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Array of purcell filters for improving field quality and reducing iron weight in wide aperture superferric magnets

P.R. Sarma [*,1], A. Dutta Gupta, S. Saha, S. Chattopadhyay

Variable Energy Cyclotron Centre, Department of Atomic Energy, Block-AF, Bidhannagar, Kolkata 700064, India

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ABSTRACT

Purcell filters are used for improving the field quality in dipoles and other magnets. These filters are voids in iron poles, which modify the field and improve the field quality of the magnets, especially in wide aperture magnets. Generally, one or two Purcell filters are used in a pole. In this work we have employed a periodic array of Purcell filters in a dipole magnet to reduce the field harmonics and improve the field uniformity. The technique has been applied to improve the design of a 9.75^0 sector dipole needed in the Super Fragment Separator (Super-FRS) of the upcoming FAIR project. A large reduction in the magnet size and weight has been obtained by using the array. A weight of 50 ton obtained in the original design has come down to 32 ton by the present method.

1. Introduction

A large number of dipole and multipole magnets are needed in the beam lines of the upcoming Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany [1]. Many of these magnets, especially in the Super Fragment Separator (Super-FRS) and its Energy Buncher section, are of wide aperture in order to accommodate a beam of large size. The optics of the beam lines require a high beam quality, which primarily depends on the field quality of the magnets. It is more so in magnets of spectroscopic application. For this, the field quality of the magnets have to be very stringent. For example, the 30° dipole of the Energy Buncher section requires a field quality of $|\Delta B/B| < 1.5 \times 10^{-4}$ in a horizontal aperture of 50 cm, where the pole gap is 17 cm. Here $|\Delta B/B|$ is the maximum field deviation in the magnets for all the field levels from the minimum to the maximum field. Another example is the Super-FRS dipole with a bending angle of 9.75° and a pole gap of 17 cm, where the field uniformity has to be better than $3{\times}10^{-4}$ over a horizontal aperture of 38 cm.

The above magnets are superferric magnets where the coils are superconducting but the field is dominantly generated by iron poles and yokes. In iron magnets the field quality mainly depends on the pole profile. As the field falls rapidly near the pole edges, the field quality can be improved by having poles of large width, and consequently making a magnet of large size and weight. This is not a smart solution and other means are used for improving the field quality without increasing the pole width unduly. Pole edge modification, edge chamfering, and pole shims [2–7] are widely used which effectively change the pole profile. Another technique is to use Purcell filters [8–14] which are voids in the pole, and modify the field profile to reduce the field deviation over a chosen aperture (Fig. 1). Purcell filters are more effective at higher fields (and, to some extent, at intermediate fields) where saturation of iron sets in. Whereas pole shims are generally very small in dimension, the Purcell filters are much larger in dimension, as they are somewhat away from the pole, and their dimensions can be more easily controlled during design simulation.

Generally a single rectangular Purcell filter is employed in dipole magnets. Two filters are also sometimes used for improving the field [15]. In our earlier work we used unconventional Purcell filters [16] where void penetrations in the pole were only partial. These methods of field profiling try to achieve the required field quality with a reasonable magnet size. However, even with the ingenious methods mentioned above, the magnet size may become too large for easy mechanical handling. For example, the Energy Buncher dipole [16] of FAIR is 69.5 ton in weight. The weight of Super-FRS dipole is about 50 ton [17]. In the present work we have endeavored to reduce the magnet weight, and at the same time retain the required field quality within the given aperture. For this purpose we have used a periodic array of Purcell filters (Fig. 1) instead of a single filter or double filters. Magnet weight has been found to decrease by a large amount using this method.

The logic of using an array of filters is as follows. A dipole magnet generates a field which is dominantly constant in the region between the poles (Fig. 2). This constant field is the dipole component.

* Corresponding author.
E-mail address: p.rudra.sarma@gmail.com (P.R. Sarma).
[1] Retired from Variable Energy Cyclotron Centre.

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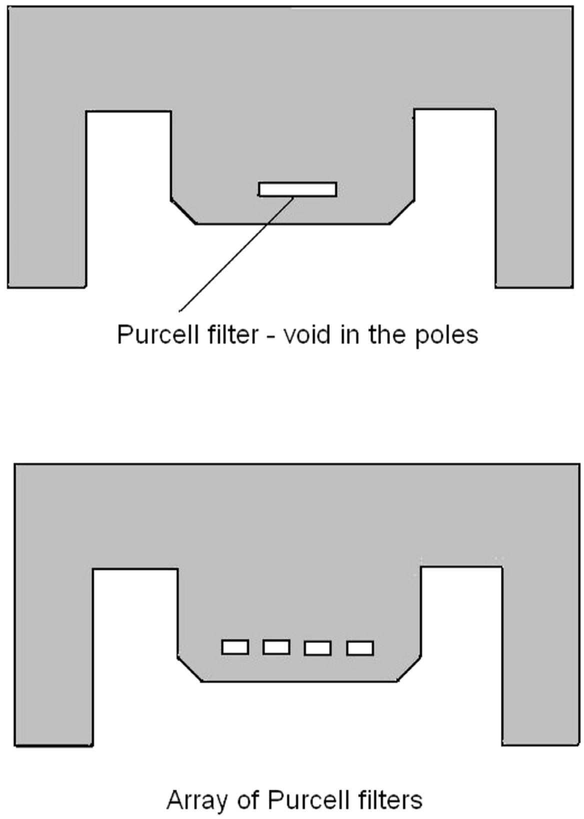

Fig. 1. Purcell filters used for improving field uniformity — single slot and an array of slots. Only half of the magnet is shown in two dimensions.

Table 1
Specifications of the Super-FRS 9.75° dipole magnet.

Bending angle	9.75°
Bending radius	1250 cm
Minimum/maximum field	0.15 T/1.6 T
Pole gap	17 cm
Usable horizontal aperture	±19 cm
Usable vertical aperture	±7 cm
Field quality ΔB/B over the whole field range	$\pm 3 \times 10^{-4}$

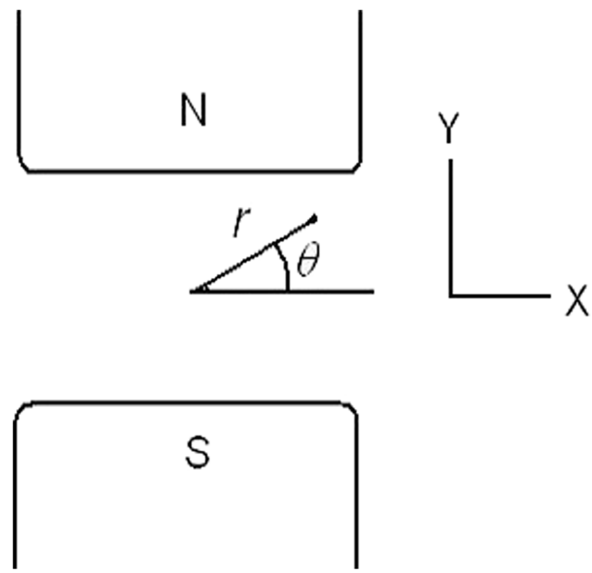

Fig. 2. Schematic dipole showing polar and rectangular coordinates.

However, there are harmonic error fields also mixed with the main field. The azimuthal magnetic field B_θ can be expressed as a Fourier function given below [18,19].

$$B_\theta = B_1\cos(\theta) + B_3 r^2\cos(3\theta) + B_5 r^4\cos(5\theta) + B_7 r^6\cos(7\theta) + \cdots \quad (1)$$

where, B_1 is the dominant dipole field coefficient, B_3 is the sextupole coefficient and so on. On the median plane the form of the field becomes

$$B_y(x) = B_1 + B_3 x^2 + B_5 x^4 + B_7 x^6 + \cdots \quad (2)$$

where x is the horizontal distance from the center of the magnet. However, for sector magnets, other smaller error terms like quadrupole term ($B_2 x$), octupole term ($B_4 x^3$) etc. also appear in the field. As can be seen from Eq. (1), the errors are periodic functions in nature. An efficient way of reducing these errors is to use either shims or Purcell filters which too should have periodic variation. A periodic or semi-periodic array of Purcell filters comes in handy in this situation. The dimensional parameters of the filter geometry can be optimized to minimize the field error and simultaneously reduce the magnet weight. We have used an array of four Purcell filters for optimizing the design of the 9.75° dipole of the Super-FRS [17]. These four void spaces generate a field modulation consisting of various periodic field components. This modulation is used for reducing the unwanted field harmonics. The magnet weight of the earlier design (FAIR design) was about 50 ton. With our technique, the weight has come down to 32.3 ton. So the magnet weight of the earlier design was 55% greater than that of the present design.

2. Field simulation and optimization of the magnet geometry

We have worked on the design of the Super-FRS dipole magnet with the following specifications given in Table 1.

As the horizontal good field aperture is much larger than the pole gap, the pole width and the yoke width are also large. Because the magnetic field is not too large (1.6 T), one can use superferric magnets which are iron magnets employing superconducting coils so as to save electrical power in the long run. The requirement of high field quality can be met by shaping the iron pole. An extra advantage of superferric magnets is that the coils are much smaller in size than the room temperature coils, and so the yoke width gets reduced to some extent.

The 3D design of the magnet has been carried out by simulating the magnetic field with the code TOSCA of OPERA group [20]. A preliminary design is first worked out with an initial pole size (and an overall magnet size) and approximate coil dimensions. Proper optimization of the magnet is then done by pole edge chamfering and introducing Purcell filters. The number of ampere-turns has been taken as 120 800 in each of the two coils and the maximum coil current is 251 A.

2.1. Optimization of the magnet geometry

We have optimized the dimensions of the Purcell filters and the side edges of the pole and brought down the field quality $\Delta B/B$ to a value which is much better than the required value of 3×10^{-4}. First, the field deviation has been reduced by a preliminary optimization of the side edges. In the next step we have optimized the geometry of the array of Purcell filters. We have adopted the random optimization technique [21] as described in detail in our earlier works [16,22–24]. The Purcell filters are rectangular slots, and the parameters which are to be optimized are indicated in Fig. 3. Apart from the 10 parameters shown in the figure, 4 more parameters have been used in the optimization. These are the dimensions of the groove shown in Fig. 3, at the pole ends. The necessity of using the groove is as follows. The magnet is to be used for a wide range of field from 0.15 T to 1.6 T. At higher field levels, field inside the pole is almost saturated. The Purcell filters have been found to