A HIGH-GRADIENT QUADRUPOLE MAGNET FOR A POLARIZED-BEAM FACILITY

MASTER

by

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$$B_k = \frac{-i \mu_0 J w^{*4k+1}}{\pi k(4k+2)} \sin(4k+2)\phi \left[\frac{1}{R_2^{4k}} - \frac{1}{R_1^{4k}} \right]. \quad (6)$$

The choice of quadrupole symmetry in expression (2) necessarily generates the w^* and ϕ dependence of (5). The term B_0 is the quadrupole field, B_1 the 12-pole, B_2 the 20-pole, etc. The choice of $\phi = 30^\circ$ makes the $k=1, 4, 7, \dots$ terms vanish. In fact, for this choice of ϕ the sum of all the remaining higher-order multipoles does not exceed 2×10^{-3} times the quadrupole field at a radius of $2/3$ the winding radius.

To investigate the effect construction errors have on the field purity the field from a single block was calculated, where expression (3) is replaced by

$$\sum_{k=0}^{\infty} \frac{w^{*k}}{z^{*k+1}} \quad (7)$$

and then integrating. The resulting expression for B then makes it easy to add the fields from four independent poles, with e.g. different radii, angles, or even more complicated shapes corresponding to possible construction errors. In general, this technique generates all multipoles of w^* so that all multipoles, i.e. dipole, sextupole, etc. are present. By use of this procedure a detailed analysis of the effects of construction tolerances has shown that achievable winding care will produce the required field purity.

Analogous procedures (but using a limiting procedure near the current element) generate expressions for the fields inside the current block so that Lorentz forces can be calculated; the effects of a (constant permeability) iron shield are calculated by using image currents in the iron. For this last case, the expression in (3) is replaced by

$$\sum_{k=0}^{\infty} \left[1 + \frac{\mu-1}{\mu+2} \frac{1}{a^{4k+2}} \right] \frac{w^{*4k+1}}{z^{*4k+2}} \quad (8)$$

where $a = b^2/r^2$ with b = inner radius of the shield and r = radius of the current element.

The magnet design program TRIM³ has been used to study the field shapes obtained when iron with variable permeability is used.

Finite Element Calculation

The program SAP6⁴ is being utilized to analyze a finite-element model of the magnet. Beam-type elements are used to model the bore tube and outer clamping structure. Plate-type elements are used to model the coil and winding post. The moduli of elasticity in the radial and azimuthal directions were provided from measurements taken from conductor-insulator assemblies patterned after the actual coil design. Three loading conditions were calculated using SAP6; assembly preload, cooldown to 4 K, and magnet energized. A representative plot of displacements calculated by SAP6 for the third condition is shown in Fig. 2. With a preload generated by 0.013 cm radial interference between the coil and the aluminum clamp rings, which increases to 0.023 cm equivalent when cooled to 4 K, a low tensile stress of about 3.4×10^6 Pa is indicated by SAP6 along the conductor-post boundary in the azimuthal direction due to the Lorentz forces. Because such tension could lead to excessive training, effort is being expended to study its elimination.

Fig. 2 Coil Deflections at 4K Due to Lorentz Forces

Conductor Design and Magnet Safety

A monolithic multifilamentary NbTi superconductor was selected with a copper to superconductor ratio of 1.8:1.0 to enhance overall current density in the coil. The aspect ratio of the finished conductor was chosen as 1.5:1.0 to help maintain coil integrity during winding. To help eliminate shorts, the monolith is insulated with 0.005 cm of Formvar and a 0.0025 cm Kapton film wrapped with 50% overlap.

Calculations made with a version of the Rutherford program QUENCH⁵ helped establish the safety of the 1000 A operating current. The program showed that with a protective resistor of 0.5Ω and reasonable choices of the adiabatic quench propagation velocity the maximum coil temperature was 250 K and the peak resistive voltage was 1400 V.

Two and Three Dimensional Winding Studies

Each pole of the magnet will be constructed by winding superconductor against a central post subtending 30° azimuthally. The post will be of stainless steel with end shapes machined numerically. A completed pole is then vacuum impregnated and cured in a mold of precise shape. Copper wire has been wound into short poles to study the details of coil winding. Much of the practice effort has been directed at obtaining the best approximation to the "constant perimeter" ends required to help assure that the conductors, when wound under tension will remain where they are placed as each layer is built up. The first model winding post was cast of epoxy with a wide thin elastic strip in a constant perimeter configuration used to determine the end shape of the post. Each layer of conductor was wound flat against the post so that it and its return layer on the other side of the post were separated 30° azimuthally. As successive layers were added it became increasingly hard to maintain winding integrity in the ends of the pole. The final layers of winding, triangular in overall section, were particularly difficult to hold in place on the ends. Since constant perimeter layers separated 90° azimuthally more naturally lie on the

surface of a cylinder in the end regions the winding technique was altered. A model post with a more complex end shape was fabricated so that the triangular portion of the pole could be wound first. Each layer of conductors is 90° apart from its corresponding return layer and the resulting winding integrity in the ends of this pole was quite high. In Fig. 3 is seen a section view of the end of an impregnated pole wound in this manner. The remaining flaws apparent in Fig. 3 will be corrected as the impregnation procedure is refined. The paths of the conductor through the ends of this pole are approximately that of semicircles when projected into a plane tangent to the winding cylinder. The radii and relative axial displacement of these semicircles is determined by imposing the constant perimeter condition on all conductors in a given layer.

Fig. 3 Study for End Turns of
Approximate Constant Perimeter

Cryostat Details

The magnet will be pool-cooled by liquid helium and a cryostat with a helium vapor cooled thermal radiation shield will be constructed for it. The particle beam design requires the quadrupole magnets to be located in four groups of four each. Thus it is cryogenically desirable to operate four magnets electrically in series, with low current leads for each magnet to provide for $\pm 10\%$ current variation within

the set, and only one pair of 1000 A vapor cooled leads required for the foursome. As installed the magnets will have common insulating vacuum, liquid helium, and thermal radiation shield system. Each individual cryostat will have independent safety vents for both the vacuum and helium vessels, however, the individual trim leads may be required for coil protection in the event of a quench.

Multilayer insulation will cover both the helium vessel and the thermal radiation shield. High strength epoxy fiberglass tension members will support the cold mass and bellows will be provided at the ends of the cryostat to provide for field connection and adjustment of the magnets. A cold bore system is contemplated, with thin beam windows at the ends of a set of magnets to maintain vacuum integrity. No thermal radiation shield will be employed in the cold bore. The iron yoke will serve as the primary coil alignment system, so that magnet axis alignment and pole rotation are precisely specified along the length of the magnet.

Results

Numerical descriptions of the ends of the winding posts are in preparation to permit the precision machining of these coil parts. Short-detection techniques for the winding line are under study, and instrumentation is being designed to permit the measurement of coil temperatures and voltages during quenching. The receipt of superconductor is expected soon so that coil construction can begin. Following preliminary coil tests in a vertical dewar, the iron yoke will be installed and field quality measurements undertaken.

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