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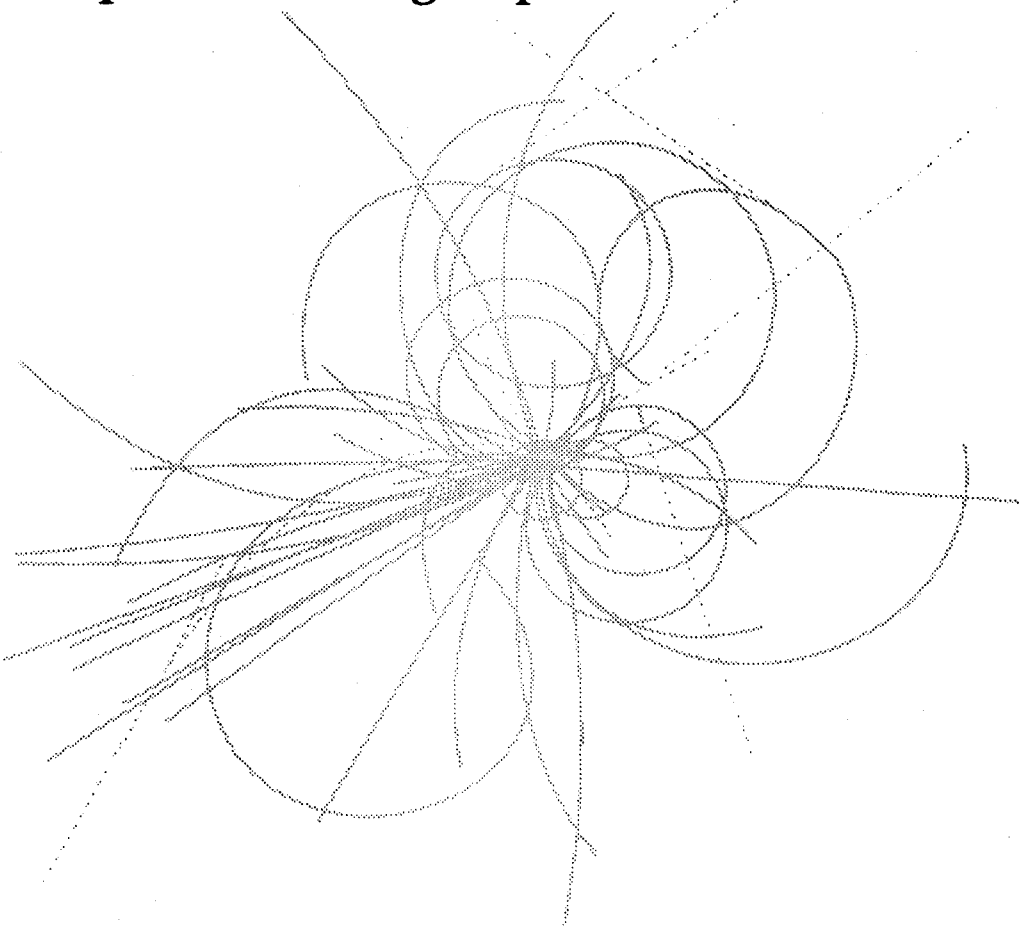

Utilization of Gamma Ray Inspection System for Tomographic Imaging and Dimensional Analysis of Complete Model Magnet Cold Masses and Collared Coil Sections

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UTILIZATION OF GAMMA RAY INSPECTION SYSTEM FOR TOMOGRAPHIC IMAGING AND DIMENSIONAL ANALYSIS OF COMPLETE MODEL MAGNET COLD MASSES AND COLLARED COIL SECTIONS

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INTRODUCTION

Non-destructive digital photon transmission imaging can be performed with the IRIS™ system to provide internal component dimensions and locations of manufactured superconducting magnets and sub-assemblies. With non-destructive evaluation of the magnet components, and sub-assemblies at critical stages of the manufacturing process, it is possible to assess the quality at each stage with the goal of improving manufacturing reproducibility and reliability. Evaluations of the feasibility of the IRIS™ system have been performed on a NbTi billet used for the production of monofilament rods used in the manufacturing of multifilament strand. It has also been used to perform inspections on collared coil sections, both 40 mm and 50 mm, as well as cold masses. The dimensional accuracy for locating the conductor winding positions in a collared coil section has been found to be +/– 80 microns. Non-destructive analysis using the IRIS™ system offers in process inspection, as well as post assembly examination capabilities previously unavailable except through destructive physical analysis by sectioning and polishing for optical inspection after vacuum impregnation. This novel inspection tool may give us deep insights into the validity of our mechanical, and electromagnetic models currently used to evaluate magnet design and may lead to substantial savings per magnet analysis.

DESCRIPTION OF THE CAPABILITIES OF THE IRIS™ SYSYEM

Over 12,000 superconducting magnets will be needed for the construction of the Superconducting Super Collider.[1] It has been estimated that an allowable failure rate for the Collider Dipole Magnets is 0.04 failures per million installed hours.[2] Clearly quality

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control will be an important issue during magnet fabrication. The suitability of using the IRIS™ system for non-destructive evaluation during magnet production has been investigated. Specifically the use of the IRIS™ system for finding flaws in NbTi billets during manufacturing of superconducting multifilament strand, examining collared coil sections, and examining cold masses will be addressed.

The devices used to acquire the images shown here contain a 10 Ci Co^{60} fan beam source and 71 scintillator assemblies, spaced in one degree increments. Each detector assembly consists of a plastic scintillator, photomultiplier tube, and discriminator card. Signals from the discriminator cards are transferred via twisted pair cables to scaler modules located in the CAMAC crate. Data are transferred from the CAMAC to a MicroVAX 3300 for processing. Figure 1 is a schematic of one of the systems used in this study.

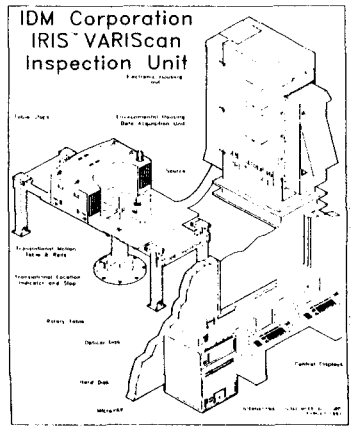

Figure 1. Schematic diagram of the IRIS™ system.

This is the IRIS™ model 004 general purpose inspection unit. In this system the source and the detectors remain fixed, and the object being scanned is rotated, thus allowing the acquisition of a tomographic image. The object to be scanned can be placed at variable distances from the radioactive source. This provides geometric magnification and can increase the machine's resolution by up to 50% . In the other system, the model 002, the source and the detectors rotate around the object being scanned. The distance between the source and the scanned object is fixed, because of this.

Several types of scans can be performed on the IRIS™ instrument. Of these the most detailed is the analytic scan, which is essentially a tomographic scan. In the higher resolution versions of the analytic scan the detector bank is rotated about the source position by fractions of a detector spacing, thus increasing the effective number of detectors. This is called subpositioning. There are seven data taking subpositions used in the highest resolution analytic scan mode. Data are taken in 1/6 degree increments as the sample is rotated through one complete revolution. It typically takes about two hours to perform a scan of this type and achieves a resolution of 1.2 mm. The lowest resolution analytic scan can be performed in approximately fifteen minutes, although the resolution suffers and is much poorer. Scan times could be reduced by a factor of twenty in a system optimally designed for SSC applications by using higher intensity sources and more efficient detectors. Increasing the number of detectors or increasing their packing efficiency could further reduce the needed scan times.

Cracks of widths between 13 and 500 microns can be measured to an accuracy of 10% using the IRIS™ system. These measurements, which are below the resolution of the machine, can be made, because of the a priori knowledge that a crack exists. This concept is referred to as detectability as opposed to resolution.

Another type of scan, called a gaging scan, is available for cylindrical or tubular objects. In this type of scan fewer rotations of the object are used and a complete image of the object is not reconstructed. Instead the dimensions of the object are found and flaws are located. Because less data needs to be acquired, gaging scans can be completed faster than analytic scans.

A digital radiography mode is also available on the IRIS™ instruments. This gives the same type of information one would find in a conventional X-ray. However the data exists in a digital form and several image processing techniques can be applied, yielding various flaw detection resolutions.

EXPERIMENTAL RESULTS

NbTi Billet Scans A NbTi billet was machined with three spherical voids of diameters of 3.18, 1.59, and 0.79 mm, for use as a sample to characterize the IRIS™ system's ability to find flaws in the production of monofilament rods used in the production of multifilament strand used in superconducting cable. The cylindrical billet had three circular holes electrically discharged machined through the diameter. Cylindrical plugs were made of material cut from one end of the billet to fit into these holes. Each plug was then cut in two lengthwise, and a hemispherical void was machined into each piece. The plugs were then cooled to dry ice temperatures and press fitted into the matching hole in the billet. This gave tolerances of a few microns between the plug and the hole in the billet.

The 3.18, and the 1.59 mm flaws were detected by the IRIS™ system, but the 0.79 mm defect was not. Part of the difficulty in detecting this flaw was the rough condition of the exterior surface of the sample billet. This increases the noise in our flaw detection algorithms. One expects a much smoother surface in a production environment. Currently these billets are inspected by ultrasonic techniques. Because of the attenuation coefficient of the NbTi material a low frequency transducer must be used for the inspection. The wavelengths used in the ultrasonic inspection sets a limit of a 2.5 mm as the minimum flaw size that can be reproducibly detected.

Figure 2, on the following page, shows an analytic scan of the billet cross section with the 1.59 mm flaw.

The flaw is clearly visible and the gaps between the plug and the surrounding billet can also be seen. A subtraction between a flawed slice and an unflawed slice can be done in order to highlight the flaw.

Taking a full tomographic scan takes too long to be practical for inspection purposes in a production environment. Flaws can be detected in a billet using a faster data acquisition mode, in which a full tomographic reconstruction is not made. Figure 3, on the following page, is a digital radiograph of the billet taken with the IRIS™ system.

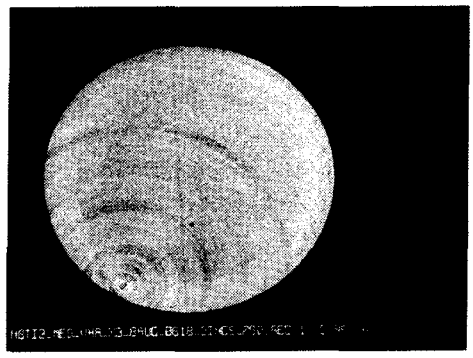

Figure 2. Analytic scan of NbTi billet, showing 1.59 mm flaw.

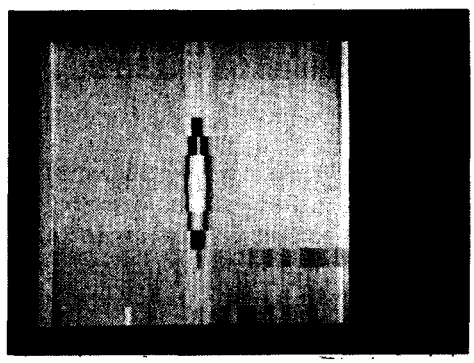

Figure 3. Digital radiograph of NbTi billet, showing 1.59 mm flaw.

This figure shows the difference between the local density and the average density measured over the entire billet. Each pixel is 1.9 mm in height. The outline of the plug can be clearly seen. It is not circular due to the aspect ratio chosen. The 1.59 mm flaw can also be seen in the center of the plug outline. Figure 4, shown on the following page, is a triangulation display in which the position of the flaw in the billet slice is shown.

This is determined from data taken by seven digital radiographs similar to that shown in Figure 3 except at different rotations. In this type of scan the number rotations has been reduced from a multiple of 360 to 7 giving a clear scan time. It is estimated that a complete scan of a billet can be outlined in two hours using this method.

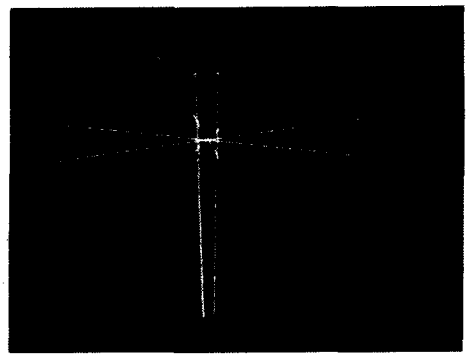

Figure 4. Triangulation of the flaw position within the NbTi billet.

Collared Coil Section Scans Figure 5 is an image of 40 mm collared coil section.

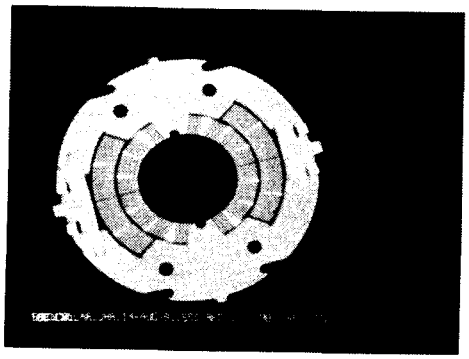

Figure 5. Tomographic image of a 40 mm collared coil section.

The copper keys and the individual conductor windings are clearly visible. Figure 6, shown on the following page, is a zoom of one of the quadrants of the collared coil section shown in Figure 5.

A damaged turn is shown in this tomographic image. Also shown are two turns which are almost in contact with each other perhaps indicating that the turn to turn insulation was extruded from between the turns due to high prestress. International Digital Modeling Corporation has developed software procedures, which utilizes our a priori knowledge of the coil geometry, to measure the conductor (turns) endpoints to within 80 microns. This is less than the resolution of our tomographic instrument. Figure 7 (also shown on the follwoing page) is an as made CAD drawing of the quadrant shown previously in Figure 6 using data obtained from this procedure.

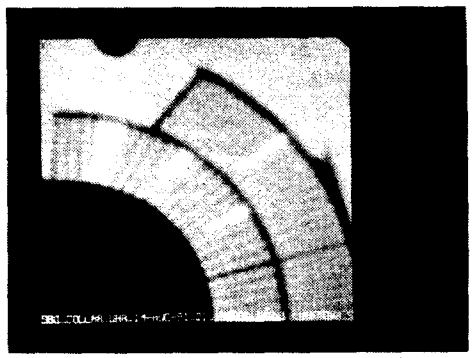

Figure 6. Tomographic image showing a damaged turn in the 40 mm collared coil section.

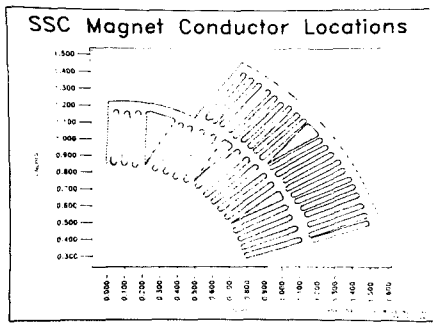

Figure 7. CAD drawing showing winding positions.

Recently a deconvolution procedure has been developed which offers increased resolution of our images. Figure 8 is an example of this improved resolution on a scan from a 50 mm collared coil section. It represents our best collared coil image to date.

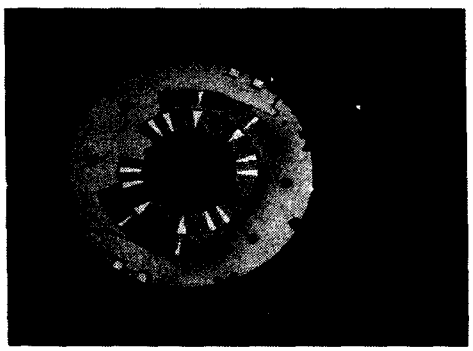

Figure 8. Tomographic image of a 50 mm collared coil section showing improved resolution using this deconvolution technique.

Cold Mass Scans Several scans of cold masses of both LBL and BNL designs have been performed. Figure 9 shows one of the scans of the LBL cold mass. The skin welds, alignment keys, and the individual conductor windings in the collared coil section can be seen. Figure 10 is an expanded region of the collared coil section shown in Figure 9, to which the deconvolution procedure has been applied. This helps resolve individual conductor positions.(Figures are on the following page.)

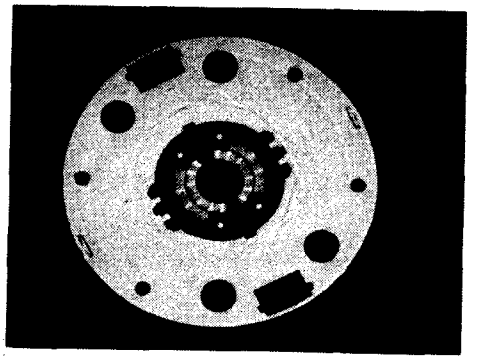

Figure 9. Tomographic image of the LBL cold mass cross section, of the NC9 design.

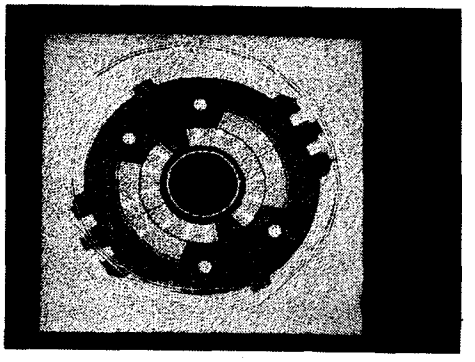

Figure 10. Expanded image of coil section, after application of the deconvolution procedure.

In order to see the conductor windings more clearly scans can be made through the gaps between the yoke packs. Figure 11 is a deconvolved image taken in this fashion. The individual turns are clearly shown in this image.

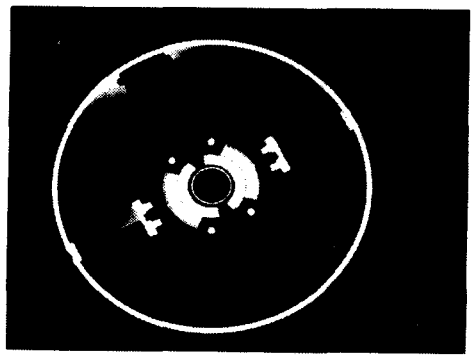

Figure 11. Tomogrpahic image shot between the yoke packs.

CONCLUSION

Several capabilities of the IRIS™ system have been demonstrated. Flaws in NbTi billets were found that are smaller then the resolution detectable by conventional ultrasonic methods. The positions of turns and integrity of insulation was determined in two collared coil sections. In addition the IRIS™ system can be used to determine conductor positions, the symmetry and angular position of conductor blocks, and the presence and size of gaps between the collar and yoke, and between the yoke and the shell in cold mass assemblies.

Our future work will involve the application of the IRIS™ system for the dimensional analysis of conductor position, yoke and shell interface, and yoke and collar interface, in a 50 mm model. The intent will be to perform this analysis first at room temperature, and then finally repeat this analysis on a cold magnet at temperature, and fully energized. In addition we intend to experiment using the IRIS™ system for alignment of the cold mass inside the cryostat, and location of the interconnect pipes for in process quality control.

References

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2. Andrew Kytasty, "Proposal for an Approach to Achieve CDM Reliability", Proceedings of the Third International Industrial Symposium on the Super Collider, Plenum Press, New York, 1991, p. 283.