PRINTED BOARDS AND WATER JET CUTTING FOR MANUFACTORING MAGNETS

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Abstract

For many years, different types of electro-magnets have used printed boards, and many approaches have been attempted in order to get high quality magnetic induction. The French AEC at Saclay, has developed a geometry that allows to construct multipole magnets having a constant field integral inside the entire gap. Sigmaphi has purchased the patent from Saclay , and now designs and manufactures multipole magnets according this method. Moreover, by means of water jet cutting, Sigmaphi has recently manufactured pole face windings for correcting a spectrometer at Oak Ridge National Laboratory (ORNL).

This paper details the manufacture of such magnets.

1 MULTIPOLE MAGNET DESIGN

Several authors[1] have designed magnet with a cylindrical shape, and both with or without an iron return yoke. Such magnets are often used for superconducting magnets. As the current density in these cylindrical magnets follows a cosine-law and as the superconducting magnets are infinetely long, they can deliver a homogeneous induction integral throughout the bore.

The object of the Saclay patent is to design multipole magnets which are not infinitely long, and which produce a constant induction (or gradient) integral inside the cylindrical bore. Moreover, these magnets are manufactured with printed board circuits, and the windings of these multipole magnets are composed of saddle shape conductors. If m is the multipole order,with m =1 for a dipole, 2 for a quadrupole etc.. β is the polar angle of the conductor and L thr length of the cylinder, the length l of the wire is given by $l = L.\sin(m\beta)$.

Each coil of the multipole is therefore a spiral, with conductors varying in length from 0 in the central region to L at the periphery. The magnet is constructed from a printed board circuit with a constant radius R . The $2\,m$ coils are composed of N conductors, with N being a multiple of $4\,m$. The current intensity is I . The axis of the cylinder, representated by the Y co-ordinate, is the beam axis. The calculations are performed by using the Biot-Savart law. The induction and the induction integral are calculated at the point M , which has the co-ordinates (XM,YM,ZM) . A conductor parallel to the Y axis, having a length l , located at a point $P(XP,ZP)$ produces at point M the following inducion integrals:

$$\int_{-\infty}^{+\infty} Bx.dY = \frac{\mu_o.I.(ZM-ZP).l}{2.\pi.((XM-XP)^2+(ZM-ZP)^2)}$$

$$\int_{-\infty}^{+\infty} By.dY = 0$$

$$\int_{-\infty}^{+\infty} Bz.dY = -\frac{\mu_o.I.(XM-XP).l}{2.\pi.((XM-XP)^2+(ZM-ZP)^2)}$$

The radiussed portions of the conductors have no effect upon the induction integrals, but the induction components produced by these radiussed portions have nevertheless been calculated in order to compare the calculations to the physical results when magnetic measurements are performed. As it is not possible to integrate the Biot-Savart law for curved conductors, the integrals have been calculated by the trapezium method.

For N conductors, using the Gegenbauer polynomials, it can be demonstrated that the field integrals at $M(r,\alpha)$ and along the axis parallel to the axis OY are calculated if $(r<R)$ by the following equations :

$$Ix = \sum_{p=1}^{p=N} \int_{-\infty}^{+\infty} Bx.dY = -\frac{\mu_o.N.I.L}{4.\pi.R}.\sin((m-1).\alpha).r^{(m-1)}$$

$$Iz = \sum_{p=1}^{p=N} \int_{-\infty}^{+\infty} Bz.dY = -\frac{\mu_o.N.I.L}{4.\pi.R}.\cos((m-1).\alpha).r^{(m-1)}$$

In other words:

$$\frac{1}{\sin((m-1).\alpha)}.\frac{Ix}{r^{(m-1)}} = -\frac{\mu_o.N.I.L}{4.\pi.R}$$

$$\frac{1}{\cos((m-1).\alpha)}.\frac{Iz}{r^{(m-1)}} = \frac{\mu_o.N.I.L}{4.\pi.R}$$

These equations demonstrate that the ratio of the field integrals to $r^{(m-1)}$ for a given angle α are constant regardless of the considered point inside the aperture.

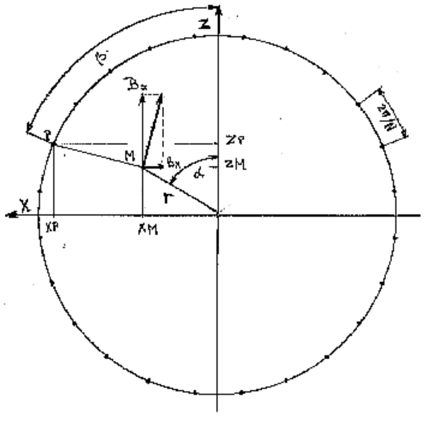

Figure 1 : Cutaway of Conductors in the cylinder

2 MULTIPOLE MAGNET MANUFACTURE

The multipole magnets are constructed as double-sided printed boards, with the copper thickness reaching 0.5 mm. The printed boards are bent into half-cylinders and so, two boards per multipole are needed. It is possible to stack several printed boards in order to realize a larger induction or for placing several types of correction at the same location. As an example, we have stacked a dipole, a quadrupole and a sextupole magnets. This can be very useful for saving room along the beam line. The exact shape and size of conductors is defined by a CAD program, and a high-resolution photograph of 2000 lines per inch is taken of the computer. Then, the printed circuits boards are manufactured by photo-etching. With this process, it is possible to produce magnets as large as 700 mm in length and 320 mm in diameter. The multipole magnets are often constructed with an iron return yoke, and sometimes with a water jacket providing an indirect cooling.

In some cases, the sine-law calls for very narrow that produces unacceptably high current density. So, for part of conductors, a slight error is introduced, and the field integral is not exactly constant. When the ratio of length to diameter is large enough, all of the multipole conductors have the correct distribution.

A 3D program allows us to calculate the induction components and the inductions integrals at any location inside the multipole magnets.

3 EXAMPLES OF MANUFACTURE

For 5 years, Sigmaphi has manufactured magnets by this method. For example, we have produced dipole magnets for the APS at the Argonne Nat'l Lab. , dipole, quadrupole and sextupole magnets for the Orsay University, France, dipole and quadrupole magnets for the French AEC centers of Saclay, Bruyères-le-Châtel and Cesta, dipole magnets for the Tesla Test Facility at DESY, Hamburg, FRG, dipole for BESSY II at Berlin, FRG, dipole magnet for LANL at LOS ALAMOS, NM...

When multipole magnets are manufactured, the magnetic performance is checked by means of a Hall magnetometer and rotating coils. The figure 2 shows the picture of printed circuit boards of dipole magnets before to be bent while the figure 3 is the picture of the same dipole magnet when it is completed and mounted around a solenoid. At last, the figures 4 and 3 shows, for this dipole, the calculated curves of the field integral and of its relative variation respectively. Since the dipole magnet has an aperture radius of 80 mm, one realizes that the integral is constan within 4.9 x10^{-4} over 93 % of the aperture.

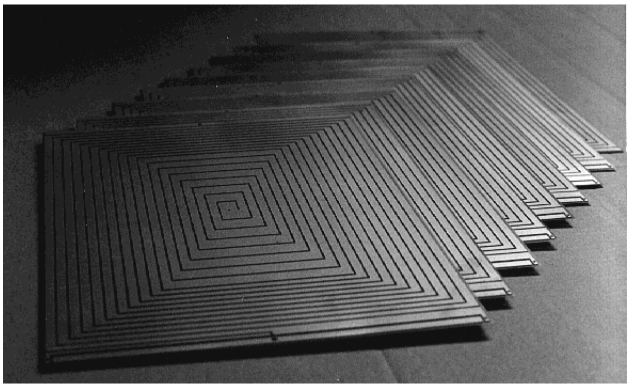

Figure 2 : Picture of Dipole Printed Boards (not yet bent)

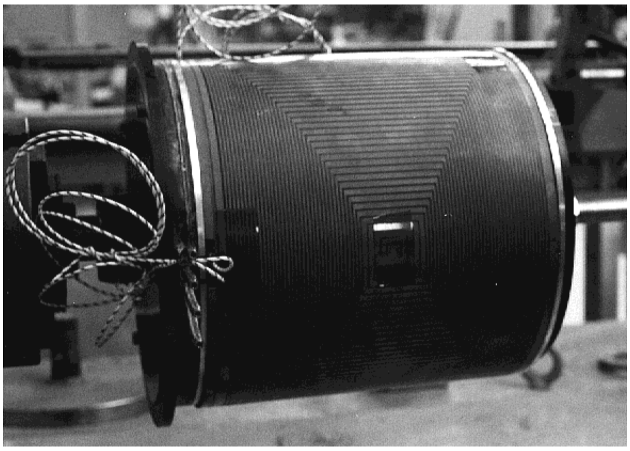

Figure 3 : Picture of Dipole Magnet after Completion

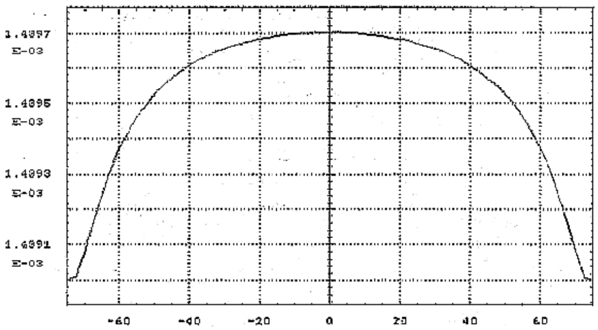

Figure 4 : Calculated Induction Integral (T.m) versus the radius (mm)

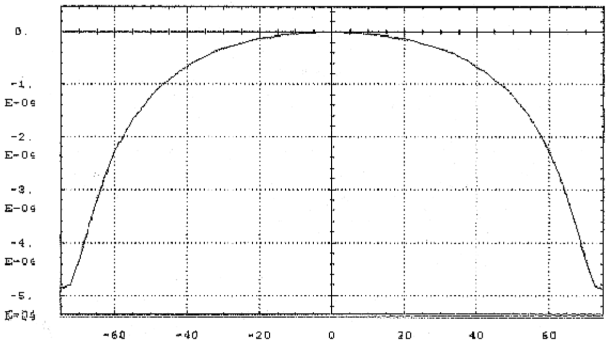

Figure5: Calculated Induction Integral Relative Variation

4 INTEREST OF THE PRINTED BOARD CIRCUITS

The printed board circuits are limited to low energy beams due to over heating caused by the weakness of the copper cross section of the conductors. For low energy beams and for corrections, the manufacture of multipole magnets by means of printed board circuits becomes very attractive for various reasons such as the field integral constancy, radial and longitudinal compactness, and the ability to stack different multipole types at the same location. It is also possible to manufacture magnets without any iron, which offers additional benefits in the case of pulse mode (Eddy currents).

5 WATER JET CUTTING PROCESS

In addition to photo-etching, one can manufacture current sheets by water jet cutting. This process is capable of supplying current sheets which are larger than those obtainable by the photo-etching process. Indeed, it is possible to get circuits as large as 2000 x 1000 mm with water jet cutting. Moreover, the thickness of the copper conductor can reach 5 mm.

Sigmaphi also uses this process for several applications , including the gradient coils for the Magnetic Resonance Imagery and the pole face windings of classic dipole magnets. For example, Sigmaphi has designed and manufactured the dipole magnets of the new mass separator of the ORNL cyclotron. These magnets require a very high field quality. They are equipped with two stacked pole face windings designed by the Poisson code. The first winding supplies a 1st order correction achieved by a magnetic index $n = -.\frac{R_o}{B_o}.\frac{\partial B}{\partial R}$, and the second supplies a 2nd order correction by $\beta = \frac{1}{2}.\frac{R_o^2}{B_o}.\frac{\partial^2 B}{\partial R^2}$, where R_o and B_o are the deviation radius and the central induction respectively. The two types of pole face windings have been manufactured , installed , checked and the results are exactly in compliance with the design. The figure 6 is the picture of the 2nd order correction pole face winding and the figure 7 is the picture of half dipole of ORNL equipped with the correction.

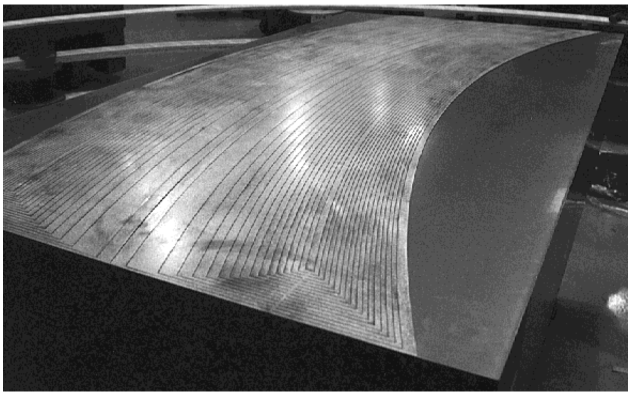

Figure 6 : Pole Face Winding made by Water Jet Cutting

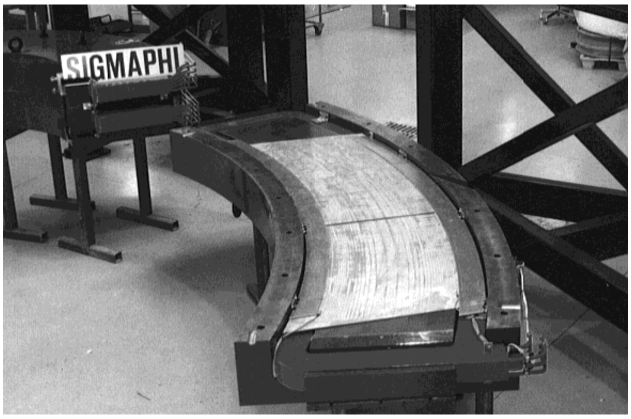

Figure 7 : Half a Dipole with Pole Face Winding

6 ACKNOWLEDGEMENTS

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REFERENCES

[1] ‘Some Analytical Methods for Winding Configuration of Ironless Beam Transport Magnets and Lenses‘ by A. Asner and C. Iselin (Magnet Technology Conference 1967)