Quench detection via Rayleigh backscattering interrogated optical fibers (RIOF)

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Outline

- Why quench in HTS is a challenge
- Rayleigh backscattering vs other optical fiber sensors
- Fiber integration techniques
- Our prior work
- More recent results
  - Coils with co-wound fiber
  - Smart REBCO conductor

Quench detection in HTS

- Slow normal zone propagation → formation of hot spots
- Difficult to detect hot spots before material degradation
- Inductive noise (especially in nuclear fusion reactors and AC applications)

Rayleigh scattering Interrogated Optical Fibers (RIOF) a candidate solution:

- Can be integrated into coils in many ways
- Strong and flexible
- Capable of high spatial resolution
- Immune to electromagnetic noise
- Continuous distributed sensing of temperature and strain

Why Rayleigh scattering?

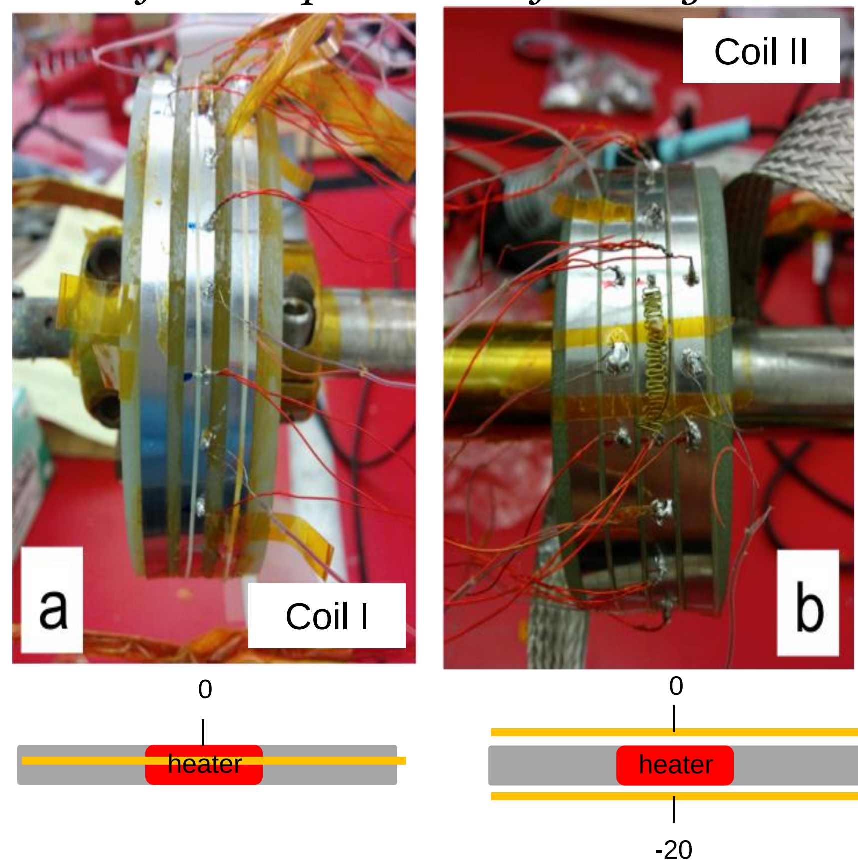
- Fiber Bragg gratings (FBGs) → point measurements, need gratings, fixed locations once fiber is manufactured
- Brillouin scattering → insufficient spatial and temporal resolution
- Rayleigh scattering → truly continuous, distributed sensor
  - Caused by random fluctuations of the index of refraction along the fiber length; like an infinite number of intrinsic FBGs on an ordinary optical fiber
  - Spatial resolution is physically limited by wavelength of light and length-scale of defects
  - Temporal resolution is limited by volume of data

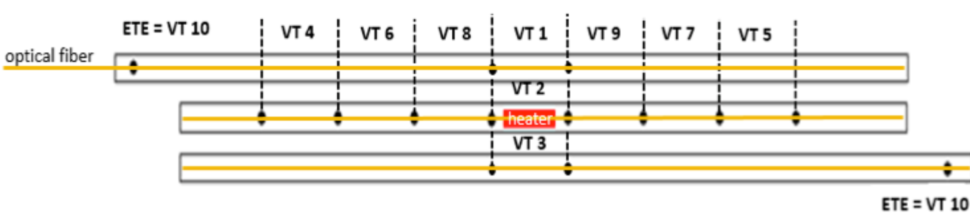
Coils with co-wound fiber

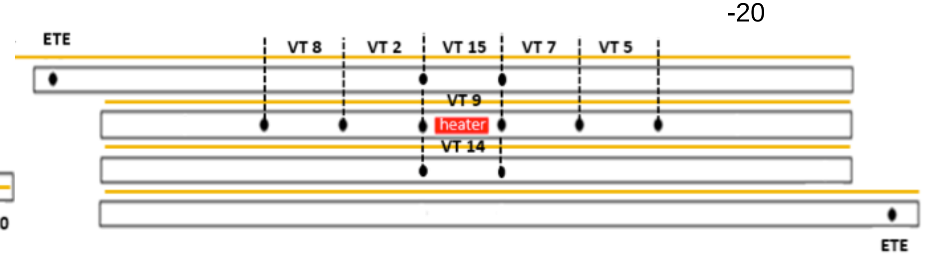
Optical fibers co-wound with conductor

- Fiber placed atop or next to conductor edge as turn-to-turn insulation
- Instrumented with voltage taps, thermocouples, embedded heater
- Coils painted with GE varnish – no impregnation
- Quench measurements at self-field, in nitrogen liquid and vapor

fiber atop *fiber edge*



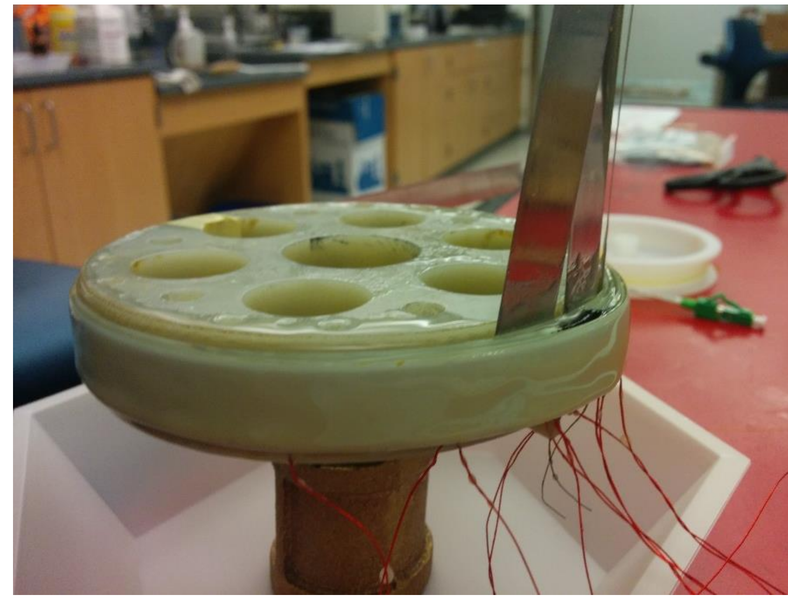




Coils with co-wound fiber

Optical fibers co-wound with conductor

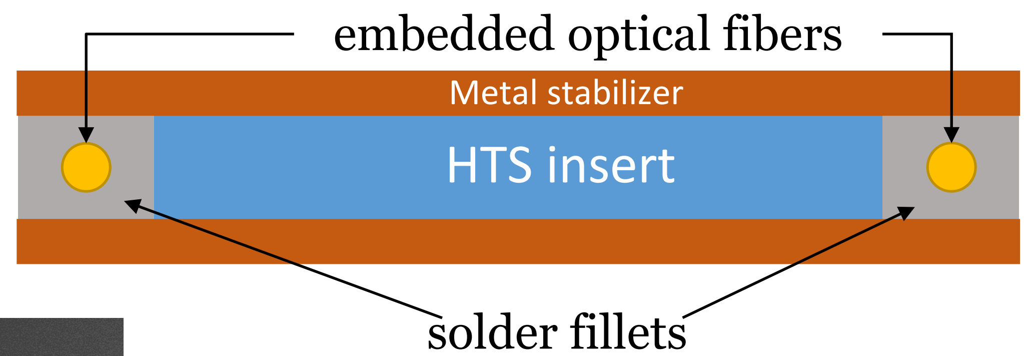
- Fiber placed next to conductor edge and attached to kapton insulation
- Instrumented with voltage taps and embedded heater
- Coils impregnated in epoxy
- Quench measurements at self-field, different temperatures

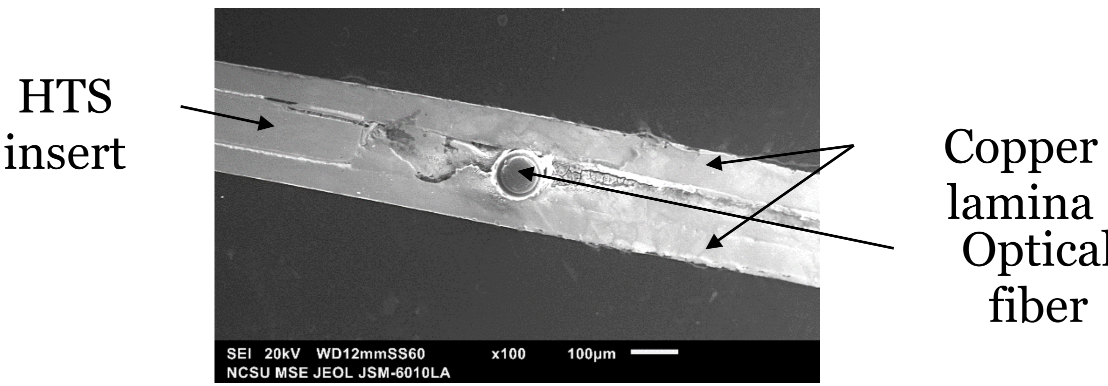


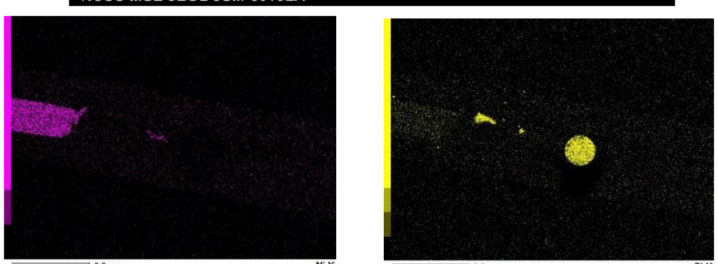
“Smart” REBCO conductor

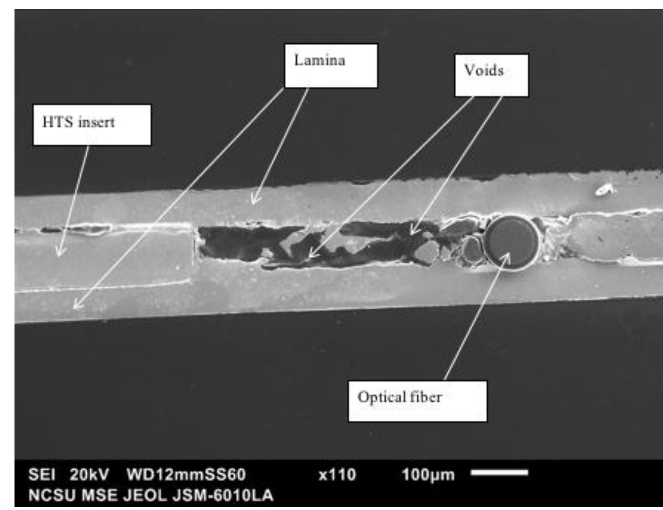
Another way to integrate an optical fiber into a magnet is to have a conductor that already contains it.

“Smart” REBCO conductor architecture (cross section)



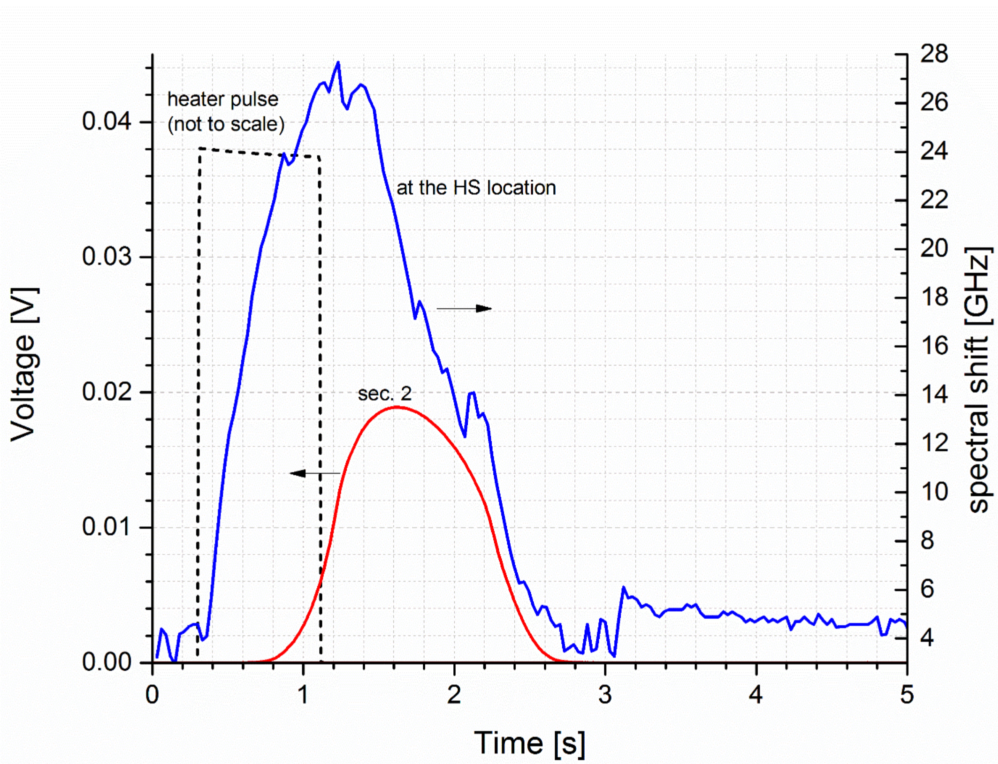




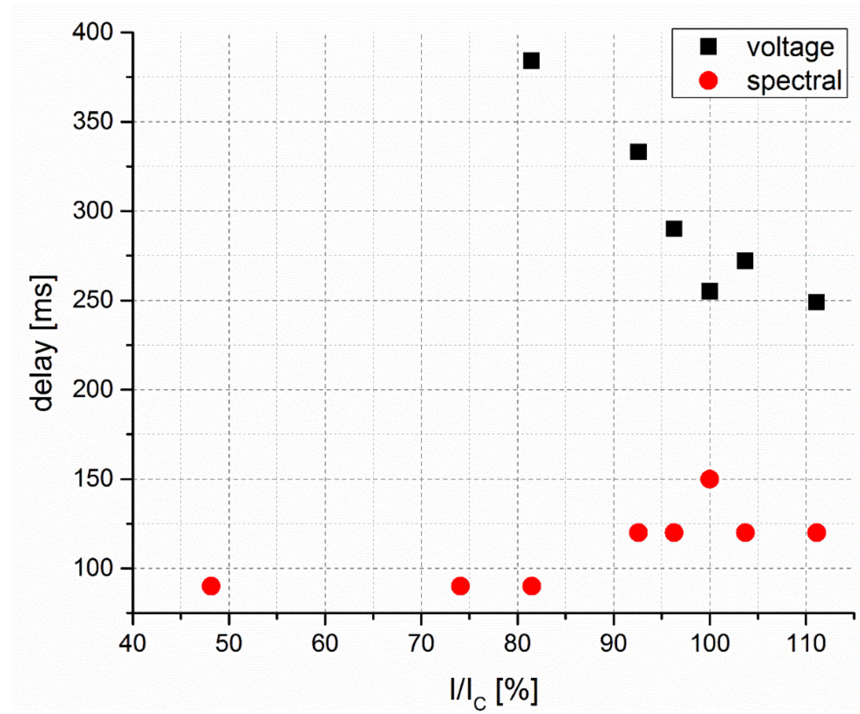


Co-wound fiber approach

Coil with fiber atop



Detection delay of voltage vs spectral shift

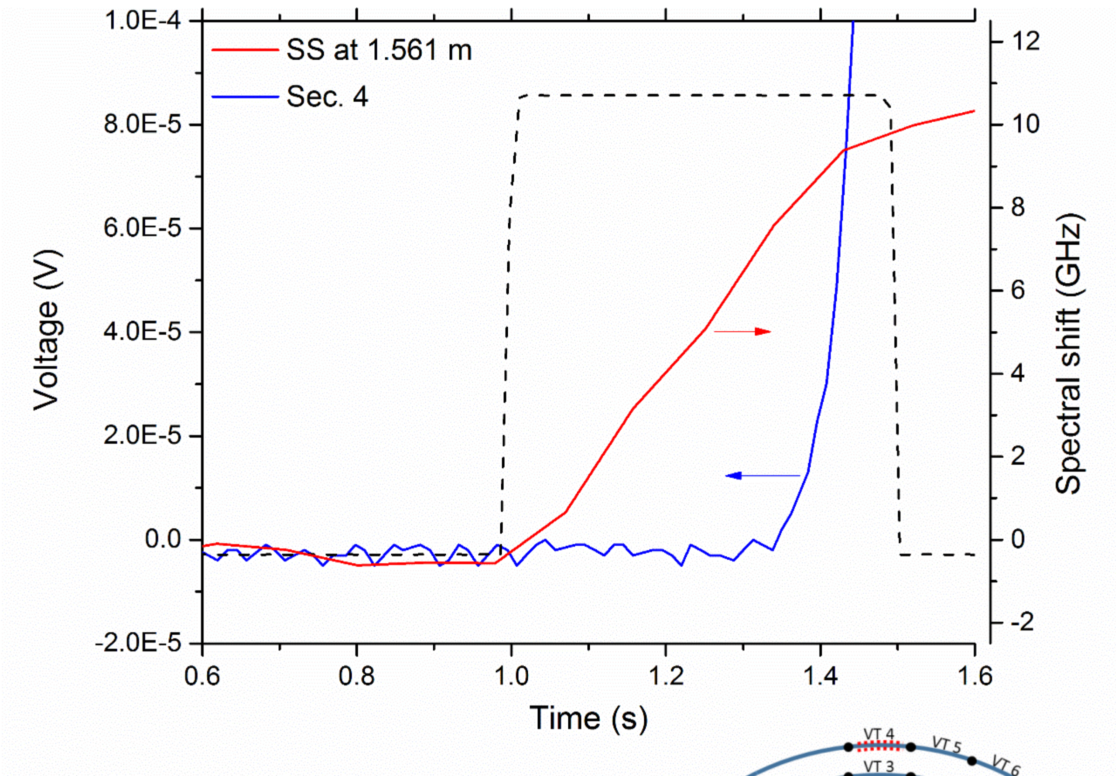


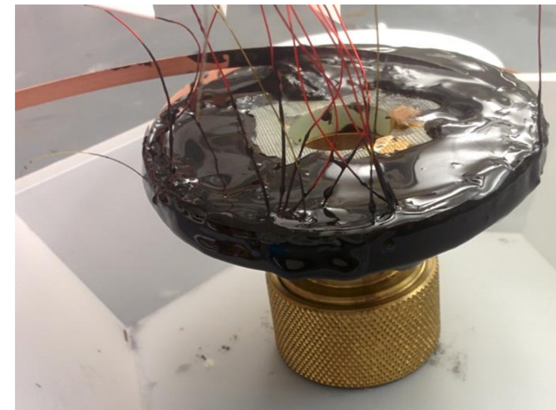
heater energy increases

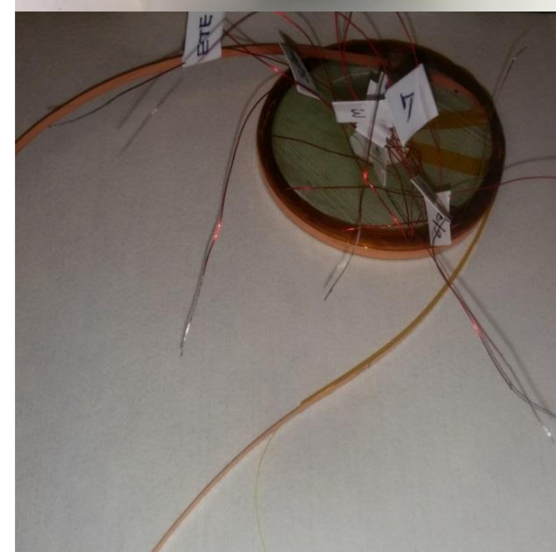
Spectral Shift always anticipates voltage, in any condition and in different coil geometry and fiber integration.

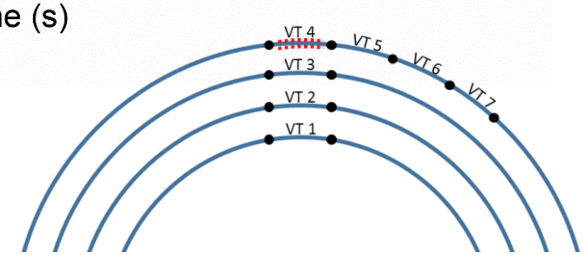
4.2 K pancake coil quench

4 mm wide YBCO, 65 mm coil inner diameter, 25 turns
650 A, self-field



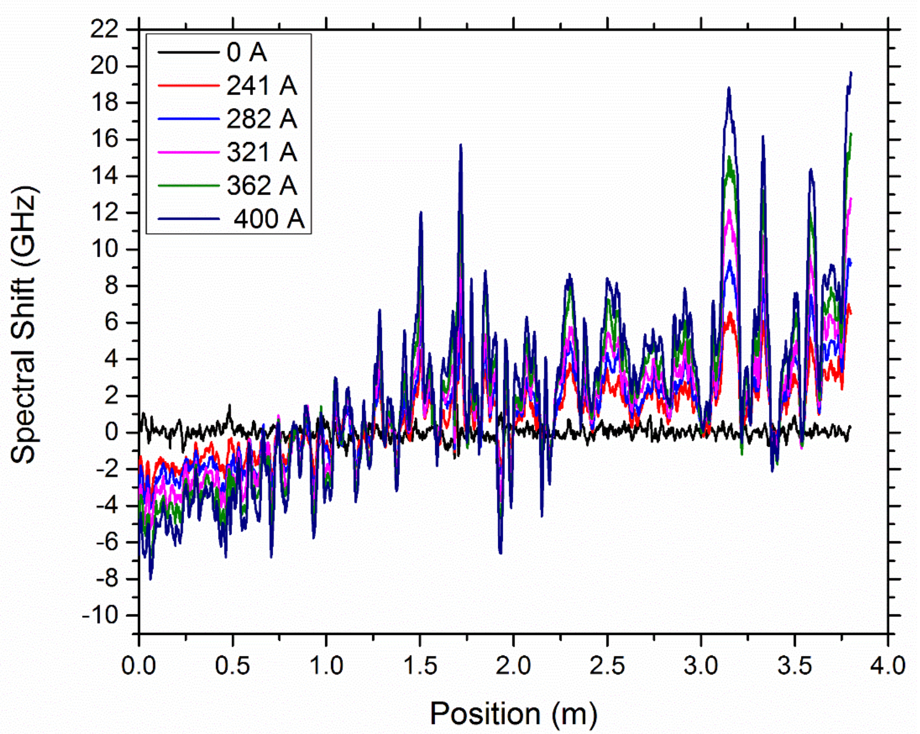


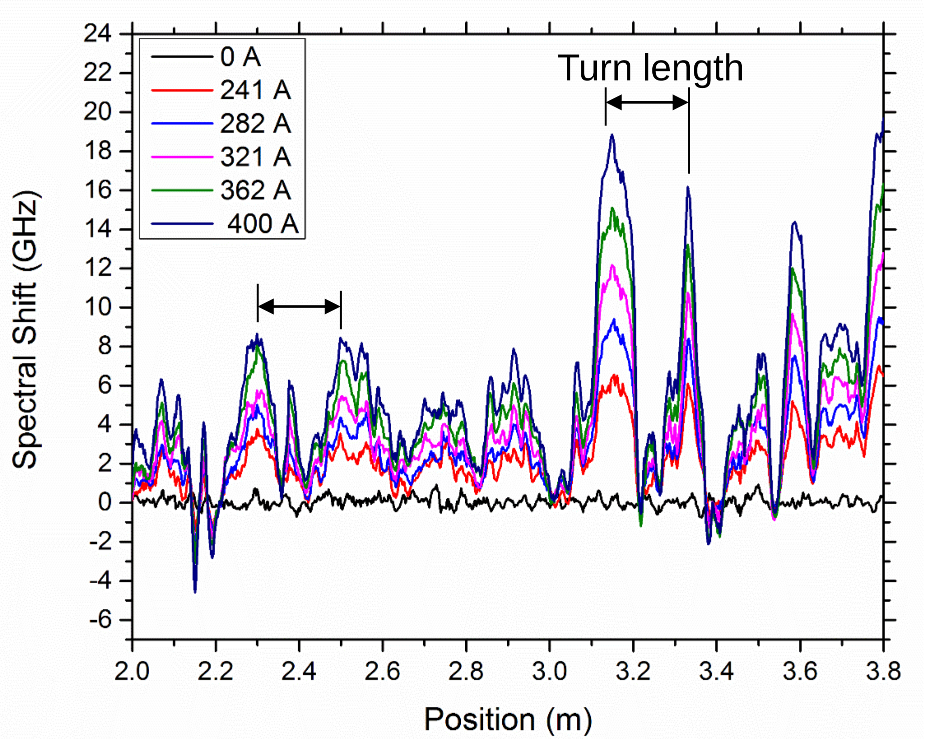




Spectral Shift during ramping

Pancake: 4 mm wide YBCO, 65 mm coil inner diameter, 25 turns
Self-field

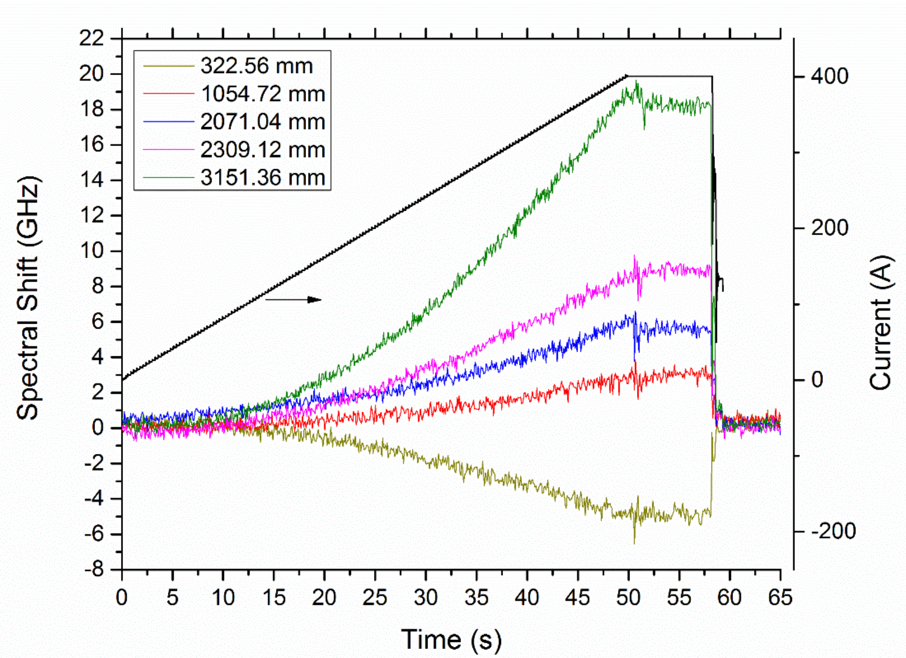


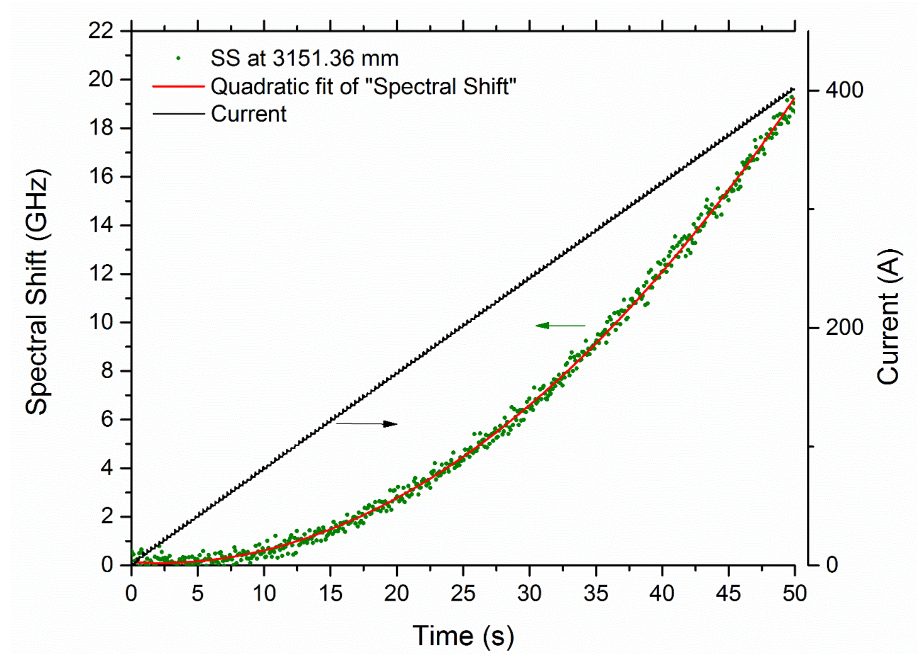


Rough periodicity equal to the turn length

Spectral Shift during ramping

Spectral Shift at five positions as a function of time



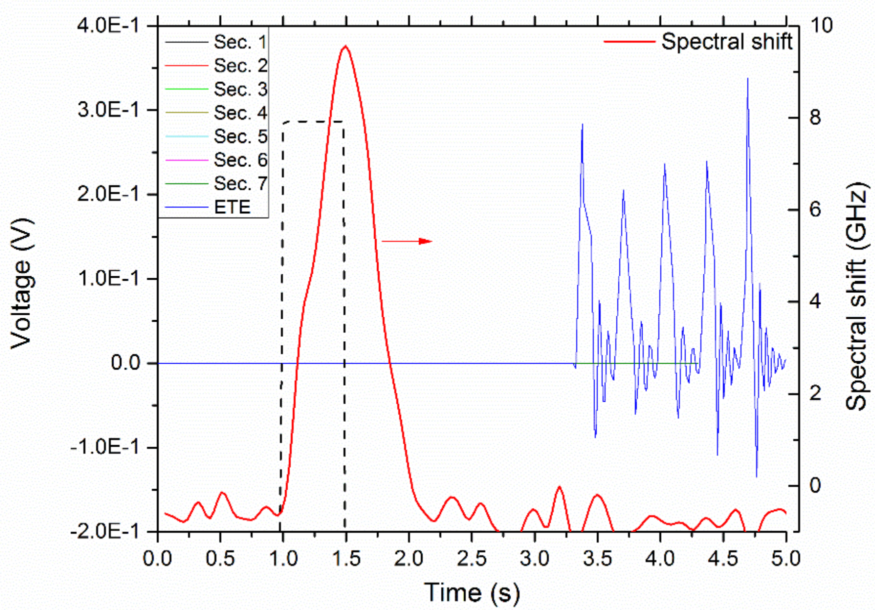


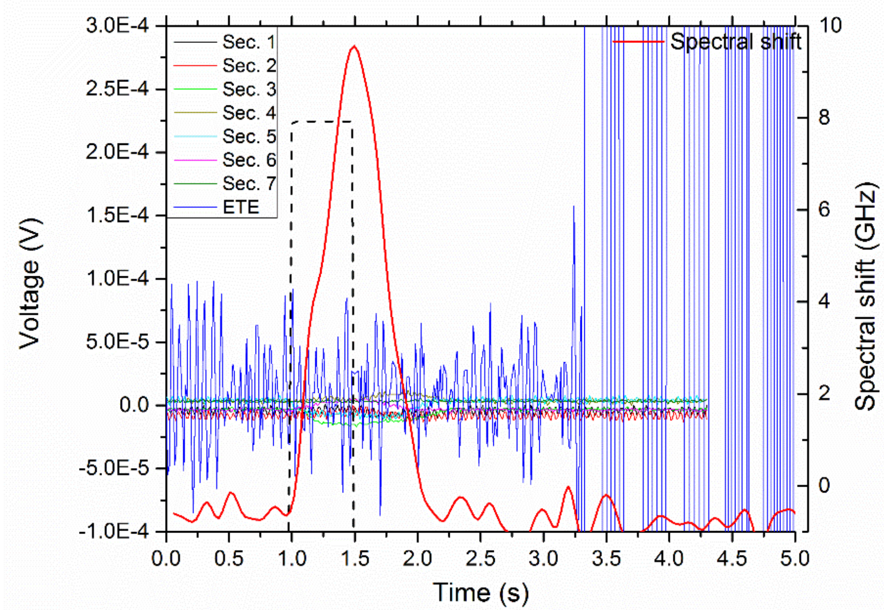
- Constant if current is constant
- Jumps back to zero if current is zero
- Quadratic for linear current ramp

Strain due to Lorentz force in self-field

$$\varepsilon \propto J^2$$

4.2 K pancake coil signals comparison

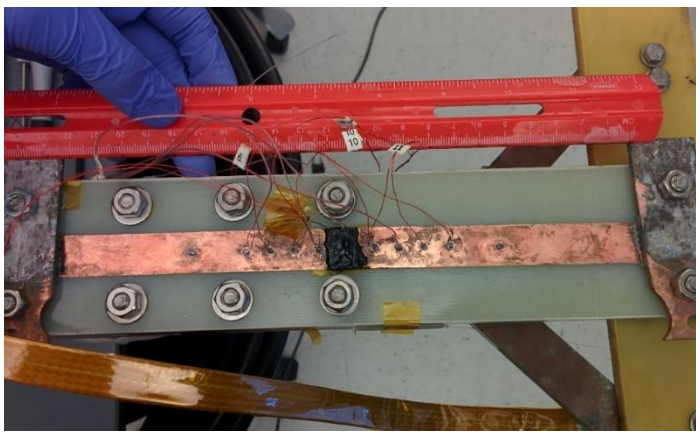


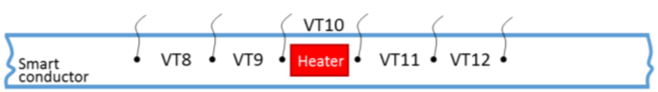


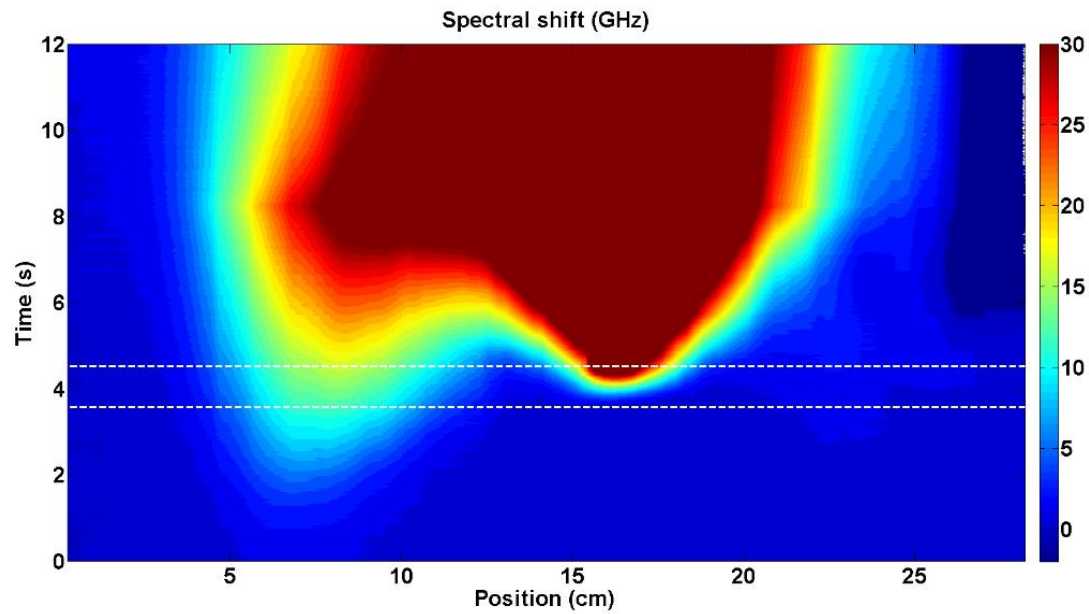
Note the dramatic difference in signal to noise ratio between voltage (noise only) and spectral shift

Smart REBCO – straight sample

- 30 cm straight sample
- Heater epoxyed at center
- 81 K, nitrogen vapor
- Transport of 100 A





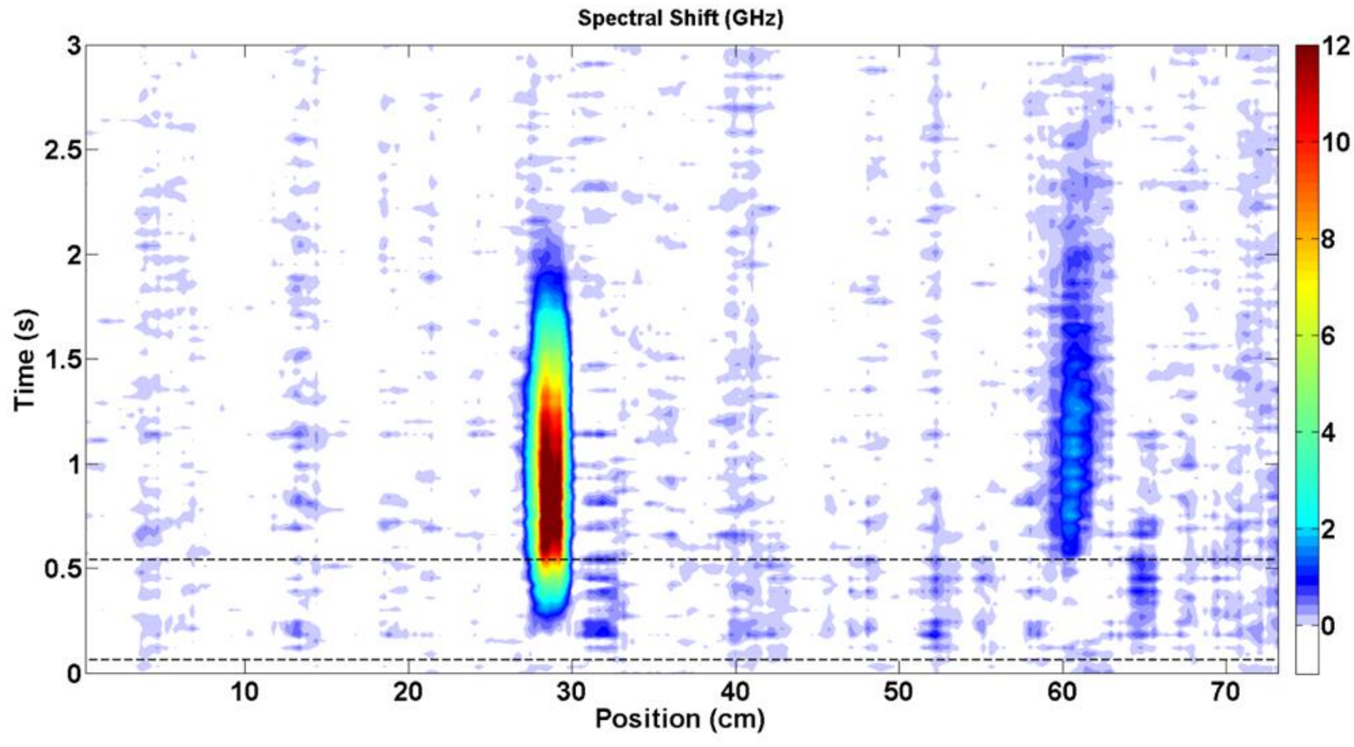


Spectral shift clearly shows that the instability was initiated by a low Ic region and then enhanced by the heat pulse.

Confirmed by multi-section Ic measurement

Smart REBCO – pancake coil

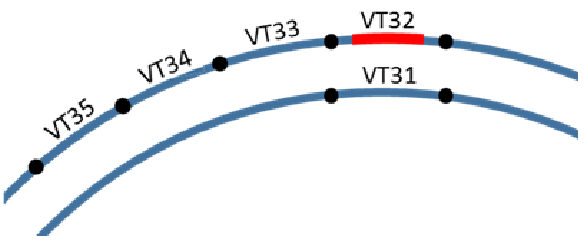
- Coil painted with GE Varnish
- Self-field
- 77 K, liquid nitrogen
- Transport of 235 A (80%I_c)



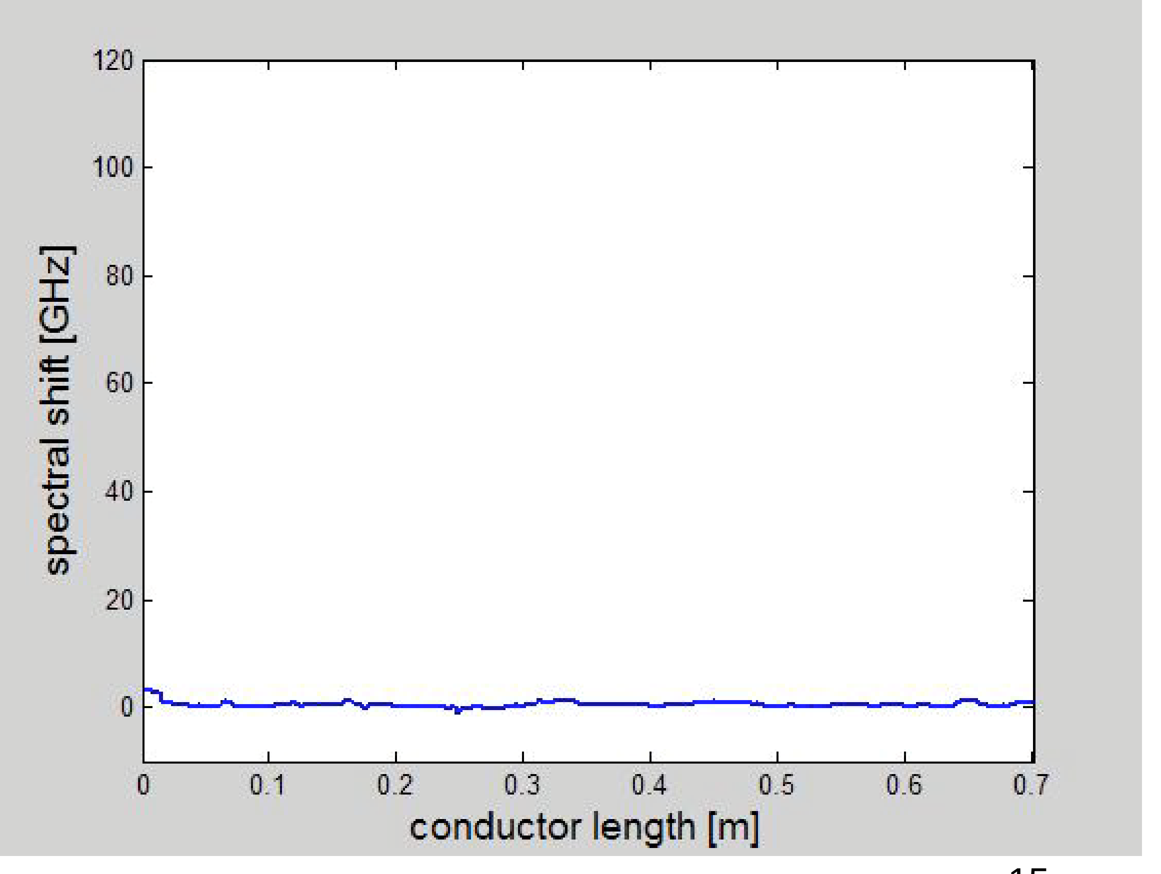
No propagation due to strong cooling yet strong spectral shift signals at .

Smart REBCO – pancake coil

- Coil painted with GE-varnish
- self- field, 14.6 K
- Transport current of 500 A



Sections 32 (heater) and 31 corresponds to positions **0.28** and **0.6 m** on the smart conductor



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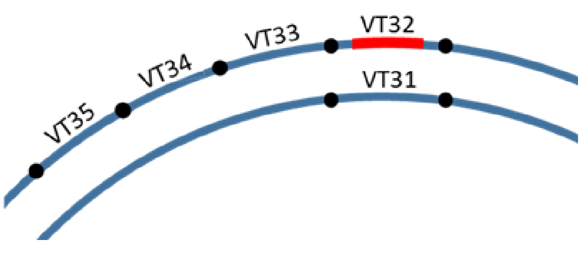

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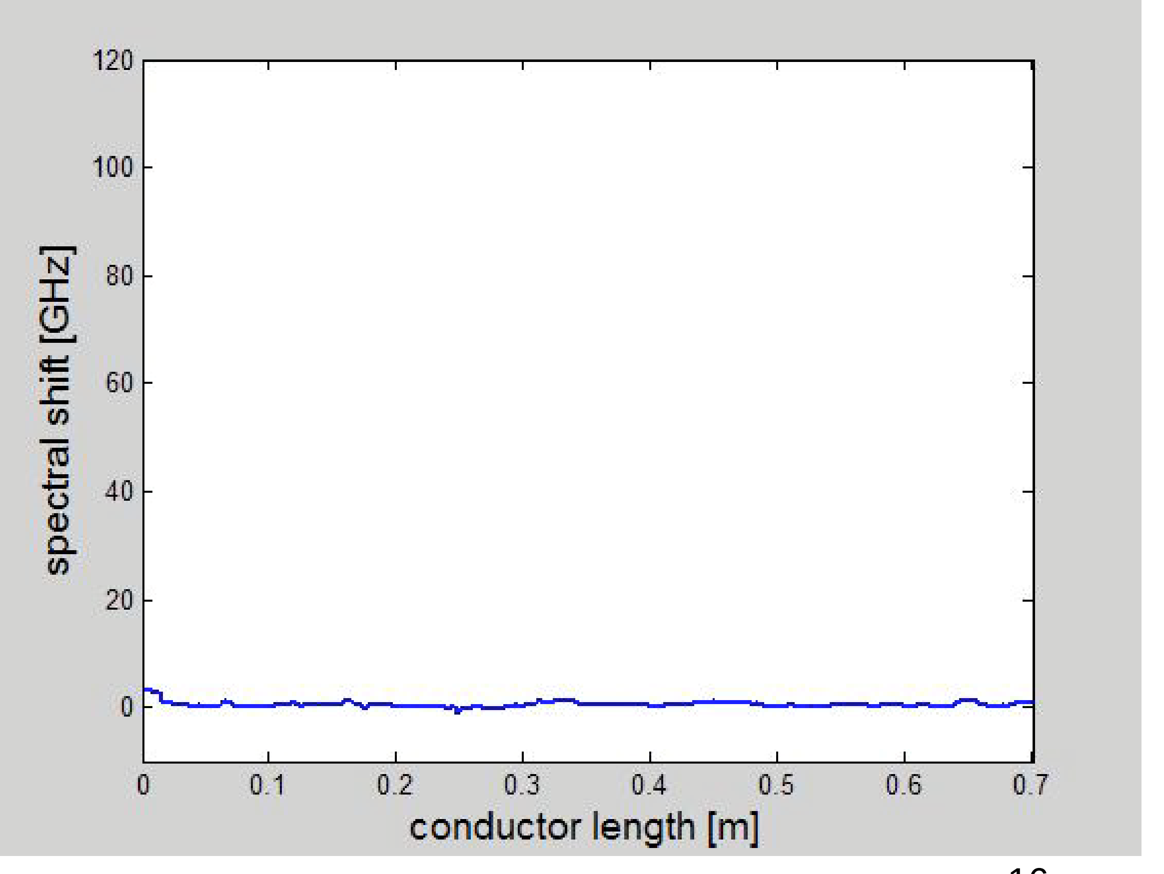

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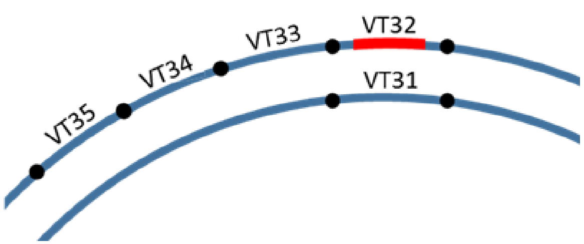
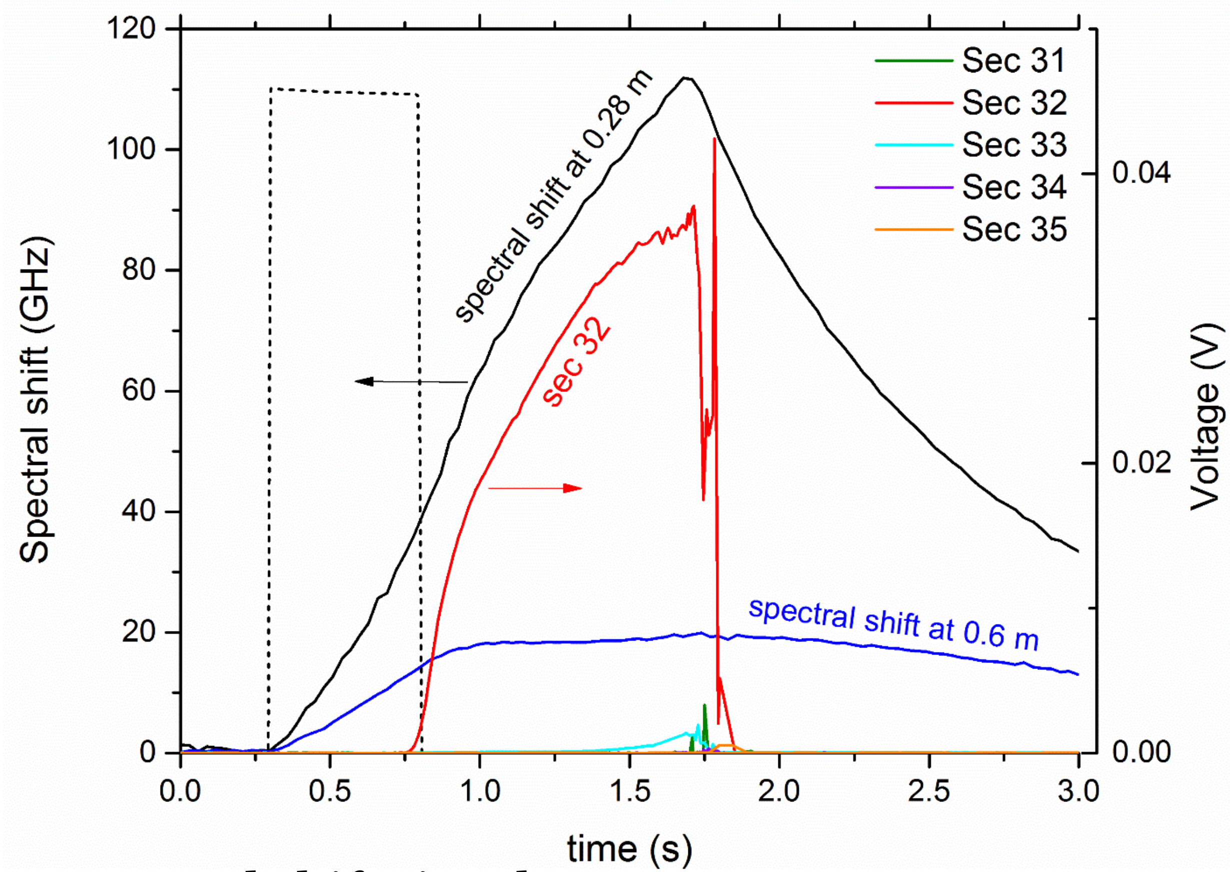


Spectral shift reacts immediately, even at 14.6 K

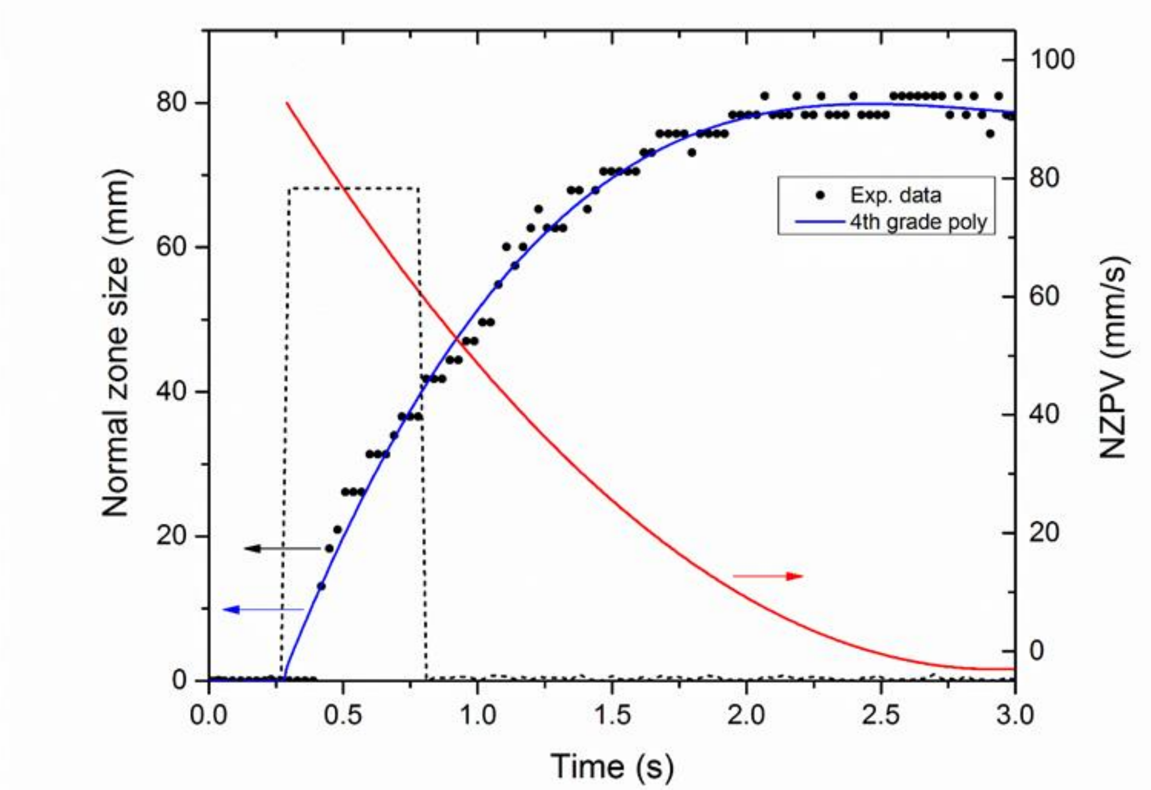
Voltage onset ~500 ms after spectral shift



Very strong spectral shift signal!

Smart REBCO - NZPV

- Pancake coil with SMART REBCO
- Spectral Shift threshold of 5 GHz to define normal zone



Determination of instantaneous normal zone propagation velocity

Conclusions

- Coils with co-wound fibers showed that RIOF is better than voltage at any temperature, down to 4.2 K
  - Spectral shift always anticipates voltage
  - It locates the normal zone with mm spatial resolution
  - Very low signal to noise ratio when voltage is noise only
- Smart REBCO concept has been demonstrated in collaboration with AMSC
  - Unprecedented fiber-conductor coupling, sensitivity and practicality
  - Unprecedented determination of normal zone size and velocity as a function of time
- Strain sensing capabilities demonstrated even with co-wound fiber approach

You can find out more…

- F. Scurti, S. Ishmael, G. Flanagan and J. Schwartz "Quench detection for high temperature superconductor magnets: a novel technique based on Rayleigh-backscattering interrogated optical fibers." *Superconductor Science and Technology* 29.3 (2016): 03LT01.
- F. Scurti, et al. "Self-monitoring "SMART" (RE)$Ba_2Cu_3O_{7-x}$ conductor via integrated optical fibers." *Superconductor Science and Technology* (2017).
- F. Scurti and J Schwartz. "Optical fiber distributed sensing for high temperature superconductor magnets." *Optical Fiber Sensors Conference (OFS), 2017 25th*. IEEE, 2017.
- F. Scurti, J. McGarrahan and J. Schwartz. "Effects of metallic coatings on the thermal sensitivity of optical fiber sensors at cryogenic temperatures." *Optical Materials Express* 7.6 (2017): 1754-1766.

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