

FIBER BRAGG OPTICAL SENSORS FOR YBCO APPLICATIONS

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Abstract

Magnetic confinement fusion reactors (tokamaks) require the development of magnets capable of generating large fields under stringent structural constraints. High temperature superconducting magnets which are well suited to this application are however vulnerable to quench occurrence during operation. Temperature and strain sensors based on fiber optics are being developed as a countermeasure to this contingency. Optical fibers with Bragg gratings are amenable to embedding within superconducting magnets to monitor temperature, strain, irradiation, and to detect quench occurrence. In a length of YBCO tape where quench propagation velocities are slow, we show that it is possible to detect the event occurrence using fiber optic sensors even with a sampling rate as low as 1 Hz. This preliminary result demonstrates the feasibility of using fiber optic sensors to monitor the temperature and strain condition along the length within a coil. These sensors could be used to provide feedback to or trigger magnet protection systems. This would be an invaluable method for mitigating damage to superconducting magnets and increasing up-time for reactors.

INTRODUCTION

In the ongoing quest to develop novel and advanced energy sources to meet the needs of 21st century population and industrial growth, nuclear fusion in tokamak reactors is considered a viable option to supplement or replace nuclear fission reactors as well as generators which use fossil fuels. Knowledge gleaned from experiments with the now decommissioned Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory and other such laboratories in the United States and around the world has led to the construction of the International Thermonuclear Experimental Reactor (ITER). This project is at the forefront of research in the development of fusion technology and is the result of an international collaboration among several countries including those of the European Union (EU), India, Japan, People's Republic of China, Russia, South Korea, and the USA.

Tokamak fusion reactors require magnets capable of generating large fields while being compact and lightweight to meet the structural considerations of reactor configuration. High temperature superconducting magnets satisfy this requirement but are susceptible to quench occurrences during operation. Temperature, strain, and radiation sensors based on optical fibers with Bragg gratings are being developed to monitor the condition of the superconductor and detect quenches when they occur.

This work is focused on determining whether or not

fiber optic sensors have the sensitivity, response time, and sampling rate to effectively detect quench occurrence and propagation in high temperature superconducting magnets. Here, we show that for a length of YBCO tape, it is possible to detect the occurrence of a thermally induced quench using fiber optic temperature and strain sensors. This result demonstrates the viability of using fiber optic sensors to monitor the temperature and strain along the length of a coil as a part of a fully integrated magnet protection system.

EXPERIMENT

A 100 mm long sample of YBCO tape supplied by American Superconductor (AMSC) was mounted between current leads on the cold head of a cryocooler as shown in figure 1. The sample was outfitted with a linear array of thermocouples mounted with Stycast 2850 FT epoxy at a spacing of 10 mm. Voltage leads were attached in order to measure the change in voltage over segments of the sample length. A Micron Optics os4200 FBG temperature probe and an os3200 FBG strain gauge were fixed with Loctite Hysol® 1C-LV epoxy symmetric about a ~2 ohm wire-wound resistive heater located at the center of the sample length. These fiber optic (FO) sensors were attached on the bottom of the sample due to the shortage of space among the thermocouple junctions and voltage leads on the top of the sample. No other resistive strain gauges were attached due to the lack of space on the sample.

A vacuum chamber base pressure of 6.3×10^{-7} mbar was achieved with a Pfeiffer Vacuum turbo pump and a model HC-4 MK2-1 SHI-APD Cryogenics helium compressor was used to achieve a minimum temperature of 18 K. No external magnetic field was used in this experiment.

Initial measurements of the critical current (I_C) were performed at 20 K and found to be over 300 A. A temperature of 65 K was chosen to suppress the critical current in order to avoid damage to the YBCO sample during quench. The critical current I_C at 65 K was 240 A and the operating point for the quench measurement was set at 150 A. I_C was determined with an electric field E criterion of $5.0E-6$ V/cm. The electric fields were obtained from section voltages divided by their section lengths respectively.

A series of quench tests were performed while successively increasing the pulse voltage from 1 V to 10 V in increments of 1 V until a quench was observed. A KEPCO BOP power supply was used to generate a 300 ms long heat pulse at the center of the sample. It was assumed, based on previous results, that in a homogeneous sample the propagation of the heat pulse and resulting quench would be symmetric about the center

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of the sample length. The critical current was re-measured after each quench to check for degradation of the superconductor.

A 1 Hz sm125 Micron Optics fiber optic interrogator was used to record the peak wavelength of the temperature and strain sensors during the generation and propagation of the heat pulse. The theory of operation of the fiber Bragg grating sensors can be found in references [[1], [2], [3], [4], [5]].

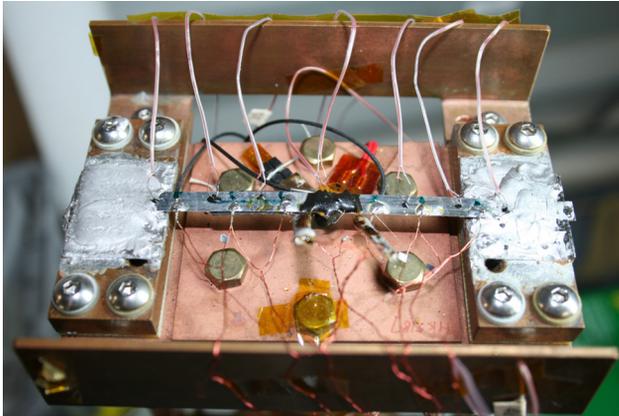


Figure 1: YBCO tape wired for temperature, strain and voltage measurement.

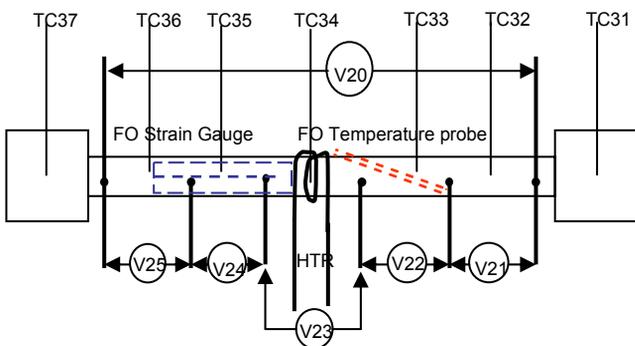


Figure 2: Schematic showing thermocouple locations and voltage leads relative to the heater in the middle of the YBCO sample. Dashed lines indicate the locations of the fiber optic strain (left) and temperature (right) sensors.

RESULTS

Figure 3 (a) shows the evolution of the heat pulse with the maximum response recorded by the thermocouple located closest to the heater. The temperature increase is progressively lower as the location of successive thermocouples increases from the center of the sample. Part (b) shows the voltage increase in the sample as the thermally induced quench was initiated and propagated through the sample. The largest increase occurred at the mid-section of the sample which was hottest. The sharp increase in voltage follows the sharp increase in temperature to its peak and subsequent dissipation. The sample length segments that are located away from the middle show less significant increases in temperature.

The peak wavelength shift for the temperature probe and strain gauge are shown in figure 4. The increase in these peak wavelengths also tracks the temperature increase and subsequent voltage increase. The data shown in figures 3 and 4 are typical of the data recorded during several observations of the heat induced quench in this experiment.

Noise in the fiber optic temperature data (fig. 4(a)) may be due to loosened contact between the probe and the YBCO tape sample after several pulses.

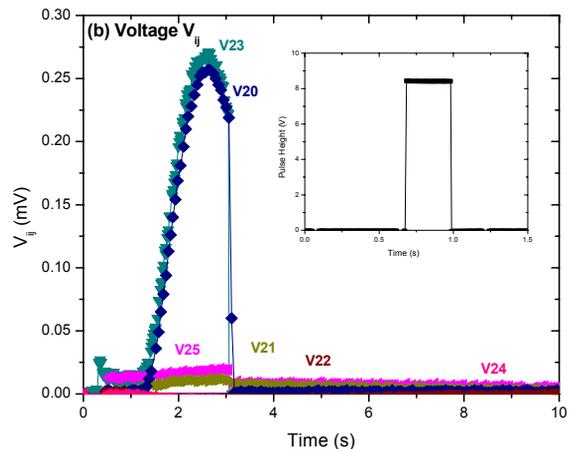
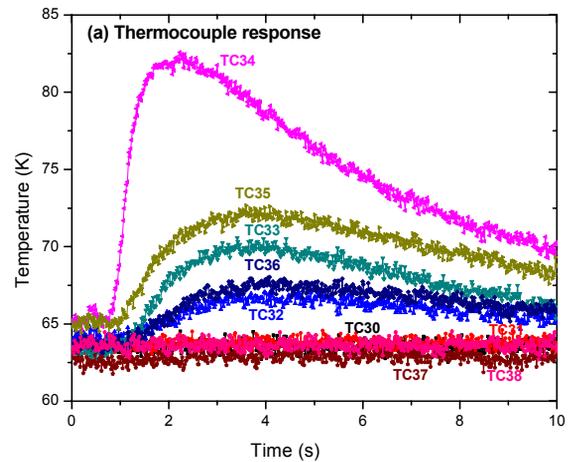


Figure 3: (a) Heat pulse propagation recorded by thermocouple array (b) quench indicated by voltage increase in the YBCO sample. The inset shows the 8.5V, 300ms pulse which initiates the quench.

DISCUSSION

The relationship between the optically measured temperature change ΔT and the wavelength change $\Delta \lambda$ for the Micron Optics os4200 probe is estimated by the equation :

$$\Delta T = \frac{\Delta \lambda_{Temp}}{S_T} \tag{1}$$

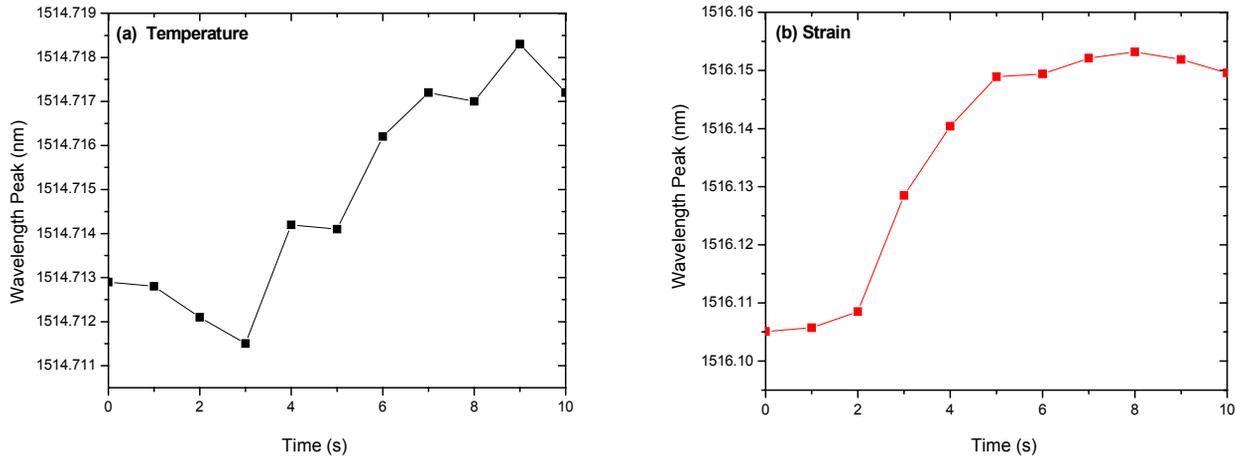


Figure 4: Shift of wavelength peak of (a) temperature and (b) strain sensors during the quench presented in Figure 3.

where S_T is the temperature sensitivity for the probe derived from calibration. S_T had a value of 2.36 pm/K for the probe used in this experiment giving a change in temperature of 2.5 K as compared to 6.7 K for thermocouple TC33. The difference between these two values maybe due to the fact that even though the two sensors are located at the same distance from the heater as shown in the schematic (Fig. 2), the FO sensor is on the bottom of the sample whereas the thermocouple is attached on top. Due to the specific architecture of YBCO coated conductor, electric and thermal properties are asymmetrical across the sample thickness, resulting in different electrical and thermal sensitivity between its top and bottom. The FO sensor has more spatial distribution than the thermocouple. The different thermal conductivities of Loctite Hysol® for the FO probe and Stycast 2850FT for the thermocouple may also have played a role in the final result.

The local strain measured optically during the quench is derived from equations 2 and 3.

$$\varepsilon = \left(10^6 \mu\text{m} / \text{m}\right) \frac{\Delta\lambda / \lambda_0}{F_G} - \varepsilon_{TO} \quad (2)$$

$$\varepsilon_{TO} = \Delta T \left[\frac{C_1}{F_G} + CTE_{YBCO} - C_2 \right] \quad (3)$$

The constants C_1 , C_2 , F_G , and CTE are obtained from Micron Optics data sheets and published data on YBCO [[4], [6]]. The change in strain measured by the FO strain gauge was -100.7 $\mu\text{m}/\text{m}$. There was no electronic strain measurement for comparison because of limited space on the YBCO sample.

CONCLUSIONS

This work clearly demonstrates the proof of principle that FO sensors can be effective for detecting quench

Instrumentation

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events in HTS magnet applications. We have shown that for a length of YBCO tape, it is possible to detect the occurrence of a thermally induced quench using fiber optic temperature and strain sensors below liquid nitrogen temperature. These results support the testing of a coil in the next phase of experiments. A higher sampling rate is recommended for the fiber optic interrogator to optimize data acquisition rate and feedback for triggering of magnet protection apparatus.

ACKNOWLEDGEMENTS

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