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Authors

van Oort, J M
Scanlan, R M
ten Kate, H H J

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Lawrence Berkeley Laboratory
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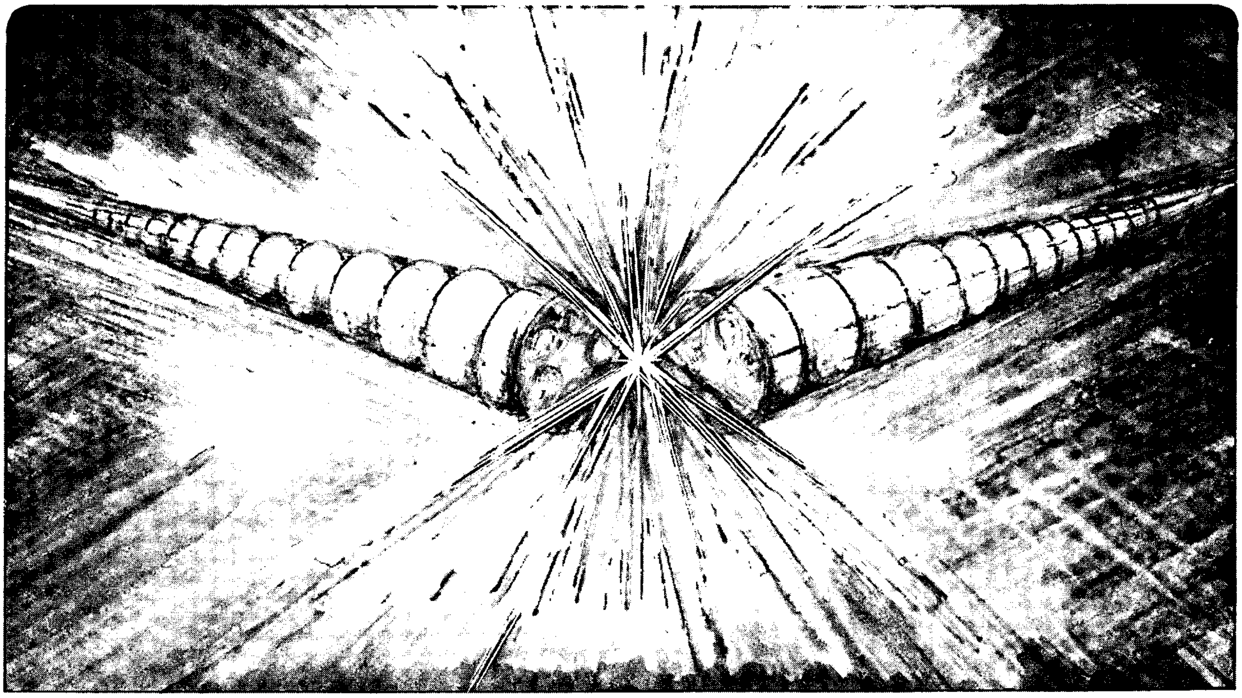

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A Fiber Optic Strain Measurement and Quench Localization for Use in Superconducting Accelerator Dipole Magnets*

Johannes M. van Oort and Ronald M. Scanlan
Lawrence Berkeley Laboratory
University of California
Berkeley, California

Herman H. J. ten Kate
Applied Superconductivity Center
University of Twente, Enschede The Netherlands

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A Fiber-Optic Strain Measurement and Quench Localization System for Use in Superconducting Accelerator Dipole Magnets

Johannes M. van Oort and Ronald M. Scanlan
Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley CA 94720, USA

Herman H. J. ten Kate
Applied Superconductivity Center, University of Twente, Enschede, The Netherlands

Abstract — **A novel fiber-optic measurement system for superconducting accelerator magnets is described. The principal component is an extrinsic Fabry-Perot interferometer to determine localized strain and stress in coil windings. The system can be used either as a sensitive relative strain measurement system or as an absolute strain detector. Combined, one can monitor the mechanical behaviour of the magnet system over time during construction, long time storage and operation. The sensing mechanism is described, together with various tests in laboratory environments. The test results of a multichannel test matrix to be incorporated first in the dummy coils and then in the final version of a 13T Nb_3Sn accelerator dipole magnet are presented. Finally, the possible use of this system as a quench localization system is proposed.**

I. INTRODUCTION

Fiber optic sensors have been used extensively in measurement of strain, temperature, pressure, magnetic field and electrical current over the past years [1],[2]. So far, no application of fiber optic strain sensors has been reported in accelerator type dipole magnets. This paper describes the use of a fiber optic strain measurement system [3] in a 13 T accelerator prototype dipole magnet "D20" currently under construction at LBL [4]. The fiber sensor system has many advantages over conventional electrical strain gauges, such as the absence of electromagnetic interference, high resolution and small size. Also, the sensor signal is not influenced by disturbances on the signal lines from the location of the probe in the cryostat to the detector outside.

Over the past years a readout system has been designed and optimized to provide for both high-speed high-resolution relative readout, and for an accurate absolute steady-state measurement of the local strain in the coil windings [5]. Both systems will be used simultaneously, and can be cross-calibrated against each other. This paper briefly describes the sensing scheme for both methods, and shows the need for accurate local strain measurements in the coil windings. Next, the results from the final test of the sensor matrix to be built into the cookie test -- i.e., a mechanical test of a short section of the coils -- and magnet windings are given. Finally, the possible use of this system to localize the origin of a quench is proposed.

II. THE EFPI SENSOR SYSTEM

An Extrinsic Fabry-Perot Interferometer (EFPI) [6] is constructed by positioning two optical fiber ends cleaved at 90° close to each other in a hollow tube, thereby forming an air cavity with length d, as shown in Fig. 1. When monochromatic light is fed in through the lead fiber, two reflections interfere at the detector. The intensity I measured is of the form

$$I = I_0 \cos\left(\frac{4\pi}{\lambda} d\right), \qquad (1)$$

with I_0 the maximum amplitude of the signal and λ the wavelength of the laser light. Using this scheme with a fixed wavelength, a relative readout as a function of the variable gap length is obtained.

When a broad-band light source, such as a super luminescent diode (SLED) or a halogen source is used, multiple wavelengths are interfering at the detector.

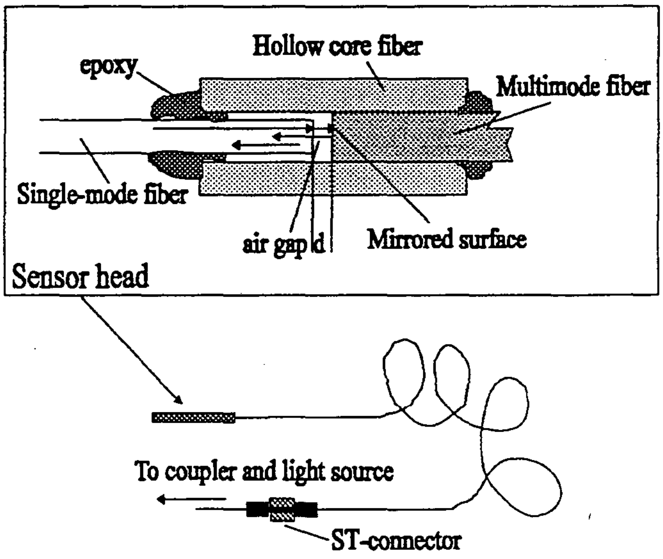

Fig.1. The EFPI sensor with its typical fiber-optic connection.

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Assuming the cell length d being constant (steady state), and looking at different wavelengths with a phase difference of π in the transfer function (1), an expression for the cell length of the following form is obtained,

$$d = \frac{\lambda_1 \lambda_2}{4(\lambda_1 - \lambda_2)}, \qquad (2)$$

in which λ_2 and λ_1 are the wavelengths corresponding to the subsequent maximum and minimum.

By capturing a spectrum of the reflected light that includes multiple maximums and minimums of the transfer function, an accurate determination of the cell length is made possible.

III. STRAIN MEASUREMENTS IN THE "D20" NB$_3$SN ACCELERATOR DIPOLE

One of the major considerations in the design of a Nb$_3$Sn accelerator dipole like "D20" is the strain under which the superconductor is placed. Since the current carrying capability of Nb$_3$Sn reduces with applied strain [7],[8], a thorough knowledge of the strain distribution in the coil windings is necessary. A compromise between the applied preload at room temperature, and the Lorentz load when the magnet is cooled down and energized has to be found. So far, no method of strain measurement has been incorporated in accelerator magnets to measure the local strain distribution and transverse pressure in the horizontal symmetry plane of a magnet. Since this is the area where the Lorentz loads will be the highest, it is important to know what the actual load on the conductor will be. A second argument is the study of stress gradients and spatial uniformity in order to make the comparison with ANSYS finite element analysis of the magnet mechanics in detail.

To monitor the strain in the 13 T dipole magnet D20, two independent strain measurement systems are incorporated in the design. The first system utilizes the conventional pressure transducers mounted in the pole pieces of the windings. This system is designed to measure the pressure on the outer windings of the four layers during assembly, wire winding, and operation of the magnet. It will also be used to correlate the readout of a set of electrical strain gauges mounted on the same transducers to the set of fiber optical strain gauges in it.

The second system is designed to measure the pressure gradient and strain in the radial and longitudinal direction, and is located in the horizontal symmetry plane of the windings, where the pressure will be greatest during operation. Allowing for measurements of the transverse pressure in this midplane, a gap of 0.8 mm has been left between the two halves of the magnet. This system consists of a sensor matrix that is put between the halves, with sensors measuring the strain in the longitudinal and radial direction, and a thin pressure transducer measuring the transverse pressure as a function of the radial distance from the bore. The transducer is designed to measure pressure up to 250 MPa with a resolution in the order of 5%. The optical strain gauges embedded directly in the matrix read the strain variations during operation, and are used to detect local temperature rise to localize a quench. The layout of the sensor matrix is shown in Fig. 2. Each sensor matrix has two transverse pressure transducers embedded to measure the pressure gradient over the coil winding in the radial direction. The transducers are made of stainless steel by wire EDM machining, and have the fiber sensors glued to them in small grooves.

The detection and data analysis system for the matrix readout is built around a liquid nitrogen cooled CCD-camera system mounted on a 0.5 m spectroscope with gratings from 600 grooves/mm to 2400 grooves/mm. The detector is coupled to a controller card with a digital optical fiber line, and controlled by a computer. The scanning speed and triggers are determined by software linked via GPIB-bus to the magnet power supply. In this way, strain can be determined as a function of the magnetic field, and the high speed relative sensors can be triggered by the electrical quench detection circuitry.

The optical fibers coming out of the magnet run from the cryostat to room temperature through a protected tube that terminates in a mechanical multiplexer. The CCD camera will read three absolute signals in parallel, and will have a maximum scan speed of the order of 1 Hz with the three channels read simultaneously. A schematic of the readout system is shown in Fig. 3.

The combined optical and electrical strain gauges built into the pole pieces are shown in Fig. 4. The sensing bridge is made of inconel 718, and has two sensing channels per block. Each channel has a full temperature compensated electrical strain gauge bridge mounted on it, with the fiber optic sensors mounted closeby. An additional fiber optic sensor is mounted to compensate for an offset in the temperature of the system.

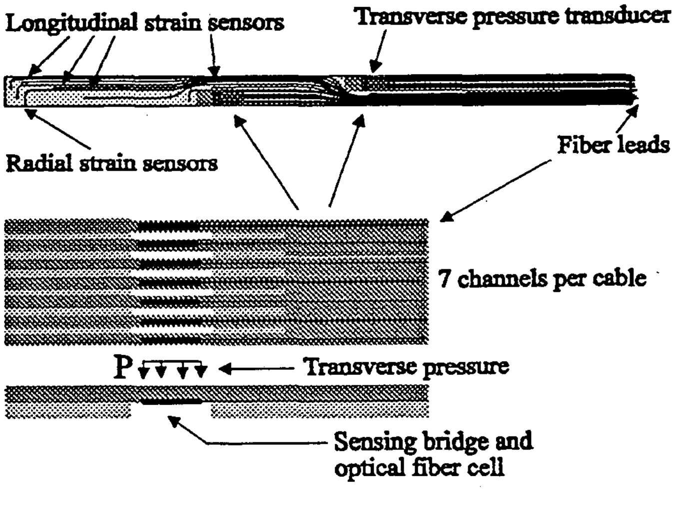

Fig.2. The sensor matrix and transverse pressure transducer.

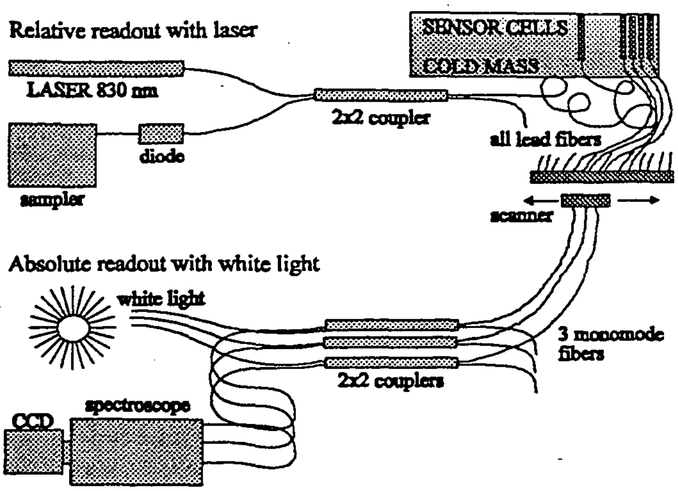

Fig.3. The setup for relative and absolute readout.

All electrical and optical leads are fed out vertically through the collar and yoke, and then led to the return end of the magnet. The protected tube with all leads is then routed to room temperature to the multiplexer block. The fibers for the absolute readout are interrupted in the multiplexer to allow for easy installation, and focused on the input fibers to the spectroscope with gradient index (GRIN) lenses. The fibers used with the laser system are connected with standard ST connectors to the laser box.

IV. TEST RESULTS OF THE MULTICHANNEL MATRIX

To test the viability of the sensor matrix in the magnet, a test matrix was made with ten fiber sensors embedded in a 0.6 mm glass fiber reinforced epoxy strip. The test matrix has a length of 30 cm, covers two cable widths of the outer layers, and uses one partially instrumented pressure transducer. The matrix is manufactured by a wet lay-up process using CTD-101 epoxy, and a subsequent heat treatment to cure the epoxy.

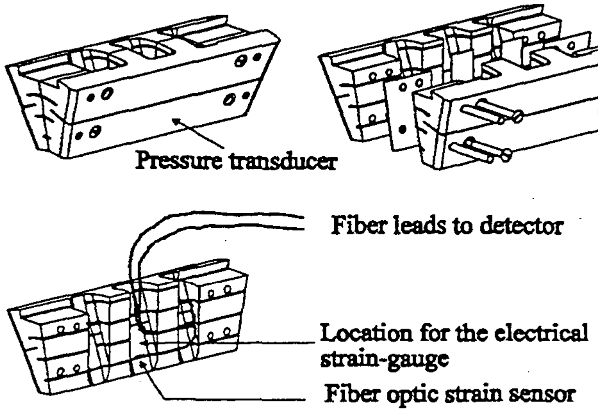

Fig.4. The combined optical and electrical strain gauge.

The matrix was tested at room temperature and at 77 K in liquid nitrogen, and has been cycled several times to assure it would not be damaged by rapid cool down. The CTD-101 epoxy is fairly well suited for cryogenic applications, although the difference in thermal contraction caused some minor cracks in the substrate at the corners of the stainless steel pressure transducer. The final sensor matrix for the magnet will be made of a slightly less stiff epoxy such as Stycast 2850FT or 1264.

The test matrix was cycled several times from 0 to 45 MPa, and next from 0 to 200 MPa (the maximum limit of the test equipment in the current configuration). No problems were observed in signal degradation or damage to the composite. The test results are shown in Fig. 5. A slight hysteresis was present in the initial cycle, which diminished in the subsequent cycles. After calibration, the resolution of the system is in the order of about 5 MPa.

V. USE OF THE MATRIX FOR QUENCH LOCALIZATION

One possible application of the fiber sensor matrix located in the horizontal symmetry plane of the dipole magnet is the localization of a quench. Whenever a quench occurs in or near the midplane, the localized thermal disturbance will be detected first by the closest fiber sensor, and subsequently by the next sensors in the matrix. This allows for extrapolation to the initial disturbance. The accuracy and response time of the system depend on the thermal properties of the material in which the sensor is embedded. In the case of the dipole magnet D20 the sensor matrix is constructed with epoxy-impregnated S2-glass fiber tape. The thermal expansion coefficient of the matrix is in the order of 6×10^{-6} K^{-1} around 4.2 K and rises to 2×10^{-5} K^{-1} at room temperature. Fig. 6 shows the calculated rise in temperature of the hot spot versus time from the quench initiation, assuming adiabatic heating of the windings.

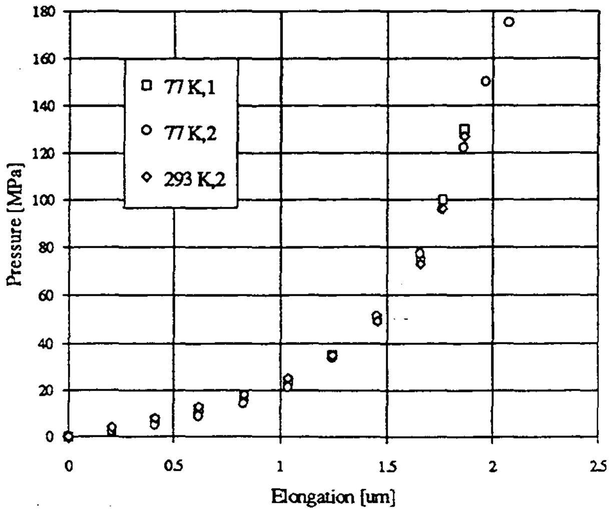

Fig.5. Measured pressure as a function of gap elongation.

The electrical quench-detection system will typically trip at 0.25 V to 0.50 V (this depends on the set point of the quench detector), with corresponding delays of 30 ms to 40 ms after initiation. With a cable current at full field of 6000 A, the temperature at 30 ms will be about 45 K in the inner layer and about 65 K in the outer layer [9]. At 40 ms these values will be 65 K and 85 K respectively. With an integral thermal expansion from 4.2 K of 2×10^{-4} at 45 K, 3.5×10^{-4} at 65 K and 5×10^{-4} at 85 K, the expansion of the fiber optic sensor cell with a length of 10 mm ranges from 2 mm to 5 mm. The minimum resolution of the fiber sensor system is in the order of 100 nm, thus a quench should be detected within the same time-resolution as with the electrical detection. With the current mechanical multiplexer controlling the fibers being monitored, the amount of channels available for immediate readout in the event of a quench is limited to three. In the initial tests the quench localization capability will only be used in the longitudinal direction of the coil windings.

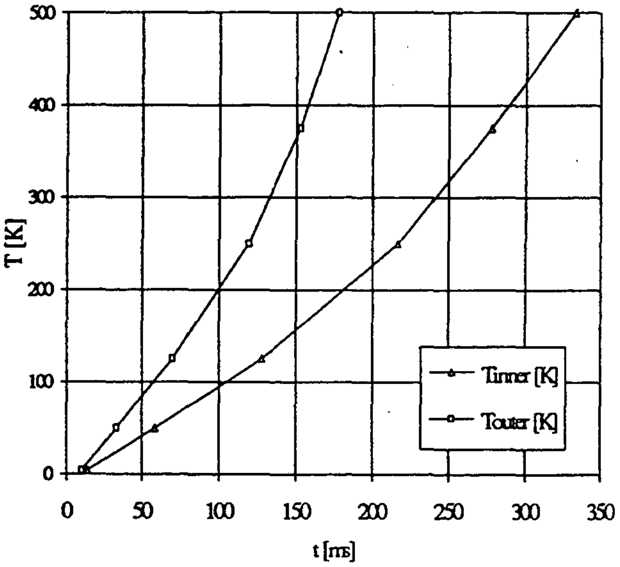

Fig.6. Local temperature rise of the hot spot after a quench.

VI. CONCLUSIONS

The ability of the fiber optic sensor system to survive in a cryogenic environment under high pressure has been demonstrated. The feasibility of the construction method by using a wet layup epoxy impregnated glass cloth for the sensor matrix for the midplane has been proven. The sensors can be used to monitor the stress and strain in the coil structure during manufacturing, cool down and testing.

The sensitivity of the fiber optic sensors for absolute readout is in the order of 50 - 100 nm, which yields a strain resolution of the order of 10×10^{-6} in the longitudinal and radial direction. The pressure resolution in the transverse direction is in the order of 5 MPa.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL AND ELECTRONIC
INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720