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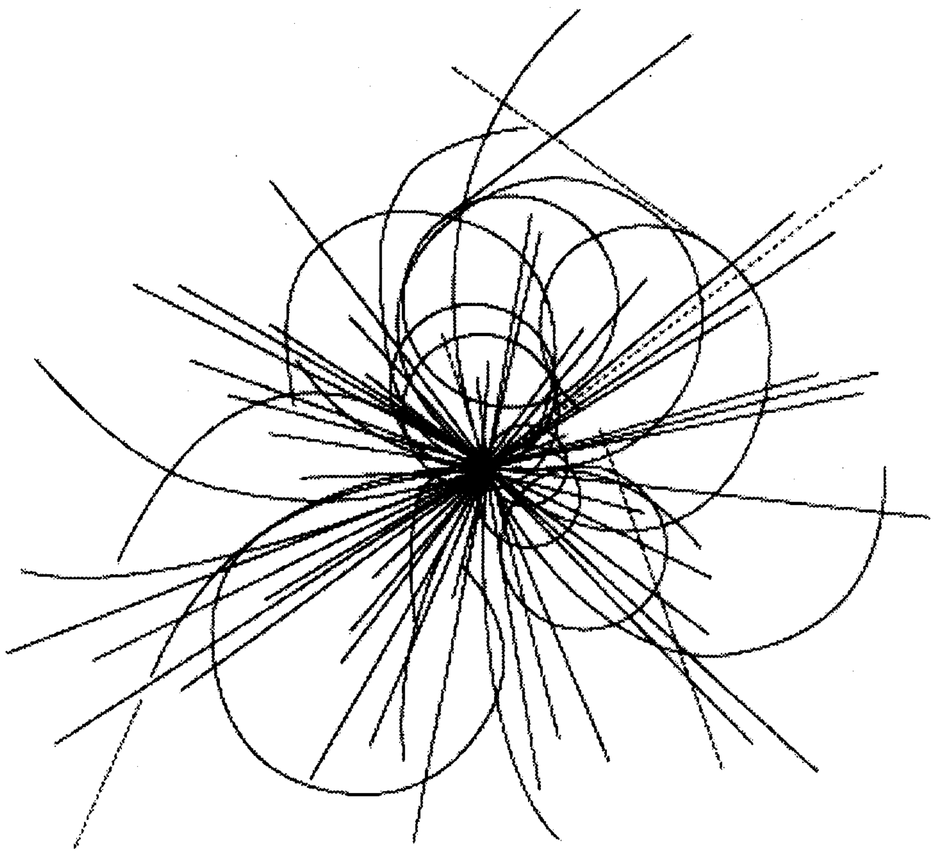

Superconducting Super Collider Laboratory

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Advances in the Use of Tomographic Inspection Techniques for Non-Destructive Analysis of Geometric Conductor Position and Correlation with Magnetic Cross-Section Modeling*

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ADVANCES IN THE USE OF TOMOGRAPHIC INSPECTION TECHNIQUES FOR NON-DESTRUCTIVE ANALYSIS OF GEOMETRIC CONDUCTOR POSITION AND CORRELATION WITH MAGNETIC CROSS-SECTION MODELING

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ABSTRACT

Industrial Computerized Tomography has been applied to magnet components in various stages of the manufacturing process. These Computerized Tomographic images can be analyzed to infer detailed dimensional information about magnet component positions (conductor, wedges, collars, etc.) throughout the magnet manufacturing process (cable winding, collaring, yoked/skinned). An analysis technique will be presented and measurement accuracies will be discussed.

INTRODUCTION

The impact of gamma ray Computerized Tomographic (CT) imaging as a medical diagnostic tool has been revolutionary. This diagnostic tool has also been applied (with much less notoriety) to industrial applications such as steel tubing (and I-beams), turbine blades, rocket motors, toxic waste drums, concrete piers, electric power poles, and electronic components to name just a few[1].

Under the direction of the Superconducting Super Collider Laboratory (SSCL) Magnet Systems Division,† International Digital Modeling Corp. (IDM) has developed CT inspection and analysis techniques for use on magnets and magnet components. These inspection techniques have been utilized to inspect a broad range of samples, which include NbTi billets, cured un-collared winding sections, 50–mm collared dipole sections, and 40–mm coldmass quadrupole sections (cf. Figure 1). The CT image shown in Figure 1 was obtained using IDM's IRIS™ VARIScan Laboratory System. The VARIScan system

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consists of a 7 Curie CO-60 isotopic source and a collimated detector aperture of 2 mm by 5 mm. Data was acquired at 1/8 degree increments with a maximum detector spacing of 0.16 mm. The nominal tomographic resolution of the VariScan Laboratory System is approximately 1.0 line pair per mm.

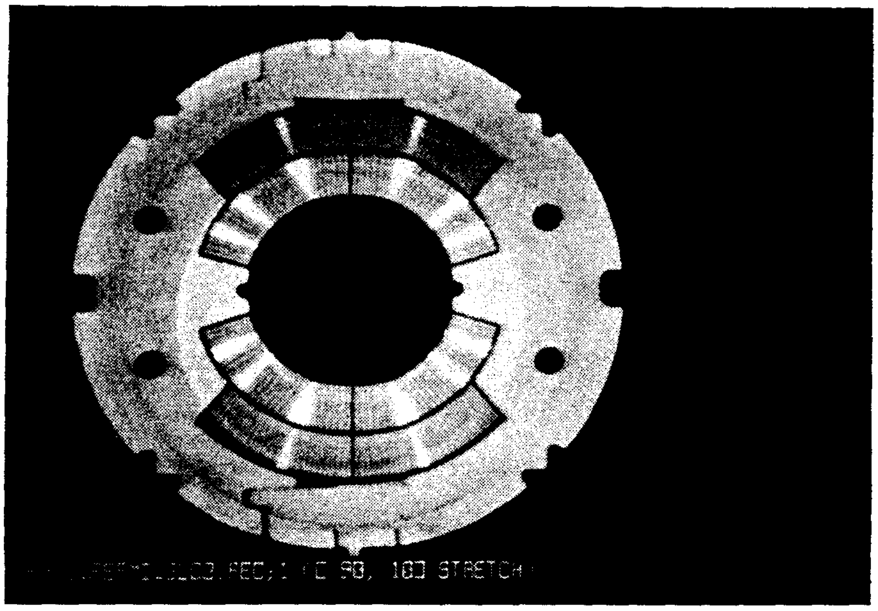

Figure 1. A CT image of a 50 mm collared magnet section. Notice the density contrast between the copper wedges (8.96 g/cc) and the cable insulation material (< 2.00 g/cc).

Results such as Figure 1 can provide a significant amount of useful information on aspects such as missing components, gross manufacturing defects, and improper assembly. Besides the large scale information "visually" obtainable from CT images, detailed dimensional information can be inferred from the full precision CT data (floating point, not 8 bit integer image data) using appropriate analysis techniques.

GENERAL DATA ANALYSIS CONSIDERATIONS

The location of features (conductors, copper wedges, collars, etc.) within magnet samples have been determined from the CT image data using the following analysis procedure. Suppose one has a group of cables which have been resolved in a CT image (cf. the sketch in Figure 2). If one selects a series of data profiles which intersect these resolved cables, then by using sensitivity analysis techniques[2] and a knowledge of the system transfer function (STF), a database of observed conductor edge locations can be generated. Knowledge of the STF is necessary because the STF has the effect of "smearing or smoothing" features within a CT data set, that is the observed CT data set is the convolution of the STF and the ideal CT data. The accumulated information in the database can be processed to determine dimensional parameters such as average insulation gap widths, average conductor thicknesses, conductor corner positions, and conductor centroid locations.

The sensitivity analysis techniques used to determine the location of conductor edges (or other magnet components) can be described quantitatively by recognizing that an observed data profile is a function of the edge locations, the densities of the conductor and insulation materials, and the STF parameter (x_k, $_c$, $_i$, and , respectively); I($x_{k,c,i,}$). Using the chain rule for differentiation gives:

$$dI\,(x_k,\rho_c,\rho_i,\sigma) = \frac{\partial I}{\partial \rho_c}d\rho_c + \frac{\partial I}{\partial \rho_i}d\rho_i + \frac{\partial I}{\partial \sigma}d\sigma + \sum_{k=1}^{n}\frac{\partial I}{\partial x_k}dx_k \quad ,$$

where the summation is over all edges of interest. For the simplest case, the densities of the conductor and insulation materials are constant for a given profile, and the system transfer function is constant for a given CT image, hence d_c, d_i, and d are equal to zero. If one assumes the conductor edges are defined by step functions and the system transfer function is well represented by a Guassian, then the sensitivity functionals, $\partial I/\partial x_k$, are Gaussians located at the positions x_k, with width. Expressing $dI(x_{k,c,i},)$ as the finite difference between the observed data profile and a theoretical (as designed) profile, and discretizing the sensitivity functionals allows one to recast equation (1) into a matrix equation. This matrix equation can be solved for the dx_k's using standard matrix inversion techniques. The dx_k's give the deviations (or correction factors) from the theoretical (as designed) locations. By adding the correction factors to the theoretical edge locations the algorithm described above can be iterated until convergence is achieved.

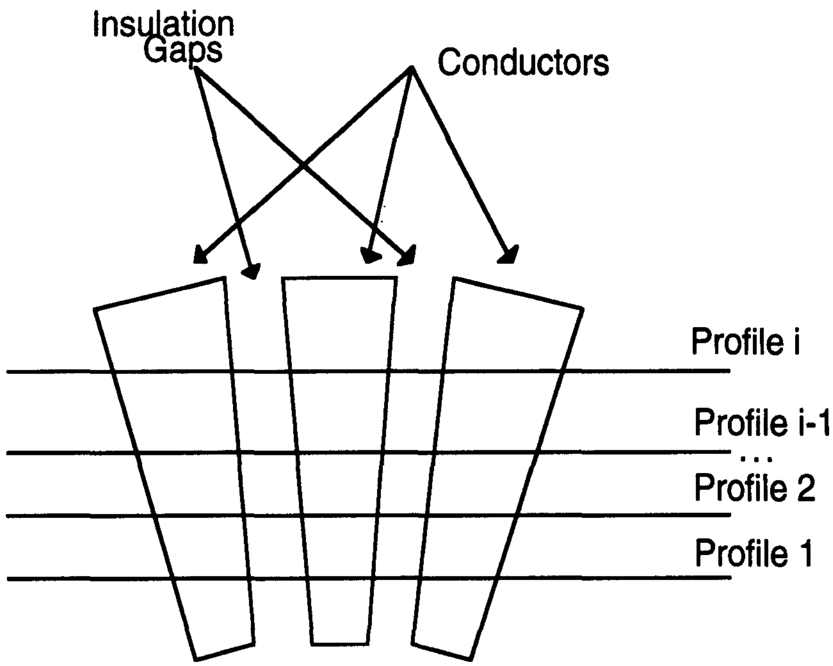

Figure 2. This sketch shows the general placement of data profiles on a set of cables (cable => conductor and insulation).

CHARACTERIZATION OF THE SYSTEM TRANSFER FUNCTION

As pointed out above, the STF acts to "smear or smooth" features within a CT data set. In order to obtain accurate and reproducible information from CT data sets, one must have an understanding of the general shape and the effective width of this function. This was accomplished by designing and fabricating the calibration/gage block.[3] The calibration/gage block was designed to simulate a 50–mm dipole coldmass. Design features include simulated windings with insulation gaps of 0.15, 0.20, 0.25, and 0.31 mm in width and separation gaps between collar/yoke and yoke/skin pieces. An effort was made to maintain the density contrast of an actual 50–mm dipole magnet.

CT data was acquired from the calibration/gage block. This information was used to determine the effective width of the STF and to verify that the STF is well represented by a Gaussian.

RESULTS AND DISCUSSION

Using the analysis techniques outlined above, preliminary results have been obtained for parameters such as average insulation gap widths, average conductor thicknesses, conductor corner positions, and conductor centroid locations. Average insulation gap widths and average conductor thicknesses have been measured with accuracies of ± 0.05 mm. Conductor positions have been determined with accuracies of ± 0.13 mm. The need for dimensional and positional information on magnet components has been widely discussed and demonstrated.[4,5,6] This need can be met with the application of industrial CT through out the magnet manufacturing process.

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