Production of Aluminum Stabilized Superconducting Cable for the Mu2e Transport Solenoid

V. Lombardo, G. Ambrosio, D. Evbota, A. Hocker, M. Lamm, M. Lopes, P. Fabbricatore, S. Curreli, R. Musenich

***Abstract*— The Fermilab Mu2e experiment [1][2], 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 Al-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.**

***Index Terms*— NbTi, aluminum, conforming, mu2e, Transport Solenoid**

I. INTRODUCTION

THE Transport Solenoid (TS) cold mass features 52 superconducting coils shrink fit into aluminum housing shells and assembled in 4 straight and 2 toroidal sections [3]. The TS coils are wound using an aluminum stabilized NbTi Rutherford cable. Similar technology has been employed, among other experiments, in the construction of the CDF and DZero detectors at Fermilab [4-5] as well as CMS and ATLAS detectors at CERN [6-7]. The TS cold mass operating current is 1730 A with a peak field on the coils of 3.4 T. The TS wire, Rutherford cable, and Al-stabilized cable were designed to satisfy all the cold mass requirements while allowing large temperature and current margins [8]. In the following the main cable parameters are summarized, the various manufacturing steps are described and the main results of the various testing campaigns are presented and discussed. Finally, a method for reliably welding TS cables is presented.

II. NBTI STRAND AND RUTHERFORD CABLE

After a prototyping campaign, 740 km of TS NbTi multifilamentary wire (Fig.1) were produced by Hitachi Cable at their SH copper facilities in Japan. Both ends of each continuous length were tested by the vendor against the specifications in Table I, while one end per length was checked at Fermilab. The two test facilities produced consistent results (Fig.2). All the produced billets exceeded specifications in Table I and were approved for cabling.

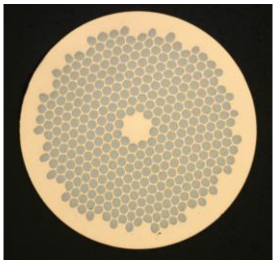

Fig. 1. TS NbTi virgin strand cross-section.

TABLE I
TRANSPORT SOLENOID STRAND DESIGN

Quantity	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

TABLE II
TRANSPORT SOLENOID RUTHERFORD CABLE DESIGN

Quantity	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

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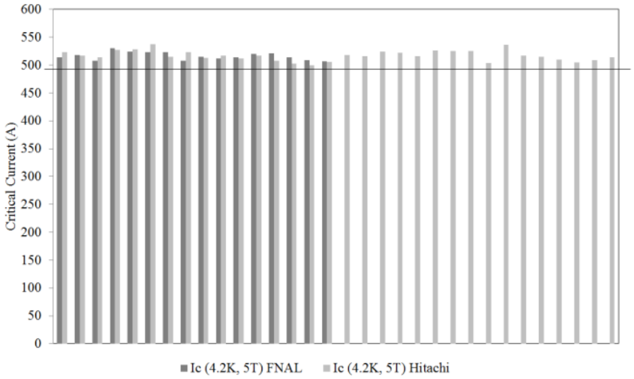

Fig. 2. Summary of I_c measurements at 5 T, 4.22 K on both ends of each billet of virgin TS wires as performed by Fermilab and the Vendor.

The cabling of the TS wire was performed by New England Electric in their facilities in Lisbon, NH. A total of 47 km of 14-strand Rutherford cable (Table II) were manufactured, tested, and shipped back to SH copper in Japan. The Rutherford cable was measured online by use of a CMM and calibrated offline by 10-stack measurements. Additionally, critical current measurements were performed on extracted strands from both ends of each single cable length, showing virtually no cabling degradation.

III. AL STABILIZED CABLE

All 52 TS coils in the cold mass share the same cable design, which is presented in Table III and Fig. 3. The TS coils vary in size and conductor length requirement, so the procured cable lengths had to be optimized to minimize scrap while accommodating the coil winding and spare requirements.

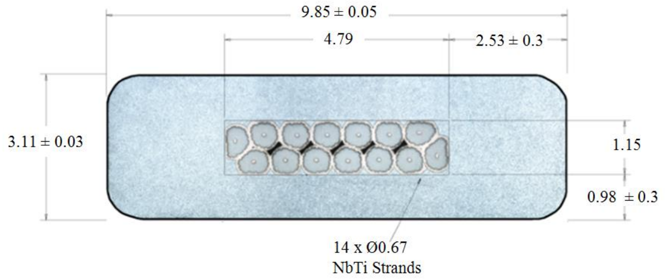

Fig. 3. TS Al-stabilized cable cross-section after conforming and cold-work.

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. The conforming of the Al around the Rutherford cable and the cold work processes were designed and tested on short lengths ahead of the production quantity. Preheating/conforming temperature and line speed were carefully optimized to deliver on all the requirements listed in Table III. A slow speed, high temperature conforming process would provide excellent bonding between the Al stabilizer and the Cu stabilizer around the NbTi filaments, while potentially degrading the critical current of the cable. Conversely, a high speed, low temperature conforming process would insure critical current retention, while potentially preventing the Al from diffusing into the Cu, leading to a poor mechanical/electrical bond between the NbTi strands and the Al stabilizer. Given the stability of this process is key for a quality conductor, all process data was recorded and reviewed for consistency for each of the conforming runs.

TABLE III
TRANSPORT SOLENOID AL-STABILIZED CABLE DESIGN

Quantity	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]

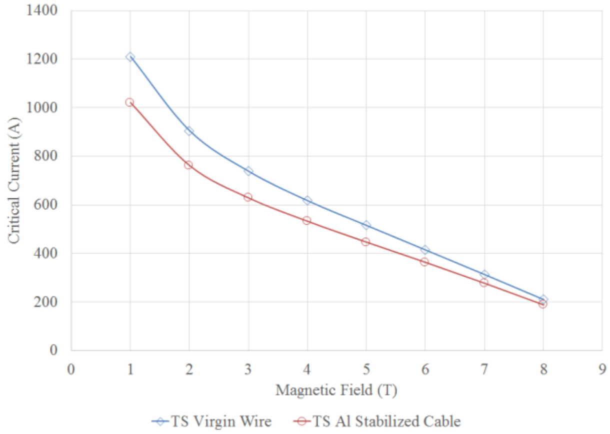

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Fig. 4. Average I_c values measured on TS virgin wires and extracted wires from stabilized cables as a function of magnetic field.

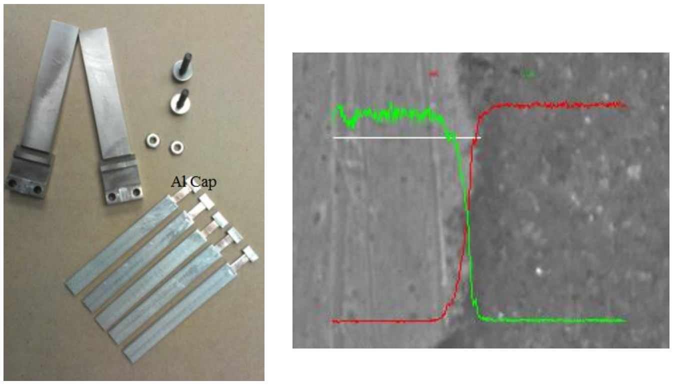

Fig. 5. (left) Al-Cu shear stress test samples; (right) SEM scan showing Cu/Al diffusion layer.

A nipple to center the Rutherford cable and a conforming die to shape the Al-stabilized cable cross-section were de-

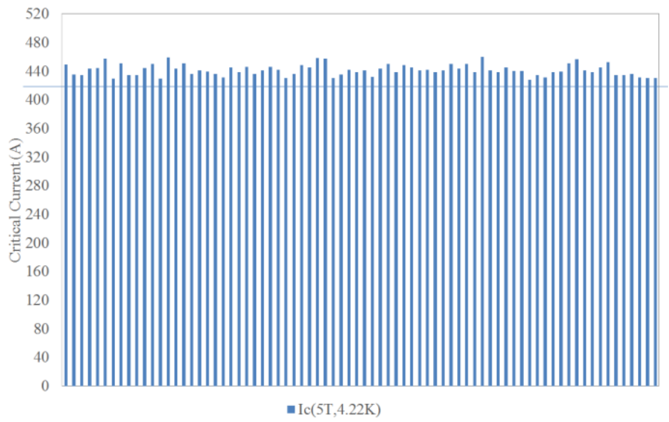

Fig. 6. Summary of I_c measurements performed at 5 T, 4.22 K on wires extracted from TS Al-stabilized cables.

signed for this process and procured to fit the TS cable dimensions. The conforming die is designed to produce a slightly larger cable with respect to the final nominal cross-section to allow for some cross-section reduction during the cold-work phase. After the conforming procedure is completed, the cable gets drawn through a cold-work die to reach the desired final size. This process was designed to increase the Al stabilizer's yield strength while retaining enough RRR to meet the specifications in Table III.

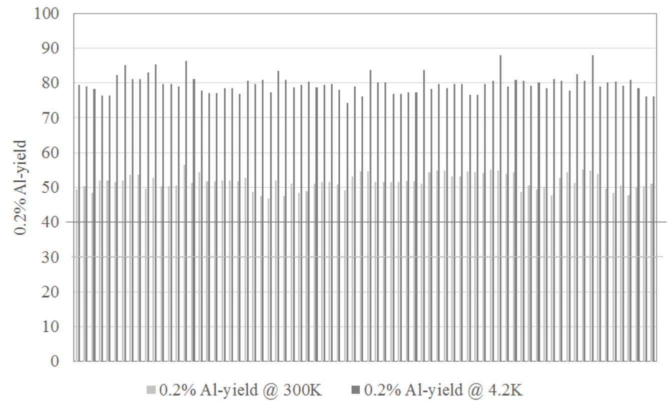

Fig. 7. Summary of Al-yield strength measurements performed at 300K and 4.2K.

For the TS cable the required trade-off could be met by allowing for a 10% reduction of the cable cross-section during cold work. Fig. 4 shows the average critical current values as a function of magnetic fields measured from virgin strands and from extracted strands from Al-stabilized cables. The drop in I_c is roughly 15%. Intermediate measurements after conforming but before cold-work show that about 5% is lost due to the conforming process while the remaining 10% is due to the cross-section reduction that happens because of the cold work phase.

Both ends of each continuous length of TS Al-stabilized cable were extensively tested both at the vendor and at Fermilab to insure compliance with specifications in Table III. 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 (Fig. 5).

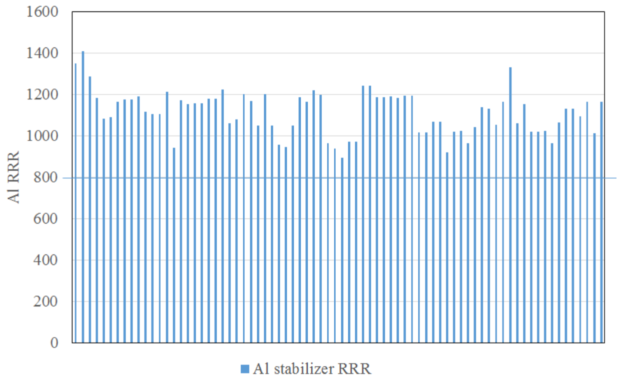

Fig. 8. Summary of RRR measurements performed on the Al stabilizer.

Additionally, the Al stabilizer was chemically etched to expose and extract wires for critical current measurement in liquid helium (Fig. 6) and Cu RRR measurements; aluminum samples were extracted from the cable via EDM and tested for RRR and yield strength both at room temperature and liquid helium (Figs. 7,8).

After testing both ends of each continuous piece-lengths against all the specifications in Table III, all lengths were found to exceed all specifications and were therefore accepted.

IV. AL STABILIZED CABLE TRANSPORT CURRENT

In addition to QC measurements on extracted wires as described in the previous paragraph, 25% of TS Al-stabilized cable lengths were tested for cable critical current at INFN-Genoa [9]. The facility features a large bore 6T superconducting solenoid and was previously used to characterize the CMS conductor. Each TS Al-stabilized cable was bent in a loop, spliced to itself with indium and secured in an Al-5083 sample

Fig. 9. (left) TS cable being assembled into sample holder; (right) TS cable ready for I_c measurement.

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holder (Fig. 9) for the critical current test in liquid helium via a transformer method. The current is induced in the Al-stabilized cable using the solenoid as primary and the sample itself as a secondary [10]. The measurement results are then self-field corrected [11] and compared to critical current measurements collected on extracted wire from stabilized cables. (Fig. 9), showing very good agreement.

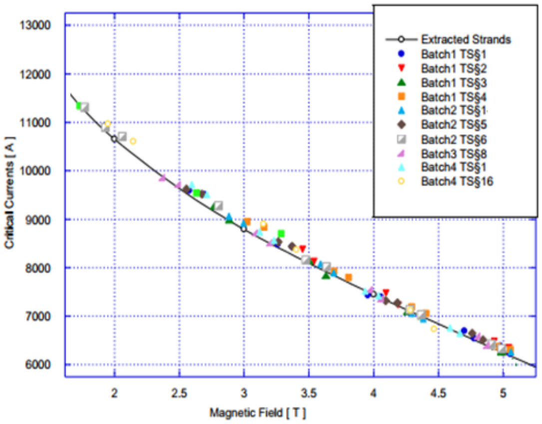

Fig. 10. Summary of TS Al-stabilized cable I_c measurement.

Additionally, samples of the TS Al-stabilized cable were easy-way bent on a radius of 10 mm and hard-way bent on a radius of 70 mm. These numbers were dictated by the space available to route the cables from the winding packs outside of the aluminum housing shells. The Al-stabilized cables were subsequently straightened and mounted for I_c test. Results were compared to data obtained on unbent cable samples and no degradation in critical current was observed.

V. WELDING TS AL STABILIZED CABLES

Several options were investigated to splice TS cables, including traditional welding, Al-Al soldering, chemical etching of the Al stabilizer and Cu-Cu solder, EM pulse, explosive, and ultrasonic welding.

For each one of these approaches, the joint resistance at liquid helium temperature and the critical current of extracted wires were measured. After an extensive test campaign, ultrasonic welding was chosen as a baseline for the production and assembly of the cold mass. SonoBond Ultrasonic was selected as the vendor to provide the ultrasonic welding machine to Fermilab. The tooling and the ultrasonic welding process was optimized in terms of energy density deposited per stitch, pulse duration, and pressure on the cable to insure a low resistivity, mechanically sound weld, while avoiding damaging the superconductor within the aluminum. The process has been found to be very clean, fast, and reproducible. Several samples were produced using the machine in Fig. 11 (left). Seven 10x10mm stiches were applied over 7 inches as shown in Fig. 11 (right). No weld prep was required and no excess material is added to the joint because of the ultrasonic welding process. 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. All tested joints held together until the cable finally broke outside of the joint area, proving the mechanical reliability of the joint.

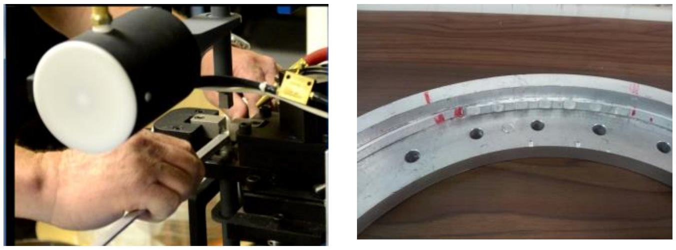

Fig. 11. (left) Ultrasonic welding machine from SonoBond; (right) TS cable ultrasonically welded for cable I_c measurement.

Additionally, longer cable samples were ultrasonically welded and then chemically etched to extract wires and assess I_c retention. Whereas traditional welding was found to substantially degrade the superconducting cable, no sign of degradation in the superconducting properties of the TS wires were found due to the ultrasonic welding process. This result was additionally confirmed by testing two Al-stabilized cables for critical current as described in Paragraph IV closing the loop with an ultrasonic weld. No cable I_c degradation was found; test results were consistent with extracted wires and previously tested cables.

CONCLUSION

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.

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