Development of Aluminum Stabilized Superconducting Cables for the Mu2e Detector Solenoid

V. Lombardo, M. Buehler, M. Lamm, T. Page, S. Curreli, P. Fabbricatore, R. Musenich

***Abstract*—The Mu2e experiment at Fermilab is designed to measure the rare process of direct muon-to-electron conversion in the field of a nucleus. The experiment comprises a system of three superconducting solenoids, which focus secondary muons from the production target and transport them to an aluminum stopping target, while minimizing the associated background. The Detector Solenoid (DS) is the last magnet in the transport line and its main functions are to provide a graded field in the region of the stopping target as well as a precision magnetic field in a volume large enough to house the tracker downstream of the stopping target. The Detector Solenoid coils are designed to be wound using NbTi Rutherford cables conformed in high purity aluminum for stabilization and then cold-worked for strength. Two types of Al-stabilized conductor are required to build the DS coils, one for the gradient section and one for the spectrometer section of the solenoid. The dimensions are optimized to generate the required field profile when the same current is transported in both conductors. The conductors contain NbTi Rutherford cables with 12 (DS1) and 8 (DS2) strands respectively and are manufactured by two different vendors. This paper describes the results of the manufacturing of production lengths of the Al-stabilized cables needed to build the Mu2e Detector Solenoid as well as the testing campaigns and main results. The main cable properties and results of electrical and mechanical tests are summarized and discussed for each stage of the cable development process. Results are compared to design values to show how the production cables satisfy all the design criteria starting from the NbTi wires to the Al-stabilized cables.**

***Index Terms*— Aluminum stabilized cables, conforming, Mu2e, superconducting NbTi cables, detector 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 3 large superconducting solenoids: the Production Solenoid (PS) with a 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 Detector Solenoid (DS) with 10.9 m length, 1.9 m warm-bore aperture, and 2 T peak field on axis [1], [2]. To build these large SC magnets, four different Al-stabilized cables have been designed: one for TS, one for PS and two for DS. Similar technologies have been used to build large detector magnets in the past [3], [4], [5]. In this work, the design and manufacturing process for the two DS cables are discussed.

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II. Detector Solenoid SC Strands Designs

The DS coils are wound using two different cables (DS1 and DS2). The two cables are manufactured by two separate vendors starting from multi-filamentary NbTi wires (see Fig. 1). The main design features for both wires are presented in Table I and Table II. During the preliminary design phase, both wires shared the same design, a 1.303 mm NbTi wire with a minimum J_c of 2800 A/mm^2 and a Cu/SC ratio of 1, routinely achievable over long lengths. Later in the procurement process, for cost-saving and schedule reasons, the DS1 wire design was modified to match the design of the Mu2e Production Solenoid cable which was awarded to the same vendor. As a result, the DS1 conductor features a larger wire and a reduced Cu/SC ratio (see Table I).

TABLE I
DETECTOR SOLENOID 1 STRAND MAIN PARAMETERS

Quantity	DS1 as designed	DS1 as procured
Standard Grade NbTi	Nb 47 ± 1 Wt% Ti	Nb 47 ± 1 Wt% Ti
Strand diameter	1.466 ± 0.005 mm	1.466 ± 0.003 mm
(Cu + Barrier) : NbTi	0.9 ± 0.05	0.9 ± 0.04
Filament diameter	≤ 40 μm	23
Filament twist pitch	30 ± 4 mm (LHS)	30 ± 3 mm (LHS)
Copper RRR	≥ 150	185 ± 25
I_c at 5 T, 4.22 K	≥ 2487 A	2621 ± 100 A

TABLE II
DETECTOR SOLENOID 2 STRAND MAIN PARAMETERS

Quantity	DS2 as designed	DS2 as procured
Standard Grade NbTi	Nb 47 ± 1 Wt% Ti	Nb 47 ± 1 Wt% Ti
Strand diameter	1.303 ± 0.005 mm	1.303 ± 0.003 mm
(Cu + Barrier) : NbTi	1.0 ± 0.05	0.94 ± 0.02
Filament diameter	≤ 40 μm	34
Filament twist pitch	30 ± 4 mm (LHS)	30.5 ± 1 mm (LHS)
Copper RRR	≥ 150	49 ± 4 (without Cu annealing); ≥ 150 after full annealing
I_c at 5 T, 4.22 K	≥ 1850 A	1880 ± 25 A

The DS1 Rutherford cable and Al-stabilized cable designs presented in the following paragraphs reflect the updated DS1 wire parameters as per Table I. A total of 146 km of DS1 and

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85 km of DS2 wire were manufactured to cover the full production orders. All the produced billets (14 for DS1 and 7 for DS2) were tested both at the vendors' site and at Fermilab.

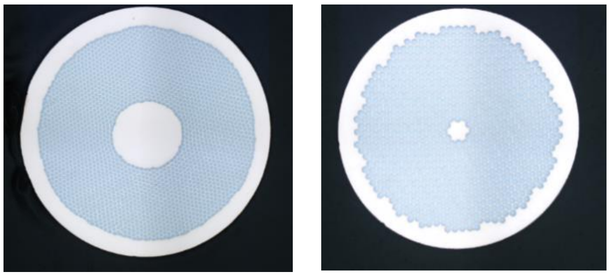

Fig. 1. (a) DS1 wire and (b) DS2 wire; wire designs are listed in Table I and II

Fig.2 shows the typical in-field properties of virgin DS1 and DS2 wires, as procured. After the test campaigns were completed, all the DS1 and DS2 billets were deemed acceptable for cabling after an internal review process.

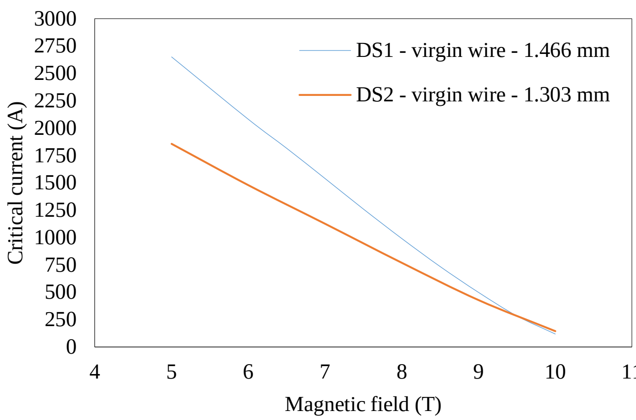

Fig. 2. Typical in-field I_c properties of DS1 and DS2 virgin wires at 4.22 K, tested on Ti-6Al-4V alloy *ITER* barrels in liquid helium bath. I_c values above 2000 A are fit based on [6], due to power supply limit.

III. Detector Solenoid Rutherford Cables

After being accepted, all the DS1 and DS2 billets were cabled in preparation for the conforming phase. Table III and IV summarize the main features of the Rutherford cable designs. The DS1 cabling was performed by Furukawa at their facilities in Japan, while the DS2 cabling was outsourced by Hitachi Cable to New England Wire Technologies.

TABLE III
Detector Solenoid 1 Rutherford Cable Main Parameters

Quantity	DS1 Rutherford cable as designed	DS1 as procured from Furukawa
Number of strands	12	12
Cable width	8.74 ± 0.01 mm	Within tolerances
Cable thickness (5 kPsi)	2.63 ± 0.01 mm	Within tolerances
Transposition angle	12 ± 0.5 deg	Within tolerances
Lay direction	Right	Right
Strand I_c (5 T, 4.22 K)	≥ 2360 A	2595 ± 80 A
Copper RRR	≥ 60	77 ± 3

TABLE IV
Detector Solenoid 2 Rutherford Cable Main Parameters

Quantity	DS2 Rutherford cable as designed	DS2 as procured from Hitachi Cable
Number of strands	8	8
Cable width	5.25 ± 0.01 mm	Within tolerances
Cable thickness (5 kPsi)	2.34 ± 0.01 mm	Within tolerances
Transposition angle	15 ± 0.5 deg	Within tolerances
Lay direction	Right	Right
Strand I_c (5 T, 4.22 K)	≥ 1750 A	1840 ± 15 A
Copper RRR	≥ 80	48 ± 4 (without Cu annealing)

To fulfill the whole production order, 9 DS1 unit lengths (11,300 meter total) and four DS2 unit lengths (7,560 meters total) were manufactured. Short samples from the beginning and end of each piece length were shipped to Fermilab for testing before the cables were accepted for conforming. Both ends of each unit length were tested for I_c, Cu RRR, broken filaments, mechanical stability and residual twist. Cable dimensions were continuously monitored using a Cabling Measuring Machine (CMM) and calibrated via offline 10-stack measurements. Un-annealed DS2 wires were used for cabling which explains the low Cu RRR which was accepted, since annealing of the Cu stabilizer is delivered by the final conforming process, as shown in the following paragraph. All cables showed results consistently above specifications and therefore were accepted for conforming.

IV. Detector Solenoid Aluminum Stabilized Cables

Both DS1 and DS2 Al-stabilized cables (Fig. 3) were designed taking into account the magnetic, electrical, thermal and mechanical requirements of the DS coil packages, as detailed in [7]. The two conforming processes were independently optimized in terms of line speed, pre-heating and conforming temperature in order to obtain a good bond between aluminum and copper stabilizers while allowing the superconducting wires to retain enough critical current to meet the specifications.

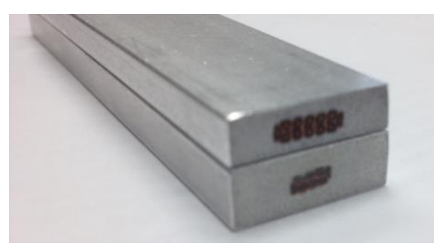

Fig. 3. DS1 and DS2 Al-stabilized cables after conforming and cold-work.

Additionally, the pure aluminum stabilizer as conformed is rather soft. Therefore, in order to achieve the desired aluminum mechanical properties, the conformed cables needs to be drawn through a cold-work die, which is optimized to apply an overall cross-section reduction in order to increase the stabilizer yield strength, while retaining enough RRR. This process is quite challenging as it needs to ensure the Al yield vs RRR tradeoff

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is satisfied while producing a cable cross-section within the demanding tolerances needed to wind the coils over multi-km lengths.

TABLE V
DETECTOR SOLENOID 1 AL-STABILIZED CABLE MAIN PARAMETERS

Quantity	As designed	As measured on procured conductor
Aluminum Stabilizer	99.998%	99.998%
Cable width at 293 K	20.1 ± 0.1 mm	Within tolerances
Cable thickness at 293 K	5.27 ± 0.03 mm	Within tolerances
Cable I_c at 5 T, 4.22 K	≥ 25000 A	$27168 \pm ^{340}_{530}$
Copper RRR	≥ 80	118 ± 6
Aluminum RRR after cold-work	≥ 800	$1981 \pm ^{350}_{436}$
Al 0.2% yield strength at 293 K	≥ 30 MPa	$56 \pm ^{2}_{3}$
Al 0.2% yield strength at 4.2 K	≥ 40 MPa	85 ± 5
Al-Cu Shear Strength at 293 K	≥ 20 MPa	47 ± 2

The thickness and width of the cables are recorded during cable fabrication and checked offline at the beginning and end of each production length. Critical current, RRR of Cu and Al, 0.2% Al yield as well as Al-Cu shear strength are checked at both ends of each continuous piece length. Tests are run by the vendors and Fermilab before each batch of conductor is accepted. Results from the production campaigns of DS1 and DS2 are summarized in Table V and Table VI.

TABLE VI
DETECTOR SOLENOID 2 AL-STABILIZED CABLE MAIN PARAMETERS

Quantity	As designed	As measured on procured conductor
Aluminum Stabilizer	99.998%	99.998%
Cable width at 293 K	20.1 ± 0.1mm	Within tolerances
Cable thickness at 293 K	7.03 ± 0.03 mm	Within tolerances
Cable I_c at 5 T, 4.22 K	≥ 12500 A	$12750 \pm ^{68}_{100}$
Copper RRR	≥ 100	108 ± 6
Aluminum RRR after cold-work	≥ 800	$1647 \pm ^{358}_{419}$
Al 0.2% yield strength at 293 K	≥ 30 MPa	$39 \pm ^{3}_{2}$
Al 0.2% yield strength at 4.2 K	≥ 40 MPa	$53 \pm ^{5}_{4}$
Al-Cu Shear Strength at 293 K	≥ 20 MPa	43 ± 5

All the results in Tables V and VI were achieved after independent optimization of both conforming processes during extensive R&D and prototype cable runs. Although similar in essence, the two process lines had several key differences and had to be separately tuned to manufacture the two cables. One of the main challenges of this technology is finding a combination of line speed, pre-heating temperature and conforming temperature that ensures the I_c vs Al-Cu bond-strength balance is achieved while remaining stable for extremely long hours. Fig. 4 shows the results of critical current measurements performed on wires extracted from stabilized DS1 and DS2 cables after conforming and cold-work. Rutherford cables are exposed by chemical etching of the aluminum stabilizer to allow for strand extraction. As mentioned, the actual shear strength between aluminum and copper is a critical property of these stabilized cables. This feature is checked offline at both ends of each piece lengths by carefully removing the aluminum in order to expose the Rutherford cable. A 5 mm Al cap is left at one end of the sample to measure the ultimate shear stress as shown in Fig. 5. Samples are also spot checked via scanning electron microscope to ensure the presence of actual inter-metallic diffusion between Aluminum and Copper. Fig. 5 and Fig. 6 show the curves and summarize the peak shear stress measured on the DS1 and DS2 production cables.

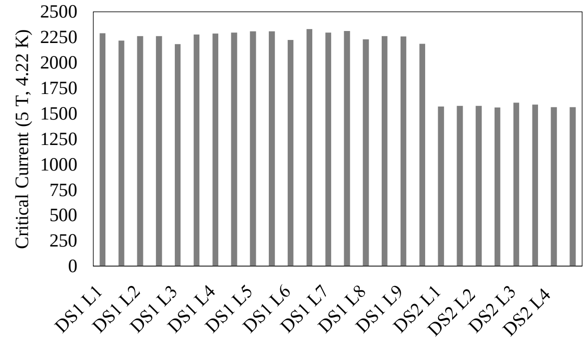

Fig. 4. Summary of I_c measurements performed on wires extracted from DS1 and DS2 cable piece lengths after conforming and cold-work.

All tested samples from DS1 and DS2 cables satisfy all the requirements as summarized in Table V and VI. Additional studies are currently underway to verify how the Al-Cu bond behaves when the cable is twisted and hard-way bent well below the nominal ID of the DS coils.

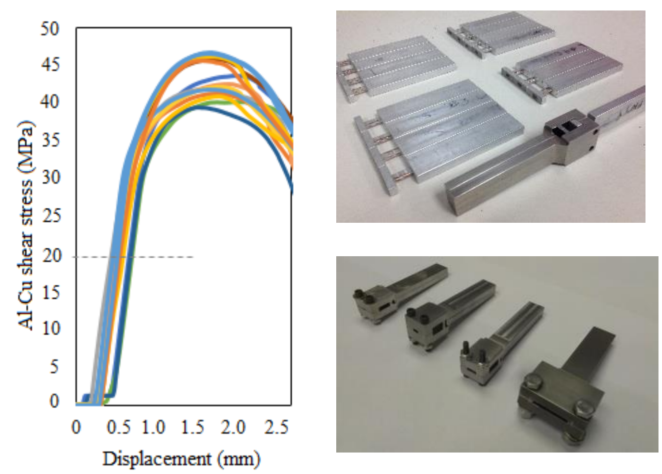

Fig. 5 (left) Typical Al-Cu Shear Stress curves measured on DS2 cables; (top right) DS2 samples with locally removed Aluminum stabilizer; (bottom right) Clamps designed to test Al-Cu bond shear strength for the 4 mu2e conductors.

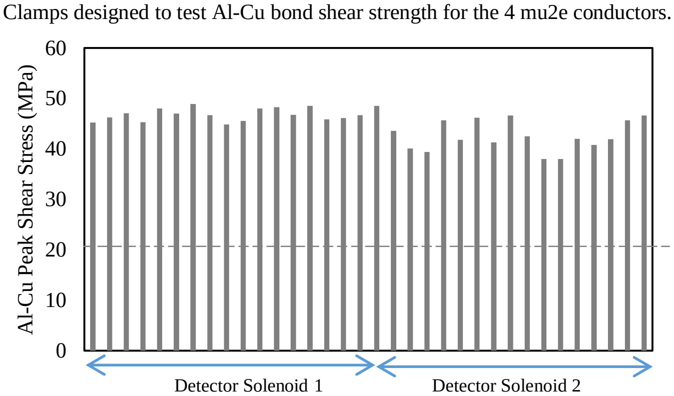

Fig. 6. Summary of Al-Cu peak shear stress as measured at room temperature on DS1 and DS2 Al-stabilized cable samples.

V. DS1 and DS2 Al-Stabilized Cable Critical Current Measurements

Critical current measurements of full DS1 and DS2 Al stabilized cable samples were performed at INFN Genoa using a method developed for the Compact Muon Solenoid (CMS) conductor as described in [8]. The facility is based on a superconducting solenoid providing a 6 T magnetic field [9] 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 [10]. The DS conductor samples are hard way bent and the two cable ends are overlapped and soldered using indium to form a closed ring, as shown in Fig. 7. The bent sample is then mounted on an aluminum alloy (5083) sample holder. The current is induced in the sample ring using the background magnet as the primary coil and the sample as the secondary one. Since the samples are hard way bent, the magnetic field is applied perpendicularly to the wide face of the cable.

Fig. 7: DS2 cable during the hard-way bending process at *INFN Genoa*

Given the high currents flowing in the cable samples, the self-field generated by the conductor is not negligible with respect to the total applied external field. As a reference, Fig. 8 shows the self-field distribution on the DS1 conductor when powered with a 10 kA current.

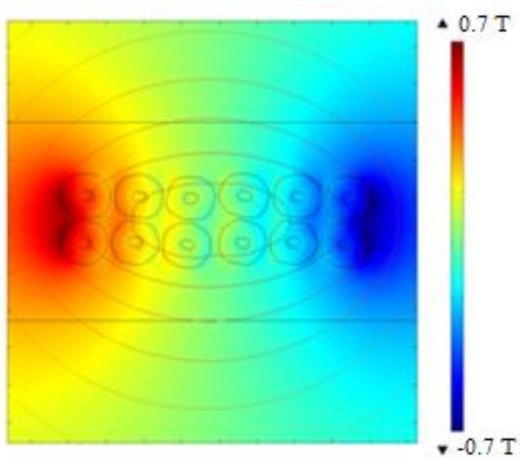

Fig. 8. Self-field distribution on NbTi filaments (B_z component only) within the DS1 cable cross-section when the cables are powered with 10 kA.

A simple and reliable method was discussed in [11] for assigning a critical field to I_c measurements on a large flat cable with magnetic field applied normally to the wide face. Briefly, 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}. The resulting field $B_{app} = B_{z\_self} + B_{ext}$ is taken as the applied magnetic field under the assumption 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. A comparison between critical current data collected from 3 DS1 and 3 DS2 Al-stabilized cables at INFN and data collected from extracted wires from the same cables at Fermilab is shown in Fig. 9. The results are found to be in good agreement.

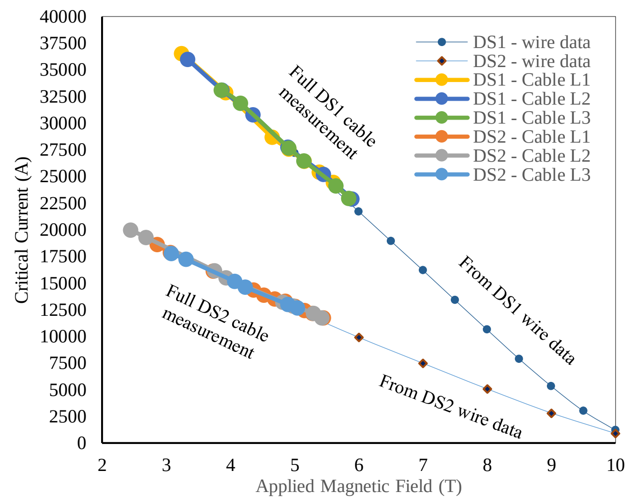

Fig. 9. Summary of I_c data from 3 DS1 and DS2 Al-stabilized cables and comparison with data collected from extracted wires from the same cables. All data points are taken at 4.22 K.

VI. Conclusion

Over 230 km of NbTi wire, 19 km of Rutherford cable and 17 km of Al-stabilized cables have been procured from two different vendors following an extensive prototyping campaign for both conductors. The production phase for the DS1 and DS2 cables has been successfully completed. The procurements for the two other mu2e conductors (TS and PS) are proceeding as planned.

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