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Quench detection via Rayleigh scattering - based fiber optic distributed sensors

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Background

High temperature superconductors (HTS) are the most promising solution for the new generation of superconducting magnets (SM)

Quench: can be caused by thermal perturbations that result in a run-away condition that leads to loss of SC and return to a resistive (normal) state.

Problem:
slow normal zone propagation in HTS → voltage measurement not the best detection method → presents challenge for time effective, reliable detection.

Proposed solution:
Direct sensing of normal zones achieved by co-winding an optical fiber with HTS conductor → very high spatial resolution (potentially sub-mm) and fast measurement to quickly identify, locate and monitor multiple normal zones in a coil

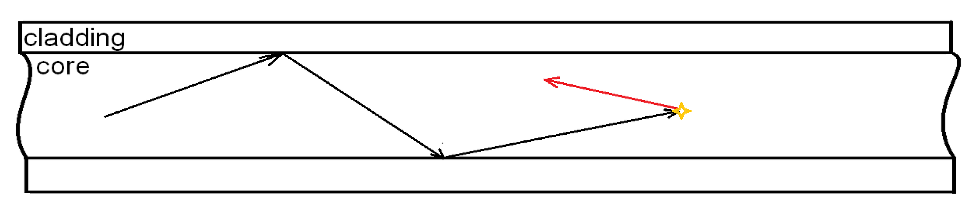
Objectives

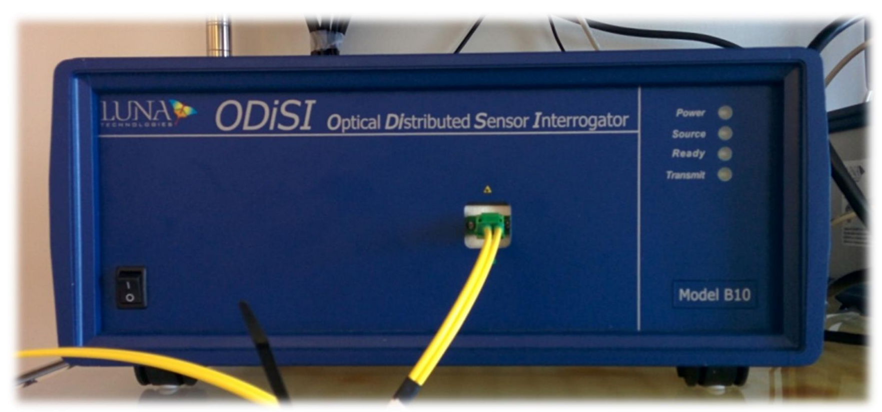
- Investigation of a quench detection system for HTS based on optical sensing for quickly providing reliable information needed to ensure protection.
- Obtaining a fiber-tape mechanical and thermal coupling sufficient to generate a clear spectral shift signal
- Prove the correlation between spectral shift and normal zones

Fiber optic (FO) distributed sensing: how it works

- Distributed sensor: telecommunication grade optical fiber
- Measured quantity: *spectral shift* - unique profile combining temperature and strain; represents the deviation between a measurement and a reference condition.
- Spectral shift measurement is based on *Rayleigh backscattering* spectra (measurement and reference) and includes heavy numerical computations
- Optical Distributed Sensor Interrogator (ODiSI) from LUNA Inc. used for interrogation returns spectral shift as a function of fiber length.
- Potentially sub-mm spatial resolution and high scan rate (scanning time depends on fiber length)
- Optical fiber is co-wound with the conductor allowing distributed sensing

Rayleigh backscattering in optical fibers



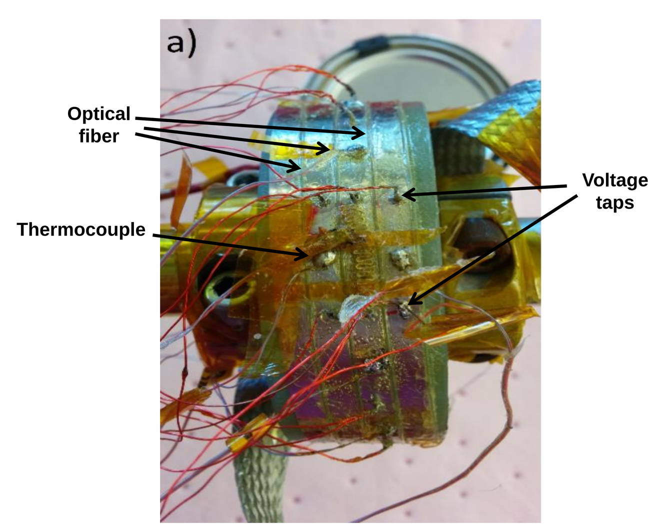


Advantages of FO detection system over conventional voltage - based

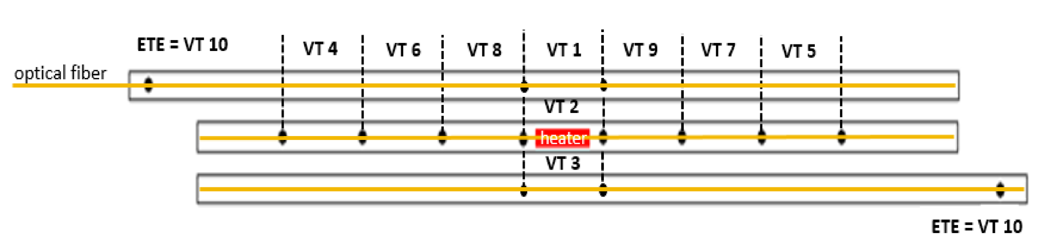
- Voltage is measured over large distance; due to low normal zone propagation velocity (NZPV), by the time the voltage becomes higher than the threshold a temperature peak at an hotspot may have irreversibly damaged the conductor.
- FO system able to detect any thermal perturbation sooner since voltage increases only if and when $T>T_{cs}$
- FO system able to locate hotspot, contrary to voltage based due to long voltage taps
- FO measurement not affected by electromagnetic noise (no cross-talk coming from any time-varying magnetic field (other magnets or plasma in a tokamak)

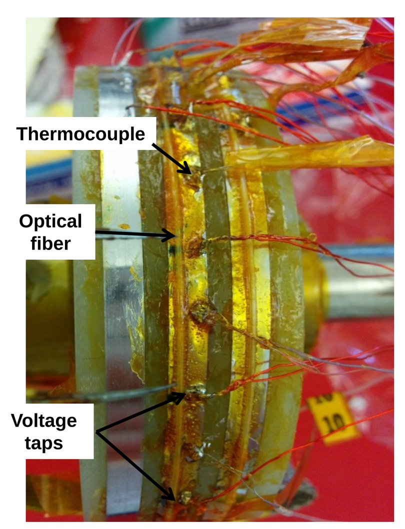
Coils

- Different HTS coils fabricated adopting different optical fiber - conductor integration configurations
- All coils instrumented with voltage taps, thermocouples, optical fiber and an embedded heater to produce a thermal perturbation
- All coils use AMSC Bi2223 tape, wound on a G-10 coil former. No epoxy impregnation

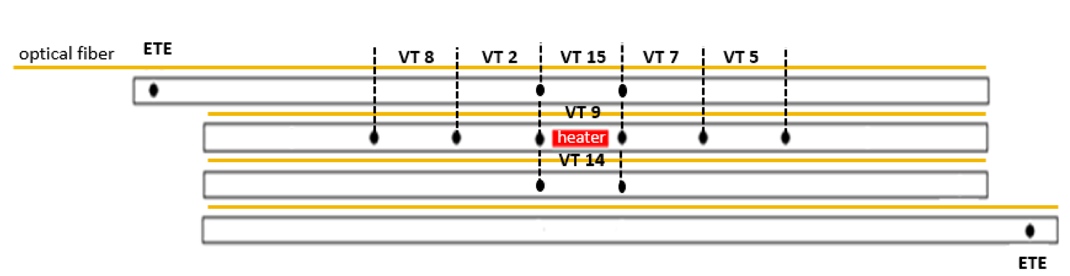


The optical fiber is attached on top of the superconducting tape, with GE Varnish.





The optical fiber runs next to the conductor, acting also as a turn to turn insulation.

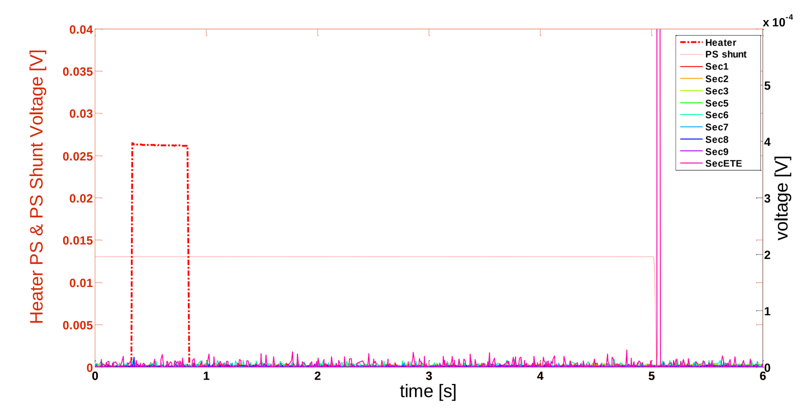


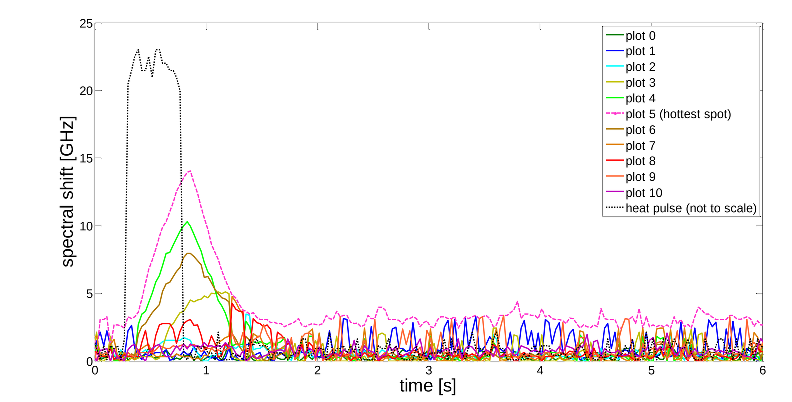
Results

Quench tests at 77 K, self magnetic field:
A perturbation is induced by means of an embedded heater aiming at producing a transition to the normal state (recovery or quench). The novel and conventional detection systems are run at the same time to detect normal zones. Voltage (by VTs), temperature (by TCs) and spectral shift (by OF) are measured

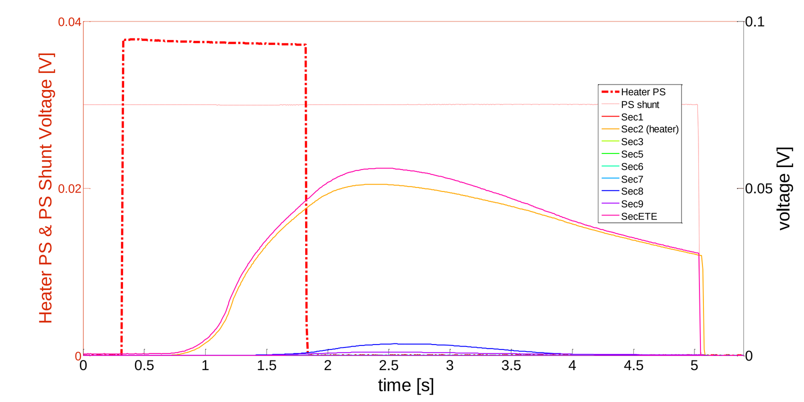
COIL WITH FIBER ATOP THE CONDUCTOR

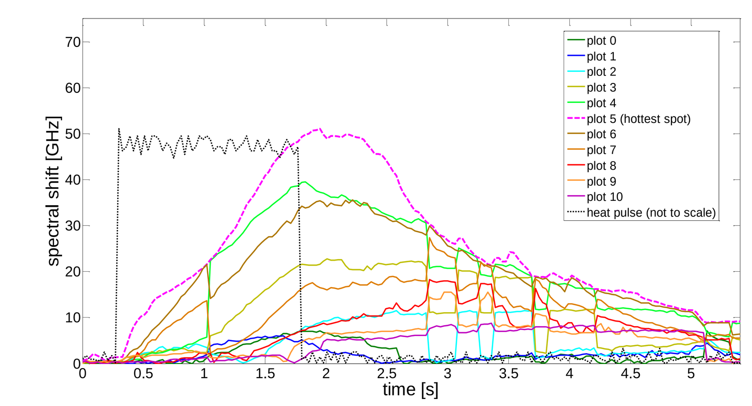
Weak disturbance – fiber optic system more sensitive than conventional one





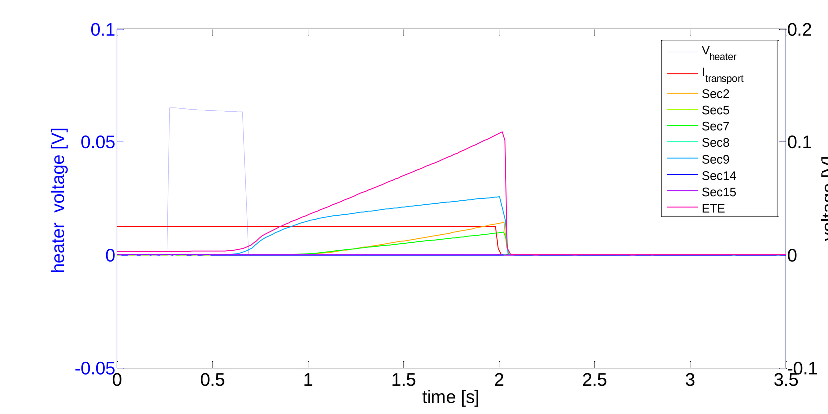
Perturbation leads to a recovery

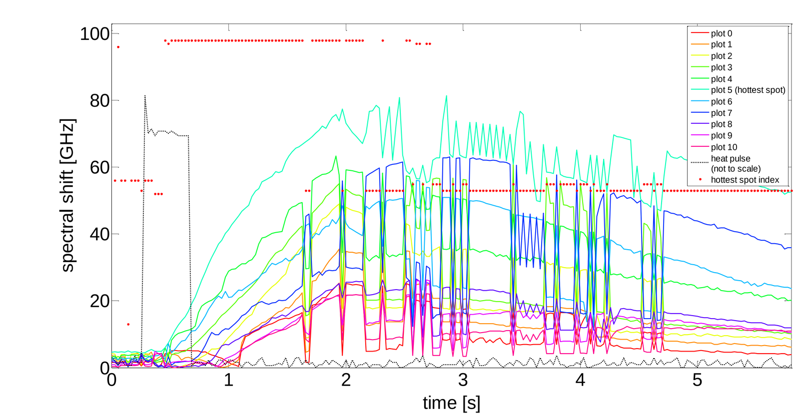


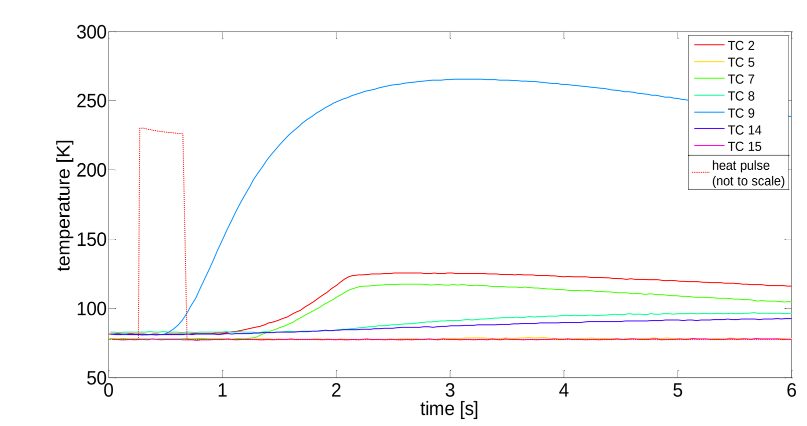


COIL WITH FIBER BESIDE THE CONDUCTOR

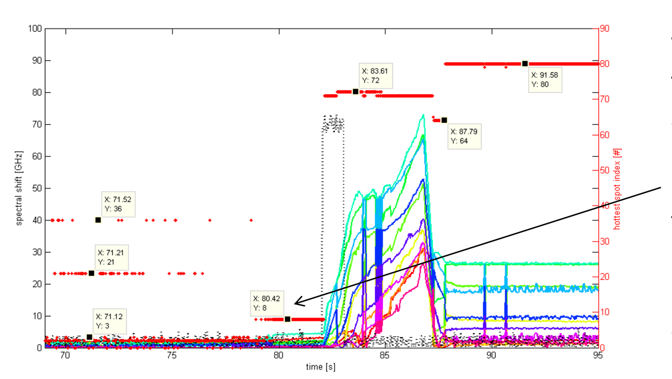
Perturbation leads to a quench



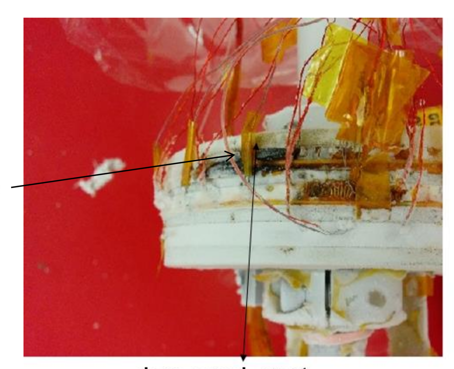




The position of a deteriorated spot on the conductor identified correctly

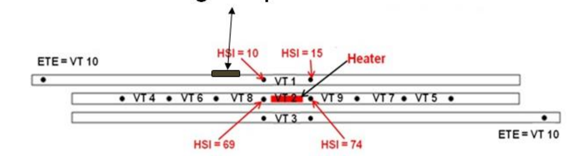


The location of the maximum spectral shift (HSI) stabilized at the spot where the tape will break overnight after several successive tests



damaged spot

Hottest spot index (HSI): position along the fiber that experienced the highest spectral shift



Summary

- Spectral shift highly related to normal zones
- Fiber optic distributed sensing correlates normal zones with the location on HTS coil
- Fast measurement (30 ms) of ~1.3 m long fiber and 0.5 cm spatial resolution
- Fiber integration provided the system with sufficiently high sensitivity @ 77 K

Conclusions

- Spectral shift signal proved to be sufficiently clear to identify and locate normal zones
- Appropriate combination of spatial and temporal resolutions allowed for a fast detection of normal zones
- Spectral shift correlated to development of normal zones makes it a perfect candidate for quench detection

VIII. Ongoing and Future Work

- Improve fiber integration
- Maximize winding packing density
- Investigation of processor landscape best suited for large data volume RT computing
- Scale up to larger superconducting systems

Acknowledgements

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