MAGNET CORRECTION BY FIGURE EIGHTS

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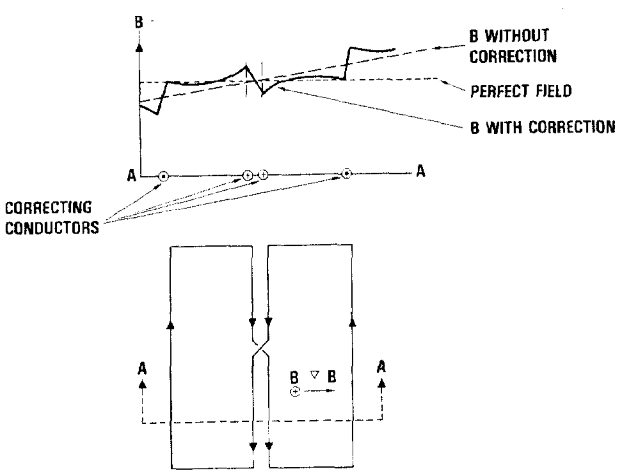
INTRODUCTION

"Figure eights" – superconducting loops with a figure eight geometry – provide an automatic, passive method for improving the field uniformity of superconducting dipole magnets. Figure eights are especially well suited for correcting iron-dominated dipoles operating at three tesla, where saturation of the iron makes it difficult to maintain acceptable field uniformity over the full operating range. By using figure eights to provide the final increment of field uniformity, the specifications and cost of the dipoles can be reduced. The figure eights themselves have very modest superconducting technology requirements and can be manufactured by mass production methods at very low cost.

PRINCIPLE OF OPERATION

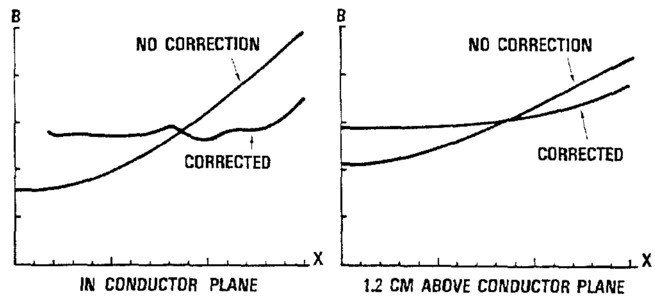
The basic geometry and principle of operation of a figure eight is illustrated in Fig 1. As the name implies, each figure eight is a continuous loop of superconductor that is twisted into a pair of oppositely connected loops of equal area. The loops can have arbitrary shape, but for correcting dipole magnets, the rectangular loops shown in Fig. 1. are optimal.

FIGURE 1
PRINCIPLE OF FIGURE 8 CORRECTION



If the figure eight is subjected to a uniform, externally-produced magnetic field, the flux linking each loop is equal and not current will flow. If, however, the external field is non-uniform with a gradient normal to the y-axis of the figure eight, a current will flow that will equalize the flux linking each loop (see Fig. 1). The effect of a figure eight in correcting the gradient in an external field is illustrated in Fig. 2, for two z positions, one in the plane of the figure eight conductor and the other 1.2 cm above the conductor plane. This later position is relevant to how figure eights would be used to correct a dipole magnet. Note that the corrected field in the conductor plane has local perturbations attributable to the near field effect of the conductor; 1.2 cm above the conductor these local perturbations have disappeared and the resulting field profile is much smoother, with nearly an order of magnitude reduction in gradient.

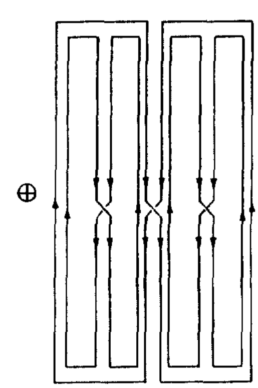
FIGURE 2
CALCULATED FIELD IMPROVEMENTS



A further reduction in gradient over a larger area can be obtained by nesting smaller pairs of figure eights within the original figure eight, as shown in Fig. 3. In principle, an arbitrary number of figure eights can be nested to correct the field to as high a degree of uniformity as needed. In practice, a doubly nested array is probably sufficient.

FIGURE 3

BY NESTING ADDITIONAL FIGURE 8's THE FIELD IS CORRECTED FURTHER



IN THE PRECEEDING FIELD, CURRENTS WILL FLOW AS SHOWN

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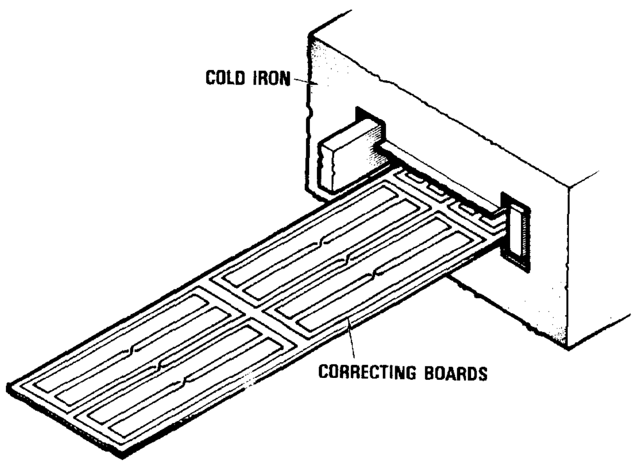
Application to Correcting Dipole Magnets.

Figure 4 shows how the figure eights would be constructed and used to correct a dipole magnet. The figure eights are mounted on thin, copper-coated insulating substrates, very much like an electronic circuit board. One circuit board is mounted on each pole face; and each circuit board carries an array of nested figure eights. The whole assembly of the magnet iron and figure eight boards is, of course, cooled to liquid helium temperatures.

FIGURE 4
INSTALLATION OF FIGURE 8's



A number of options for fabricating the figure eights have been identified. For best results, the superconductor must be positioned on the substrate with good accuracy. Nb_3Sn could be plasma sprayed or vapor deposited through a mask. This would be done in a two-step process to provide an insulating bridge at the crossover. An alternative means of fabrication would be to use NbTi sheets that are punched to shape and then bonded to the copper substrate. Either technique is amenable to mass production and should be able to produce the figure eight boards at very low cost (relative to the magnets they will be used with).

The superconductor requirements and mechanical forces on the figure eights are very modest. for a typical three tesla magnet, the current is less than 200 A for a few tenths of a percent correction. A 0.001 inch by 0.1 inch strip of either NbTi or Nb_3Sn is entirely adequate.

DISCUSSION

Figure eights could prove to be an inexpensive method of improving the field uniformity of dipoles from large accelerators such as the SSC. Their principal virtue is simplicity and low cost. Their action is wholely passive, and they can correct differential nonuniformities without special tailoring. They relax both the design specifications and the construction accuracy requirements for the dipole magnets. Finally, because of their intrinsic ability to correct time and spatially varying gradients, they provide a new degree of design flexibility for saturated iron dipoles and offer the prospect of an increased operating range with acceptable field uniformity.