

Challenges and Design of the Transport Solenoid for the Mu2e Experiment at Fermilab

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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 magnet system for this experiment is made of three warm-bore solenoids: the Production Solenoid (PS), the Transport Solenoid (TS), and the Detector Solenoid (DS). The TS is an “S-shaped” solenoid set between the other bigger solenoids. The Transport Solenoid has a warm-bore aperture of 0.5 m and field between 2.5 and 2.0 T. The PS and DS have respectively warm-bore aperture of 1.5 m and 1.9 m, and peak field of 4.6 T and 2 T.

In order to meet the field specifications the TS starts inside the PS and ends inside the DS. The strong coupling with the adjacent solenoids poses several challenges to the design and operation of the Transport Solenoid. The coil layout has to compensate for the fringe field of the adjacent solenoids. The quench protection system should handle all possible quench and failure scenarios in all three solenoids. The support system has to be able to withstand very different forces depending on the powering status of the adjacent solenoids.

In this paper the conceptual design of the Transport Solenoid is presented and discussed focusing on these coupling issues and the proposed solutions.

Index Terms— Aluminum stabilized cable, Mu2e, Solenoid coupling, Superconducting magnet, Transport Solenoid.

I. INTRODUCTION

THE Mu2e experiment [1] at Fermilab aims at exploring physics beyond the Standard Model by seeking direct muon to electron conversion in the field of a nucleus. The magnet system (Fig. 1) of this experiment consists of: (i) the Production Solenoid (PS) with 4.5 m length, 1.5 m warm-bore aperture, and 4.6 T peak field on axis; (ii) the Transport Solenoid (TS) with 13.4 m length, 0.5 m warm-bore aperture, and 2.5 T peak field on axis; (iii) the Detection Solenoid (DS) with 10.9 m length, 1.9 m warm-bore aperture, and 2 T peak field on axis.

The main goal of the Transport Solenoid is to transport the muons created by a proton beam hitting a target inside the PS, selecting their charge and momentum, and reducing as much as possible the background. These goals are achieved by the

S-shape of the TS, a set of field requirement [2] including negative gradients in the straight sections, and collimators set in the warm bore, which is the muon beam line.

The TS is strongly coupled with the larger adjacent solenoids (PS and DS). This coupling impacts the field, the quench protection, and the forces, which may change significantly in case of quench or failure of PS or DS.

The Transport Solenoid (Fig. 1) is made of three straight sections (TS1, TS3 and TS5) housing the collimators and two toroidal sections (TS2 and TS4) making 90° bends in opposite directions (Fig 1).

Half coils of TS3, together with TS1 and TS2 coils are set in a single cryostat (TSu). Similarly all other coils are set in the TSd cryostat. A removable window, set between the TSu downstream and the TSd upstream flanges, stops antiprotons and separate the upstream vacuum of the beam line from the less clean downstream vacuum.

All TSu/TSd coils are powered in series reducing to the minimum the number of leads and the complexity of powering and protection system. The quench protection strategy is based on extracting most of the energy on a dump resistor. The coils are pre-assembled and tested in modules (with two coils in each module) in order to reduce the complexity and the time of the assembly. The support system is optimized for allowing control of the interfaces and for reducing stresses during cooldown and warm-up.

II. CONDUCTOR

The conductor is an aluminum stabilized NbTi Rutherford

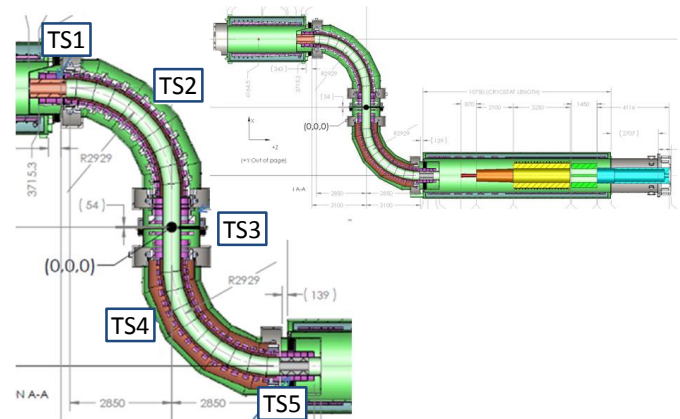


Fig. 1. Left: cross-section of the Transport Solenoid showing the five magnetic components and the two cryostats. Right: the whole magnet system of the Mu2e experiment.

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cable. This kind of conductor is typically used for detector magnets in particle accelerators and colliders. Aluminum stabilizer was chosen, instead of copper, because during warm up it completely recovers [3] the RRR damage due to irradiation. The most upstream coils of the TSu are expected to receive $\sim 3 \cdot 10^{-6}$ DPA per year during operation.

The strand diameter and Rutherford cable thickness selected for the TS have been used for the conductor of the BELLE detector solenoid [4] at KEK.

The conductor parameters are shown in Table I. The insulation is made of fiberglass tape, wound with some overlap, with resulting thickness of 0.15 mm per side. Epoxy impregnation is going to complete the insulation.

Each TS magnet (TSu and TSd) is powered by a dedicated power supply. The operating current is 1730 A and the operating engineering current density is 47 A/mm². The peak field on TS coils (in TSu) is 3.4 T. The operating current fraction on the load line at 5.1 K is 56%. The temperature margin at 5.1 K and 3.4 T is 1.87 K. The minimum quench energy (computed by QLASA [5], [6]) is 0.32 J for the RRR values shown in Table III taking into account the degradation due to irradiation. The volumetric enthalpy margin is 6.8 mJ/cm³. The TS conductor was designed in order to have sufficient temperature and enthalpy margin for accommodating possible energy releases in the coils during energization when coils will be displaced by the electro-magnetic forces.

TABLE I
MAIN PARAMETERS OF TSU MAGNET

Symbol	Unit	Value
Strand diameter	mm	0.67
Number of strands		14
Cu/nonCu ratio in the strand		1
Initial RRR of Cu matrix/Al stabilizer		150/800
Al-stabilized cable width	mm	9.85
Al-stabilized cable thickness	mm	3.11
Maximum allowable coil temperature (T_{peak})	K	5.1
Cable critical current at 5 T, 4.2 K	A	5900
Inductance	H	4.7
Energy	MJ	7.1
Operating current	A	1730
Peak field along magnet central axis	T	2.5
Peak coil field (B_{peak})	T	3.4
Operating current fraction on load line at T_{peak}		56%
Thermal margin at B_{peak} , T_{peak}	K	1.87

Main parameters of the TSu (Transport Solenoid Upstream) magnet. The TSd (TS Downstream) magnet has the same cable design and slightly lower peak field and energy.

III. MAGNETIC DESIGN

The transport solenoid (TS) is formed by 52 short solenoid-type coils. Fig. 2 shows the complete Mu2e coils for the magnetic system. The main objective of the TS is to transport the beam from the production target to the stopping target. The beam drifts vertically in the toroidal sections. Negative particles drift upwards and positive particles drift downwards. The drift is also proportional to the momentum of the particles. An asymmetric collimator [7] placed in the second straight section (TS3) makes the charge and momentum selection.

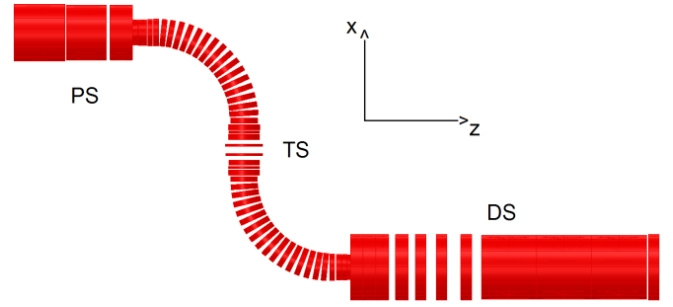


Fig. 2. Mu2e Solenoid system

In general, the magnetic requirements for the TS are that no positive longitudinal field gradients are allowed in the straight sections in order to avoid backgrounds [2]. This requirement is particularly challenging for the TS3, which has a relatively large gap in the middle of its coils to allow the replacement of the anti-proton window. The longitudinal gradient requirement was achieved by increasing the inner diameter of the TS3 coils as well as using shorter solenoids that allow a better shaping of the field.

The yaw angles of the coils that form the curves were adjusted in order to center the beam in the collimators. This effect is caused by the fringe field of the adjacent solenoids (PS and DS) extending over the curves. The fringe field causes the beam to have a horizontal offset that could reduce significantly the muon transmission [7]. In general the angles of the coils were adjusted with an extra 1° yaw rotation in most TS2 coils and 1.2° in most TS4 coils. A trim power supply for TS2 coils is under consideration for vertical correction before the TS3 collimator [7].

The impact of coil and structure tolerances on the magnetic requirements as well as on the magnetic center was studied. The results [7], [8] show that the magnetic design is very robust, meeting all requirements even when significant coil misalignments are present.

A significant challenge for the TS design and operation comes from the large electro-magnetic forces and their dependence on the powering status of the adjacent magnets. Table II summarizes the total forces in x and z directions (according to Fig. 2) on TSu and TSd under different powering scenarios.

The magnetic design defines the coil positions and angles under cold and powered operating conditions. Thermal contraction and magnetic forces will alter those positions and angles from the room temperature assembly. Therefore quality assurance measures are envisioned during coil module production and magnet commissioning.

TABLE II
TOTAL FORCES ON TSU AND TSd

		All on	PS Off	DS Off	TSu Off	TSd Off
TSu	Fx	-1411	-1402	-1398	-	-22
	Fz	-1297	9	-1307	-	-1296
TSd	Fx	1413	1400	1402	24	-
	Fz	941	952	-10	941	-

Total forces on TSu and TSd under different powering scenarios.

Units are in kN.

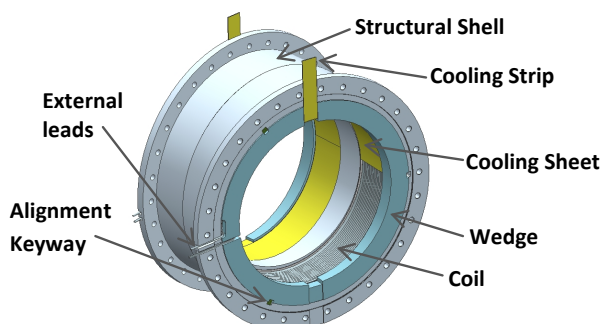


Fig. 3. Solid model of typical TS module with coils. A cooling sheet was removed to shown the coil.

IV. COIL FABRICATION AND STRUCTURAL DESIGN

TS coils will be wound on collapsible mandrels, shrink fitted into aluminum shells (modules) and then combined together into a single cold mass and power unit. The modules (Fig. 3) in the toroidal sections house two coils, some modules in the straight sections may house three coils. The shells are manufactured from forged cylinders made of aluminum alloy (5083-O) bored at both ends to make room for the coils. The shells used in TS2 and TS4 are cut in a wedge-like shape and the ends are bored along different axes in order to generate the toroidal shape. This fabrication technique assures great freedom in the optimization of the coil orientation, for instance allowing a small yaw of some TS2 and TS4 coils. The coil dimensions, with outer diameter in the range 0.9-1.2 m and length shorter than 0.2 m, favor using the shrink-fit technique for insertion into the shells.

The modules (consisting of a shell and two coils) are bolted together. Pins and mating features avoid shear or rotation between adjacent modules. Cylindrical plates or wedges between the coils of adjacent modules provide the axial support and prestress.

The electro-magnetic loads are transferred to reinforced sections of each cryostat through the support system consisting of 20 supports (Fig. 4) made of Inconel 718: six radial (in the direction of the toroid main radius) supports, four axial supports close to each end, and six vertical supports. The radial supports react only tensional loads. The axial supports may act both under tension (normal operation) and under compression (in case of failure of an adjacent magnet). The supports can be adjusted at cold in order to fine tune the positions of the TS coils with respect to the PS and DS coils, and for optimization of the muon selection and transport [8]. The largest coil displacement during energization, including cryostat deformation, is less than 3 mm.

The configuration of the cryostat and the axial supports at the PS side are designed to allow a clear path for the proton beam tube that passes nearby on its way to the Production Solenoid.

After cooldown and during normal operation the peak equivalent stress in the coils is 27.5 MPa and 25.3 MPa respectively. It can increase up to 27.6 MPa in case of failure of adjacent magnets.

The protection of the TS is designed in order to start a fast

ramp down as soon as a quench or failure is detected in either the PS or DS. Nonetheless the support system and the structure of the TS have been designed for withstanding any possible force condition with stresses never exceeding 33.7 MPa in the structure and 200 MPa in the supports, well below the maximum allowable stress for the selected materials.

V. IRRADIATION AND COOLING

All TS1 and the first TS2 coils are sufficiently close to the proton target in the PS to receive non-negligible heat and radiation. Therefore the heat and radiation shield [2] inside the PS has been optimized for protecting also the TS. This optimization together with a reduction of the beam power, with respect to the first design iteration, has reduced the peak power density to $0.1 \mu\text{W/g}$, the peak dose to 3 kGy/yr, and the peak displacements per atom to $3 \cdot 10^{-6}$ per year in the TS coils, which are very manageable values.

All TS coils are indirectly cooled by single phase pressurized (~ 3 bar) helium flow driven by a circulating pump. The helium (4.7 K) flows through cooling tubes welded to cooling strips (made of high purity aluminum), which are welded to the outer surface of the module structures or set on the coil inner surfaces and potted with them.

Most of the static heat load to the cold mass comes through the supports (1.3 W for each axial or radial support) and it is intercepted by routing the cooling pipes around the cold joint of the supports. At about mid-length of the supports there is also an 80 K cooling point. An 80 K thermal shield protects the coils from the radiation coming from the walls of the cryostat and the warm bore.

The analysis and optimization of the TS cooling system is in progress. Preliminary results show all coils below 5.1 K.

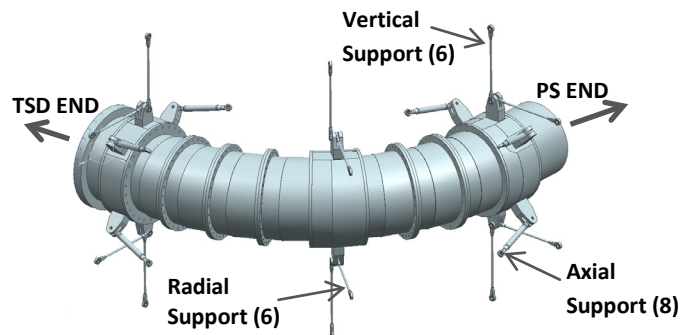


Fig. 4. TSu structure with supports.

VI. QUENCH PROTECTION

The quench protection strategy in the Transport Solenoid is based on extracting most of the energy to external dump resistors rather than relying on the quench to propagate through a series of small coils, which is inefficient and could damage the magnets. If the resistive voltage component exceeds the quench detection threshold of 0.5 V for more than 1 second, the current is shunted through a 0.34 ohm dump resistor (to limit voltage at leads below max 600 V) and the power supply is switched off.

The main parameters of the TSu quench protection system are shown in Table III. The TSu stored energy at nominal operating current is 7.1 MJ (with the adjacent magnets powered off). In this analysis 10.4 MJ of stored energy was used to account for coupling with the adjacent magnets and to have some margin. The inductance was scaled accordingly. The RRR was assumed to be 400 in the aluminum and 100 in the copper allowing for some degradation due to irradiation over the whole experiment lifetime.

The hot spot temperature was computed using the numerical code QLASA [5], [6] in the adiabatic condition, assuming that the quench propagates only in the quenching coil. The “High Field” column in Table III shows the results when the quench starts in the peak field area of the coil with the highest field (3.4 T). The “Low Field” column shows the results for the case when the quench starts in a low field (1.0 T) area of a coil with a low peak field (2.2 T). The hot spot temperature is well below 120 K (the maximum acceptable temperature) in both cases, even with these conservative assumptions. In both cases the transverse quench propagation is faster than the longitudinal propagation. In case of a quench starting in a low field area the transverse propagation helps to keep the detection time relatively low. A dedicated system will be used for the protection of the leads where there is no chance of transverse propagation.

The layer to layer voltages do not exceed 25 V, and the maximum voltage between the leads of each coil does not exceed 150 V. The ground insulation is 2 mm thick and made of several layers (minimum 6 layers) of fiberglass cloth. The layer to layer insulation is 0.25 mm thick and made of 0.125 mm thick fiberglass tape with 45% overlap.

The study of Quench Protection failure scenarios has shown that the worst case is a quench in a single coil that goes undetected and does not propagate to the adjacent coils. In this case, if the quench starts in the peak field area of the coil under the highest field (3.4 T), the hot-spot reaches 53 K in 10.3 seconds. At this point the voltage across the coil is 12.3 V, it is detected by the power supply and the current is switched to the dump. When all current is extracted the hot-spot temperature is 108 K. If the quench starts in the smallest TS coil, it takes 12.6 seconds for the voltage to exceed 12 V, and the hot-spot temperature is 117 K after all energy is extracted. Failure of the current switch will be prevented by redundancy.

TABLE III
TSU QUENCH PROTECTION PARAMETERS

Symbol	High Field	Low Field
Copper/aluminum RRR	100/400	
Operating current (A)	1730	
Max field in quenching coil (T)	3.4	2.2
Field where quench starts (T)	3.4	1.0
Energy with coupling & margin (MJ)	10.4	
Inductance with coupling & margin (H)	6.95	
Dump resistance (ohm)	0.34	
Quench detection threshold (V)	0.5	
Validation time (s)	1	
Hot spot temperature (K)	66	65

VII. PROTOTYPING, FABRICATION AND TEST

The TS modules (consisting of coils integrated into the support shells) are going to be fabricated in industry. Each module will be cold tested at Fermilab as part of the acceptance process. All following steps (cold mass assembly, cryostat assembly and integration, and commissioning tests) will be performed at Fermilab.

Before the cold test of each module a single stretched wire system will be used to check that the individual coil angles, with respect to the aluminum module alignment features, are within the allowed tolerances. This operation should be possible with at least two modules (four coils) assembled together, and will allow checking for systematic angle errors introduced by manufacturing or assembly.

A system of displacement sensors will be used to monitor the change in coil positions and angles, with respect to the fixed cryostat, during TS cool down and powered state. If necessary, cryostat supports will be used to adjust these positions. In addition, the supports will be instrumented with strain gauges to get a measure of the electro-magnetic forces.

A prototype cable is being fabricated by Hitachi and New England Wire Technology. So far the strand and the Rutherford cable have met all specifications. Part of the prototype cable is going to be used for a TS2 prototype module, which is planned to be tested in spring 2014 at Fermilab.

VIII. CONCLUSION

The design of the Transport Solenoid of the Mu2e experiment at Fermilab has faced several challenges because of the strong interaction of this S-shaped 13.4 m long solenoid with the adjacent larger solenoids (PS and DS). The design has addressed these challenges in several ways, for instance: same coils have an extra yaw angle in order to compensate the fringe field from PS and DS; the support structure (made of modules) can easily accommodate coils with different yaw providing radial and axial prestress; the quench protection system can handle the energy of the TS plus its coupling with PS and DS plus some extra energy for margin; the support system can handle electro-magnetic forces in all powering and failure scenarios.

A prototype cables is under fabrication and a prototype module will be fabricated and tested in order to demonstrate the concept.

ACKNOWLEDGMENT

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