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A METHOD TO MEASURE THERMAL DEFORMATION OF SUPERCONDUCTING MAGNET CROSS SECTIONS

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A Method to Measure Thermal Deformations of Superconducting Magnet Cross Sections

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***Abstract*—The precision measurement of the cable positioning in superconducting coils is of great interest both at room and liquid nitrogen temperatures because mechanical and thermal deformations affect the quality of the magnetic field. The paper describes a new two-coordinate measuring device, which is able to obtain scanned images of flat composite samples at liquid nitrogen temperature. The sample is cooled at 77 K into a flat quartz tray to permit the optical access to the sample from the bottom. The comparison of the images taken at room and liquid nitrogen temperatures by a high-resolution flatbed scanner gives the thermal contraction of the components.**

***Index terms*—superconducting coil, thermal contraction, flatbed scanner**

I. Introduction

In the last few years the improvement of the optical resolution of commercial flatbed scanners, and of the tooling software required for image processing, has made it possible to reach an accuracy of a few tens of microns in the measurement of two-dimensional samples. The potential of commercial flatbed scanners for measuring composite two-dimensional samples is discussed in a previous study [1]. Compared with other optical devices, scanners offer several advantages. First, a scanned bitmapped image can be easily analyzed and transformed mathematically. Second, the correction of perspectives is not required like in other techniques (e.g., photogrammetry). Third, the software applied to analyze scanned images is complete and easily available (Photoshop™, PhotoPlus™, CorelPhoto-Paint™, etc.) However, it should be remarked that the optics of a scanner differ significantly from that of a microscope, and an accuracy in the measurements better than 10μm is extremely difficult to obtain.

This paper describes the device and the method applied to measure deformations in flat composite objects both at room and liquid nitrogen temperatures. We study the arrangement that makes possible to protect the optical system from the drastic drop of temperature, and avoid image distortions caused by water condensation. We emphasize the importance of using good standards (i.e., reference images of known dimensions used to calibrate the measurements) and adequate scanners to obtain sufficient accuracy. Here, the method is applied to obtain a high-resolution image of a cross-section of an LHC dipole at liquid nitrogen temperature.

Many methods have been developed to measure thermal contraction in homogenous samples at low and high temperatures: push-rod dilatometers [2], twin-telemicroscopes [3], interferometers [4], parallel plate capacitors [5], x-rays [6]. However, little work has been done for the measurement of thermal deformations of composite samples with several different materials [7].

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II. Design

A. Scanner Characteristics

The internal components of flatbed scanners are basically three: sensors, optical interface and stepper motor.

Sensors, generally Charged-Coupled Devices (CCD), are very sensitive to temperature variations, and consequently must be thermally isolated for cold measurements. A configuration similar to EPSON 12000 (Fig. 1), in which CCD sensors are far away from the scanner window, is the most advisable for cold measurements and was chosen here.

All commercially available scanners are optically calibrated for a given separation distance between the scanner window and the array of sensors. Therefore, only scanners which can obtain a focussed image of the sample several millimeters over the scanner window will be of interest for cold measurements. The optical length between sample and CCD must be as long as possible to reduce the defocusing effect. The use of mirrors in the optical interface helps to increase this optical length.

The stepper motor is calibrated in many scanners in moving increments, which are identical to the scanner resolution (steps in other scanners can be ½ of the scanner resolution). However, when a sample is placed several millimeters over the scanner window, the X- and Y- axes have different scales. Therefore, the dimensions along horizontal and vertical axis must be scaled.

B. Standards and Scanner Calibration

An image with known dimensions is used as a standard to calibrate the scanner. All measurements on the scanned image are based on the position of two-coordinate points. Usually, points are defined as the intersection of two thin lines. However, scanners, similar to the human eye, detect the boundary lines between two complementary colors much better than thin lines on uniform backgrounds. For this reason, we found that an adequate configuration for the standard is a matrix of equally separated black squares of 2 mm on a white or transparent background. The corners of the squares were used to calibrate the measurements.

The more the distance between the sample and the scanner window is increased, the more the scale factor between X- and

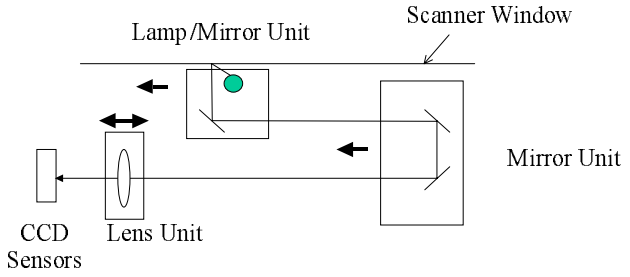

Fig.1. Arrangement of the optical components for the scanner EPSON 12000.

Y-axis is reduced. The dimension of the vertical axis does not depend on this separation distance, because the increments of the stepper motor are conserved during the scanning process. However, the dimension of the horizontal axis changes because the separation between the sample and the convergent lens increases. Figure 2 shows the scaling variation for increasing distances between the standard and the scanner window. The linear behavior is in agreement with the geometrical behavior of a convergent lens.

C. Uncertainty in the Measurements

The accuracy of the method for room temperature measurements was determined by measuring the distance between two points of the standard along the horizontal and the vertical scanning directions. Table 1 shows the obtained standard deviations for two different optical resolution scanners. In general the uncertainty in length decreases with the optical resolution of the scanner along the horizontal direction, while it depends on the characteristics of the stepper motor for vertical measurements.

The relative motion of the lens and mirror units for the scanner EPSON 12000 generates an uncertainty in length along the vertical scanning direction larger than expected. The static disposition of the detection system requires two different speed motors, for which the calibration of the relative motion is more complicated than for a single motor.

D. Experimental Setup

Figure 3 illustrates the different components of the device as they were designed to resist the direct addition of liquid nitrogen. Each component (i.e., quartz tray, height-adjustable shelf, scanner and outer chassis) has a well-defined function to assure the adequate thermal isolation of sensors and electronic components of the scanner.

Immediately after the addition of liquid nitrogen, heat is transmitted from the scanner to the tray in three different ways: conduction, radiation and convection. The adequate selection of materials and the correct disposition of the components reduce considerably the flux of energy. However, the large amount of energy involved during the cooling process makes it necessary to carry out all measurements before the whole system (tray, shelf and scanner) has reached thermal equilibrium.

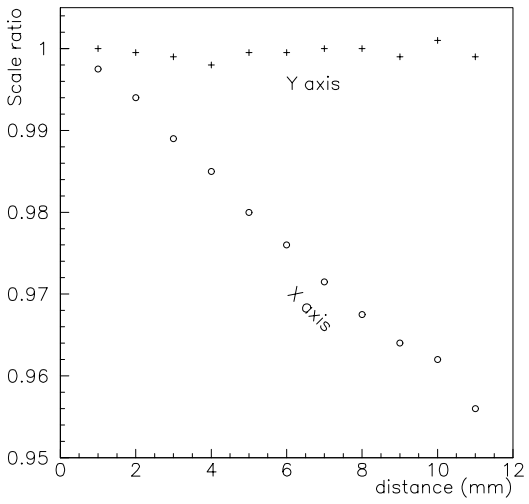

Fig. 2. Decrement of the horizontal scale of the scanned image for increasing distances between the scanner window and the sample

TABLE I
UNCERTAINTIES IN HORIZONTAL AND VERTICAL SCANNING DIRECTIONS FOR TWO DIFFERENT FLATBED SCANNERS

Uncertainties for room temperature measurements (Standard deviations for a length of 37.2 mm)	
EPSON 12000 (Optical resolution=800 spi)	
$\sigma_x = 0.015$ mm	$\sigma_y = 0.022$ mm
Simplex (Compeye) (Optical resolution=300 spi)	
$\sigma_x = 0.035$ mm	$\sigma_y = 0.025$ mm

The choice of quartz to build the tray is motivated by two reasons. First, the very low thermal expansion coefficient for quartz avoids it from breaking, when liquid nitrogen is added directly into the tray (another transparent material that resists the direct addition of liquid nitrogen is Pyrex). Second, the very low thermal diffusivity of quartz permits a considerable increase in the number of measurements before the scanner cools.

The height-adjustable shelf consists of a 5 mm thick frame of glass-fibre, which holds a 3 mm conventional glass window. To avoid glass window bending and the subsequent fracture, the dimensions of the glass window can only be a few centimeters larger than the quartz tray it is holding. Additionally, the 2 mm thick air chamber below the glass window reduces considerably the transmission of heat by conduction between the scanner and the sample. The use of glass instead of quartz is motivated because glass transitivity vanishes for infrared radiation of wavelength longer than 3 mm. This type of radiation is emitted by the scanner, which behaves like a blackbody at room temperature.

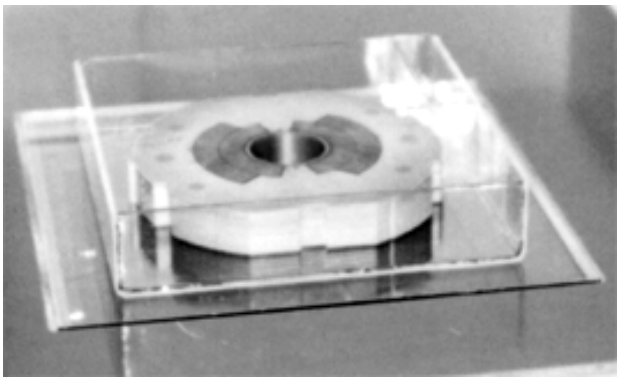

Fig. 3. Experimental set-up: a 5 cm-thick slice of a collared coil of a LHC short dipole prototype, inside the quartz tray, is placed on the glass window of the scanner (photo). The scheme of the device is shown in the drawn.

The cooling of the components inside the scanner is mainly caused by air convection. Fortunately, this cooling process is very slow for CCD sensors, and measurements can be carried out before reproducibility of the scanned images is affected.

III. Experiment

To measure the modifications in cable positioning due to thermal contraction, we used a 5 cm-thick slice of a collared coil used for the LHC short dipole prototypes. The slice was first placed in the quartz tray, and the image framed with a preview scanning. Afterwards, the magnet cross section was removed from the tray and the standard was scanned once with a resolution of 800 samples per inch (spi), conserving the scanning dimensions of the preview image. Then the magnet cross section was placed again into the tray and scanned at room temperature.

The cooling process of the sample down to 77 K was carried out in two steps. In the first step, the magnet cross section was cooled down to approximately 150 K by placing a polyethylene bag full of liquid nitrogen on the upper part of the collared coil slice. In such a way, the sample was cooled by conduction without affecting too much other components of the device. After 10 minutes, the bag was removed, and liquid nitrogen added into the tray. The magnet cross section was scanned when the liquid nitrogen stopped boiling.

The condensation of water in the inner face of the scanner window was the worst inconvenience for obtaining good quality images. However, a 2-mm-thick air chamber below the quartz tray delayed the condensation of water by about 10 minutes after the addition of liquid nitrogen into the tray.

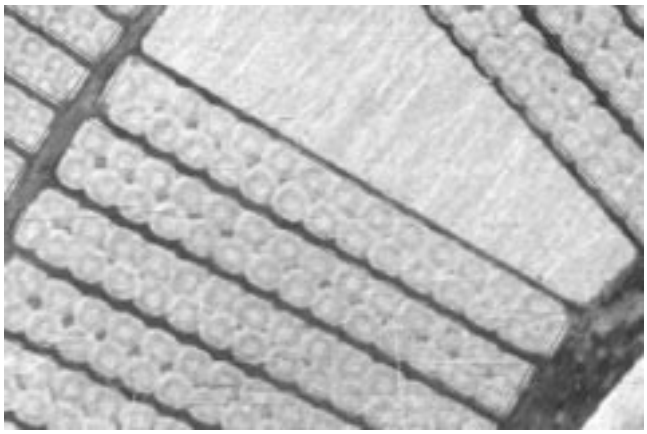

Fig. 4. Detail of the dipole cross section scanned at 77 K. The nominal positions of the conductors are plotted (thin lines) to evaluate the effect of coil deformations.

To measure the cable positioning on the scanned images we used the program AutoCAD [8]. Since the scanned images of the standard and of the magnet cross section (at room and liquid nitrogen temperatures) had identical size and resolutions, their comparison gave the real dimensions of the sample. The main routines of the program AutoCAD were then used to measure lengths, angles or the position of the points in the scanned images.

To determine the orientation of the magnet we applied least square fitting to the keystone vertex points at both sides of the horizontal symmetry axis of the magnet. The slope of the line gave the orientation angle. The position of the center of the magnet in the image reference frame was obtained by taking the geometrical center of all these points. Figure 4 includes a part of the scanned image of a dipole cross section at 77 K. We also developed some software to postprocess the obtained coil deformation to evaluate the effect on the field quality. An input file with the deformation of each conductors can be generated; these data can be used by ROXIE [9], a code developed at CERN for the evaluation of magnetic field in magnet cross sections. The nominal design of the magnet in the format of a ROXIE input file can also be superimposed to the scanned image to have a direct view of the effect of coil deformations.

IV. Conclusions

A simple and effective method of measuring cable positioning in magnet cross sections at room and liquid nitrogen temperatures has been described. The maximum uncertainty in length is estimated to be in the range between 10 and 30 μm for optical scanner resolutions larger than 800 spi, and sample scanning dimensions smaller than 100 x 100 mm.

The achievement of good quality scanned images for cold measurements required flatbed scanners of long optical interfaces between the sample and the lens. Also the arrangement of CCD sensors, far away from the scanner

window, facilitated the scale reproducibility of the scanned images.

The thermal isolation of the electronic components of the scanner considered the three possible ways of heat propagation: conduction, radiation and convection. The final arrangement of the device involved materials of low heat diffusivity (quartz), high resistance to the direct addition of liquid nitrogen (quartz), low transmission of radiation in the infrared region (glass) and low thermal conductivity (air chamber).

The correct scaling of the image along the horizontal and vertical scanning directions required one to make use of one two-coordinate standard. The standard characteristics were in agreement with the scanner optics. Therefore, thin lines were discarded. The boundary line between two complementary colors was more adequate for two-coordinate measurements with the scanner.

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