U.S. MAGNET
DEVELOPMENT
PROGRAM

CCT4 Test Results

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Test highlights

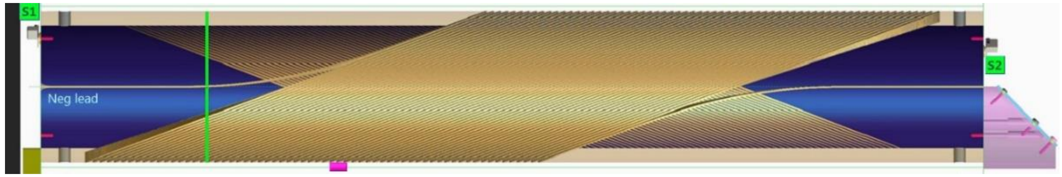
- We have tested CCT4 (three cooldowns, over 120 quenches) and learned about its training behavior, quench locations, minimal quench energy and protection margins

- We have collected unique high-frequency acoustic data for the majority of CCT4 training ramps (over 1 TB of data) following evolution of AE with training. The data analysis is ongoing, and some early results will be presented

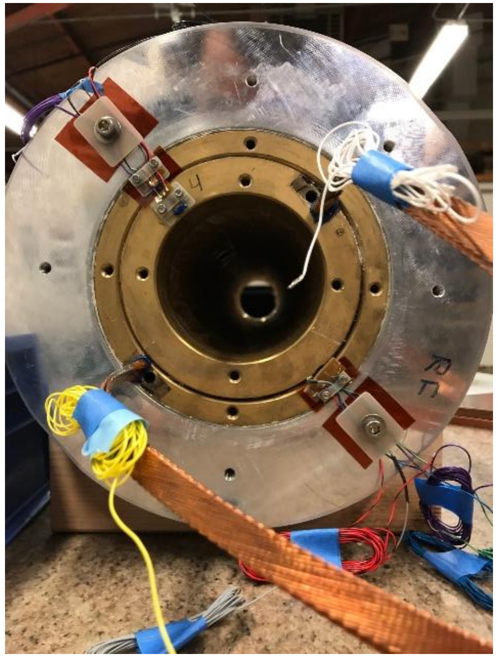
- We found two distinct regimes of training (to be presented in the technology session), and directly measured correlation between thermal effects and mechanical disturbances

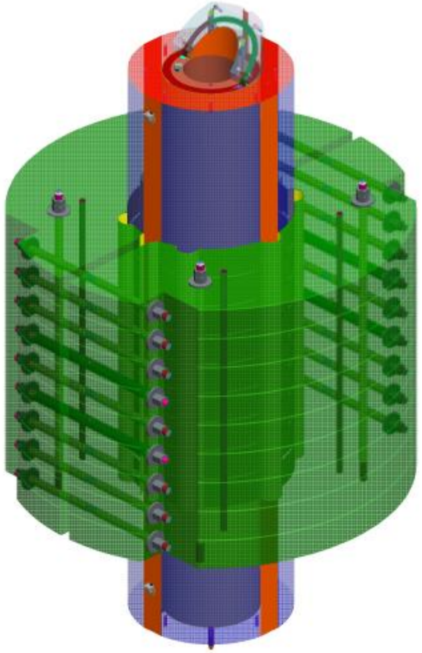
- We qualified new instrumentation for active monitoring of magnet mechanical interfaces

CCT4 test timeline and objectives



- Initial cooldown was started on Jul 22, magnet was cooled to 4.2 K
- Compressor malfunction lead to a warmup to ~ 170 K
- Second cooldown to 4.2 K was started on Aug 6, two weeks of testing
- Thermo-cycle (third cooldown) completed in Jan 2018

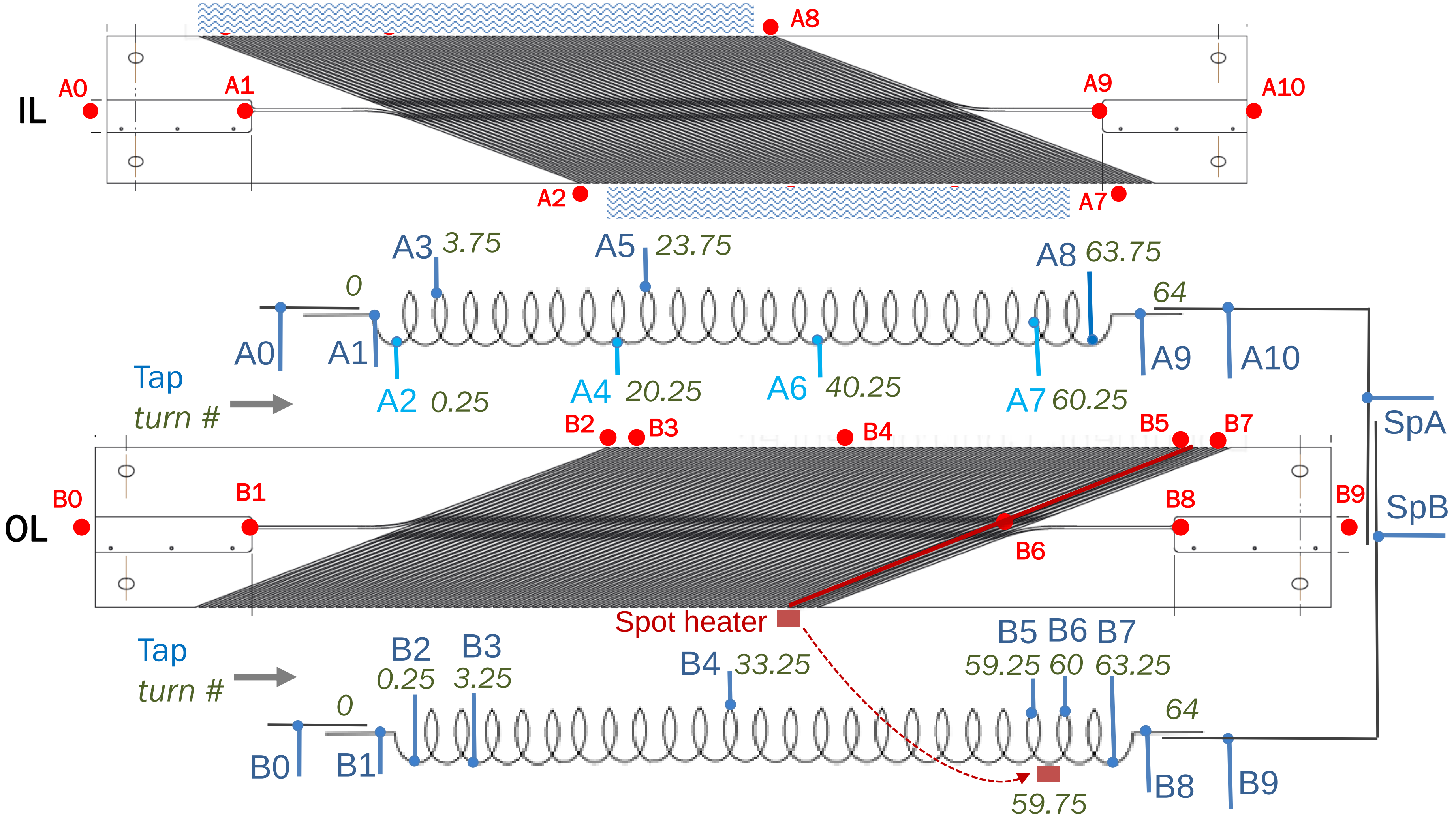




- Training
- Ramp-rate quenches at 30-200 A/s
- Forced extractions at various current levels up to 13 kA
- Heater (MQE) tests
- Magnetic measurements (z-scan and stair-step cycle)
- Quench memory

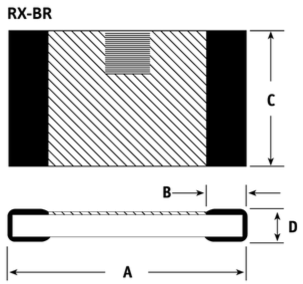
❑ Quench locations
❑ Origin of training
❑ Validation of mechanical and electrical models

Voltage tap instrumentation

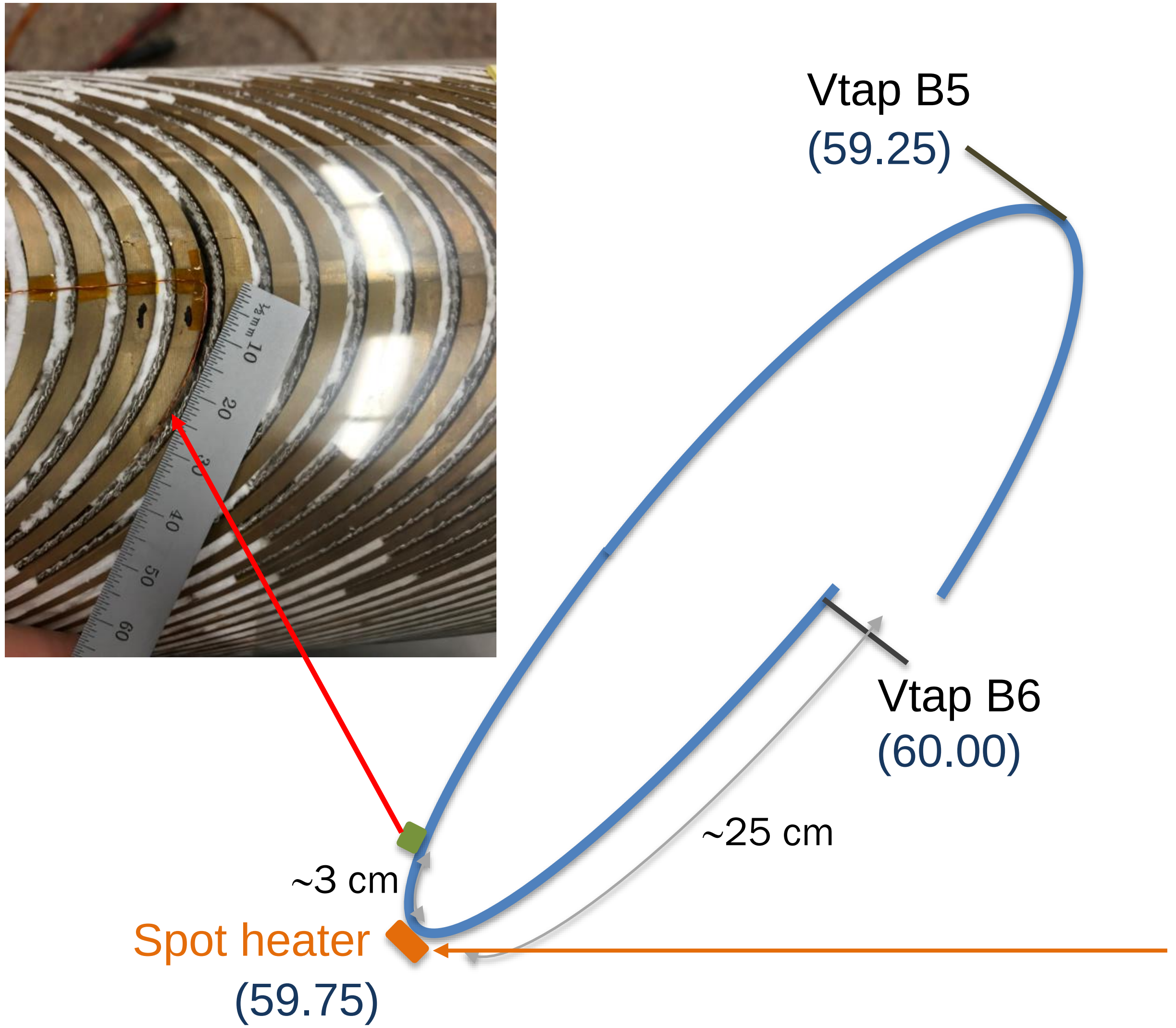


Polyimide copper-laminated voltage tap traces

In-winding thermometer and spot heater



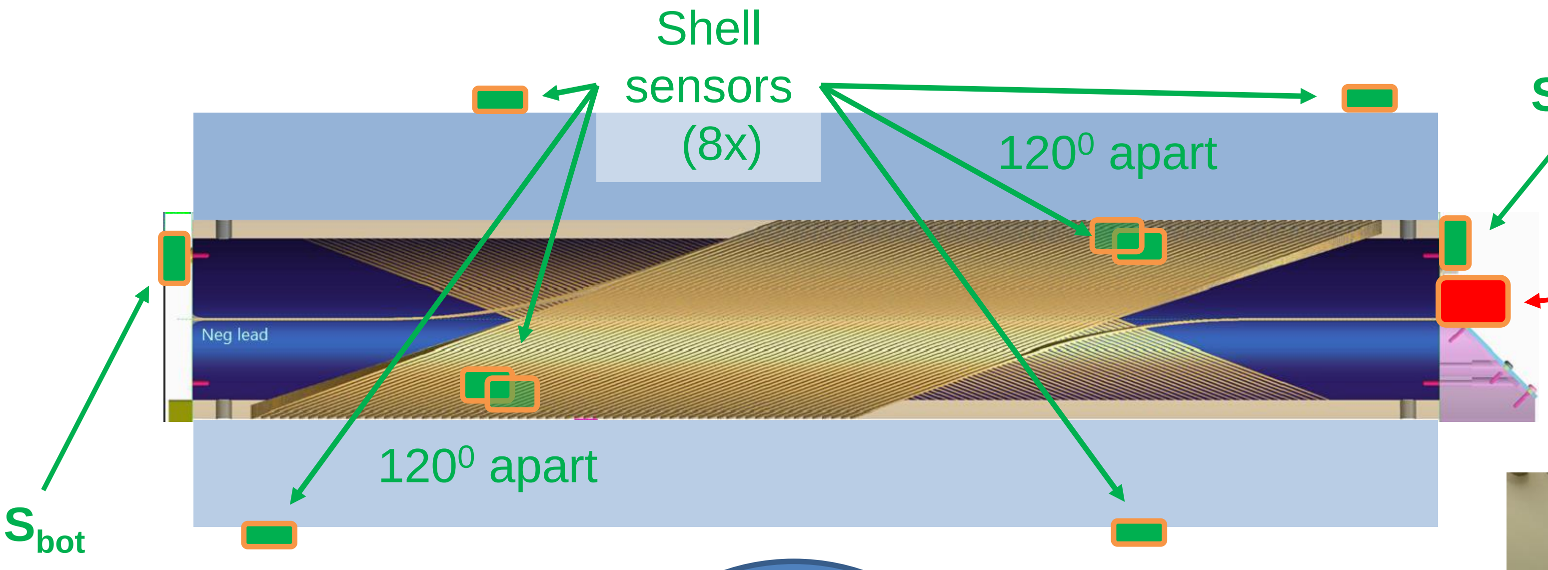
RuO bare chip thermometer (Lakeshore) ~1 mm^2



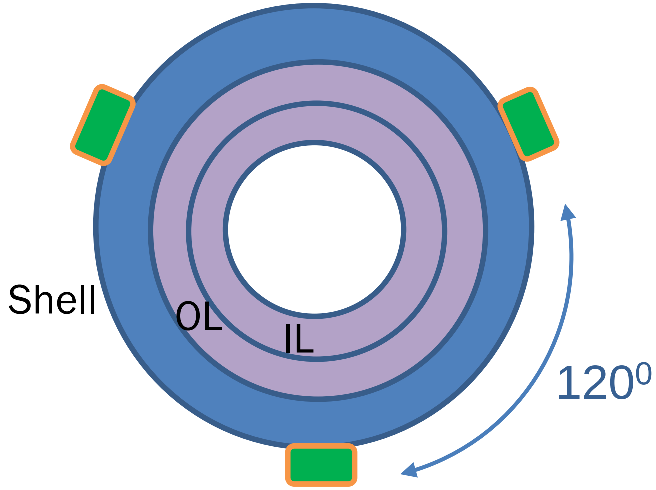
Spot heater is inserted in the cable groove at the pole location (in the 5th turn from the RE, OL)

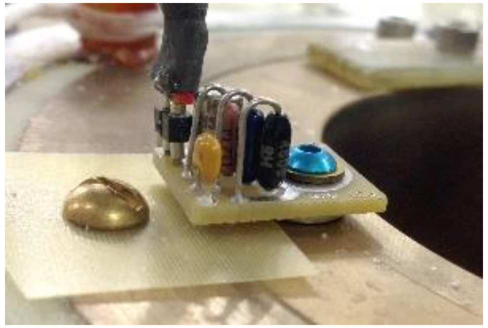
SS spot heater on polyimide substrate; ~3 Ω resistance RT

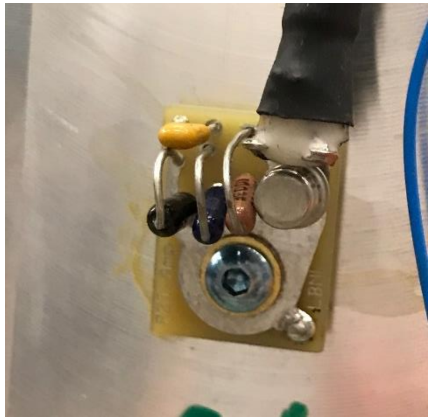
Acoustic instrumentation



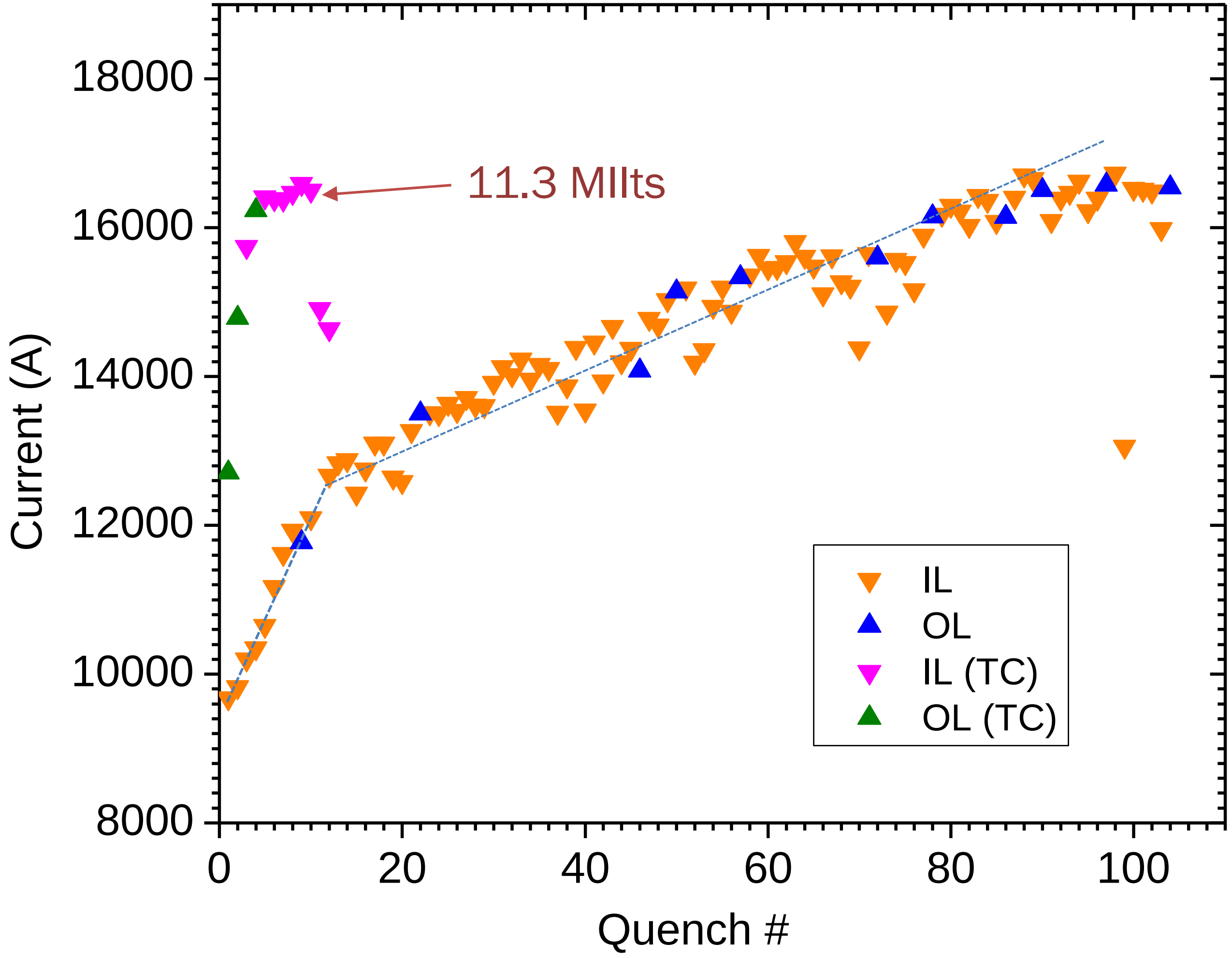
Pulse transducer







Training summary

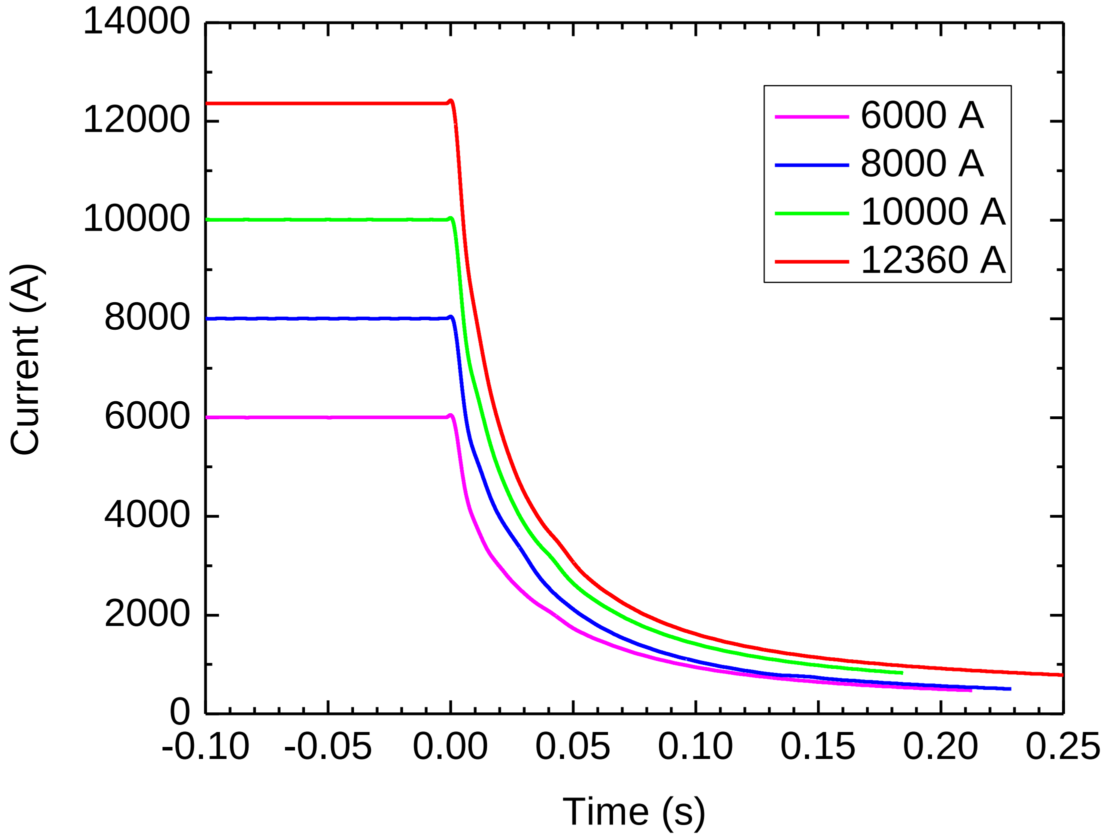


- 104 training quenches in total
- 11 quenches in the OL, the rest is IL
- Highest quench current: **16731 A**
- Bore dipole field: **9.14 T**
- Field at the conductor: 10.32 T
- “Short sample” limit: 19.3 kA (4.5 K)

- Good quench memory after thermal cycle: reached above 16 kA in 4 quenches
- Highest quench current is 16590 A (quench #9)

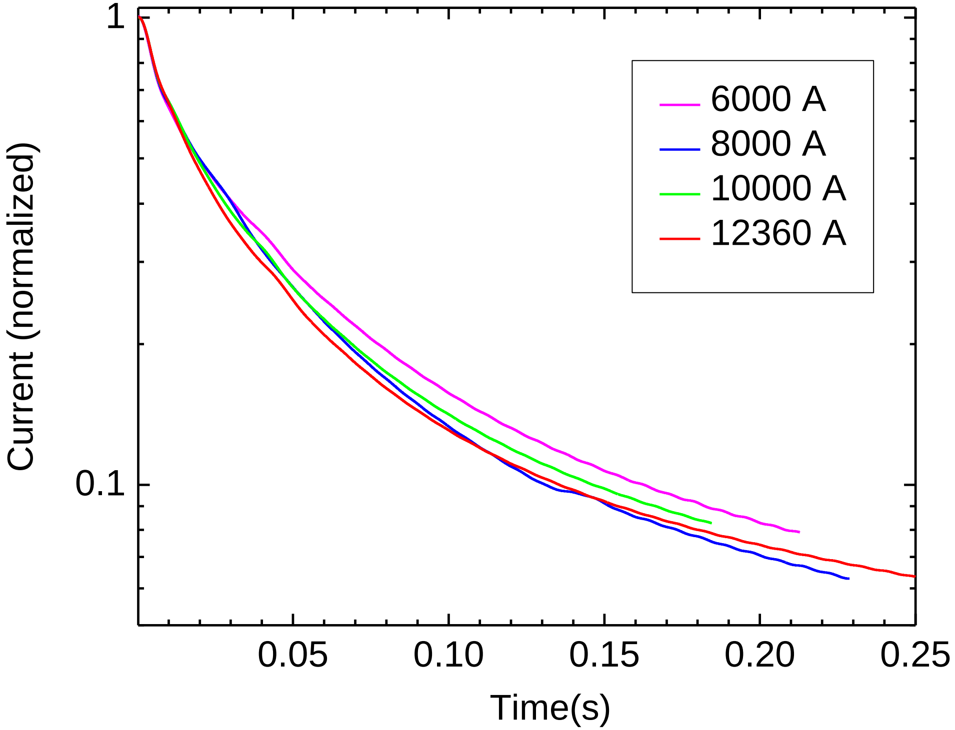
A remarkable linear trend is observed for the most part of the training, with an abrupt change of slope at ~ 13 kA

Current decay (extractions)



Series of current extraction (no quench) on 30 mΩ dump resistor at various current levels

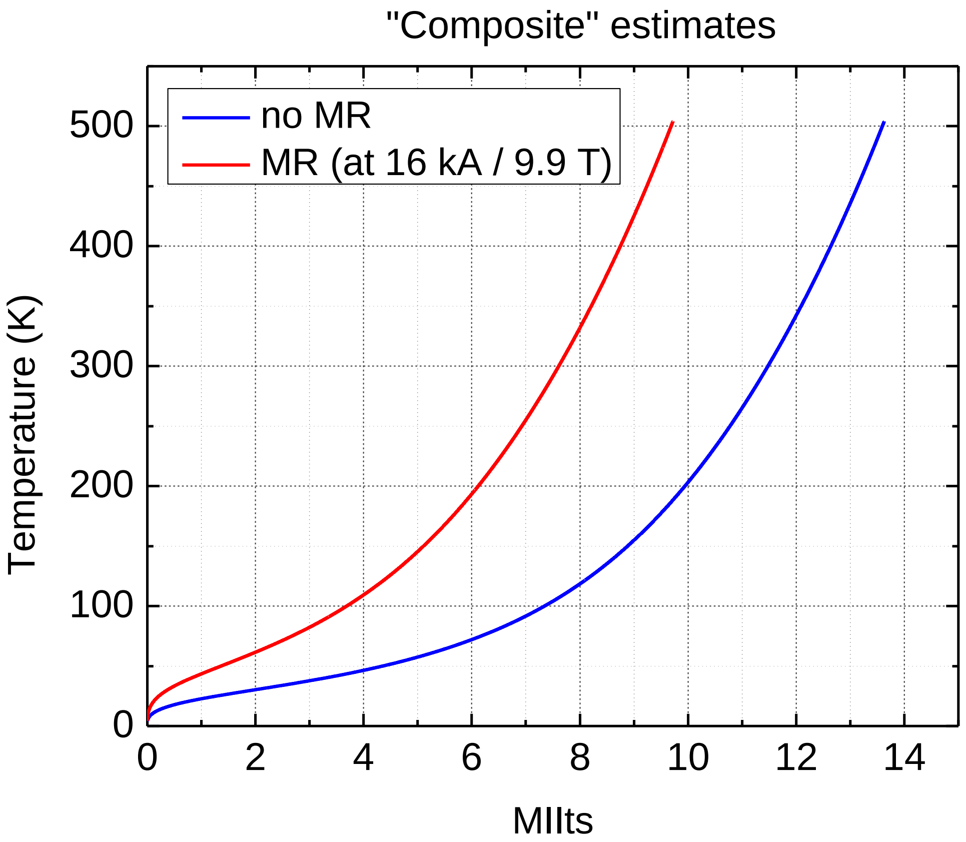
- Current decay rate is much faster than exponential, indicating **a significant effect of eddy currents and inter-filament coupling on the dynamic inductance**. To be modeled with ANSYS simulations.

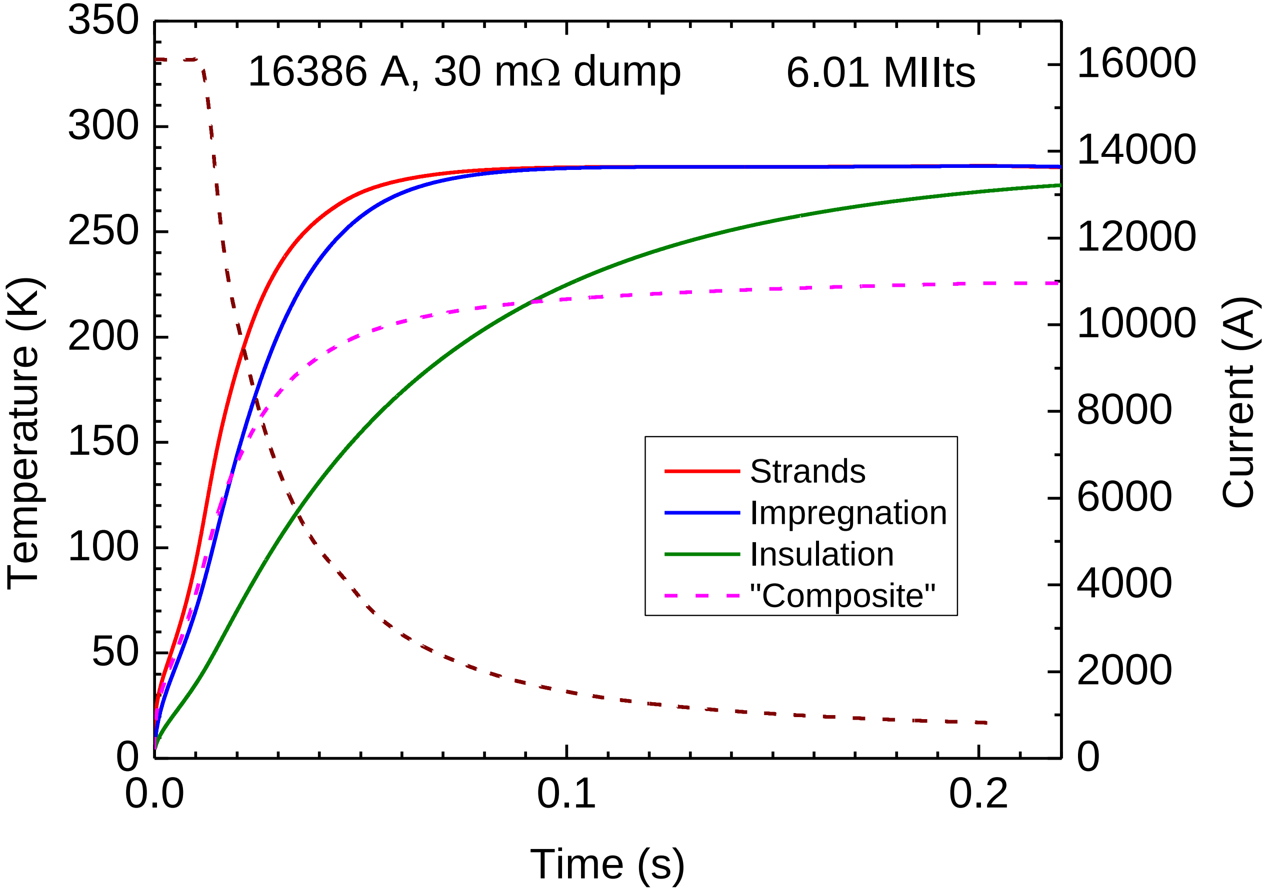


Hot spot temperature

d_{str} = 0.80 mm
# of strands = 23
$r_{Cu/Sc}$~0.83 (45.4 % Cu)
RRR = 238

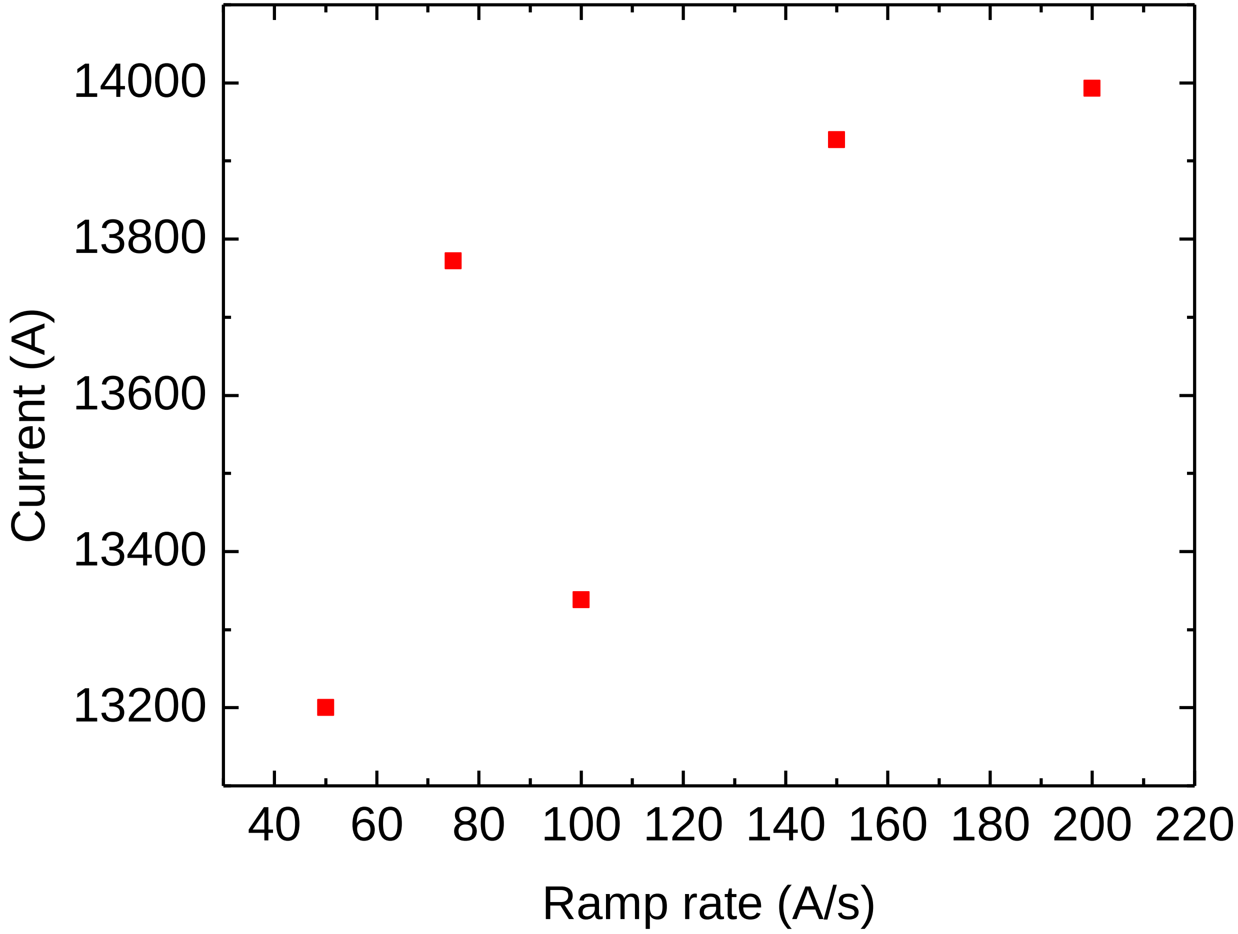
W_{cable} = 10.1 mm
D_{cable} = 1.4 mm
W_{ins} = 10.5 mm
D_{ins} = 1.8 mm





Calculation worksheets by E. Ravaioli

Ramp rate dependence

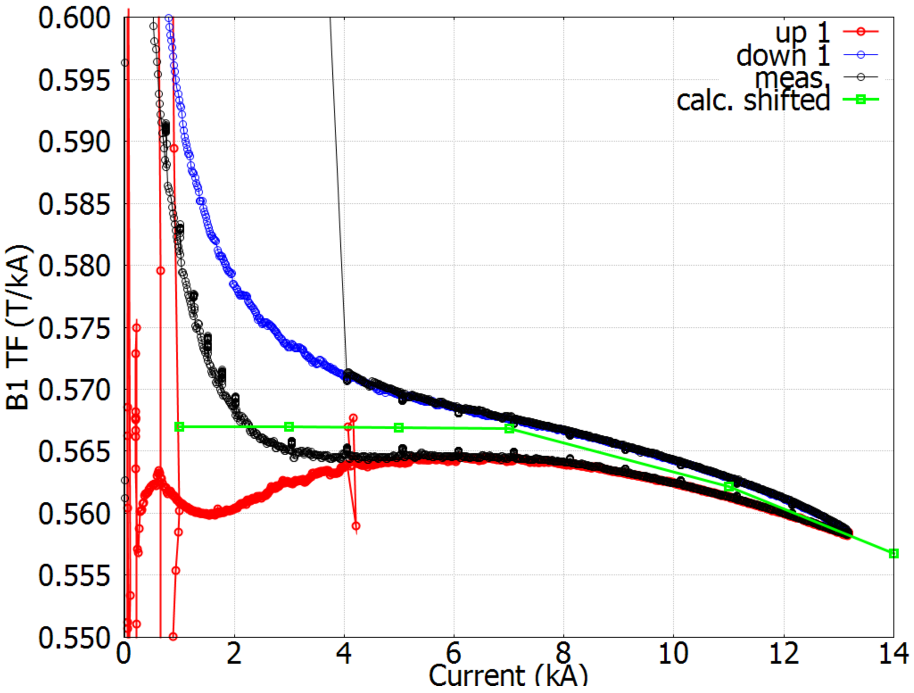


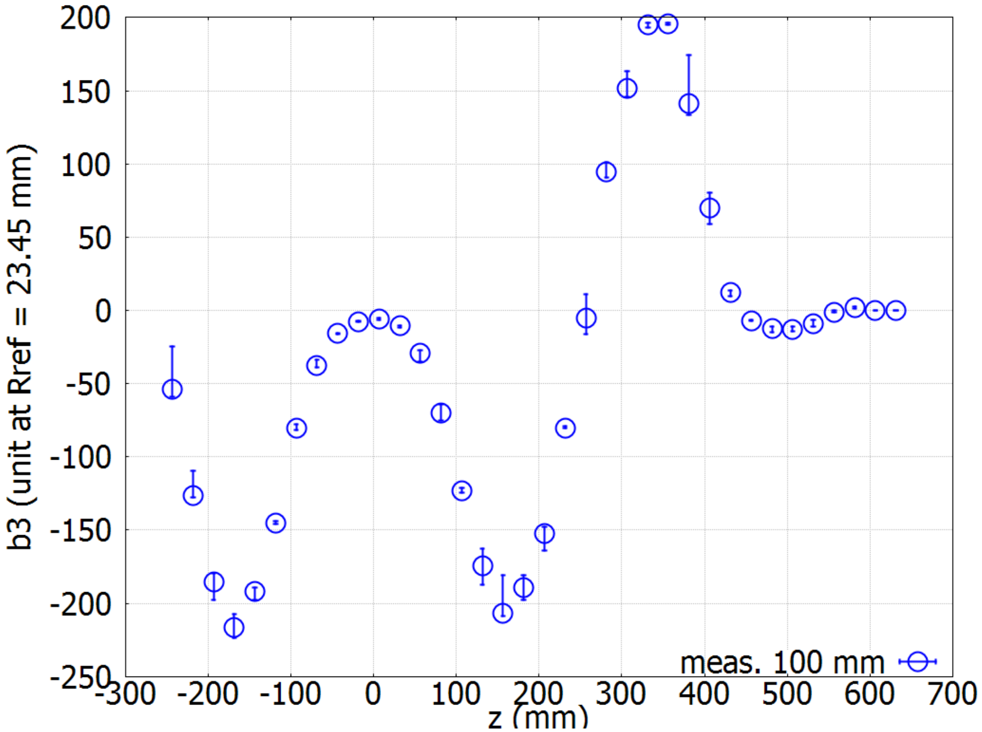
- The ramp-rate study was conducted after quench #28 (13612 A, at 30 A/s)
- No apparent ramp-rate dependence is seen up to 200 A/s (magnet just keeps training…)
- Next regular quench at 30 A/ was at 14125 A

Magnetic measurements

Joe DiMarco at FNAL developed the probe:

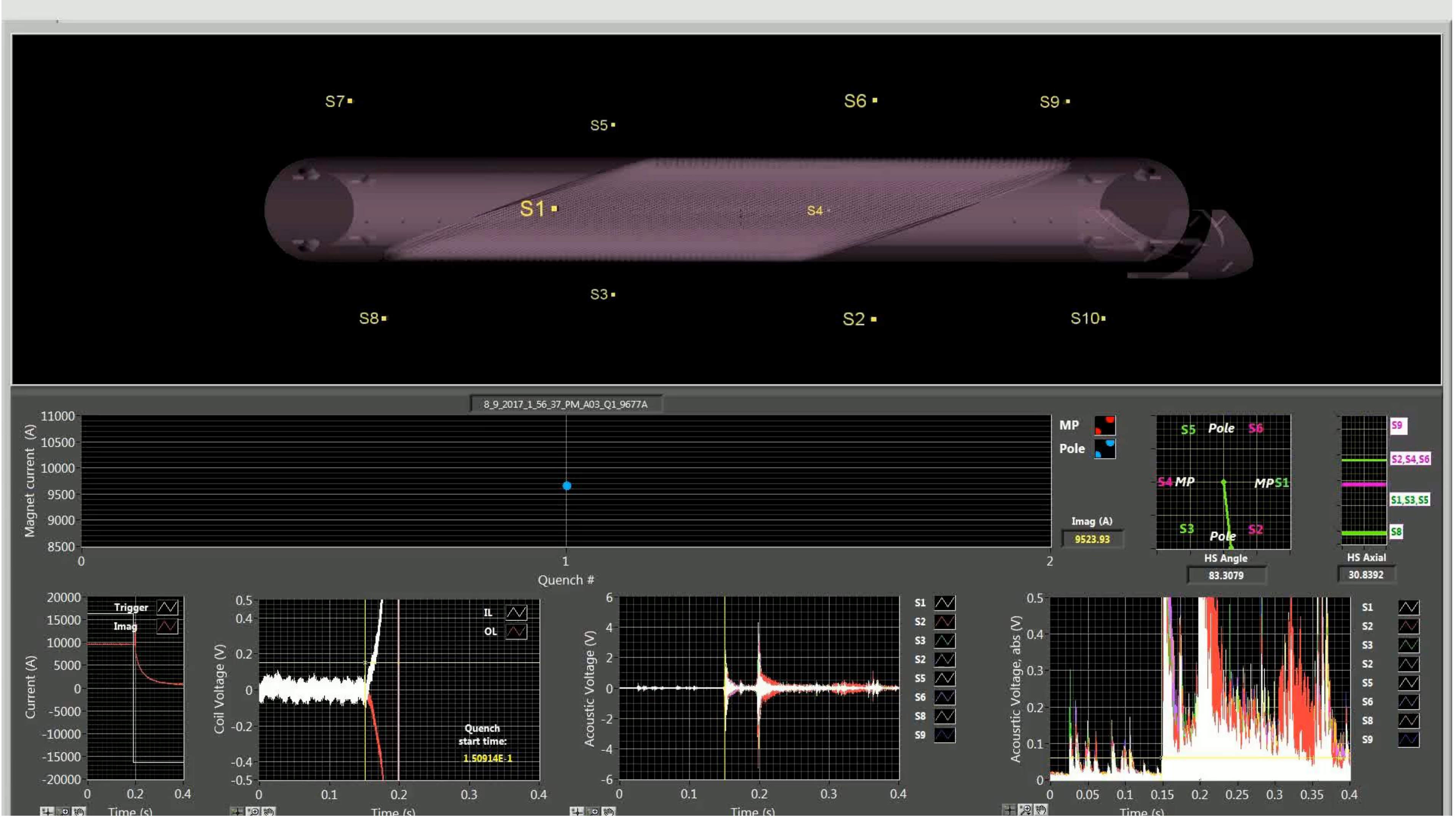
- Better spatial resolution with 25 mm length (CCT2/3 used 100 mm long probe)
- 23.45 mm reference radius (52% of available aperture, limited by the anticryostat)





(***by Xiaorong Wang***)

Quench locations: beginning of training



8_9_2017_1_56_37_PM_A03_Q1_9677A

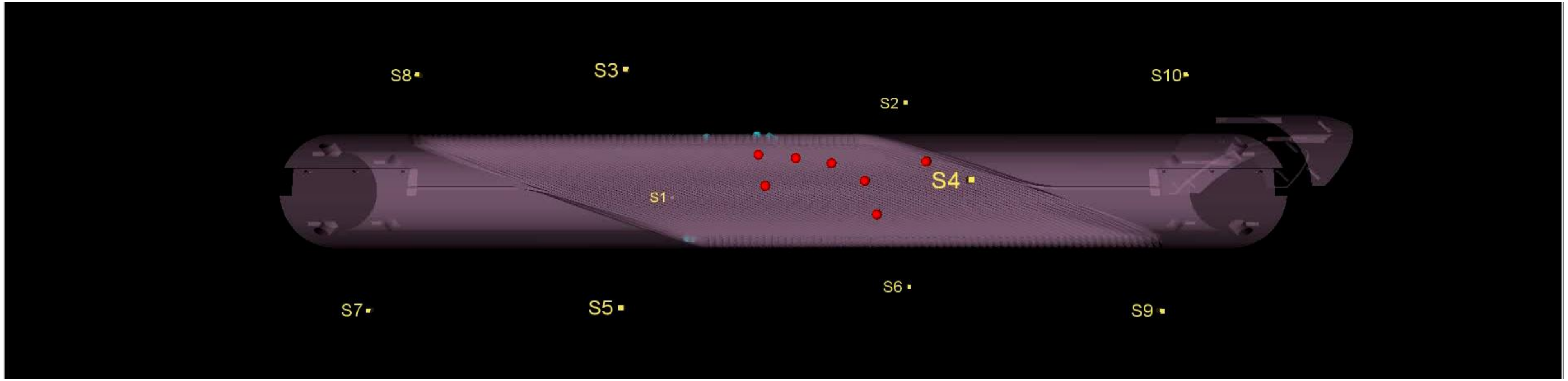
Imag (A): 9523.93

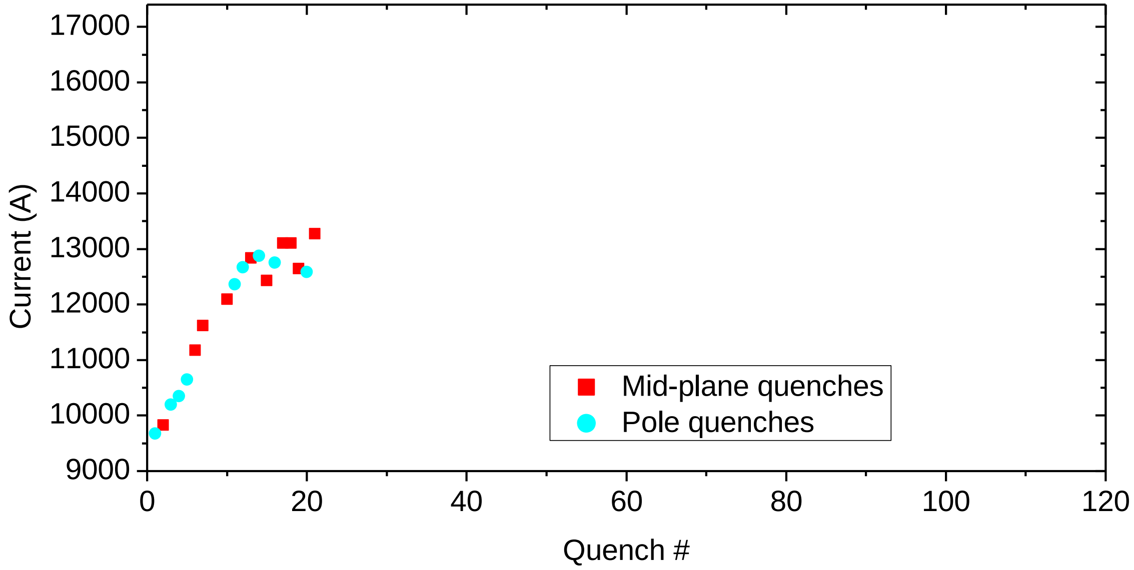
HS Angle: 83.3079

HS Axial: 30.8392

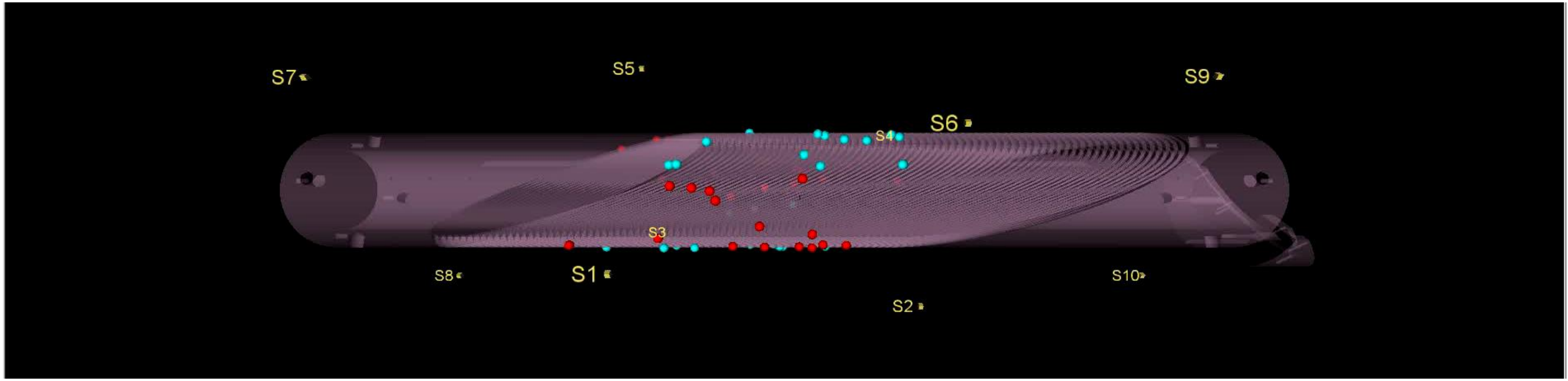
Quench start time: 1.50914E-1

Quench locations in the IL: beginning of training

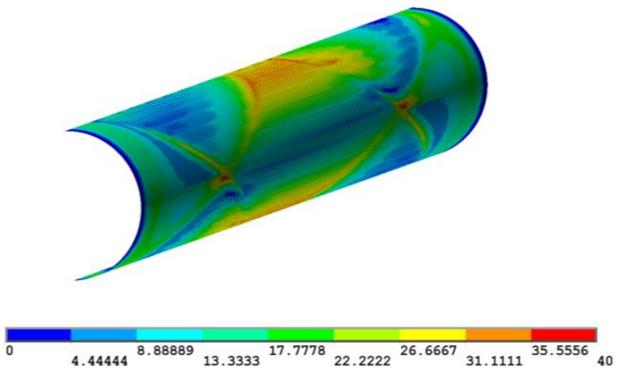


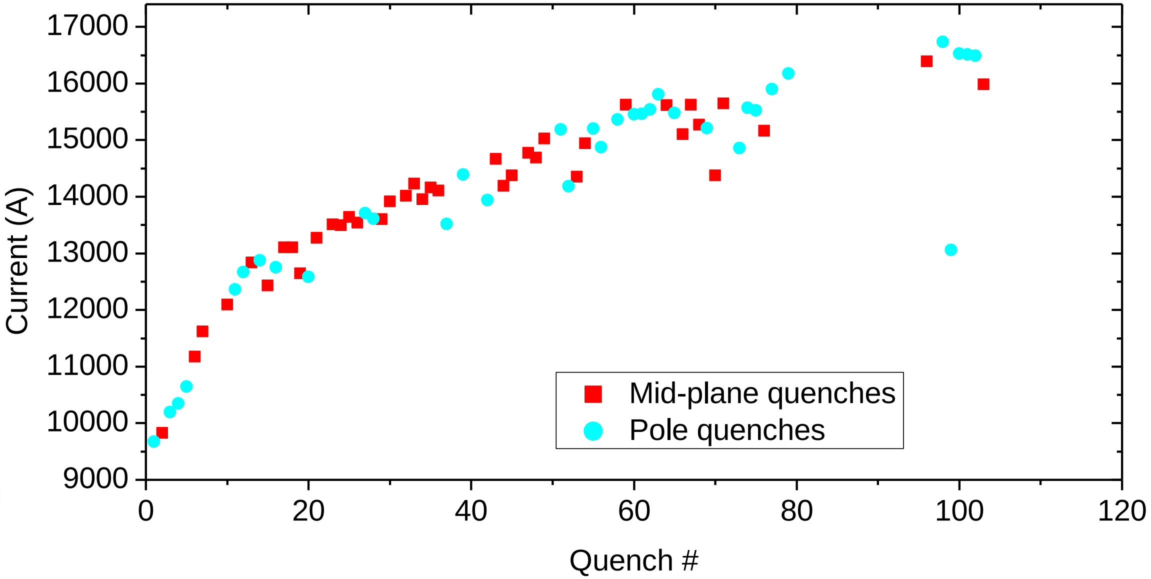


All IL quench locations

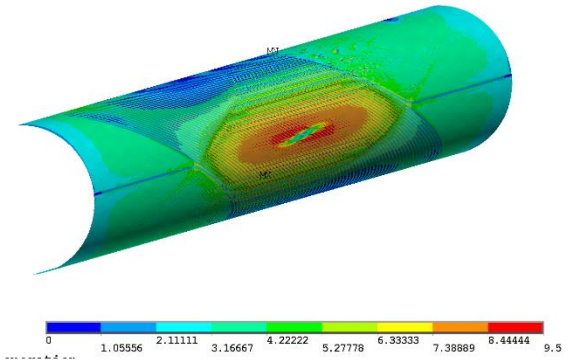


Shear stress (bonded)





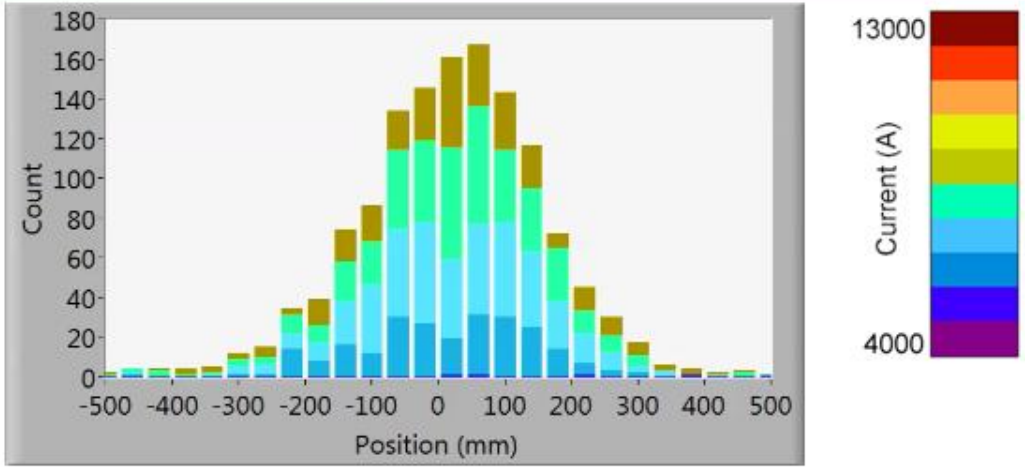
Shear stress (slip plane, μ=0.2)



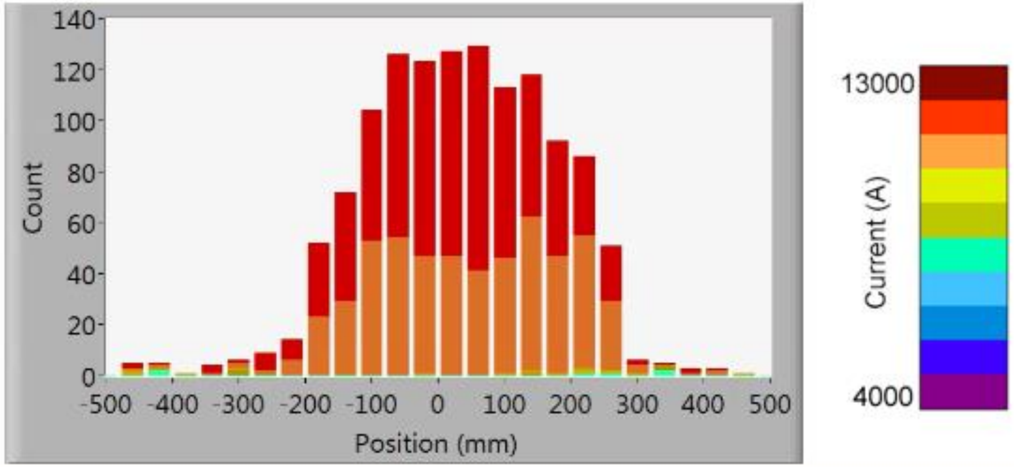
(by L. Brower)

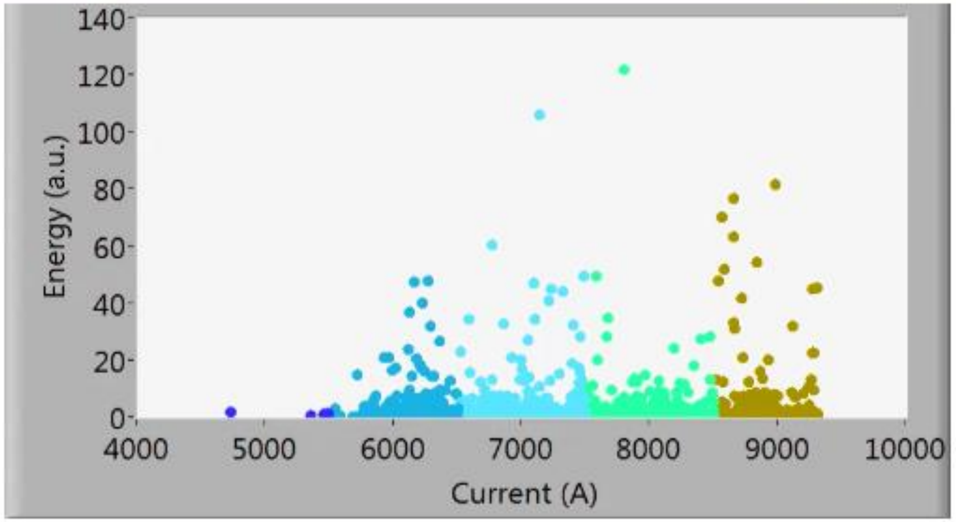
AE distribution and its evolution with training

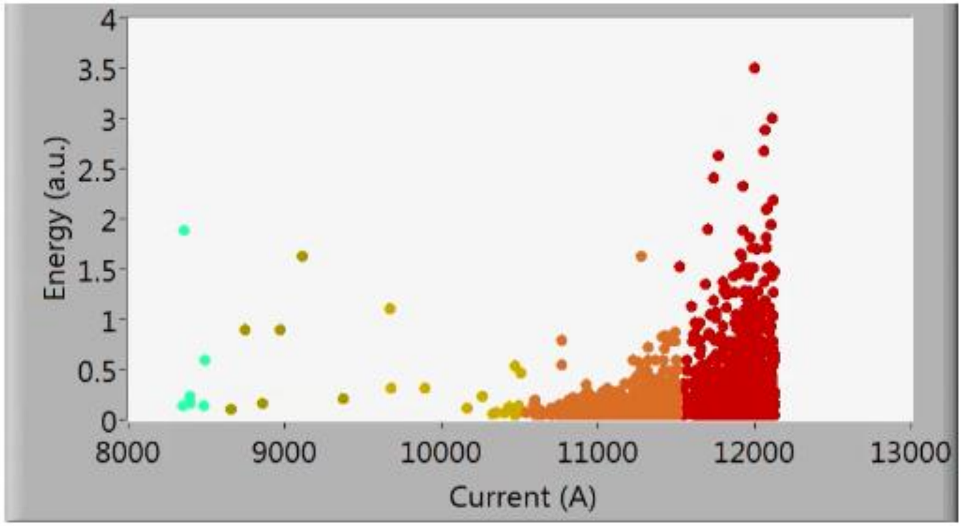
Q1



Q20

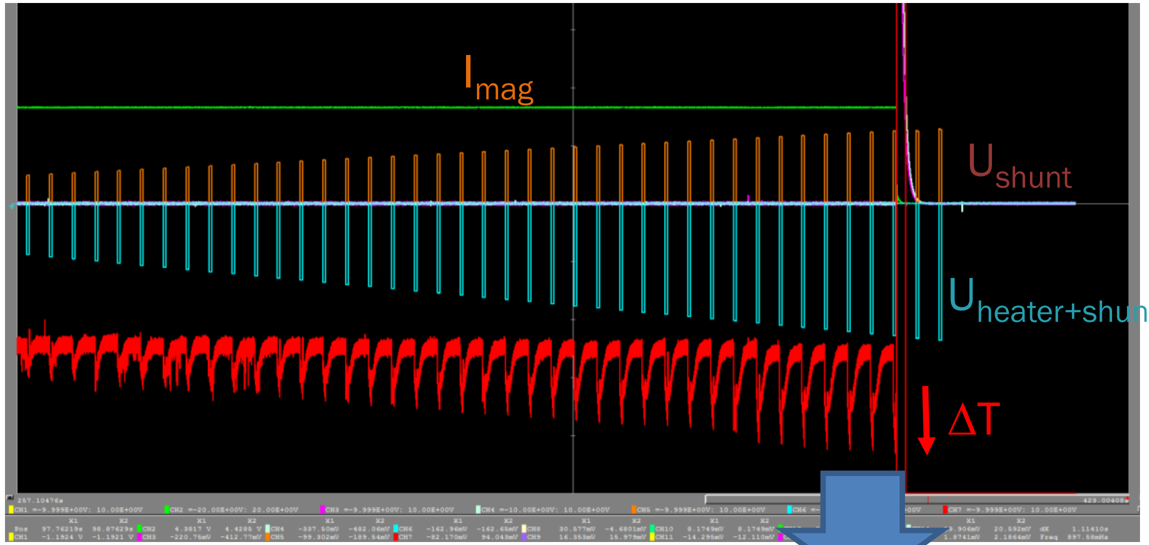


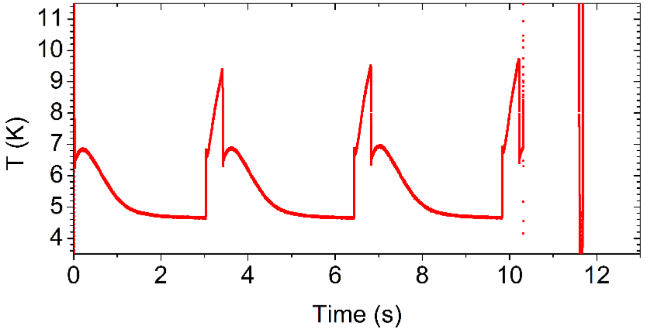


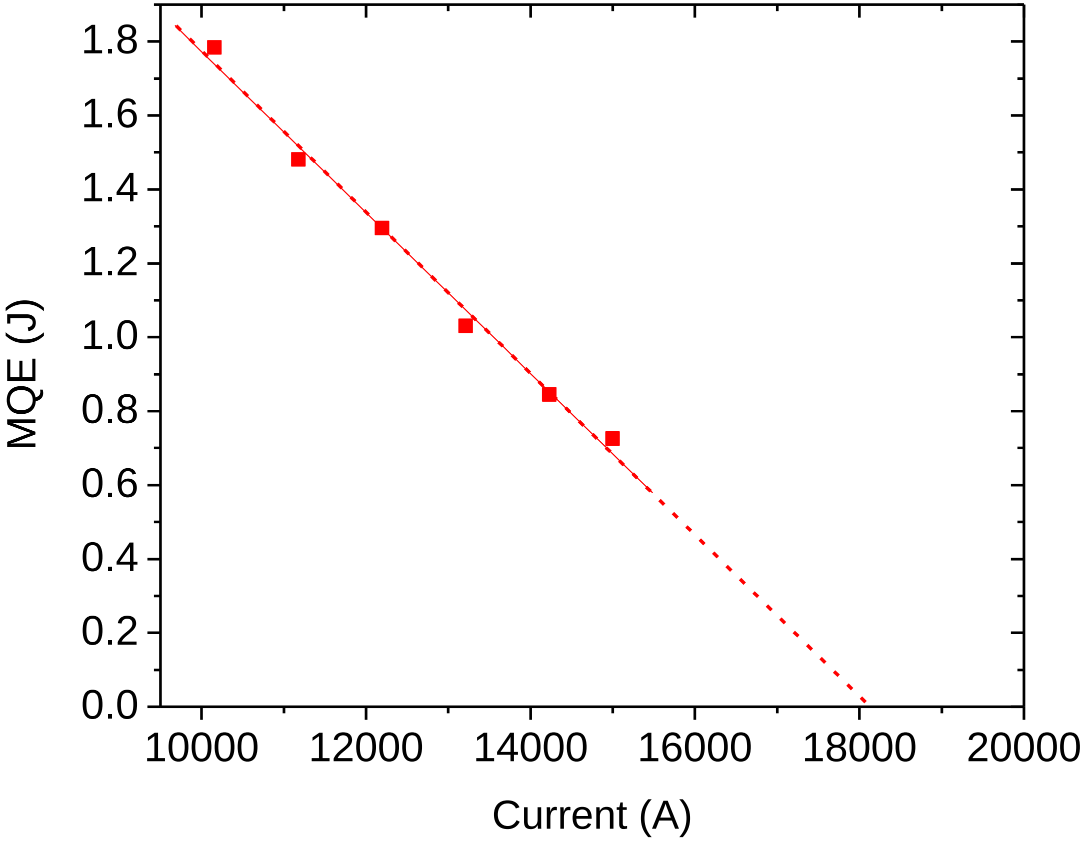


Minimal quench energy measurements

Spot heater was fired periodically for 400 ms at 3 s intervals, gradually increasing the deposited energy by increasing heater power



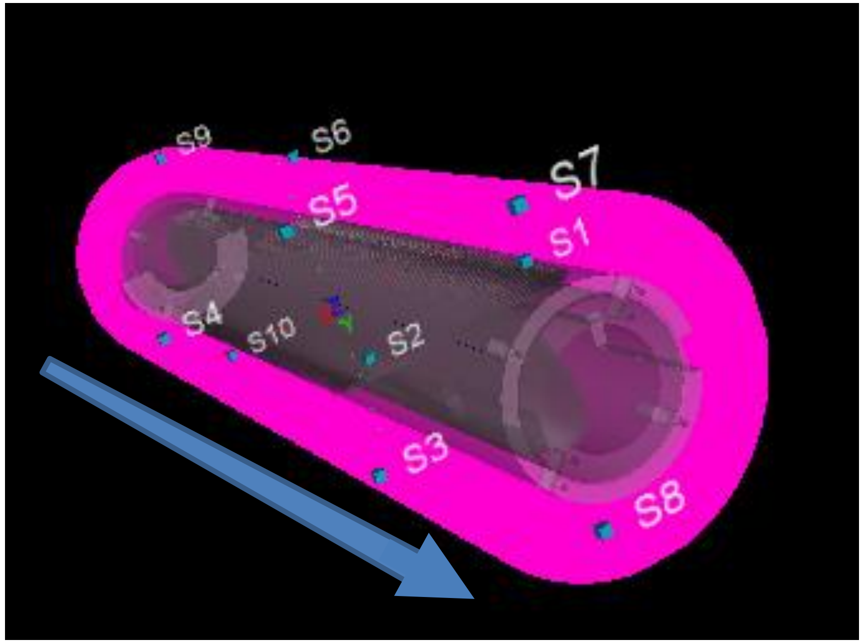




- Data to be used for validation of the thermal models

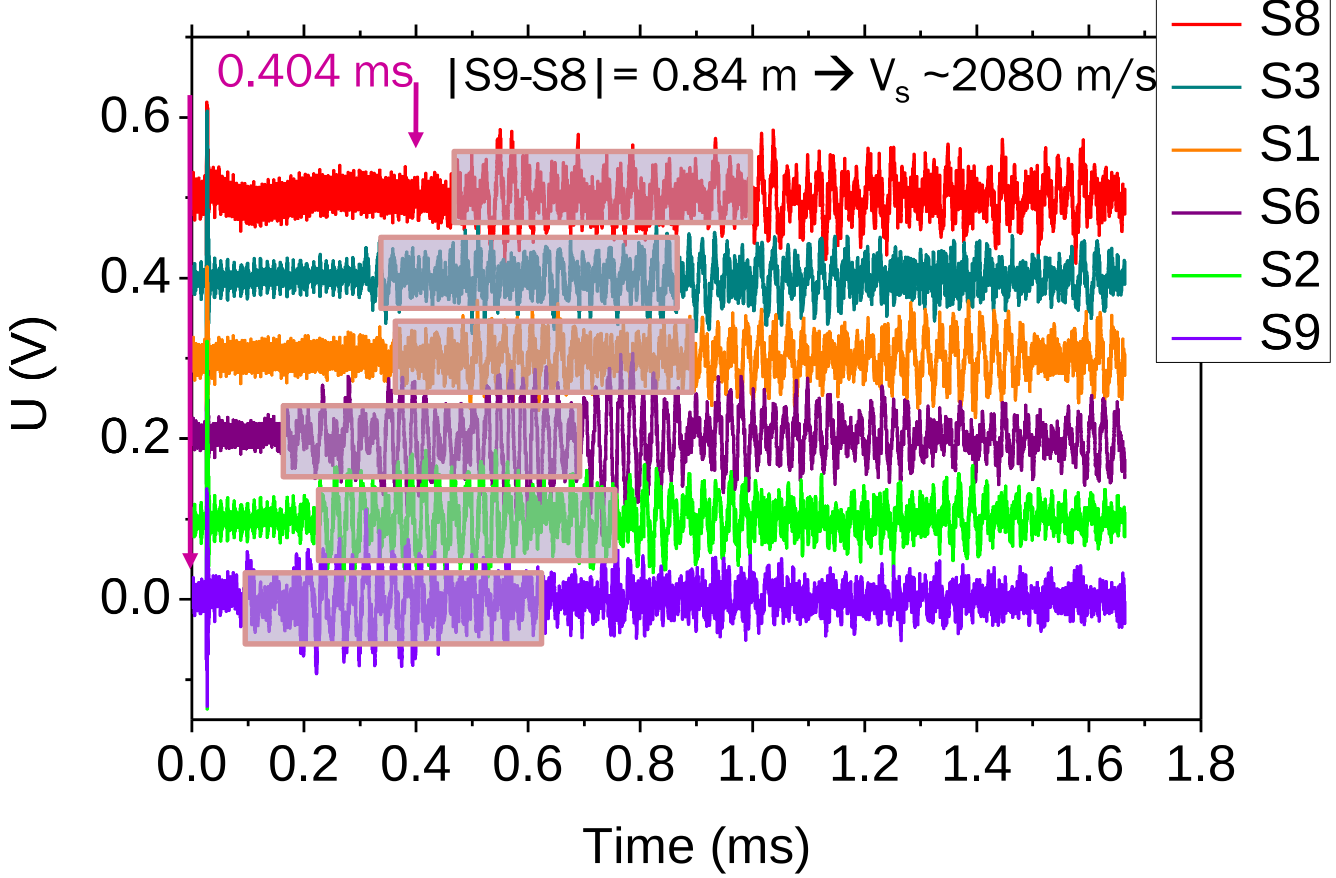
Pulses monitoring of the CCT4 magnet

Transducer is mounted on the inner layer mandrel; powered with a 100 V / 14 μs rectangular pulse at 1-10 Hz repetition rate



Pulse propagation:
S9 –> (S2 S4 S6) –> (S3 S2 S7) -> S8

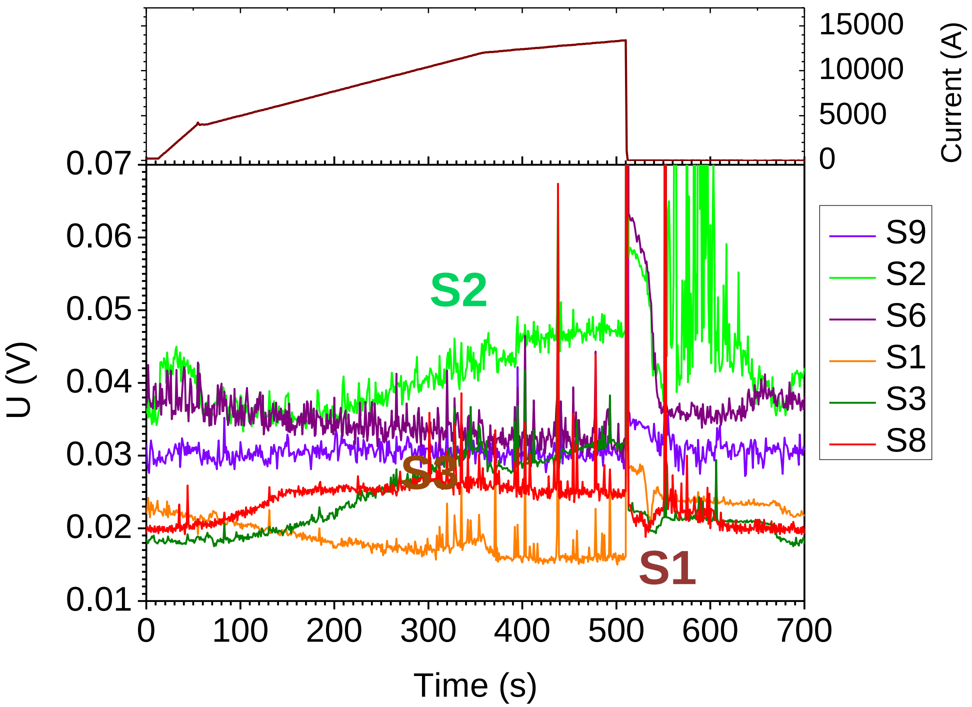
Waveforms are offset by 0.1 V on y-axis for clarity



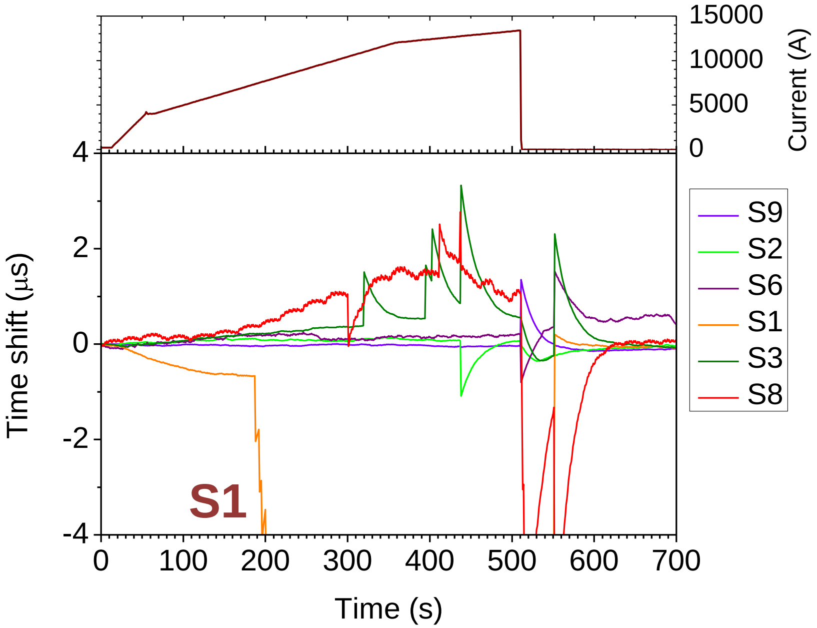
0.5 ms window is set individually for each waveform, and then periodically monitored with each pulse

Locating variation of mechanical contacts

Transmitted pulse amplitude



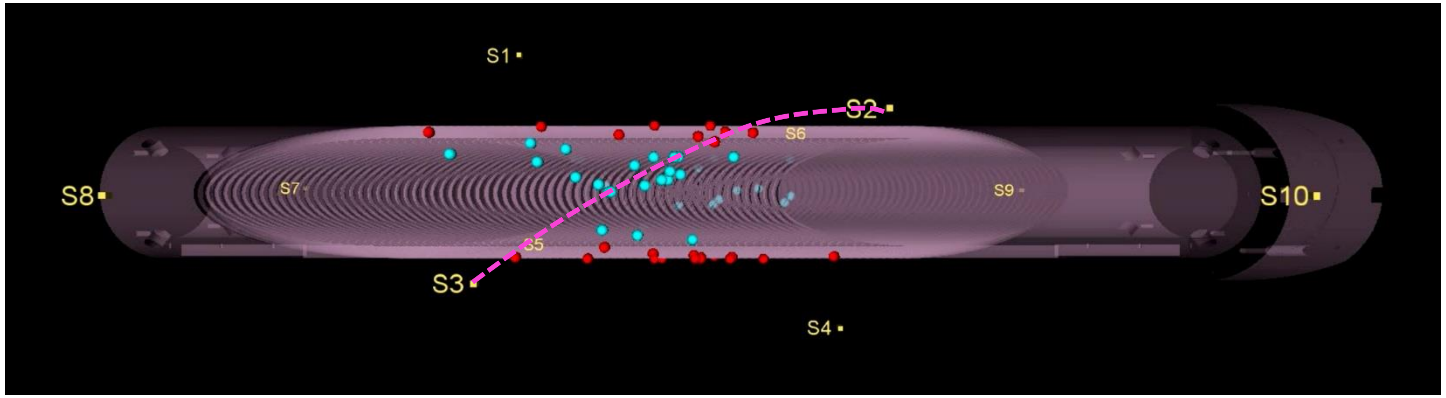
Relative time shift



Time shift is found by cross-correlating the initial "reference" waveforms with the consecutive ones.

Same principle as in:. *M. Marchevsky and S.A. Gourlay, Appl. Phys. Lett. 110, 2017 doi:10.1063/1.4973466*

- As magnet deforms under stress, sensors <u>S2 and S3 are seeing an improving mechanical contact</u> between shell and inner / outer layers, while S1 is seeing a loss of mechanical contact.



Summary on the test results

- The CCT4 magnet reached quench current: 16731 A, corresponding to bore dipole field of 9.14 T.
- This represents ~86% of the calculates short-sample limit at 4.5 K
- Training is rather lengthy; shows a remarkable linear trend characterized by distinctly different slope in the low and high current range of the training curve
- Hot spot temperature is below 300 K at 16.4 kA with no active protection by heaters or CLIQ
- When tested at ~70% of I_{ss}, quench current appears to be independent on ramp rate, up to 200 A/s.
- Quench energy is measured as ~ 0.5 J at 16 kA
- Quench locations form a distinct cluster in the pole region at the beginning of training, followed by a more linear spreading of locations along the midplane
- During ramping AE sources are initially distributed uniformly, but tend to cluster towards coil ends as training progresses
- New technique for monitoring mechanical interfaces is validated; signs of partial de-bonding were observed

Future prospects, issues, worries, needs…

We plan to test CCT5 later this year. As layers of this magnet will likely be impregnated separately, new challenges appear for installing acoustic instrumentation. But it also provides new opportunities for installing inductive quench antennas on a trace and/or fiber-optic instrumentation in the gap between layers.

Magnet test facility at LBL suffers from ongoing infrastructure-related problems:
- 37 year old helium liquefier => NEED A NEW ONE ASAP!
- Same aged capacitor banks of the SCR-based extraction system => IGBT based extraction
- Under-rated current leads and over-used connector/wiring interfaces => new cryostat header

Under-staffing by the engineering and technical personnel:
- One MTF electrical engineer who is also involved in other projects in Engineering division and cannot be present during the entire test campaign
- One electrical tech shared by all projects, including magnet testing

- Increasing pressure to accomplish concurrent testing projects within the same infrastructure