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Super hybrid quadrupoles

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ABSTRACT

A new model of quadrupole composed of permanent magnetic material, coils and soft magnetic material is proposed for the new Brazilian Synchrotron Light Source (Sirius). These quadrupoles must have flexibility about 30% of the total gradient in order to correct the linear effects caused by the insertion devices on the beam dynamics. This flexibility is obtained using coils while permanent magnets are used to supply the constant gradient.

1. Introduction

The new Brazilian Synchrotron Light Source (Sirius) will operate at the energy of 3 GeV with a low emmitance electron beam (less than 2 nm.rad). This machine is being idealized to save as much electrical energy as possible and therefore, it is called a "green" particle accelerator.

Magnets made of permanent magnetic materials (PMMs) could be a promising alternative for electron storage ring. It is probably going to be the new trend for magnetic lattices. Until now, only FermiLab has applied this technology in large scale for its anti-proton recycler [1]. In our case, the use of PMMs was encouraged during a price drop, especially in the Chinese market, which reached its minimum at the beginning of 2010. After this period, the rare earth cost has increased significantly. But, as the PMM corresponds just to a small fraction of the magnet total cost, the idea is still feasible. However, some challenges as the variation of remanent field with the temperature, differences of remanent field among blocks, designs of high performance and difficulties of handling, should be taken into account.

For this new ring, both, bending magnets (dipoles) and quadrupoles have permanent magnetic materials in their structures, in order to supply the constant fraction of the magnetic field.

In the case of the quadrupoles, a maximum integrated gradient of 7 T (28 T/m in a length of 0.25 m) is required and 30% of this value must be variable. Such flexibility is calculated aiming to correct the linear disturbances created by the insertion devices on the beam optics.

There are many articles related to different geometries and sources of magnetic field proposed for quadrupoles. Most of them are electromagnetic, with total field flexibility. For those made of PMMs, some models have shown flexibility, obtained by means of mechanical adjustments. Halbach proposed to change the strength of the quadrupole rotating an outer steel ring with attached PMMs around the magnetic center, while four steel poles, also having attached PMMs, stay fixed [2]. Volk et al. placed some cylindrical magnets, magnetized across the diameter, at the quadrupole corners , which could be rotated to vary the strength of the gradient [3]. Bondarchuk et al. had used soft ferromagnetic shunting elements to provide variations in the gradient [4]. Gottschalk and Taylor created a method of achieving strength adjustments by uniformly displacement of all four PPMs [5]. A double ring structure was presented by Iwashita et al. [6], where each structure was made of PMM arrays and there was an outer ring free to be rotated.

The model presented here is composed of hard magnetic material (NdFeB), soft magnetic material with high permeability and high magnetization of saturation (1010 carbon steel), but the field flexibility is now provided by coils. These coils work with low current density in order to reduce the electrical power and consequently generating less heat. The PMMs are estrategicaly located and their dimensions calculated to minimize the excitation required for the coils. Since the magnets made of permanent magnetic and soft magnetic materials are called hybrids, the

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Table 1
Quadrupole main specifications.

Total gradient–G (T/m)	28
Total integrated gradient (T)	7
Nominal length (mm)	250
Bore radius (mm)	27.5
Gradient flexibility (%)	30
Minimum free gap between poles (mm)	15
Multipoles: $B_n(x)=(k_n/G)\cdot x^{n-1}$	
B_6(@10 mm)	5×10^{-5}
B_{10}(@10 mm)	5×10^{-8}

name proposed for the model treated in this article is "super hybrid", because we have added the coils as another active element.

Table 1 lists the main characteristics specified for the quadrupole.

B_n are the fields generated by each coefficient k_n of the polynomial fitting made on the quadrupole magnetic field at transversal position 10 mm. Such coefficients are associated to the multipolar expansion, where, for geometrically perfect quadrupoles, only $n=2$ (quadrupole), $n=6$ (dodecapole), $n=10$ (20-poles) and so on, are allowed.

2. Magnetic studies

Quadrupoles made of permanent magnetic materials have been proposed since the beginning of the 1980s and they continue to be a subject of great interest. Again, Halbach belongs to the pioneers in the implementation of accelerator magnets made with PMMs [7–9]. He suggested the first geometries and arrangements as well as provided analytical treatment in terms of multipolar composition. The improvements have not stopped yet: the search for higher fields [10] and different geometries [11] for quadrupoles are subjects of current studies. The cited papers contain usefull references for deepening in magnets with PPMs. As already mentioned, it is reported here a new quadrupole design, employing PPM technology, which is capable to allow the gradient changing of $\pm15\%$ over the main gradient by means of coils.

It is possible to do a preliminary 2D analysis using the circuital Ampère's Law and the magnetic flux conservation, considering some symmetric properties related to the geometry of the magnet. This simple analysis brings out important correlations among relevant variables such as quadrupole gradient (G), size of the magnetic block (w_b, h_b), field flexibility and total current in the coils (NI). These equations allow the evaluation whether such configuration of quadrupole is advantageous.

Fig. 1 corresponds to 1/8 of the total quadrupole cross section and the magnetic field B circulates on the proposed circuit indicated by the dashed line.

Eq. (1) describes the integration over all the circuit indicated.

$$\frac{1}{\mu_0}\int_0^R B\cdot \mathrm{d}l+\frac{1}{\mu}\int_{\mathrm{core}} B\cdot \mathrm{d}l+\frac{1}{\mu_0}\int_{\mathrm{pm}} B\cdot \mathrm{d}l=NI+M\cdot h_b, \tag{1}$$

where the first integral is over the 45° sloped line in the air gap, the second one is over all parts of ferromagnetic core and the third is over the permanent magnet region (pm), where the permeability taken is the same as the vacuum permeability (μ_0). M is the magnetization and h_b the block height. The product $M\cdot h_b$ is equivalent to the superficial current of a block homogenously magnetized.

Some simplifications are taken into account: the magnetic permeability of the ferromagnetic core (μ) is much higher than

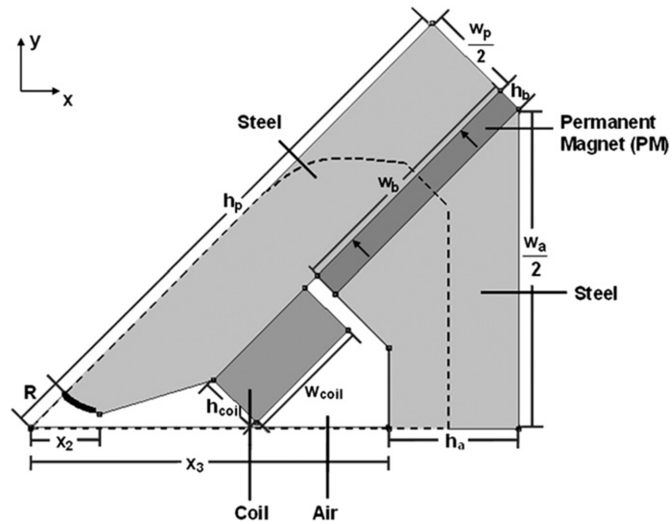

Fig. 1. Quadrupole main dimensions and the magnetic circuit for Ampère's law application.

the vacuum permeability (μ_0), there is no fringe field getting away longitudinally (z-axis) in the air gap and by symmetry B ($B=G\cdot r$) is perpendicular to the bottom horizontal line (in this plane). All these considerations yield in Eq. (2), where B_b is the average field inside the magnetic block and B_r is the remanent field. ($B_r=\mu_0\cdot M$) It is known *a priori* that there is flux leakage at some parts, like those signed by oblongs in Fig. 7.

$$\frac{GR^2}{2}+B_b h_b=\mu_0 NI+B_r h_b. \tag{2}$$

By the magnetic flux conservation, a good approach could be done equalizing the flux through the magnetic block to the flux that crosses the horizontal axis (plane) from $x=0$ up to $x=x_3$, although it is known that there is a small flux returning at the upper side of the magnetic block, as previously mentioned.

The field profile for the region from $x=0$ to $x=x_2$ is approximately $B_y=G\cdot x$. From x_2 to x_3, the proposed profile is given by

$$B_y(x)=B_0+\frac{B_1}{x}, \tag{3}$$

where B_0 and B_1 can be found using the following boundary conditions:

$$B_y(x_2)=Gx_2 \tag{4}$$

$$B_y(x_3)=0. \tag{5}$$

Resulting in:

$$B_0=\frac{Gx_2^2}{x_2-x_3} \tag{6}$$

$$B_1=-\frac{Gx_2^2x_3}{x_2-x_3}. \tag{7}$$

Fig. 2 shows a typical profile of B_y over the x axis.

We can observe that by using such field profile, it is also introducing error to this very simple modeling.

The conservation of the magnetic flux conduces to the equality

$$B_b w_b=\int_{x_2}^{x_3}\left(B_0+\frac{B_1}{x}\right)\cdot \mathrm{d}x+\int_0^{x_2} Gx\cdot \mathrm{d}x, \tag{8}$$

given the following expression for the field inside the magnetic block:

$$B_b=-\frac{Gx_2^2}{w_b}\left[\frac{1}{2}+\frac{x_3}{x_2-x_3}\ln\left(\frac{x_3}{x_2}\right)\right], \tag{9}$$