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LBL SUPERCONDUCTING ACCELERATOR DEVELOPMENTS*

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1. Superconducting Experimental Accelerator

We are now actively working toward the fabrication of pulsed dipoles for the recently proposed LBL Superconducting Experimental Accelerator. This proton synchrotron is designed to accelerate protons from 50 MeV to 5 GeV/c at a maximum dipole field of about 50 kG. Sixteen dipoles, each some 1.5 meters long are required. The coil inside diameter is approximately 15 cm if a bent, or curved, magnet is used. A larger number of shorter, greater diameter, straight magnets are required if curved magnets are not used to solve the sagitta problem. A pulse energy loss of 300 joules/meter-cycle can be achieved with a repetition rate up to 30 cycles/minute using advanced superconducting cables and well ventilated coil construction. Conceptual drawings of the "curved" dipoles appear as Figures 1, 2. A photograph of a mechanical model is Figure 3.

2. LBL Superconductivity -- High Energy Physics

A general review of the LBL Superconductivity program as directed toward High Energy Physics applications was given in Particle Accelerators in 1970.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
The major elements of the overall program are:

(i) Pulse Dipoles — Superconducting accelerators.
(ii) Transport (dc) magnets — beam lines.
(iii) Fundamental and materials studies.
(iii) Cryogenics — refrigeration, cryostats, transfer lines, operation, etc.

3. Pulse Dipoles

Since 1970 we have built and tested 10 pulse dipoles with winding internal diameters of 7.5-10cm, and physical lengths of 40-45cm. The first 8 magnets have been reported on previously. The 8th dipole achieved short sample performance of 40 kG central field with iron return, was pulsed for hundreds of cycles to 35 kG at a B-dot of 70 kG sec⁻¹, and had an energy loss at 4.2°K of about 150 joules per meter per cycle. Figure 4 shows dipole #8 in its iron return yoke.

"Identical" dipoles #9 and #10 were built simultaneously as a test of the reproducibility of the fabrication technique used. Magnetic field measurements are used for this comparison. Short and long multipole measuring coils are used at power and audio frequencies at 300°K, 77°K, and 4.2°K. The long multipole coils and Hall probes are used with dc excitation at 4.2°K and the magnets have been operated with and without iron return yokes about the straight section. G-10 fiberglass clamped rings are used to restrain the end sections, and in the non-iron case, the straight sections. Pulsed losses are also taken at various frequencies and maximum currents, and the losses in the 2 dipoles compared. Overall, the 2 magnets are "identical" to about the limit of our measurement precision, which is about 1-2 parts per thousand for most of the multipole field components.

One method of describing the magnetic field properties of these superconducting magnets is through the use of circular harmonics which can be applied to either the central two-dimensional portion of the straight section or to the integrated field through the entire magnet.

$$B_r = B_0 \sum_{n=1}^{\infty} C_n \frac{\sin \theta \beta_n}{\sin \theta_a}$$
\[ B_r = \text{field at a radius } r, \text{ and angle } \theta. \]
\[ B_o = \text{dipole field for dipole magnet if } C_1 = 1. \]
\[ C_n = \text{multipole components for multipole or order } n. \]
\[ r = \text{reference radius}. \]
\[ a = \text{inside winding radius (other radii could be used)}. \]
\[ \beta_n = \text{phase angle for given multipole}. \]

In our measurements the measuring coils are approximately at the beam radius of \(2/3\) a or 2.54 cm. In Table I we list the central field harmonics taken with a 5 cm long set of coils. There is little difference in the results taken at 60 Hz and 500 Hz. In the right hand column, the expansion at the beam radius is listed; only the sextupole component is larger than \(1 \times 10^{-3}\) the dipole component and a sextupole correction winding on the bore tube can cancel most of that.

Table II lists the integral data for dipoles #9 and #10. The multipole components are larger than the two-dimensional values of Table I because the magnet ends have larger distortions than the straight sections -- these end effects have been calculated and relatively small axial translations are required to make the integral values approach the two-dimensional values. The two dipoles can be seen to be "identical" to within \(1 \times 10^{-3}\) dipole field. As can also be seen, the integral field is improved when iron is placed around the better field straight section.

Figure 5 shows the three current block per quadrant construction in exploded view. The rigid, but permeable to helium, coil construction can be clearly seen.

Figure 6 shows the assembled magnet lacking only the outer cooling passages and force restraining system. Figure 7 shows dipole #9 assembled with fiberglass containing rings and multipole measuring coils ready to be lowered into the two-meter long vertical Dewar.

4. Transport (dc) Magnets - Bevatron Beam Line

A superconducting beam line consisting of one dipole in one cryostat followed by a quadrupole doublet in a second cryostat has been in operation at the Bevatron since March 1973.

Both
TABLE I - HARMONICS FROM MEASUREMENTS OF CENTRAL FIELD

Dipole 9 (Measuring coil length = 5 cm) - T = 300°K - No Iron

<table>
<thead>
<tr>
<th>n</th>
<th>Cn, f = 60 Hz</th>
<th>Cn, f = 500 Hz</th>
<th>Cn(2/3)n-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref. Radius 3.8 cm</td>
<td>Ref. Radius 3.8 cm</td>
<td>Ref. Radius = 2.5 cm</td>
</tr>
<tr>
<td>1</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0005</td>
</tr>
<tr>
<td>3</td>
<td>0.0049</td>
<td>0.0048</td>
<td>0.0022</td>
</tr>
<tr>
<td>4</td>
<td>0.0010</td>
<td>0.0009</td>
<td>0.0003</td>
</tr>
<tr>
<td>5</td>
<td>0.0046</td>
<td>0.0048</td>
<td>0.0009</td>
</tr>
<tr>
<td>6</td>
<td>0.0013</td>
<td>0.0013</td>
<td>0.0002</td>
</tr>
<tr>
<td>7</td>
<td>0.0061</td>
<td>0.0057</td>
<td>0.0005</td>
</tr>
<tr>
<td>8</td>
<td>0.0011</td>
<td>0.0012</td>
<td>0.0001</td>
</tr>
<tr>
<td>9</td>
<td>0.0081</td>
<td>0.0081</td>
<td>0.0003</td>
</tr>
<tr>
<td>10</td>
<td>0.0026</td>
<td>0.0025</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

\[ B_r = B_0 \sum \sin n(\theta - \phi_n) \]

TABLE II - HARMONICS FROM FULL FIELD INTEGRALS

(Measuring coils length ≈ 60 cm, extend beyond both ends)

<table>
<thead>
<tr>
<th>n</th>
<th>Cn, Dipole #9 4.2°K, no iron 200A-1200A</th>
<th>Cn, Dipole #10 4.2°K, no iron 200A-1200A</th>
<th>Cn, Dipole #9 300°K, Iron 200A-1200A</th>
<th>Preliminary Cn (2/3)n-1 Iron (Beam radius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.0013 ± 0.0002*</td>
<td>0.0013 ± 0.0001*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.0206 ± 0.0003</td>
<td>0.0224 ± 0.0014</td>
<td>0.0124</td>
<td>0.0055</td>
</tr>
<tr>
<td>4</td>
<td>Coil Inoperative</td>
<td>0.0011 ± 0.0002</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.0195 ± 0.0004</td>
<td>0.0228 ± 0.0007</td>
<td>0.0106</td>
<td>0.0021</td>
</tr>
<tr>
<td>6</td>
<td>0.0024 ± 0.0002</td>
<td>0.0012 ± 0.0003</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Standard deviation of components in 200A-1200A range, 6 points. Expected error in any Cn ≤ 5x10^-4.
cryostats are fed from one CTI model 1400 helium liquifier-refrigerator in closed cycle mode. Runs longer than 40 days have become routine and the entire operation is carried out by the regular Bevatron operating personnel.

The dipole has a warm bore aperture of 20 cm, an effective length of 83 cm, and a maximum dipole field of 40 kG. Each of the quadrupoles has the same warm bore of 20 cm, effective length of 63 cm, and gradient greater than 2.1 kG cm\(^{-1}\). At about 60\% of the above excitations, the beam line has been used with secondary π minus beams of about 2 GeV/c. Various aspects of the beam line and refrigeration complex can be seen in Figures 8, 9, and 10.

5. Conductor Development and Testing

Our pulse and transport magnets use multicore NbTi superconductor in copper. The need for fine NbTi filaments for the pulse magnets has made it necessary to cable many composite conductors together and the development of satisfactory cables has been a continuing program. The hysteresis loss in the conductor is roughly proportional to the NbTi filament diameter and one wishes to make this as small as possible. The coupling of the wires within a cable affect the pulse capability of a conductor which we usually characterize by a doubling B-dot, that B-dot at which the coupling loss is equal to the hysteresis loss at zero B-dot. Other conductor problems have to do with cost, ease of fabrication and cooling. We have built and tested a number of solenoids to measure the above effects and have reported on it elsewhere. Typical loss \(V_b\) B-dot data for a solenoid are shown in Figure 11.

Our most recent conductor tests have included wires with 3000 filaments each 5μ in diameter, and cable made from wires with 1345 filaments each 3μ in diameter. In both cases, the B-dot was greater than 50 kG sec\(^{-1}\) and, therefore, are adequate for use in rapidly pulsed synchrotrons. Some additional development is still required to develop cables of equal performance but with more desirable mechanical properties.
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Fig. 1 - Superconducting Accelerator

Magnet-Cross-Section
Fig. 2 - Superconducting Accelerator Magnet - Plan View
Fig. 3 - Superconducting Accelerator Magnet

Mechanical Mock-Up
Fig. 4 - Pulse Dipole #8 - With Iron
Fig. 5 - Pulse Dipole #9 - Exploded View
Fig. 6 - Pulse Dipole #9 - Assembled-Coils

Visible
Fig. 7 - Pulse Dipole #9 -G-10 Rings

Multipole Measuring Coils
Fig. 8 - Bevatron Beam Line

Superconducting Transport Magnets
Fig. 9 - Bevatron Beam Line -

Superconducting Transport Magnets
Fig. 10 - Bevatron Beam Line

Superconducting Transport Magnets
Fig. 11 - Magnet Pulse Loss $V_g$ B-Dot
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