Production of Aluminum Stabilized Superconducting Cable for the Mu2e Transport Solenoid

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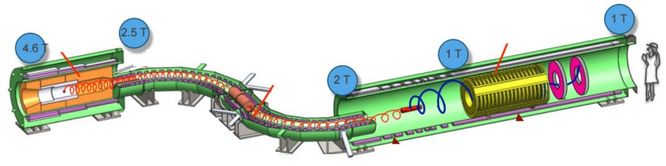
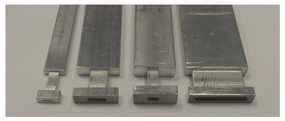
ABSTRACT

The Fermilab Mu2e experiment, currently under construction at Fermilab, has the goal of measuring the rare process of direct muon to electron conversion in the field of a nucleus. The experiment features three large superconducting solenoids: the Production Solenoid (PS), the Transport Solenoid (TS), and the Detector Solenoid (DS). The TS is an "S-shaped" solenoid that sits in between the PS and the DS producing a magnetic field ranging between 2.5 and 2.0 T. This paper describes the various steps that led to the successful procurement of over 740 km of superconducting wire and 44 km of Al-stabilized Rutherford cable needed to build the 52 coils that constitute the Mu2e Transport Solenoid (TS) cold mass. The main cable properties and results of electrical and mechanical test campaigns are summarized and discussed. Critical current measurements of the full stabilized cables are presented and compared to expected critical current values as measured on extracted strands from the final cables after chemical etching of the aluminum stabilizer. A robust and reliable approach to cable welding is presented and the effect of cable bending on the transport current is also investigated and presented.

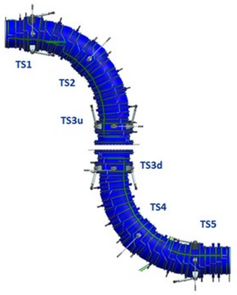
MU2E AND THE TRANSPORT SOLENOID AT A GLANCE

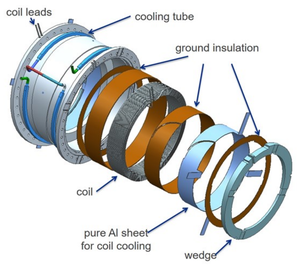




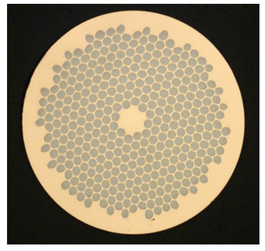
TS	DS1	DS2	PS
14x0.67mm Cable size: 9.85x3.11mm	12x1.466mm Cable size: 20.1x5.27mm	8x1.303mm Cable size: 20.1x7.03mm	30x1.466mm Cable size: 30.1x5.52mm

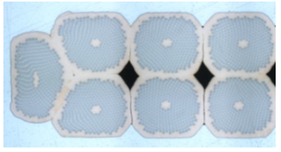
	PL needed for coil winding	Spare production lengths	Total Production Length
Transport Solenoid	14x1540mm 22x800	2x1540m 2x800m	~ 44km
Detector Solenoid 1	8x1100m	1x1100m	~ 10km
Detector Solenoid 2	3x1750m	1x1750m	~ 7km
Production Solenoid	3x1700m 2x1300m 1x1500m	3x1700m	~ 14km

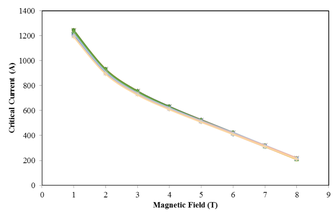


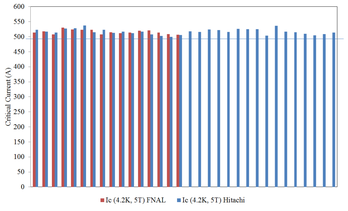


TRANSPORT SOLENOID NBTI WIRES AND RUTHERFORD CABLE









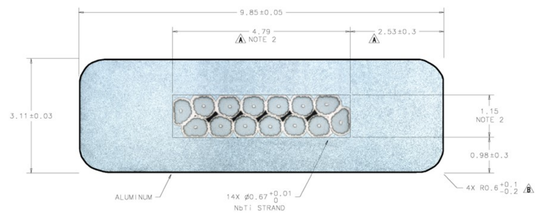
TS Wire	Specification
Standard Grade NbTi	Nb 47 ± 1 Wt% Ti
Strand diameter	0.67 ± 0.005 mm
(Cu + Barrier) : NbTi	1.0 ± 0.05
Filament diameter	≤ 30 μm
Number of filaments	342
Filament twist pitch	15 ± 2 mm (LHS)
Copper RRR	≥ 150
I_c at 5T, 4.22 K	≥ 494 A
n-Value at 5 T, 4.22 K	≥ 30

TS Rutherford Cable	Specification
Number of strands	14
Cable width	4.79 ± 0.01 mm
Cable thickness at 5 kPsi	1.15 ± 0.006 mm
Transposition Length	52 ± 3 mm
Lay Direction	Right
Extracted strand I_c at 5T, 4.22K	≥ 469 A
n-Value at 5T, 4.22 K	≥ 30
Copper RRR	≥ 150
Residual Twist	≤ 45 degrees

TRANSPORT SOLENOID AL-STABILIZED CABLE

The entire order with Hitachi Cable consisted of 16x1540 m lengths and 24x800 m lengths for a total of 44 km of Al stabilized cable . Pre-heating/conforming temperature and line speed were carefully optimized to deliver on all the requirements listed in Table below.

TS Stabilized Cable	As designed	As procured
Aluminum Stabilizer	99.998%	99.998%
Al RRR before conforming	≥ 1500	≥ 1700
Cable width (bare) at RT	9.85 ± 0.05 mm	Within tolerances
Cable thickness (bare) at RT	3.11 ± 0.03 mm	Within tolerances
Extracted strand I_c at 5T, 4.22 K	≥ 422 A	[428-460]
n-Value at 5 T, 4.22 K	≥ 30	[39-47]
Copper RRR	≥ 90	[90-99]
Aluminum RRR after cold-work	≥ 800	[941-1408]
Al 0.2% yield strength at RT	≥ 30 MPa	[47-56]
Al 0.2% yield strength at 4.2 K	≥ 40 MPa	[74-88]
Al-Cu Shear Strength at RT	≥ 20 MPa	[24-48]

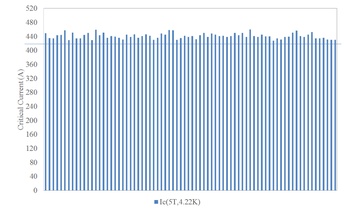


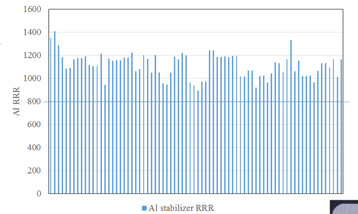
Pre-heating → Conforming → Cold-work

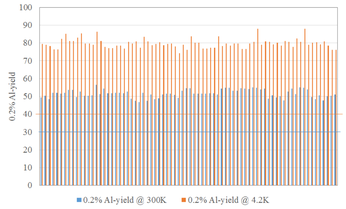
TRADEOFF BETWEEN IC AND AL/CU BOND

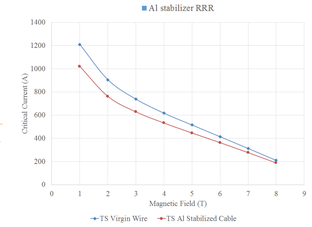
TRADEOFF BETWEEN AL YIELD AND AL RRR

PROPERTIES OF TRANSPORT SOLENOID AL-STABILIZED CABLE

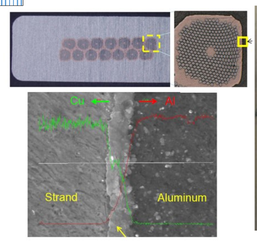


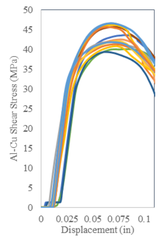






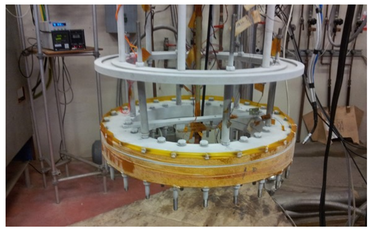
- To establish the quality of the bond between Al and Cu stabilizers, samples from both ends of each continuous length were prepared by locally removing the Al to expose the superconducting cable, while still preserving a small aluminum cap at the end of the sample (Fig. 5). The caps were then clamped and pulled via an Instron machine to measure the ultimate Al-Cu shear stress and compare it to specifications. Additionally, for each length, cross-sections were polished and scanned via SEM to evaluate the presence and the thickness of the diffusion layer between Al and Cu

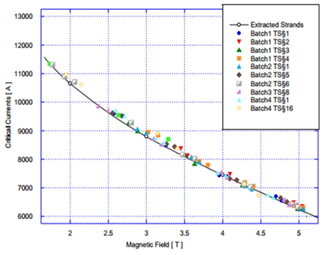


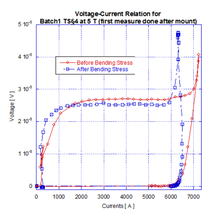


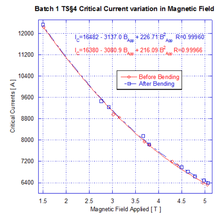
CABLE CRITICAL CURRENT TESTS

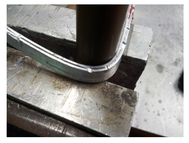
Each TS stabilized cable was bent in a loop, spliced to itself with indium and secured in an Al-5083 sample holder (Fig. 9) for the critical current test in liquid helium via a transformer method. The current is induced in the stabilized cable using the solenoid as primary and the sample itself as a secondary



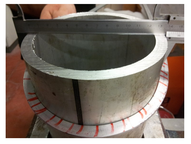






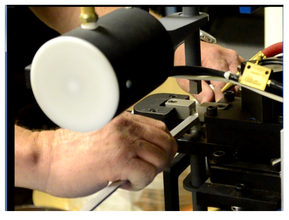


Easy way bent R=10mm



Hard way bent R=70mm

ULTRASONIC WELDING OF TS CABLES



- Tooling and ultrasonic welding process optimized for TS cable
- The process has been found to be very clean, fast, and reproducible
- All the available samples were tested for resistance in LHe, consistently measuring between 0.4 and 0.6 nΩ for a 7 stitch joint over 7 inches.
- Mechanical properties of the joint were also tested by performing pull tests on welded samples via Instron
- NO critical current degradation due to welding, both confirmed via extracted strand and cable critical current tests.

CONCLUSIONS

Over 740 km of wire and 44 km of TS Al stabilized cable were successfully manufactured, tested, and approved. Cable critical current measurements were carried out to validate extrapolations based on short sample measurements. A robust and reproducible method to weld TS stabilized cable was validated through resistance measurements and critical current measurements. All the TS cable has been received by Fermilab and it currently is with the TS cold mass vendor. The cable is fully insulated and is now being used for coil winding