Epoxy interfaces in superconducting accelerator magnets

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Minimizing quench training in Nb-Ti and Nb_3Sn superconducting accelerator magnets

- The key for Nb-Ti magnets is to minimize conductor motion.
  - Insulation is prepreg Kapton.
  - The tool is to apply sufficient prestress, using the collar structure invented by the late Prof. Alvin Tollestrup.

- The epoxy-impregnated Nb_3Sn magnets have many other factors in play.
  - Insulation is weaved S-glass sleeve with others at interfaces.
  - Disturbances may result from fiber breaking, matrix/resin cracking or fiber/matrix debonding, superconductor/matrix debonding, tooling/matrix debonding.
  - The interface can be affected by moisture, sizing of the insulation, no. of ply of the insulation, and the surface preparation etc.
  - However, there are few or no conclusive findings.

Nb_3Sn superconducting accelerator magnets – key experimental facts

- **Most of cosine-theta (CT) Nb_3Sn magnets quench at the pole region (Fermilab's 14.5 T, MQXF, HQ etc.).**

- **For CCT, it is less clear where are the quenches and what failure modes or mechanical stresses cause them?**

Tensile properties of glass/epoxy composite – important for ends of CT, pole regions of CCT, and solenoids

FIBRE → / PROPERTY	High Strength Carbon	Al_2O_3 / SiO_2	S- Glass	Kevlar 49	E - Glass
UTS (MPa)	3700	3030	3600	3800	2700
E (GPa)	228	220	87	131	76
CTE (contraction) (10^{-6}/°C)	-0.4	1.8	2.3	-2.0	5.0
Failure Strain (%)	1.5	1.2	5.6	2.8	5.0
Density (g/cc)	1.80	2.19	2.49	1.44	2.56

(David Evans, ICMC 2019)

- **CCT pole region tensile stress so far is far away from creating tensile failure.**

The S-2 glass fibre and epoxy interface

- Many factors at play: Fibre damages, uniformity of fiber distribution and alignment, multi-ply construction, moisture.
  - **The Ininterlaminar shear strength (ILSS) for the CTD101K, with 50 Vol% satin weave S-2 glass (short beam shear test).**

Shear Properties

Temperature [K]	Shear Strength [MPa]	Flexural Modulus [GPa]
76	108.0	27.9
4	120.0	34.1

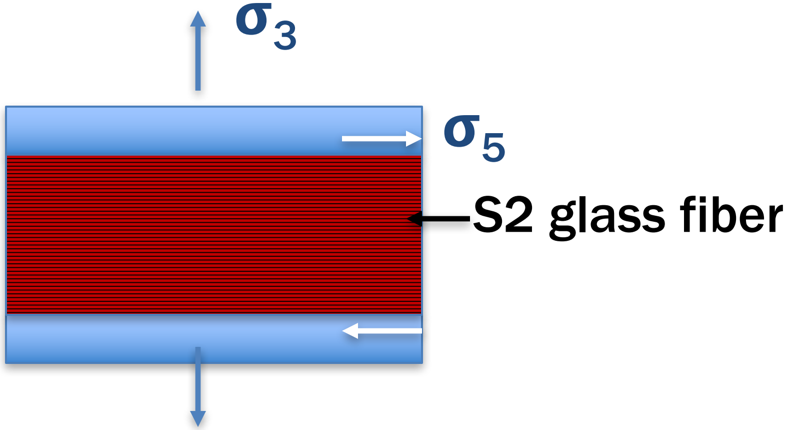
Source: CTD.

- **New measurements for CTD101K at CTD indicate that ILSS at 76 K can be 95 MPa (sample by CTD), and 85 MPa (sample by LBNL, Silane not removed). Samples of NHMFL mix61 to be measured at 76 K. The ILSS of the NHMFL mix61 at RT (LBNL sample, CTD test) is 35 MPa.**

Perhaps a source of training in CCT, and less likely for CT.

More from Krave.

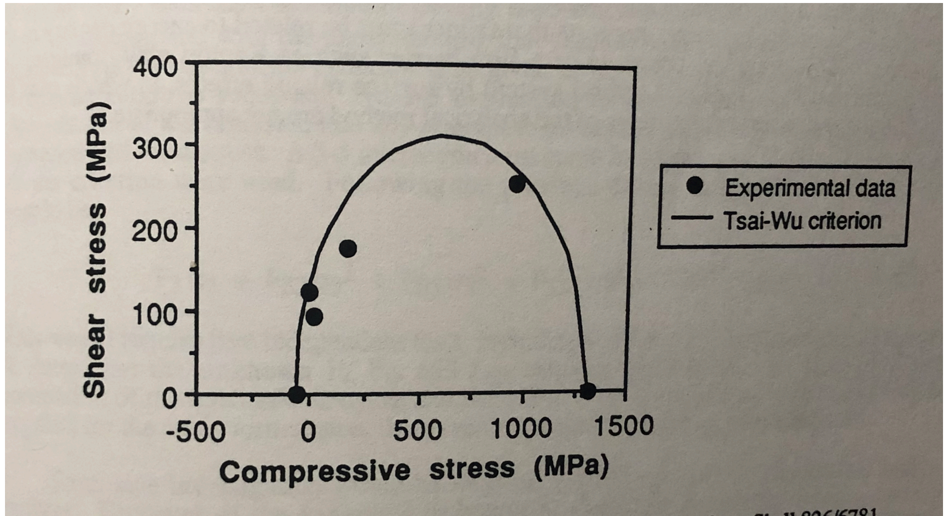
Composite and metal (pole, wedge, CCT mandrel, solenoid mandrel) interface



- Through thickness compression
- Through thickness tension
- Biaxial shear/compression

Tsai-Wu failure criterion:

$$F_3\sigma_3 + F_{33}\sigma_3^2 + F_{55}\sigma_5^2 = 1$$



'igure 5. Tsai-Wu failure criteria and experimental shear/compression data from Shell 826/6781 nsulation system.

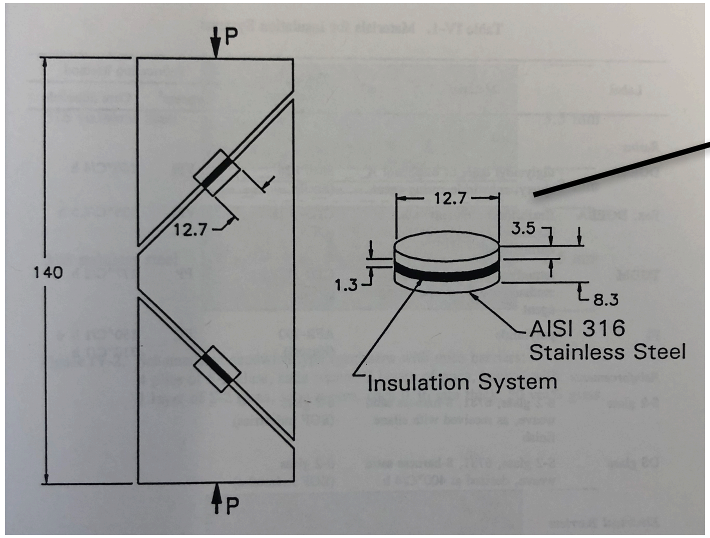
J. Schutz, P. Fabian, ICMC 1995, failure criteria for low temperature irradiated organic composite insulation systems., in US ITER insulation irradiation program final report

Through thickness tension and interlaminar tension

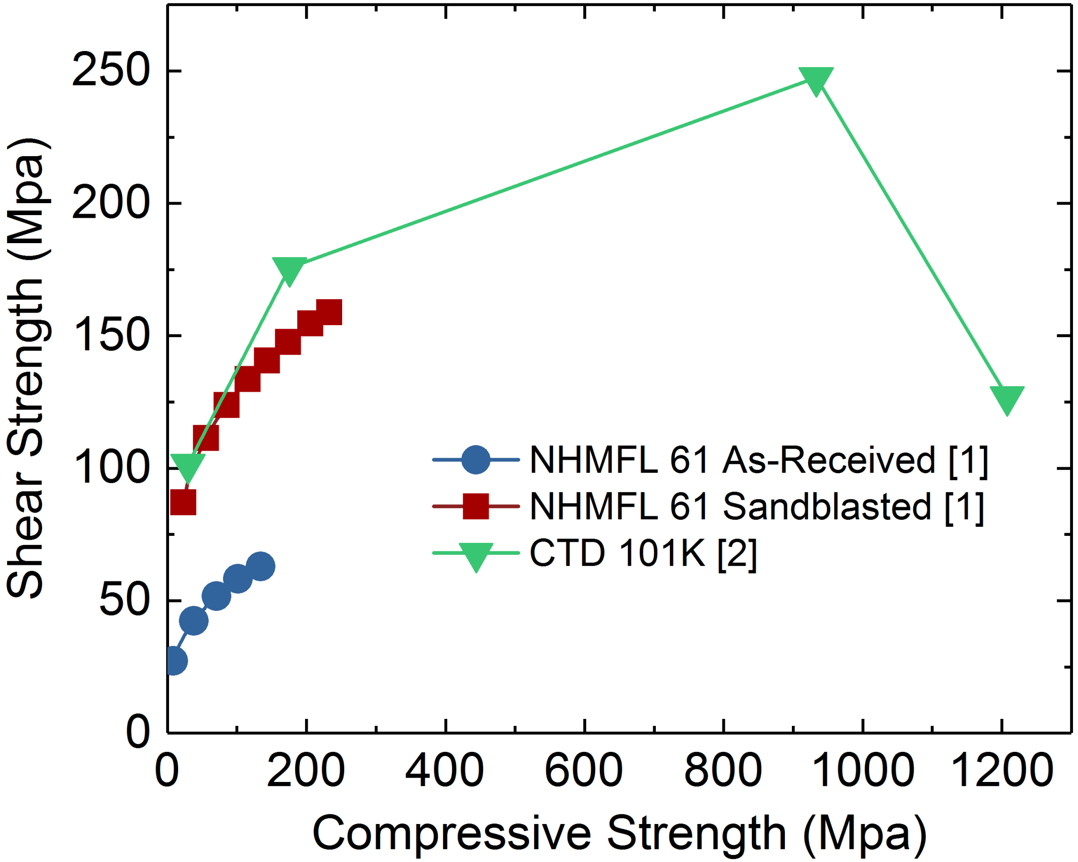
- **Very little data in literature.**
- **Experiments ongoing at the CTD.**

- **A critical parameter for solenoid and CCT.**

ITER biaxial compression/shear tests



- **Sample is a fiber-glass/epoxy sandwiched between two stainless steel 316.**
- **Insulation - 50 vol.% S-2 glass.**



- **Most of ITER US insulation program samples failed cohesively.**
- **NHMFL reports that most of their samples failed adhesively. (Hard to believe for the sandblasted samples).**

A Perin reports shear strengths between epoxy and Cu at as low as 50 MPa with 45-dgree biaxial compression/shear tests (LHC project report 504).

[1] Compressive-Shear Measurements of NHMFL 61 Epoxy – S-glass to Stainless Steel with and without Surface Abrasion, Iain Dixon Yuhu Zhai Vince Toplosky
[2] P.E. Fabian, /10.1016/0011 2275(95)90890-R

Single-lap shear strength by Shijian Yin at LBNL indicates a much lower shear strength <15 MPa

- **According to ASTM D1002**
- **Test rate – 0.05 inch/min**
- **One layer S-2 glass (unreacted) at the overlap area.**

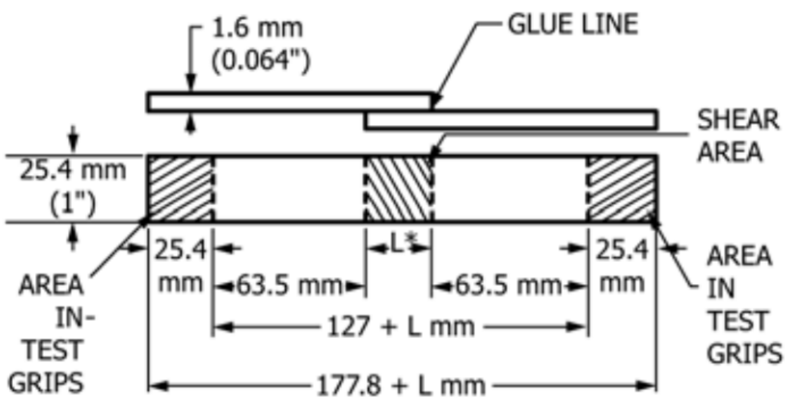
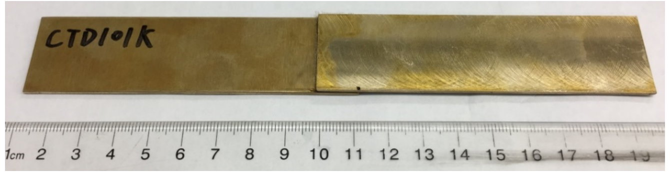
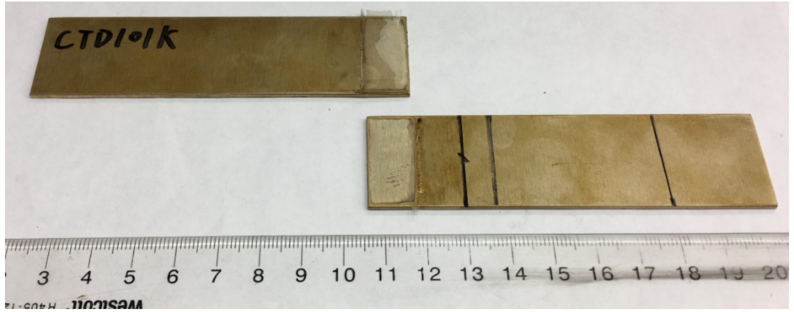


FIG. 1 Form and Dimensions of Test Specimen

Before test

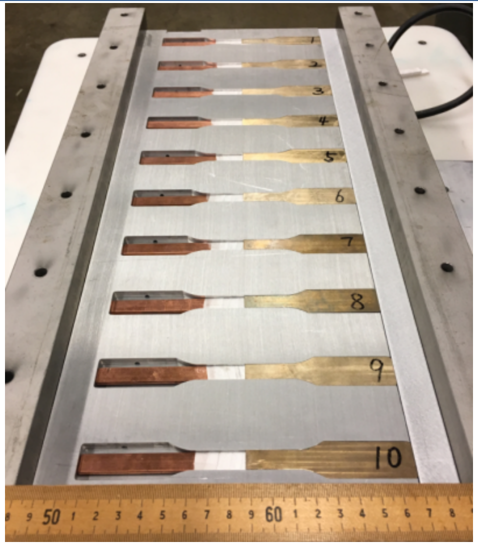


After test



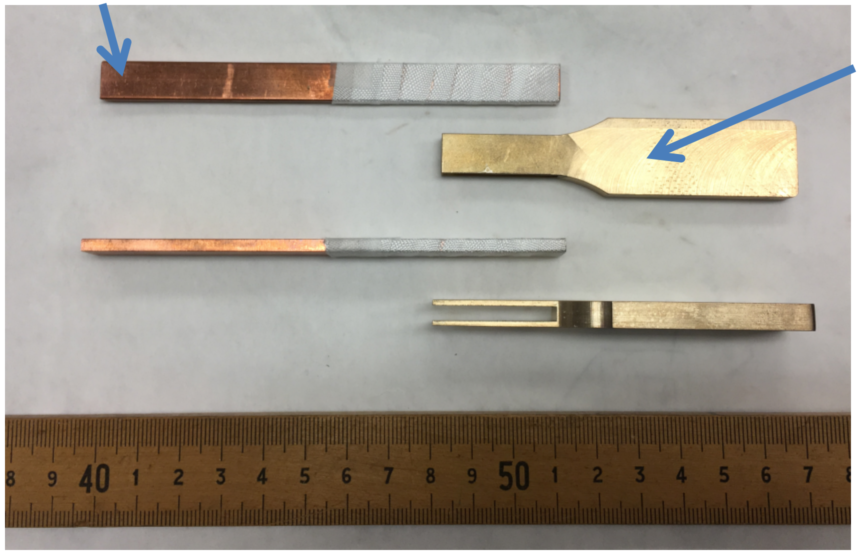
Yin's results consistent with results from CEA – SACLAY.

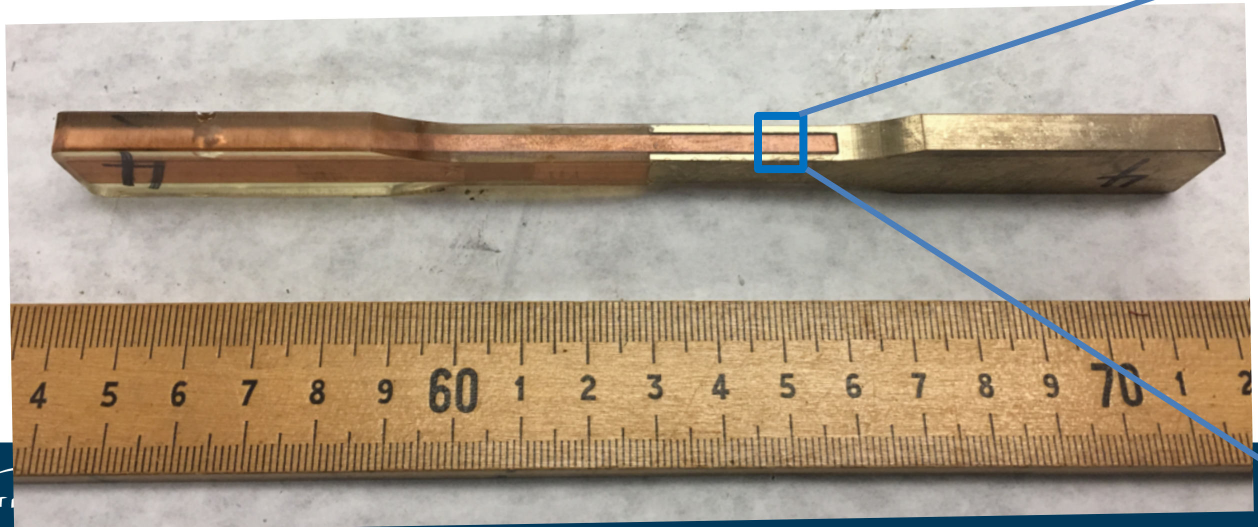
Double-lap shear test sample confirms that the critical shear strength is smaller Than 15 Mpa.



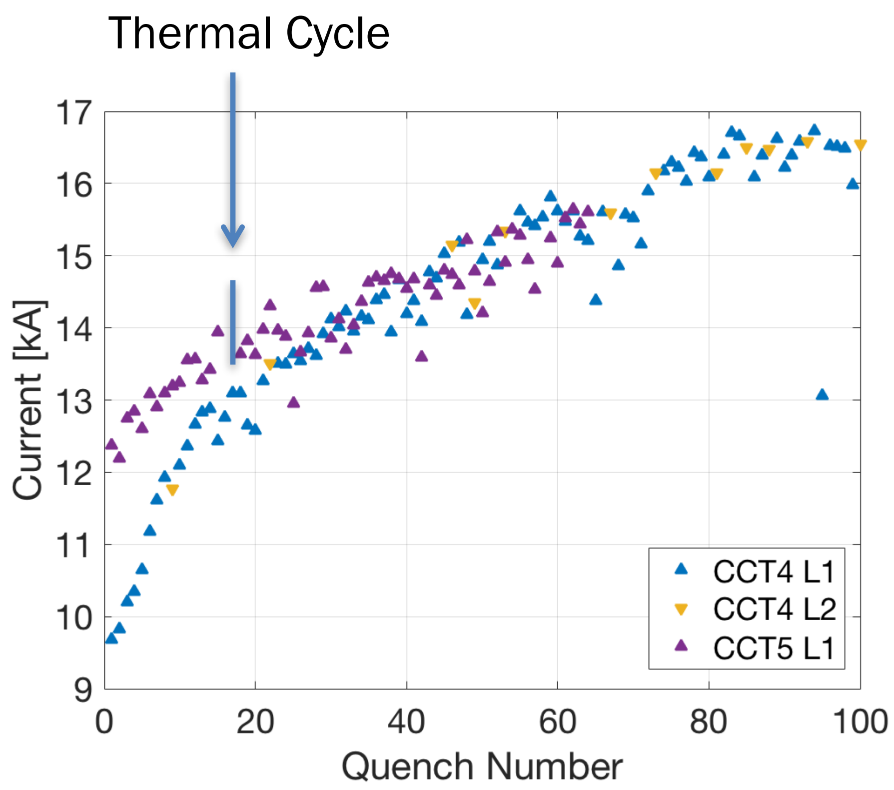
Cu

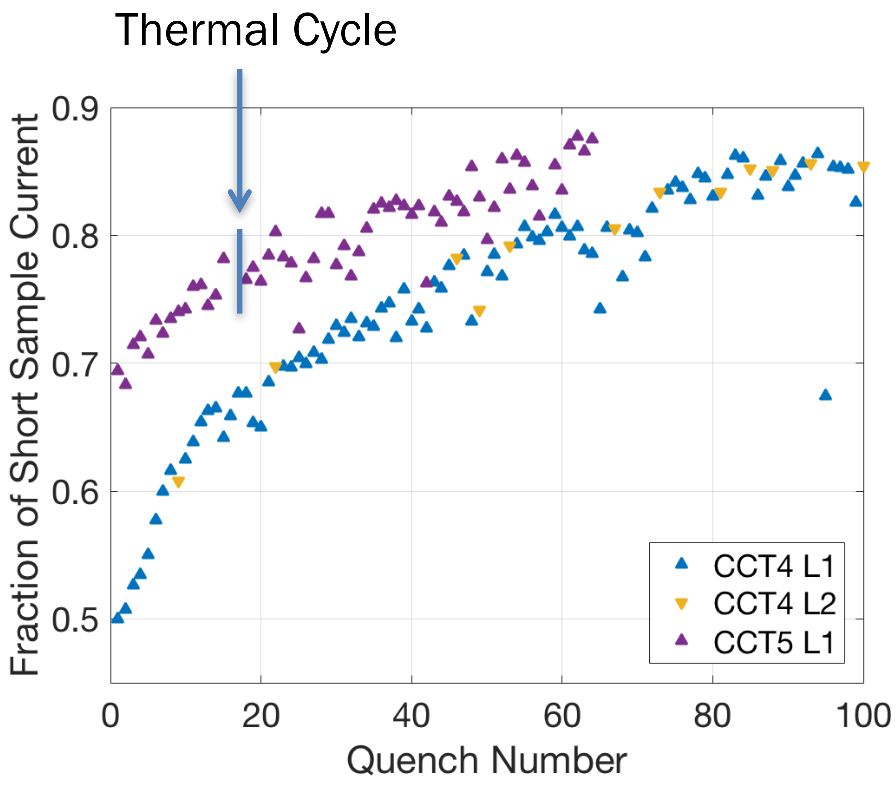
954 Aluminum bronze





CCT4 versus CCT5 – why CCT5 has a less lengthy training? (Let's first assume that this is not a fluke.)

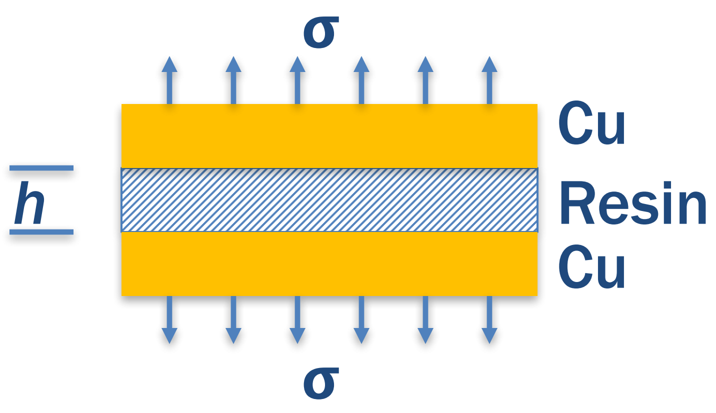




Quench Current Relative to SSL

Courtesy of Diego Arbelaez and the LBNL Nb_3Sn CCT team

All epoxy resins become brittle <77 K. The work of fracture differs. Where the NHMXL mix61, and potentially CTD-701x, may have an advantage.



$$\sigma = \frac{\int_{4\,K}^{RT} E\Delta\alpha dT}{1-2\mu}$$

If $\frac{\sigma^2 h}{4E} > \gamma$, resin cracks.

γ is the work of fracture.

CTD101K is similar to ITER CS epoxy. And NHMFL mix61 similar to 71A.

	ITER CS	71 A	ATLAS ECT variants			
	DGEBF/ MTHPA*	DGEBF POPDA	DGEBF/ PPGDGE 50/50	DGEBF/ PPGDGE 60/40	DGEBF/ PPGDGE 80/20	DGEBF/ PPGDGE 100/0
	Work (J/m²)	Work (J/m²)	Work (J/m²)	Work (J/m²)	Work (J/m²)	Work (J/m²)
RT	103	899**	2241**	353	310	205
	± 12			± 53	± 42	± 58
77K	199	525	396	359	249	110
	± 13	± 67	± 27	± 49	± 49	± 25
4.2K	61	178	128	100	93	63
	± 5	± 10	± 9	± 2	± 9	± 3

*MTHPA – methyl tetrahydrophthalic anhydride – typically Huntsman HY 917

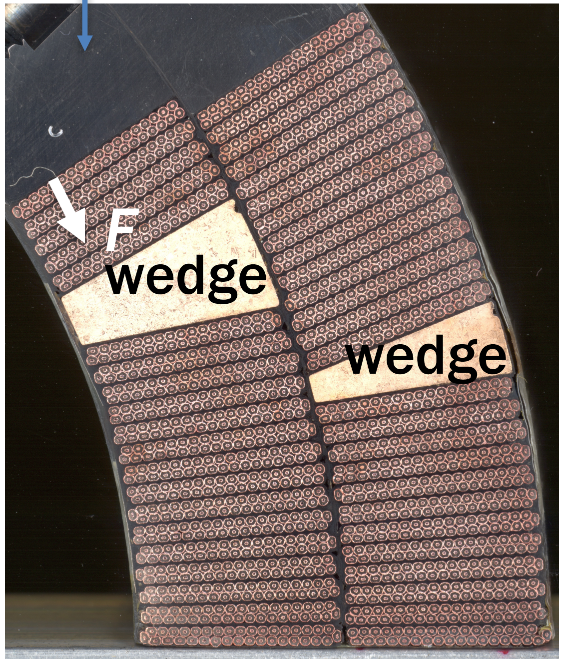
**Results at RT are geometry dependent - no single value for the work of fracture.

Resins		DGEBA / POPDA	DGEBA/ Anhyd.	100/0	60/40
Thermal Stress (MPa)	4K	95	124	124	101
Cracking Index (mm)	4K	0.36	0.07	0.07	0.19

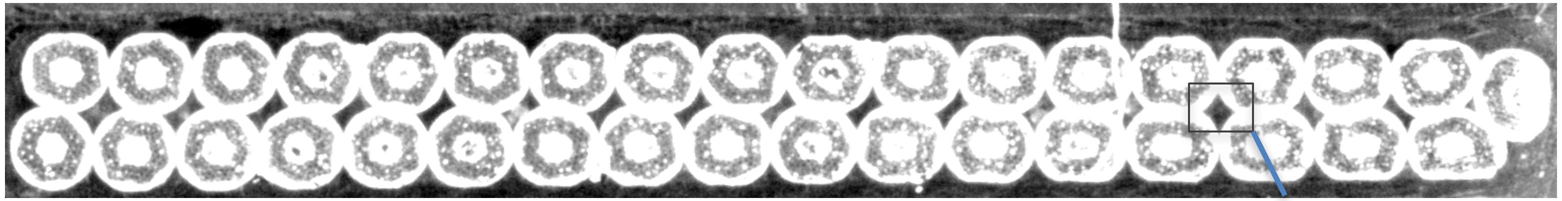
Work of fracture and cracking index data from D. Evans, ICMC2019.
RAL-71A (POPDA hardener – the toughest epoxy for cryogenic uses – David Evans)

Micro-cracking in the neat resin between strands inside a Rutherford cable. At the pole region of CT magnets when the F_θ drops to zero, and everywhere for CCT magnets.

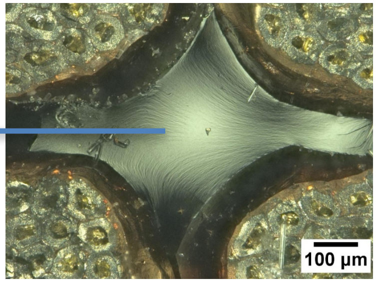
Ti-alloy pole

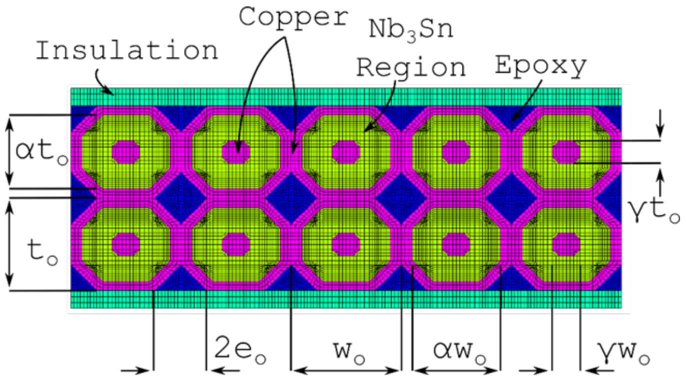


HQ-C06, Hugh Higley



Neat resin, as large as 0.4 mm





G. Vallone, MT26. Prediction of the Reversible Critical Current Degradation in Nb3Sn Superconducting Accelerator Magnets.

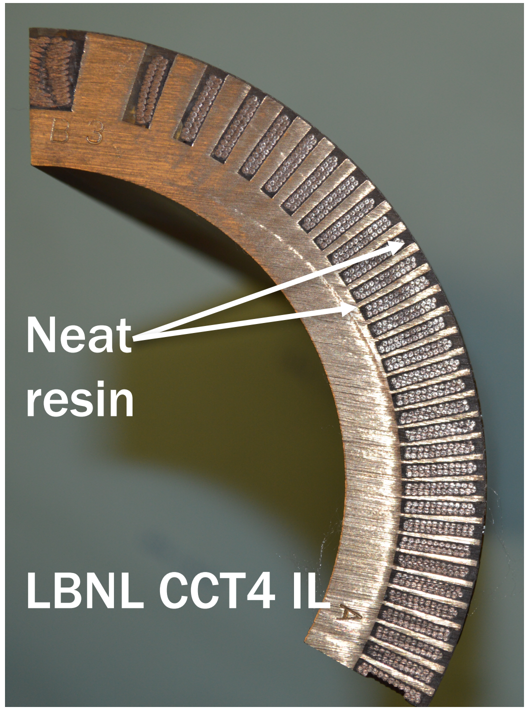
FEM ANSYS APDL model. Nonlinear Cu (bi-linear model), linear and isotropic epoxy, linear and anisotropic fiber/epoxy.

Cool down with pre-compression. energization shifts the azimuthal strain at the pole region towards tensile by 0.5% at the pole, while there is a constant tensile 0.6% axial strain.

I would like to see some CT coils cooled down without precompression and then assembled.

Credits to Akira Yamamoto for initially raising questions about controlling cracking of epoxy between strands inside a Rutherford cable.

The reason that the training of NHMFL-mix61 impregnated CCT5 is less lengthy than that of CCT4 perhaps lies with the fact of less matrix/epoxy cracking.



The neat resin pockets are larger than 0.4 mm in many locations. Cool down mostly without pre-compression. **They** crack upon cooling down.

The neat resin pockets that are smaller than 0.4 mm start to crack with energization.

I would like to see some Nb_3Sn CCT coils cooled down with precompression.

Final comments in the spirit of modeling workshop

Modeling superconducting accelerator magnets at the level of glass/epoxy composite and their interfaces is not easy due to anisotropic and nonlinear materials properties and defects in the system that originate more from fabrication.

To start, compute equivalent strain in neat epoxy. Stress management approaches are being developed for superconductors to go to higher field. A stress management for resin is needed to control training.

Acknowledgements

- Andrea Haight (CTD) and Steve Krave for the ongoing phase II collaboration.
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- David Evans for discussions.
- All LBNL BCMT colleagues.