DESIGN OF THE HIGH RESOLUTION SPECTROMETER BENDING MAGNETS FOR LASL*

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Abstract

The bending magnet design of the LASL High Resolution Spectrometer is presented. Design requirements and considerations are given. The novel magnetic design of the central portion and ends of the magnet are briefly explained. Magnet parameters and mechanical design features are discussed.

Introduction

One of the instruments designed for the Los Alamos Medium Physics Facility (LAMPF) is a very large magnetic spectrometer known as the High Resolution Spectrometer. The High Resolution Spectrometer, or HRS, is a quadrupole-two bending magnet system (QDD) with a vertical dispersion plane and a resolution of 50 kV for 800 MeV particles. The magnet system is azimuthally positionable about a vertical axis which runs through the spectrometer target. [1]

A model of the HRS installed in a hemispherical underground concrete structure is shown in Fig. 1. The two large bending magnets, each weighing 264,000 lb, are shown supported in the rotatable structure. Centers of gravity of these bending magnets are 12 and 29 feet above the experimental hall floor level which gives an idea as to the size of this instrument.

Design Requirements and Considerations

The basic design requirements for the HRS bending magnets specified by LAMPF are given in Table I.

Table I. Basic HRS bending magnet design requirements.

Beam aperture	10 cm x 65 cm (dispersion plane)
Magnetic length at aperture centerline	75 deg bend at a 3.5 m radius or 4.581 m length
Magnetic length off the aperture centerline	Varies because of curvature required for higher order beam dynamic corrections
Normal operating field range with 10 cm x 65 cm aperture	7.5 - 14 kG
Maximum operating magnetic field with reduced aperture	19 kG
Excitation	d.c.
Variation of the field line integral over all paths through the magnet	2 parts in 10^5

Also, the following adjustable field trimming capabilities were specified:

1. Dipole field levels over each magnet third (25 deg of arc) to be independently adjustable.

2. Sextupole (0.2% of the nominal field at maximum aperture) and quadrupole (0.2% of the nominal field at maximum aperture) corrections also to be independently adjustable distributed over each magnet third.

A number of considerations had to be taken into account along with the design requirements for the bending magnets. The magnets ultimately have to be installed in a structure in a confining "Igloo." Crane capabilities available for installation of these bending magnets in the Igloo limits the size of any one piece to 50 000 lb. It follows that the magnet design must allow for piecemeal installation of the magnets into the rotatable structure. Magnet size is an important consideration only as far as overall cost is concerned.

Design

Central Portion of Magnet

To achieve a field uniformity of a few parts in 10^5 in the central portion of an iron pole magnet requires machining and positioning tolerances of the same order. Presently available machine tools are incapable of economically achieving these tolerances for the large pole tips of the HRS bending magnets, which makes this type of design unattractive.

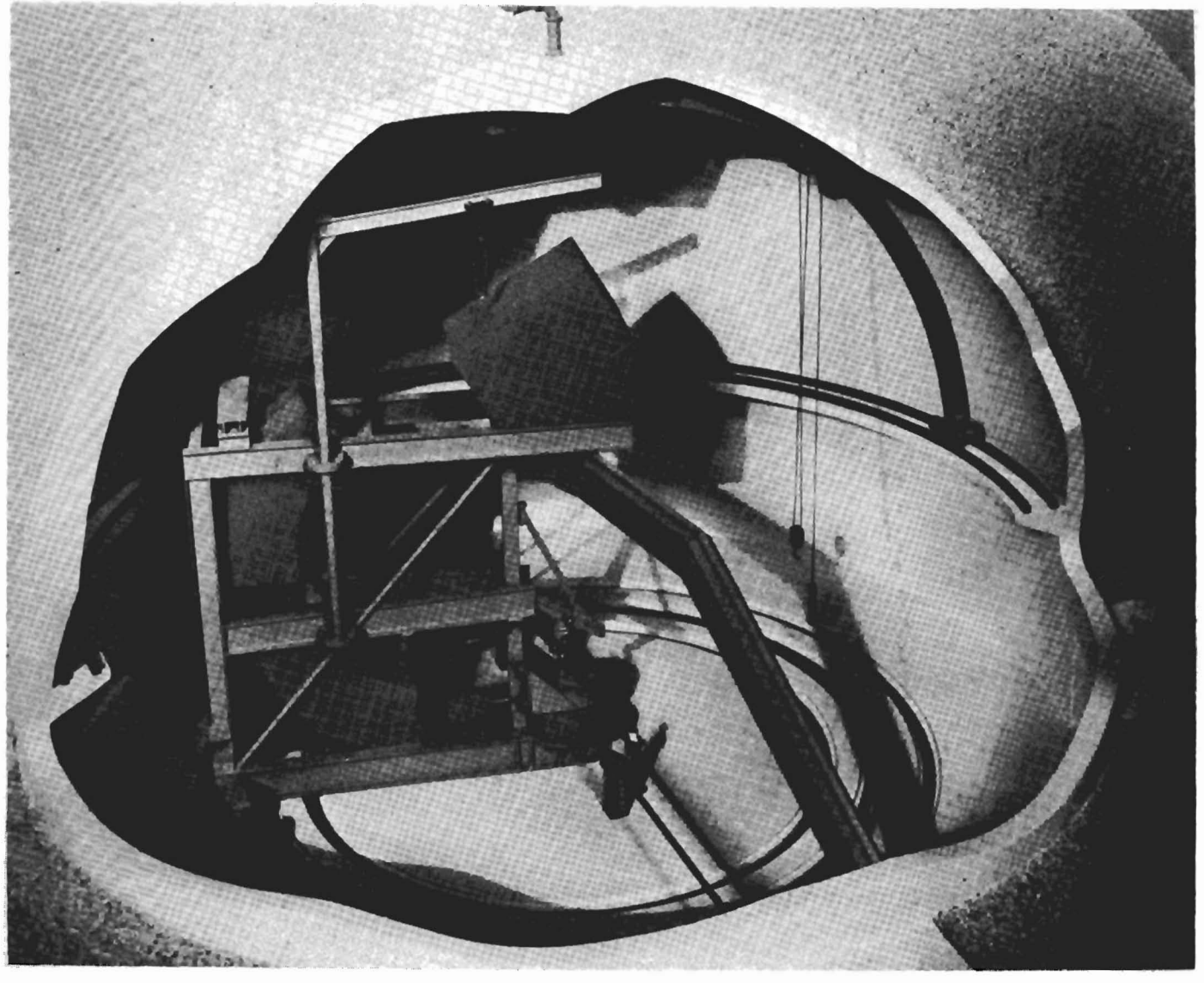

Fig. 1. HRS Model

To achieve the specified field integral tolerance for the bending magnets a novel approach conceived and developed by Klaus Halbach, Lawrence Berkeley Laboratory, has been pursued. Briefly, the scheme is as follows: Fabricate the magnet to conventionally achievable tolerances nominally one part in 10^3 for the bending magnets. Correct the field inhomogeneities by appropriately energizing correcting windings placed in slots behind the pole faces.[2] The net effect of energizing a correcting winding is to change the tangential field component on the pole face in the region closest to the correcting winding slot. This effect in turn changes the field distribution in the magnet gap. Not only can these correcting windings correct the aperture field inhomogeneities, but they can also introduce small distributed quadrupole, sextupole, and higher-order field components to the aperture field. A test magnet using the above scheme of correcting windings has been built and tested at LASL. Results indicate that the correcting windings work as predicted.

The iron configuration and placement of correcting windings developed for the HRS bending magnets is shown in Fig. 2. Correcting winding effects were studied in detail with MIRT[3] for the configuration shown.[4] Computer runs showed that correcting windings could modify saturation effects in the aperture field and small distributed sextupole fields could be introduced. The pole tip profile was optimized for infinite permeability with the computer program MIRT. Three half gaps of overhang were required from the edge of the aperture to the wall of the vacuum chamber.

A side view of the upper bending magnet core with the main coil and field terminators is shown in Fig. 3. The requirement of having adjustable quadrupole and sextupole fields over each 25 deg or arc necessitated three sets of correcting windings. The lead slots for the correcting windings are shown coming through the yoke on the side of the magnet. To adjust the dipole field over each 25 deg of arc coils can be wound around the inner and outer legs of the yoke. Actually, trimming windings are only necessary for the first and last 25 deg arc sections of the magnet; the central portion of the field can be adjusted by varying the excitation in the main coil.

Magnet Ends

For the two HRS bending magnets, field boundaries were specified for each end of each magnet as curves which included corrections to the fourth order in the beam dynamics.

The two parts in 10^5 tolerance on the field integral makes the design of the ends difficult. It is imperative to have adjustability in the ends primarily because it is not possible, from a practical point of view, to machine and position end tips to the tolerances indicated.

To achieve the specified effective field boundaries within tolerance, Klaus Halbach suggested the following approach:

1. Machine first and second order corrections into the pole ends with normal machining tolerances.

2. Third and fourth order corrections for one field level are obtained by use of the field terminators in the following modes.

   a. Movement of the entire field terminator.

   b. Movement of individual nose sections of the field terminator.

3. Corrections for saturation over the design field range are accomplished by energizing coils wrapped around the field terminators between the nose sections and around the return legs.

The machined pole end corrections are concave or convex circular arcs when viewing the dispersion plane of the magnet (see Fig. 3). Looking at the magnet end sectional view, Fig. 4, the circular arcs follow a radius equal to 0.83 gaps. This radius allows the effective field boundary movement to be very insensitive to different magnet field levels.[5]

It also follows that the above-indicated uses of the field terminators can also be used to make some corrections to the beam optics. If necessary auxiliary coils can be placed in the regions bounded by the yoke, main coils, field terminators and aperture. Energizing these coils can move the effective field boundary.

To give some idea of the flexibility of this scheme, field terminator sensitivity coefficients for the geometry shown in Fig. 4 are given in Table II.[5]

Parameters

Magnetic and engineering design parameters for the High Resolution Spectrometer are given in detail in Table III.[6] The magnetic design parameters were obtained in part from computer

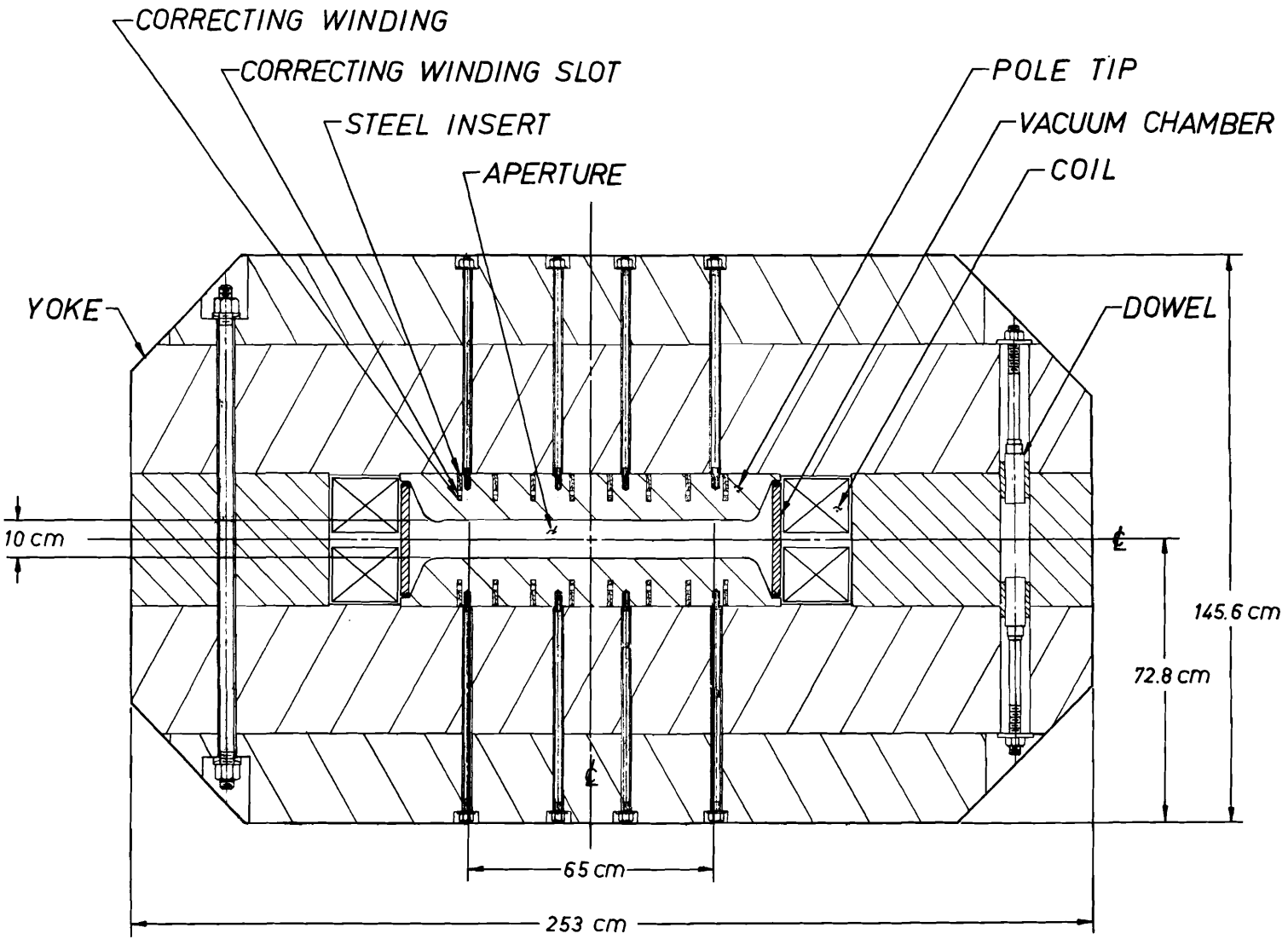

Fig. 2. HRS Bending Magnet Typical Radial Cross Section

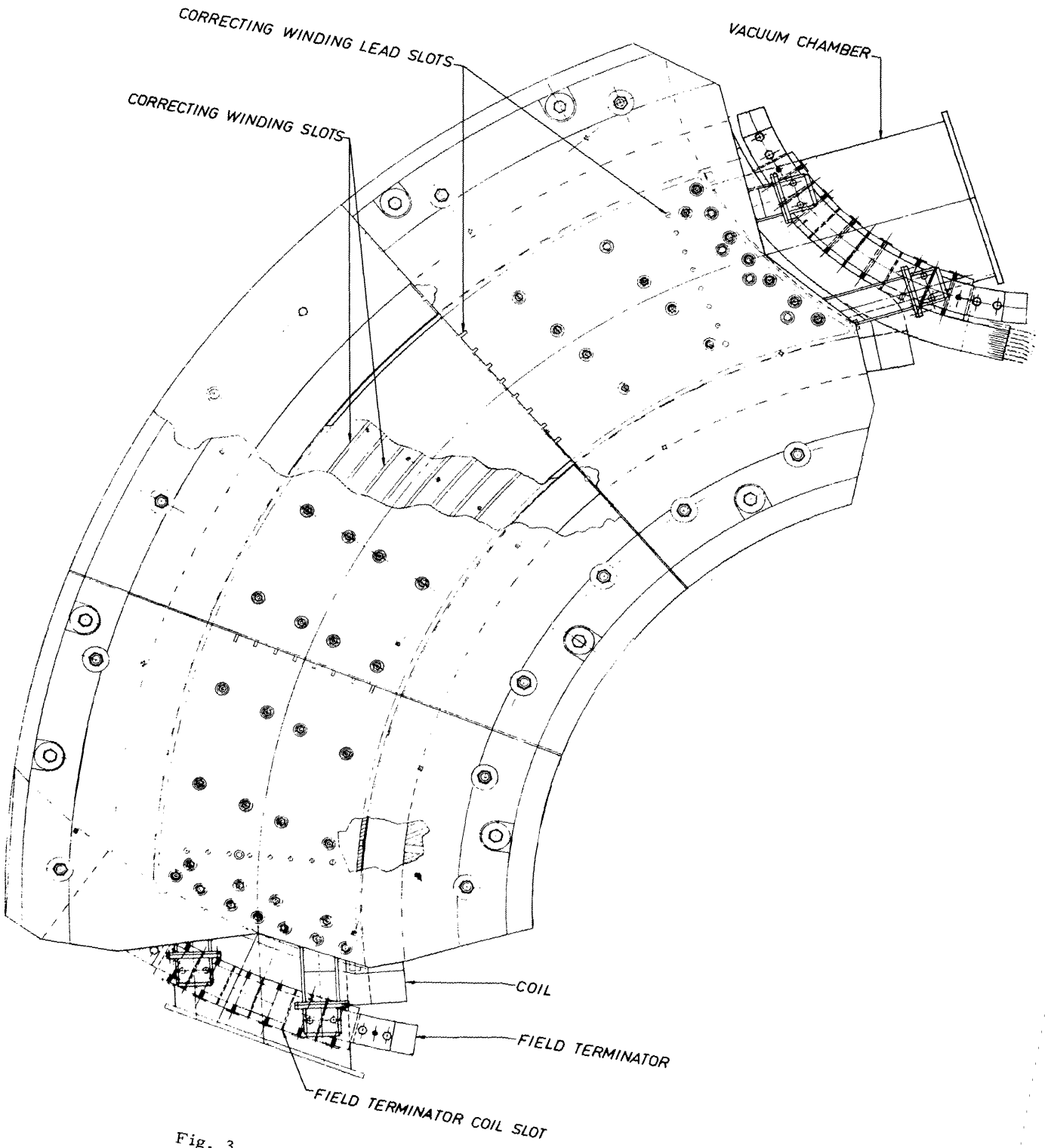

Fig. 3. Side View of Upper HRS Bending Magnet

studies using MIRT and POISSON[7] and the engineering parameters were selected for a suitable engineering design.

Table II. Field terminator sensitivity coefficients.

Condition	Effective field boundary movement
Nose section moved in and out from yoke	0.1056 cm per cm of nose travel
Field terminator moved in and out from yoke with nose section stationary	0.0335 cm per cm of field terminator travel
Energizing of field terminator coils	$\frac{3.5735}{B_o}$ I movement in cm where: I = A turns B_o = nominal gap field in G

Table III. High Resolution Spectrometer magnetic and engineering design parameters.

Magnetic design parameters:	
Peak magnetic field	20 kG
Magnet gap	10 cm
Pole face width	95 cm
Peak magnet A turns	187,000 A turns
Magnetic efficiency at 20 kG	85%
Peak stored energy	0.71×10^6 J
Engineering design parameters:	
Core	
Yoke length at 3.5 m radius	456.9 cm
Core weight	255,000 lb
Coil	
Conductor (copper)	0.760 in.^{2} x 0.400 in. i.d. hollow conductor
Conductor cross-sectional area	0.446 in.^{2}
Number of coils per magnet	2
Number of turns/coil	56
Conductor length/coil	2473 ft
Coil resistance	0.0497 Ω
Coil packing fraction	0.60
Conductor weight/magnet	8550 lb
Magnet current, power, and time constant	
Peak current	1670 A
Peak current density	3744 A/in.^{2}
Peak voltage (2 coils)	166.0 V
Peak power	277.2 kW
Inductance (2 coils)	0.510 H
Time constant (L/R)	5.1 sec
Magnet cooling	
Cooling water temp rise	20°C
Max. water flow rate/magnet	52.7 gpm
No. of cooling circuits/magnet	14
No. of turns/cooling circuit	8
Max. water flow rate/circuit	3.76 gpm
Max. water pressure drop/circuit	175 lb/in.^{2}

Mechanical Design

The integral vacuum tank - pole tip configuration shown in Fig. 2 evolved as the minimum cost configuration for the bending magnets. A separate vacuum chamber undoubtedly would be more reliable but the increase in cost of the magnet and power supplies could not be justified.

Vacuum Chamber

Accordingly, the vacuum chamber was designed as a vessel having only four "walls" with gasketing so arranged that the top and bottom "walls" were the pole tips themselves. The predicted radiation levels were low enough and the vacuum requirements not stringent, permitting the use of relatively soft elastomeric gasketing. Hycar rubber, 55 Shore hardness material was selected for gasketing material.

The major difficulty with this design is that repair of a leaky gasket requires costly disassembly of the magnet. To reduce the probability of such a leak, all joints were double gasketed with "pump outs" for the space between gaskets. This arrangement has been used for many years at LBL with excellent reliability.

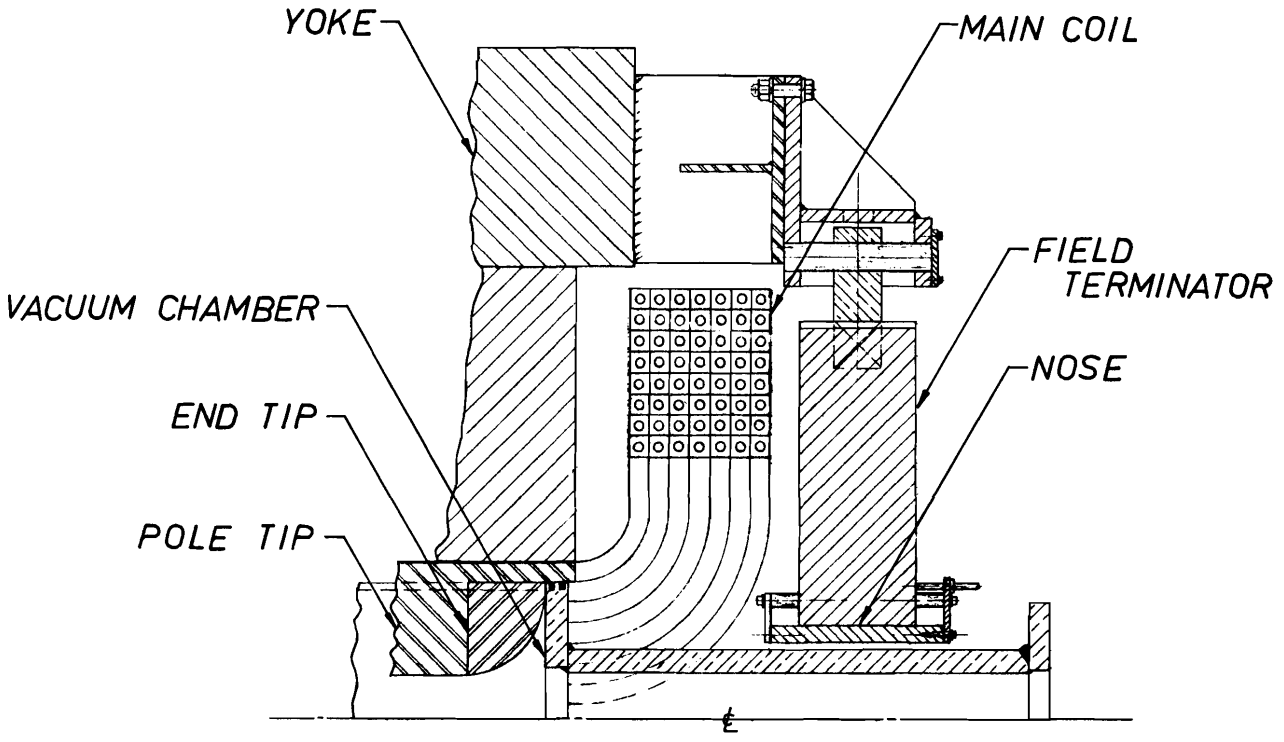

Fig. 4. HRS Bending Magnet End - Sectional Detail

Coils

The d.c. excited coils are of conventional construction except for their large size. The insulation system consists of double-lapped glass tape vacuum impregnated with an unmodified low viscosity epoxy resin (EPON 826), Polyglycol diepoxide resin (DER 736) and an aromatic amine hardener (TONOX) formulation per LBL Specification M20C.[8]

Core

The yoke steel assembly shown in Fig. 3 evolved primarily from rigging considerations; the weight of any piece of steel was limited to a maximum weight of 50,000 lb. Basically, the core is held together with the inner and outer legs which extend the full length of the magnet. The side yoke sections, three on each side, attach to the inner and outer legs. The pole tips are attached to the side yoke sections. For ease of assembly, radial positioning is achieved with shoulders and dowels are used for azimuthal locating. Figure 2 shows the shoulders and dowels.

Pole tip steel was specified as AISI Type 1008, fully killed and vacuum degassed.[9] Core steel was of the AISI Type 1010 and a fully-killed variety.[10]

Because of the cylindrical nature of the bending magnets, the best type of machine tool for fabrication of the bending magnets is a vertical boring mill. Locating large enough and available machines of this type did take some effort. Eventually, ten were located, six in the United States, two in Japan, and one each in both Germany and Sweden.

Acknowledgement

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