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.

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.

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

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.
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 $10^5$ for the bending magnets. Correct the field inhomogeneities by appropriately energizing correcting windings placed in slots behind the pole faces. 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 for the configuration shown. 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.
Fig. 2. HRS Bending Magnet Typical Radial Cross Section
Fig. 3. Side View of Upper HRS Bending Magnet
studies using MIRT and POISSON\textsuperscript{7} and the engineering parameters were selected for a suitable engineering design.

Table II. Field terminator sensitivity coefficients.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Effective field boundary movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose section moved in and out from yoke</td>
<td>0.1056 cm per cm of nose travel</td>
</tr>
<tr>
<td>Field terminator moved in and out from yoke</td>
<td>0.0335 cm per cm of terminator travel with nose section stationary</td>
</tr>
</tbody>
</table>

Energizing of field terminator coils:

\[
\frac{3.5735}{B_0} I \text{ movement in } \frac{\text{cm}}{\text{cm}}
\]

where:

\[
I = A \text{ turns}
\]

\[
B_0 = \text{nominal gap field in G}
\]

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

<table>
<thead>
<tr>
<th>Magnetic design parameters:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak magnetic field</td>
<td>20 kG</td>
</tr>
<tr>
<td>Magnet gap</td>
<td>10 cm</td>
</tr>
<tr>
<td>Pole face width</td>
<td>95 cm</td>
</tr>
<tr>
<td>Peak magnet A turns</td>
<td>187,000 A turns</td>
</tr>
<tr>
<td>Magnetic efficiency at 20 kG</td>
<td>85%</td>
</tr>
<tr>
<td>Peak stored energy</td>
<td>(0.71 \times 10^6) J</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engineering design parameters:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Yoke length at 3.5 m radius</td>
<td>456.9 cm</td>
</tr>
<tr>
<td>Core weight</td>
<td>255,000 lb</td>
</tr>
</tbody>
</table>

| Coil                                          |                                             |
| Conductor (copper)                            | \(0.760 \text{ in.}^2\) x \(0.400 \text{ in. i.d.}\) hollow conductor |
| Conductor cross-sectional area                 | \(0.446 \text{ in.}^2\)                     |
| Number of coils per magnet                    | 2                                           |

Number of turns/coil 56
Conductor length/coil 2473 ft
Coil resistance 0.0497 \(\Omega\)
Coil packing fraction 0.60
Conductor weight/magnet 8550 lb

Magnet current, power, and time constant:

- Peak current 1670 A
- Peak current density \(3744 \text{ A/in.}^2\)
- 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.
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

The authors wish to thank H. A. Thiessen and N. Tanaka of LASL, ultimate users of this equipment, for their direction and encouragement; Klaus Halbach, who conceived and developed the magnetic design of these bending magnets and with whom we worked closely; Ron Yourd, for his efforts in modifying the computer programs and assisting in the field calculations; Bob Fulton, for his assistance with the core design; Adair Roberts, for his effort with the coil design; and Maggie Petersen, for her superb secretarial services.
References


7. POISSON is an improved version of TRIM (originally written by A. M. Winslow, J. Computer Phys. 1, 149 (1967)). And was developed by K. Halbach, R. Holsinger, and J. R. Spoerl.

