Conceptual Design of a Permanent Quadrupole Magnet with Adjustable Strength

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Abstract

The conceptual design of a quadrupole magnet is described that uses both permanent magnet material and soft iron. The quadrupole gradient can be adjusted without affecting the field distribution, and the basic design principle can be used to build dipole and other multi pole magnets.

1. Introduction

Variable strength permanent magnet particle beam handling elements have, until now, been used only when the field strength could be changed without affecting the field distribution in the region occupied by the beam. The only such devices that are used extensively are wigglers and undulators. Specific suggestions have been made[1,2] to make the beam optical properties of pure rare earth cobalt (REC) quadrupoles variable, but they have not been widely implemented because they changed the field distribution together with the focusing strength, complicating the beam optical properties significantly. The conceptual design presented here does not suffer from this shortcoming: the field strength can be changed without modifying the field distribution. At least six organizations are contemplating the construction of high energy electron storage rings for the production of synchrotron radiation and/or operation of free electron lasers, and in most cases, permanent magnet rings are seriously considered, and decisions about these rings are due in the near future. It is clear that the availability of variable strength permanent magnets makes permanent magnet rings much more attractive and, hence, this paper could be important for the decision between permanent magnets and electromagnets.

2. Variable Strength Permanent Magnet Quadrupole Design Concept

Figure 1 shows a schematic cross section of the quadrupole, with the green areas identifying soft iron, and the arrows indicating the direction of the easy axis in the permanent magnet material.

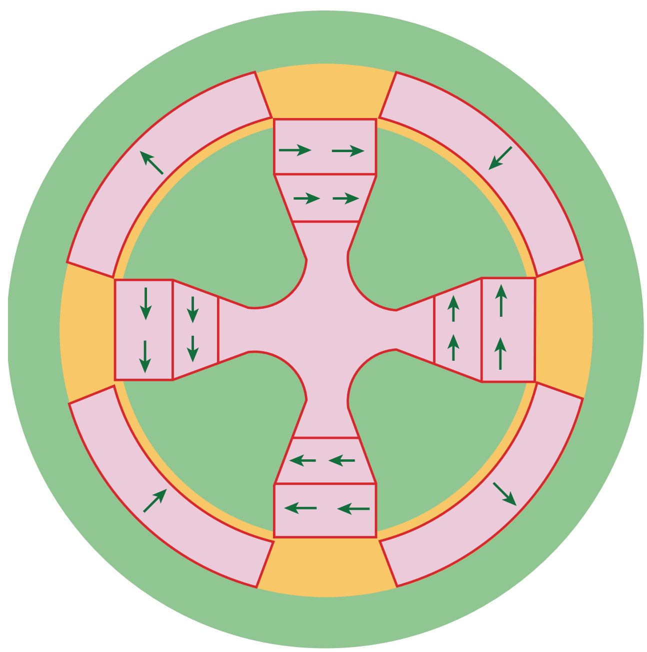

Figure 1— Schematic cross section of a variable strength permanent quadrupole magnet.

The preferred permanent magnet material is REC (and here it is referred to in that way). Some of the oriented ferrites with a straight magnetization curve far into the second quadrant of the magnetization curve can be used as well, but they will lead to much weaker magnets.

To change the strength of the quadrupole, the outer steel ring, with the attached REC, is rotated about the center of the magnet, while the four steel poles, with the attached REC, stay fixed. Depending on the distribution of the REC in the magnet, the excitation of the pole, and with it the strength of the fields, can be continuously reduced from the maximum value down to a small fraction of it.

3. Discussion of the Most Important Design Details and Magnet Properties

1) Figure 1 is meant to show only the concept, not specific details. For instance, for a variety of reasons the REC attached to the steel ring would not consist of one curved piece, but would actually be assembled from several prismatic blocks.

2) Preliminary calculations show that pole tip fields of at least 1.2 T, and probably 1.4 T, can be achieved with commercially available materials.

3) In order to achieve strong fields, the region immediately beyond the end of the hyperbolic pole contour has to be very careful designed to avoid either excessive saturation of the steel or driving the REC into the nonlinear part of its magnetization curve. The fact that the strength is variable has no effect on the maximum obtained field.

4) The field distribution in the aperture is controlled by the steel surface in its vicinity, just as in a conventional quadrupole, and techniques developed for them can be directly applied. The location of the REC pieces has practically no effect on the field distribution in the aperture as long as all poles are excited with equal strength.

5) The REC generates the flux in the aperture and equal excitation of all four poles is very important. Fortunately, the effect of excitation errors (as well as assembly errors) on field quality are well, and quantitatively, understood.[3] Combined with an analysis of the effect of REC manufacturing errors, procedures are being developed that assure sufficiently accurate excitation of the poles to guarantee very good field quality. These procedures are expected to be so effective that REC with relatively poor tolerances can be used, reducing the price of the REC significantly.

6) When the strength of the field is reduced by rotating the outer ring with the attached REC, invariance of the geometry of the whole structure under rotation by 90° is not violated. One therefore does not get new harmonics in addition to the ones that are allowed by this rotational invariance, namely $n = 2$ (= fundamental), 6, 10, 14, ... Even though the symmetry of the flux distribution in the outer part of the poles is destroyed by the rotation of the outer ring, this will have only little effect on the allowed harmonics since this asymmetry occurs in a region of extremely large permeability. It can also be shown, and will be detailed in a future paper, that the modification of the harmonic content because of the movement of the REC is negligible if the permeability of the steel is assumed to be infinite. The only remaining modification of the field distribution associated with a field reduction is, therefore, produced by saturation of the steel pole and can be dealt with in exactly the same way as is done in conventional electromagnets.

7) Since the four poles "float" magnetically, it important to protect them from external magnetic perturbations. Unless there is an absolute guarantee that such perturbations will not occur, it is advisable to have mirror plates at the end of the quadrupole. To reduce the total amount of REC, and to avoid harmful saturation of the steel, one should use REC between the ends of the steel poles and the mirror plates.

4. Conclusions and Generalizations

Compared to the pure REC quadrupole,[1] adjustable REC-steel hybrid will be less compact; one will probably achieve comparable gradients; one will obviously *not* be able to imbed the hybrid into solenoidal (or other) fields. The detailed engineering design is probably more difficult than for the pure REC quadrupole, since there are more aspects that require very careful design and attention to detail. Most of these details require a very good qualitative and quantitative understanding of subtle aspects of the magnetic circuits that make up the whole hybrid quadrupole.

It is quite obvious that the concept outlined above is equally applicable to other multipole magnets. The dipole magnet seems somewhat different than the others, but closer examination shows that dipoles will be just as easy to build as quadrupoles, but it will probably be difficult to reach more than 1.2 T, at least if field strength control over a wide range is required.

Publishing History

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