TRANSPORT SOLENOID (TS) MAGNET SYSTEM FOR THE Mu2e EXPERIMENT AT FERMILAB

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Figure 1. TS Overall layout (assembly at Fermilab premises – Photo Courtesy of Fermilab)

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 – the one provided by ASG), and the Detector Solenoid (DS).
The Transport Solenoid is a "S-shaped" solenoid Magnet System placed in between the other bigger solenoids (DS & PS). It has a warm-bore aperture of 0.5m and produces a field varying in between 2.0 and 2.5 Tesla.
The strong coupling with the adjacent solenoids poses several challenges to the design and operation of the Transport Solenoid.
The main goal of the Transport Solenoid is to transport the muons created by a proton beam hitting a target inside the PS, selecting the muons by charge and momentum and carrying the required slow muons to the detector after some time delay.

These goals are achieved by the S-shape of the Transport Solenoid, a set of field characteristics including negative gradients in the straight sections, and collimators set in the warm bore, which is the muon beam line.
The Transport Solenoid 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.
The half-coils of TS3, together with the TS1 and TS2 coils are set in a single cryostat (TSu).
Similarly, all other coils are set in the TSd cryostat.

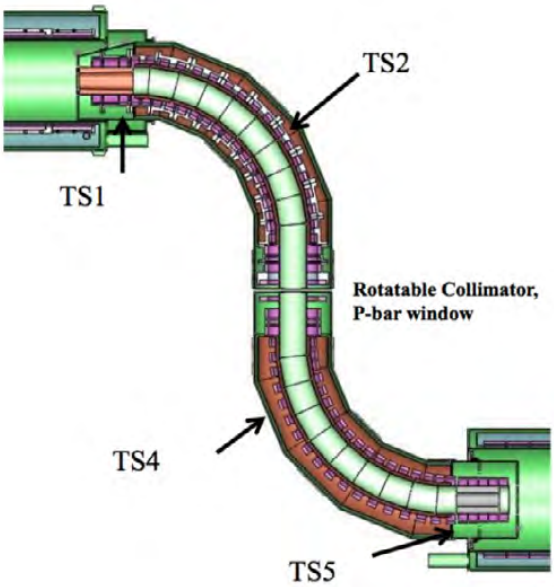


Figure 2. TSu & TSd detailed layout

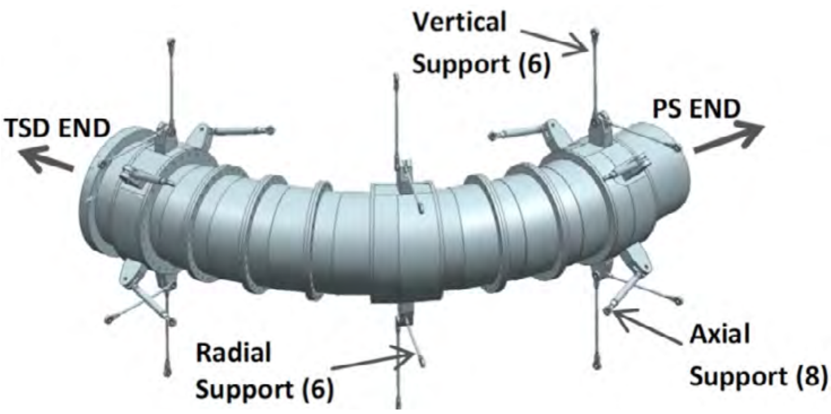
The Transport Solenoid system consists of 52 superconducting solenoid coils integrated into 27 Modules that form 14 Units.
The entire assembly composes the so-called "S-shaped" structure.
The TSu cryostat contains the TS1, TS2 and TS3u coils while the TSd cryostat contains the TS3d, TS4 and TS5 coils.

Table 1 below summarizes the Modules and Coils for the two TSu and TSd sub-assemblies:

TS	Test Unit	Module	Coil #	Layers	Turns/layer	Turns
TSu	TSUN-6	TSMD-1	TSCL01	5	16	80
			TSCL02	8	25	200
		TSMD-2	TSCL03	11	15	165
	TSUN-4	TSMD-3	TSCL04	12	17	204
			TSCL05	12	17	204
		TSMD-4	TSCL06	12	17	204
			TSCL07	16	17	272
	TSUN-3	TSMD-5	TSCL08	16	17	272
			TSCL09	16	17	272
		TSMD-6	TSCL10	16	17	272
			TSCL11	17	17	289
	TSUN-1	TSMD-7	TSCL12	17	17	289
			TSCL13	17	17	289
	TSUN-2	TSMD-8	TSCL15	17	17	289
			TSCL14	18	17	306
		TSMD-9	TSCL16	18	17	306
			TSCL17	18	17	306
	TSUN-5	TSMD-10	TSCL18	18	17	306
			TSCL19	18	17	306
		TSMD-11	TSCL20	20	17	340
			TSCL21	12	17	204
	TSUN-7	TSMD-12	TSCL22	16	17	272
			TSCL23	13	8	104
		TSMD-13	TSCL24	15	17	255
			TSCL25	43	8	344
TSd	TSUN-13	TSMD-14	TSCL26	42	8	336
			TSCL27	13	17	221
		TSMD-15	TSCL28	14	8	112
			TSCL29	14	17	238
	TSUN-12	TSMD-16	TSCL30	10	17	170
			TSCL31	12	17	204
		TSMD-17	TSCL32	12	17	204
			TSCL33	15	17	255

TS	Test Unit	Module	Coil #	Layers	Turns/layer	Turns
TSd	TSUN-9	TSMD-18	TSCL34	15	17	255
			TSCL35	15	17	255
		TSMD-19	TSCL36	15	17	255
			TSCL37	16	17	272
	TSUN-8	TSMD-20	TSCL38	16	17	272
			TSCL39	16	17	272
	TSUN-10	TSMD-21	TSCL40	16	17	272
			TSCL41	16	17	272
		TSMD-22	TSCL42	16	17	272
			TSCL43	16	17	272
	TSUN-11	TSMD-23	TSCL44	16	17	272
			TSCL45	14	17	238
		TSMD-24	TSCL46	14	17	238
			TSCL47	11	17	187
	TSUN-14	TSMD-25	TSCL48b	9	14	126
			TSCL49b	8	14	112
		TSMD-26	TSCL50b	5	14	70
		TSMD-27	TSCL51	3	14	42
			TSCL52	3	14	42

All the TSu/TSd coils are powered in series, thereby minimizing the number of leads and the complexity of the powering and protection systems.
The coils are pre-assembled as modules and tested at 4K in order to reduce the complexity and the time of the assembly.
The support system is optimized to facilitate control of the interfaces and to reduce the stresses during cooldown and warm-up.



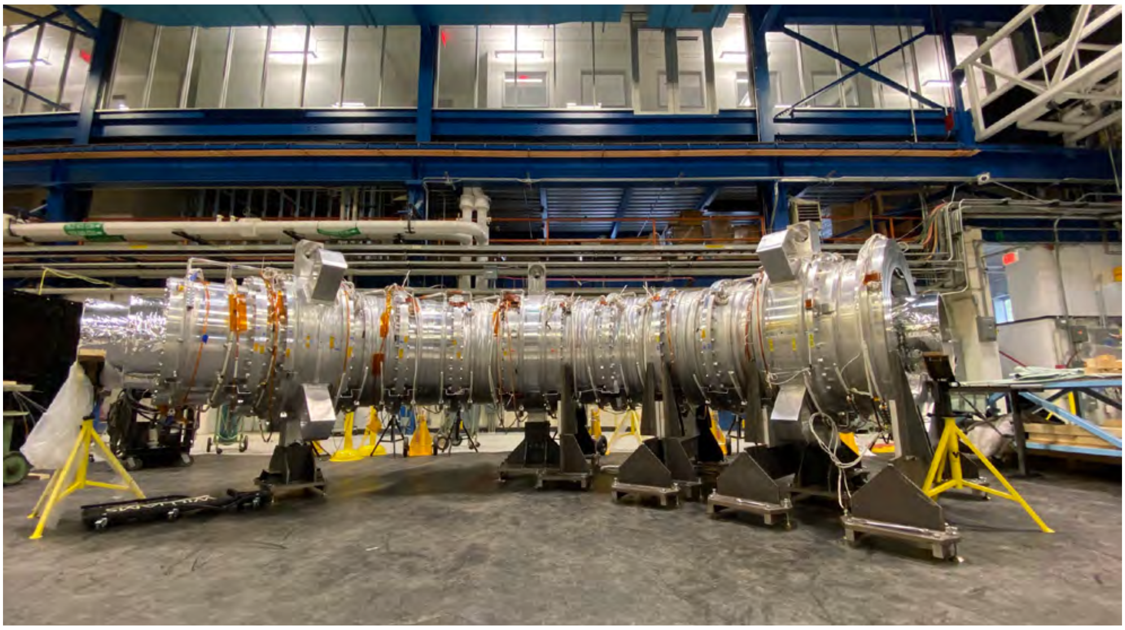


Figure 3. TSu assembled at Fermilab premises (Photo Courtesy of Fermilab)

The conductor is an aluminium stabilized NbTi Rutherford cable.
This kind of conductor is typically used for detector magnets in particle accelerators and colliders.
The conductor parameters are shown in Table 2. The conductor is wrapped by fiberglass tape, wound with 50% overlap, with a resulting thickness of 0.15mm per side.
VPI Epoxy impregnation is used to complete the insulation.
Each TSu and TSd subassembly is powered by a dedicated power supply.
The operating current is 1730A and the operating current density is 47A/mm2.
The peak field on TS coils is 3.4T.

Table 2 Below are the main parameters of the TSU Conductor:

Symbol	Unit	Value
Strand diameter	mm	0,67
Number of strands		14
Cu/non Cu 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
Cable critical current at 5T, 4.2K	A	5.900
Operating current	A	1.730
Test current	A	2.100
Peak field along the magnet central axis	T	2,5
Peak coil field (B_{peak})	T	3,4
Thermal margin at B_{peak}, T_{peak}	K	1,87

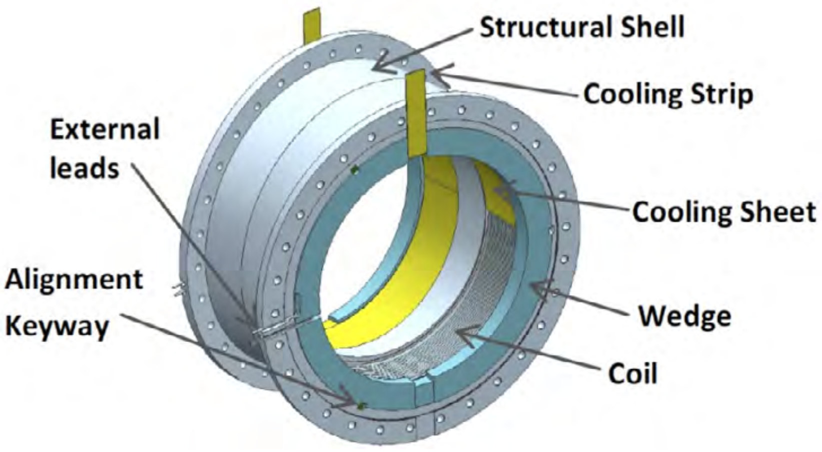
The Coils

The “S shaped” Transport Solenoid (TS) consists of 52 solenoids which select and transport the selected muons towards a collection target. At the end, the Detector Solenoid has an axially graded solenoid at the upstream end to focus transported muons onto a collection target, and a spectrometer solenoid at the downstream end to accurately measure the momentum of the outgoing elections produced by the conversion process.

The main steps of the fabrication of each component of the TS system are the following:
— Winding on a collapsible inner mandrel. A cooling thermal sheet made of aluminium alloy is integrated in the inner diameter before the first layer is wound.
— Vacuum potted impregnation phase.
— Resin excess removal.
— Coil is turned to obtain a perfect cylindrical outer surface in order to allow proper shrink fitting into the Al-housing.

Each coil is fabricated using a continuous unit length of superconductor: no internal joints are present.
The Splice joints between the coils are realized on the outer surface of the housing.
During the final testing of the Units at the Fermilab premises, every unit is powered up to 120% of the operating current in order to gain acceptance.

The Coil module



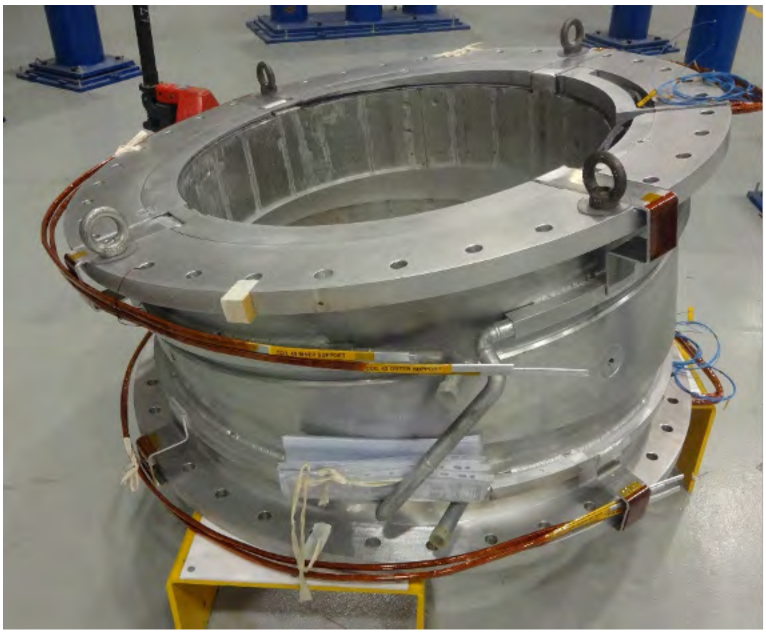


Figure 4. TS Module

The Coils

Each module can house two coils, which are inserted from each end. Each housing is warmed up, allowing sufficient clearance for coil insertion followed by a shrink fit process.
The coil outer diameter interference with respect to the housing inner surface is 0,5mm at room temperature.

The Module consists of:

→ A housing shell
This is a huge structure that surrounds one or two solenoids. The shrink fitting operation applies sufficient prestress to the coils for withstanding the Lorentz Forces generated during energization. The shell is fabricated using a 5-axis industrial milling machine and a CNC lathe.

→ A cooling circuit
This is an aluminium alloy hollow square pipe that surrounds the shell. Inside, liquid helium flows at 4.2K. By thermal conduction it cools down the module itself.
The cooling circuit is welded to the shell's outer surface. Heat is conducted from the coil to the cooling system by conduction and by strips of pure aluminium connected to the coil inner surface.

→ Two or more splice boxes
These boxes contain the electrical joints between the coils of the same module and between two adjacent modules.

→ Wedges & spacers
The coils are retained by the wedges to give each coil the required axial pre-compression while the spacers are realized by thin Al shims used to compensate the different coil heights.

→ Flanges
These are used to bolt the modules to each other. This is necessary to form the "S shaped" structure.

→ One or two coils

The main steps of the Module assembly process are the following:

Coil fabbrication

The coils are designed and fabricated with sufficient insulation on the outer diameter to ensure a minimum insulation thickness (after machining) of 4mm.
The total conductor length used for realizing the 52 coils was about 36km with a single length varying from 200m to 1.200m.

Shell fabrication

Each shell is produced following these steps:
1) The outer surface is machined to the final dimensions.
The inner surfaces where the coils are going to be housed are rough machined only.
2) After step 1) the pipes for the cooling circuit are welded to the shell outer surface and tested in order to be pressure and leak proof.
In parallel each coil is wound, impregnated and machined.
3) The inner surfaces ID where the coils were going to be housed are fine machined to the dimension resulting from the coil turning operation.
The interference at room temperature is specified by the Customer to be 0,5mm on the diameter at room temperature.
The shell ID fine machining is performed at constant temperature.

Coils shrink fitting into the housing

This operation consists of heating up the housing to a temperature of 110°C and then performing the shrink fitting operation on both sides.
The operation is carried out using special tooling to centre the position of each coil and to allow the flipping of the structure in order to repeat the operation on the opposite side.

Figure 5. Shrink-fitting operation at ASG premises

The Unit

The fourteen units have been assembled at ASG's premises between the end of September 2018 and October 2020.
The assembly consists of bolting by high strength Al-alloy screws the flanges and then welding the "crossover pipe" that connects the two modules hydraulically. A pressurization test followed by LN2 thermal cycles and the final leak test completes the test campaign carried out on each module.

Figure 6. Last Unit (Unit 14) assembled at ASG premises in October 2020