

Splice, Bus and High Current HTS Lead Tests for the Mu2e Solenoid System

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Abstract—The Muon-to-Electron conversion experiment (Mu2e), under development at Fermilab, set out to search for new particles (beyond the very successful Standard Model) by detecting electrons originating from neutrino-less conversion of the muon under the nuclear force. The Mu2e magnet system consists of three large superconducting solenoids. Each solenoid has several coils that are wound separately. The coils are made from aluminum NbTi Rutherford cable, electrically connected in series to operate them under a limited number of Power Converters. Usage of HTS power leads and reliable superconducting bus system and splice joints are essential to the assuring safe, continuous and cost effective operation of these magnets. In this paper we summarize the HTS power lead, bus and splice test results.

Index Terms—HTS Leads, LTS splice joints, superconducting bus.

I. INTRODUCTION

ONE OF the future flagship experiments at Fermilab is the Muon-to-Electron conversion experiment (Mu2e) [1]. The goal of Mu2e is to find evidence for new particles beyond the Standard Model by detecting electrons that are emerging from neutrino-less conversion of the muon under the nuclear force. This goal can be accomplished with an experimental setup that includes an 8 kW 8 GeV proton beam interacting with a tungsten target to generate muons, and an S-shaped muon beamline surrounded with solenoids that filters and guides the muons into the detector region where the conversion electrons are identified and their momentum is measured.

The Mu2e solenoid magnet system [2] consists of three superconducting solenoids: Production Solenoid (PS), Transport Solenoid (TS), and Detector Solenoid (DS). All three solenoids are conduction cooled superconducting magnets. Current is supplied to these magnets through the feedbox power leads and superconducting (SC) bus. In order to reduce the heat consumption of the solenoid system it was decided that high temperature superconducting (HTS) power leads will be used in the feedboxes.

A sufficient number of HTS power leads were left over from the Tevatron era to support the mu2e solenoid power system. These ASC HTS power leads [3] were designed to

operate at 6000 A in a liquid Helium bath. In contrast, the Mu2e solenoids will be cooled indirectly using cooling tubes [2] and the maximum operating current is 10150 A. A Feedbox design that contains liquid Helium for cooling the bottom end of the current leads and incorporates feed-throughs for the buses to make a transition from liquid He cooling to conduction cooling is quite complicated. In order to simplify the feedbox design and, at the same time, qualify the ASC leads for Mu2e operation, it was decided to conduct special current lead tests in a vacuum environment. The leads would be conduction cooled at the bottom end of the leads, which is a similar approach as envisioned to cool the superconducting bus.

A reliable superconducting bus system with adequate splice joints is essential for safe operation of the Mu2e solenoid system. It is important to develop solid splice joints that are cooled properly under a vacuum.

The ASC HTS leads tests were combined with the Mu2e SC bus and splice tests in a single dewar test configuration. The focus for the current lead tests was to demonstrate stable current lead operation under vacuum and under Mu2e maximum operating current values and the focus for the splice tests was to measure splice resistances at full current and to demonstrate that the chosen cooling technique is adequate for cooling the bus and splices as well. A careful run plan was developed to obtain optimum run time and to obtain all the necessary results.

In this paper we summarize the ASC HTS lead, bus and splice test results.

II. TEST SETUP

The test was performed at Fermilab's Magnet Test Facility in a test dewar that was previously used to test Tevatron HTS Power leads [3] and LHC HTS Power leads [4]. A riser was added to the neck of the test dewar to accommodate the long bus-splice sample (see Fig.1). Since the bus would be conduction cooled, the dewar would be under vacuum and not filled with LHe. The LHe inlet, therefore, was modified to be directly connected to a cooling block of one of the power leads. LHe flow would pass through both of the power lead blocks, through the bus cooling tube, and finally to a LHe reservoir. This reservoir had a LHe gauge and a heater installed. During operation the heater power was adjusted to maintain the He liquid level, assuring LHe flow through the cooling blocks and cooling tube and therefore providing adequate cooling.

The cooling blocks were directly soldered to the bottom

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end of the power leads. Since the ASC HTS leads were constructed using a relatively low temperature solder between the internal HTS tapes and the copper/LTS terminal located at the bottom end of the lead, an even lower temperature solder (Indalloy 1E, which is 52% indium, 48% tin) had to be used to avoid melting this joint. Note that the cooling block also served to make the LTS-LTS Rutherford cable connections between the power leads and the bus-splice sample. The aluminum cladding was removed from the bus by chemical etching so the LTS-LTS joint could be made.

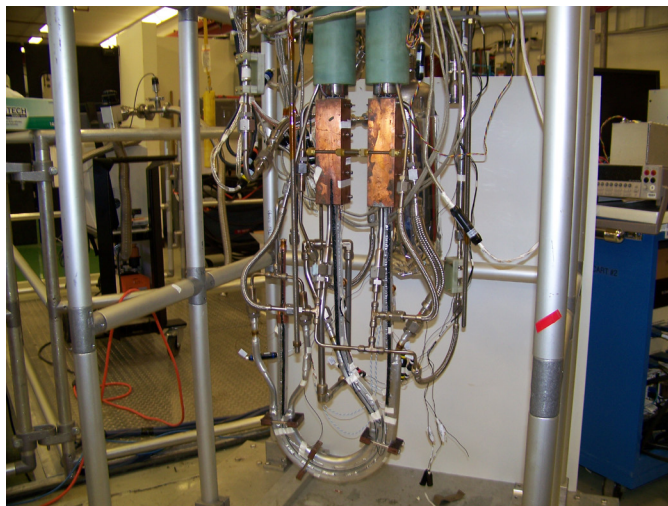
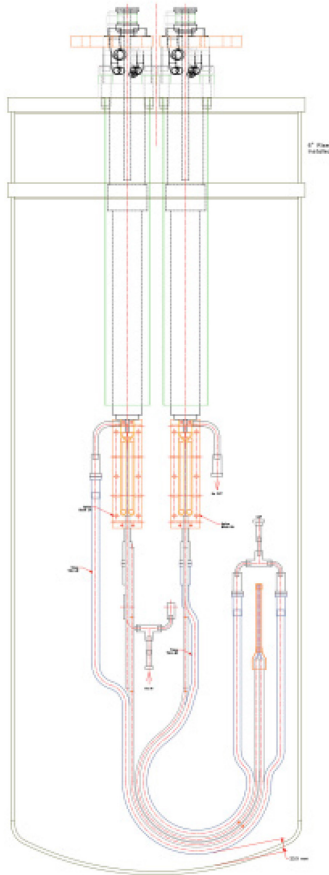


Fig 1. Upper part of the figure shows the layout of the Stand 3 test dewar. The lower one shows the final configuration of the insert that contains the bus-splice sample, reservoir (wrapped with MLI) with the rest of the plumbing and instrumentation wires.

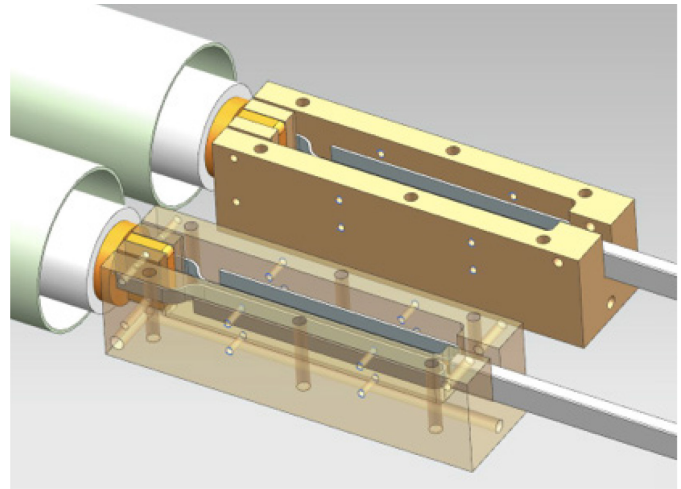


Fig 2. Cooling blocks attached at the bottom end of the power leads..

Riken cable [5] was used for the bus-splice sample since Mu2e cables were not available at the time this test was carried out. Riken cable was chosen since the cross section of its aluminum stabilizer was comparable to the DS and PS cables and it can carry the desired 10 kA current (see table I for the Riken cable parameters).

The cooling tubes and the bus segments were pre-bent to the desired shape prior to welding them together. Special welding procedures were developed for welding the cooling tubes (6061-T6 aluminum “D” tube with 0.63 in inner diameter) to the Riken cable and making the two lap-welded splice joints. Thermal couples embedded into 2 mm deep holes drilled into the Riken cable were used to monitor the temperatures during the welding process. To minimize I_c degradations of the LTS part of the cable the temperature was kept below 340° C.

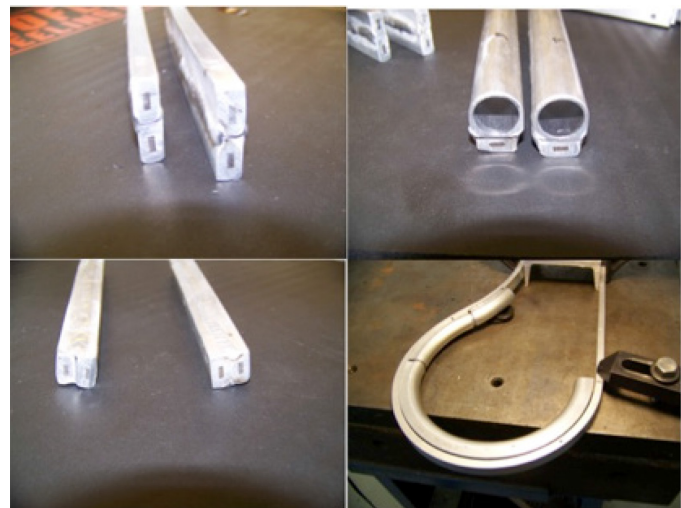


Fig 3. Splice and cooling tube samples.

Three different types of splices were made, including two 250 mm long lap splices. One of them was welded along the wide edges and the other one along the narrow edges. The third splice joint was a 120 mm long “praying hands” joint. The aluminum cladding was etched away and the bare

Rutherford cables were soldered together using 40/60 SnPb solder.

The power leads and the bus-splice sample were instrumented with voltage taps (4 per power lead and 10 for the bus-splice sample) and temperature sensors (3 per Power lead and 3 for the bus-splice segment). Heaters were attached onto the surface of the lap joints at the midpoints and at the tip of the praying hands joint.

III. TEST RESULTS

It was demonstrated in [3] that the Tevatron ASC HTS leads could operate at 10000 A with a large margin. The main objective of these power lead tests was to prove that it could operate at the desired 10150 A (full operating current for the PS) continuously in a vacuum environment.

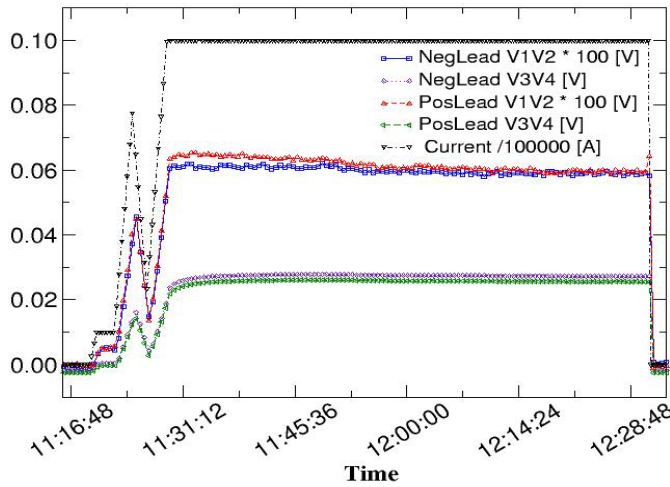


Fig. 4. Power leads steady operation is shown at 10150 A.

The first challenge was to make the lead vacuum leak tight. The ASC lead was designed to have leak tight separation between the helium and nitrogen heat exchanger volumes. The HTS tapes were enclosed in two leak tight stainless steel cylinders. The bottom copper terminal that closes the helium heat exchanger is a solid block. Helium flows into the inner cylinder volume through a small tube; therefore, the helium flow through the lead can be controlled by limiting the helium to flow through these inlet tubes. Unfortunately, this region of the lead had a vacuum leak, which was through the Rutherford cable that was soldered into the copper block. This was not an issue for operating the lead in LHe bath but was a problem for operation in a vacuum. The solution to this problem was to close off the tube. The drawback to this solution was that restricting the flow of LHe vapor through the HTS section increases heat load into the cold end; however, the increase was not significant: the leads could perform in steady operation for more than an hour (see Fig 4.) at full current. Steady operation means that the voltages across the leads (V1V2 HTS section, V3V4 Copper section) are not increasing during the same operating conditions. LN2 flow rates were the same as we have measured them in the past operating the leads in a helium vapor environment.

TABLE I
RIKEN CABLE PARAMETERS

Strand	Diameter	1.15 mm
	Cu/Sc	0.90
	RRR	115
Rutherford Cable	Thickness	2.15 mm
	Width	5.82 mm
	Number of strands	10
Aluminum Claded Cable	Thickness	8 mm
	Width	15 mm
	RRR of the Aluminum	> 500

The other operational experience was to observe that the temperature sensors that were mounted in the HTS leads are not reliable in a vacuum environment. They were originally installed for helium bath operation and could not be accessed for remounting. The leads were successfully qualified for the Mu2e experiment and the operation of the leads will not rely on temperature sensor readings. A voltage-based feedback loop will be used to control the LN2 flow through the leads under current. At zero current operation, a fixed flow rate will be applied to keep the leads cold.

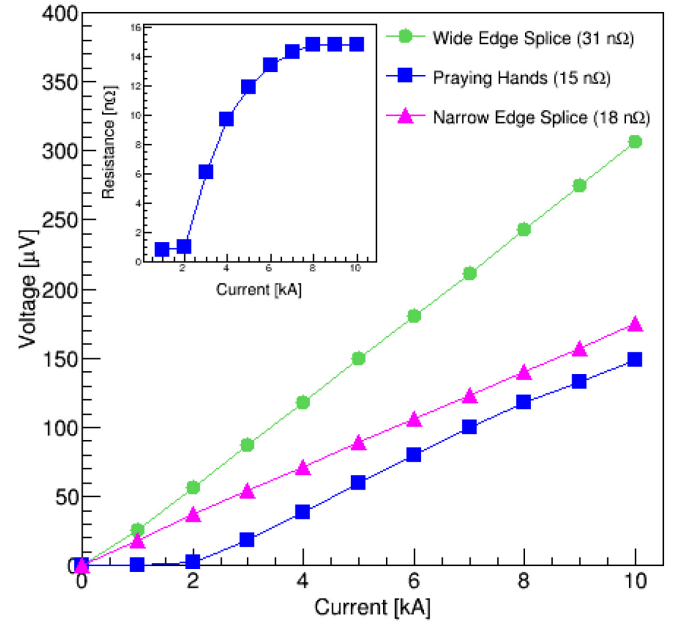


Fig. 5. Splice resistances for three splices: wide edge, narrow edge and praying hands splices. The inserted figure shows the resistance change as a function of current for the praying hands splice.

The measured splice resistance values are summarized in Fig. 5. These resistance values are higher than expected. Based on a simple model one can expect that the resistance of a 250 mm long lap joint (in the superconducting state) is in the sub nΩ range if the resistance is dominated by the Aluminum matrix resistance (even if we assume a longer current path through the side of the conductor through the weld seams). Conversely, if the splice is just above the transition temperature of the superconductor the resistance is around 60 nΩ. The observed high resistances can be explained only with increased contact resistance between the copper and aluminum matrix.

The praying hands joint resistance is changing as a function of current. It increases with current and at high

current values the resistance saturates. The SnPb solder is a weak superconductor therefore it is expected that the resistance of the joint at low current will be lower than at high current values since at relatively low B-field (self field) values the superconductor turns into normal state. The resistance at high current values was a lot higher than expected. Such a high resistance can only be explained with increased contact resistance between the Rutherford cable and the solder. It is most likely that the etching process left some aluminum residue on the surface of the Rutherford cable so the copper to aluminum contact resistance remained the same as we have observed for the other two splices. On the other hand at the middle part of the Rutherford cable the aluminum is not present. This allowed the SnPb solder to flow in between the strands making a “superconducting path” between the copper parts of the Rutherford cables.

Fig. 6. shows the results of the heater study. First the current was ramped up to 5 kA then the heater power was gradually increased in order to initiate a quench propagation in the bus. Once the heater power reached 25 W it was reduced to 22 W in order to verify stable and reproducible cooling conditions. At that point the leads current was increased to 10 kA. No quench propagation was observed and the measured peak temperature was close to 200 K.

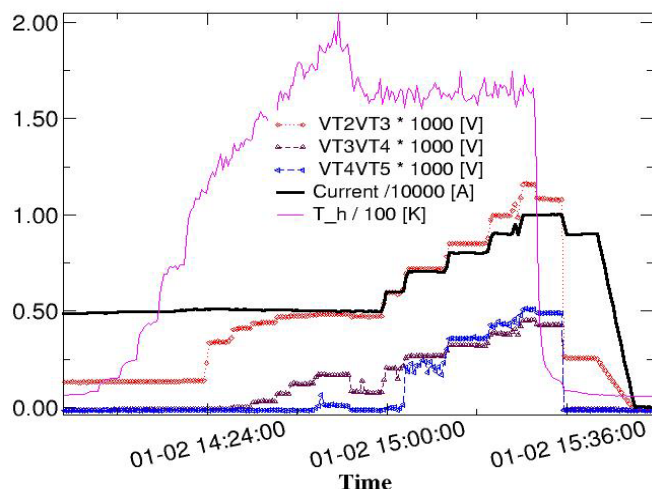


Fig. 6. Three adjacent voltage segments are plotted as a function of time. Segment VT2VT3 contains the wide edge splice. VT3VT4 and VT4VT5 are bus segments. T_h measures the temperature of the splice at the midpoint opposite side where the heater was installed.

The splice resistance did not change until the mid point surface temperature of the lead reached 70 K. Finally, increasing the heater power further resulted in the VT3VT4 bus segment developing resistance. At this point the entire splice must have been resistive, which means that the full current was flowing in the Aluminum matrix. The measured 70 n Ω value was in a good agreement with the estimated 60 n Ω value.

Once the heater was turned on there was a clear change in the resistance of the splice, but the splice still conducted current; though the Rutherford cable within the aluminum matrix was still in a normal state. The same was observed in the bus as well. Once we have lowered the current back to 9 kA the Rutherford cable within the splice and the bus turned back into a superconducting state

This test shows that this type of bus and splice cooling design is very robust. It can support even very high resistive joints and even if part of the bus is driven into a normal state no run away condition occurs. This cooling scheme allows a wide selection of bus and splice designs for the Mu2e experiment.

IV. CONCLUSIONS

Tevatron ASC HTS power leads were successfully tested in a vacuum environment up to 10150 A of current and exhibited stable operation. The splice resistances were higher than expected due to the high contact resistance between the aluminum cladding and the Rutherford cable; however, the splice and bus cooling scheme was very robust. No quench propagation was observed under extreme splice heating conditions.

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