IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

SUPERCONDUCTING COMBINED FUNCTION MAGNETS*

H. Hahn and R.C. Fernow
Brookhaven National Laboratory, Upton, New York 11973

Summary

Superconducting accelerators and storage rings, presently under construction or in the design phase, are based on separate dipole and quadrupole magnets. It is here suggested that a hybrid lattice configuration consisting of dipoles and combined function gradient magnets would (1) reduce the number of magnet units and their total cost and (2) increase the filling factor and thus the energy at a given field. Coil cross sections are presented for the example of the Brookhaven Colliding Beam Accelerator. An asymmetric two-layer cable gradient magnet would have transfer functions of 10.42 G/A and 0.628 G cm^{-1}/A versus 15.77 G/A and 2.03 G cm^{-1}/A of the present separate dipoles and quadrupoles.

Introduction

Superconducting high-energy proton accelerators and storage rings presently under construction or in the design stage are all based on separate function dipoles and quadrupoles. This choice followed naturally in view of their advantages[1-3] for conventional magnet rings as demonstrated by machines such as the FNAL-PS, CERN-SPS, and KEK-PS. In the context of a search for cost saving alternatives to the standard Brookhaven Colliding Beam Acclerator project, the suggestion was made to reconsider the merits of superconducting combined function magnets.[4]

Although superconducting and conventional magnets are in principle equivalent as to their use in synchrotron lattices, there exist several technical differences which require a new evaluation of the relative merits of the combined versus separate function solutions. The arguments presented here are specific to the CBA magnets without claiming general validity. There are, however, several points which are believed intrinsic to superconducting magnets and which impact on the discussion in a general sense:

i) The dipoles and quadrupoles are cryogenically and electrically connected in series. Consequently, the tune flexibility expected from separate function magnets cannot be easily realized in superconducting magnets. Working point adjustment is, in fact, achieved by separate trim coils, or an electrical bypass.

ii) A comparison of the packing density, i.e., the effective magnetic length divided by the minimum slot length is in the case of superconducting magnets significantly smaller than in conventional magnets. For example, it is 80% for the CBA dipole and 54% for the quadrupole versus 94% and 90% respectively for the SPS magnets. Consequently the use of separate quadrupoles is inefficient in terms of tunnel circumference. It is suspected however that a cold bore solution with continuous vessels would improve this situation.

iii) Superconducting magnets are essentially air core magnets with iron saturation entering only as a perturbation. Whereas conventional gradient magnets operate at a field of about 2/3 the level of pure dipoles, the loss in field in superconducting gradient magnets depends on the gradient required and could be smaller.

iv) The magnet unit cost can be split into a part independent of length plus a contribution more or less proportional to length. For CBA dipoles the contributions are roughly equal. Short quadrupole units are relatively expensive. Consequently, cost savings can be expected from superconducting gradient magnets.

v) The heatload of a quadrupole unit is relatively large (3.5 W) when compared with that of a dipole (4.6 W). Elimination of the quadrupoles would thus allow some savings in the refrigeration system.

It goes without saying that the use of combined function magnets is not a new invention. The advantages of superconducting combined function magnets have been pointed out previously by Sampson.[5] His specific proposal was for a quasi-combined function magnet design in which a quadrupole winding, similar to the trim windings, is situated inside the dipole coils. However, it was recognized that the force distribution on the quadrupole winding would be considerably more difficult to deal with in this design than in the pure dipole case. This concept was thus not pursued at the time.

The discussion in this paper is based on a hybrid lattice configuration consisting of pure bending dipoles as well as focussing gradient magnets.[6] Adoption of a hybrid lattice minimizes the integrated quadrupole requirements and retains the advantages with respect to beam dynamics of separate function lattices (i.e., quasi-orthogonality of horizontal and vertical controls). The gradient magnet is obtained with an asymmetrical coil configuration resulting in a simple, containable force distribution.

The present study led to the conclusion that a hybrid lattice with separate dipoles and gradient magnets would (1) reduce the number of magnet units and thereby the total cost of the machine and (2) increase the packing factor and thus the beam energy at the maximum operating field. This conclusion has been derived for the Brookhaven Colliding Beam Accelerator project, but presumably it would also apply to other situations.

Gradient Magnet Cross Sections

Our early discussion[4] of combined function solutions was based on a two-layer symmetrical coil cross section in which the inner layer produced a pure quadrupole and the outer a pure dipole field (Fig. 1). This solution could, in principle, be operated as a true separate function lattice with separate excitation of quadrupole and dipoles. Detailed studies, however, revealed problems with this solution due to an undesirable inward-directed force distribution. Furthermore, the symmetrical solution has the unavoidable property that at certain angles the current of the inner and outer coil flow in opposite directions. The symmetrical solution is therefore inefficient in the use of superconducting material. An asymmetric true combined function coil, on the other hand, has a force distribution which resembles that of a dipole

*Work performed under the auspices of the U.S. Department of Energy.

0018-9499/83/0800-3402$01.00© 1983 IEEE

coil and, presumably, can be constructed with the techniques already developed.

The discussion in this paper assumes a specific solution of an asymmetric gradient magnet. This design was obtained after a long iterative optimization procedure in which the dipole transfer function was maximized while keeping the gradient constant. It is believed that the particular configuration is satisfactory with respect to quench propagation and that the coil winding can be done with existing tooling.

The cross section of the proposed combined function coil[7] is shown in Fig. 2. There are 77 turns per half coil which are lumped into 7 blocks, of which 4 blocks are in the inner and 3 in the outer layer. This coil configuration produces the theoretical transfer functions, infinite-μ and warm dimensions, of

$$B_G/I = 10.423 \text{ G/A}$$
$$G/I = 0.628 \text{ G cm}^{-1}\text{/A}$$

For reference, the standard CBA dipole (Fig. 3) produces $B_D/I = 15.766$ G/A with 106 turns[8] and the quadrupole transfer function is 2.026 G cm^{-1}/A. The design field quality is expressed in terms of its multipole coefficients

$$\frac{\Delta B}{B_o} = \sum_n b_n \, (x/a)^n$$

with a = 4.4 cm being the aperture radius or about 2/3 of the inner coil radius r_i = 6.566 cm. B_o is the local dipole field. The design field harmonics are shown in Table I. For the purpose of comparison with the standard CBA dipole, the harmonics have to be normalized i.e., multiplied by the ratio 10.423/15.766. Table I confirms that the proposed gradient magnet is consistent with storage ring tolerances.

Lattice Requirements

In this section the impact of adopting gradient magnets on the lattice requirements are explored. The half cell of the CBA lattice consists of 3 pure dipoles and 1 quadrupole ($n_D = 3$, $n_Q = 1$, $n_G = 0$) which in the case of a hybrid lattice would be replaced by 2 dipoles and one gradient magnet ($n_D = 2$, $n_G = 1$, $n_Q = 0$).

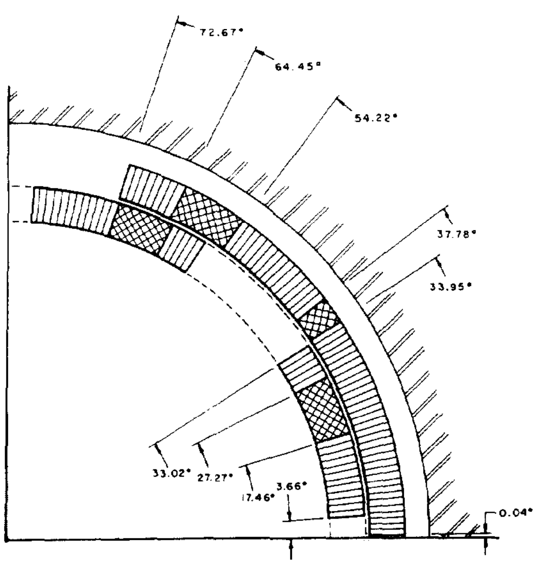

Figure 1. Symmetrical combined function magnet coil.

Table I. Design Field Harmonics at 4.4 cm

Harmonic n	$b_n \times 10^4$		
	GRADIENT MAGNET Local Dipole	GRADIENT MAGNET Normalized	CBA DIPOLE
2	-31.6	-21.0	-26.1
3	0.0	0.0	0
4	0.0	0.0	- 4.3
5	0.0	0.0	0
6	0.0	0.0	0.4
7	0.0	0.0	0
8	0.0	0.0	0.1
9	- 0.4	- 0.3	0
10	2.2	1.5	0.1
11	- 1.2	- 0.8	0
12	- 4.1	- 2.7	- 0.3
13	- 0.2	- 0.1	0

The quadrupole requirements are, in thin lens approximation, given by

$$G \, \ell_G = 4 \, L^{-1} \, \bar{B}\rho \, \sin \tfrac{1}{2} \phi$$

where G is the gradient, ϕ the phase shift per cell and the particle momentum is expressed by $\bar{B}\rho$. The cell length and the length of the focussing element is given by L and ℓ_G. The dipole requirements per half cell are obtained from

$$n_D \, B_D \, \ell_D + n_G \, B_G \, \ell_G = \int_{HC} B \, d\ell$$

where B_D, B_G and ℓ_D, ℓ_G represents the bending fields and magnetic lengths of the dipole and gradient magnets respectively.

The maximum geometrically permissible dipole length follows from

$$\ell_D = \frac{\frac{1}{2} L - (n_D + n_G + n_Q) \, \ell_E - n_D \, \ell_V - \ell_F}{n_D + \ell_G/\ell_D}$$

where
ℓ_E = difference of vessel and magnetic length (61 cm)
ℓ_V = minimum vessel separation (54 cm)
ℓ_F = free space for trim magnets (1.2 m)

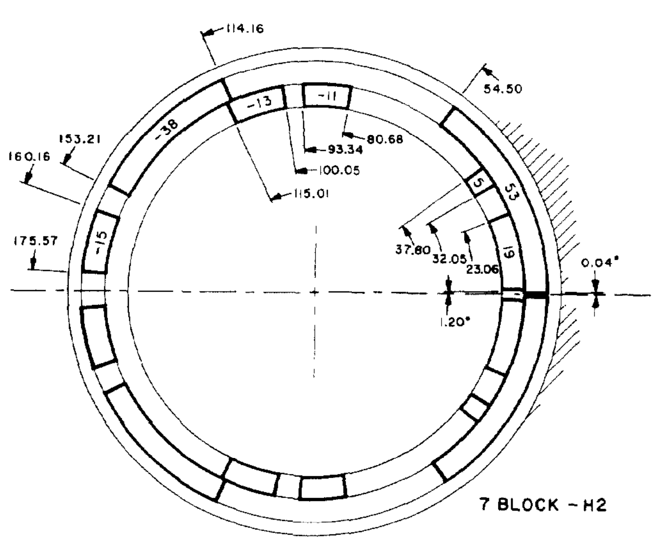

Figure 2. Asymmetrical gradient magnet coil.

Table II
Separate Function and Hybrid Lattice Requirements

	CBA	Hybrid 9 Cell	Hybrid 10 Cell
Cell length, L(m)	39.5	39.5	35.55
Phase shift/cell, ϕ	90°	90°	81°
$\int_{HC} B\, d\ell$ (Tm)	69.1	69.1	62.2
λ	77.4	77.4	86.0
ℓ_G/ℓ_D	0.323	0.903	1.067
ℓ_D(m)	4.36	5.39	4.46
B_D(T) @ 400 GeV	5.28	4.94	5.16
$N_D + N_G$	732	744	816
N_Q	348	120	120
Magnet Heat Load %	100	84	91
Relative Cost %	100	87	94

Under the assumption that bending and focussing magnets are excited by the same current, one finds for the length ratio

$$\frac{\ell_G}{\ell_D} = \frac{n_D\,(B_D/I)\,\lambda\,\sin\frac{1}{2}\phi}{L\,(G/I) - n_G\,(B_G/I)\,\lambda\,\sin\frac{1}{2}\phi}$$

with $$\lambda = \frac{4\,\bar{B}\rho}{\int_{HC} B\, d\ell}$$

The above formulae were applied to the standard separate function CBA lattice and an alternate hybrid lattice. The numerical results are summarized in Table II. The number of quadrupoles, N_Q, in the hybrid solution represent the insertion quadrupoles. The relative cost estimate was obtained by using the approximation cost/unit = 1 + 0.25 × length (m).

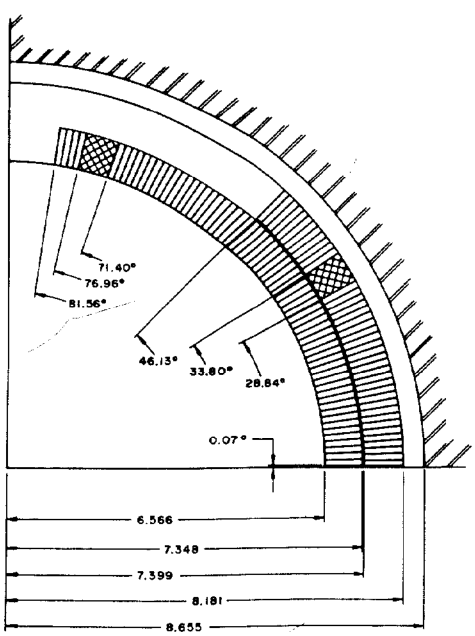

Figure 3. CBA dipole coil cross section.

Not discussed in this paper are saturation effects in asymmetric magnets. However it has been verified that the additional requirements are within the capabilities of the planned trim coil system. No detailed study of the impact on aperture and luminosity was carried out but it is clear that the 9 cell solution with longer dipole magnets would have some aperture loss unless the magnets are curved. Minimal impact on luminosity is expected for the 10-cell solution.

Conclusion

The numerical results presented in Table II confirm our expectation that the use of gradient function magnets leads to cost savings as well as lower operating dipole fields. In order to take full advantage of gradient magnets, longer dipoles than presently used in CBA would be required. However even with magnets of the present length one would gain by adopting gradient magnets. It must be admitted that in practical terms the idea came too late for acceptance in the CBA project. The results, nevertheless, point to a solution which deserves serious considerations in future accelerator projects.

Acknowledgments

The authors would like to acknowledge helpful discussions with Drs. J. Claus and P.A. Thompson as well as other members of the Combined Function Magnets task force.

References

1. M.G. White, Princeton Report (1953, unpublished).

2. F.A. Ferger, E. Fischer, E. Jones, P.T. Kirstein, H. Koziol, and M.J. Pentz, Proc. Intern. Conf. High-Energy Accelerators, Dubna (1963) p 338.

3. G.T. Danby, J.E. Allinger, and J.W. Jackson, Proc. 6th Intern. Conf. High Energy Accelerators, Cambridge, Mass (1967), p.49; and IEEE Trans NS-14, No. 3, 431 (1967).

4. H. Hahn, Brookhaven National Laboratory ISABELLE Project Technical Note No. 362 (1982, unpublished).

5. W.B. Sampson, Brookhaven National Laboratory Informal Report BNL-19934/AADD 75-2 (1975, unpublished).

6. A.A. Garren, G.R. Lambertson, E.J. Lofgren, L. Smith, Nucl. Instr. Meth. 54, 223 (1967).

7. R.C. Fernow and H. Hahn, Brookhaven National Laboratory, ISABELLE Project Technical Note No. 370 (1982, unpublished).

8. R.C. Fernow, Brookhaven National Laboratory, CBA Project Technical Note No. 403 (1983, unpublished).