Design and fabrication of the Mu2e cryogenic distribution system

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Abstract. The muon-to-electron conversion (Mu2e) experiment at Fermilab will search for the charged lepton flavor-violating conversion of muons to electrons in the field of an atomic nucleus. The Mu2e experiment is currently in the design and construction stage and is expected to begin operations in 2022. The Mu2e experiment uses four large superconducting solenoid magnets including a Production Solenoid (PS), an Upstream and Downstream Transport Solenoid (TSu and TSD) and a Detector Solenoid (DS).

This paper will focus on the cryogenic distribution system for these four solenoid magnets. Liquid helium will be supplied from two re-purposed Tevatron satellite refrigerators. A large cryogenic distribution box (DB) is located in the Mu2e building to distribute the required cryogens to each of the four solenoid magnets. Each solenoid magnet will have a dedicated transfer line and cryogenic feed box (FB). The solenoid magnets each require two liquid helium circuits and two liquid nitrogen circuits.

The most unique feature about this cryogenic system is that the assemblies for the start of the superconducting portion of the power leads are mounted in feed boxes that are in the range of 23 m to 31 m away from the solenoid magnets. The cryogenic feed boxes are located remotely to provide protection from radiation damage and high magnetic fields. The power leads are NbTi superconducting cable stabilized with high conductivity aluminum. The 6061-T6 aluminum grade was selected for the transfer line piping so that the piping would thermally contract at the same rate as the power lead. A major concern for this transfer line is that a small helium leak could create an electric discharge arc due to the Paschen effect. This paper includes a description of the design features and testing done to ensure that the power leads are protected from the Paschen effect while still being adequately cooled to liquid helium temperatures.

1. Introduction
The muon-to-electron conversion (Mu2e) experiment at Fermilab will search for the charged lepton flavor-violating conversion of muons to electrons in the field of an atomic nucleus [1-3]. The Mu2e experiment is currently in the design and construction stage and is expected to begin operations in 2022. In the beam direction the first solenoid is the Production Solenoid (PS), which is a 1.8 m aperture axially graded solenoid with a peak field of 5 T used to focus secondary pions and muons from a production target located in the solenoid aperture [4-5]. Next are upstream and downstream transport solenoids (TSu and TSD), which sign/momentum-select and transport the subsequent muons towards a stopping target [6-8]. The beam then enters the Detector Solenoid, which is an axially graded solenoid where the electrons from the decays of muons that were transported to the aluminum stopping target, located at the DS entrance, are measured in a spectrometer located within the DS volume [9-10]. The solenoids have a 23 K temperature difference limit between the LHe cooling tubes and the cold mass. The inner and outer thermal shields have a temperature difference limit of 50 K between the inlet and valve.
Therefore, warm gas mixing is incorporated into the DB and nitrogen warm gas mixing is incorporated in the FB. Key parameters for these magnets are shown in Table 1.

|                | PS     | TSu    | TSd    | DS     |
|----------------|--------|--------|--------|--------|
| Max Operating Current [A] | 10,150 | 1,730  | 1,730  | 6,114  |
| Peak Axial Magnetic Field [T] | 5.0    | 2.5    | 2.5    | 2.0    |
| Max Stored Energy [MJ]     | 79.7   | 7.1    | 5.7    | 26.1   |
| 5K Heat Load [W]           | 67     | 44     | 42     | 32     |
| 80K Heat Load [W]          | 128    | 252    | 252    | 539    |

2. Process Overview
Helium refrigeration for the Mu2e solenoids is supplied by two repurposed Tevatron satellite-style refrigerators that were relocated to the Muon g-2 experiment building at Fermilab. Each refrigerator has a capacity of 600 W at 4.5 K. Piping was extended from the Tevatron A0 compressor building to the Muon campus so that the existing set of four Mycom 2016C compressor skids could be re-used. A 60,000 L (15,000 gal) LN₂ tank was installed to supply LN₂ to the satellite refrigerators as well as provide cooling for the distribution system and solenoid thermal shields and intercepts. An overview of the cryogenic distribution system is shown in figure 1 and the refrigerator transfer line (RTL) is shown in figure 2.

3. Refrigerator Transfer Line
Most of the refrigerator transfer line (RTL) between the Mu2e refrigerators in the Muon g-2 building and the Mu2e building was recycled from the “right bend” transfer line that connected to the Central Helium Liquefier (CHL) to the Switchyard Service Building, which is where protons were directed from the old Main Ring to external target areas. The helium supply is concentric with the helium return to function as a long counter-flow heat exchanger. The transfer line to the Mu2e building is approximately 150 m (500 ft) long. Three new expansion boxes were designed to account for the thermal contraction of the transfer line. The first expansion box is located within the refrigeration room and includes a phase separator. The second expansion box is located outdoors and is designed for thermal contractions of up to 14” (355 mm). The overpressure relief valves are mounted outside on the second expansion box,
which minimized changes when copying the design of the legacy Switchyard expansion box, minimized pressure drop during relief events by locating the relief valves in middle of the pipe run, and reduced the oxygen deficiency risk in the Mu2e building. A third expansion box is used to make the corner around the Mu2e building, where the transfer line enters the building and is connected to the DB. A 3-D model showing the major cryogenic components within the Mu2e building is shown in figure 3.

**Figure 2.** Photo of the Muon $g$-2 experiment building. The large vertical tank on the left is the LN$_2$ storage tank. In the foreground is the middle expansion box on the refrigerator transfer line.

**Figure 3.** The 3-D conceptual model of the Mu2e solenoid magnets and cryogenic distribution system components located inside the Mu2e building.

4. **Distribution Box**

The DB is the interface between the refrigerators, helium storage dewar, and each FB. It is a vacuum jacketed valve box 6 feet in diameter, 18 feet long, weighing 11,600 pounds, and containing 27 extended stem cryogenic valves, 2 heat exchangers, 1 pressure vessel, 20 female bayonets, and a liquid nitrogen cooled aluminum thermal shield. Liquid helium from the RTL enters the DB which routes it to the 3,000 L liquid helium storage dewar. All connections between the DB, storage dewar, and FBs are u-tubes. The dewar functions as both a phase separator to remove helium vapor generated in transit through the long RTL and as liquid helium inventory to allow for a slow ramp down of the current supplied to the solenoids in the event of liquid helium supply disruption. The liquid helium from the
The DB collects helium vapor from the storage dewar and the four FBs and routes the vapor to the RTL where it returns to the refrigerators. The DB also receives liquid nitrogen supplied by the RTL. A phase separator inside the DB removes the nitrogen vapor generated in the RTL and then the DB routes liquid nitrogen to each of the FBs. Nitrogen vapor vents locally from both the DB and the FBs. A 3-D model of the DB internal piping is shown in figure 4 and a photograph of the DB is shown in figure 5.

The solenoids are divided into four semi-autonomous cryostats. Each solenoid can be cooled down or warmed up independent of the state of the other solenoids. It is expected that beam radiation will degrade the thermal conductivity of the PS solenoid conductor aluminum stabilizer such that a periodic thermal cycle to room temperature to re-anneal the aluminum will be required. During cooldown and warmup each solenoid has temperature constraints which are defined by the stress generated by the thermal gradient between the solenoid cooling tubes and the solenoid cold mass. Twenty-two temperature sensors in the DB monitor temperatures during both cooldown and steady state processes. The DB contains two heat exchangers (HX) that allow for the controlled cooldown or warmup of an individual solenoid from 300 K to 80 K. Cooling power is provided by liquid nitrogen exchanging with the helium gas in a stainless steel plate heat exchanger with the characteristics listed in Table 2.

| Helium-Nitrogen HX | Helium-Helium HX |
|--------------------|------------------|
| Mass flow          | Nitrogen stream  |
| Helium stream       | 17.0 g/s         |
| Nitrogen stream     | 46.2 g/s         |
| Input temperature   | 300 K            |
| Output temperature  | 81.6 K           |
| Nominal pressure    | 200 psig         |
| Pressure losses     | 0.36 psi         |
| Cooling power       | 19.2 kW          |
|                    | To Solenoid      |
|                    | 100 g/s          |
|                    | 300 K            |
|                    | 81.6 K           |
|                    | 200 psig         |
|                    | 0.36 psi         |
|                    | From Solenoid    |
|                    | 117 g/s          |
|                    | 268 K            |
|                    | 95 K             |
|                    | 50 psig          |
|                    | 2.2 psi          |
|                    | 106 kW           |

In parallel to the Helium-Nitrogen heat exchanger a brazed aluminum Helium-Helium heat exchanger utilizes the helium gas exiting a solenoid to cool incoming room temperature helium gas. The primary cooldown helium mass flow will be through this Helium-Helium heat exchanger. The Helium-Nitrogen heat exchanger will add cooling power as necessary. The nominal total helium mass flow rate required for cooldown is 30 g/s which is split between these two heat exchangers. The Helium-Helium HX is sized for cooling or warming multiple solenoids simultaneously, with key parameters listed in Table 2.

For each of the four solenoids cooldown from 300 K to 80 K is expected to take on the order of 72 hours. This time has been estimated using detailed coupled thermal-mechanical FEA models. The piping and valves associated with the cooldown and warmup processes are located outside of the DB LN$_2$ cooled thermal shield wherever possible to minimize steady state heat loads. The cryogenic valves associated with the cooldown process are mounted at an elevation above the liquid helium piping and valves utilized during steady state operation to provide additional thermal separation. Cooling power below 80 K is provided by the refrigerators which can provide up to 4 g/s of helium liquefaction at 5 K each. Cooldown of each solenoid from 80 K to 5 K will take on the order of 100 hrs, again estimated with coupled thermal-mechanical FEA models, and will be ultimately be dependent upon the fraction of available refrigeration available for cooldown versus the fraction required to maintain any solenoids that are already at liquid helium temperature.

5. Solenoid Magnet Power Leads
Two types of recycled power leads are used to supply power to the solenoid magnets, which are referred to as the American Superconductor Corporation (ASC) leads and the High Intensity Neutrino Source (HINS) leads. The ASC leads were originally used as part of the Tevatron accelerator, but have been modified for use at higher currents using indirect cooling [11]. The trim leads were reused from the High Intensity Neutrino Source [12]. The ASC leads are located on every FB, whereas the HINS leads are only installed on the TSu/Tsd FB.
Each FB has a dedicated helium supply and return line that is used for cooling the power leads in the solenoid transfer line. Each FB contains a Venturi flowmeter to measure the flowrate in the lead cooling circuit, which may have flowrates up to 5 g/s. Bimetallic transition jointes are used to join the austenitic stainless steel piping in the FB to the 6061-T6 aluminum piping used in the solenoid transfer line (STL). Aluminum piping was chosen for the transfer line so that the piping would contract at the same rate as the aluminum stabilized conductor during warmup and cooldown.

6. Feedboxes
Each FB has liquid helium supply, gaseous helium return, and liquid nitrogen supply u-tubes connecting it to the Distribution box. A 3-D model of the FB is shown in figure 6. Each FB has a transfer line stub that is field welded to the transfer line extending down to the solenoid magnets. The TSu FB and TSd FB are identical, while the PS FB and DS FB are also identical. The two FB designs are very similar, but have some important differences due to the different number of power leads and the helium flow regime.

![Figure 4. The 3-D model of the internal piping for the Distribution Box. The nitrogen supply and return are dark green and light green respectively. The helium supply and return are dark blue and light blue respectively. The piping for cooldown and warmup is shown in red. The nitrogen phase separator vessel is located in the bottom left corner.](image)

![Figure 5. Photograph of the distribution box and 3,000L liquid helium dewar being moved into their final installation locations. The transfer line from the refrigeration plant comes into the building through the left wall, then extends down along the wall to make the connection to the distribution box.](image)

A key project requirement was that each solenoid magnet should be able to be cooled down, energized, or warmed up independent of the state of the other solenoid magnets. The FB is designed for a 20 year design lifetime with up to 100 full thermal cycles. The residual resistance ratio of the aluminum stabilizer in the conductor is expected to degrade over time in the high radiation fields. The magnets may need to be periodically warmed up to anneal the leads and restore the electrical and thermal conductivities of the aluminum stabilizers.

Each FB contains the relief devices that also protect the transfer line and solenoid magnets. The relieving system may need to protect the system from more than 100 full quench events after commissioning and must be designed accordingly. The relief devices cannot be mounted directly on the solenoid magnets due to the expected rapid deterioration of valve sealing materials in the high radiation fields near the magnets. Similarly, all pneumatic control valves must be mounted on the FB to avoid radiation damage to the diaphragm.

The PS and DS magnets use a liquid helium thermosiphon cooling scheme. There is a supply manifold at the bottom of the cryostat and a return manifold at the top of the solenoid cryostat. The manifolds are connected by an array of vertically oriented semi-circular siphon tubes to distribute
cooling flow across the magnet. The major advantage of the thermosiphon cooling scheme is the high reliability relative to using a circulation pump. The scheme also helps maintain a uniform temperature since the helium flow rate spontaneously adapts to the heat load distribution. The PS FB and DS FB contain Venturi flowmeters designed to measure liquid helium flowrates up to 71 g/s.

The TSu and Tsd magnets use a forced flow cooling scheme [13]. The TSu FB and Tsd FB contain Venturi flowmeters designed to measure liquid helium flowrates up to 15 g/s. The helium is subcooled using a coil in the FB phase separator. Approximately 9 g/s of liquid helium leaves the FB nominally at 1.6 bar.g. The helium returns to the FB as a two-phase mixture with a quality of approximately 0.5. The return helium flows into the phase separator, where the lower pressure liquid is used to subcool the supply flow. The vapor from the FB phase separator is returned to the refrigerator.

Figure 6. A 3-d model showing the as-delivered state of the TSu/Tsd FB is shown to the left. A cut-away view of the TSu/TSu FB with the power leads installed is shown on the right. The power leads and piping installed by FNAL are shown in yellow and the helium phase separator is shown in pink. The nitrogen supply and return are dark green and light green respectively. The helium supply and return are dark blue and light blue respectively.

7. Solenoid Transfer Lines
The Solenoid Transfer Line (STL) transports cryogens between the FB and the solenoid magnet. In addition, the STL have the unique feature of incorporating the superconducting bus between the FB and the solenoid. Due to the superconducting bus and the difficulties associated with passing the bus through a vacuum break, the FB, STL, and solenoids share a common insulating vacuum. Once installed access to the STL will be difficult due to concrete shielding installed to mitigate beam radiation. The STL piping was designed without using bellows or braided flexible hoses to minimize the probability of small helium leaks that could lead to electrical discharge arcs due to the Paschen effect.

The aluminum stabilized superconducting bus is located at the center of the STL as shown in figure 7. Paschen breakdown during a solenoid quench is a low-probability high-risk concern with respect to the superconducting bus. A helium leak into the common insulating vacuum could cause a solenoid to quench. During a quench voltages as high as 600 V can be generated as the stored energy in the solenoid is extracted through dump resistors. If the helium pressure in the insulating vacuum
space is in the Paschen regime the conductor could arc to other parts of the STL which are at ground potential and cause significant damage. An electrical insulation scheme has been developed and tested with pressure sweeps through the Paschen regime to prevent helium gas from contacting conductor. The conductor is insulated with 0.025 mm thick Kapton tape in 2 layers with 50% overlap and is applied uniformly by a wrapping machine. On top of the Kapton tape Von Roll 7031 varnish is sprayed to provide a secondary layer of protection.

Figure 7. 3-D model of STL cross-section.

Red: LN$_2$ Supply
Green: LN$_2$ Return
Yellow: Conductor LHe Supply & Return
Purple: Solenoid LHe Supply
Orange: Solenoid LHe Return

The bus is cooled by a parallel cooling pipe containing liquid helium. Two-piece bolted clamps provide a thermal conduction path between the conductors and the cooling pipe, as shown in figure 8. G10 sheet is positioned between the two conductors themselves and between the clamp and the conductor to prevent the clamping force from compromising the Kapton and varnish electrical insulation due to the presence of any imperfections. The clamps are spaced at 12 inch intervals throughout the length of the transfer line. The thermal performance of the clamping assembly was tested in a cryocooler test stand and found to have adequate conductance to remove both thermal radiation and resistive heating due to splices in the superconducting bus. The superconducting bus is supported by the cooling clamps and cooling pipe. This scheme eliminates any thermal conduction from mechanical supports at higher temperatures directly to the bus. The cooling pipe and clamps are supported by G10 spacers supported by the STL thermal shield. The bus cooling pipe does not enter the solenoid and turns around at the interface between the STL and solenoid. The clamps also restrain the repulsive magnetic forces between conductors. In addition to the clamps, a fiberglass wrap secured with epoxy is located at the midpoint between clamps to provide additional restraint on the PS STL.

The solenoid liquid helium supply and return pipes are also supported by the cross-shaped G10 spider within the thermal shield. The estimated heat load on the STL is 140 W at 80 K and 14 W at 5 K. Due to pressure drop constraints the solenoid inner and outer thermal shields are cooled by separate liquid nitrogen cooling circuits. The STL thermal shield consists of short sections of overlapping aluminum cylinders which are not welded to each other thus decoupling the mechanics of the shield from the thermal contraction of the pipes within the shield. For the majority of the STL the two thermal shield return circuits are fabricated from d-tube and the flat side of these d-tubes are plug welded to the shield.

Butt welds between aluminum pipes often have significantly more internal protrusion than butt welds between stainless steel pipes typically used in cryogenic service. The ASME B31.3 piping code allows 2.5 mm of internal protrusion for aluminum pipe wall thicknesses between 2 mm and 6 mm, but allows only 1.5 mm of internal protrusion for the same thicknesses on all other piping materials. Each STL circuit contains on the order of 40 welds total from the FB to the solenoid and back to the FB. A butt weld with internal protrusion acts as an orifice which creates additional pressure drop which is of particular concern for the PS and DS gravity driven thermosiphon cooling loops. For the DS STL updating the thermosiphon two-phase flow model with orifices that represent the ASME B31.3 Code allowable internal protrusion reduced the predicted liquid helium mass flow rate by 34%. This predicted mass flow rate reduction and internal protrusion observed in practice welds led to the decision to perform all STL piping welds by placing an outer sleeve around the two pieces of pipe being joined and performing fillet welds on both ends of the sleeve thus preserving the full pipe aperture.
8. Conclusion
The design activities have been completed and fabrication is well underway on the Mu2e cryogenic distribution system.

9. References
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