U.S. MAGNET DEVELOPMENT PROGRAM

Test of an Alumina-filled wax large-aperture Nb_3Sn canted cos-theta dipole.

M. Baldini,

J. DiMarco, S. Krave and S. Stoynev

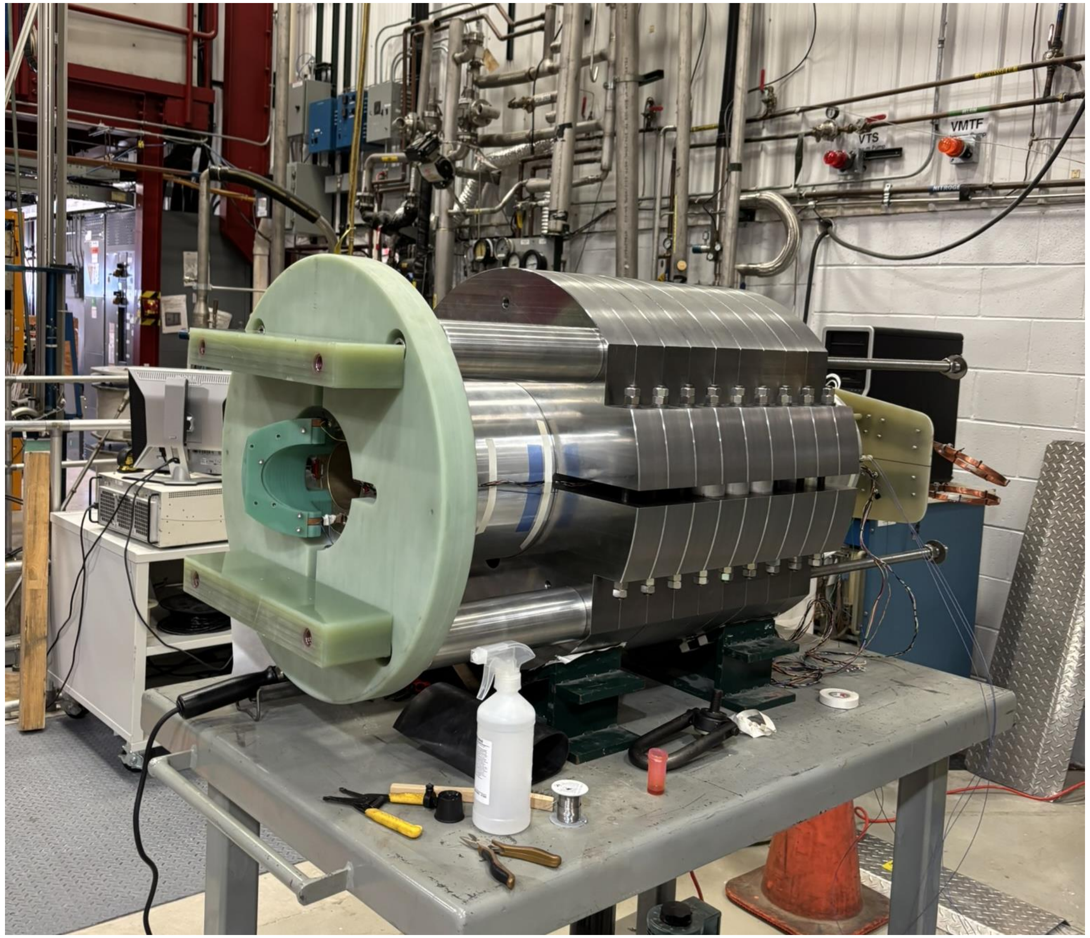
MDP meeting October 8 2025

Outline

- CCT5- W (design by D. Arbelaez and LBNL team)
  - **Nb_3Sn conductor**
  - Impregnated with filled wax
  - 90 mm bore

  - **The magnet was designed and fabricate at LBNL**
  - **Tested at FNAL because of power supply limitations at LBNL**
  - **Test campaign started on June 18 and it was completed a couple of weeks ago.**

  - **Magnet is now warm ready to be removed from the pit**

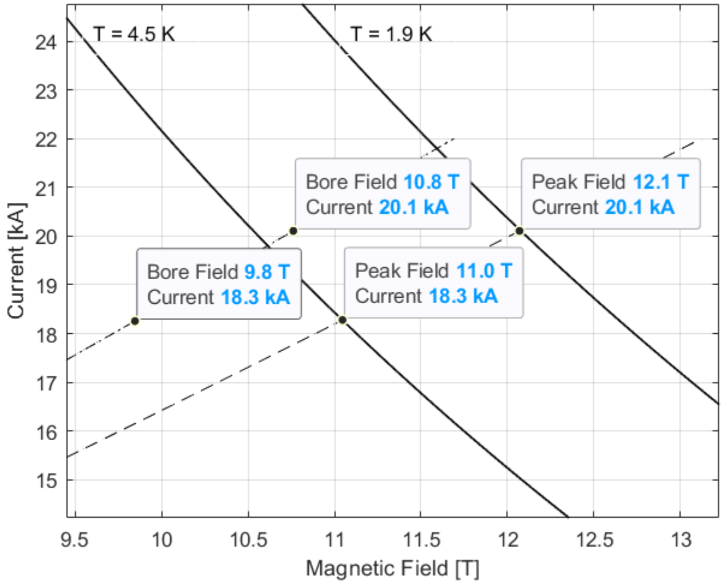


CCT5-W Test Objectives

- Probe training behavior and operating limit of filled wax impregnated CCT magnet that is otherwise identical to CCT5 (90 mm aperture, ~ 10 T bore field at 4.5 K)

- Probe memory after thermal cycle
- Probe temperature dependence of training and operating limit.

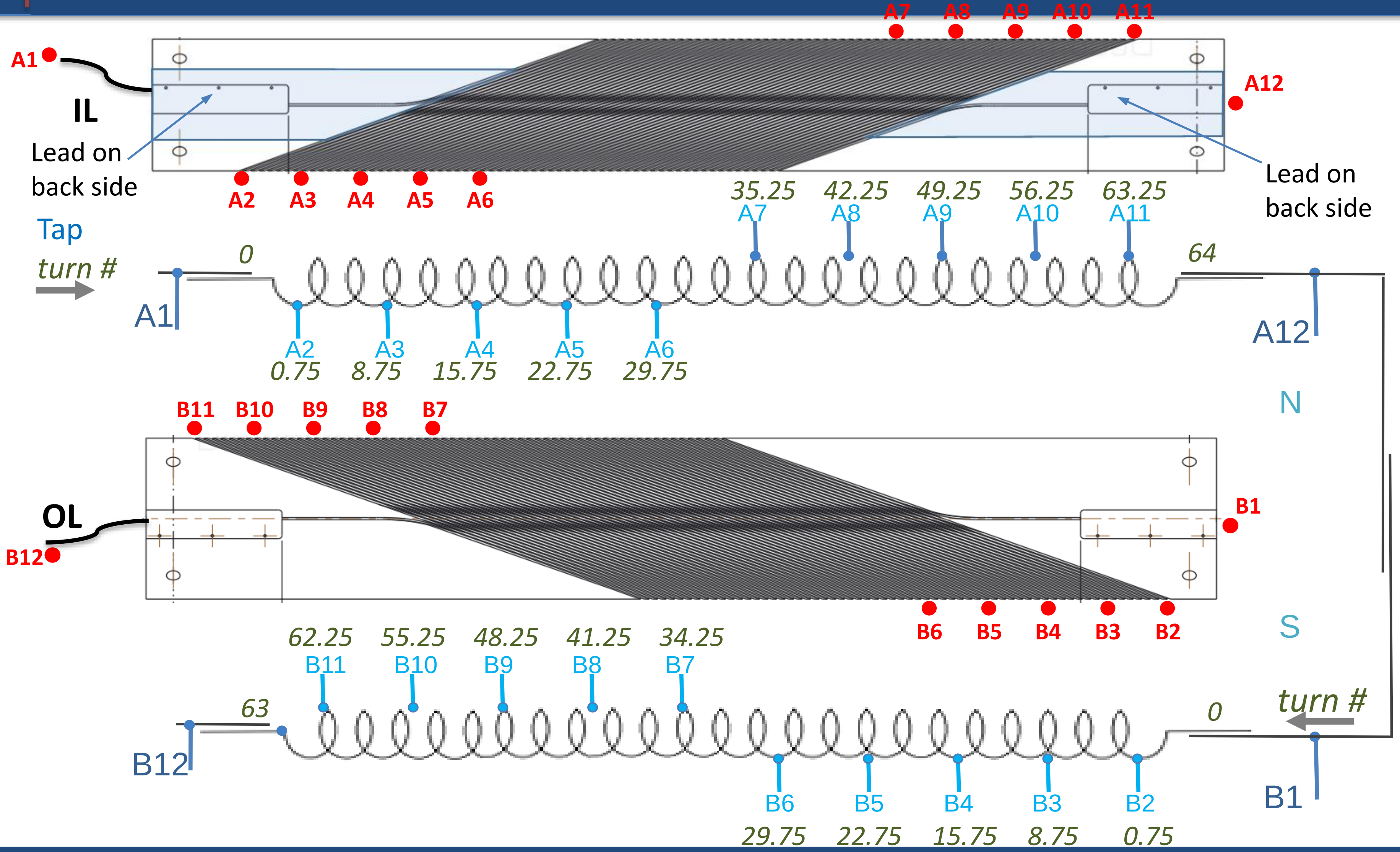
- Estimated SSL current is 18.3 kA at 4.5 K and 20.1 kA at 1.9 K



CCT5W voltage tap arrangement

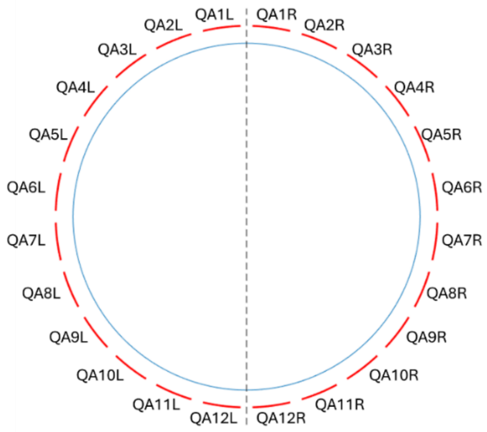
- 10 internal voltage taps per coil (20 total)
- Voltage taps wires on Nb-Ti leads on both lead end and return end (4 total)

First thermal cycle we did not have A11-A12 segment properly established



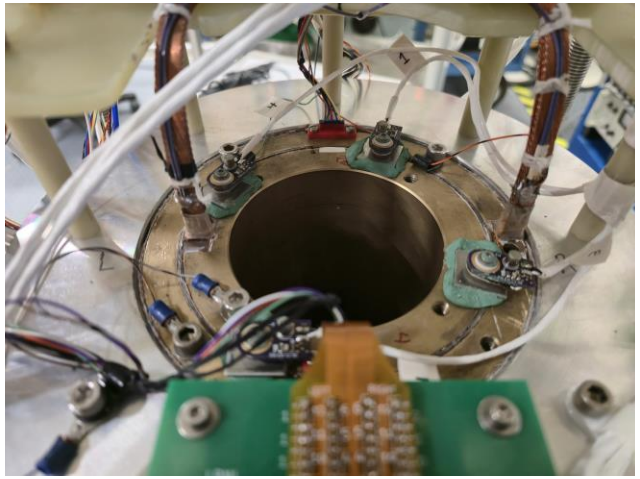
CCT5-W Instrumentation provided by LBNL

- Strain gages
  - 2 azimuthal / longitudinal strain gage stations on the shell at the midplanes (4 channels)
- Quench antennas
  - 12 quench antenna signals (24 elements with left/right subtraction)
- RF sensor (2): top head modification
- Optical fiber on the shell (2)



Instrumentation provided by FNAL

Acoustic sensors: #8 installed on the top and bottom of the magnets



Warm bore flex Quench Antenna:

- 28 mm antenna with slanted channel orientation (2 × 10 channels) and another one with 10 straight channels
- 41 mm antenna with 16 channel that can slide over
- 100 kHz sample rate

CCT5-W test plan

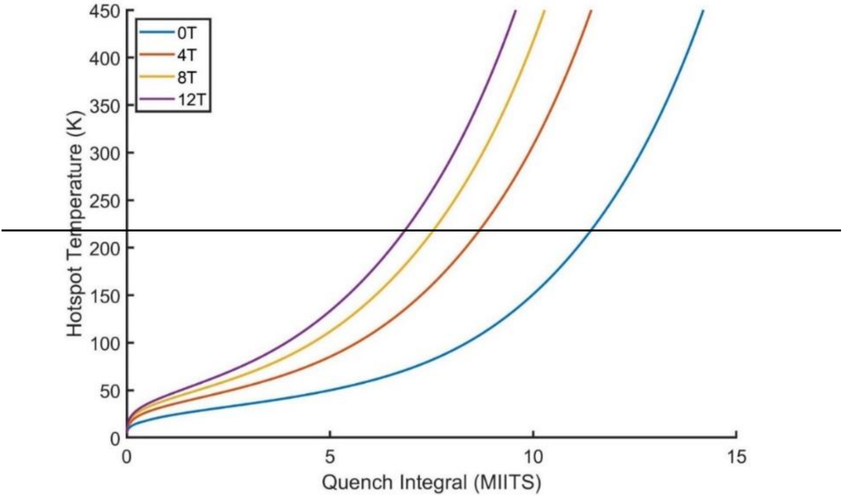
- **At 4.5 K operation with 30 mΩ dump resistor:**

  The maximum current will be limited to 18.3kA, 8.5 MIITS

  - If no quenches occur, stop and trip each 2 kA starting from 10 kA and check current discharge time and MIITs to make sure the magnet can be protected.
  - Ramp to 20/50 A/s up to 19kA.
  - Ramp rate studies

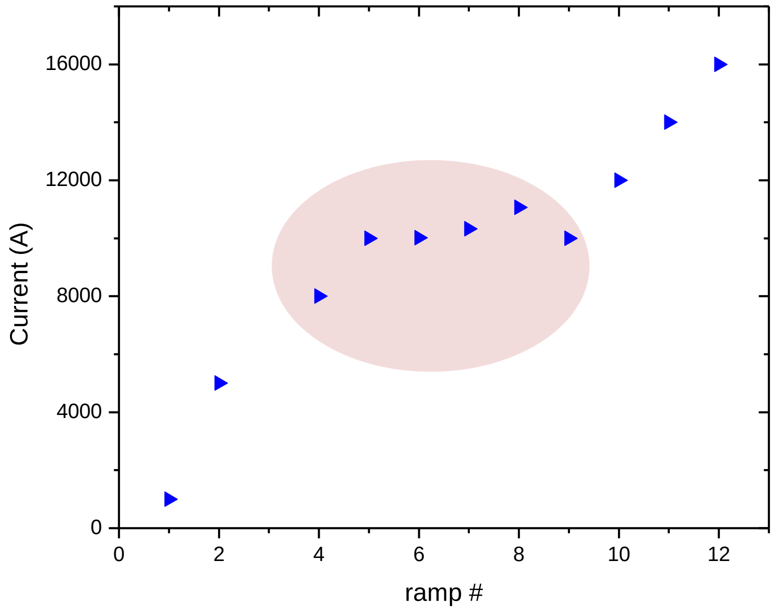
- **At 1.9 K operation with 30 mΩ dump resistor:**
  - The maximum current will be limited to 20.1 kA and 8.5 MIITs
    - Temperature dependence studies (2.2/2.8/3.4/4.0/4.5 K)
    - Magnetic measurements

CCT5-W MIITS assuming RRR=291



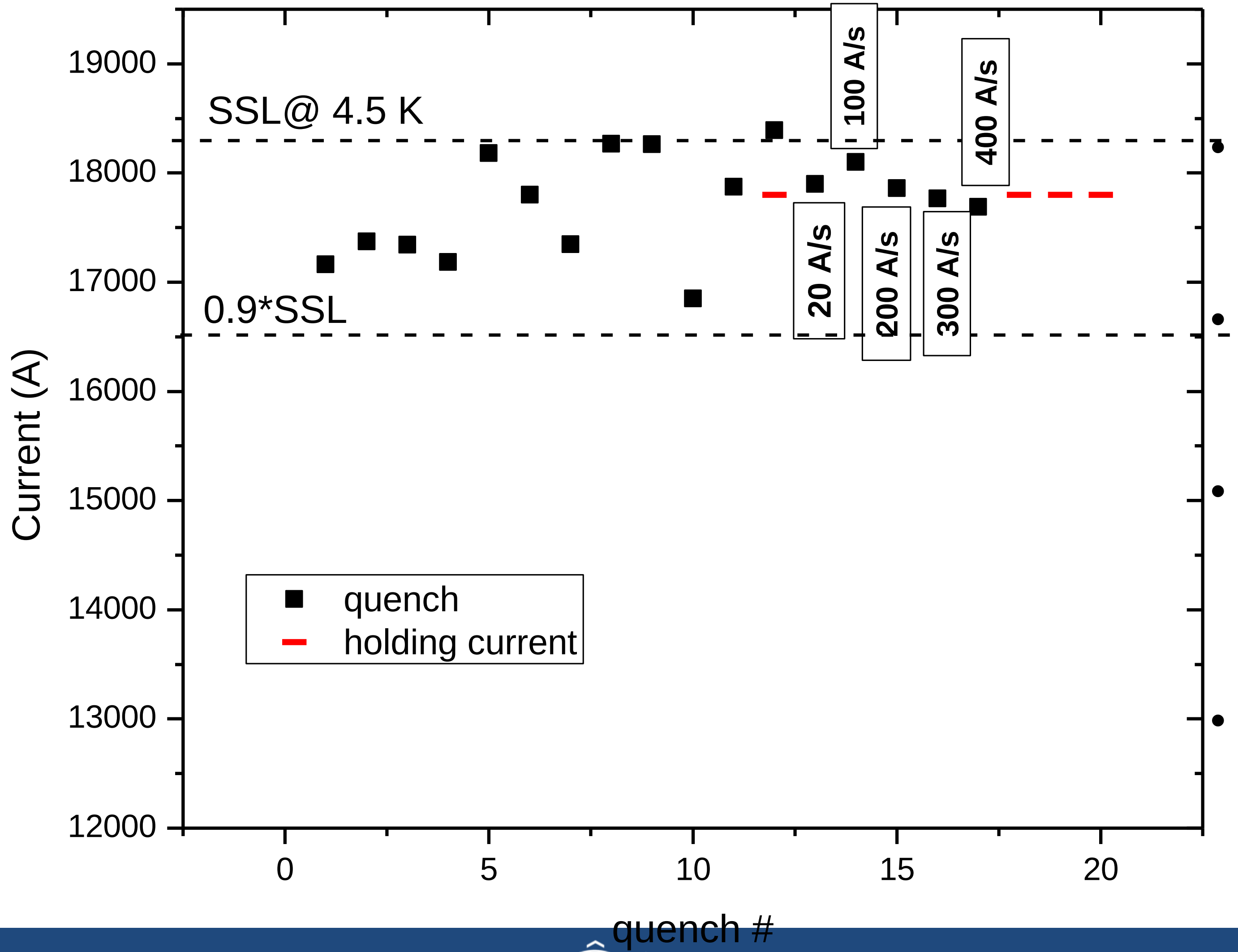
Available MIITs are around 8-8.5 @8-10 T
We expected to use 5 MIITs during currents decay at high current.

Test was started with a very conservative approach.
For I>10 kA: ramp to current levels were performed with 2kA steps and then trip.



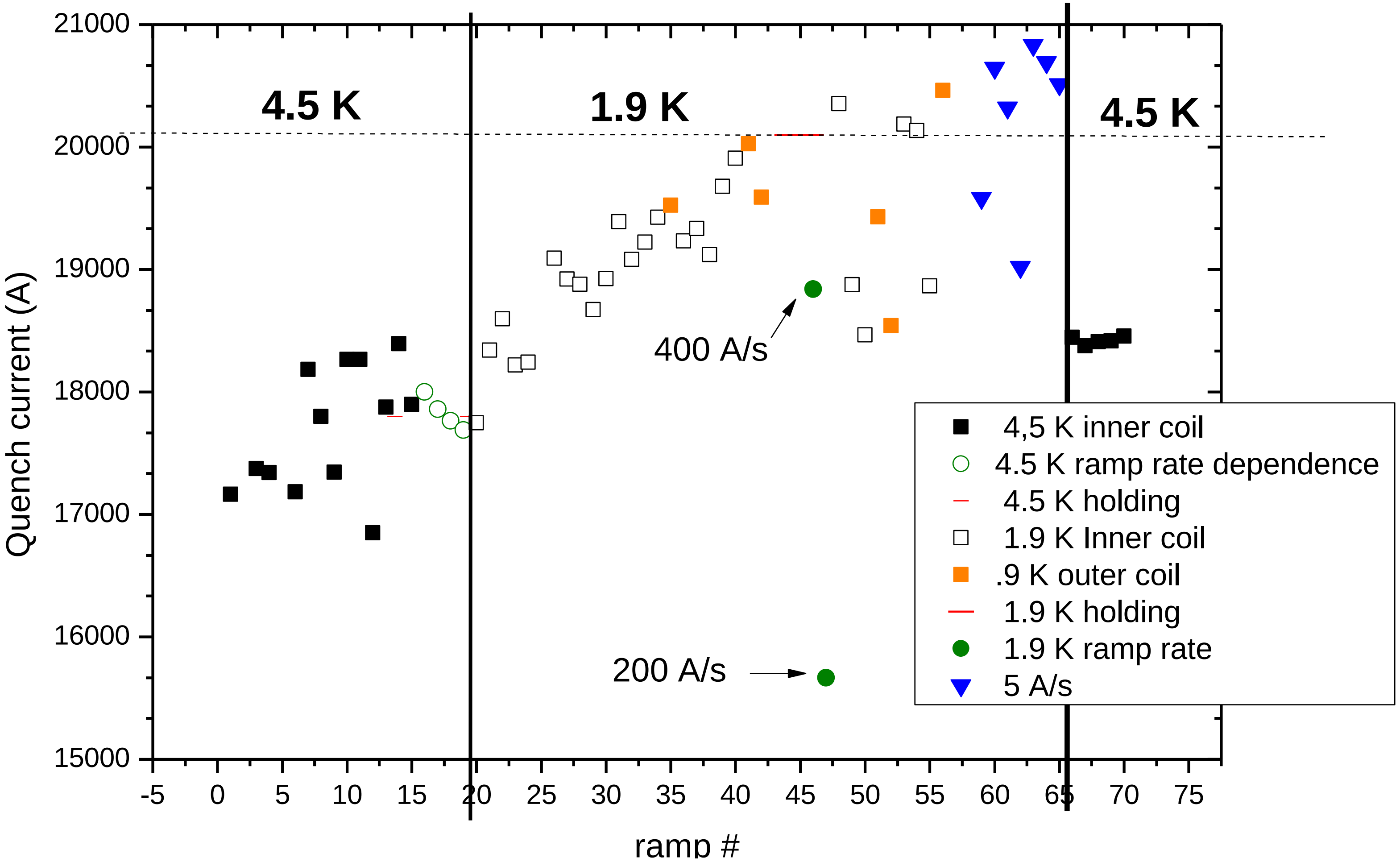
- **Voltage threshold was increased from 50 to 250 mV**
- **Nominally 3 ms dump delay, 1.8 ms actual delay (to see voltage rise)**

"Training quenches at 4.5 K"



- From quench 4: 250 mV detection voltage and 1.8 ms delay
- Ramp 13: we ramp to 17.8 kA, hold current for 10 min then ramp and quench at 18.4 kA
- The last three ramps: ramp up to **17.8 kA (97% SSL)**, **hold current for 10 min** and ramp down to 0.
- All quenches were in the inner coil: A04-A03, A07-A07

Training quenches at 1.9 K

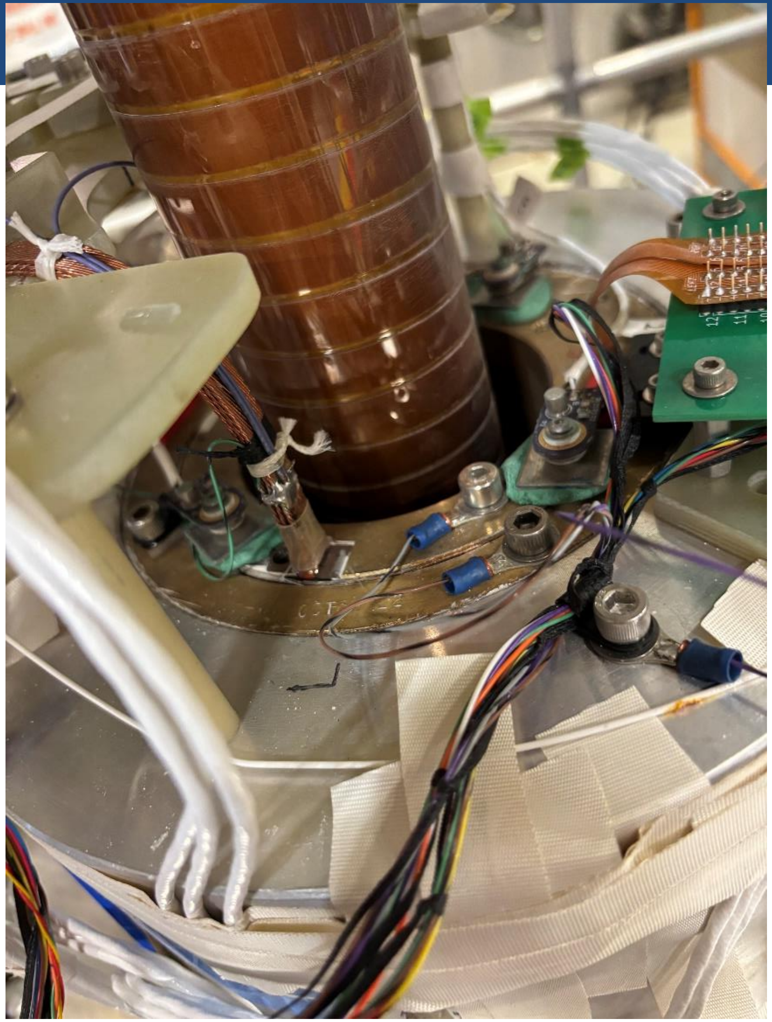


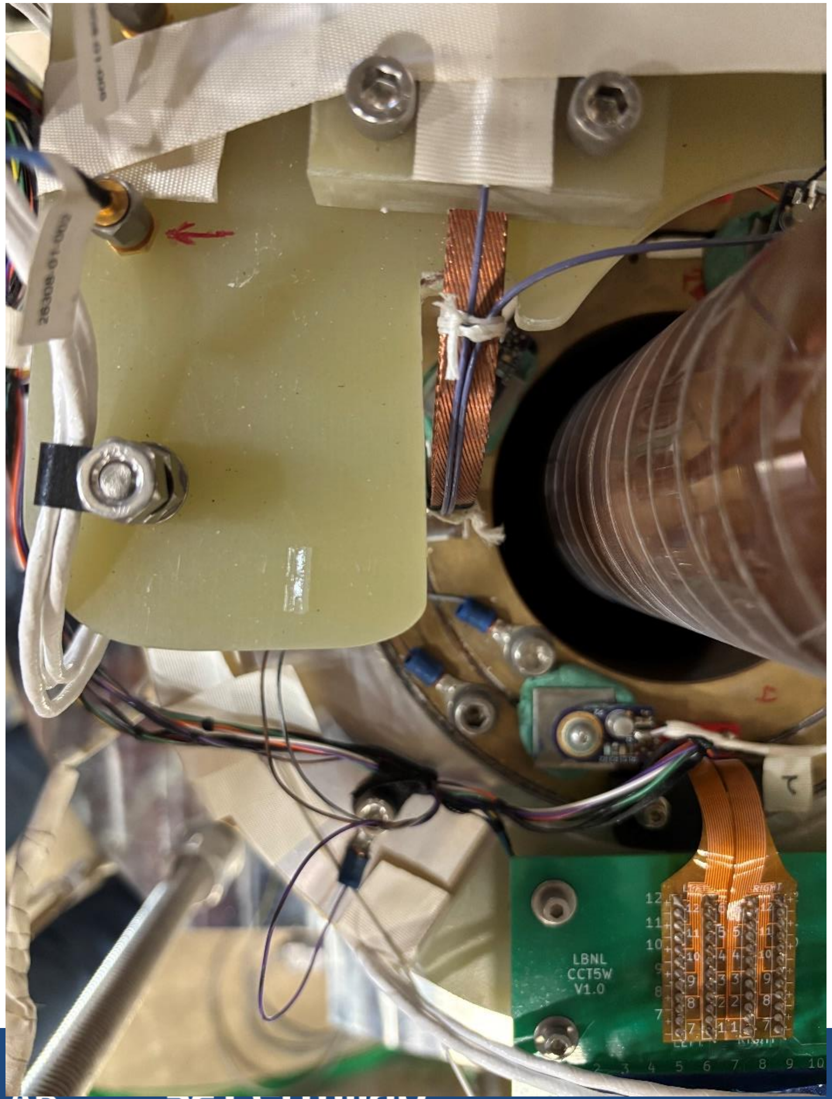
- CCT5-W is training at 1.9 K
- Ramp #35: first quench in the outer coil
- Holding current for 10 min at 20100 A (100% SSL)

- Ramp rate dependence:
- Ramp #46 at 400 A/s: quench at 18839 A
- Ramp ##47 at 200 A/s: quench ar 15667 A (78% SSL)

- Erratic behavior after that
- No significant change ramping at 5 A/s
- Stable behavior at 4.5 K

Thermal cycle

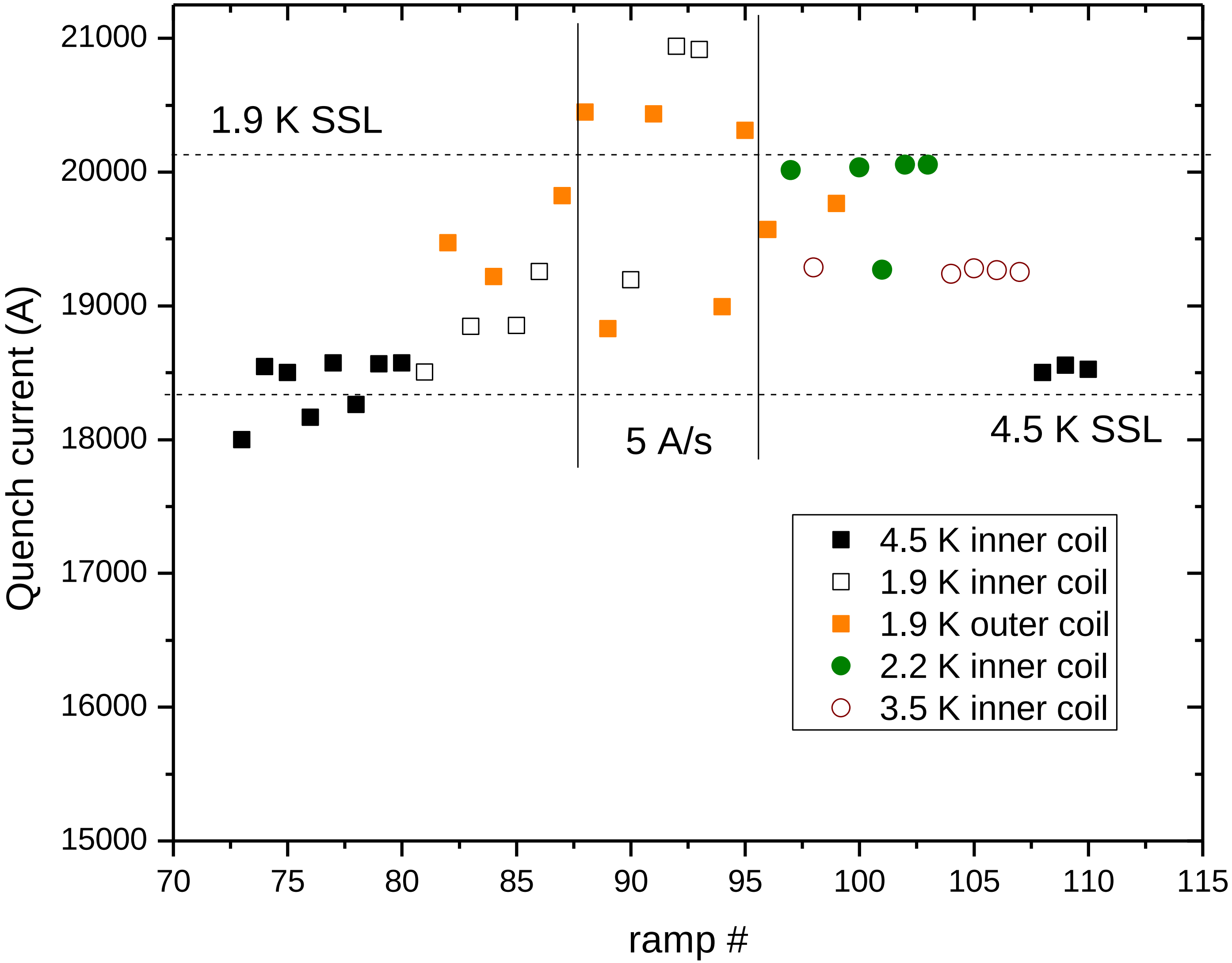




- Magnet was partially lifted from the pit
- Strain gauges were rewired
- Voltage tap segment A11-A12 was re-established
- Fibers were broken

- Some small was flakes can be seen on the magnet

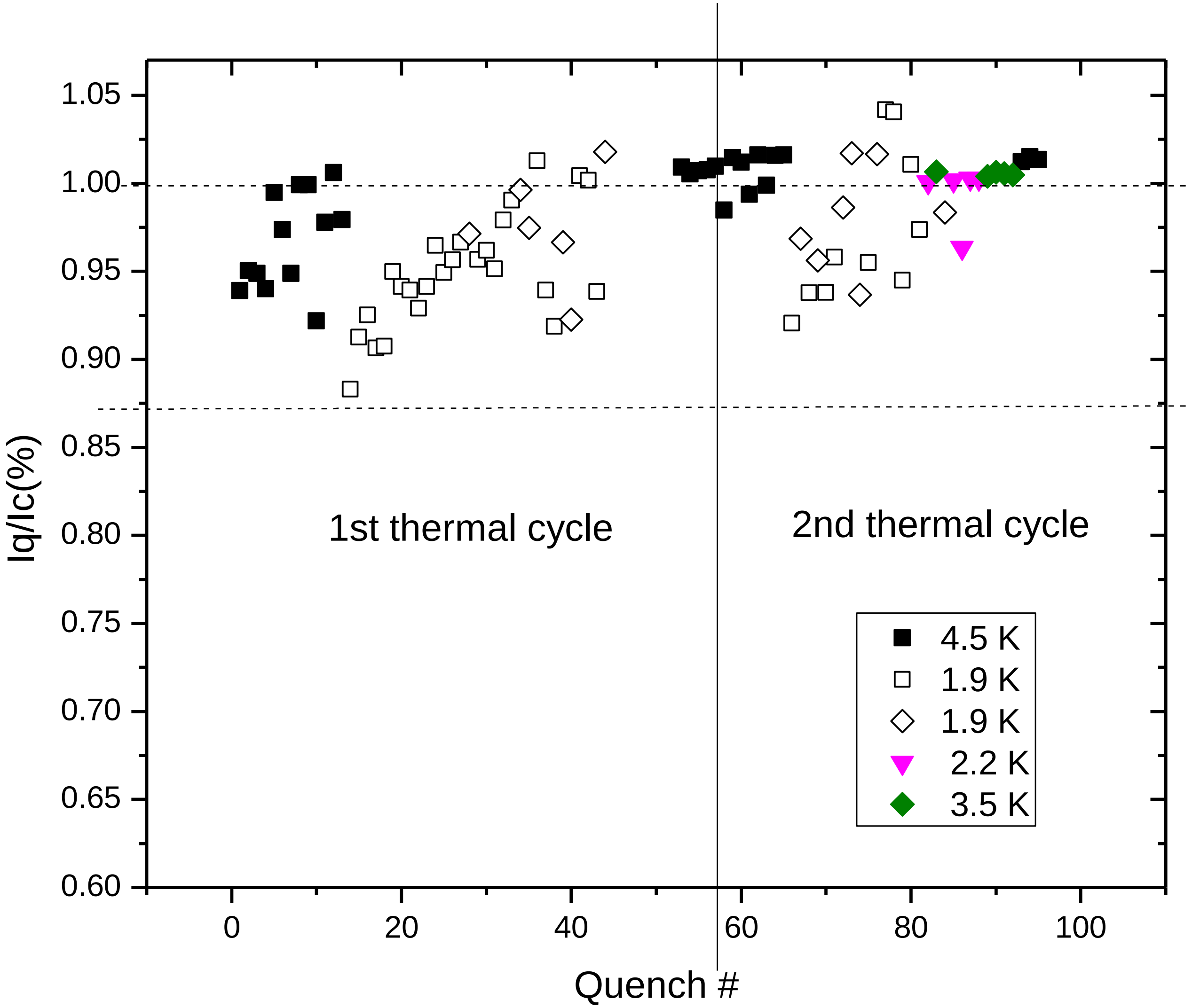
2nd Thermal cycle



- Quenches at 4.5 K are consistent with what was observed in the 1st thermal cycle
- Quenches current values at 2.2 K and 3.5 K are also stable.

- Behavior at 1.9 K appear more erratic.
- More quenches in the outer coils
- Highest quench current at 20939 A ramping at 5 A/s (104% SSL).

Percentage of Short Sample Limit

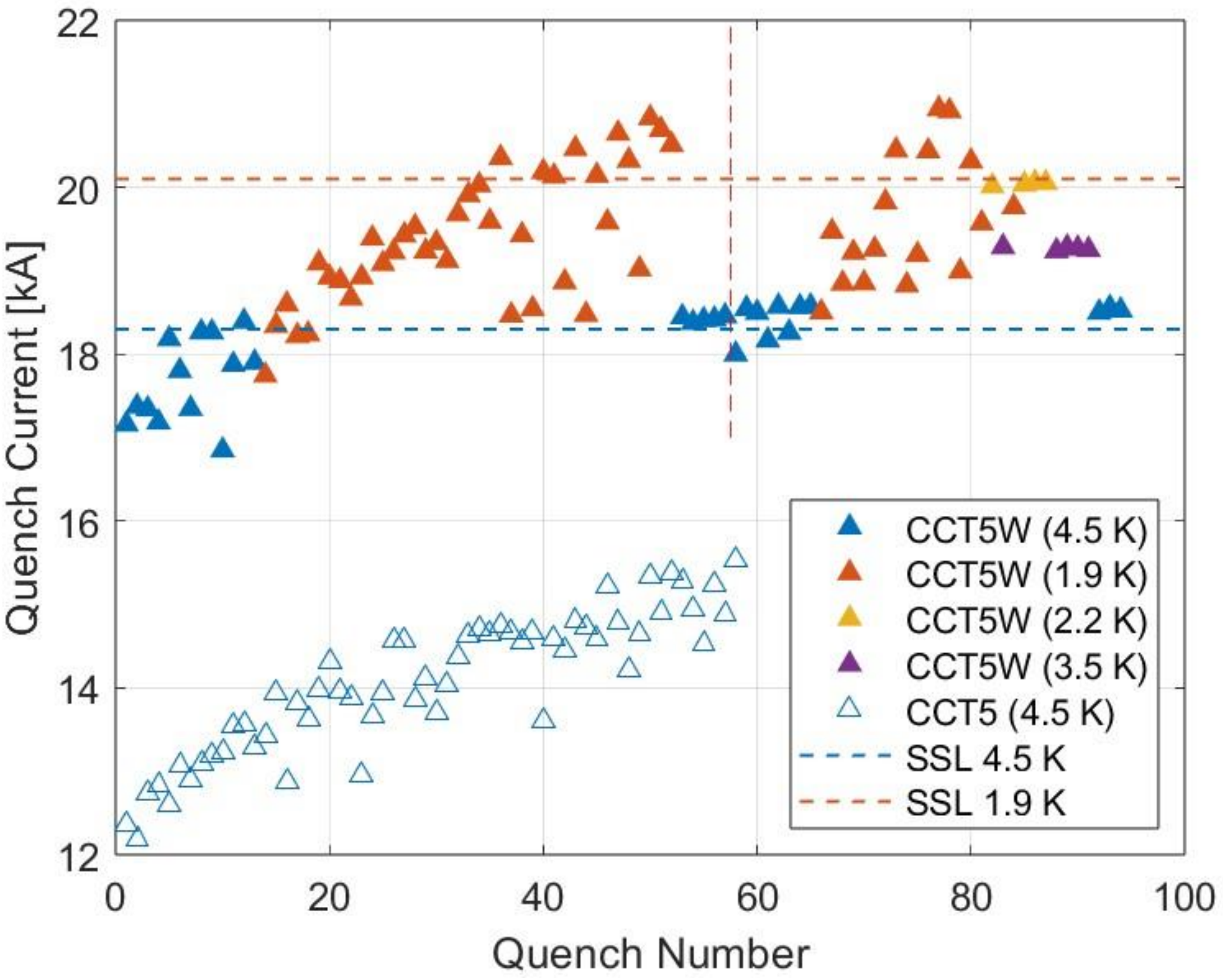


Iq/Ic ratio calculated for each measured temperature

All quenches observed during ramps at 20 A/s or 50 A/s are in within 85%< Iq<104%

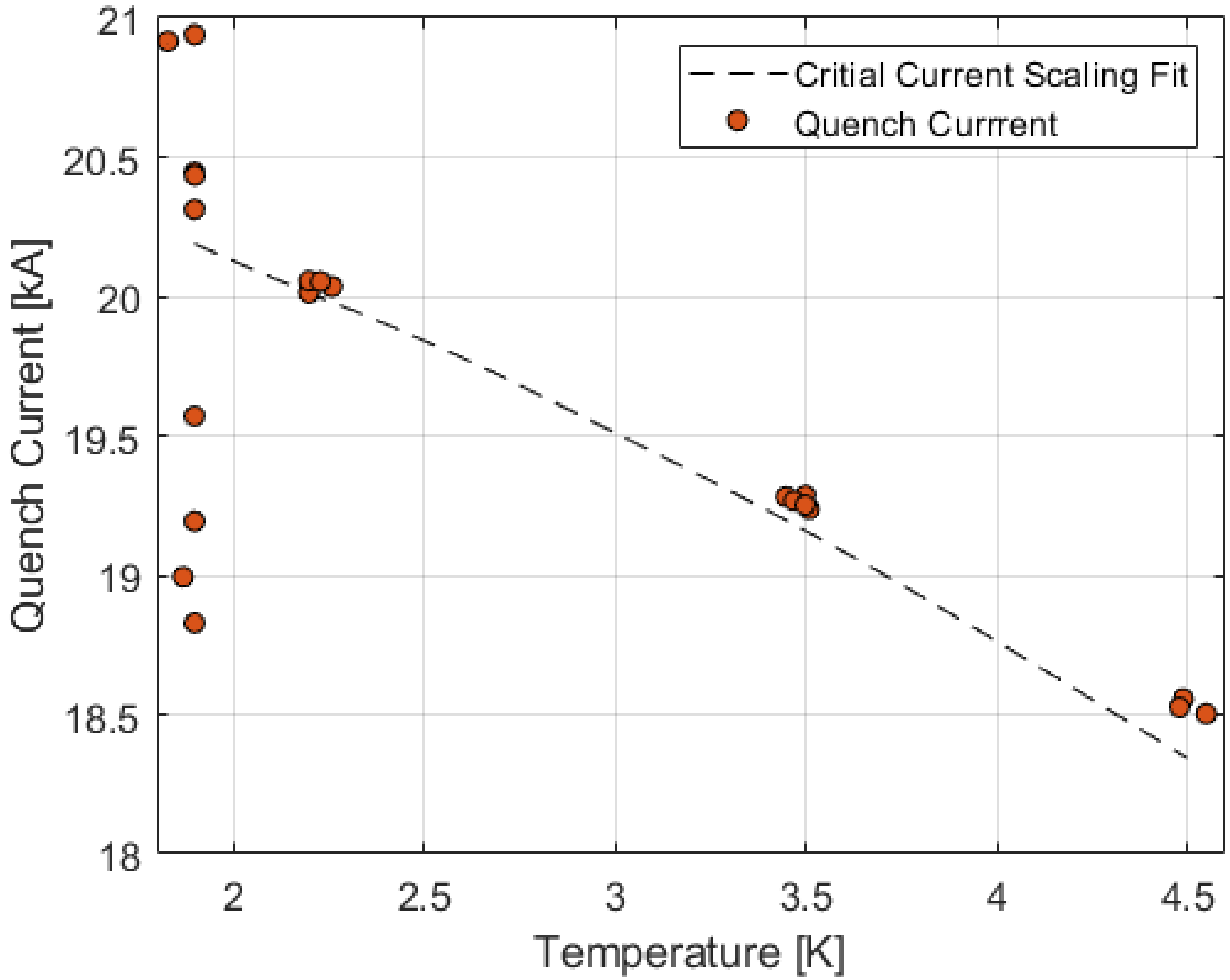
No good memory at 1.9 K

CCT5-W vs CCT5



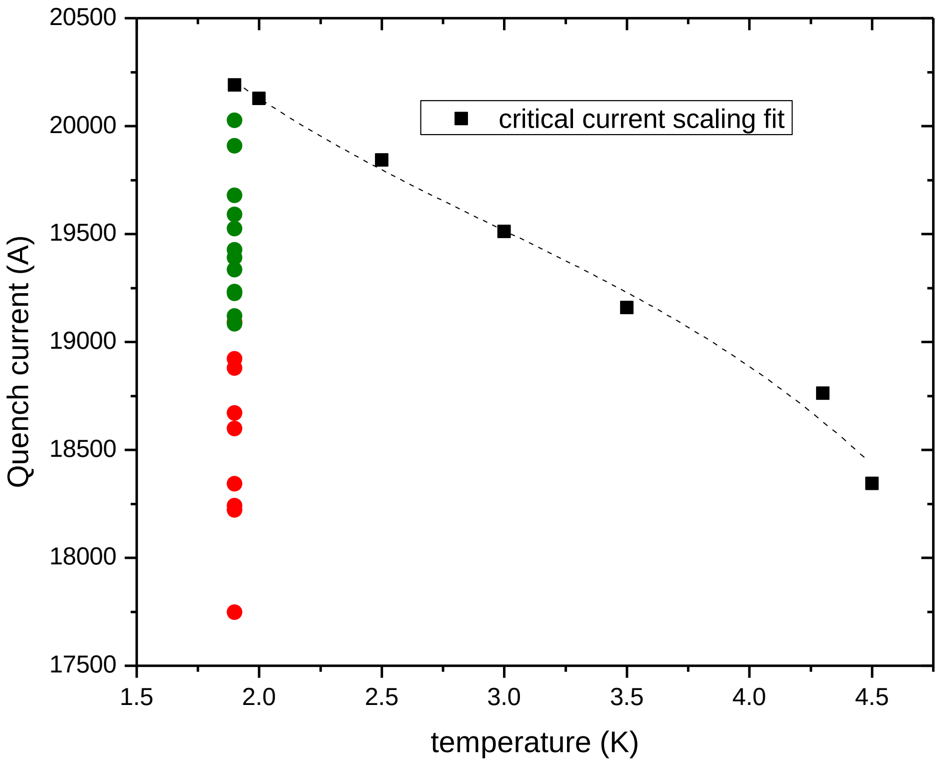
Magnet performances significantly improved from CCT5

Temperature dependence



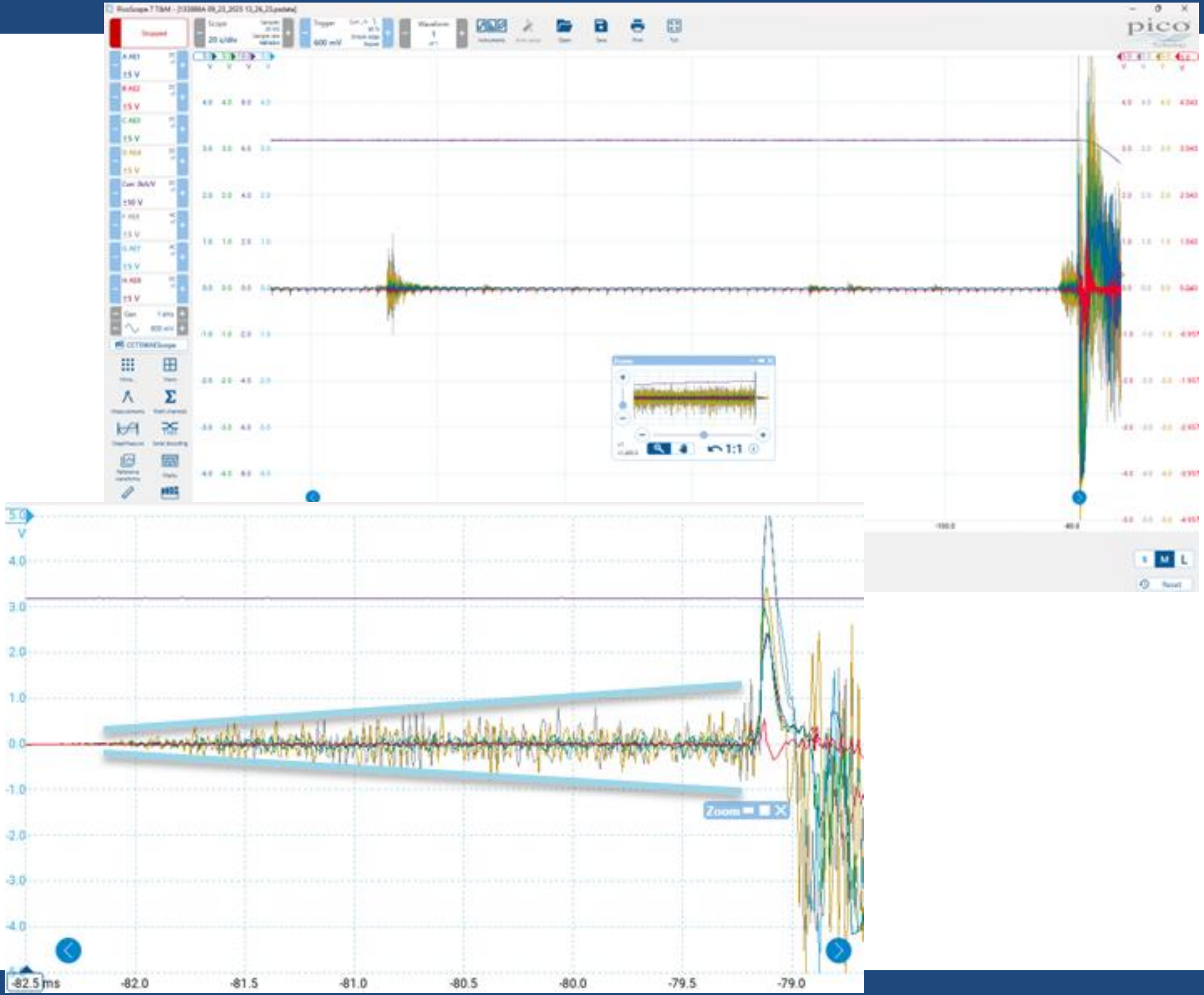
Final nine 1.9 K quenches

First 20 1.9 K quenches



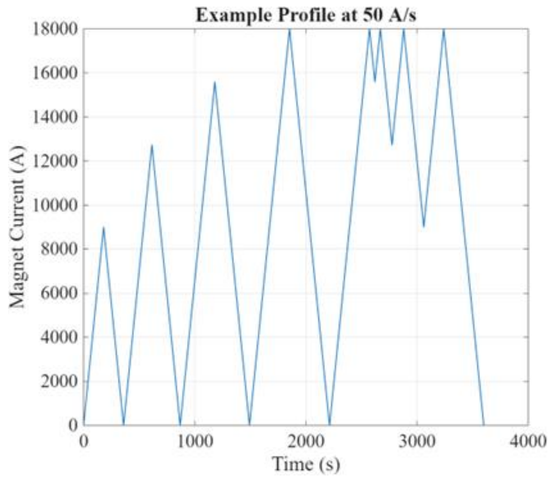
Acoustics sensors preliminary results (S. Krave)

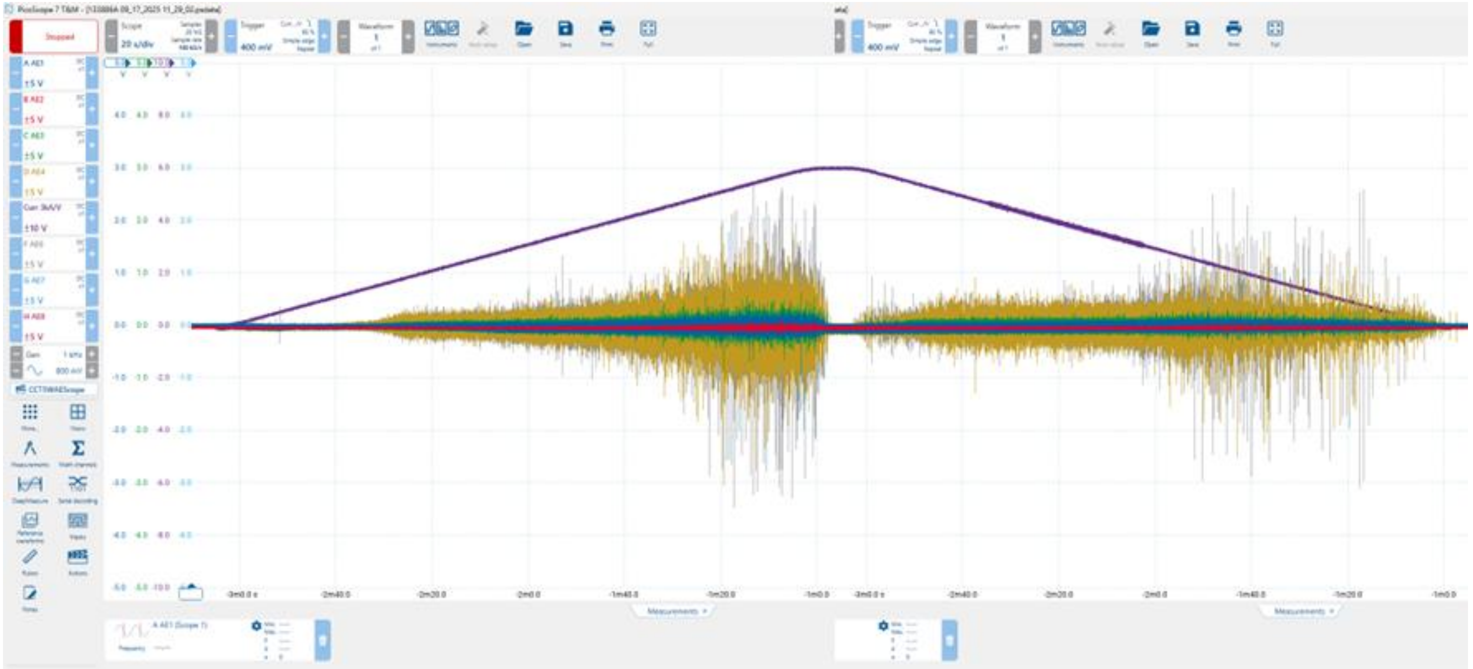
- Instrumentation:
  - AE Sensors on both sides of magnet
  - Half-coil bucked VT and current clamp
- General Behavior: No acoustic events directly before quench
- The onset of quench corresponds to crescendo of acoustic noise (local boiling?)
  - Fast ~2.5 ms before detection



Hysteresis loops (S. Krave)

- Ramps in multi-step profile at multiple ramp rates
  – Separate ramp rate, history and AE Rate scaling, reversibility WRT acoustics





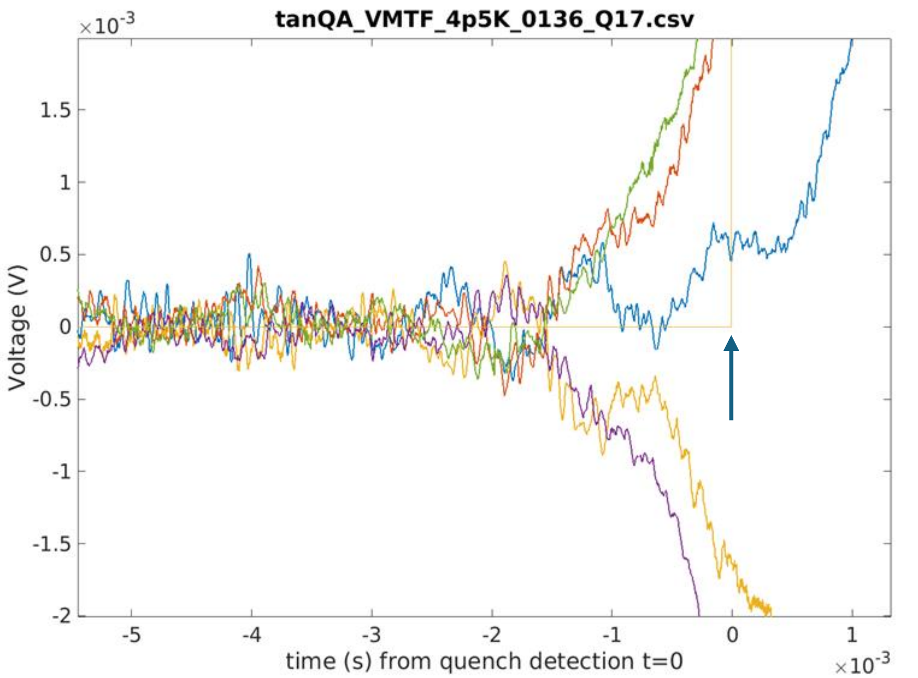
Quench Antenna (J. DiMarco)

Three types of QA were used:

- Inter-layer QA
- Warm-bore slant QA with 28mm dia.
- Tangential warm-bore QA array with 42 mm dia.

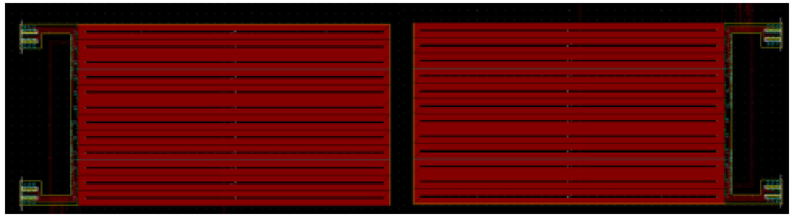
Data taken typically for entire ramp, all tests

~1.3 Tb data – starting to go through, but will take time…

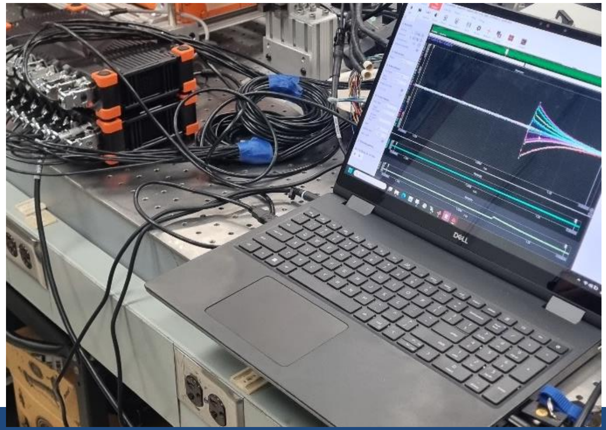


Signals with 60 Hz filtering

Inter-layer QA installed during assembly (16-bit, 50kHz acq)



24-bit, 200 kHz sampling DAQ



Second warm bore QA
16 tangential loops around 41mm diameter cylinder; 2-layer pcb, 36 turns total

28mm dia. warm bore QA with slant and asymmetric bucked windings

Magnetic Measurements @ 1.9 K (J. DiMarco)

- Z-scan with 25mm steps z=[-0.5,0.5]
- Ramps to 17.8 kA with probe at Z=0 at 20, 40, 80 A/s
- ‘Stair-step’ measurements to 17.8 kA
- ‘Accelerator profile’ with injection porch at 960A

Stationary measurements used the 26mm long coil at Z=0, since the straight-section is very short

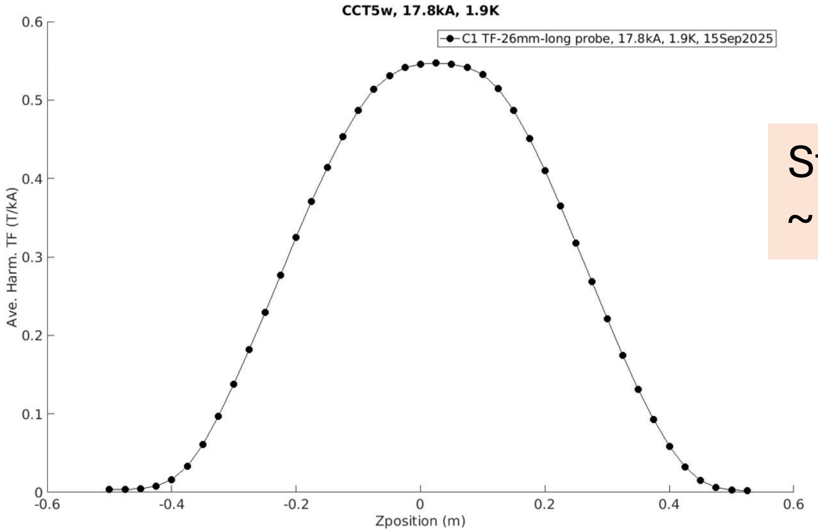
Vertical drive with encoder and slip rings

45 mm diameter rotating coil

130mm-long coil

26mm-long coil

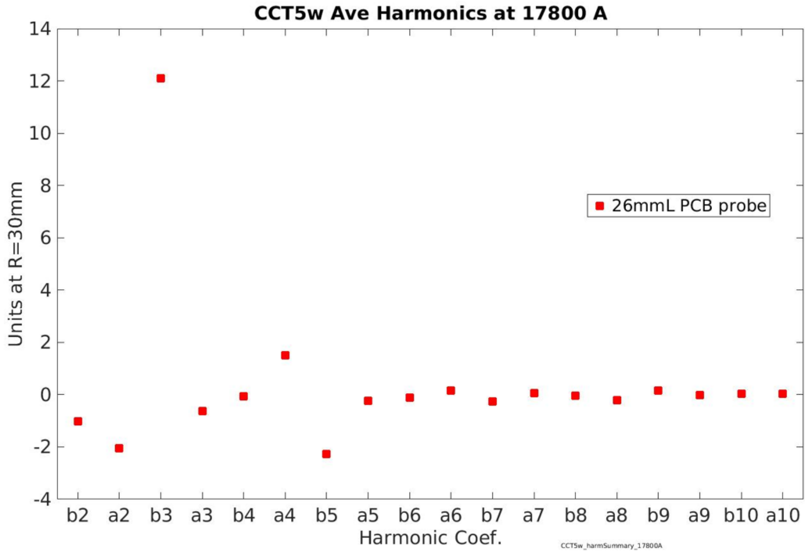
Magnetic Measurements @ 1.9 K (J. DiMarco)

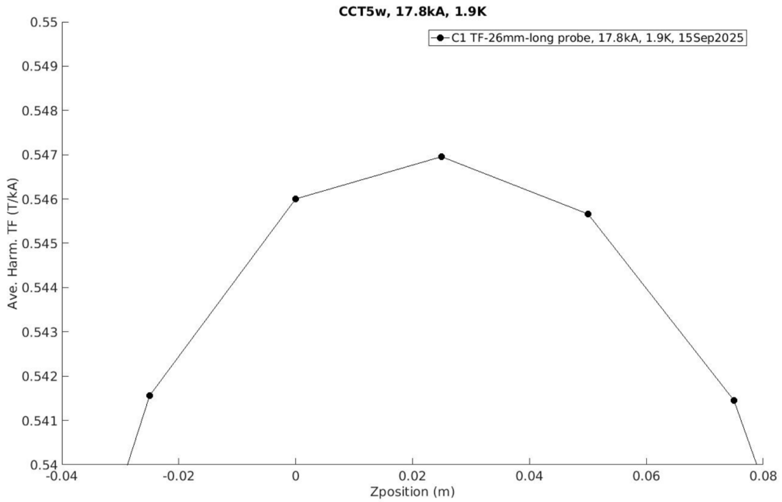


Strength Transfer Function ~ 0.547 T/kA

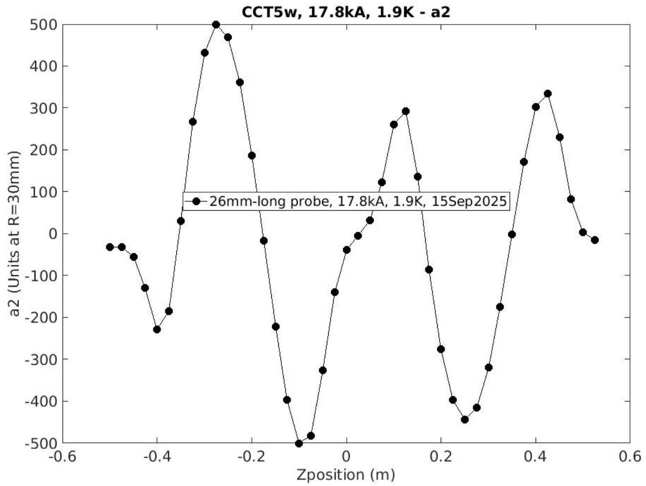
Z-scan at 17.8kA
Magnetic field= 9.74T

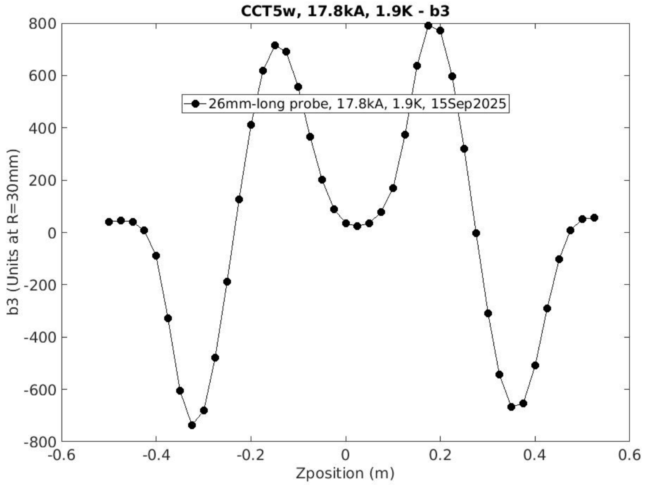
Harmonics at center (0.02m position) < 5 units (except for b3 (normal sextupole))

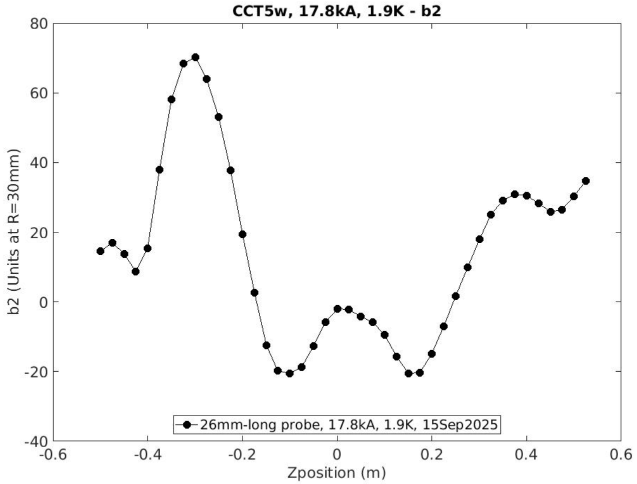




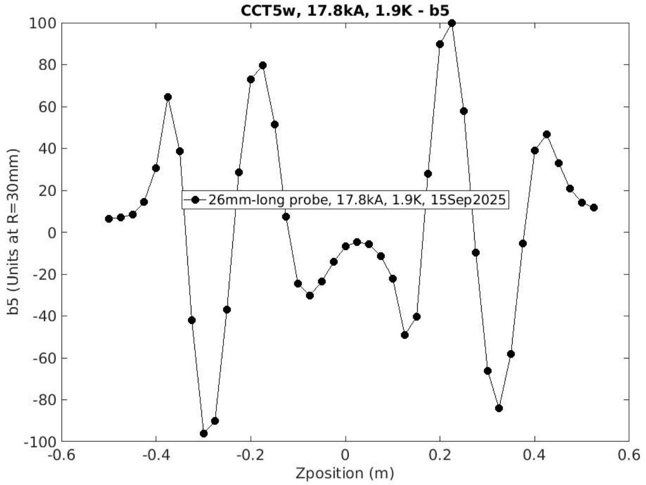
Magnetic Measurements @ 1.9 K (J. DiMarco)



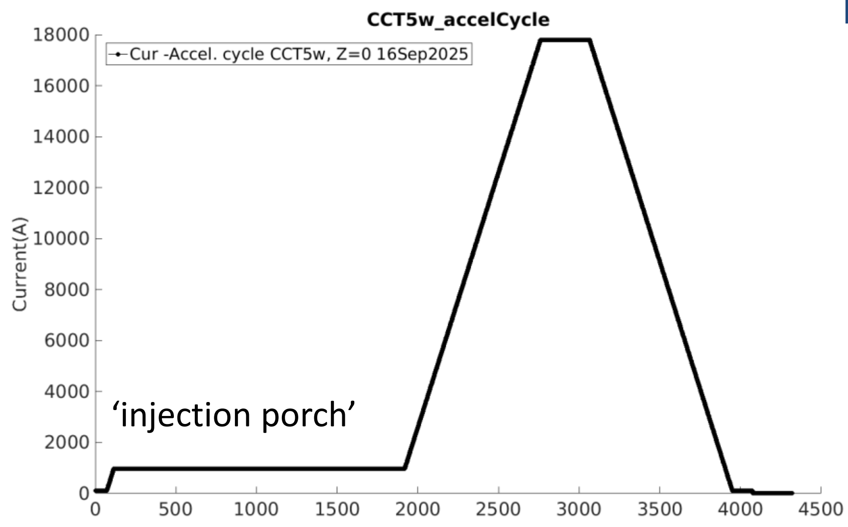




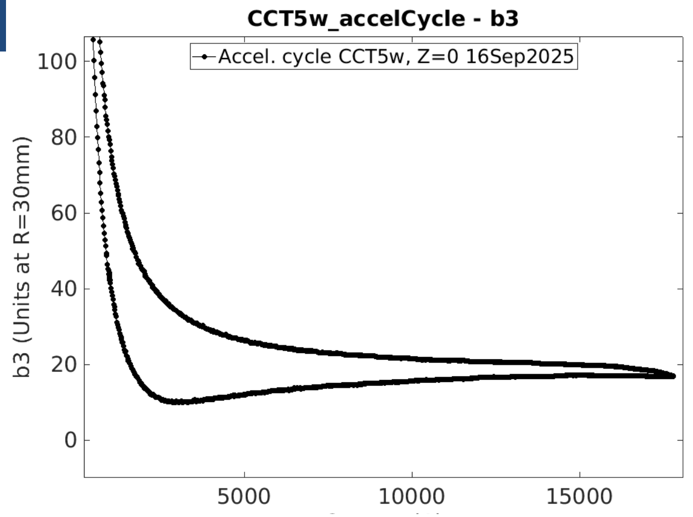
End-field harmonics
(most of the magnet!)

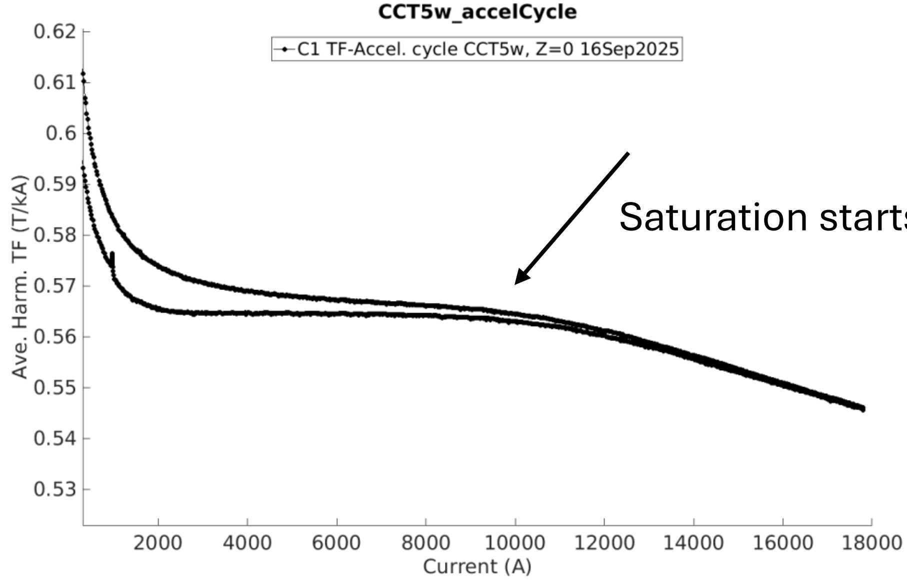


Accelerator profile @ 1.9 K (J. DiMarco)

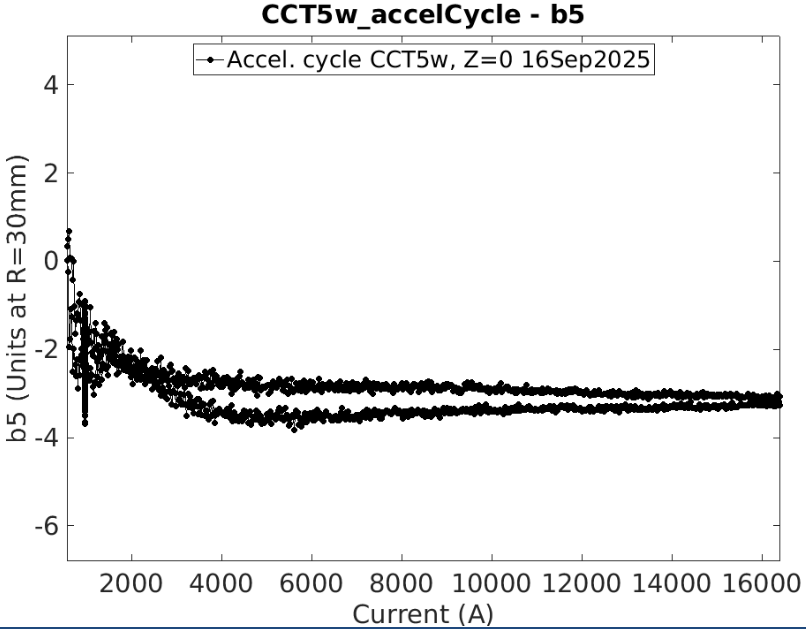


Strength/harmonics during accelerator profile





Saturation starts at ~10 kA



Conclusions

- Allumina-filled wax large-aperture Nb_3Sn CCT magnet was designed and fabricated at LBLN.
- The magnet was successfully tested at 4.5 K and 1.9 K at Fermilab.
  - The first quench at 4.5 K has been observed at 93% of short sample limit
  - The first quench at 1.9 K has been observed at 88% of short sample limit
  - Magnet trained at 1.9 K then it developed a more erratic behavior.
  - Highest current reached at 1.9 K was 20.9 kA which corresponds to 104% of SSL.
  - Quenches in the outer layer were only observed at 1.9 K
  - A maximum bore field of ~9.74 T was measured at 17.8 kA.
  - Analysis of acoustic sensor, quench antenna and fiber data is ongoing.
  - Temperature dependence shows that the magnet behavior diverge from prediction at 1.9 K

ramp #	Quench #					
20	14	17747		A10-A09		
21	15	18342		A07-A06		
22	16	18598		A08-A07		
23	17	18221		A08-A07		
24	18	18241		A10-A09		
25	--			--		
26	19	19091				
27	20	18922		A08-A07		
28	21	18879		A05-A04		
29	22	18671		A05-A04		
30	23	18923		A06_05		
31	24	19390		A08_07		
32	25	19083		A09_08		
33	26	19224		A08-A07		
34	27	19427		A05-A04		
35	28	--		--	19525	B09_B08
36	29	19232		A07-A06	--	--
37	30	19334		A05-A04	--	--
38	31	19120		A04-A03	--	--
39	32	19679		A04-A03	--	--
40	33	19909		A07-A06	--	--
41	34	--		--	20027	B04-B03
42	35	--		--	19590	B08-B07
48	36	20355		--	--	--
49	37	18877		A08-A07	--	--
50	38	18467		A05-A04	--	--
51	39	--		--	19428	B10-B09
52	40	--		--	18542	B10-B09
53	41	20187		A10-A09	--	--
54	42	20133		A06-A05	--	--
55	43	18865		A09-A08	--	--
56	44	--		--	20461	B06-B05
59	46	--	19582	A12-A10		
60	47	--	20646	A04-A03		
61	48	--	20322	A04-A03		
62	49	--	19019	A03-A02		
63	50	--	20832	A02-A01		
64	51	--	20692	A04-A03		
65	52	--	20510	A04-A03		

81	66	--	18503	--	--	--
82	67	--	--	--	19470	B07_08
83	68	--	18847	A04-A03	--	--
84	69	--	--	--	19219	B04_03
85	70	--	18852	A04_03	--	--
86	71	--	19256	A10_09	--	--
87	72	--	--	--	19822	B03-B02
88	73	--	--	--	20446	B05_04
89	74	--	--	--	18828	B08_07
90	75	--	19193	A05_04	--	--
91	76	--	--	--	20434	B08_07
92	77	--	20939	A02_01	--	--
93	78	--	20915	A02_02	--	--
94	79	--			18993	B03_02
95	80	--			20312	B04_03
96	81	--			19571	B05_04
99	84	--			19765	B04_03