475.04.04 Mu2e Detector Solenoid

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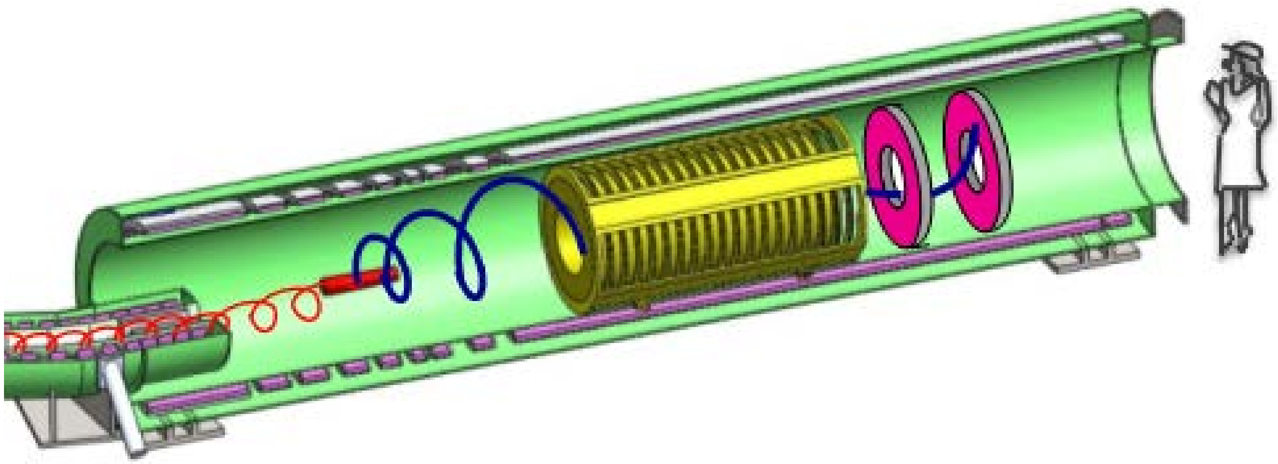
L3 for Mu2e Detector Solenoid
October 21-24, 2014

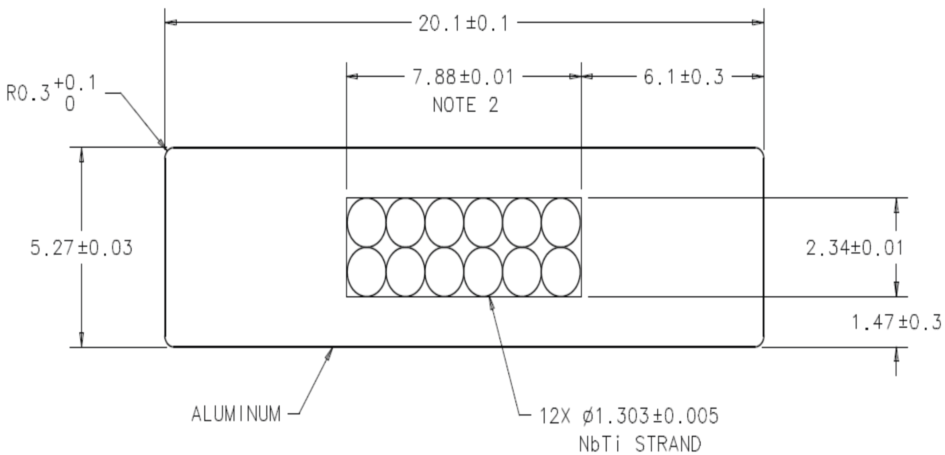
Requirements: Overview



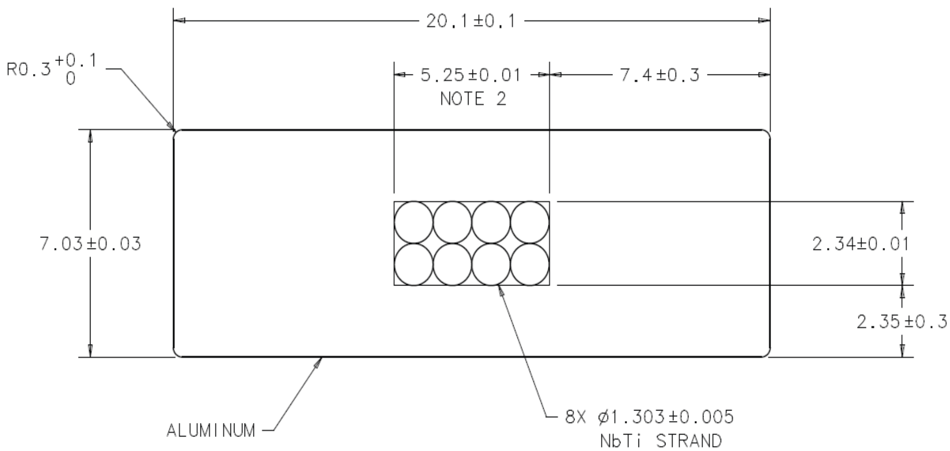
- Provide volume for the Mu2e experiment:
  - 1.8 m aperture, 10 m length
- Provide precision magnetic field:
  - Graded field region (2 T to 1 T) to focus muons on stopping target and deflection of conversion electrons towards spectrometer
  - Uniform field region (1 T) for precision tracking and calorimetry

Design: Cable

DS uses Al-stabilized NbTi Rutherford cable



“Narrow” Conductor (“DS1”)



“Wide” Conductor (“DS2”,)

Cable	Number of Units	Unit Length
DS1	9	1100 meters
DS2	4	1750 meters

Furukawa (DS1)

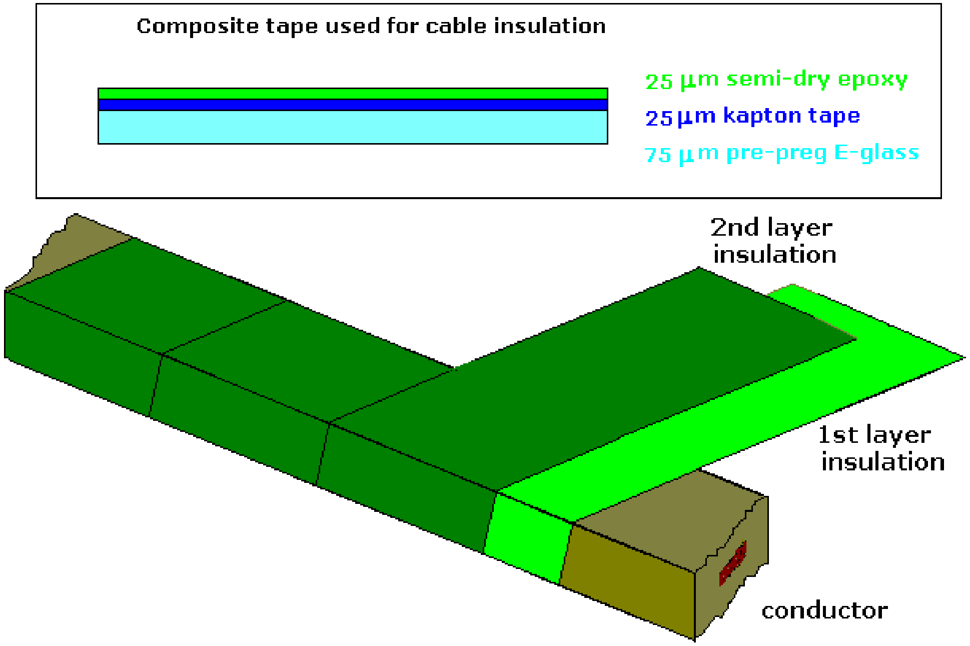
Hitachi (DS2)

Order for production quantity of DS cable has been placed

- **Furukawa: SC wire is in production**
- **Hitachi: SC wire completed. Start of Rutherford cable production.**

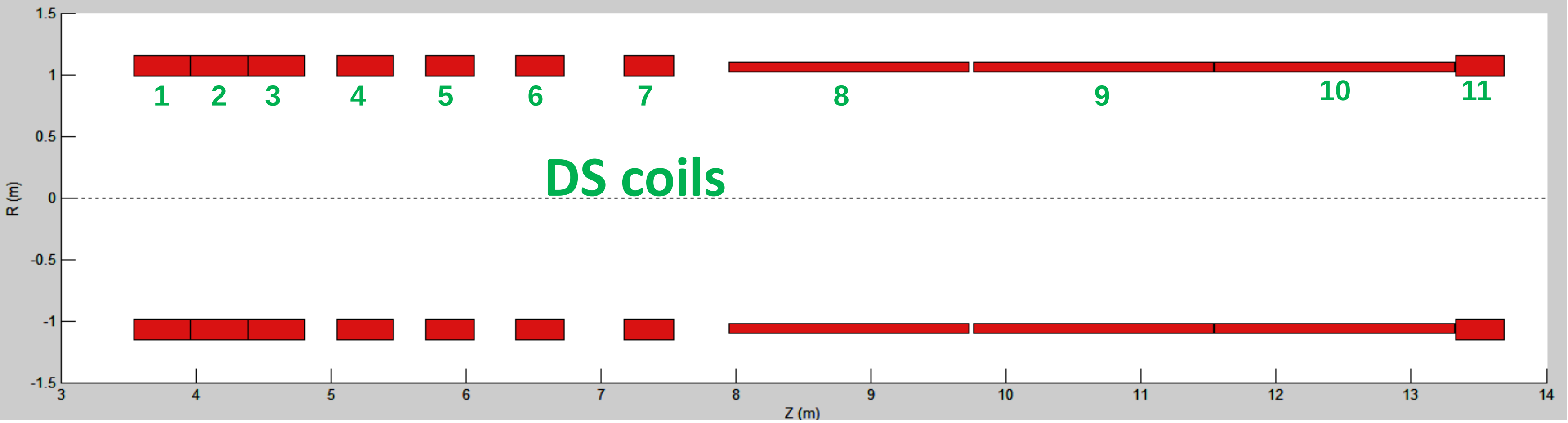
Design: Insulation Scheme

- Require good electrical insulation, radiation resistance, and high thermal conductivity
- Same type of cable insulation as used in the ATLAS Central Solenoid



- 2 layers of composite tape for conductor cable insulation
- All gaps between turns and layers to be filled with epoxy
- Additional ground insulation between coils and support structure

Design: Coils

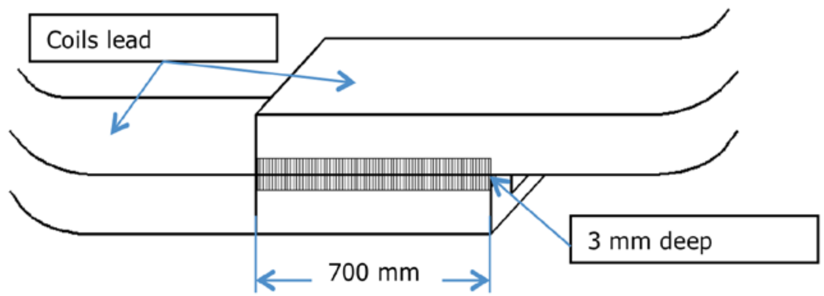


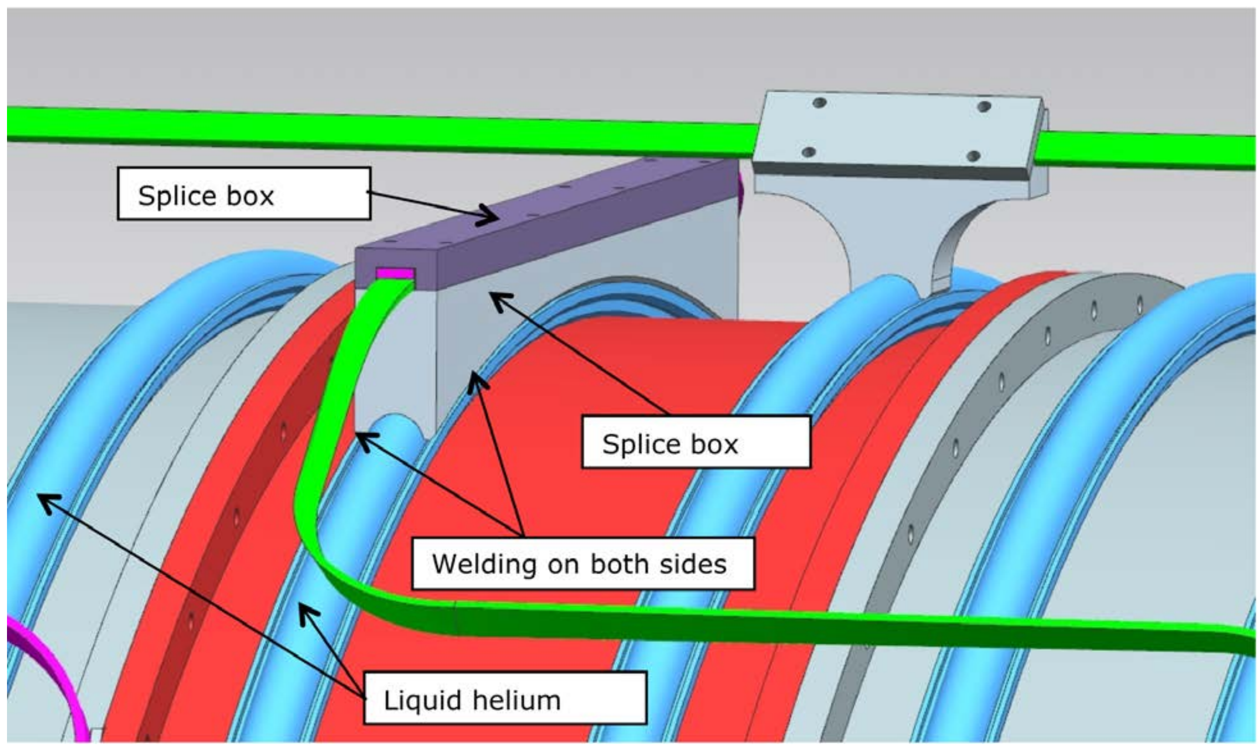
- DS has 11 coils
- Single-layer in tracker/calorimeter region
- Double layer everywhere else

Coil #	Coil IR [m]	Coil OR [m]	Coil Length [m]	#ZC [m]	# Layers	#Turns Per Layer	Total #Turns
1	1.0500	1.0915	0.42075	3.7489	2	73	146
2	1.0500	1.0915	0.42075	4.1739	2	73	146
3	1.0500	1.0915	0.42075	4.5989	2	73	146
4	1.0500	1.0915	0.42075	5.2519	2	73	146
5	1.0500	1.0915	0.36325	5.8801	2	63	126
6	1.0500	1.0915	0.36325	6.5701	2	63	126
7	1.0500	1.0915	0.36325	7.3971	2	63	126
8	1.0500	1.0705	1.8310	8.8178	1	244	244
9	1.0500	1.0705	1.8310	10.6528	1	244	244
10	1.0500	1.0705	1.8310	12.4883	1	244	244
11	1.0500	1.0915	0.36325	13.6425	2	63	126

Design: Splices

- Welded joint splices
- 700 mm splice length
- Welding Aluminum on both narrow sides
- No additional solder material
- 3mm weld penetration depth
- NbTi temperature cannot exceed 350 C for >15 minutes
- Splice box designed to provide mechanical support for splices
- Made from 1100 Al
- Splice box length is 700 mm
- Splice box base welded to Helium cooling pipe
- Voltage taps and temperature gauges on both splice ends

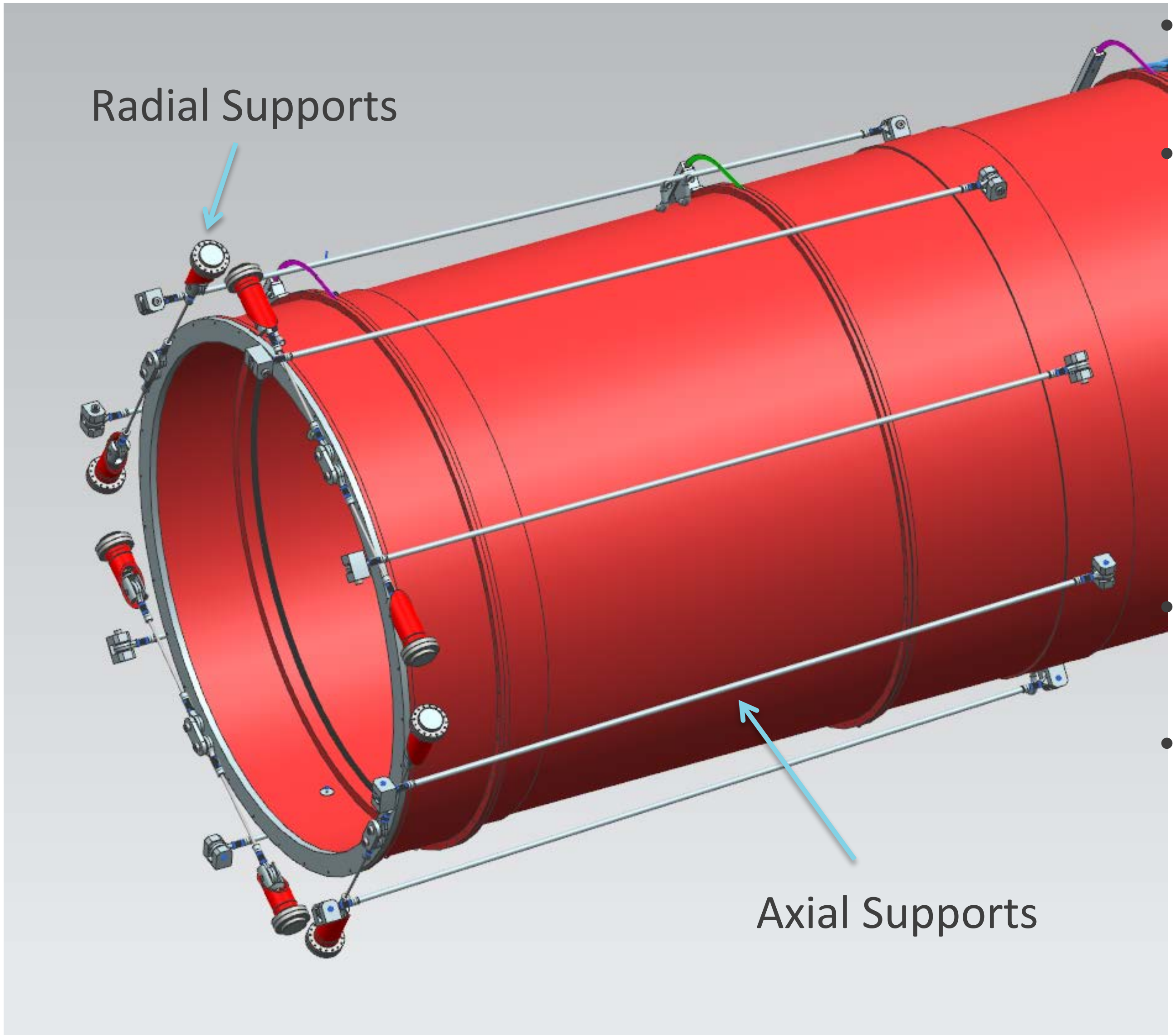




Design: Cold Mass

- Coils are inserted into outer support Al shells to form a spool piece
- Requires shrink fitting (*interference fit*) to maintain radial pressure between coils and shells
- Cold mass consists of spool pieces and spacers
- Spacers needed to obtain correct magnetic profile
- Spacers can be machined to assure precise positioning of coils

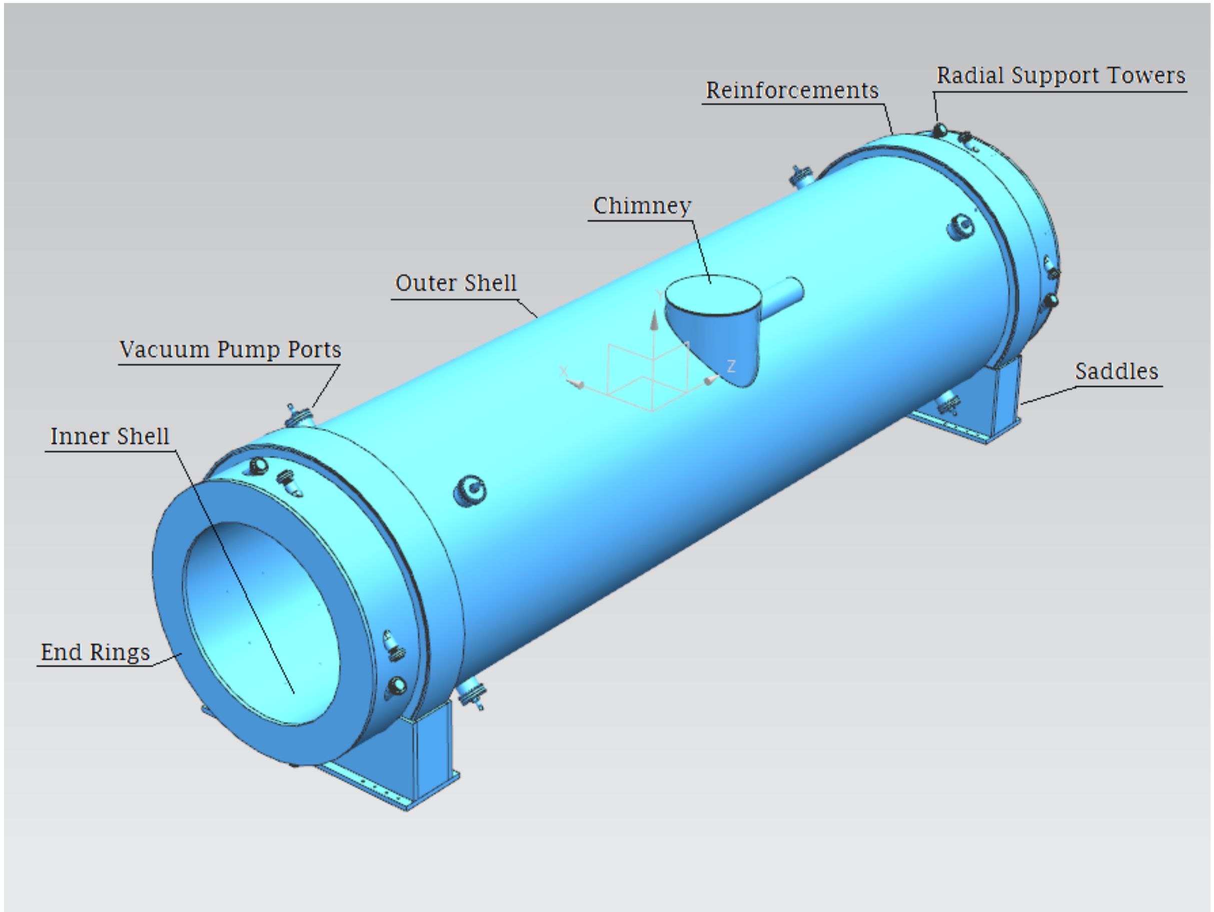
Design: Cold Mass Support



- Inconel 718 used for both axial and radial cold mass supports
- Forces:
  - Dead weight: 110 kN
  - Magnetic forces:
    - DS-TS interaction: Pull towards each other
    - DS coil interaction: radial forces trying to expand coils, axial forces trying to push coils together
    - De-centering forces due to TS-DS interaction
- Design loads
  - Axial supports: 1000 kN
  - Radial supports: 70 kN
- More simulations:
  - Heat loads through cold mass supports
  - Contraction of coils under temperature and magnetic loads
  - Deflection of cold mass under gravitational load

Design: Cryostat

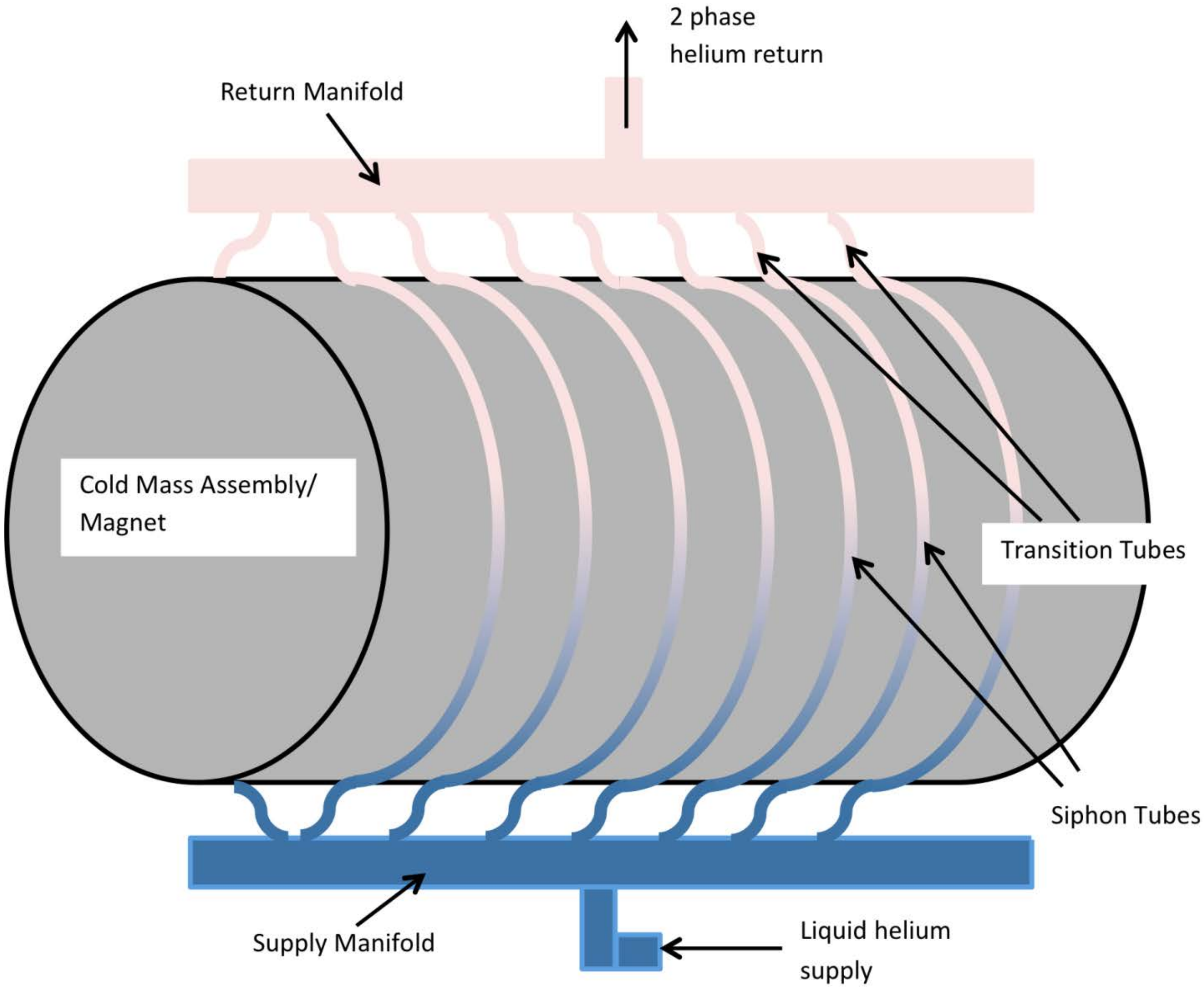
- ~10 m long
- ~2.7 (1.9) m OD (ID)
- Stainless steel
- Openings in outer shell:
  - Chimney for transfer line
  - Vacuum ports
  - Radial support towers
- Bore must accommodate ~10 tons of equipment via rails attached to inner shell



Changes since CD-1

- Decision to use thermosiphon cooling scheme for cold mass assembly
- Magnet length changed

Thermosiphon cooling scheme

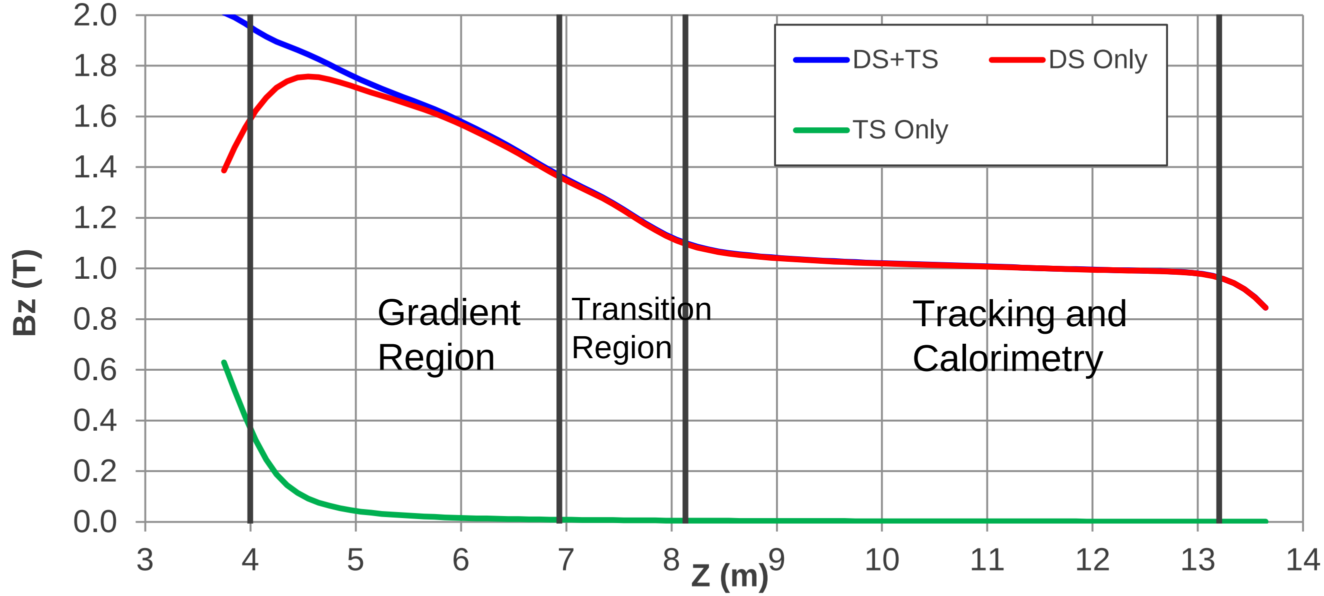


Value Engineering since CD-1

- Overall stable design:
  - Develop RDR, technical drawings and solid model for potential vendors
- Similar design approach for both DS and PS

Performance: Magnetic Field

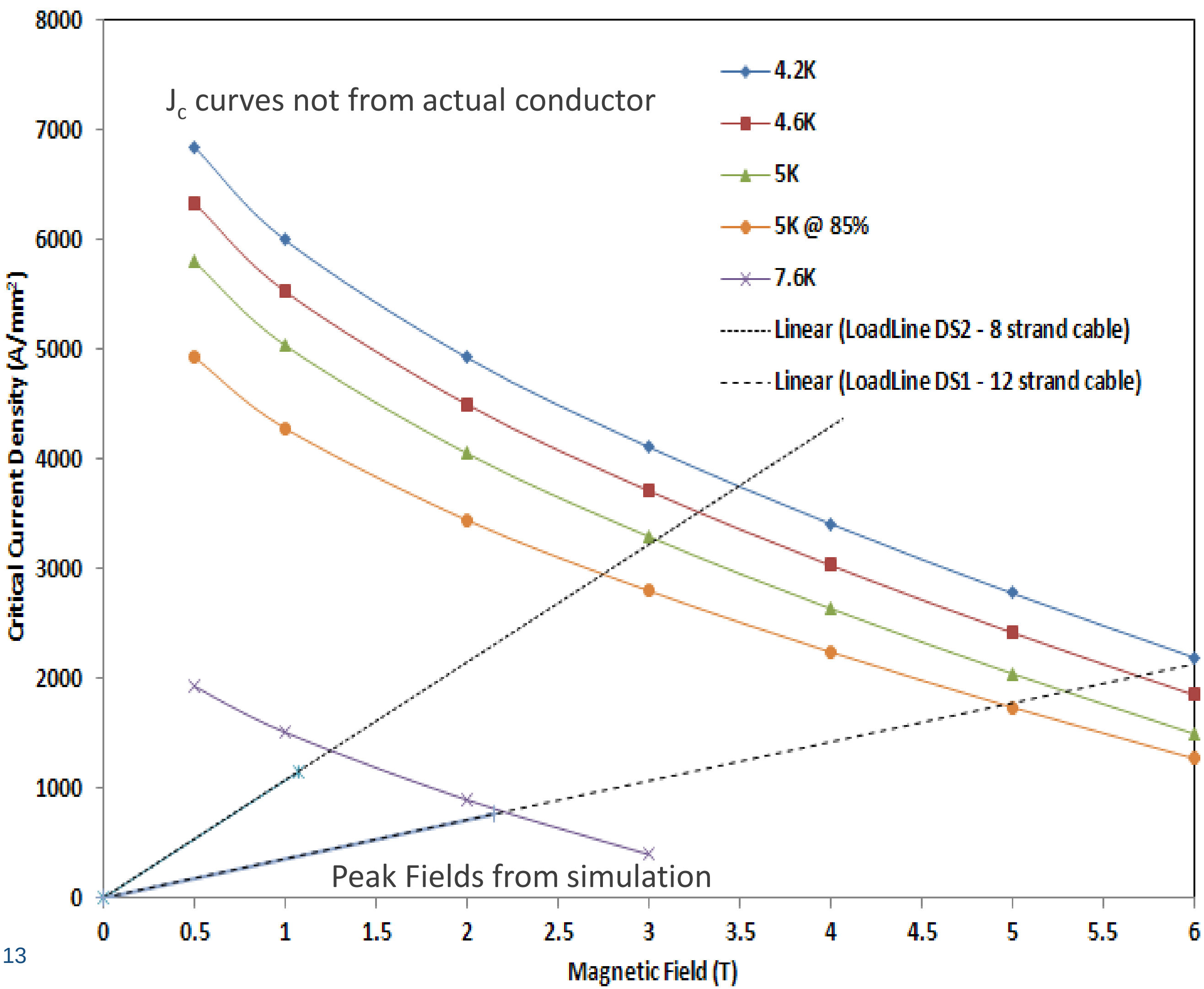
- Field maps with coil displacement errors were generated assuming manufacturing tolerances
- Mu2e Tracking group used these field maps as inputs to their track reconstruction algorithms
- Mu2e Tracking group verified that inputs satisfied physics requirements



DocDB 3942

Performance: Operating Margins

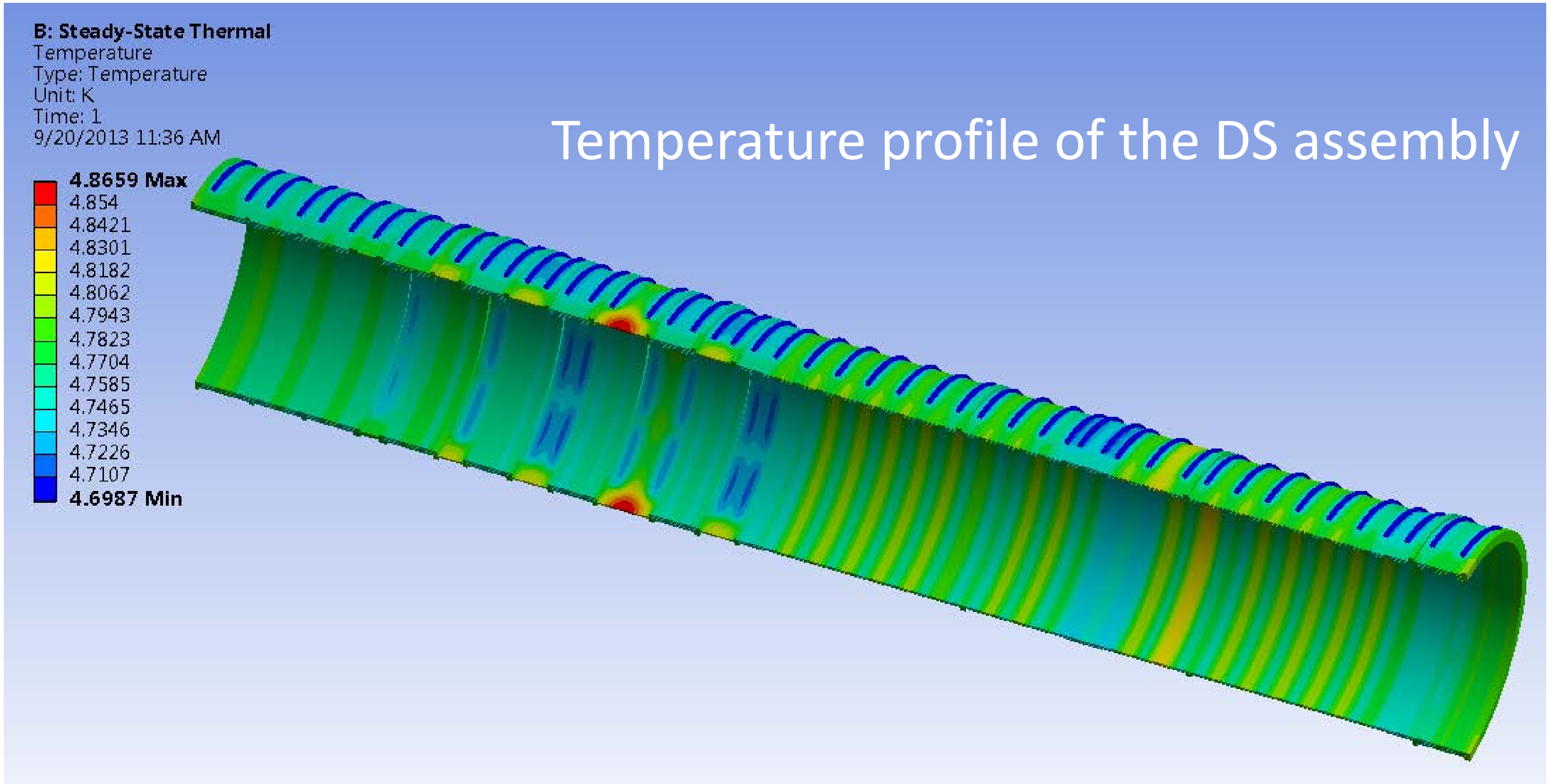
Cable critical current density in the field range of interest at reference Temp. (4.2 K), operating temp. (5 K), and 7.6 K to account for margin



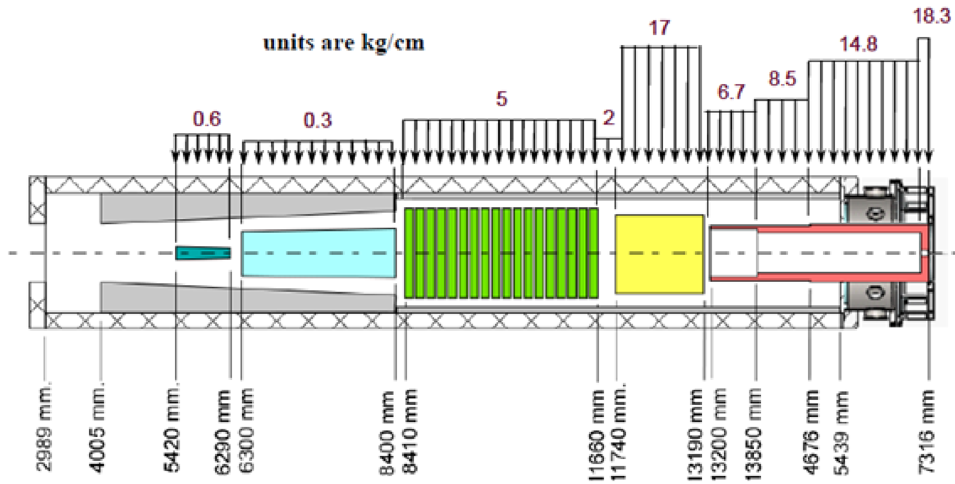
- Cable designed to operate at least at 45% of conductor quench current
- 2.5 K temperature margin w.r.t. conductor temperature of 5 K
- Peak field in narrow conductor is 2.15 T
- Peak field in wide conductor is 1.07 T
- Larger margins in all other segments

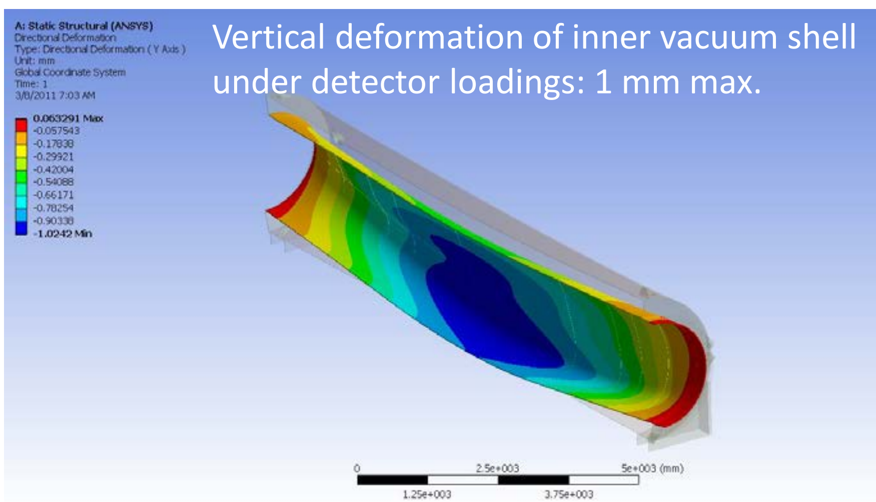
Performance: Thermal Analysis

- Performed extensive modeling, to estimate cooling tube size and locations taking into account insulation material properties (FEA)
- Temperatures do not exceed 5 K

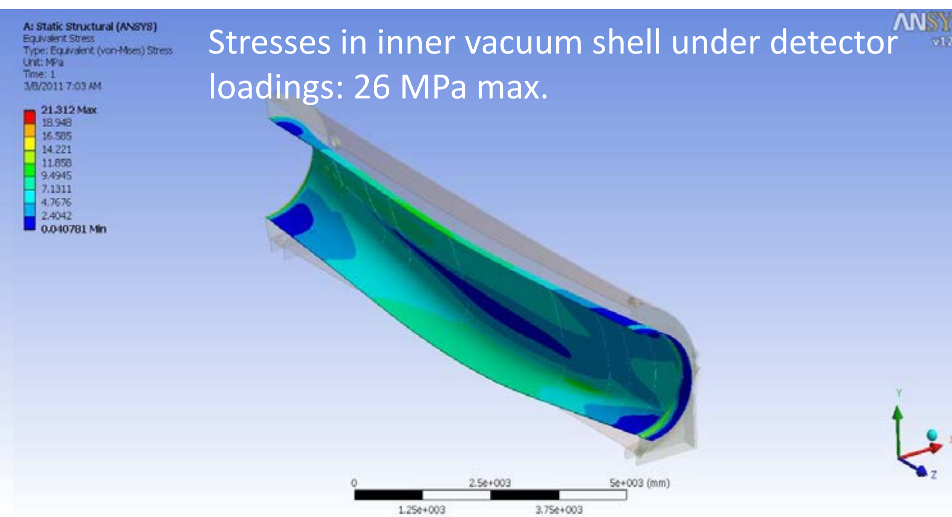


Performance: Loads on Inner Shell





Vertical deformation of inner vacuum shell under detector loadings: 1 mm max.



Stresses in inner vacuum shell under detector loadings: 26 MPa max.

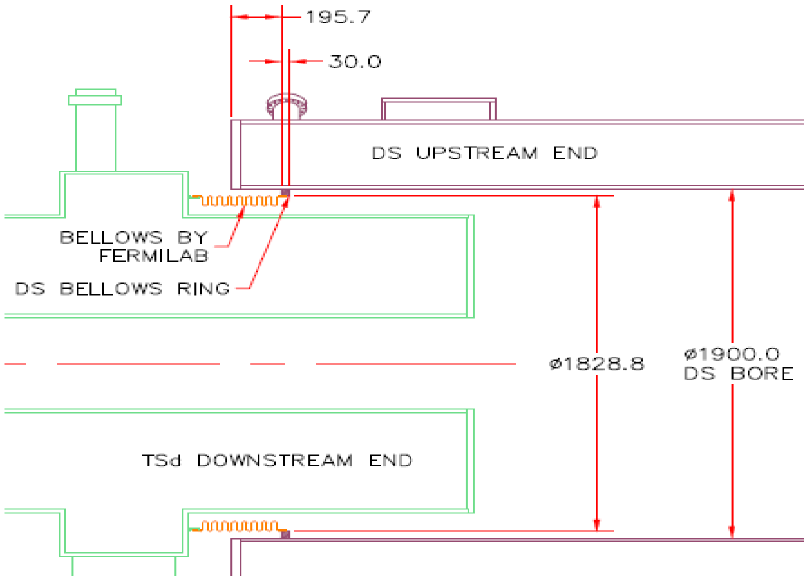
Instrumentation

Sensor	Quantity	
Coil Voltage Taps (Actual Primary & Redundant V-Taps)	24	Quench Protection
Lead Voltage Taps (Actual Primary & Redundant V-Taps)	4	
Splice Resistance (# of Splices) [2-wire Channels]	10	
Cold Mass Temperature (Cernox)	29	Temperature Sensors
Warm-up & Cool Down Temperature (Cernox)	12	
Supply & Return Manifolds Temperature (Cernox)	8	
80K Temperature (Platinum) (Shields & Cu. Leads)	24	
Strain (Axial & Radial Support Rods)	24	Strain Gauges
Reflective Position Sensors (Coldmass)	12	Position Sensors

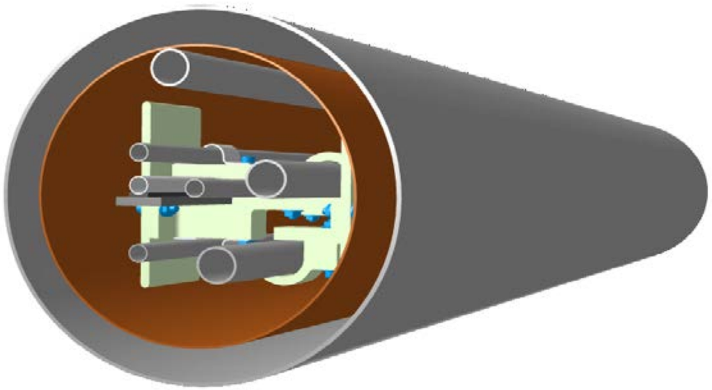
(D. Orris)

Interfaces

- DS-TS interface:
  - DS connects to TSd to provide a common Muon Beamline Vacuum System volume
  - Connection via a flexible bellows
  - Allows axial/lateral movement from cool-down and magnetic forces
- Transfer Line:
  - Attached to the side of the chimney
  - 10 inches OD
  - DS superconductor, cryogenic piping
- Instrumentation Port:
  - To route instrumentation wiring



Connection Between DS and TSd



Transfer Line Cross Section

Remaining work before CD-3

- Order final engineering design of DS by the magnet vendor
- Conduct technical review of the final DS design
- Prepare final design and drawing of DS support stand

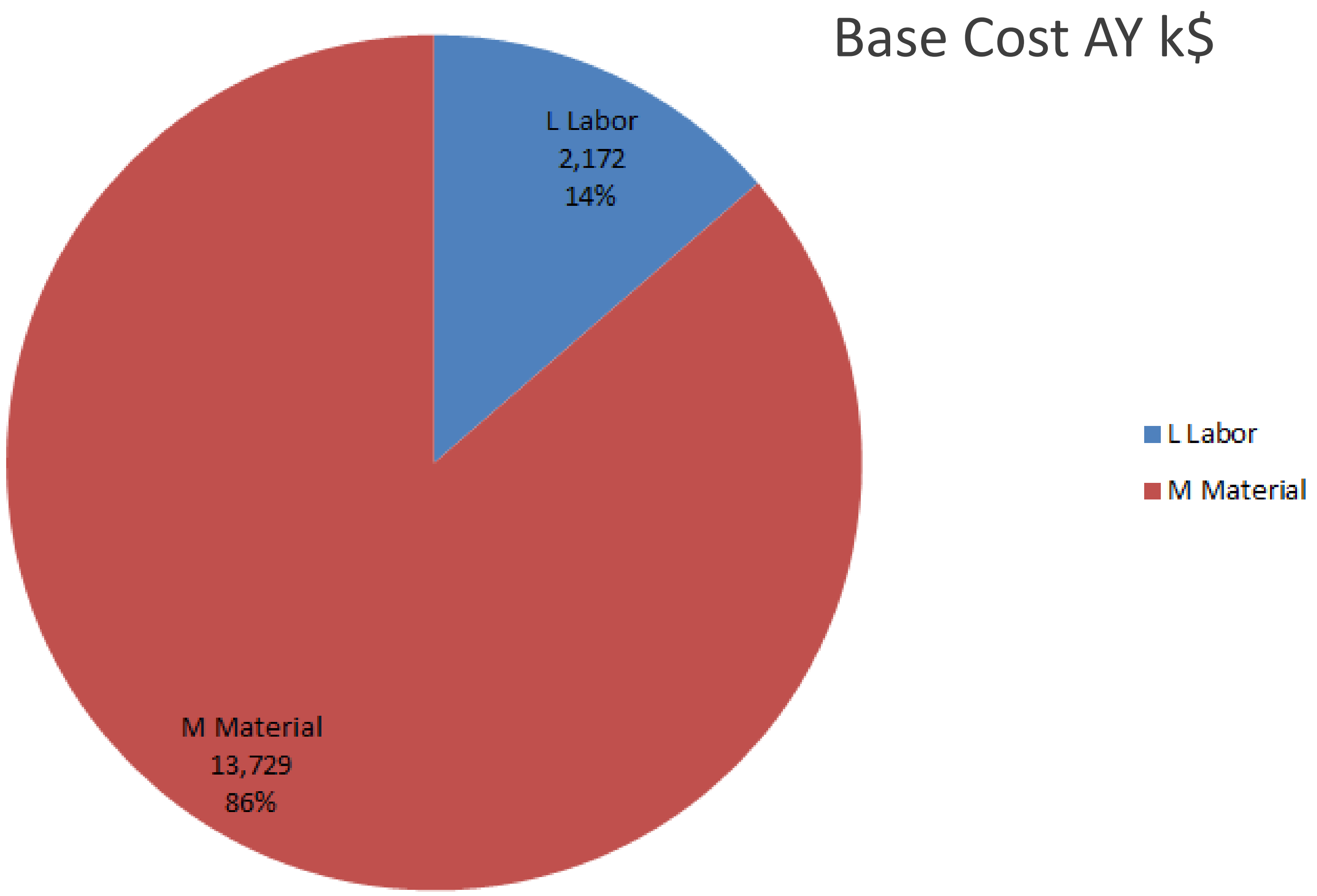
Quality Assurance

- The reference design has been reviewed by magnet experts, fulfills all the requirements, complies with the structural codes and has appropriate margins used in similar magnets:
  - The magnet vendor has flexibility in changing the reference design to optimize the fabrication process. The vendor is responsible for demonstrating that the modified design still meets the requirements.
  - Technical review of the final DS design is conducted before the magnet vendor is granted permission to fabricate the magnet.
- The magnet vendor has to implement a quality assurance plan that meets the requirements for the design and construction of DS:
  - Traveler system calling out all fabrication steps with internal sign-offs.
  - Hold points prior to critical operations.
- Vendor oversight by FNAL team
- Model coil to validate the magnet production tooling
- Extensive acceptance testing:
  - On the production cable prior shipping it to the magnet vendor
  - On the magnet at the vendor site (warm/cold).
- Details are outlined in our Procurement Specification document (DocDB 3670)

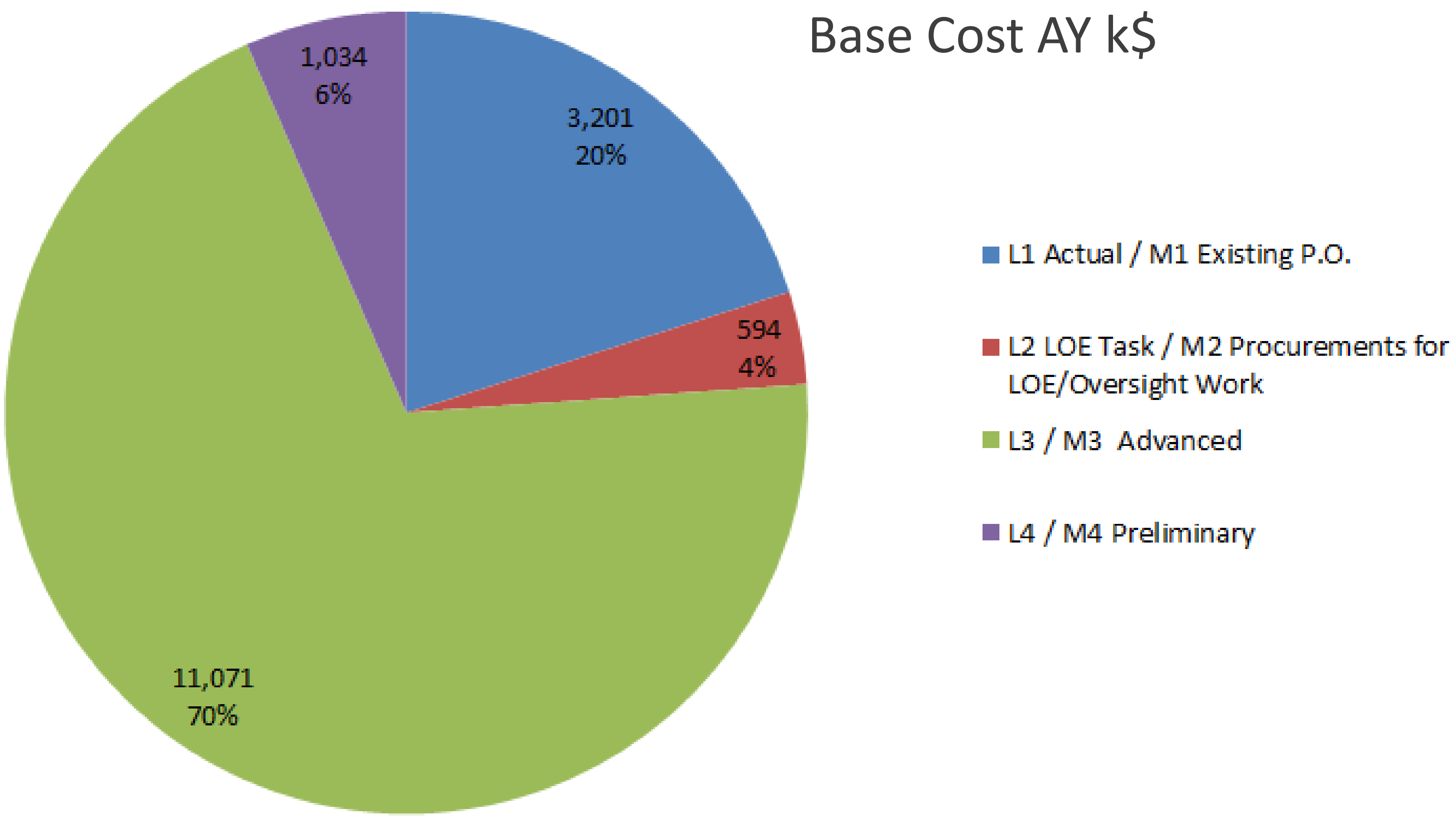
ESH&Q

- Cryogenic:
  - Potential for oxygen deficient atmospheres (ODH). An (ODH) analyses will be conducted. Emergency response procedures will be developed for responding to alarm systems.
- Stored Magnetic Energy:
  - 26 MJ of stored energy in DS the powering circuit. Quench protection systems have been designed to dissipate the stored energy in the solenoids in a controlled and safe fashion.
- Coupled Magnetic forces:
  - There are large forces within the DS itself as well as between the DS and TS. The DS is designed to resist these forces, but access to the magnet will be restricted during the times when it is powered.
- Stray Magnetic Fields:
  - >5 gauss fields are of particular concern because they can affect medical electronic devices (pacemakers); fields >600 gauss can impact ferromagnetic materials. The fringe field analysis document is in DocDB - Mu2e Document 1381.
  - The DS has no return yoke. Access will be restricted when it is powered and warnings will be posted for persons with pacemakers.

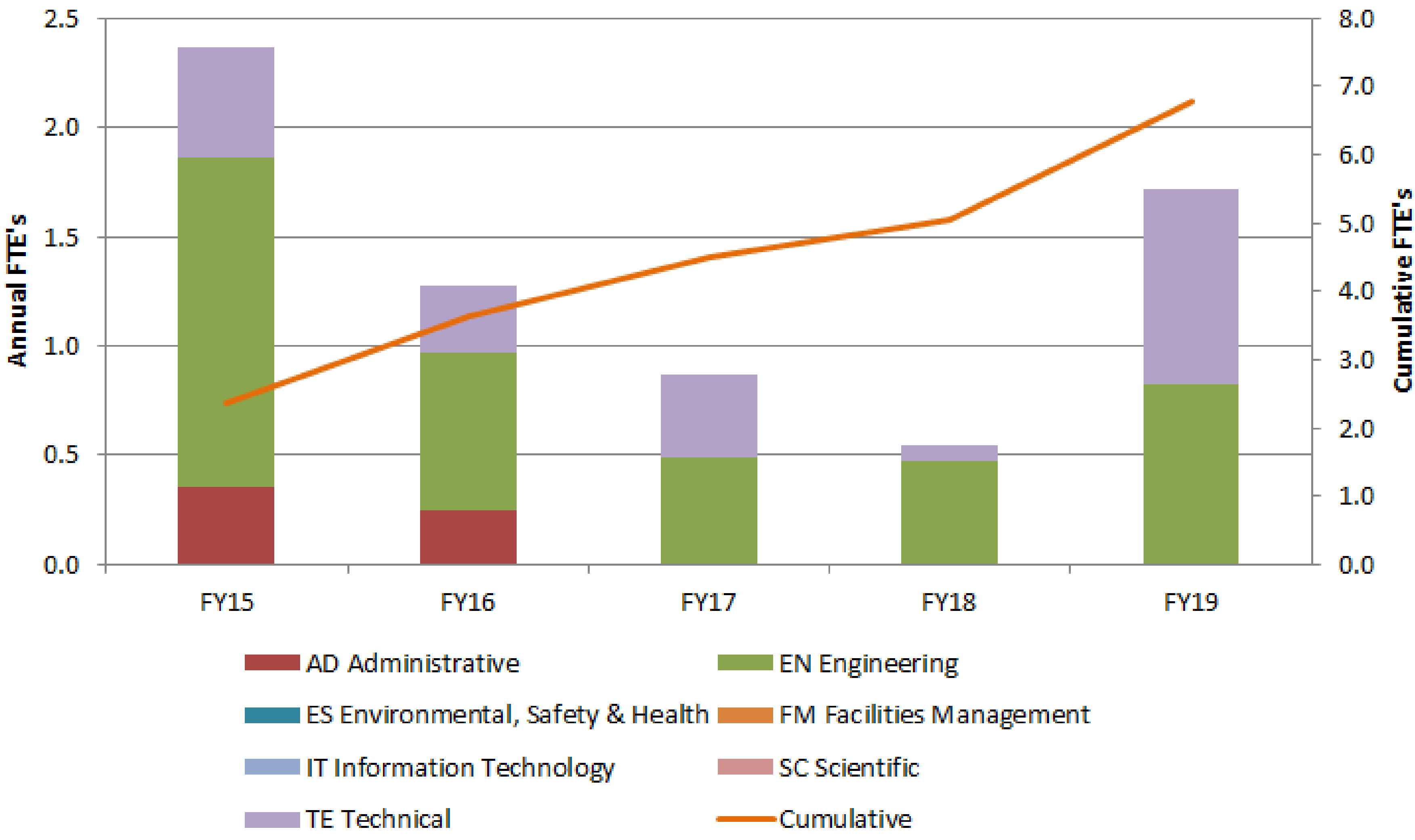
Cost Breakdown Labor vs Material



Quality of Estimate



Labor Resources by FY



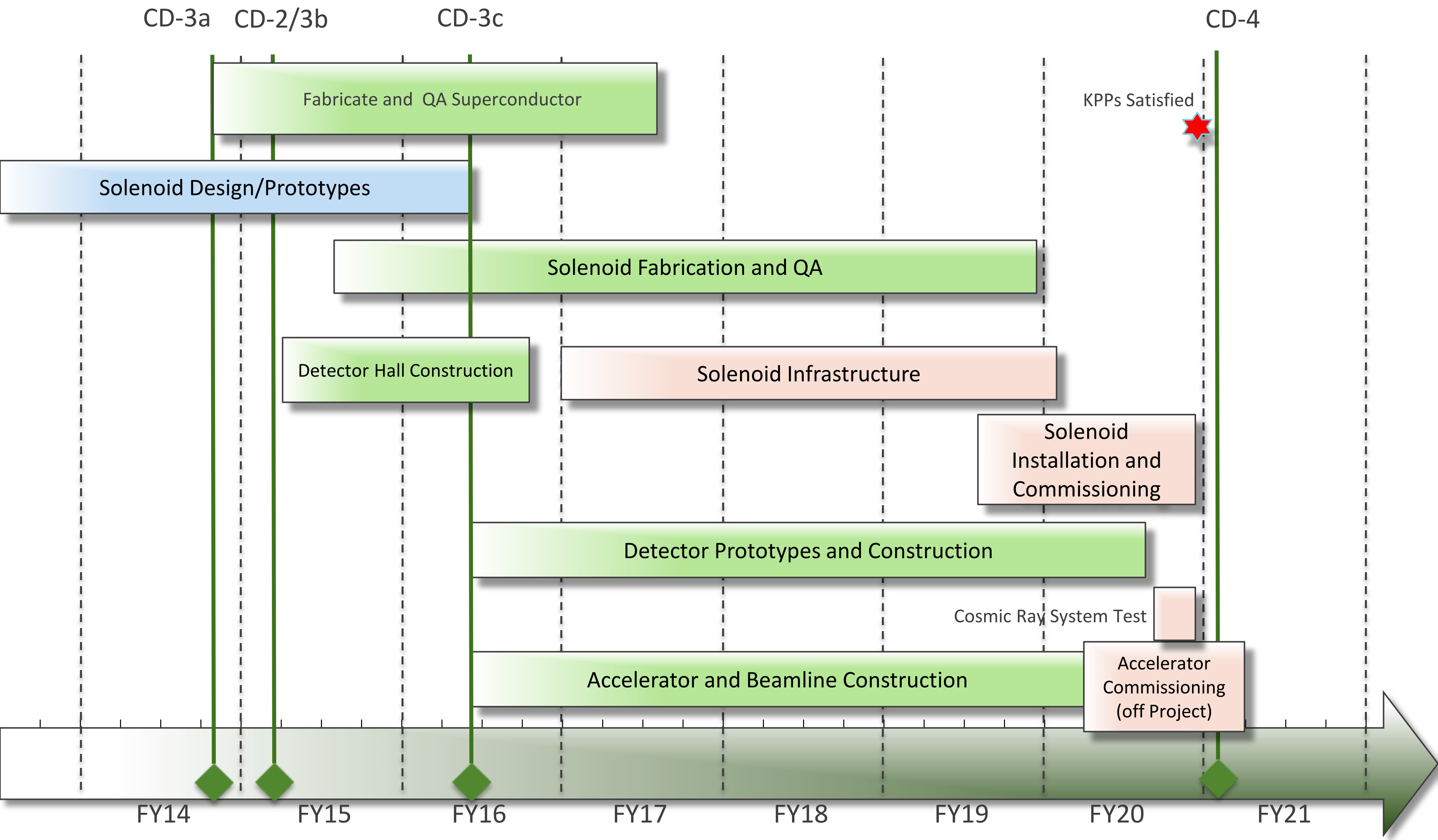
Cost Table

	Base Cost (AY k$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining costs)	% Contingency on ETC	Total Cost
475.04.04 Detector Solenoid	13,729	2,172	15,901	2,290	15%	18,191
Grand Total	13,729	2,172	15,901	2,290	15%	18,191

Milestones

- 10/27/14: PO issued for DS final design
- 7/2/15: Final design complete for DS support stand
- 2/24/16: DS construction authorized
- 4/5/19: Magnet arrives at FNAL

Schedule



CD-3a
CD-2/3b
CD-3c
CD-4
Fabricate and QA Superconductor
KPPs Satisfied
Solenoid Design/Prototypes
Solenoid Fabrication and QA
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Detector Prototypes and Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Summary

- A detailed set of requirements and specifications for the DS, including RDR, TDR, drawings, and solid model have been developed
- A vendor for the DS has been identified and the initial contract to develop the final design will be issued shortly
  - Cost and schedule for DS incorporates information provided by vendor
- Production quantity of DS cable is being fabricated
- DS is ready to move into the final design phase