combination relief-valve tube and safety lead with its thermal-oscillation-preventing check valve. We are adapting production sheet-metal techniques to the fabrication of these end parts in order to minimize their cost.

D. Quadrupole

The present quadrupole design is shown in Fig. 3 of the main text. Its design reflects many of the solutions we have developed for the dipole. Its three-shell design makes it different from the dipole, but we believe we can still wind it from two continuous wire lengths. It will share its cryostat with the trim magnets discussed below.

E. Trim Magnets

Trim magnets are planned to be wound as air-core magnets. All correction elements will be housed within every package with the proper leads being connected as needed. This integration is possible because the windings can be wound as concentric shells made from single strands of our superconducting wire. The shunted main-current bus will be shielded from the beam by an iron sleeve placed over the trim windings.

F. Magnet Stands

The magnet stand is shown in Fig. VI-3. The stands are placed at the fifth points of the dipoles to keep magnet deflection to a minimum. Shims are used to produce the main adjustments rather than screws. This simplicity follows the philosophy used in the Main Ring, where minimum adjustment worked successfully. The new magnet's position necessitates removal of a portion of the Main Ring magnet stand. A cross piece will be added to this stand to maintain its original strength. The position of the new magnets allows them to be easily threaded through the Main-Ring stands for rapid installation.

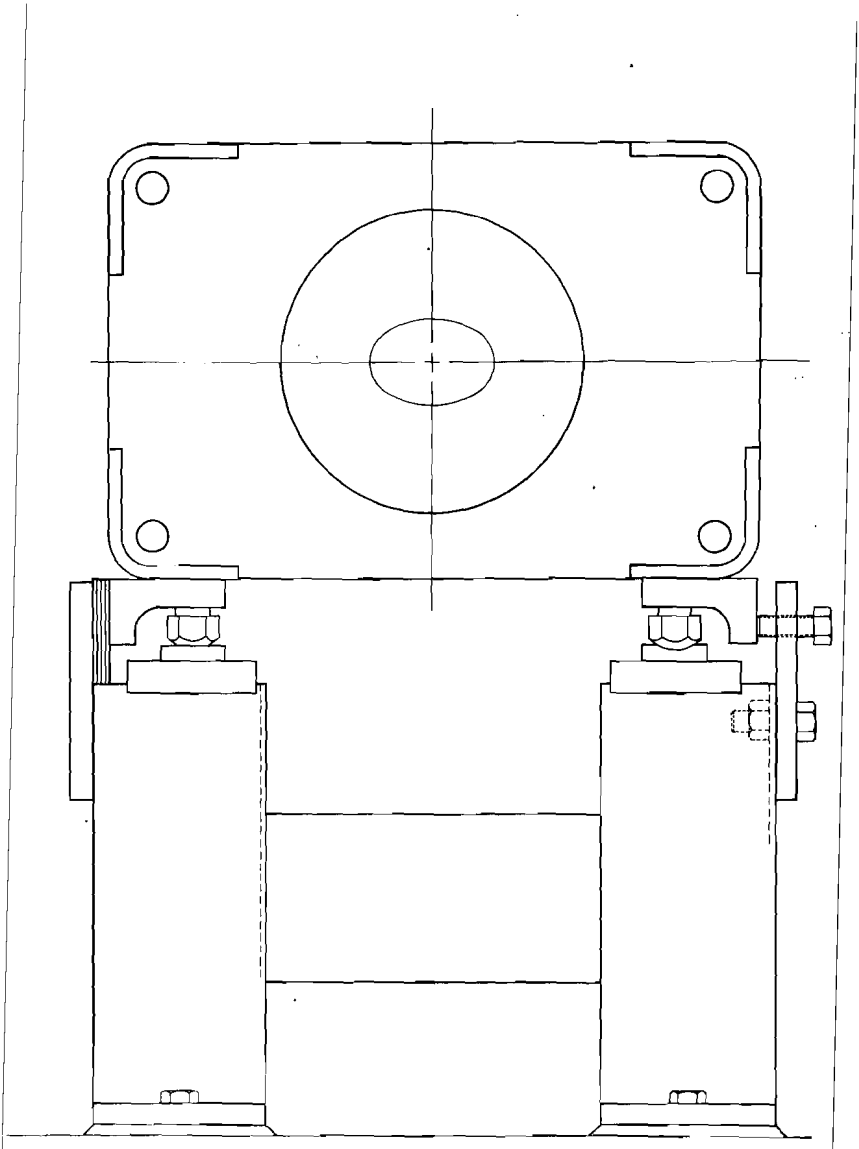

Fig. VI-3. Magnet stand.