ELECTRO-MECHANICAL CHARACTERIZATION of REBCO CONDUCTORS AND JOINTS

for use in

NHMFL 32 T ALL SUPERCONDUCTING MAGNET

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INTRODUCTION

Characterization of YBCO Coated Conductors is done in support of the design and construction of a 32T all-superconducting magnet at the NHMFL.

The test program serves to;

1. Document the variability in production grade conductors.
2. Confirm the performance and margins of safety.
3. Identify potential problems areas.

OUTLINE

Background

- Magnet and conductor description

Physical Dimension Measurements

- Measurements of thickness and width of conductor with optical microscope

Tensile Tests

- 77K and 4 K Stress-Strain Curves of conductors w/ varying thickness of copper
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Ic vs Axial Strain, Tensile and Fatigue Tests

- T = 77 K, Single conductors and Lap joints.
- Measure Ic as a function of applied tensile strain.
- Fatigue Tests to confirm retention of Ic as a function of cyclic stress.

Conclusions and Future Work

BACKGROUND

<u>Magnet system</u>

- 32 T, 4.2 K, 34 mm cold bore
- Uniformity over 1 cm DSV 500 ppm
- Stored energy 8.3 MJ
- Expected cycles/20 years 50,000

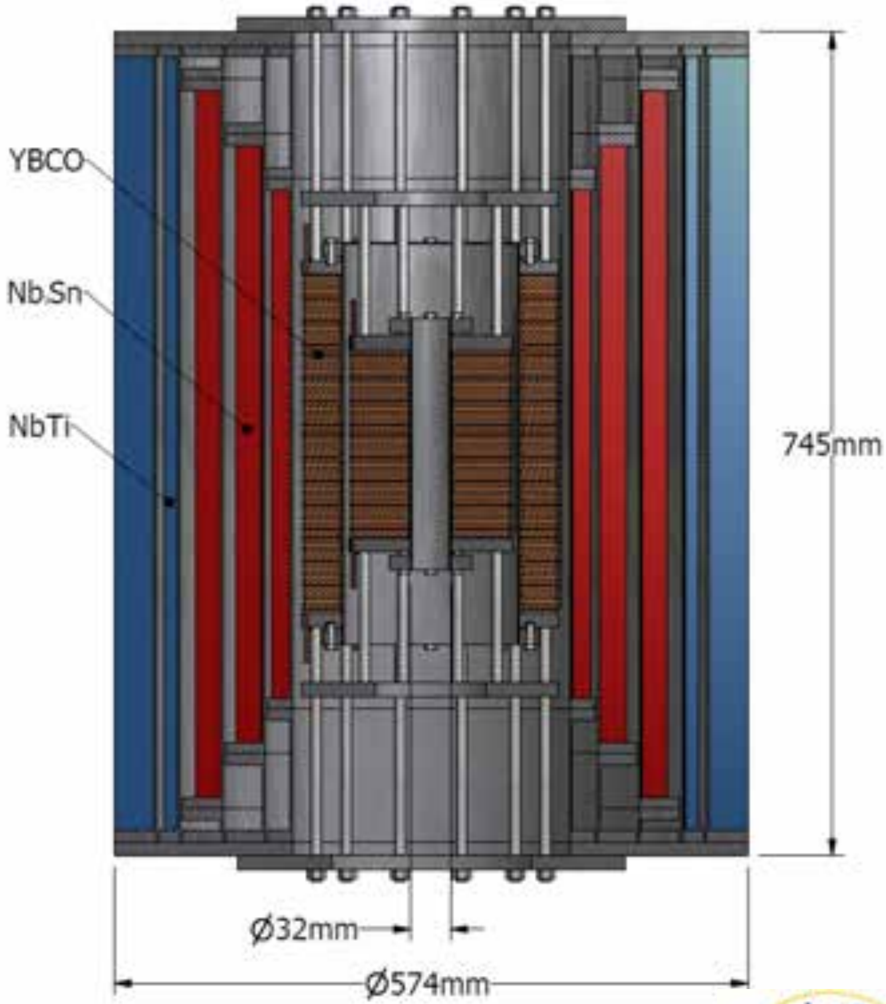
<u>Inner coils</u>

- **Pancake wind**
- **Dry wind**
- **Insulated co-wind steel reinforcement**
- Average current density 193/170 A/mm^2
- Copper current density 428 A/mm^2
- Stress in windings 363/378 MPa
- REBCO conductor length 10 km

<u>Outer magnet</u>

- 15 T, 250 mm bore, Nb3Sn/NbTi, 7.0 MJ
- Commercial supply

32 TESLA SUPERCONDUCTING MAGNET



Thickest surround copper available ~100 um corresponds to suitable operating current 170 – 180 A.

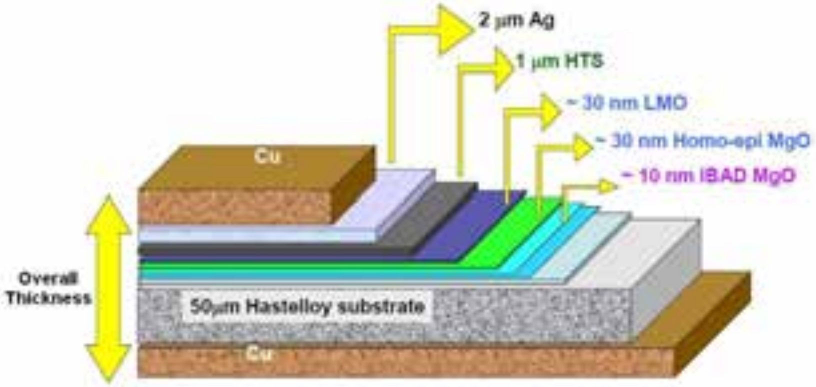
BACKGROUND

MATERIAL:

- Production grade YBCO superconducting composite tape produced by Superpower Inc.
- A series of conductors with variable thickness copper stabilizer (range 40 μm to 100 μm)

Conductor ID	Approx. Ic, T = 77K, B=0T [A]	Avg. X-section width x thk [mm]	Avg Cu. thk/side ** [μm]	Cu Area / Hastelloy Area
SP20	130	4.09 x 0.10	21	0.98
SP18	99	4.12 x 0.12	35	1.54
SP07	102	4.13 x 0.13	38	1.67
SP26	124	4.15 x 0.15	50	2.18

** Cu thickness = average tape thickness - nominal hastelloy thickness

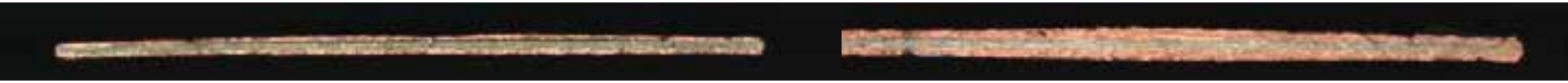


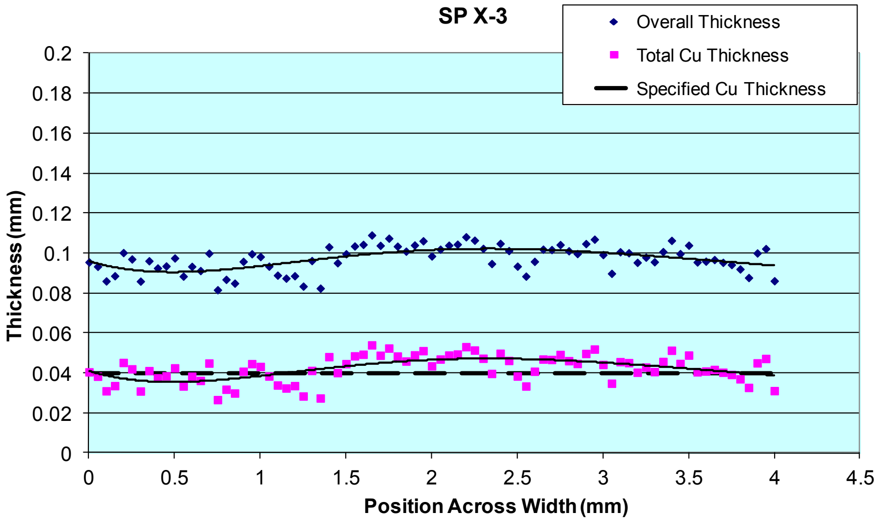
End view photo of SP07 conductor shows Surround Cu Stabilizer (SCS) and Hastelloy substrate.

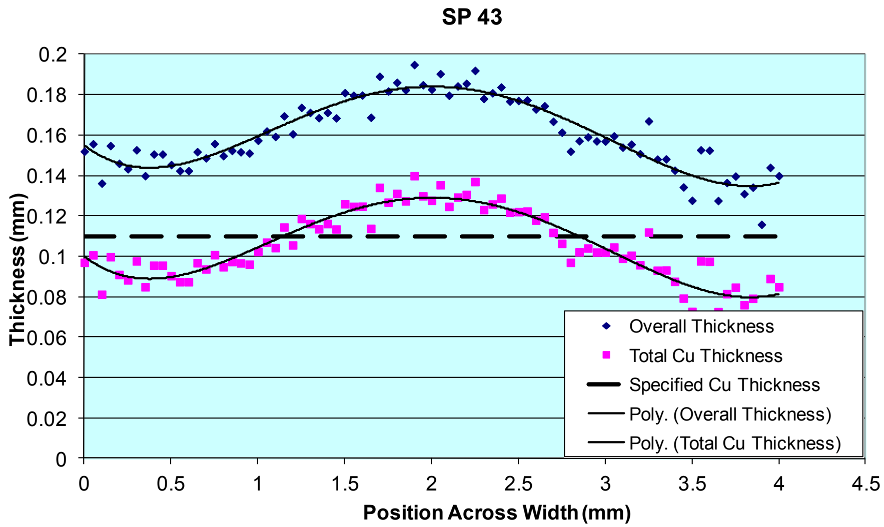
Measurement of conductor thickness profile using inspection microscope

40 um total copper

110 um total copper





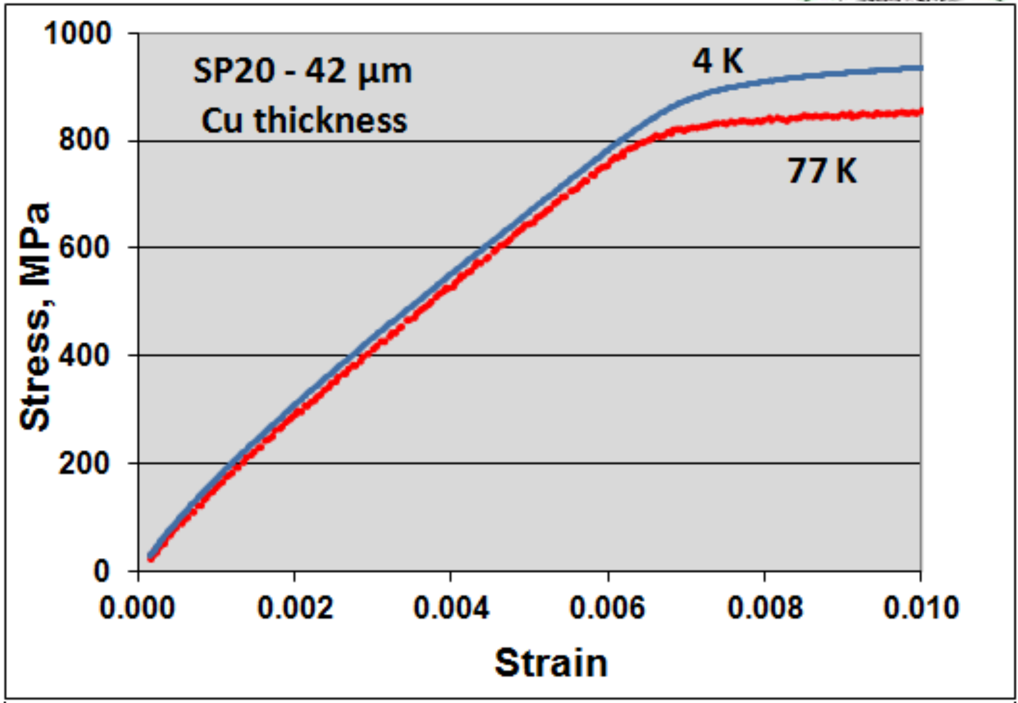


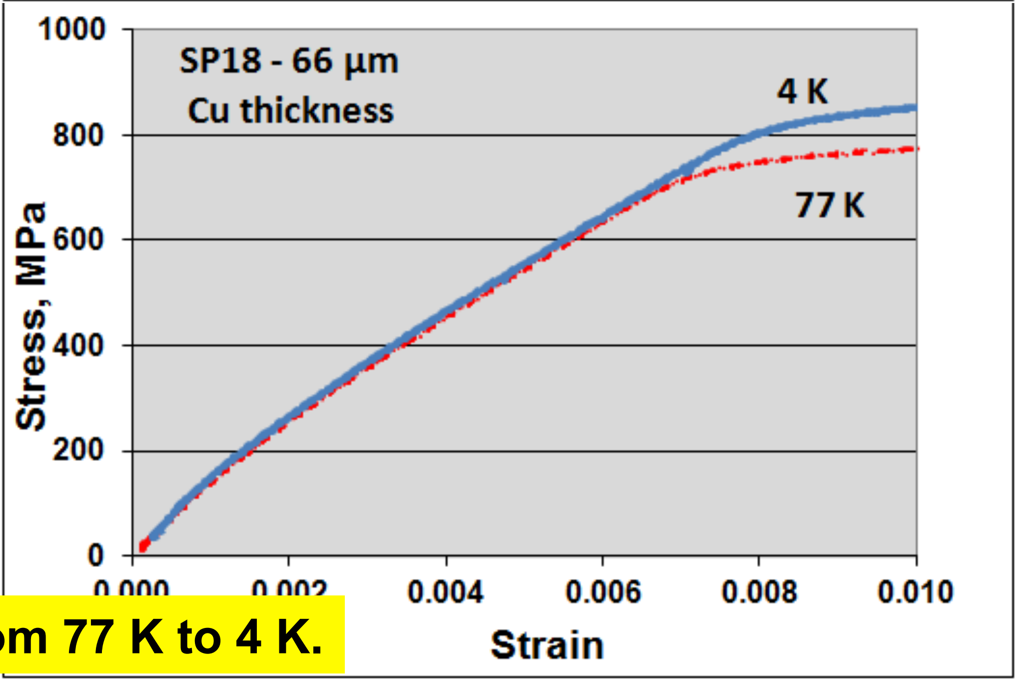
With 40 µm copper, conductor is relatively flat, minimum dog-bone.

With 100-110 µm copper, conductor is thick in center by ~ 10 %.

Additional copper for protection is found to be accompanied by a distribution in conductor thickness, resulting in a decrease in packing factor,
reduced radial thermal conductivity, and reduced structural compactness.

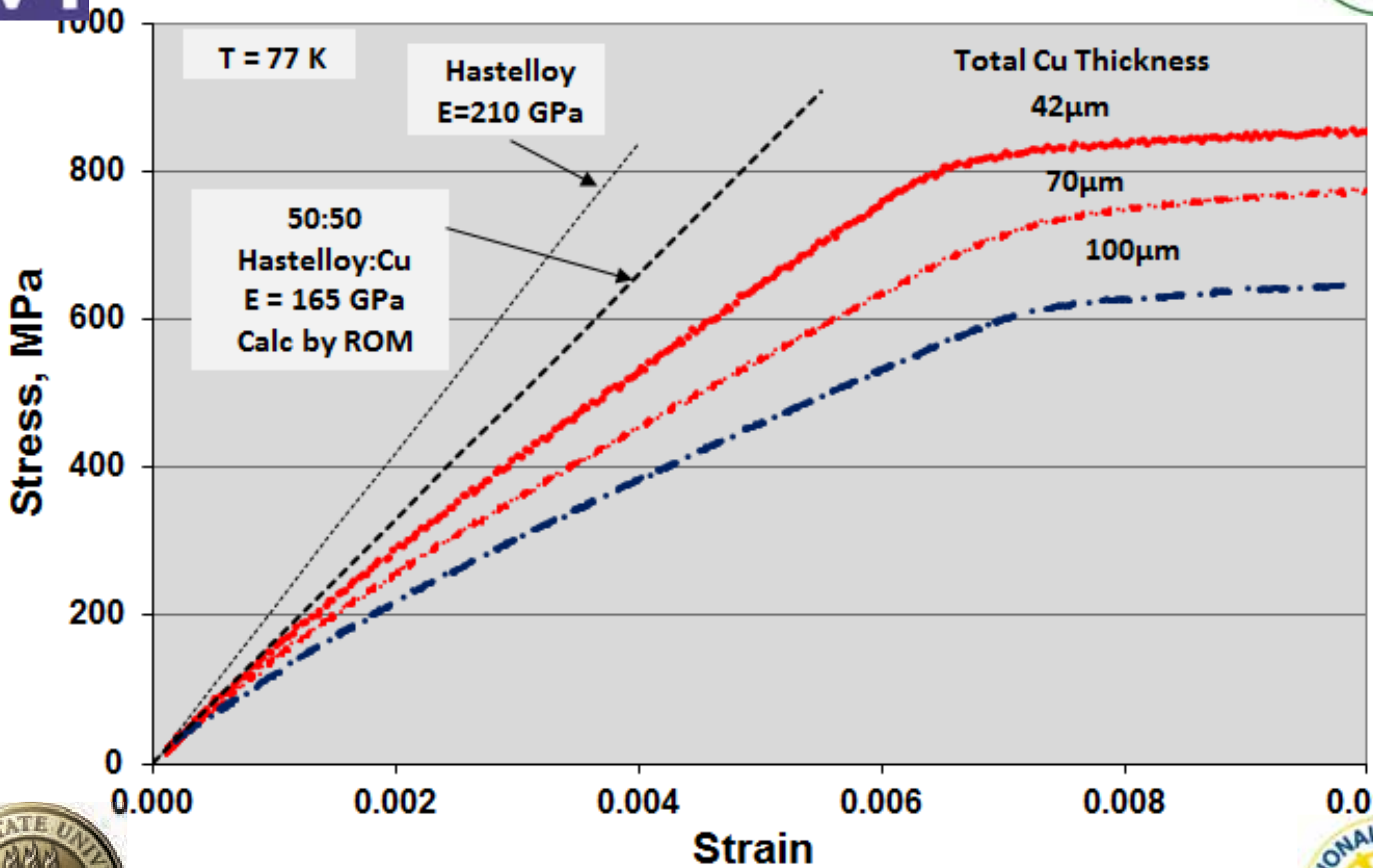
YBCO Tensile Testing



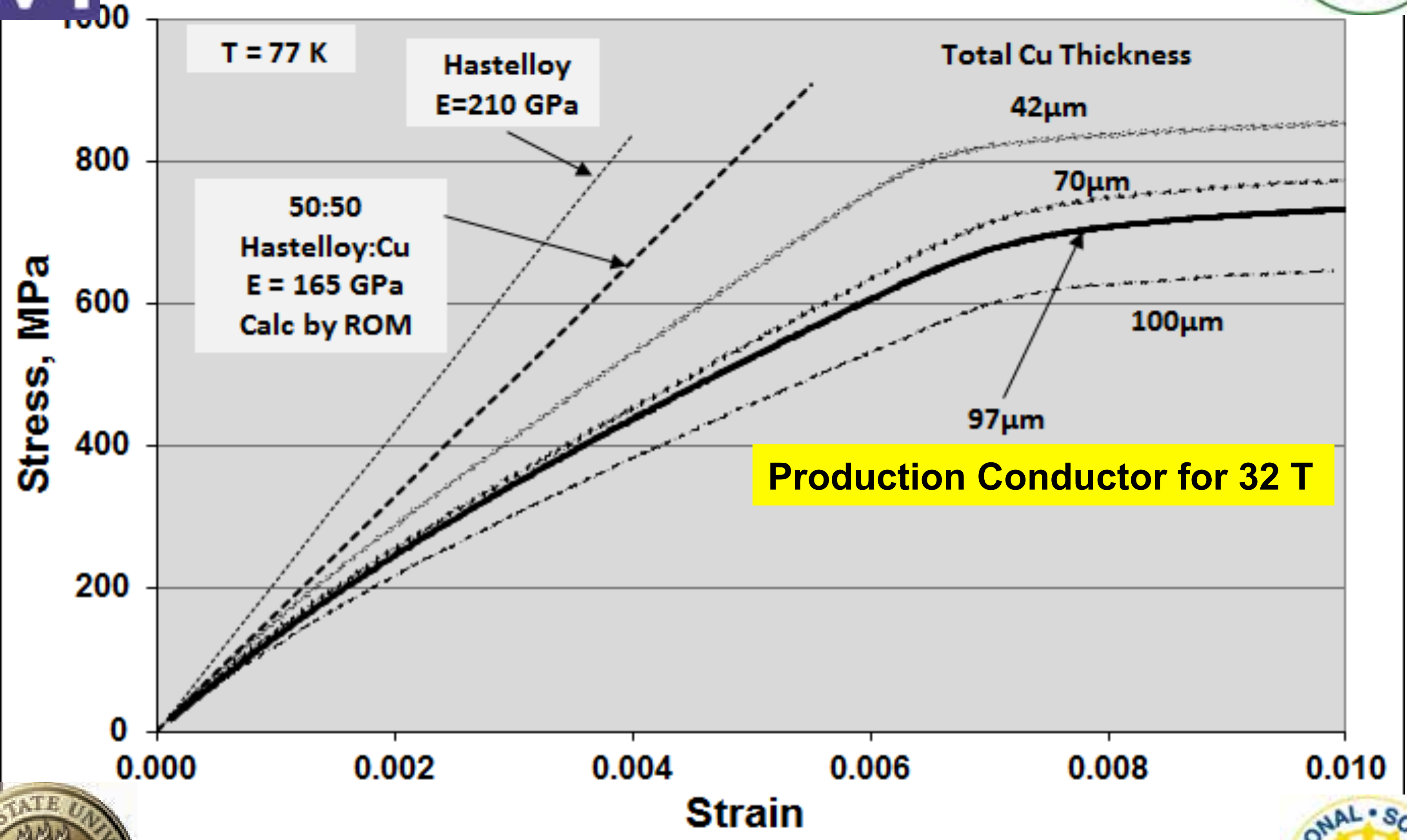


5-10 % increase in strength from 77 K to 4 K.

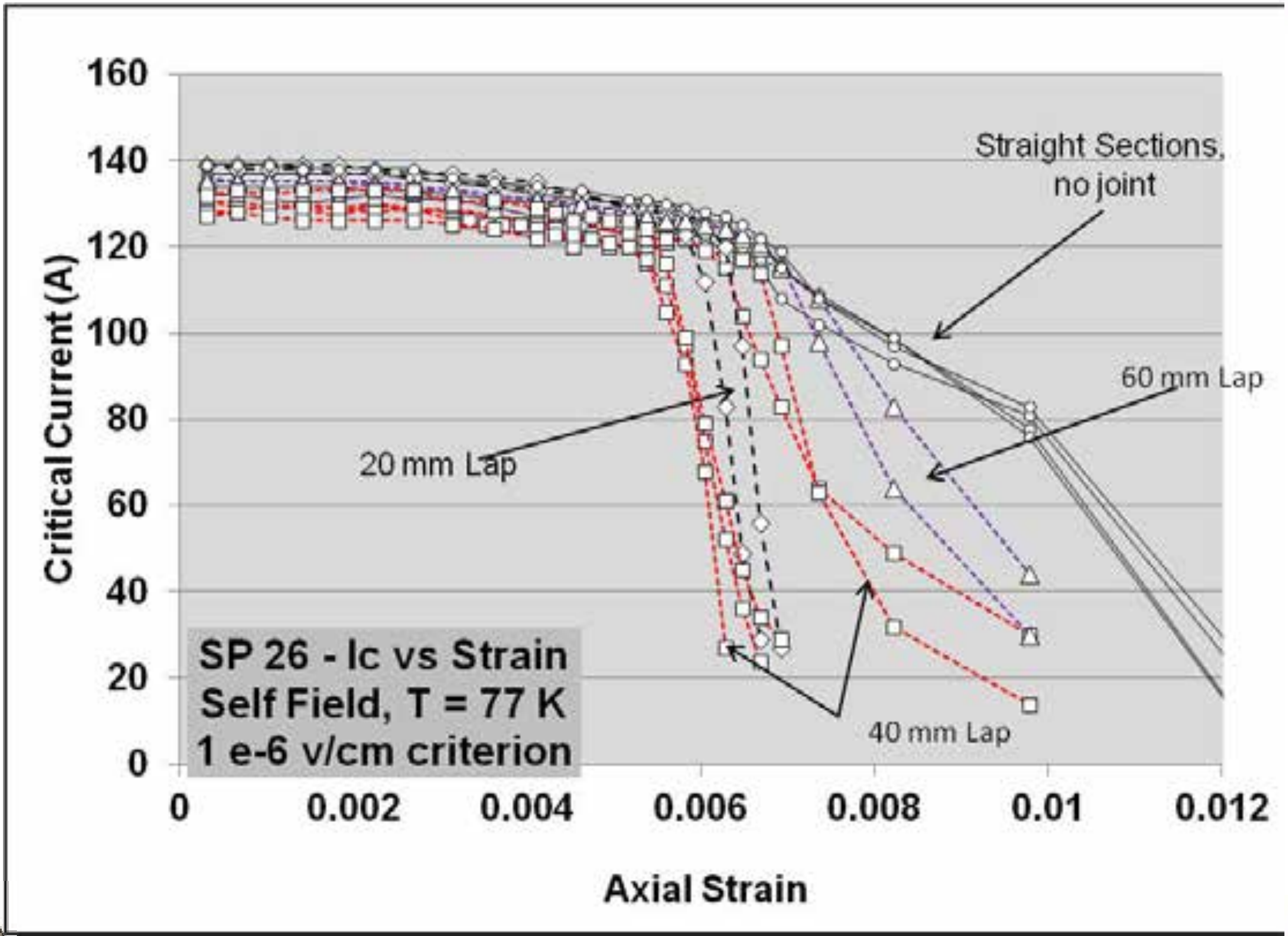
77K YBCO Reference Stress-Strain Curves



77K YBCO qualification Stress-Strain Curves



Lap Joint Reference Data



Lap Joint Test Observations

• The 10 to 15 % variation in Ic is approximately the same as observed in any single conductor piece length.

• The ~ 35% difference between the two materials may be more representative of the variation in Ic at 77 K that is likely to occur from piece to piece in production length conductors.

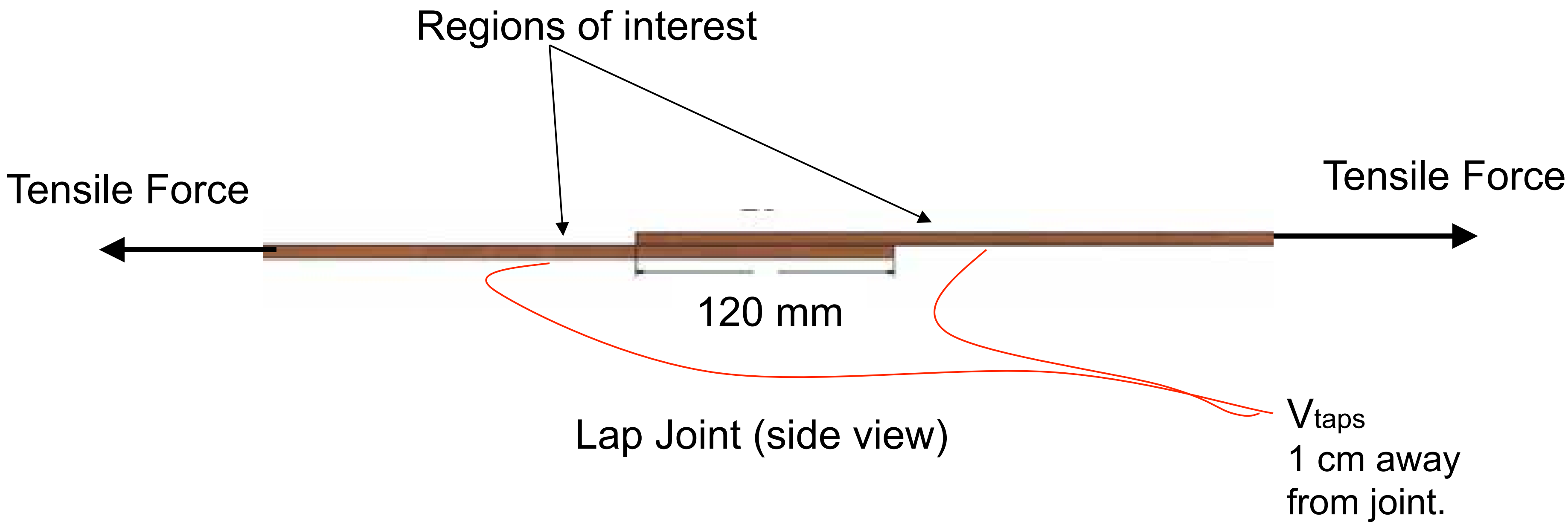
• The average lap joint resistance for the 40 mm lap joints is independent of the axial tensile stress

SP07 ~ 50 nano-ohms SP26 ~25 nano-ohms

• A few tests were carried out to fracture and in all cases the fracture occurred at the grip end indicating excellent lap joint axial tensile strength and shear strength.

• The 60 mm long lap joint Ic is about equivalent with single conductor, at around 0.5% strain both start to exhibit degradation.

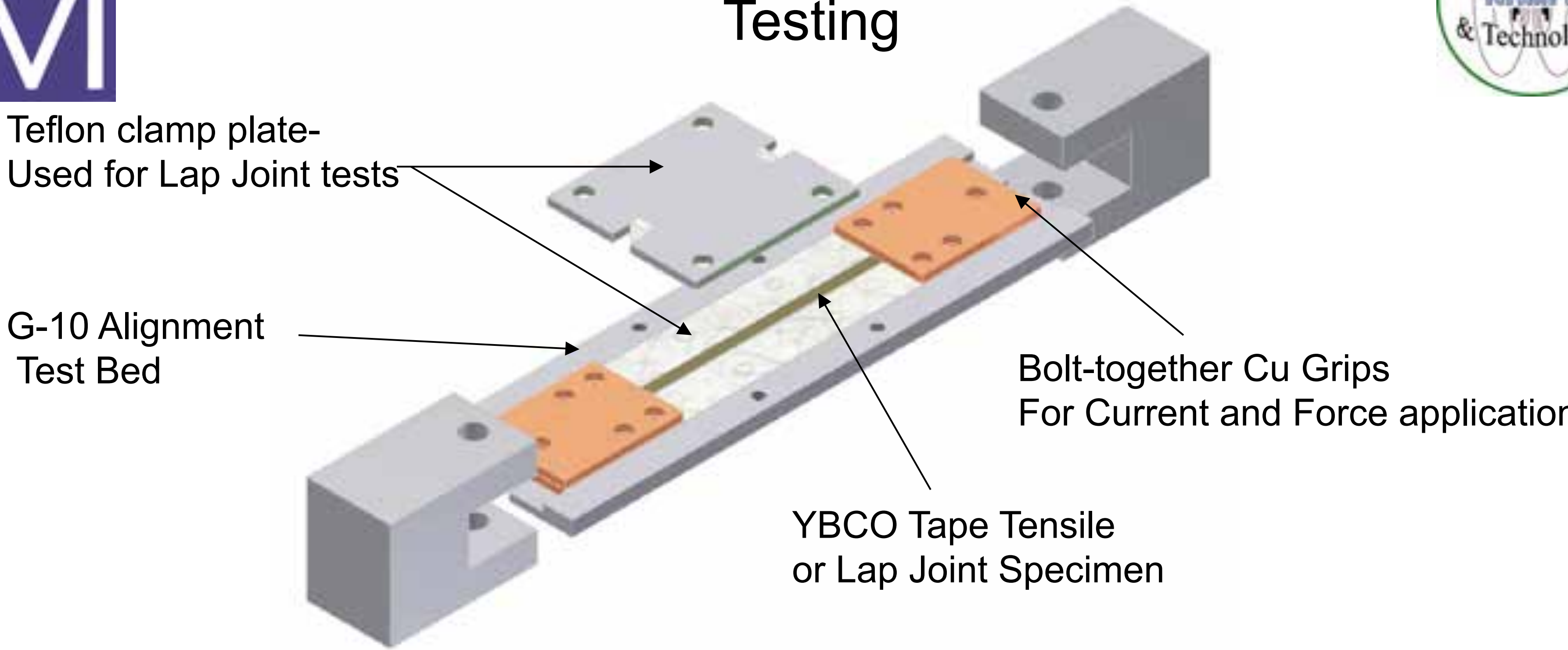
Lap Joint Tests

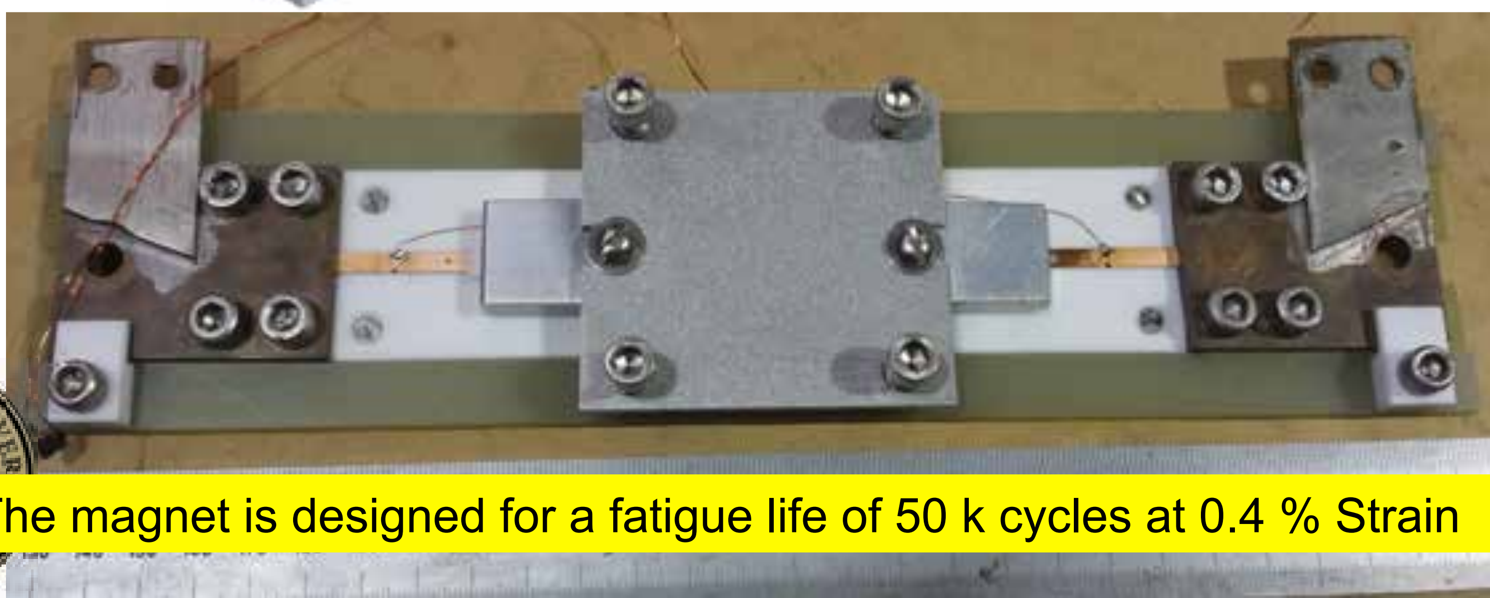


The strain is calculated for the region of interest from the applied tensile force

32 T lap joints are 120 mm long

Ic vs Strain, Conductor and Lap Joint Fatigue Testing



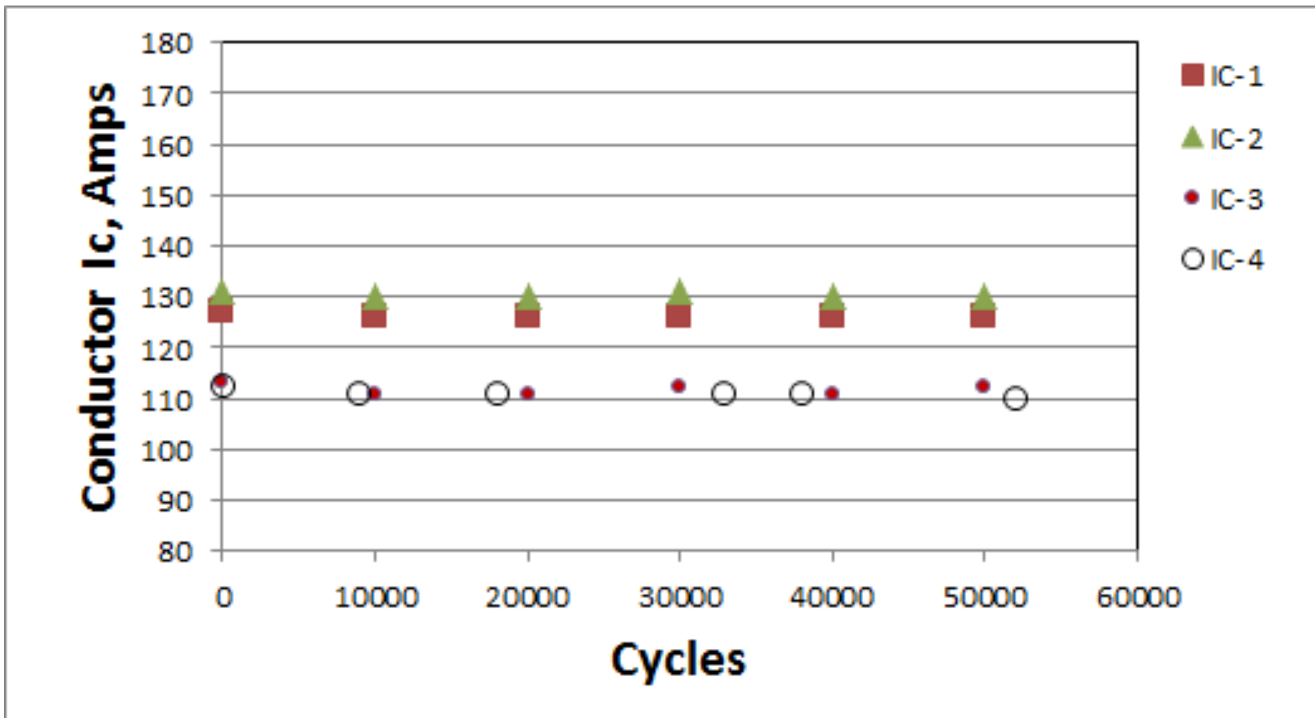


The magnet is designed for a fatigue life of 50 k cycles at 0.4 % Strain

FATIGUE RESULTS

	Spec.	% Design Strain	Max Cyclic Strain, %	Ic at Peak Cycle Strain						Comments
Cycles				1	10000	20000	30000	40000	50000	Cycle Count for Ic confirmation
Single Conductors	IC-1	120	0.48	127	126	126	126	126	126	No Ic degradation,Test stopped at 50,000 cycles
	IC-2	120	0.48	131	130	130	131	130	130	No Ic degradation,Test stopped at 50,000 cycles
	IC-3	120	0.48	113	111	111	112	111	112	No Ic degradation,Test stopped at 50,000 cycles
	IC-4	120	0.48	112	111	111	111	111	110	No Ic degradation,Test stopped at 50,000 cycles
Lap Joints	LJ-1	100	0.4	143	141	140	140	140	140	No Ic degradation,Test stopped at 50,000 cycles
	LJ-4	120	0.48	123	122	123	122	4		Ic failure between 30k and 40 k cycles

All four single conductors survived 50 k cycles with no sign of degradation



FATIGUE RESULTS

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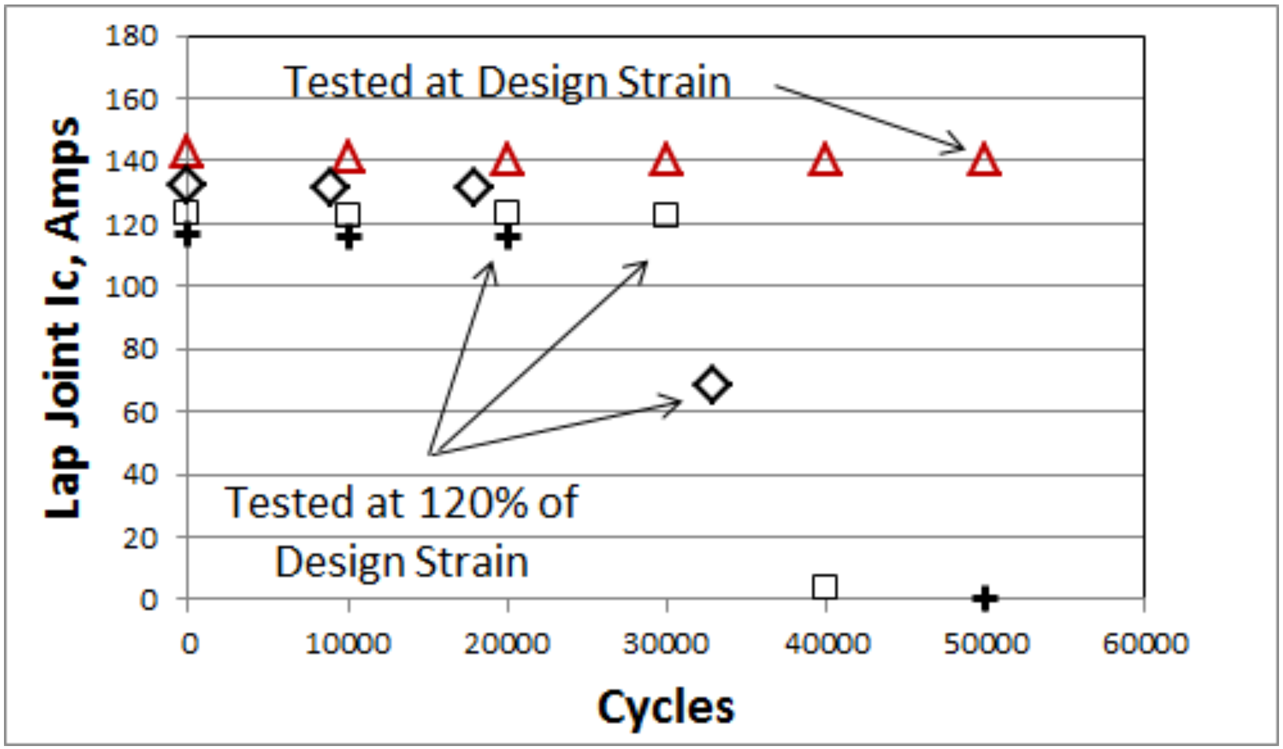
Single Conductors	IC-1	120	0.48	127	126	126	126	126	126	No Ic degradation,Test stopped at 50,000 cycles
	IC-2	120	0.48	121	120	120	121	120	120	No Ic degradation,Test stopped at 50,000 cycles
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] at 50,000 cycles
	IC-4	120	0.48	112	111	111	111	111	110	No Ic degradation,Test stopped at 50,000 cycles
Lap Joints	LJ-1	100	0.4	143	141	140	140	140	140	No Ic degradation,Test stopped at 50,000 cycles
	LJ-2	120	0.48	132	131	131	68			Ic failure between 20k and 30 k cycles
	LJ-3	120	0.48	117	116	116			0	Ic failure between 20k and 50 k cycles
	LJ-4	120	0.48	123	122	123	122	4		Ic failure between 30k and 40 k cycles

Three of four lap joints failed (Ic degradation) prior to 50 k cycles



CONCLUSIONS

1. R&D efforts at NHMFL, in collaboration with Superpower, enabled the determination of conductor specifications for this challenging magnet project.
2. The critical specifications for the conductor are difficult to achieve and the production grade conductors requires careful inspection and qualification testing.
3. The tensile strength of the production conductors meet requirements.
4. The Ic of the production conductors and joints meets requirements.
5. The conductor's superconducting and strain performance show no signs of degradation over the expected fatigue life of 50 k cycles at 20% higher strain level than the maximum operating strain.
6. Only one lap joint has been qualified to meet the fatigue life requirement of 50 k cycles at the design strain.
7. Three lap joints have failed after approximately 30 k cycles at 20 % higher than the design strain fatigue test.

FUTURE WORK

Conduct more fatigue tests to establish the fatigue life safety margin.

Confirm the electro-mechanical performance of both the conductor and joints at longer fatigue lives.
Factor of safety on strain is probably a more severe test than necessary.

Specifically :
Conduct several more 77 K Fatigue tests at Design Strain for 1.0×10^6 cycles.

THANK YOU FOR YOUR ATTENTION