

Aluminum Stabilized Superconducting Prototype Cable Development for the mu2e Transport Solenoid

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Abstract—The Fermilab Mu2e experiment seeks to measure the rare process of direct muon to electron conversion in the field of a nucleus. The experiment makes use of three large superconducting solenoids: the Production Solenoid (PS), the Transport Solenoid (TS), and the Detector Solenoid (DS). The TS is an “S-shaped” solenoid with a warm-bore aperture of half a meter and field between 2.5 and 2.0 T. The three solenoids are based on four different types of Al stabilized NbTi conductors. All the conductors are composed of a Rutherford cable embedded in an aluminum matrix through a conforming process. This paper summarizes the properties and characterization of 3,000 meters of Al-stabilized prototype cable for the Transport Solenoid (TS). The main results of electrical and mechanical tests are presented and discussed for each stage of the cable development process. In addition to measuring the critical current of extracted strands at Fermilab, samples from each piece length were measured at INFN Genoa. Results are compared and discussed.

Index Terms— Aluminum stabilized cables, conforming, mu2e, superconducting cables, Transport Solenoid.

I. INTRODUCTION

THE Mu2e experiment at Fermilab aims at exploring physics beyond the Standard Model by seeking direct muon to electron conversion in the field of a nucleus. The experiment makes use of three large superconducting solenoids: the Production Solenoid (PS) with 4.5 m length, 1.5 m warm-bore aperture, and 4.6 T peak field on axis; the Transport Solenoid (TS) with 13.4 m length, 0.5 m warm-bore aperture, and 2.5 T peak field on axis and the Detection Solenoid (DS) with 10.9 m length, 1.9 m warm-bore aperture, and 2 T peak field on axis [1] [2]. To build this set of large magnets, a total of four different Aluminum stabilized superconducting cables have been designed (TS, PS, DS1 and DS2). For the Transport Solenoid, the wire and Rutherford cable designs are based on the conductor used for the BELLE detector solenoid [3] at KEK. The TS cable operating current is 1730 A, whereas the peak field on TS coils is 3.4 T; this allows generous temperature and critical current margins for safe operation [4]. A total of 3,000 meters of prototype TS cable were ordered and completely manufactured. In the following the main results of this development process are summarized and discussed.

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II. TRANSPORT SOLENOID SC STRAND

The TS strand (Table I) is a multi-filamentary wire with a nominal diameter of 0.67 mm featuring a minimum I_c of 494 A at 4.22K, 5T, corresponding to a J_c of 2,800 A/mm², which is achievable on an industrial scale. A total of two billets were produced by Hitachi Cable for an overall length of 80,000 m.

TABLE I
TRANSPORT SOLENOID STRAND MAIN PARAMETERS

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, 4.22K	≥ 494 A
n-Value at 5T, 4.22K	≥ 30

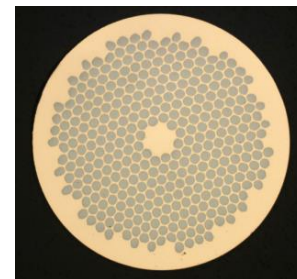


Fig. 1. Cross-section of a Transport Solenoid NbTi virgin strand

Thorough testing was performed both at the Vendor site and at Fermilab to insure the wire met all the specifications. This included I_c , (Fig. 2-3), n-Values, Cu RRR, Cu/SC ratio, filament diameter, spacing, and twisting, continuous wire size and ovality as well as eddy current scans.

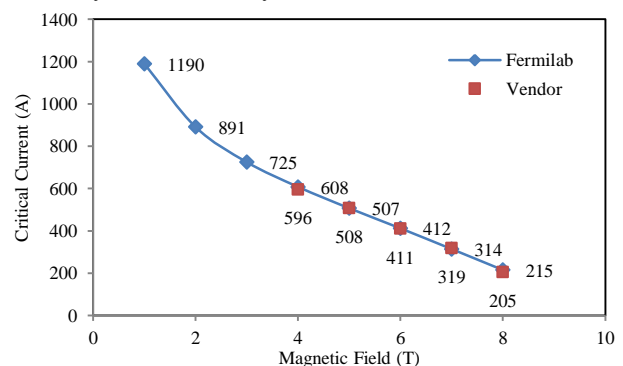


Fig. 2. Typical comparison of I_c values measured on TS virgin strands.

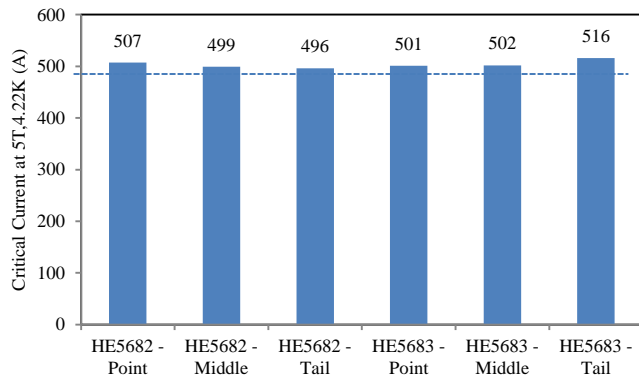


Fig. 3. I_c data collected from beginning, middle and end sections of each billet.

Correlation between Fermilab and vendor's data was found to be extremely good across the spectrum (Fig.2); all the strands exceeded the requirements and were accepted on schedule.

III. TRANSPORT SOLENOID RUTHERFORD CABLE

After being accepted, the SC strands were shipped to New England Wire Technologies, to be cabled into two continuous piece-lengths for a total of 5,440 meters. Table II summarizes the main features of the TS Rutherford cable design and Fig. 4 shows a detail of the cable cross-section.

TABLE II
TRANSPORT SOLENOID RUTHERFORD CABLE MAIN PARAMETERS

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, 4.22K	≥ 30
Copper RRR	≥ 150
Residual Twist	≤ 45 deg

The cabling tooling and process were first tested on a short length of cable, which was shipped to Fermilab for approval. The short length was tested, among other things, for critical current, RRR, broken filaments, mechanical stability and residual twist. Cable dimensions were continuously monitored by New England Wire Technologies using a CMM and calibrated via offline 10-stack measurements. Strands were appropriately marked before being cabled and properly mapped within the cable cross-section to make sure that wires from each billets were cabled, extracted, tested and compared to the relative I_c measured on virgin wires. The critical current degradation was found to be less than 2%, whereas a 5% was accounted for during the cable design.

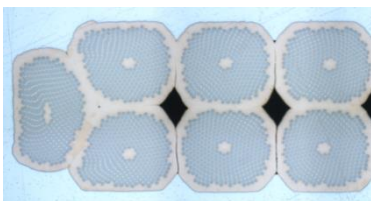


Fig. 4. Detail of the TS Rutherford cable cross-section.

The short length of Rutherford cable exceeded all the cable specifications with margin, so the full length was commissioned. Short samples from the beginning and end of each piece length were shipped to Fermilab for testing before the cable was accepted. During this phase only, all the cold measurements were performed exclusively by Fermilab. Fig.5 summarizes the critical current results, showing values consistently above specifications. Both piece-lengths were accepted and shipped back to Hitachi Cable for the final conforming phase.

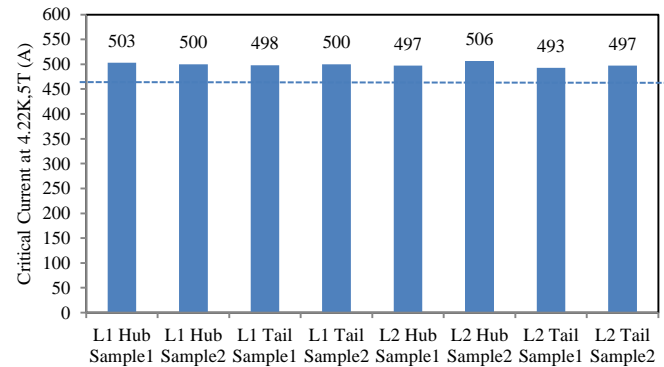


Fig. 5. Summary of I_c data collected from wire extracted from both ends of each continuous piece-length of TS Rutherford Cable.

IV. TRANSPORT SOLENOID ALUMINUM STABILIZED CABLE

The design of the Al-stabilized cable was performed taking into account the magnetic, electrical, thermal and mechanical properties and requirements of the TS coil packages [4]. The final cable cross-section is shown in Fig. 6, while the design parameters and the results from the prototype campaign are summarized in Table III.

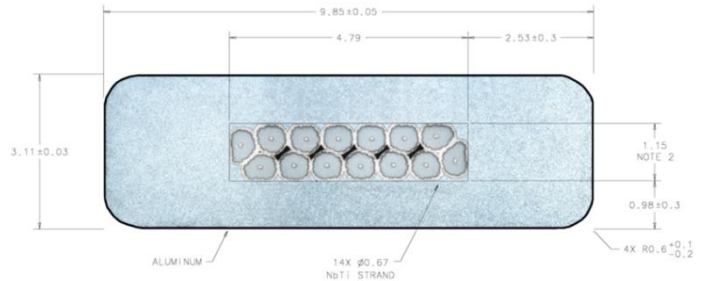


Fig. 6. Cross-section of the Transport Solenoid Al-stabilized cable

TABLE III
TRANSPORT SOLENOID AL-STABILIZED CABLE MAIN PARAMETERS

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
Cable I_c at 5T, 4.22K	≥ 5900 A	5950-6300 A
n-Value at 5T, 4.22K	≥ 30	38-45
Copper RRR	≥ 100	100-104
Aluminum RRR after cold-work	≥ 800	925-1160
Al 0.2% yield strength at RT	≥ 30 MPa	45-56
Al 0.2% yield strength at 4.2K	≥ 40 MPa	74-84
Al-Cu Shear Strength at RT	≥ 20 MPa	35-46

Three unit lengths for a total of 3,000 meters were manufactured by Hitachi Cable by conforming high purity Aluminum around the Rutherford cable produced by New England Wire Technologies. The cable pre-heating, line speed and conforming temperatures were optimized to achieve a good bonding between the Al stabilizer and the Cu matrix while retaining as much I_c as possible. After the conforming phase, the cable needs to be cold-worked in order to achieve the mechanical requirements for the Al-stabilizer. This process needed careful optimization in order to attain the right balance between yield and RRR of the stabilizer. For TS, this was accomplished by applying a 9% overall area reduction to the cable cross-section. Results summarized in Fig. 7-10 show how all the cold-worked TS cable piece lengths met all the electrical and mechanical requirements.

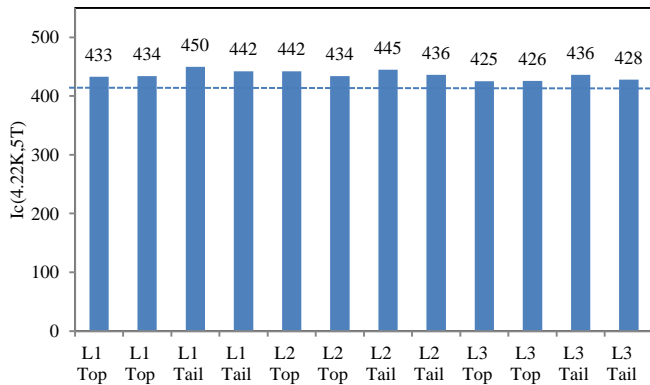


Fig. 7. Summary of I_c measurements performed on wires extracted from both ends of each Al-stabilized cable unit length after cold-work. Strands are extracted by chemically etching the Al-stabilizer.

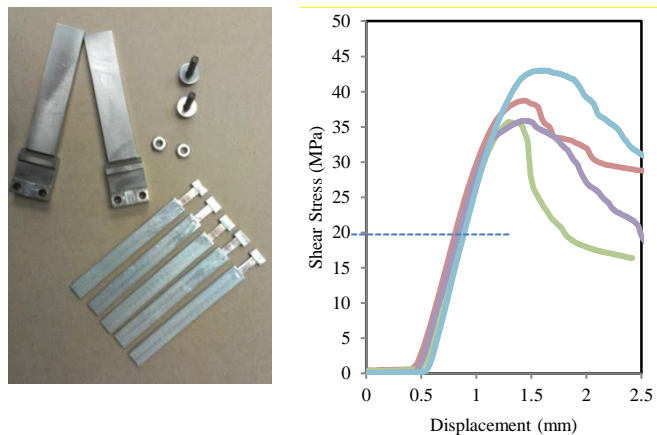


Fig. 8. Left: TS samples with partially removed Aluminum stabilizer to check the quality of the bonding. Right: Example of shear stress curves between the Aluminum stabilizer and the TS Rutherford cable. Measurements were performed at room temperature.

The Al-Cu bonding properties were checked using cold-worked cable short samples cut from both ends of each continuous piece-length. The aluminum was locally machined in order to expose the Rutherford cable (Fig. 8, left) while a 5 mm aluminum cap was left intact. A clamp specifically designed for the TS conductor was used to pull the cap via an *Instron*[®] machine to measure the ultimate shear stress

between the Aluminum stabilizer and the superconducting cable (Fig.8, right). The shear stress measured on all the TS prototype cable lengths exceeded the specification of 20 MPa at room temperature with a sizeable margin, showing values between 35 and 46 MPa. In addition to destructive pull-tests, the quality of Al-Cu bonding was investigated by polishing cable cross-sections from both ends of each piece length to insure the presence of a diffusion layer between the Aluminum stabilizer and the copper matrix in the superconducting wires. The cross-sections analyzed for the TS prototype showed an intermetallic diffusion layer thickness between 1.5 and 2 μm , which is representative of a good bonding.

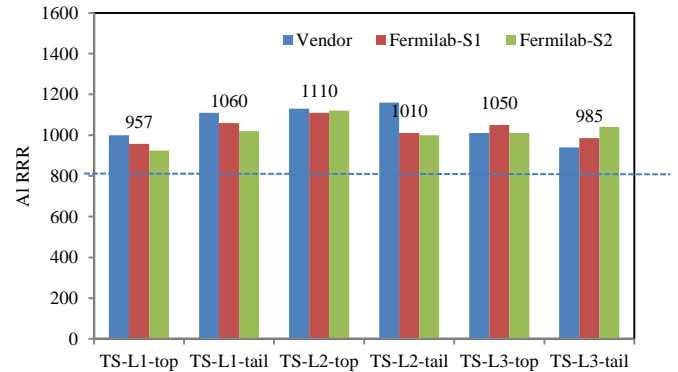


Fig. 9: Summary of RRR measurements taken from Al stabilizer samples extracted from the cable cross-section via EDM.

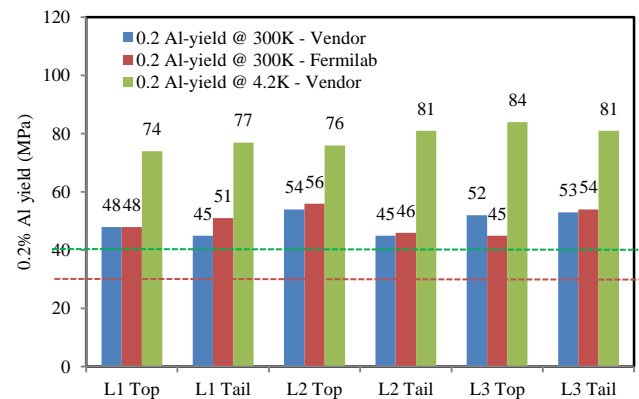


Fig. 10. Summary of 0.2% Al-yield measurements taken from Al stabilizer samples extracted from the cable cross-section via EDM. Measurements were performed both at room temperature and liquid helium temperature. In both cases, the specifications are met with margin.

V. CABLE CRITICAL CURRENT MEASUREMENTS

The critical current measurement of full TS conductor samples (including the Al stabilization) was performed using the facility Ma.Ri.S.A. at INFN Genoa, via the methods developed for characterizing the CMS conductor [5]. The facility is based on a superconducting solenoid providing a 6 T magnetic field [6] in a 500 mm bore hosting a cryostat with a 440 mm diameter. The samples are closed in a low resistance loop and the current is induced using the direct transformer method [7]. The TS conductor samples are bent on their higher inertia axis (hard way bent) and the two ends are overlapped

and indium soldered to form a continuous ring. The resulting ring is finally mounted inside an aluminum alloy (5083) sample holder as shown in Fig. 11.



Fig. 11: Sample holder for in-field I_c cable testing at INFN Genoa.

The current is induced in the sample ring using the background magnet as the primary coil and the sample as the secondary one. The magnetic field is applied perpendicularly to the wide face of the cable. When performing the critical current measurement of high current conductor one has to face the problem related to the definition itself of the critical magnetic field, because the field generated by the conductor may be a not negligible fraction of the total applied field. As an example, Fig. 1 shows the self-field distribution on the TS conductor when a current of 10 kA flows through it. In [8] a simple and reliable method was discussed for assigning a critical field to a I_c measurements on large flat cable with magnetic field applied normally to the wide face. Shortly, the average component of the magnetic field normal to the wide face B_{z_self} is evaluated on the two strands exposed to the highest magnetic field and summed to the external magnetic field B_{ext} .

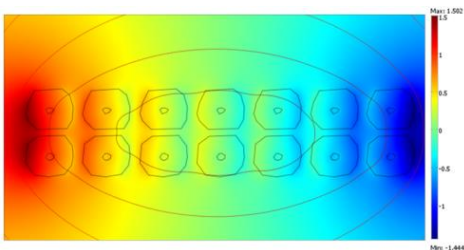


Fig. 12. Self-field distribution on NbTi filaments within the cable cross-section when the cable is powered with 10kA.

The resulting field $B_{app} = B_{z_self} + B_{ext}$ is taken as the applied magnetic field. Basically one can see that only the two considered strands are contributing to the voltage drop along the conductor. Using this approach, the measured $I_c(B_{ext})$ can be directly compared with the critical current measured on extracted strands without any self-field correction. This method is alternative to the peak field correction consisting in summing up the peak self-field to the external field for both the cable and the strand. Fig. 13 shows a comparison between I_c data collected from Al-stabilized cable at INFN and data collected from extracted wire from the same cables at

Fermilab. The results are found to be in good agreement.

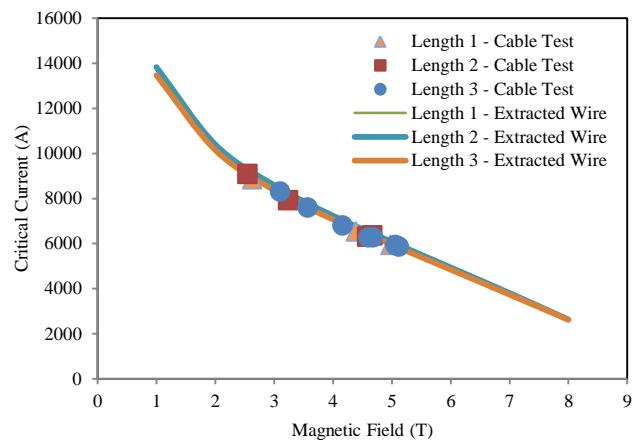


Fig. 13. Summary of I_c data from Al-stabilized cables and comparison with data collected from extracted wires from the same cables.

VI. CONCLUSIONS

The prototype phase for has been successfully completed on schedule with the delivery of 3,000 meters of TS cable. A TS-style prototype coil is currently being manufactured in industry using two of the three piece lengths. The production phase has recently been launched, with the goal of producing 700 km of superconducting wire and 44 km of TS Al-stabilized cable needed to build the entire Transport Solenoid. The whole experiment will need over 70 km of Al-stabilized cable to be completed.

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