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Strain response of superconducting magnets during excitation and quench training based on polymer-FBG and cryogenic strain gauge measurements

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Background

Intense magnetic field and current of superconducting magnet can induce intense and nonuniform stress in coils that may initiate the quench during operation, it is essential to study that mechanical behavior of superconducting coil and support structure as the magnet is energized. Currently, the conventional resistance strain gauge(RSG) and optical fiber Bragg gratings (FBGs) were usually used to investigate strain induced by Lorentz force or cooling, or detect a quenching for a LTS or HTS. Unfortunately, FBGs with hard package or bare FBGs both have very fragile mechanical performance at cryogenic temperature, so it's necessary to improve mechanical property of FBGs at cryogenic environment, then, to develop the double strain measurements system(FBGs + RSG) monitoring the strains of the on-line superconducting magnets.

Objective

This paper presents an approach to monitoring the strain response of two different LTS magnets during excitation and quench training using homemade polymer-FBGs which can enhance mechanical properties of FBGs at cryogenic environment(4.2K). For the purpose of comparison, conventional resistance strain gauges(RSG) were also used to monitor their electromagnetic strains, the steady-state strains of the superconducting magnets were also valuated by means of a FEM.

Conclusion

- We studied the strain response of two superconducting magnets with different LTS materials and configurations based on homemade polymer-FBGs and conventional RSG strain measurement methods during excitation and quench, and numerical analysis of the strain fields was also carried out in the two LTS magnets based on FEM.
- These measurements show that polymer-FBGs strain sensors embedded within the magnet structure exhibit better stability and reproducibility at cryogenic environment(4.2K) and intense magnetic field, and also reveal more attractions like smaller size, immunity to electromagnetic interferences, non circuits compensation and sensing performance of internal strain measurments.
- The quench feature can be also detected with observations of abrupt strain pulse when a quench occurs based on polymer-FBG and conventional RSG measure methods, and the abrupt strain pulse was detected by polymer-FBGs was earlier than conventional RSG, and exerts better reliability and stability than conventional RSG during quench occurs.

Strain measurement methods

Resistance strain gauges(RSG)

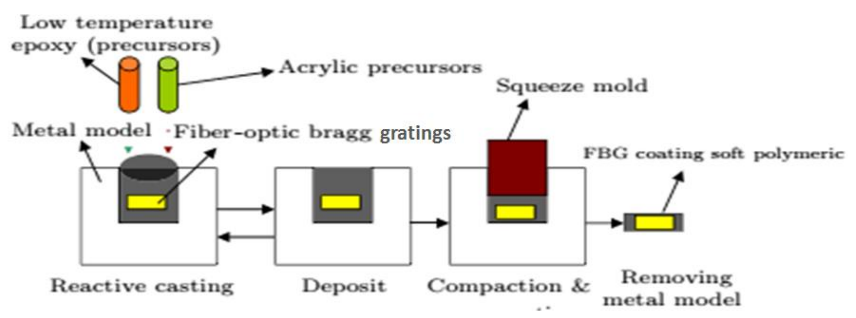
Resistance strain gauges(RSG)

RSG(KFL series, 4mm × 2.7mm, 120Ω, KYOWA produced) with half wheatstone compensation bridge circuit. It's a conventional method to detect strain of superconducting magnet.

Wireless strain acquisition

Wireless strain acquisition with communication protocol IEEE802.15.4 and maximum transmission rate 250Kbps in air was used to connect the resistance strain gauge(RSG).

Polymer- optical fiber Bragg gratings(Polymer-FBGs)



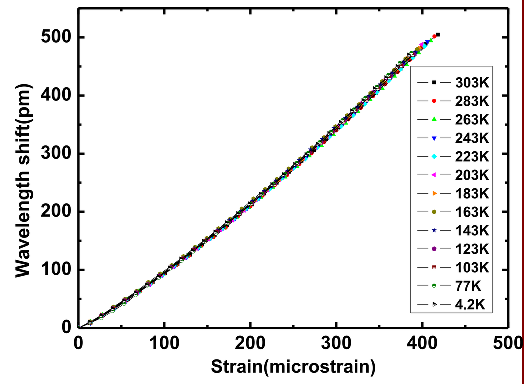
Processes of homemade polymer-FBGs

Polymer-FBGs

Interrogation system (Optical System200)

Experiment calibration for polymer-FBGs strain sensors:

A polymer-FBGs was attached on a copper plate, then, Tensile load was applied to the copper plate at different constant temperature.

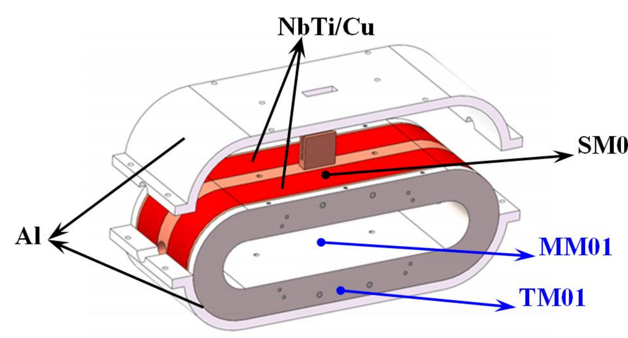


Wavelength shift of the polymer-FBGs versus applied strain

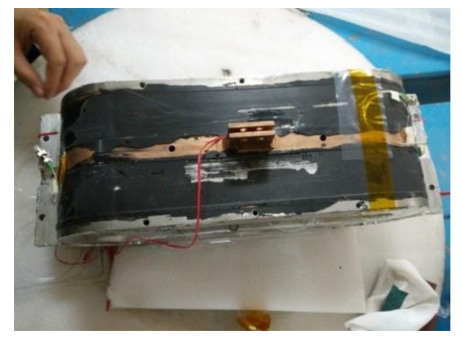
- The FBGs with polymer coating can enhance mechanical properties at cryogenic environment(4.2K).
- The wavelength shift showed good linear dependence on the applied strain, and the strain sensitivity of the polymer-FBGs is temperature independent.

Two different LTS magnets

NbTi/Cu racetrack superconducting magnet



Magnet structure and locations of sensors

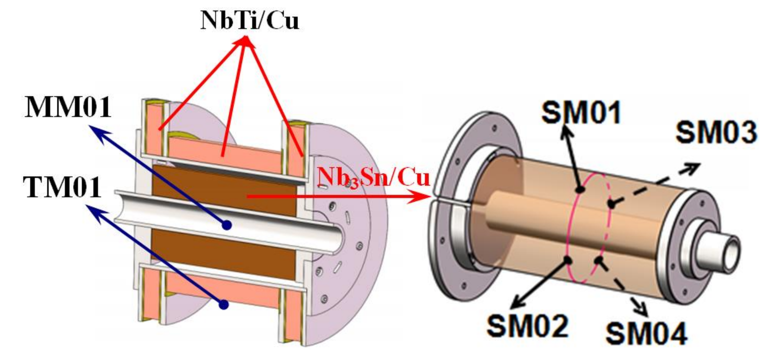


Magnet real structure and strain sensors attachment

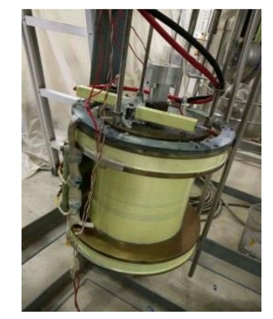
Maximum central magnetic field is 3.25T. MM01 , TM01 and SM01 are Hall sensor, temperature sensor and strain sensor, respectively.

Polymer-FBGs and RSG as strain sensors were embedded within the overbanding structure and attached onto the surface of coil.

Hybrid superconducting solenoid($NbTi/Cu+Nb_3Sn/Cu$)



Magnet structure and locations of sensors



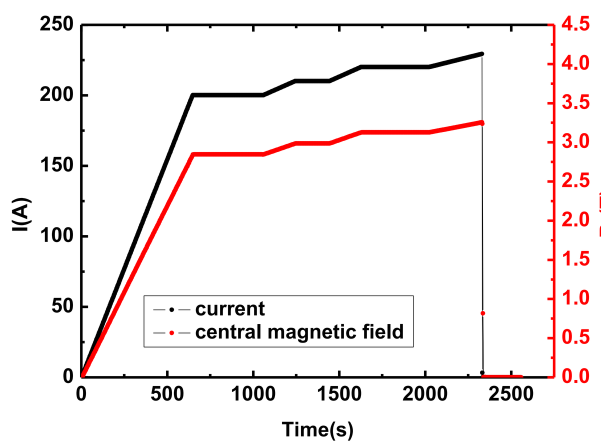
Magnet real structure

The hybrid superconducting magnet with field up to 10T was designed and fabricated, consisting of Nb_3Sn/Cu and NbTi/Cu concentric solenoids.

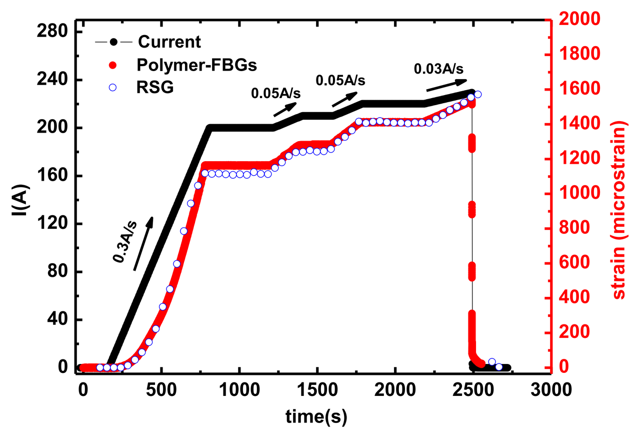
Four distributed polymer-FBGs labeled SM01~SM04 were attached on the surface of Nb3Sn/Cu solenoid to detect hoop strain of the central Nb3Sn/Cu solenoid.

Results

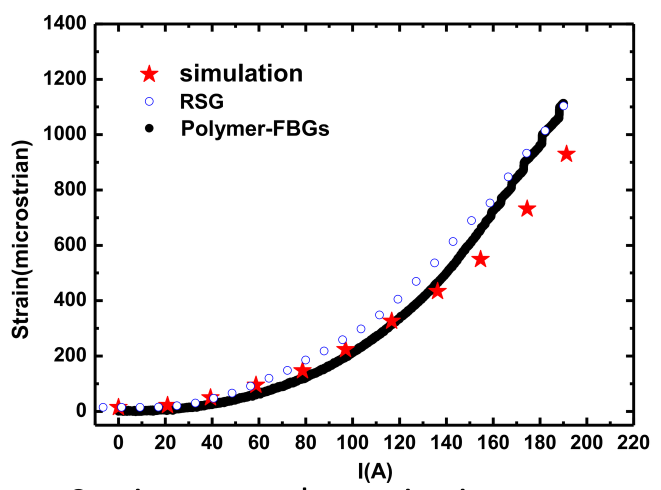
NbTi/Cu racetrack superconducting magnet



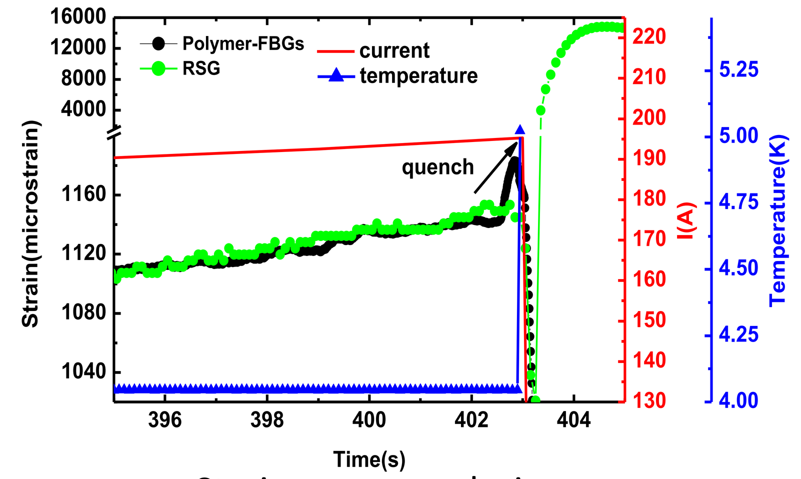
Current and central magnetic field during excitation and quench



Strain response of the superconducting magnet during excitation and quench



Strain versus the excitation current of the superconducting magnet

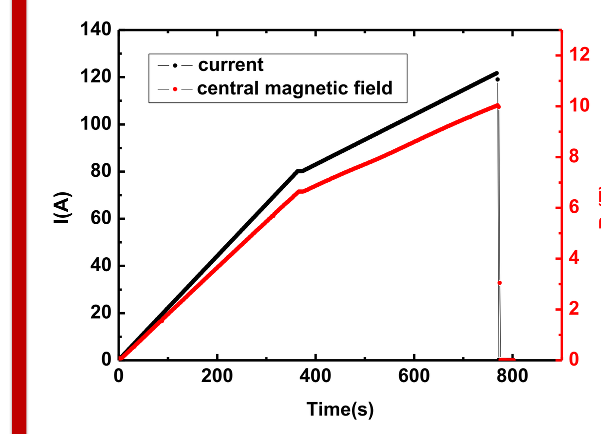


Strain response during excitation, pre-quench and post-quench

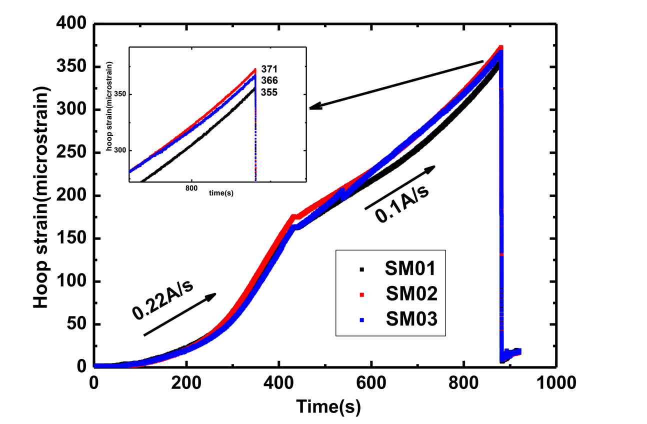
- The superconducting magnet is charged from 0A to 230A until the coils spontaneous quenched, the central magnetic field of 3.25T was achieved .
- The strain increases to a value of about 1510με with the transport current reaches to 230A until a quench occurs.
- The strain results of Polymer-FBGs agree well with conventional RSG, and the histories of the strain and applied current are almost synchronous.

- In comparison with the results of Polymer-FBGs and RSG have better agreements with the numerical results.
- Polymer-FBGs exhibits an abrupt strain pulse before of quench occurs, but the abrupt strain pulse of RSG almost simultaneously occurs with quench, and exhibits an undesired outcome that appeared much larger abrupt strain pulse after quench.
- Polymer-FBGs as a strain sensor also able to detect the quench of superconducting coil the same as conventional RSG, and have better reliability and stability.

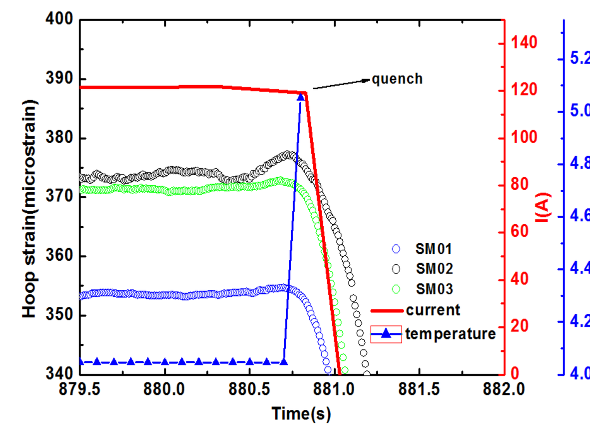
Hybrid superconducting solenoid($NbTi/Cu+Nb_3Sn/Cu$)



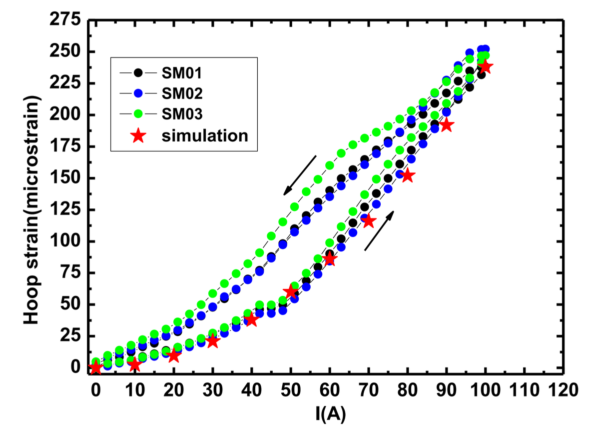
Current and central magnetic field during excitation and quench



The hoop strain of the superconducting solenoid during excitation and quench



Strain response during excitation, pre-quench and post-quench



Hoop strain versus loading and unloading transport current

- The spontaneous quench occurs at magnetic filed of 10T, the corresponding excitation current reaches to 122A.
- Hoop strain of each location is almost the same, and the maximum strain is 371με, 366με, 355με, respectively. Then, hoop strain abruptly reduces to about 0 after quench occurs.
- It's indicated that the Polymer-FBGs have good stability and reproducibility at cryogenic environment(4.2K) and intense magnetic field.

- The small oscillations on the strains are observed by using embedded polymer-FBGs with low acquisition rate at different locations during a pre-quenching.
- The results of hoop strain are almost same at the different locations of the circumference of the solenoid , and they are resonable agree with the FEM simulation during excitation. Since the turn-to-turn friction was restrained during unloading transport current in the SC coils, the hoop strain during unloading transport current is larger than during loading transport current.

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