ARDAP Meeting “Teo-BR” and Barrel Sample Summary

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DOE ARDAP - Enhancing Domestic Production of High Temperature Superconducting $Bi_2Sr_2CaCu_2Ox$/Ag wires for High Field Magnets

10/11/2024

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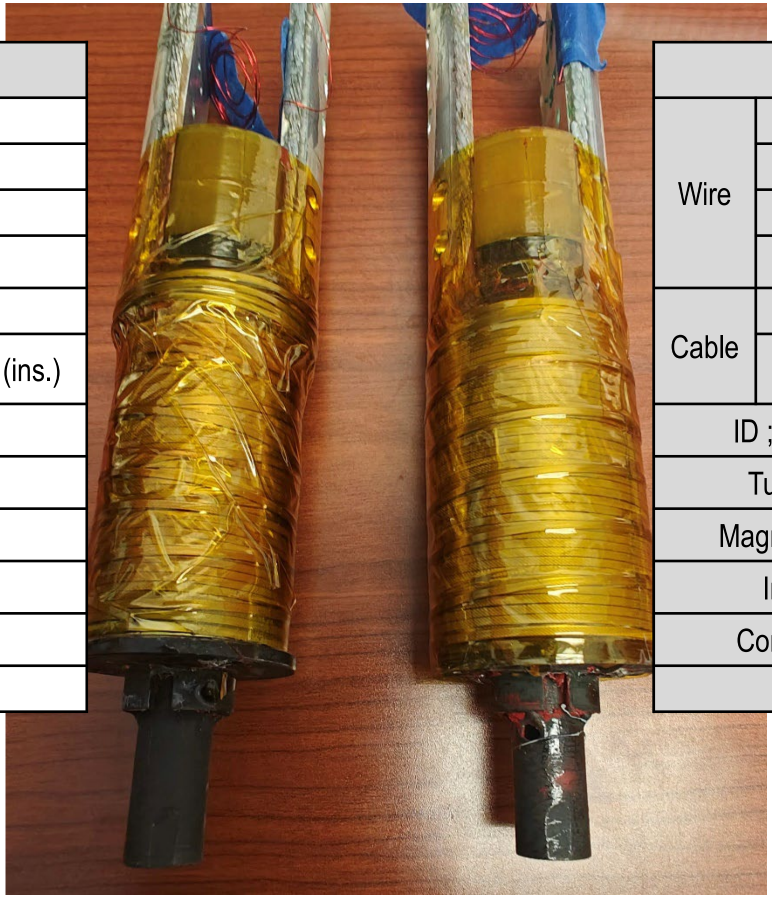
Two Cable Solenoids Combine “TEO” and “BR” Designs

Teo-BR-1 Cable Solenoid		
Wire	Product No.	PMM240205 – ARDAP #1
	Powder	Engimat G2A-07A_HS (37 x 18)
	Insulation	Pure Alumina (Nextel) Braid
	Diameter [mm]	Φ 0.7 (bare)
Cable	ID, Size	LBNL-2007A, 6-strand
	Geometry	2.35 x 1.22 mm (bare) / 2.5 x 1.5 mm (ins.)
ID ; OD ; Height [mm]		12.1; 32.4; 60.0
Turn ; Layer (Total)		22; **6** (132)
Magnet constant [mT/A]		2.4
Inductance [mH]		0.09
Conductor length [m]		10
Status		Ready for Test



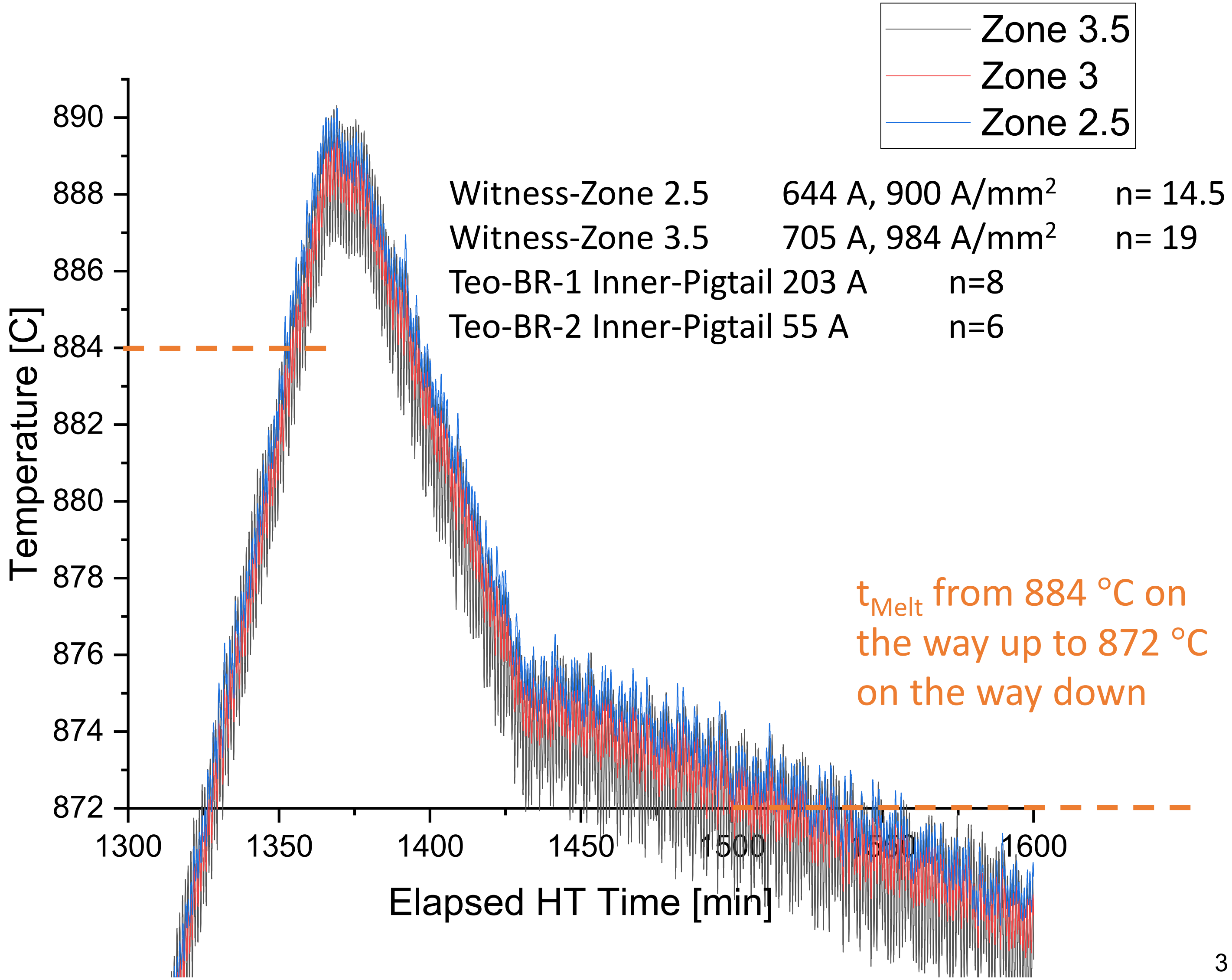
Teo-BR-2 Cable Solenoid		
Wire	Product No.	PMM240325 – ARDAP #2
	Powder	Engimat G2A-14A_HS (37 x 18)
	Insulation	Pure Alumina (Nextel) Braid
	Diameter [mm]	Φ 0.7 (bare)
Cable	ID, Size	LBNL-2008 A, 6-strand
	Geometry	2.35 x 1.22 mm (bare) / 2.5 x 1.6 mm (ins.)
ID ; OD ; Height [mm]		12.1; 38.4; 60.0
Turn ; Layer (Total)		22; **8** (176)
Magnet constant [mT/A]		3.7
Inductance [mH]		0.2
Conductor length [m]		14
Status		Ready for Test

- Cable received 07/15
- Insulation 07/23 - 07/29
- Mandrel Welding 07/24
- Mandrel oxidation 07/25 - 07/29
- Resistive magnet time awarded 07/29
- Ag terminals machined 07/31

- Winding 07/31-08/02
- OPHT reaction 08/07-08/9
- Epoxy VPI 08/12-08/15
- Two magnets ready for testing by 08/16
- Testing 08/19-08/23

Teo-BR Deltech Over-Pressure Heat Treatment was Well-Behaved

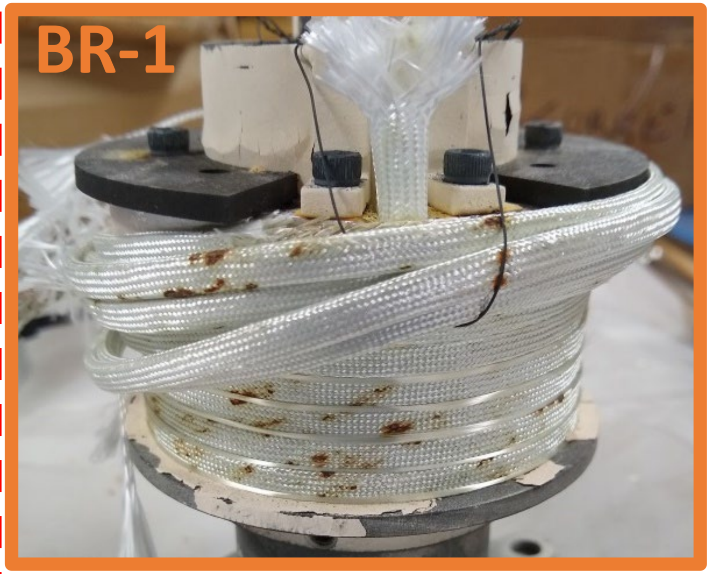
- T_{Max} < 890
- Control < ±2 °C
- t_{Melt}< 3.25 hours



Unexpected leakage despite alumina insulation

Deltech Furnace

BR-1



BR-2

Teo-BR-1

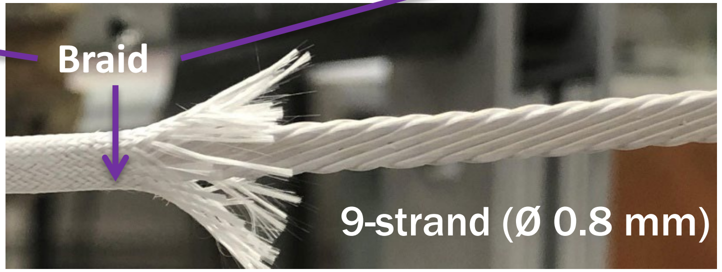
Teo-BR-2

MTI Furnace

Barrel
LBL-2007-B

Alumino-silicate
“Mullite”

Alumina “Nextel”



Alumina does not react with Ag, but once leak happens both fiber types will react with liquid Bi-2212

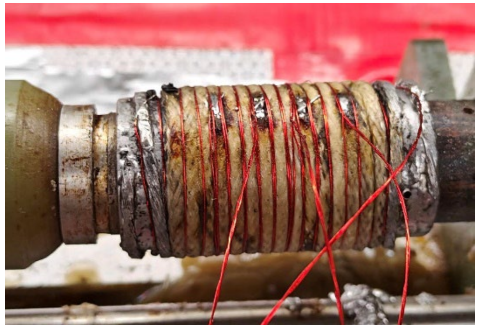
Alumina Braid
6-strand (Ø 0.7 mm)

Cable Barrel Performance Close to Short Sample Limit

Cable LBL-2007-B wound as single layer on-top of round-wire barrel mandrels and OPHT in MTI furnace by Jianyi Jiang. T_{max} 888 °C

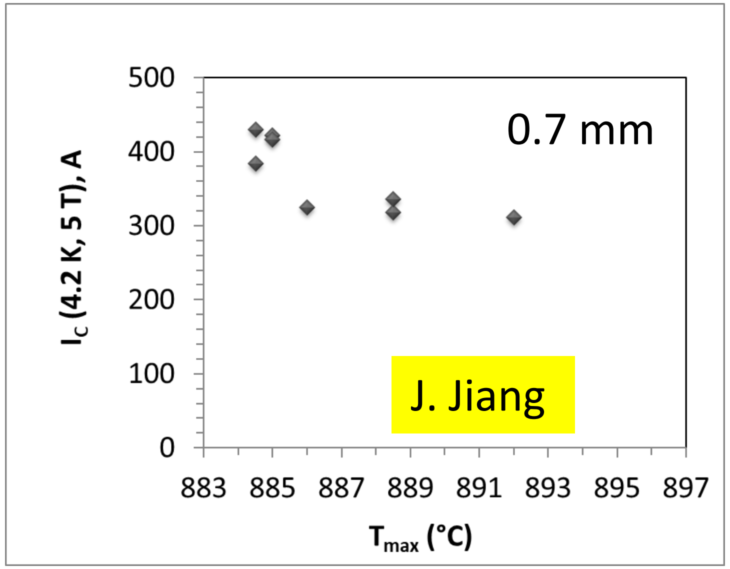
Post OPHT

Terminal Prep



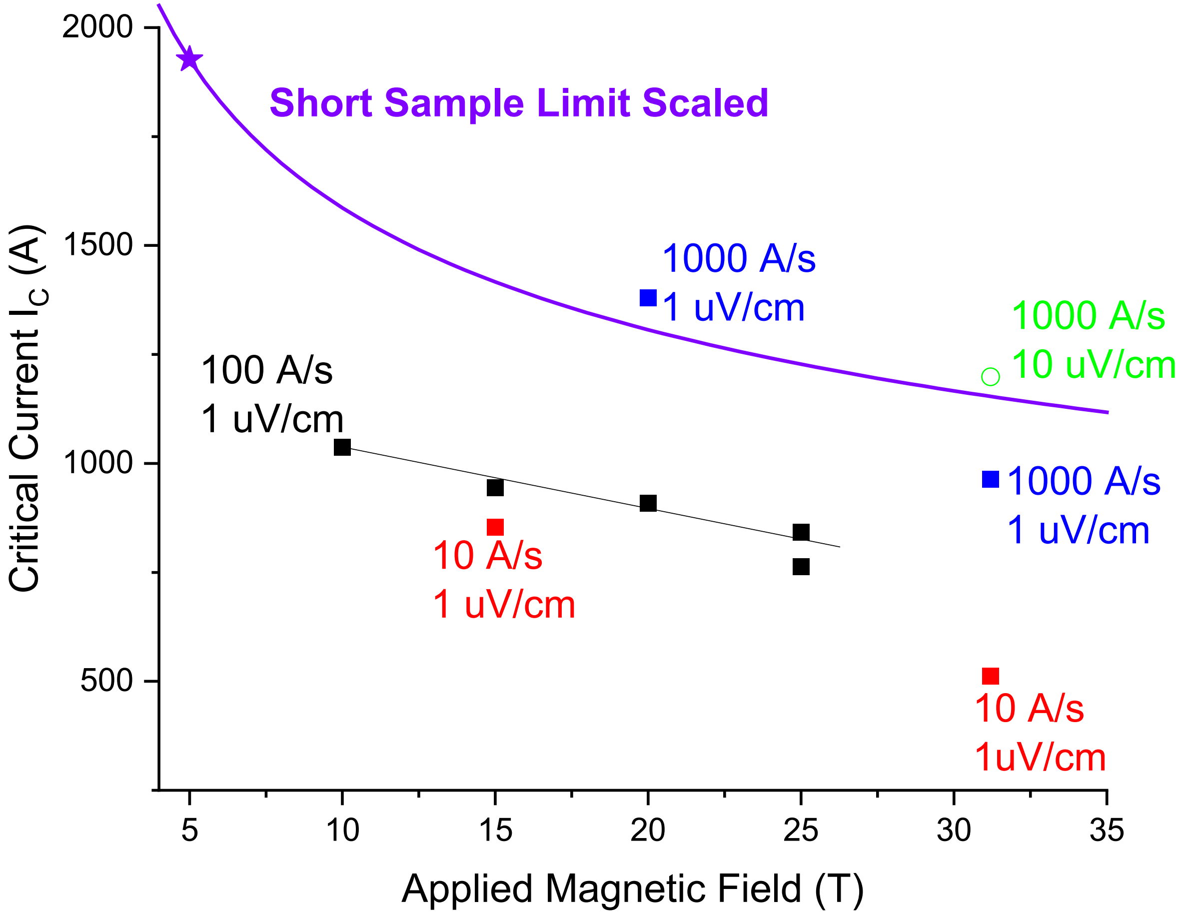
3-turn central voltage taps & 1 spanning entire barrel

Ic(4.2K, 5T) of PMM240205-07



I_C (4.2 K, 5 T, 888°) = 328 A

328 A x 6 strand *cos(12°) = 1926 A

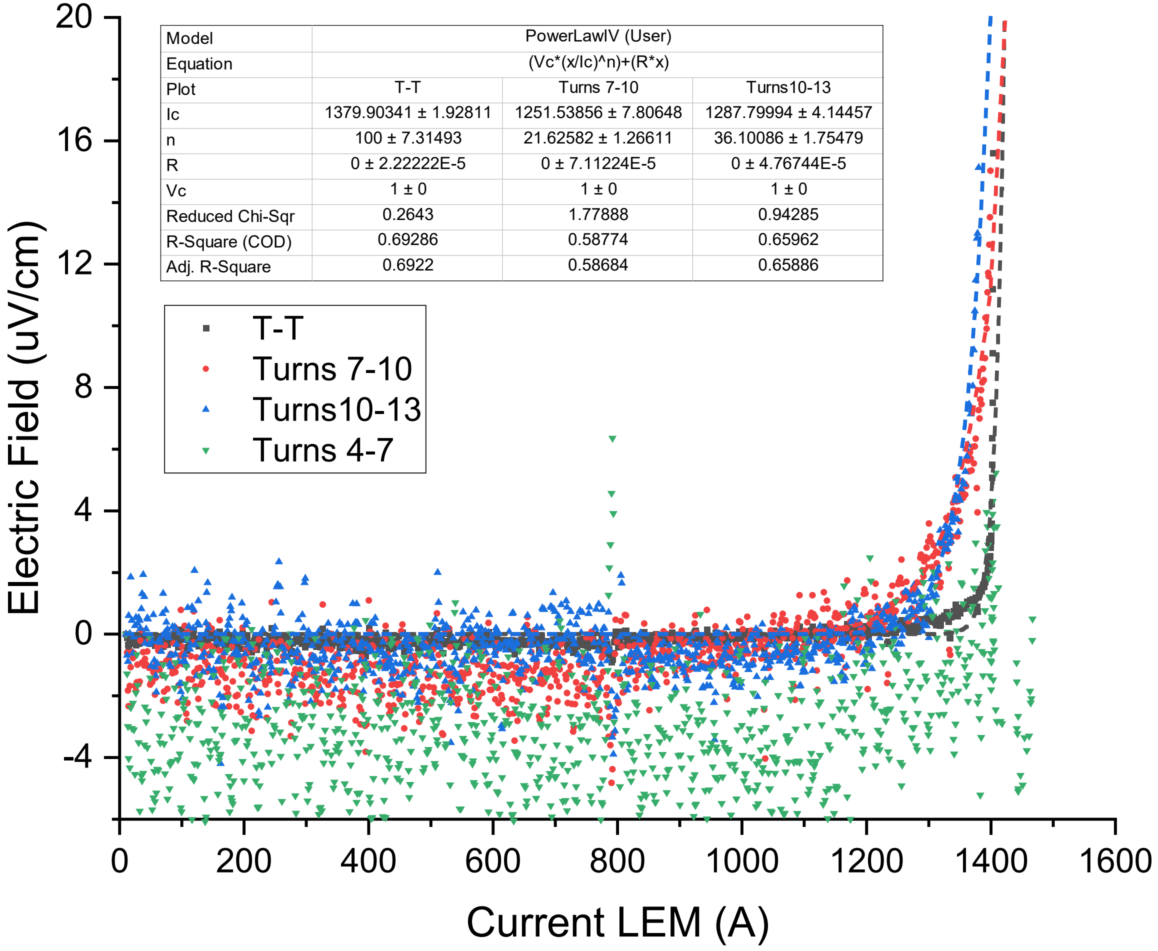


Despite terminal heating and trapped helium bubble, high ramp rates enabled performance characterization

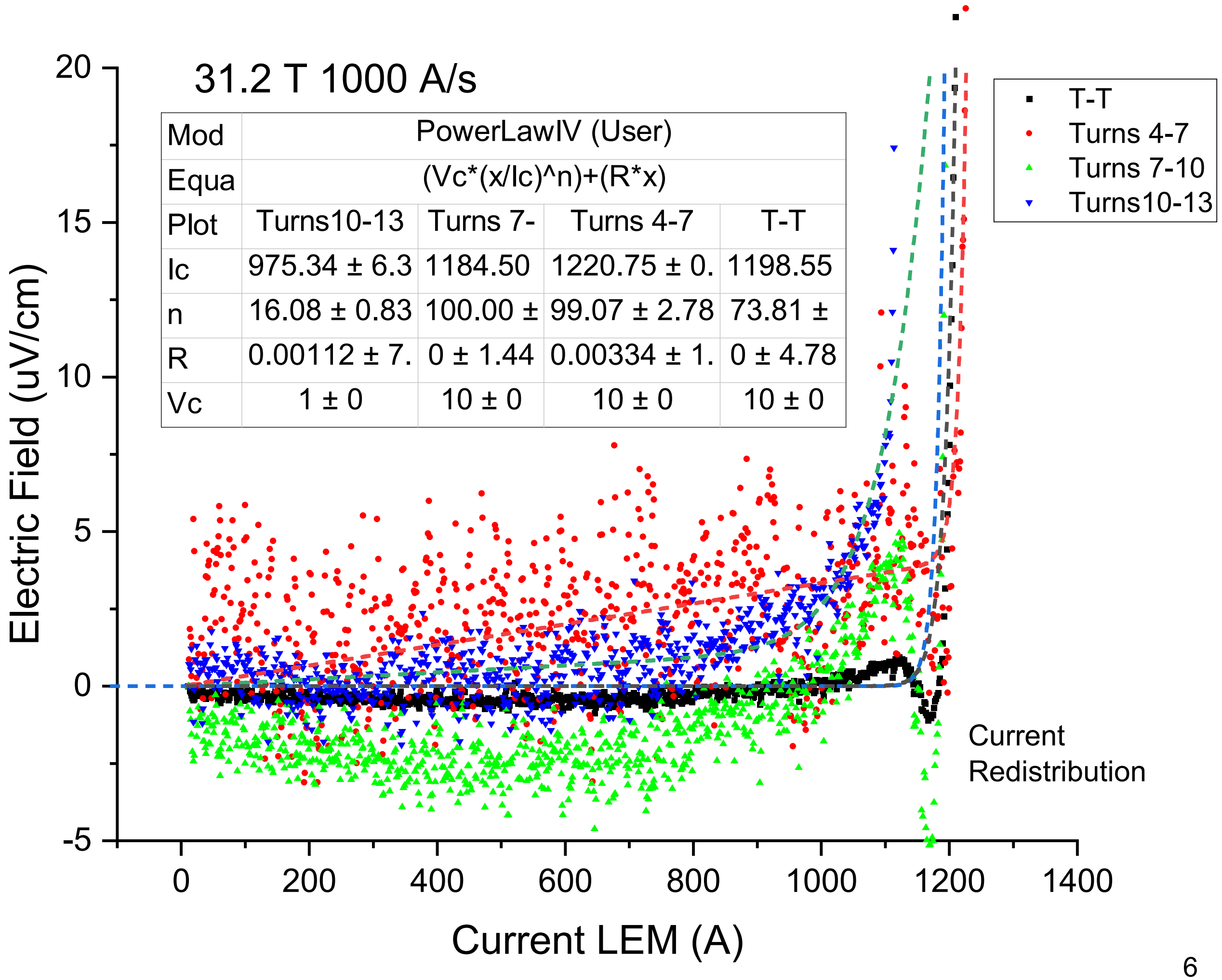
Barrel outrunning heating to see cable performance

Even high ramp rates showed signs of current redistribution and early shift from strand level power-law index (~20) to higher index (~100), indicating possible temperature rise at highest currents

20T run6 1000 A/s



Model	PowerLawIV (User)		
Equation	(Vc*(x/Ic)^n)+(R*x)		
Plot	T-T	Turns 7-10	Turns10-13
Ic	1379.90341 ± 1.92811	1251.53856 ± 7.80648	1287.79994 ± 4.14457
n	100 ± 7.31493	21.62582 ± 1.26611	36.10086 ± 1.75479
R	0 ± 2.22222E-5	0 ± 7.11224E-5	0 ± 4.76744E-5
Vc	1 ± 0	1 ± 0	1 ± 0
Reduced Chi-Sqr	0.2643	1.77888	0.94285
R-Square (COD)	0.69286	0.58774	0.65962
Adj. R-Square	0.6922	0.58684	0.65886



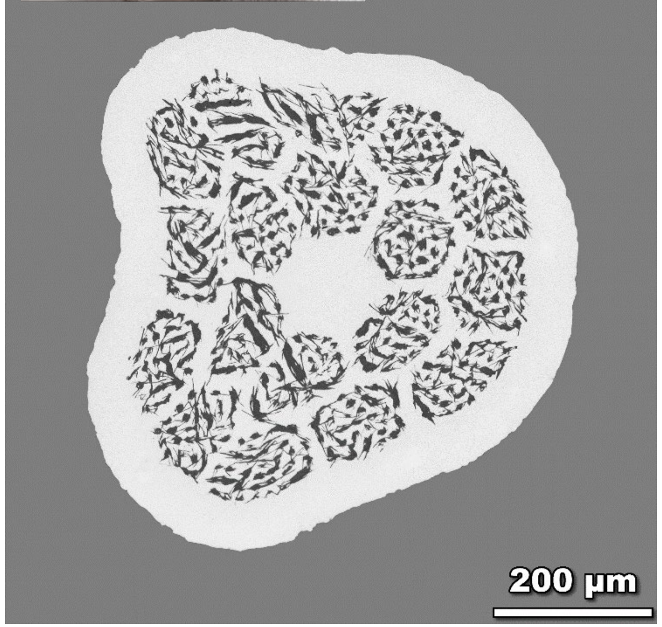
Mod	PowerLawIV (User)			
Equa	(Vc*(x/Ic)^n)+(R*x)			
Plot	Turns10-13	Turns 7-	Turns 4-7	T-T
Ic	975.34 ± 6.3	1184.50	1220.75 ± 0.	1198.55
n	16.08 ± 0.83	100.00 ±	99.07 ± 2.78	73.81 ±
R	0.00112 ± 7.	0 ± 1.44	0.00334 ± 1.	0 ± 4.78
Vc	1 ± 0	10 ± 0	10 ± 0	10 ± 0

Cable and Strand Cross Sections Extracted from Barrel Pigtail

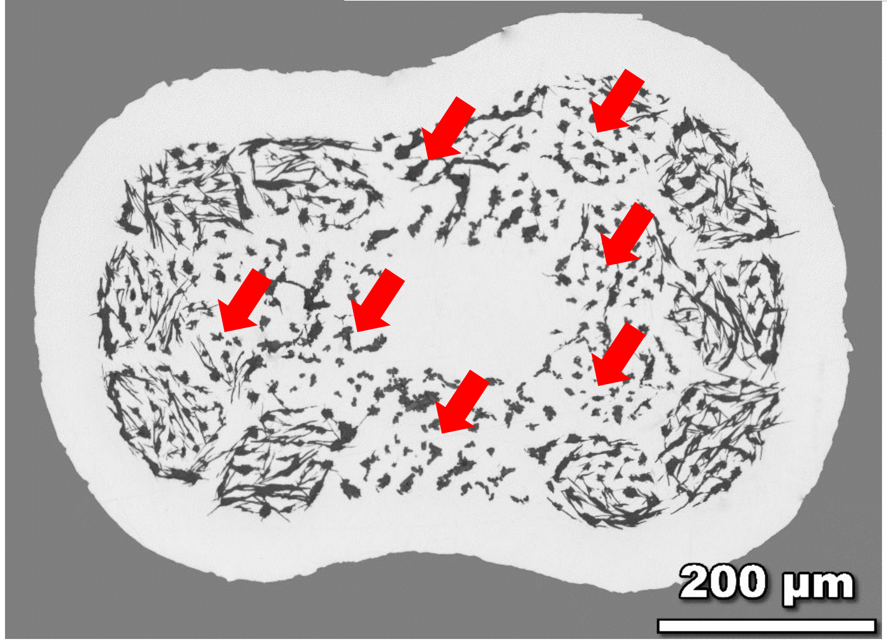
Pigtail

Leaked strand Cut from the pigtail for imaging

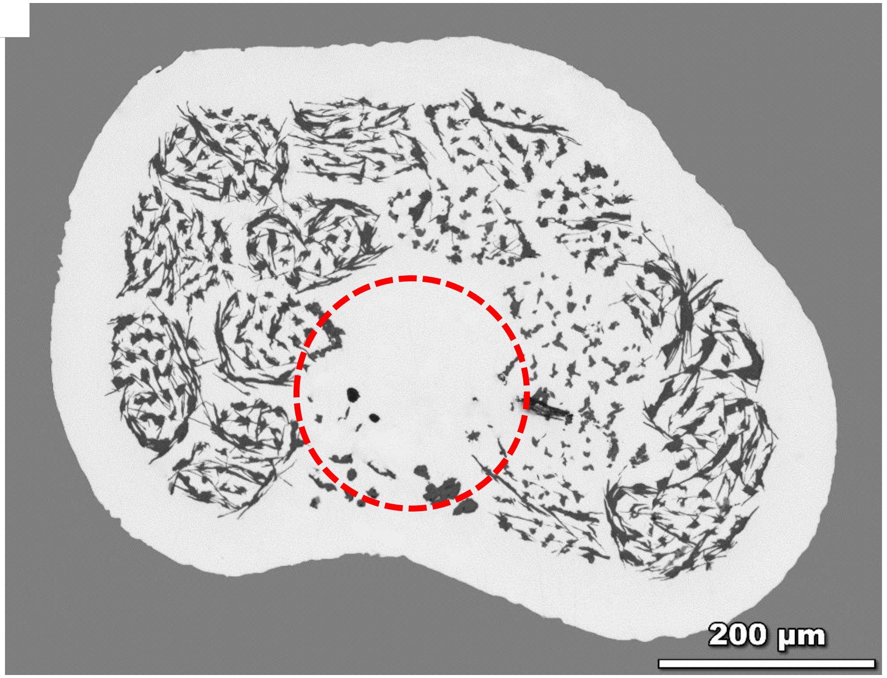
S. Barua



Good section

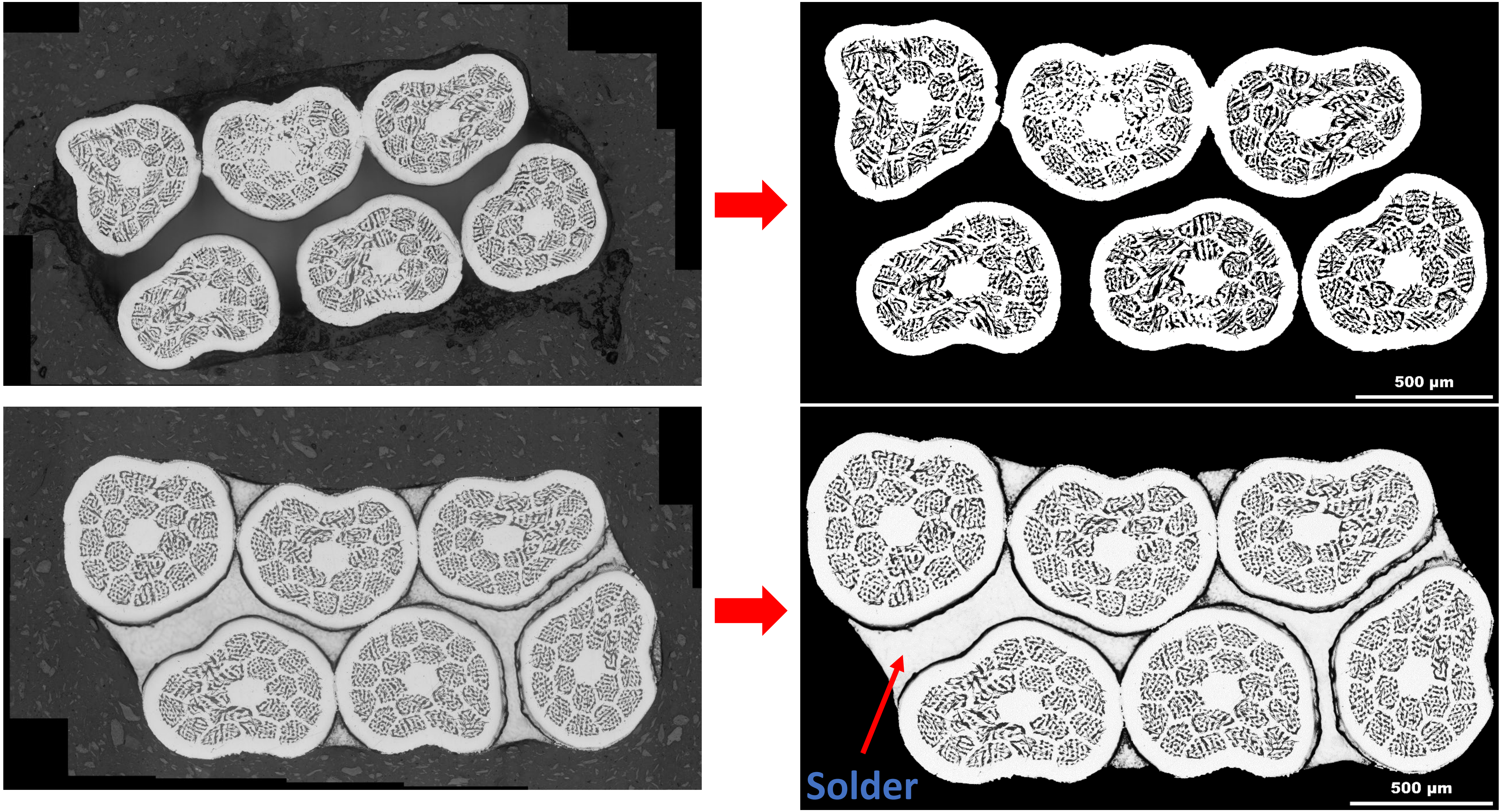


Most of the bundles are affected by the leakage

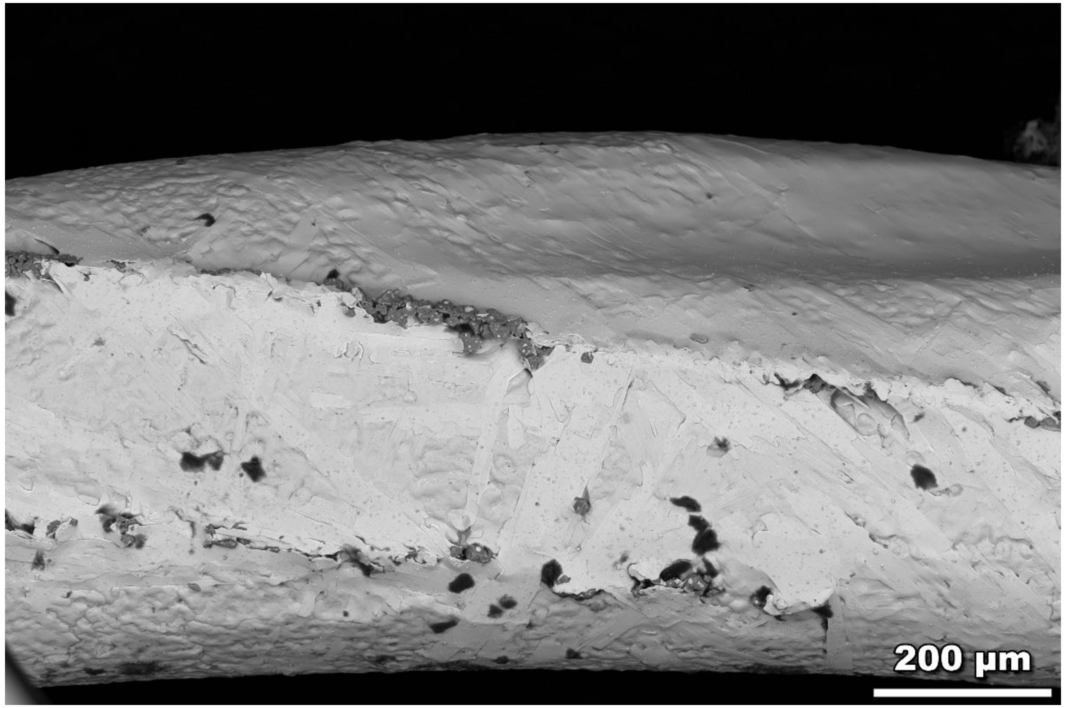


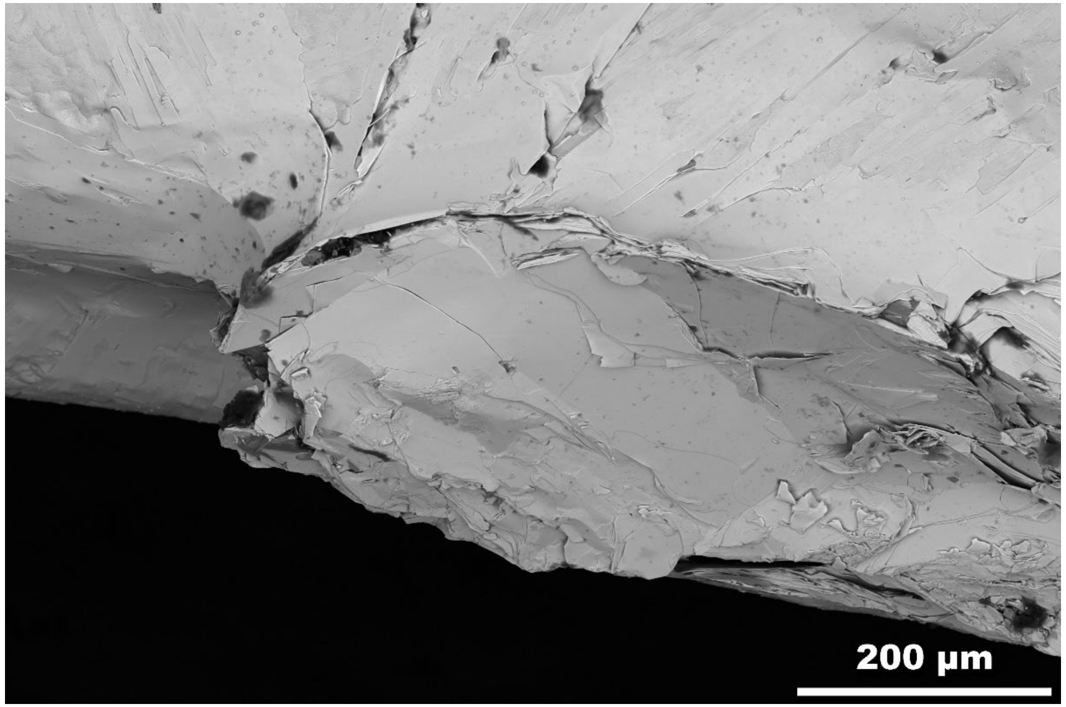
Two Hexagonal bundle disappeared

Number of Affected Strands Varies Along Cable

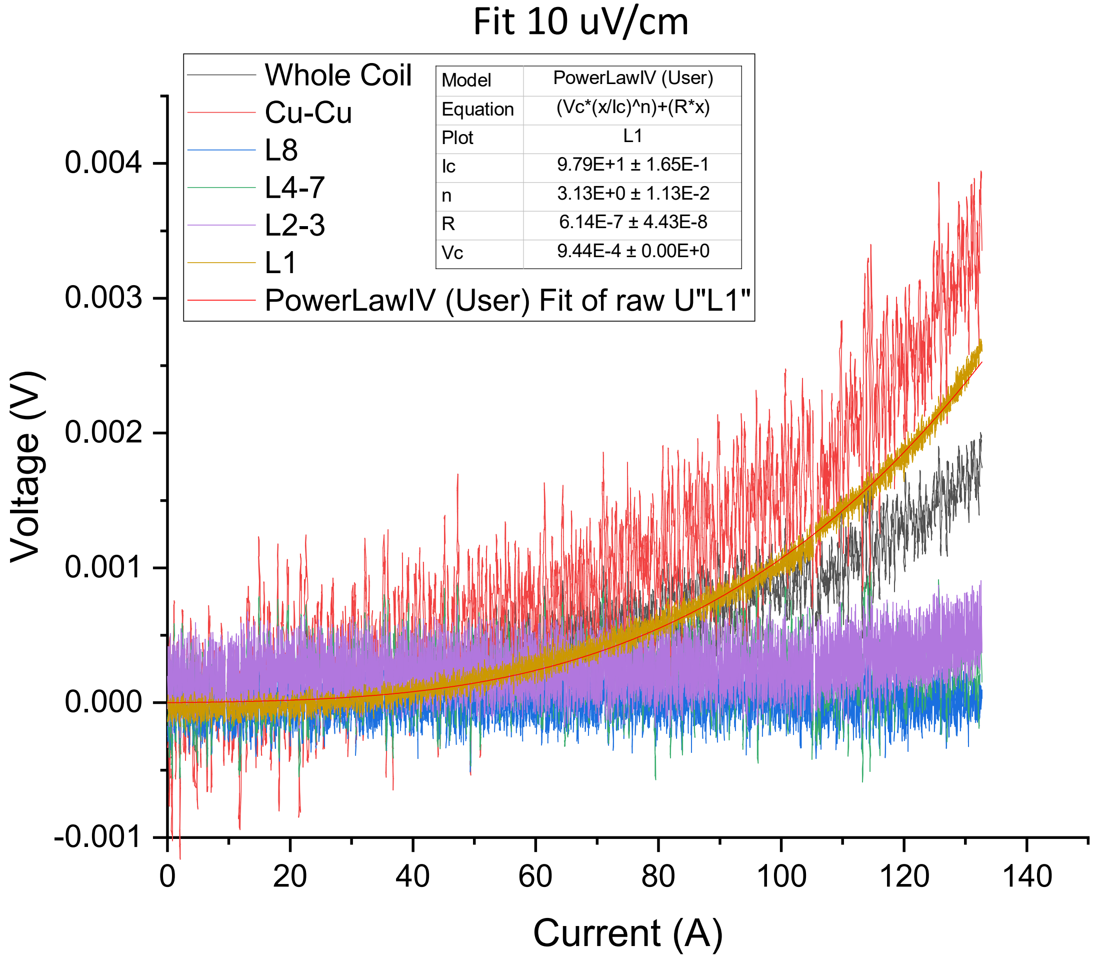


SEM-BSD image of wire surface extracted from cable

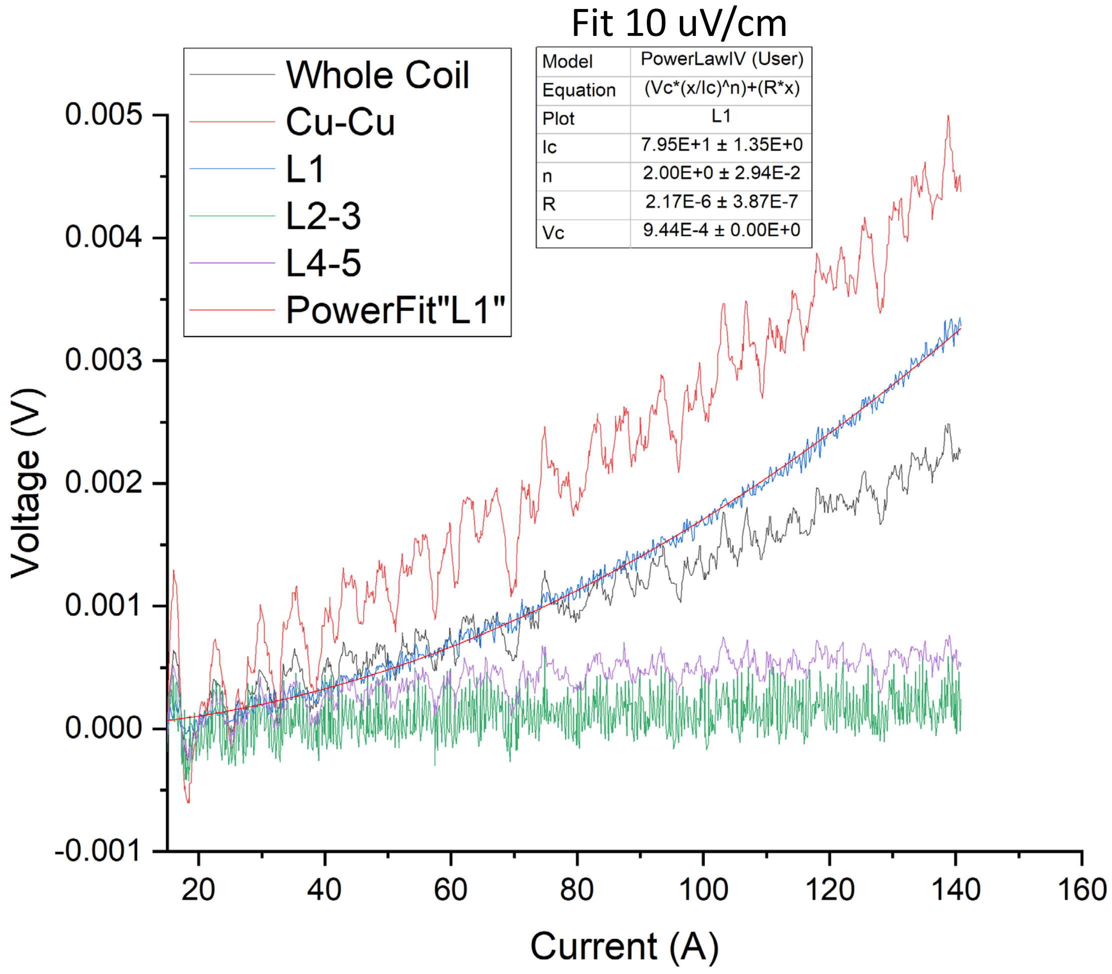




Teo-BR 1&2 Performance Limited by Inner Layer



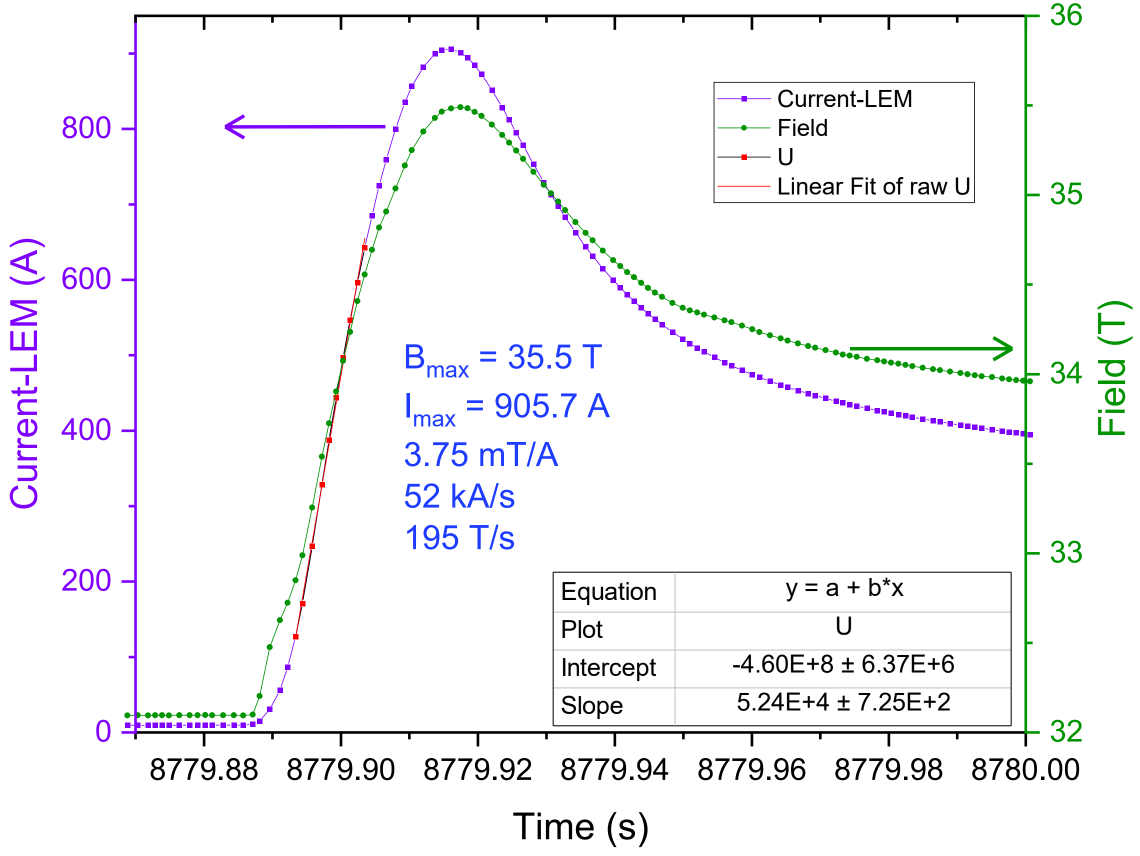
Teo-BR-2 31.2 T VI curve with inductive offsets removed. Layer 1 is fit to a power law with a low index value ~3. 10 A/s



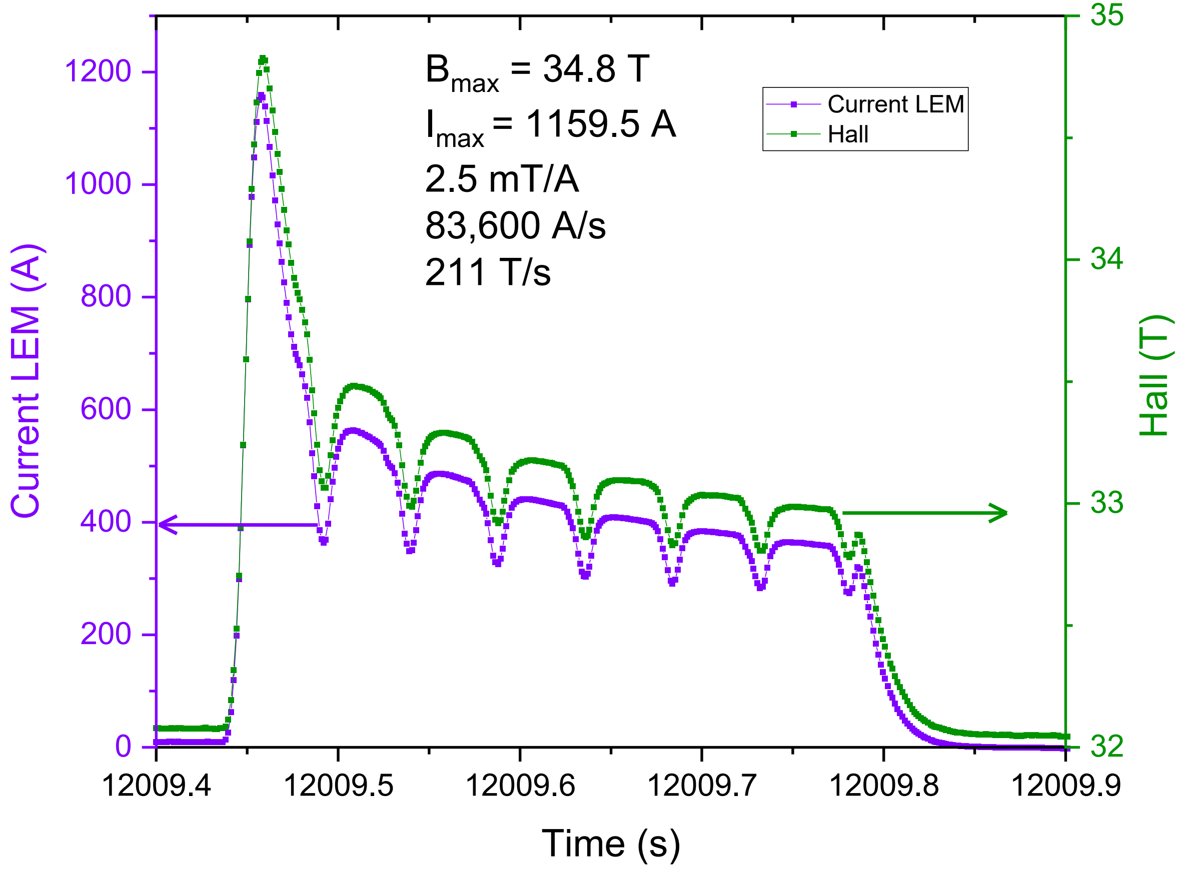
Teo-BR-1 31.2 T VI curve with inductive offsets removed. Layer 1 is fit to a power law with a low index value ~2. 100 A/s

Low Inductance and Current Sharing Enable **200 T/s to +3.4 T**

To evaluate cable magnet operation and demonstrate resilience, we ramped at max slew-rate into the quench resistance limits with our 10 V supplies



Teo-BR-2, 31 T high ramp rate field generation.



Teo-BR-1, 31 T high ramp rate field generation.

Summary – A Lot Learned in a Short Time

- Extending “Teo” and “BR” design features to cables we were able to get from cable to test coil in 1 month to take advantage of 31 T NHMFL Resistive Magnet time
- Demonstrated Cable Magnet Technology
  - Insulation, terminals, winding, VPI
  - Low-inductance and high-stability allowed 200 T/s fast-ramping and target field production despite limiting section.
- Revealed an unknown-unknown quickly so we can delve into the science
  - We can start by looking into contamination, 0.7 mm sheath thickness and filament spacing, tight bend radius samples with and without over-pressure
- Next Steps
  - Continued post-mortem investigations
    - coil-cross sections for radial leakage amount
  - Are barrels of other cable compactions worth measuring now despite spread of performance possible from leakage?
  - Extracted strand barrels and short samples +OPHT
  - Cable surface imaging