FERMILAB-SLIDES-23-239-TD

Fiber optic sensing for strain and temperature

Instrumentation and Diagnostics for Superconducting Magnets Workshop

Apr 24 – 28, 2023, Paestum

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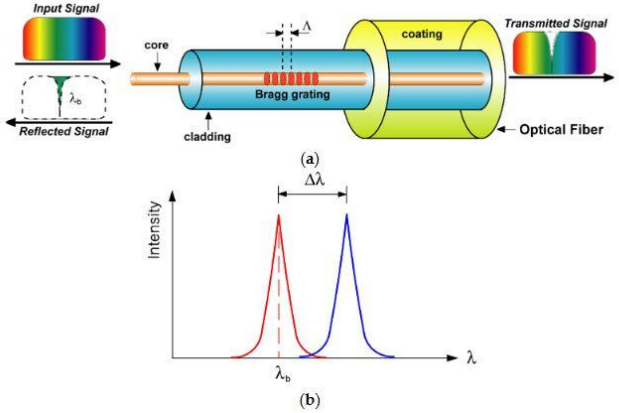
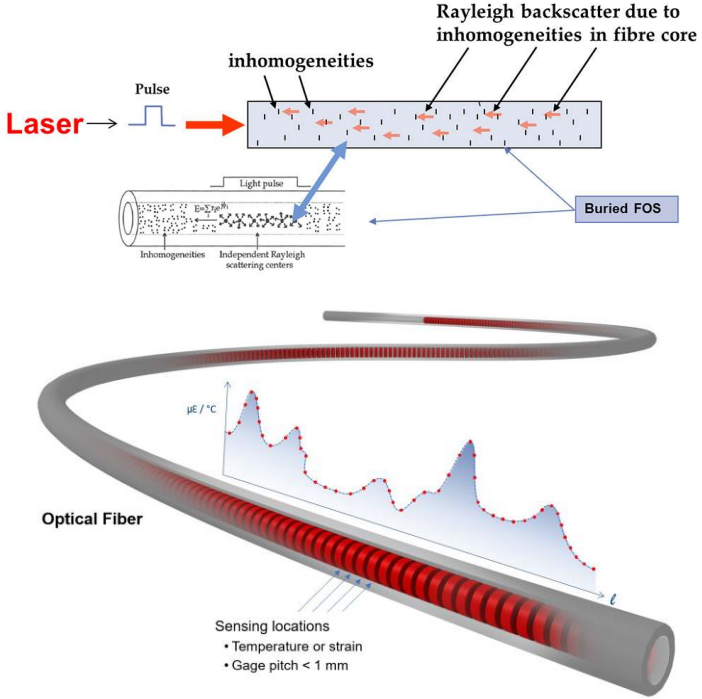
Fiber optics sensor



FBG sensor: discrete sensor

Rayleigh sensor: distributed sensor



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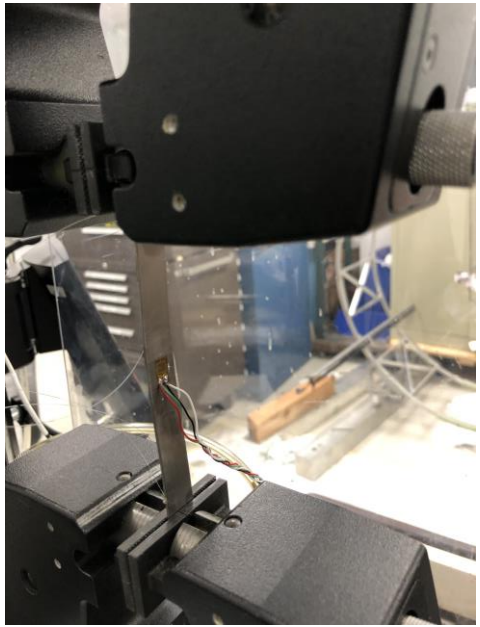
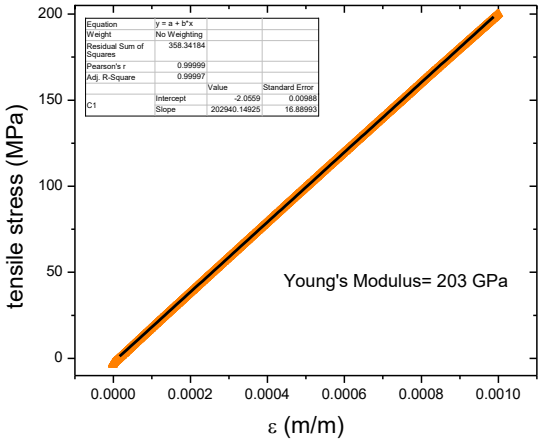
Outline

- Fiber optics implementation at FNAL
- FBG fibers:
  - Calibration test
  - Feedthrough line for the Vertical magnet test facility
- Distributed fiber optics for strain and temperature measurements
  - Calibration test
  - Strain maps (Steve K.)
  - Quench detection
- Future plans



Purchase FBG fiber for HBM
8ch interrogator
Polyimide or Ormocer fibers with 4 sensors
Sensor length 6 mm



- AISI 1080 steel and Ti
- Instron press in IB3 up to 200 MPa
- Fibers vs strain gauges
- Tensile vs Poisson strain

Young modulus measured with FBG sensors is in very good agreement with what is expected for steel and Ti.

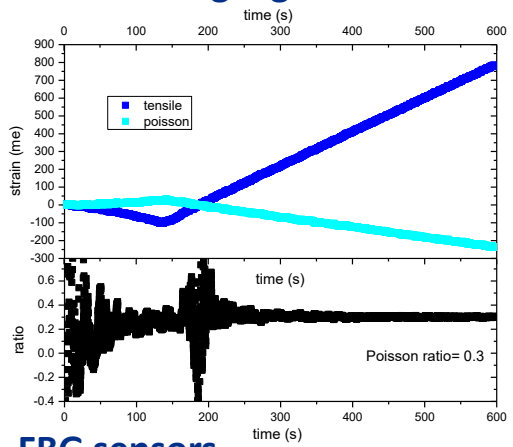
Tensile stress test in Liquid Nitrogen

- Tensile stress was applied up to 200 MPa in Liquid Nitrogen
- Strain variation is around 800 me for both strain gauge and fibers
- Poisson ratio is 0.3

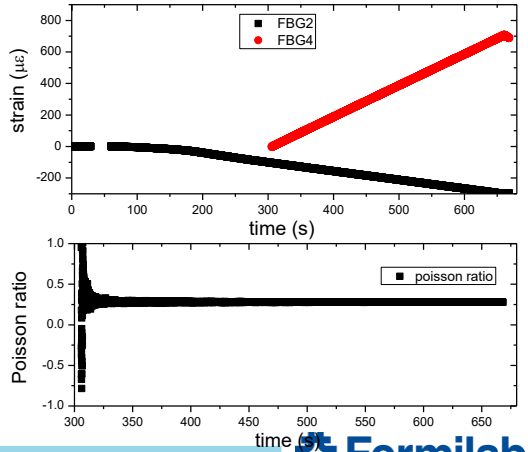
Issues during cooldown

- Signal was lost on some sensors
- Absolute value after cooldown was not correct

Strain gauges



FBG sensors



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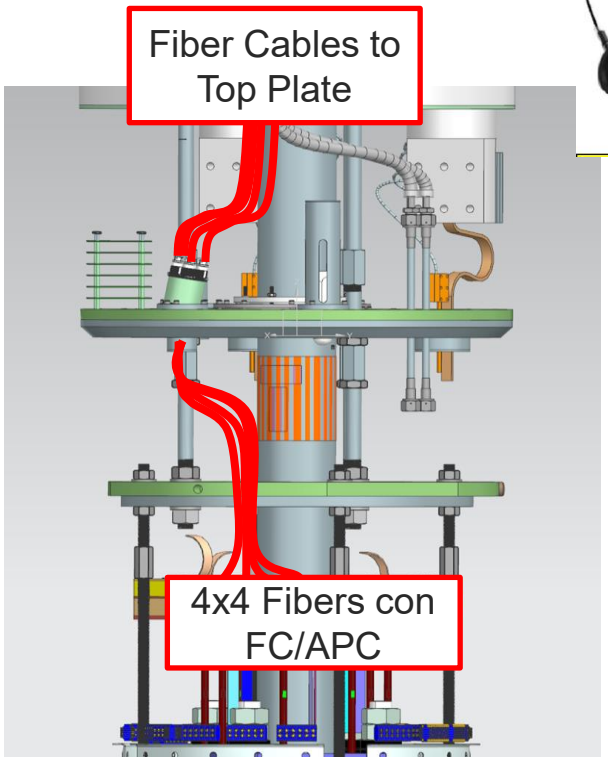
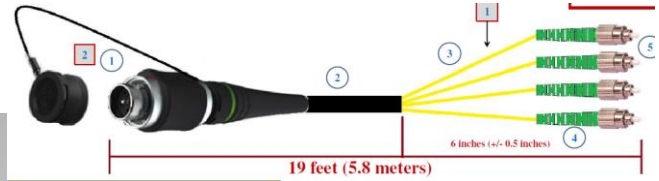
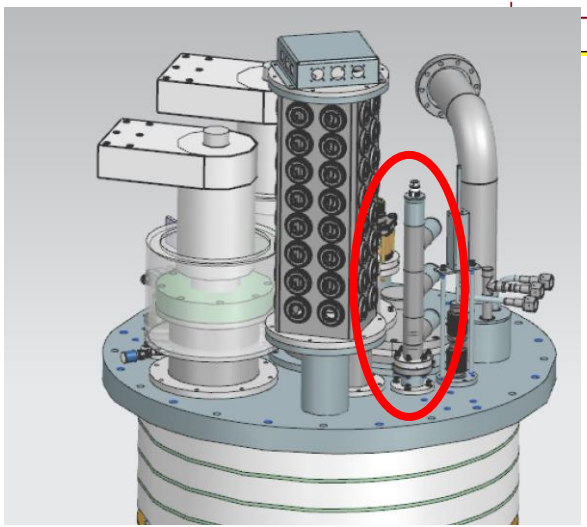
Fiber feedthrough in vertical magnet test facility







- G-10 Lambda Plug
- Fisher connectors
- Connector potted with Stycast 2850

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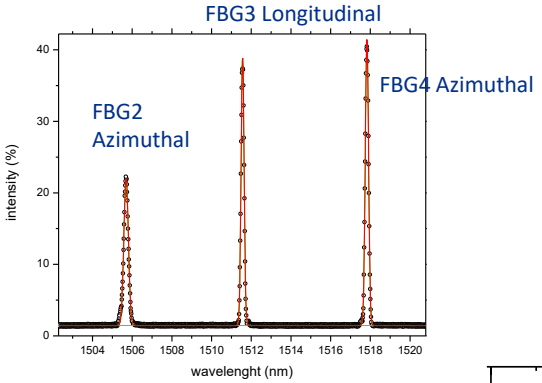
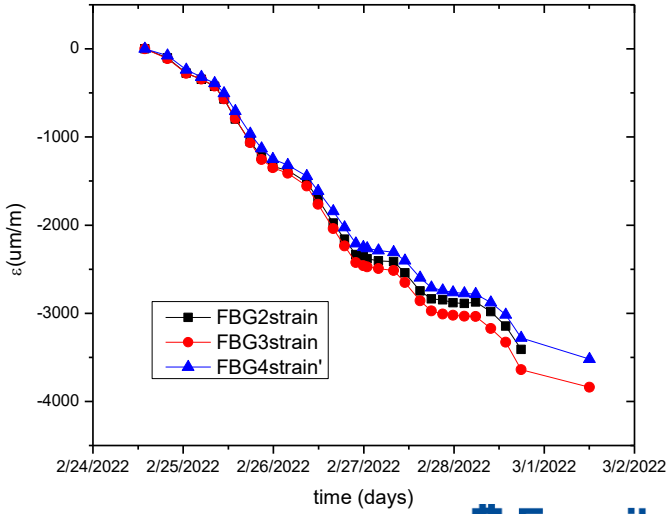
Mirror magnet cooldown (March 2022)



FBG2= 1508.013 nm
FBG3= 1514.049 nm
FBG4=1520.063 nm

- @4.5 K only two sensors are still alive
- Strain is consistent for each FBG sensor
- At cold the strain variation without T compensation is around 4000 um/m



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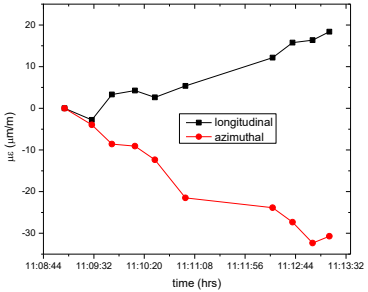
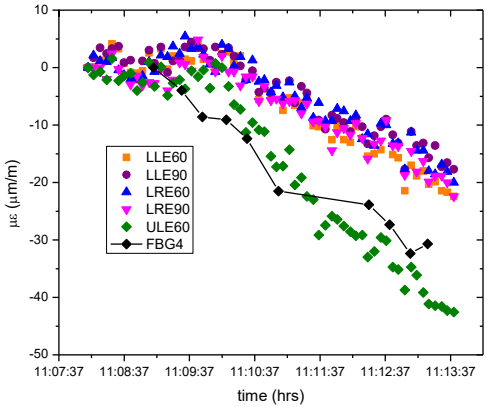
Mirror magnet powering

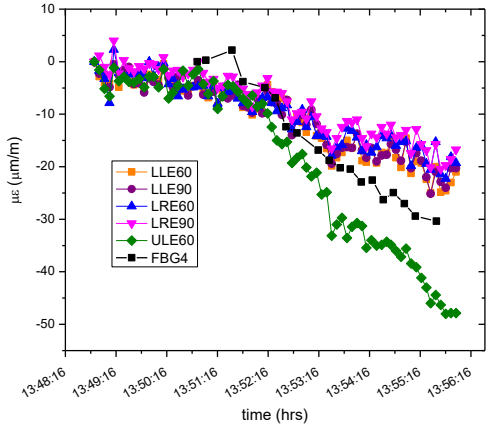


At cold only two sensors are still alive
FBG3 is longitudinal
FBG4 is azimuthal
The closest strain gauge is labeled ULE60

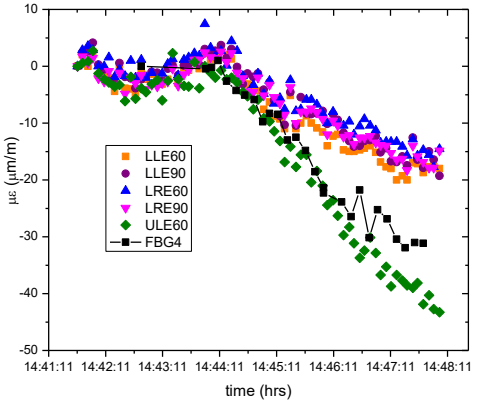
Training and quench 1



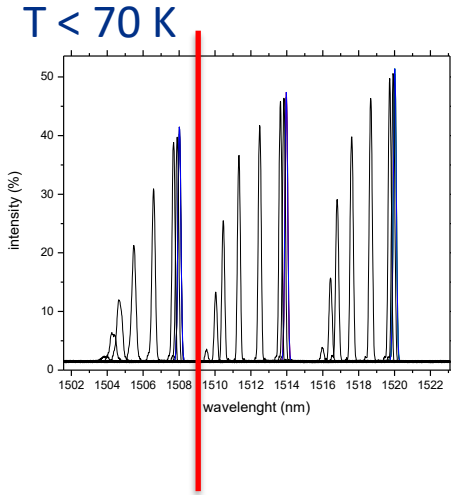
Training and quench 2

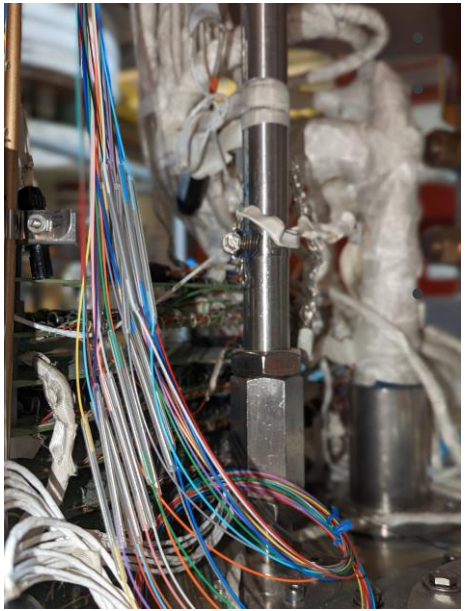


Training and quench 3

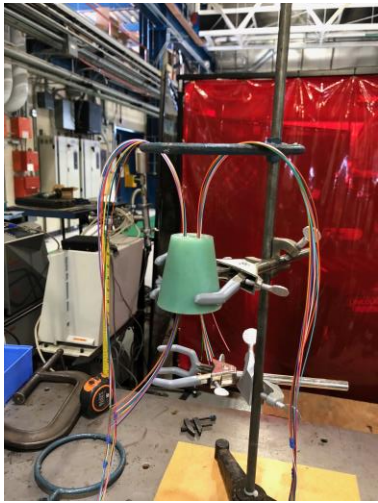


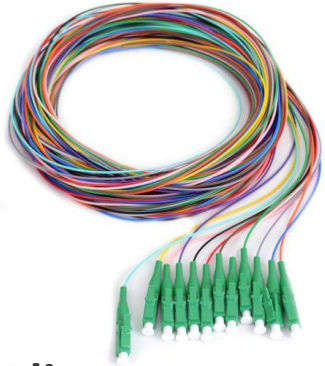
New feedthrough line for the Vertical magnet test facility

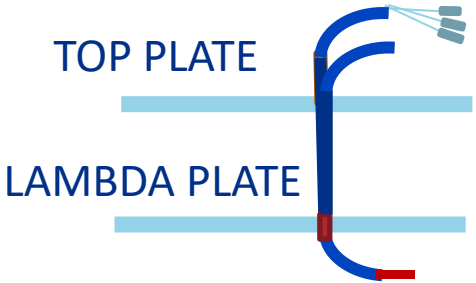




Very low signal < 70 K
Implemented solution:
use of pigtail cables spliced below the lambda plate
Both FBG and Rayleigh

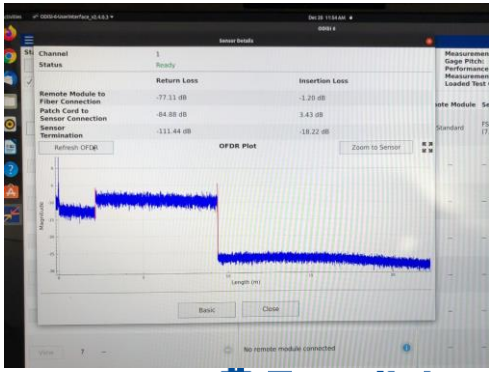






No signal loss at the splice

Line will be tested in the next couple of months



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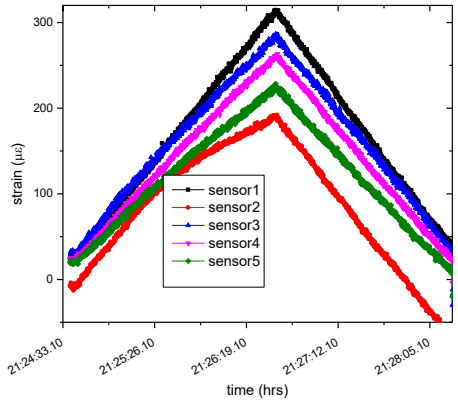
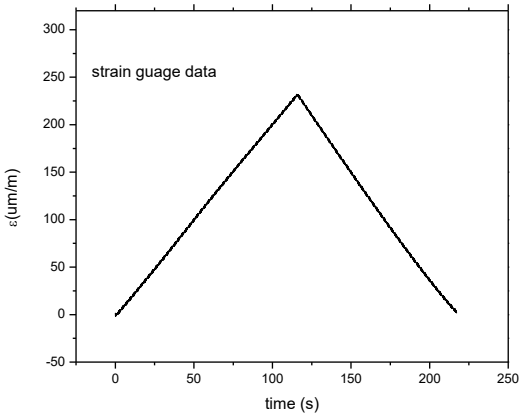
Distributed fibers: calibration on steel bar

Laboratory Directed R&D

- Purchase the interrogator
  - strain sensors
  - fibers encapsulated in Teflon tube: temperature sensors

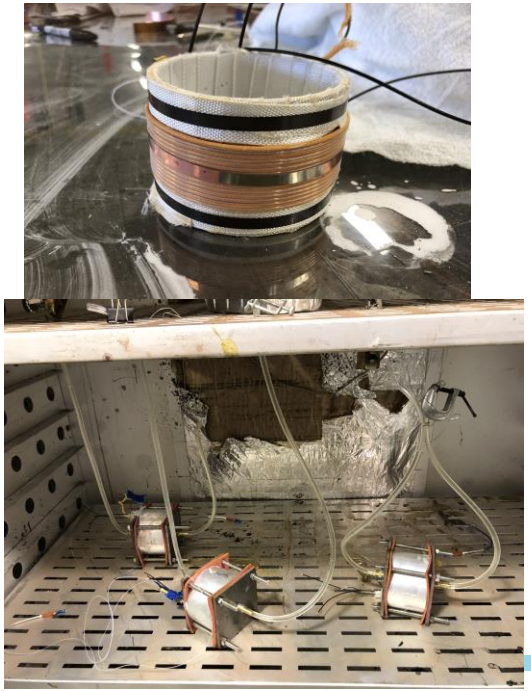


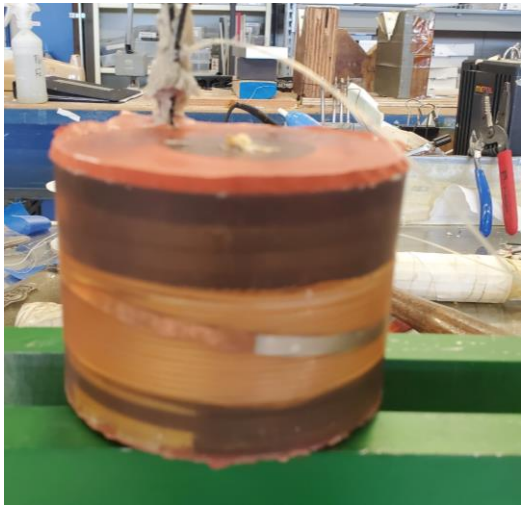


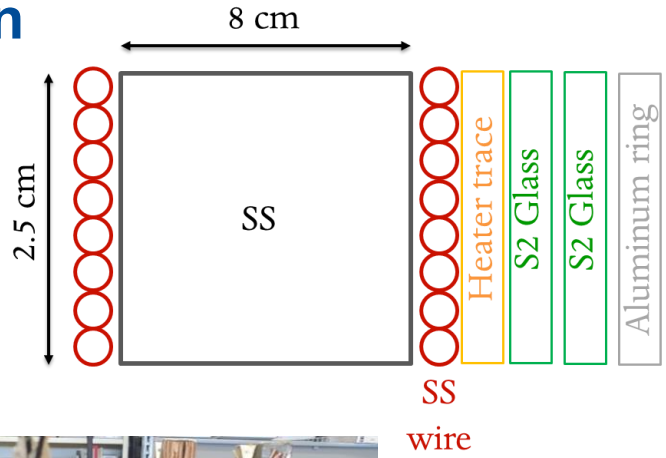
3 segments of fiber were glued on each side of the steel bar
Observe the spectrum of entire length of the fiber
Pinch the fiber and identify specific position along the sensor

Distributed fiber sensor: quench detection

Fabricate several small solenoids with NiCr wire and wind a standard strain and temperature fibers sensors







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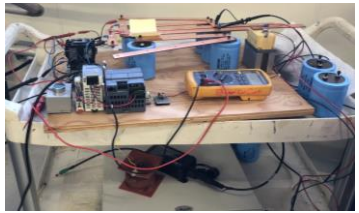
Distributed fiber sensor: quench detection

TEST #	Voltage	Capacitance	t	Energy stored
	V	mF	ms	*J*
1	10	27	13.5	1.3
2	35	27	13.5	16.5
3	40	27	13.5	21.6
4	28	54	27	21.1
5	40	54	27	43.2
6	28	108	54	42.3
7	20	162	81	32.4
8	25	162	81	50.6
9	30	162	81	72.9
10	21	324	162	71.4

Capacitor bank (up to 12 capacitors): 27 to 324 mF

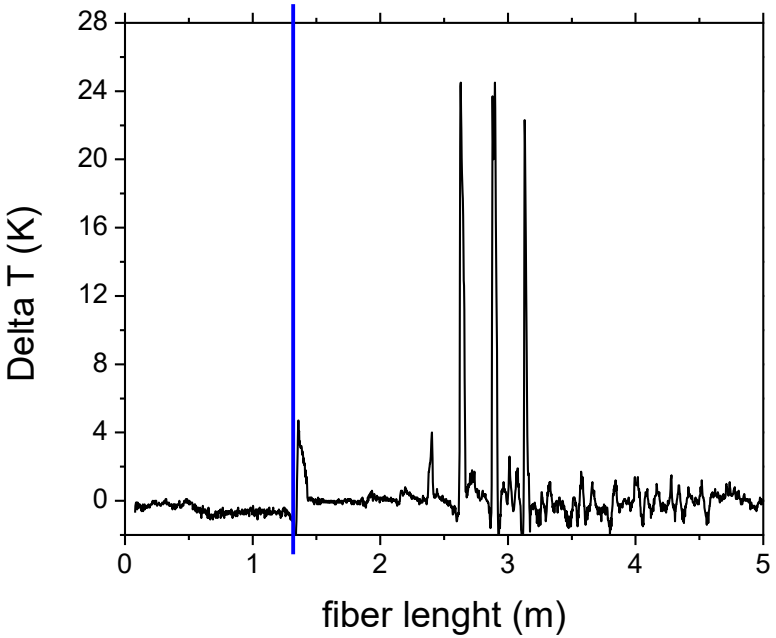


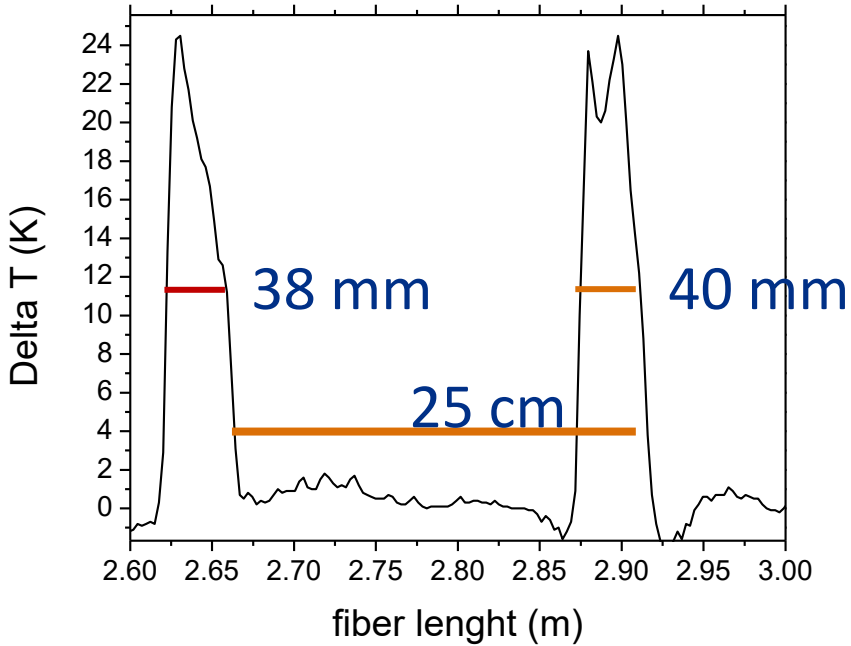
TEST PARAMETERS

- 5 m long temperature sensors
- Sample rate 160 Hz and spatial pitch 2.6 mm.
- Spot heater size (covering 3 solenoid turns): 5 mm wide, 40 mm long and 2.5 um thick

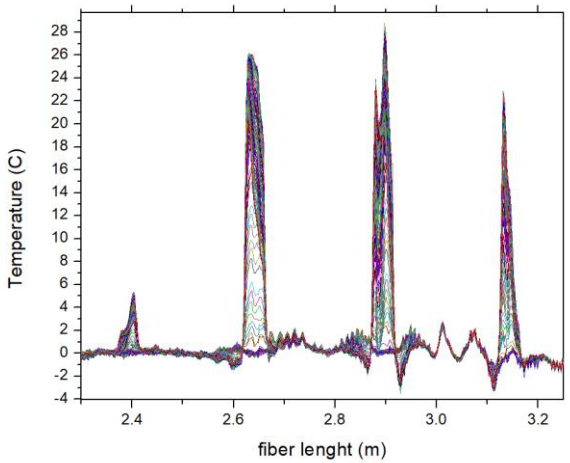
Test in Liquid N

Distributed fiber sensor: quench detection

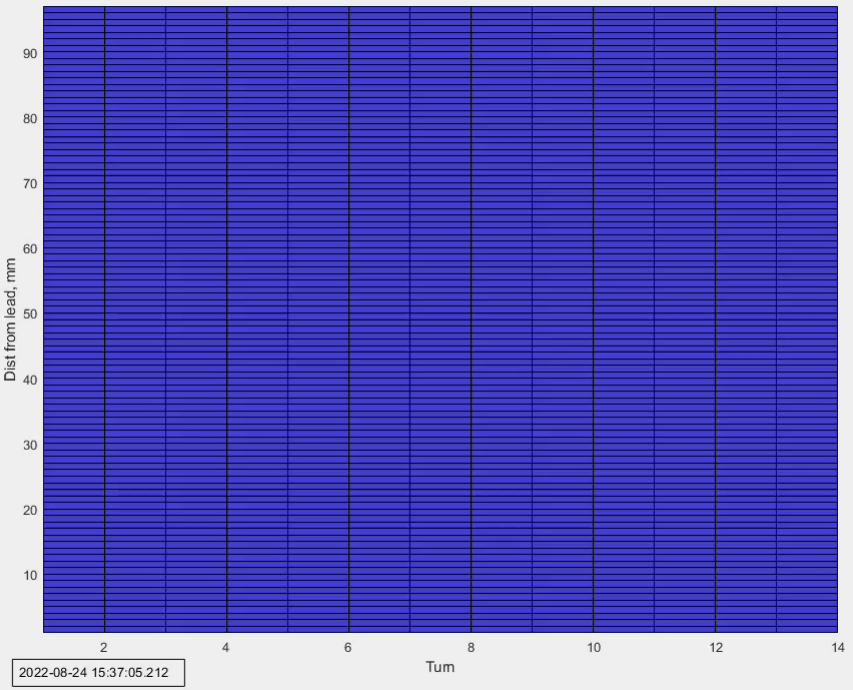




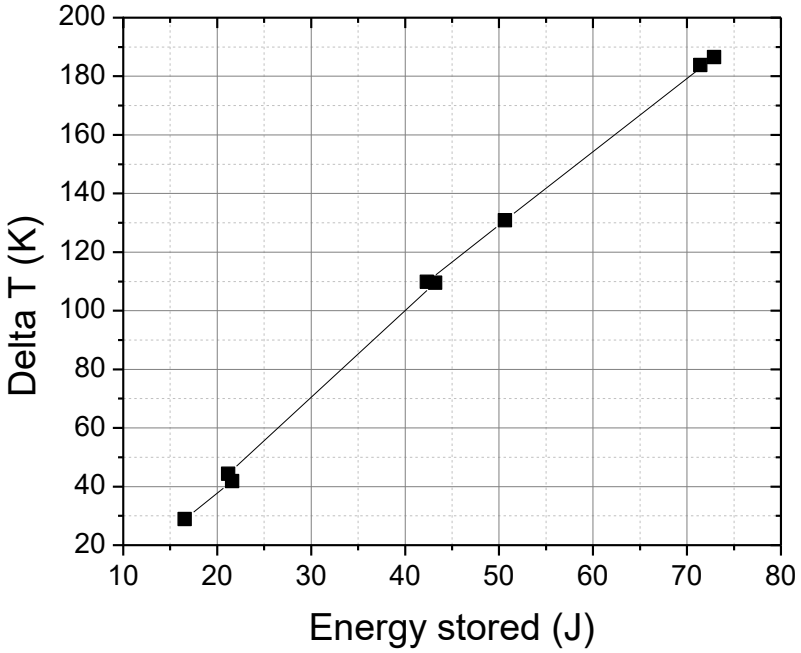
Distributed fiber sensor: quench detection



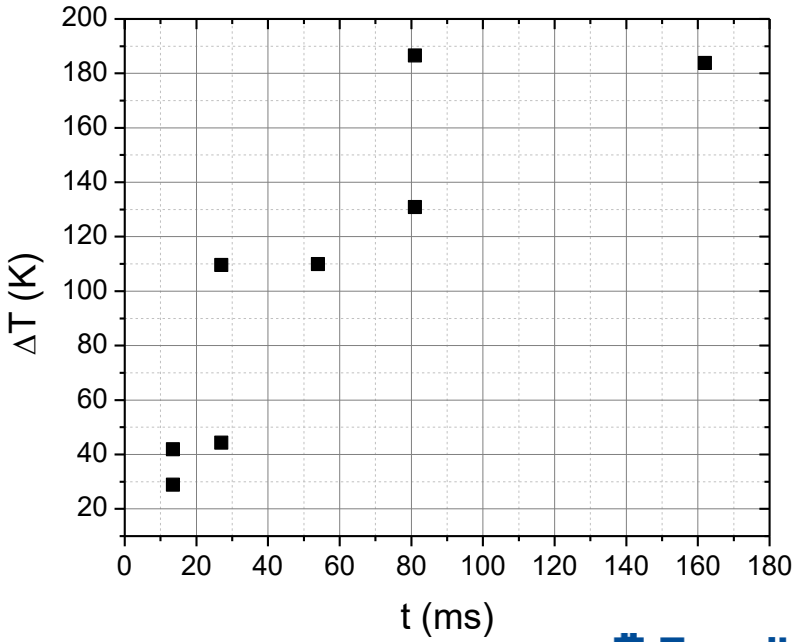
40 V 54 mF



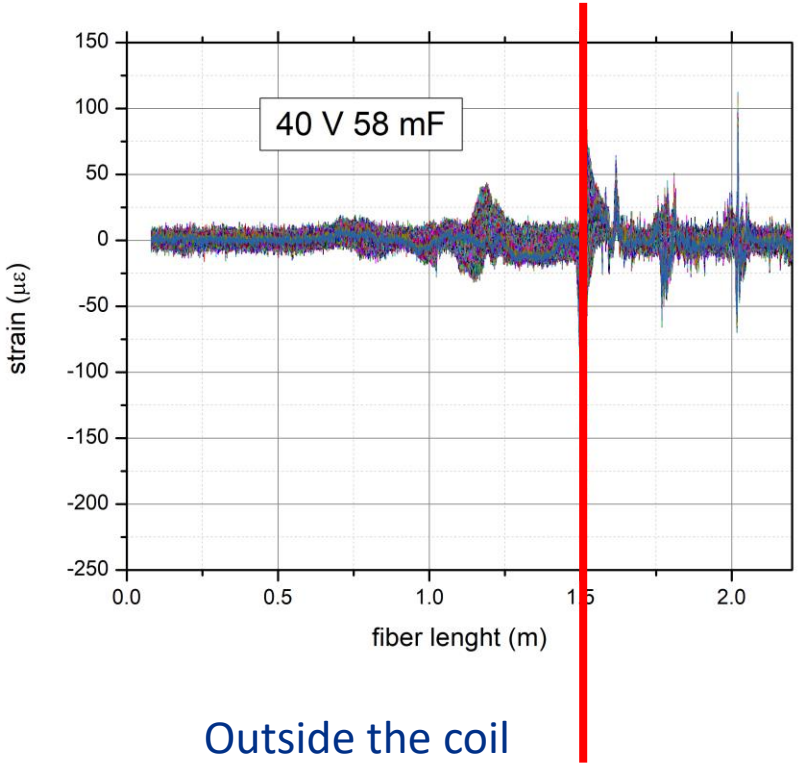
Distributed fiber sensors: quench detection



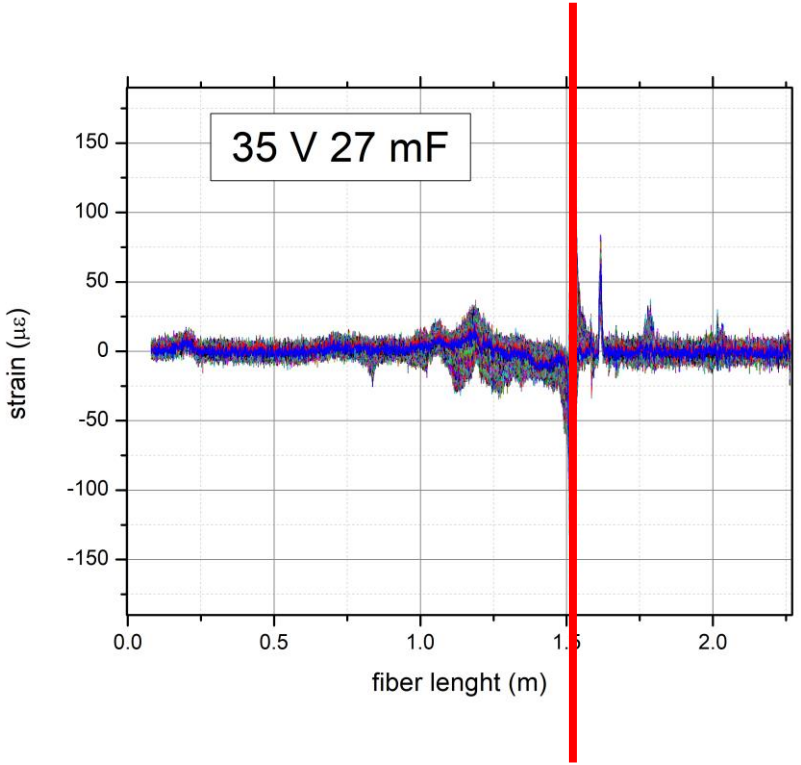
Temperature variation vs time constant
200 K variation in 100ms which is consistent with Nb3Sn coils during quench



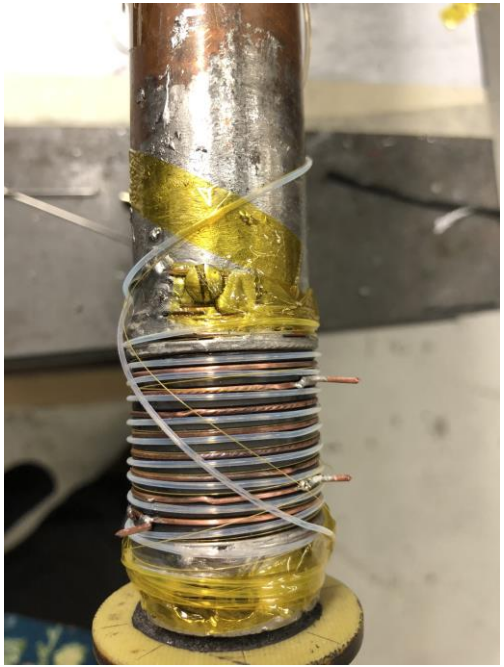
Distributed fiber sensors: quench detection



Outside the coil



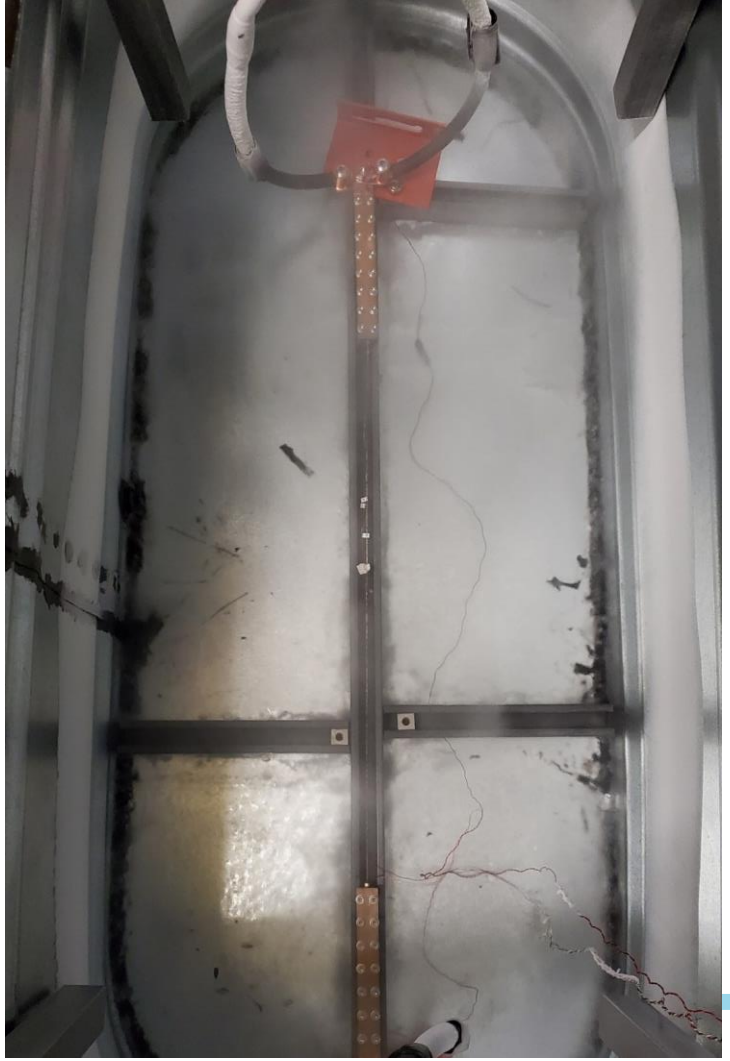
Temperature sensor in Li He



Test sensitivity of
Strain and temperature
sensors in Liquid He

Nb3Sn witness sample
Ic measurements

Repeat experiment with a
spot heater



Future plan: test REBCO cable in Liquid N and He

- Star REBCO cable
- Corc REBCO cable

- Wrap a temperature and a strain distributed optical sensor around it
- Perform a quench propagation study in Li Nitrogen
- Repeat the test in Liquid He

Conclusions

- Fiber feedthrough line have been implemented in the vertical magnet test facility at FNAL
- Stable diagnostic probe for testing of R&D Magnets at FNAL

DISTRIBUTED SENSORS

- QUENCH DETECTION:
  - temperature fiber sensors were successfully used to measure T variations in quench like conditions in small solenoid
  - Data collected with temperature fiber sensors are easier to interpreter than strain sensors
- FUTURE PLAN
  - Investigate T sensitivity at 1.9 K
  - Quench propagation study on a REBCO cable

Parameter		Specification			Units
Gage Pitch[1]		0.65 mm	1.3 mm	2.6 mm	
Number of channels		1, 2, 4 or 8 channels			
Maximum sensor length per channel		10 (Standard) or 50 (Extended range)			m
Gages (measurement locations) per meter of sensor		1,538	768	384	gages/m
Measurement rates (Rates are aggregate; divide by number of active channels to determine the per-channel rate)	2.5 m mode	62.5	125	250	Hz
	5 m mode	40	80	160	Hz
	10 m mode	25	50	100	Hz
	20 m mode	12.5	25	50	Hz
	50 m mode	-	10	20	Hz