DESIGN AND PERFORMANCE OF PRINTED CIRCUIT STEERING MAGNETS FOR THE FLASH INJECTOR

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Abstract

Printed circuit boards offer a simple method for the design of hysteresis free, compact air coil magnets. The emphasis for the steering magnets developed for the FLASH injector is placed on a high integrated field strength for a short magnetic length to cope with space limitations in the injector beam line. The possibility to combine a pair of orthogonal steerers at the same longitudinal position has been realized by two layers of printed circuit boards. Design principles and magnetic measurements will be discussed.

INTRODUCTION

The distance between exit of the RF gun and entrance to the superconducting accelerator module is fixed by beam dynamics considerations at the FLASH injector. A number of components like a dark current kicker and collimator, a spectrometer dipole, laser mirror and various diagnostics components need to be integrated into the short beam line of about 1.2 m length between gun exit and entrance of the module. A high degree of integration and short components length are therefore necessary.

With two steerers for each transverse plane the beam position and angle at the entrance of the accelerating module can be controlled, whereby one steerer should be located close to the gun exit and the other one close to the entrance of the accelerating module. The integrated field strength of each steerer should allow for a kick angle of some mrad. Since the momentum of the beam in the gun section is about 5 MeV/c integrated field strength of some $17{\cdot}10^{-6}$ Tm are therefore required. Iron loaded magnets achieve the required field integrals easily, but hysteresis, remnant field and cross coupling of steerers for orthogonal planes are difficult to handle at the low field strength. These problems can be avoided with iron free air coils, but a sufficient field integral and field quality needs to be granted.

DESIGN PRINCIPLES OF PRINTED CIRCUIT MAGNETS

Magnets based on printed circuit boards have been used for example at the Lawrence Radiation Laboratory back in 1971 [1] or recently at the University of Maryland [2], where not only dipole magnets but also quadrupole magnets have been built. The patterns etched onto the printed circuit boards generate $\cos\theta$ like current distributions when the board is bent into a cylindrical shape and can hence be designed to generate any desired multipole field.

Printed circuit boards can be ordered with custom design in industry and are hence easily made. The high precision and reproducibility of the production process are the basis for a good field quality. In addition allows the flat geometry to transfer heat efficiently from the board into a metallic structure with large cooling fans.

While for electronic boards in general only small currents need to be transported through the copper layer on the board, which requires only thin layers of copper, the copper layer for the present application should be as thick as possible. It needs to be noted, however, that the minimal width of an etched conductor and the minimal distance between two conductors is limited by the etching process. Both increase with increasing thickness of the copper layer. Doubling the thickness of the copper layer does therefore not lead to a gain of two in achievable field integral.

Only the current flowing parallel to the beam contributes to the net angular steering. The magnetic components generated by the currents going along circular segments perpendicular to the beam axis modify the local field profile, but cancel in the relevant field integral.

In order to generate a pure dipole field the current density $J_z = {dI}/{rd\theta}$ on a cylindrical shell around the beam axis has to be proportional to the cosine of the azimuth angle θ. In case of a wound magnet this is achieved by varying the number of turns and position accordingly. In case of a printed circuit a simple rectangular spiral pattern (Figure 3) forms the current distribution. The $\cos\theta$ current profile can be realized in the integral over the longitudinal direction by varying the length of the conductors in accordance to the azimuth angle and/or by choosing the appropriate azimuth angle.

Two boards, each with one spiral, bent into half circles form a dipole. Thus for a dipole of length l and inner radius r the board has a size $l \times \pi r$.

For a short magnet, i.e. $l < \pi r$, the resistance of the magnet is dominated by the conductors going in θ direction, due to length and small cross section. These conductors should hence have a minimal spacing and a maximal width, so that the resistance is minimized.

A constant current density going in θ direction is in this case favourable. Continuity of the current relates the current density in z direction J_z to the current density in θ direction J_θ by [3]:

$$J_z\, r\, d\theta = J_\theta\, dz \qquad (1)$$

Thus it follows that the current density in z needs to scale as:

$$J_z \propto \frac{dz}{d\theta} \qquad (2)$$

If we define a function $f(\theta)$ which shall describe the variation of the conductor length versus the azimuth angle, the relation $\frac{dz}{d\theta} \propto \frac{df(\theta)}{d\theta}$ holds, which is used to replace $dz/d\theta$ in Eq. 2. The required cos θ distribution shall be realized only in the integral over the magnet length:

$$\int \frac{dI}{d\theta} dz \propto \cos\theta \tag{3}$$

The integral yields a multiplication with the conductor length, so that Eqs 2 and 3 lead to the differential equation:

$$f(\theta)\frac{df(\theta)}{d\theta} \propto \cos\theta \tag{4}$$

which is integrated to:

$$f(\theta) = \frac{l}{2}\sqrt{1-\sin\theta} \tag{5}$$

The normalization has been chosen so that $f(\theta)$ describes half the conductor length. Inversion of Eq. 5 yields the position of the *i*-th conductor as:

$$|\sin\theta| = 1 - \left(\frac{2 f_i}{l}\right)^2 \tag{6}$$

FLASH INJECTOR STEERING MAGNETS

The FLASH injector steering magnets have a mechanical length of 45 mm and an inner radius of 35 mm. This allows mounting the steerer on top of a DN40 flange or on a 63 mm beam pipe. The latter one is used as entrance tube of the accelerating module. Figure 1 gives an example for an installation situation.

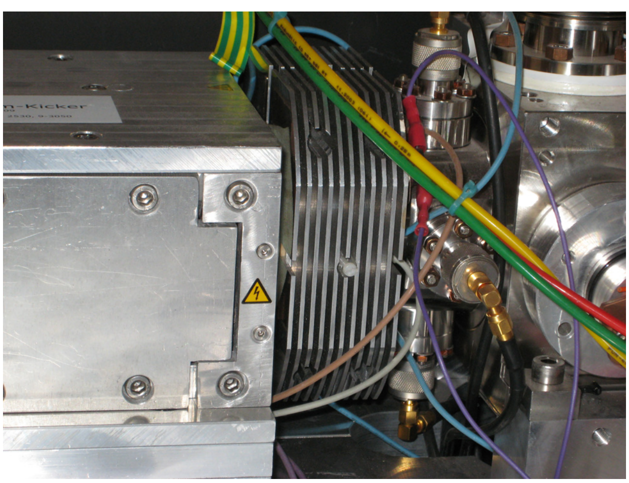

Figure 1: A steerer in the FLASH injector beam line between the dark current kicker on the left and a BPM on the right.

A steerer consists of two large outer half shells with cooling fins, two pairs of printed circuit boards and two thin inner half shells (Figure 2). The two pairs of printed circuit boards form an inner and an outer layer and can be mounted either to act into the same direction or to act perpendicular to each other. Correspondingly two different boards for slightly different radii had to be produced. The printed circuit boards are insulated with Kapton foil and layers of heat conducting foam rubber are placed between the boards. The outer shells are slightly undersized, so that the heat conducting foam rubber builds up a pressure which guarantees an equal contact with high thermal conductivity to the metal shell. The outer and inner shell parts are made from Aluminum. Screws through the outer shell, the boards and the inner shell fix the position of the boards and can be used to fix the magnet on the beam pipe.

The base material of the printed circuit boards is 200 µm thick and is coated with 400 µm thick copper layers on both sides. The spiral pattern is etched onto both sides, in a way that they can be connected in the center and the inward and outward going current add up.

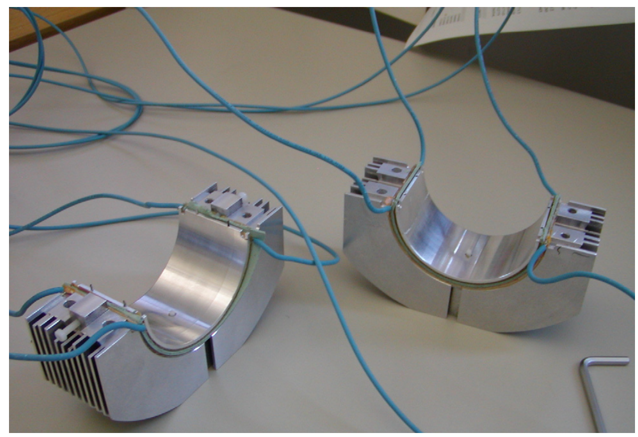

Figure 2: Disassembled steerer. The two layers of printed circuit boards are mounted to act into the same direction in this case.

With a large number of turns, i.e. a fine spiral pattern, a given integrated field strength can be reached at a lower current than with a small number of turns. However, the resistance of the structure increases not only due to the increased path which the current has to take when the number of turns is increased. In addition the width of the conductors has to be reduced due to the fixed length of the magnet and to make room for additional gaps between the conductors. In contrast to a case with constant cross section, as it can be realized to some extend for a wound magnet, a smaller number of turns is favourable here. A better field quality can however be reached with a larger number of turns.

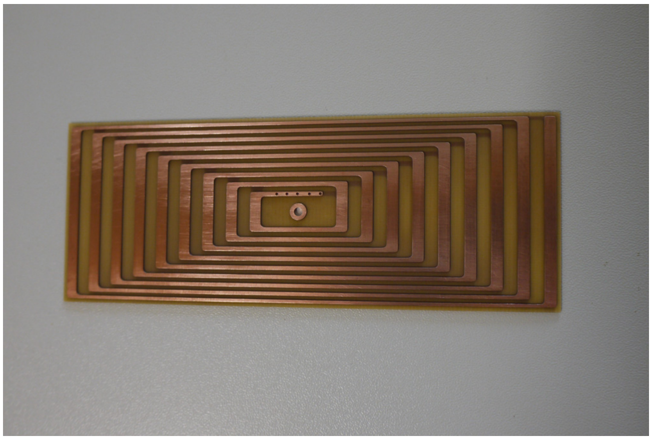

Figure 3: Printed Circuit board for the steerer magnet. An equivalent spiral pattern is etched onto the backside.

Figure 3 shows the printed circuit board for the FLASH steering magnet with 9 turns. For the 400 µm thick copper layer the minimal gap between two conductors is specified as 950 µm and the minimal width of the conductor is specified as 700 µm. The resistance of a pair of coils is 0.33 Ω at room temperature and increases to about 0.4 Ω at 75 °C. In a laboratory measurement, with purely conductive cooling, a coil temperature of 88 °C was reached when the steerer with two pairs of coils was powered with 7 A, corresponding to a power loss of nearly 40 Watt. This temperature is save, since the coils can withstand temperatures of 115 °C without problems. In a practical environment additional heat transfer through the beam pipe leads to a reduction of the temperature.

When the fields generated by the two pairs of boards act into the same direction an integrated field of $107 \cdot 10^{-6}$ Tm at 7 A is reached corresponding to a kick angle of 6.3 mrad for a 5 MeV/c beam. For the orthogonal mounting only half the field strength is reached in each plane. (In principle currents up to sqrt(2)·7 A could be run through one dipole if the orthogonal dipole is off.)

With the available equipment at DESY field measurements at these low field values are limited in precision but sufficient for the FLASH injector. After background subtraction integrated quadrupole components of $-5 \cdot 10^{-6}$ T/A and sextupole components of $1 \cdot 10^{-4}$ T/m/A have been found. A relative strong scattering of these components indicates that they are influenced by the relative alignment of he boards to each other. Especially the mounting in orthogonal planes posses some difficulties which limits the achievable precision.

ACKNOWLEDGEMENT

Special thanks to K. Kschioneck, K. Klose, Y. Holler and B. Regel for help during construction and measurements of the steerers.

REFERENCES

[1] R. T. Avery et al, 'Printed Circuit Steering Coils' Particle Accelerator Conference PAC 1971, Chicago.

[2] W. W. Zhang et al, 'Design and Field Measurement of Printed-Circuit Quadrupoles and Dipoles' PRST-AB 3, 122401, 2000.

[3] M. Venturini 'Lie Methods, Exact Map Computation and the Problem of Dispersion in Space Charge Dominated Beams' Ph. D. thesis, University of Maryland, 1998.