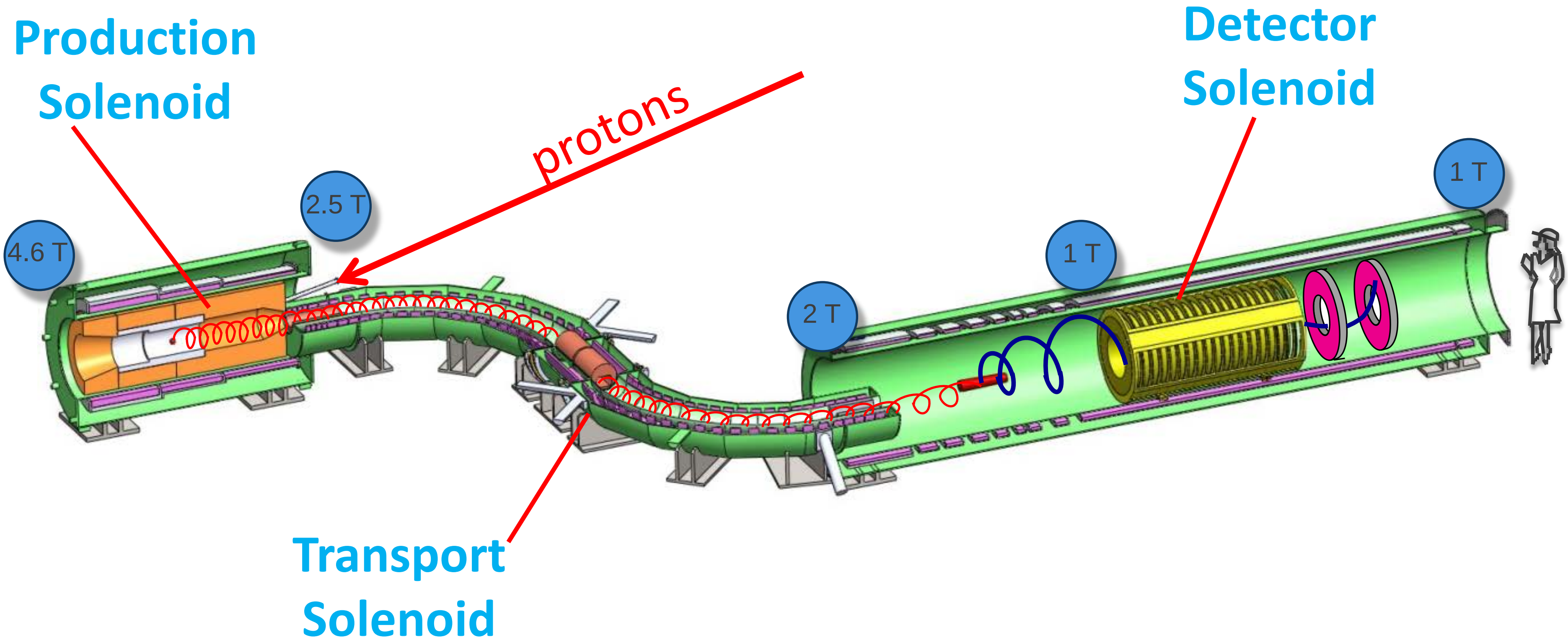
# 475.04 Solenoid System

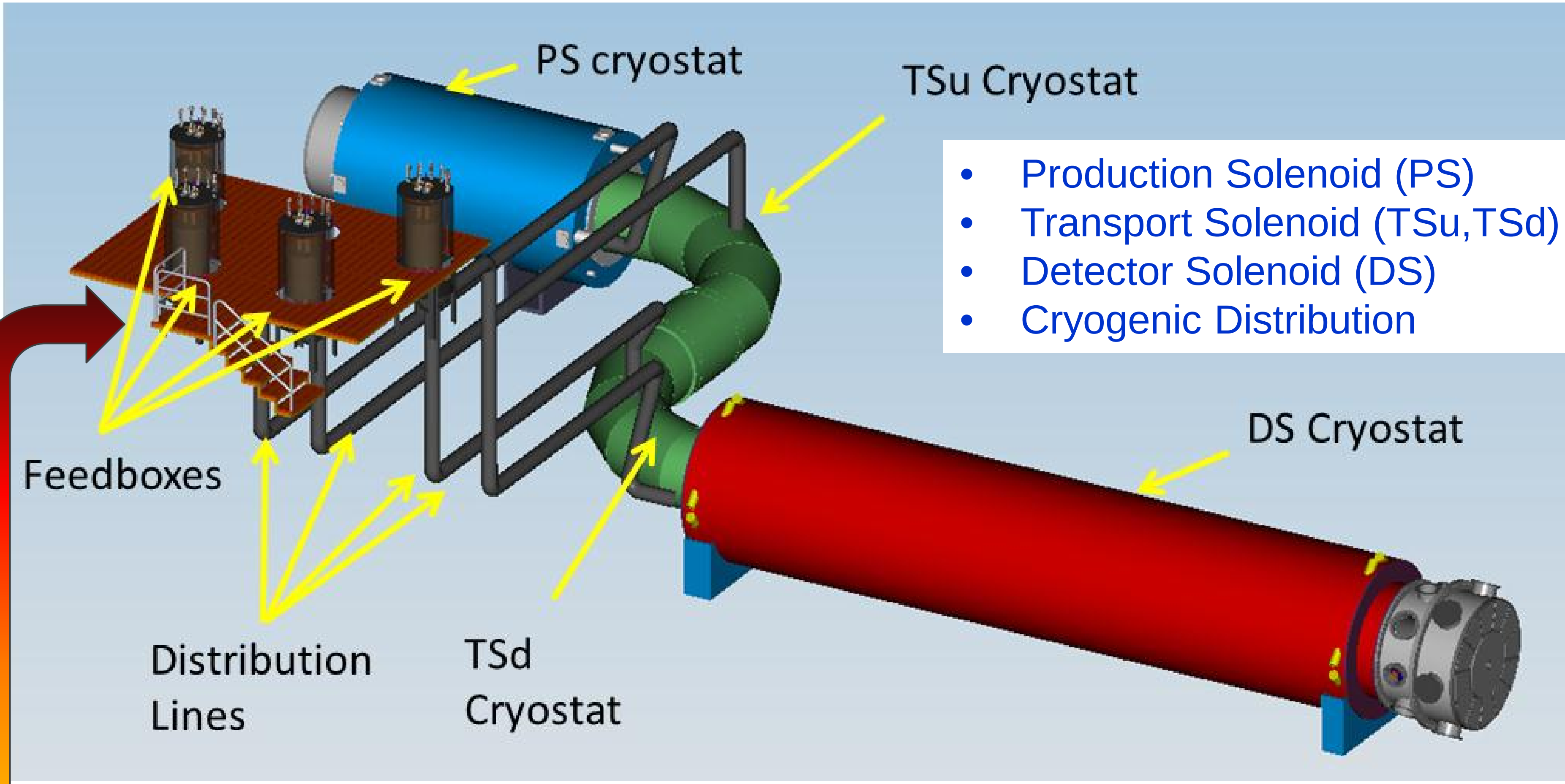
Michael Lamm
L2 for Solenoids
7/8/2014

# Mu2e Solenoid System

- Three solenoids, provide magnetic field for experiment



# Mu2e Solenoids Scope




- Production Solenoid (PS)
- Transport Solenoid (TSu,TSd)
- Detector Solenoid (DS)
- Cryogenic Distribution

- Cryo distribution box
- Power Supply/Quench Protection

- Field Mapping
- Ancillary Equipment
- Installation and commissioning

# Procurement Strategy

- **PS and DS will be built in industry**
  - Final engineering design done by industry based on detailed requirements and specifications and reference design
- **TS will be designed/built “in house”**
  - Cryostat, coil assemblies and mechanical supports built by outside vendors
  - Final assembly and test at Fermilab
- **Cryo Distribution components fabricated industry**
- **Recycle TeV HTS leads and Power converters**
- **Quench protection electronics purchased from industry whenever possible**

# Requirements Overview

There are several requirement's document covering L2 Solenoid deliverables.  They are all available on review web site.

- Production Solenoid  mu2e-docdb-945
- Transport Solenoid mu2e-docdb-947
- Detector Solenoid mu2e-docdb-946
- Cryo Distribution mu2e-docdb-1244
- Power Supply System mu2e-docdb-1237
- Quench Protection mu2e-docdb-1238
- Magnetic Field Mapping mu2e-docdb-1275

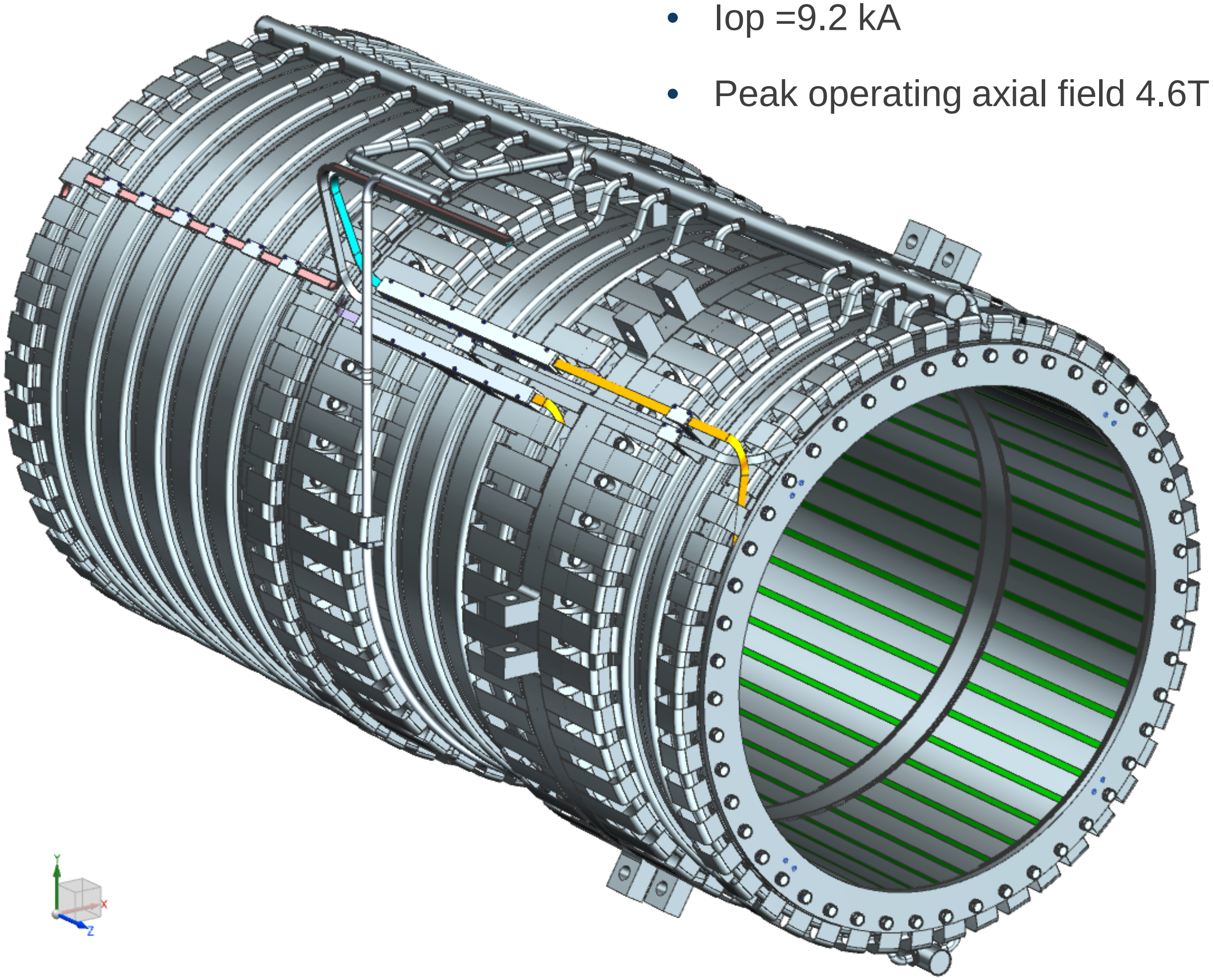
# General Solenoid Requirements

- Magnetic field requirements, described in the TDR and in supporting documents, are complex. Generally speaking field must meet the following:
  - Straight Sections
    - Negative monotonic axial gradient to prevent trapped particles. (potential source of backgrounds)
  - Toroidal Sections
    - Matched to central collimator geometry for muon momentum selection
- To verify that the solenoid system meets the field performance standards
  - Generate field maps within coil fabrication tolerances
  - Field Maps are vetted with collaboration for muon transmission, background generation and tracking efficiency and resolution

# Operational Requirements

- Reliable superconductor operation at full field life of experiment
  - Large temperature margin (>1.5K) and Jc margin (>30%) typical of detector solenoids and based on a recommendation from an early (May 2011) technical design review.
- Individual operation of magnets and cryostats
  - Cryostats cooled down and powered independently
  - Individual magnets do not rely on mechanical support of adjacent magnets
- Cryogenic operation
  - Liquid helium Indirect cooling
  - One Fermilab Satellite refrigerator for steady state operation
- Operation due to radiation damage
  - 7 MGy over life of solenoid.  (irreversible damage limit of epoxy)
  - Conductor and stabilizer to operate for 1 year at nominal beam intensity without loss of performance, can be repaired by room temperature anneal

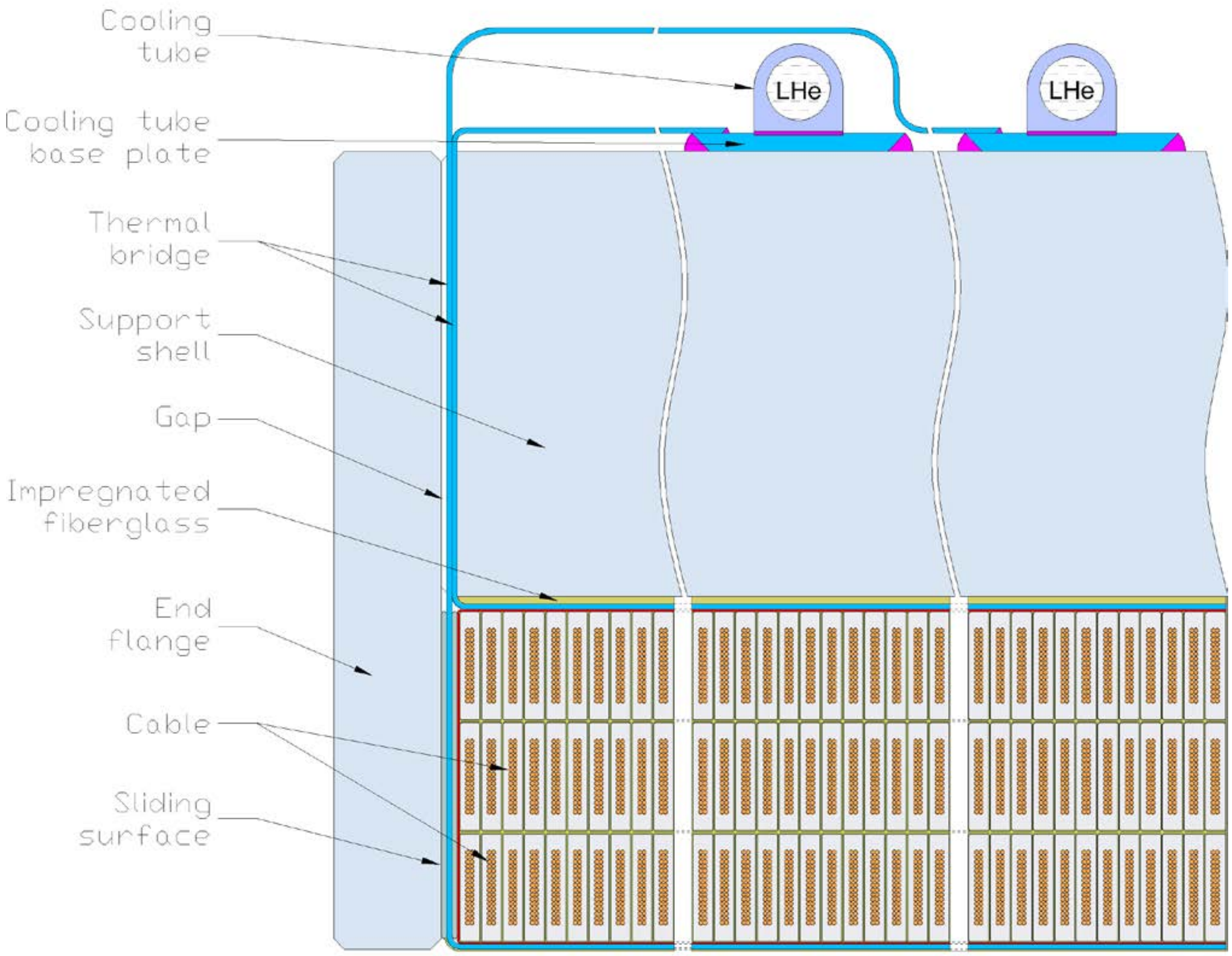
# Design: Production Solenoid (PS)



- 1.6 m aperture
- Iop =9.2 kA
- Peak operating axial field 4.6T

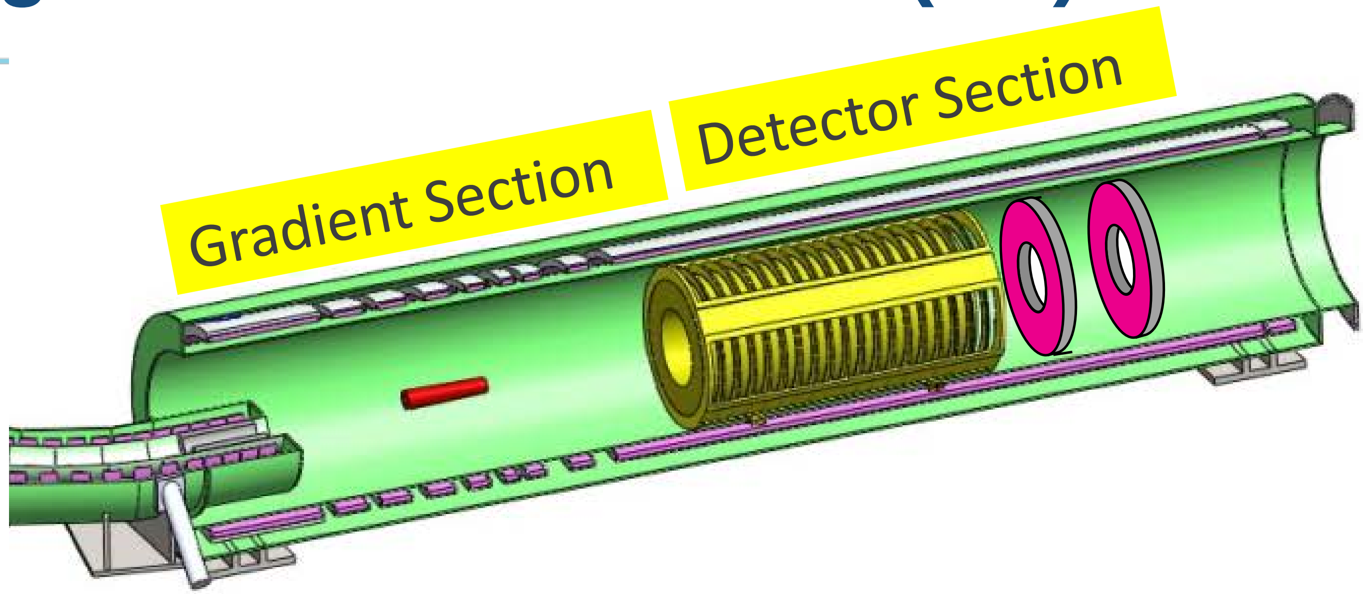
- PS consists of three coil modules with 3-2-2 layers of the same Al-stabilized cable wound in the “hard way”;
- Each module has an outer support structure made of Al 5083-O to manage the forces;
- The shells are bolted together to form a single cold mass assembly.
- The coil modules are installed inside of cryostat using axial and transverse supports.

# PS Coil Components



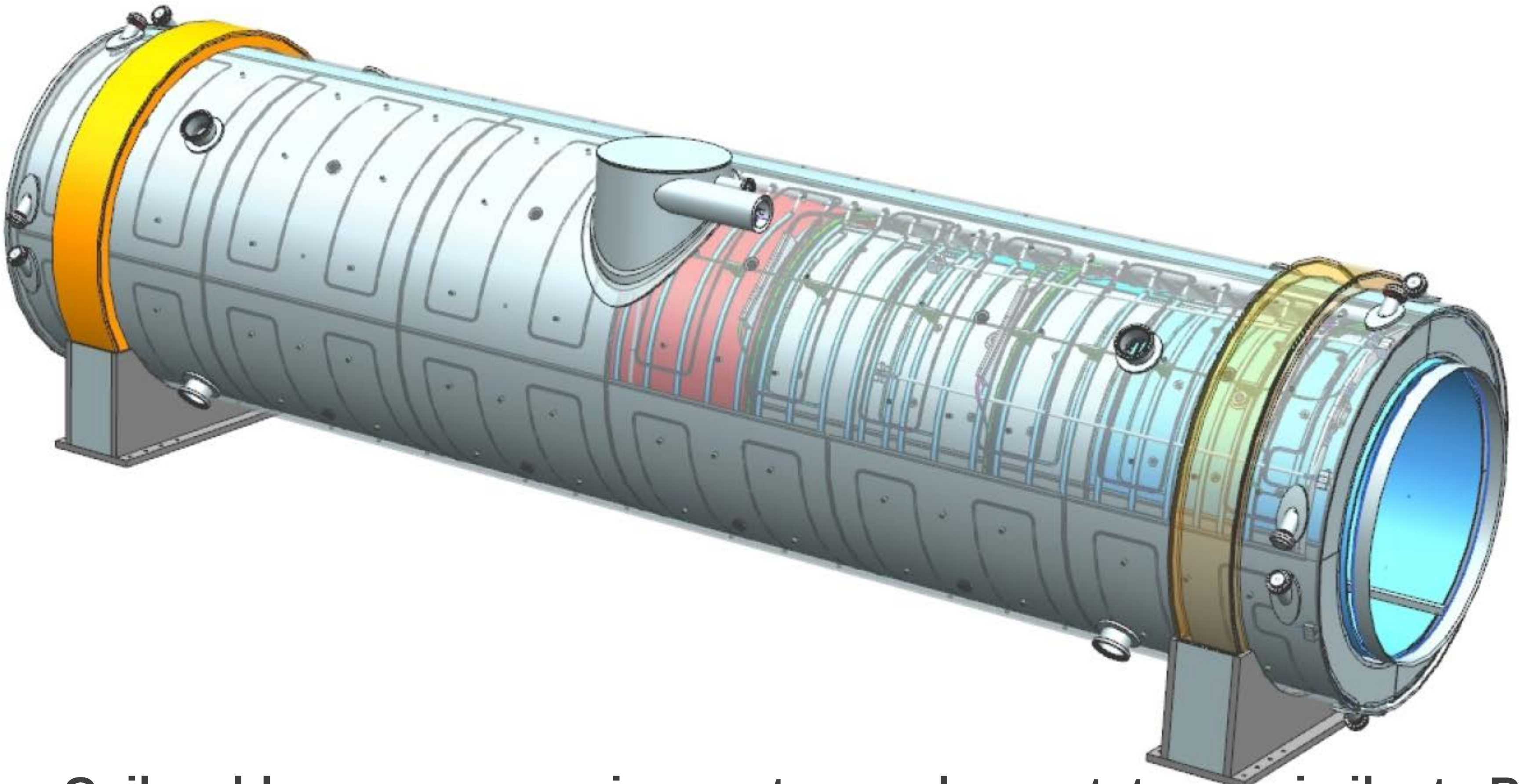

- Cables;
- Cable insulation;
- Ground insulation;
- Thermal bridges;
- Coil-shell buffer;
- Washer plates;
- Support shells;
- End flanges;
- Sliding layers;
- Cooling tubes.

# Design: Detector Solenoid (DS)



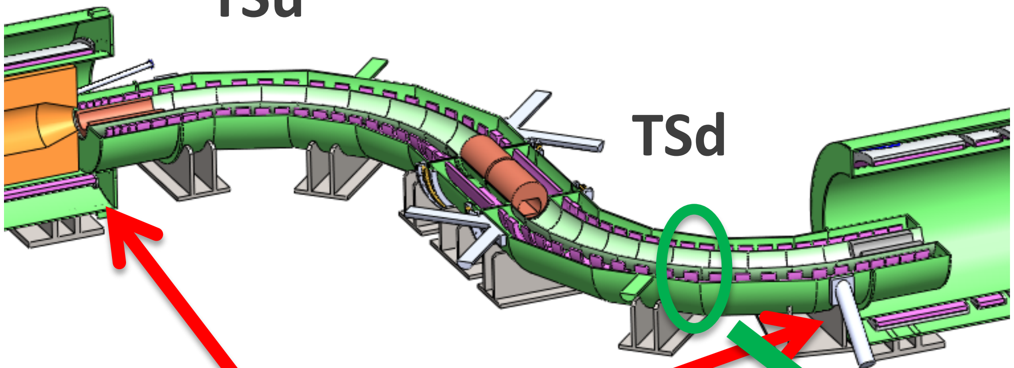

- 1.8 m Aperture    Operating Current ~6kA
- Gradient section 2T➔ I T field
- Spectrometer section 1 T field with small axial gradient superimposed to reduce backgrounds
- 11 Coils in total
  - Axial spacers in Gradient Section
  - Spectrometer section made  in 3 sections to simplify fabrication and reduce cost

# Solid Model of Detector Solenoid



- **Coil, coldmass, suspension system and cryostat very similar to PS**
  - Aluminum Stabilizer NbTi
  - Outer aluminum support structure
  - Coils units bolted together…

# Design: Transport Solenoids (TS)




Mechanical and Magnetic interface

with PS and DS

Once bolted together defines coils

placement➔magnetic field

Modules will be built in Industry

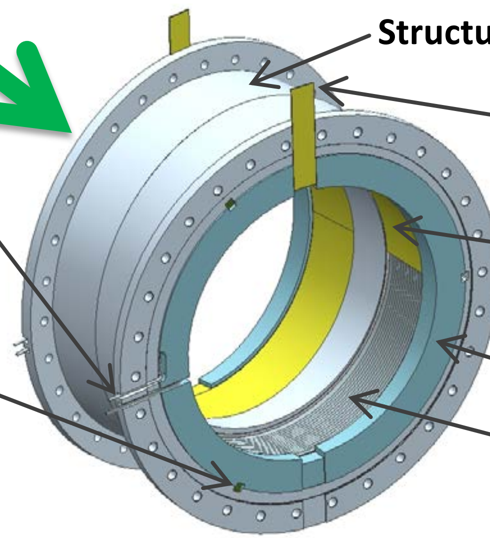
Two cryostats TSu and TSd

Separate cryogenic lines

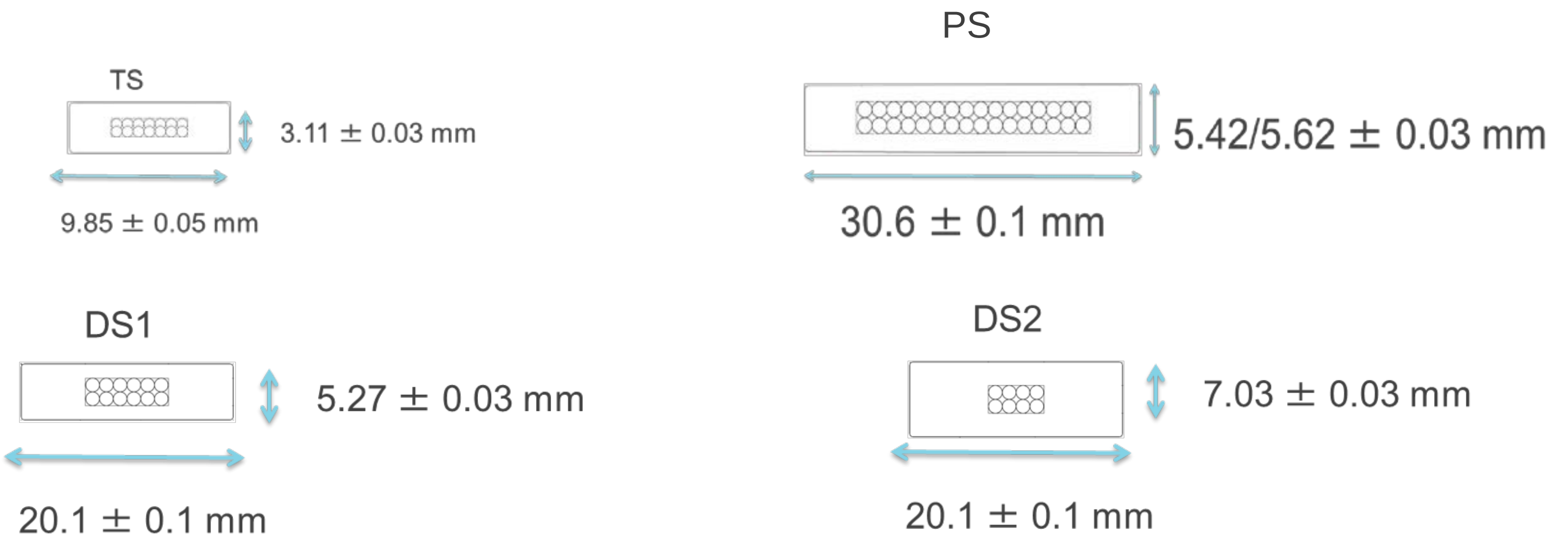
Separate power system

52 short solenoid coils

Typically 2 coils per module



# Design: PS/TS/DS1/DS2 Conductor




- **NbTi Rutherford cable with aluminum co-extruded stabilizer**
  - **SC content sized for Specific Magnet Requirement for Current and Temperature Margins**
  - **TS/DS: 99.998% aluminum for high electrical and thermal conductivity**
  - **PS, use special Ni Doped Aluminum Alloy developed for Atlas Central Solenoid, for high strength and high conductivity**
  - **~75 km of conductor required for project**

# Changes since CD-1

- Solenoid Designs have been stable since CD-1
  - Small change to DS coil pack geometry to introduce a small axial gradient to reduced backgrounds
- Incremental changes to Quench Protection, Power System, Cryogenics and Field Mapping
  - These will be detailed in our breakout sessions

# Value Engineering since CD-1

- Several Value Engineering changes prior to CD-1

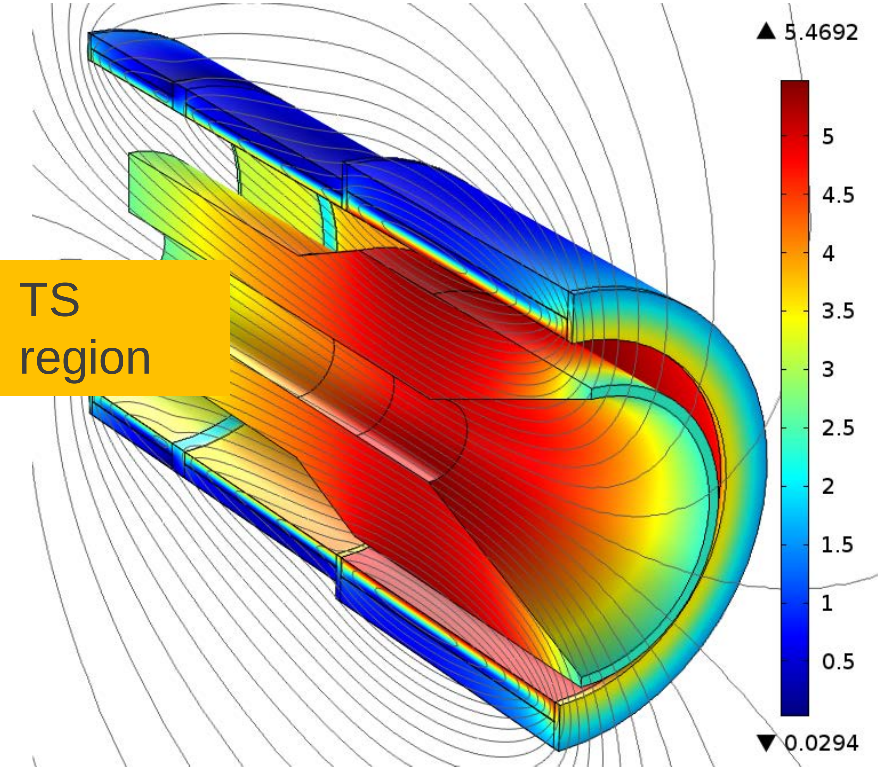
POST CD1:

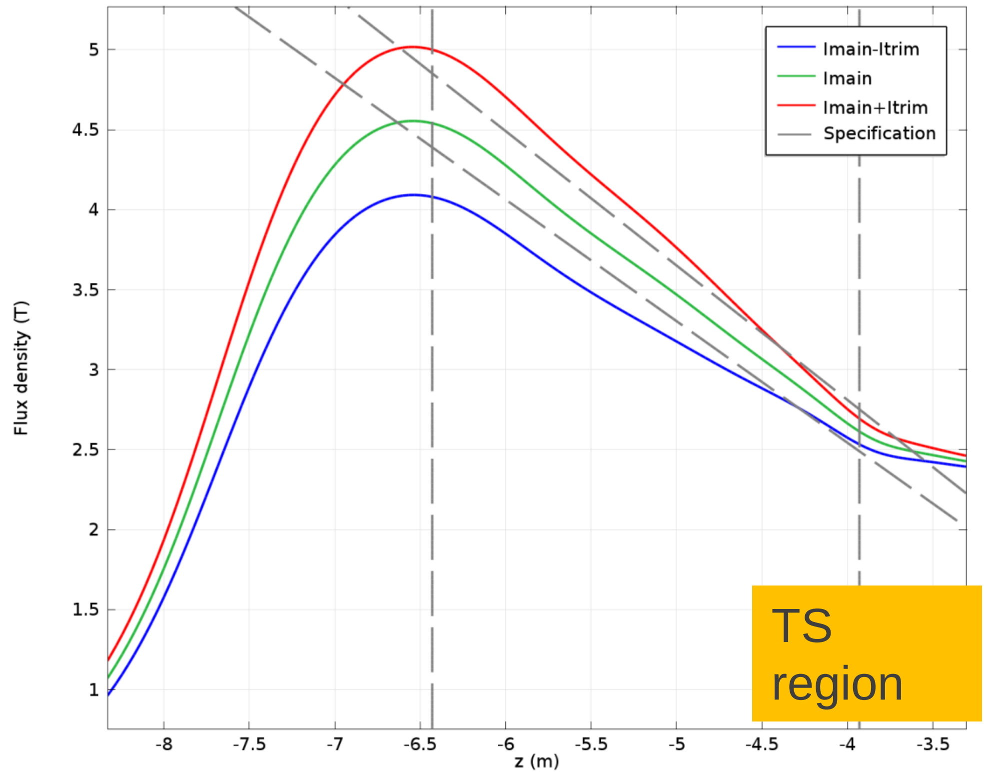
- Decision for DS to employ Thermal Siphon cooling is largely driven by value engineering (see next slide)
  - Allows for similar coil and feedbox fabrication & design
  - Allows vendors to fabricate both magnets with similar tooling
- We will recycle gently used Tevatron power supplies and extraction circuit components

# Downselects

- DS and TS cooling scheme decision
- Thermal Siphon (natural convection) vs. Forced Flow
  - Passive, no valves at magnet, no cryo pumps at feedbox **but**
  - Geometry dependent, must fill from bottom, exit from top and difficult to adjust once implemented
  - PS cooling scheme has always been thermal siphon
- Select Thermal Siphon for DS to simplify magnet and feed box fabrication. Distribution line carrying cryogens makes a small penetration through cosmic ray wall.
- Select Force Flow for TS because of the complex geometry of coils and support structure, and distribution line may have to be routed through experimental hall floor to accommodate shielding.

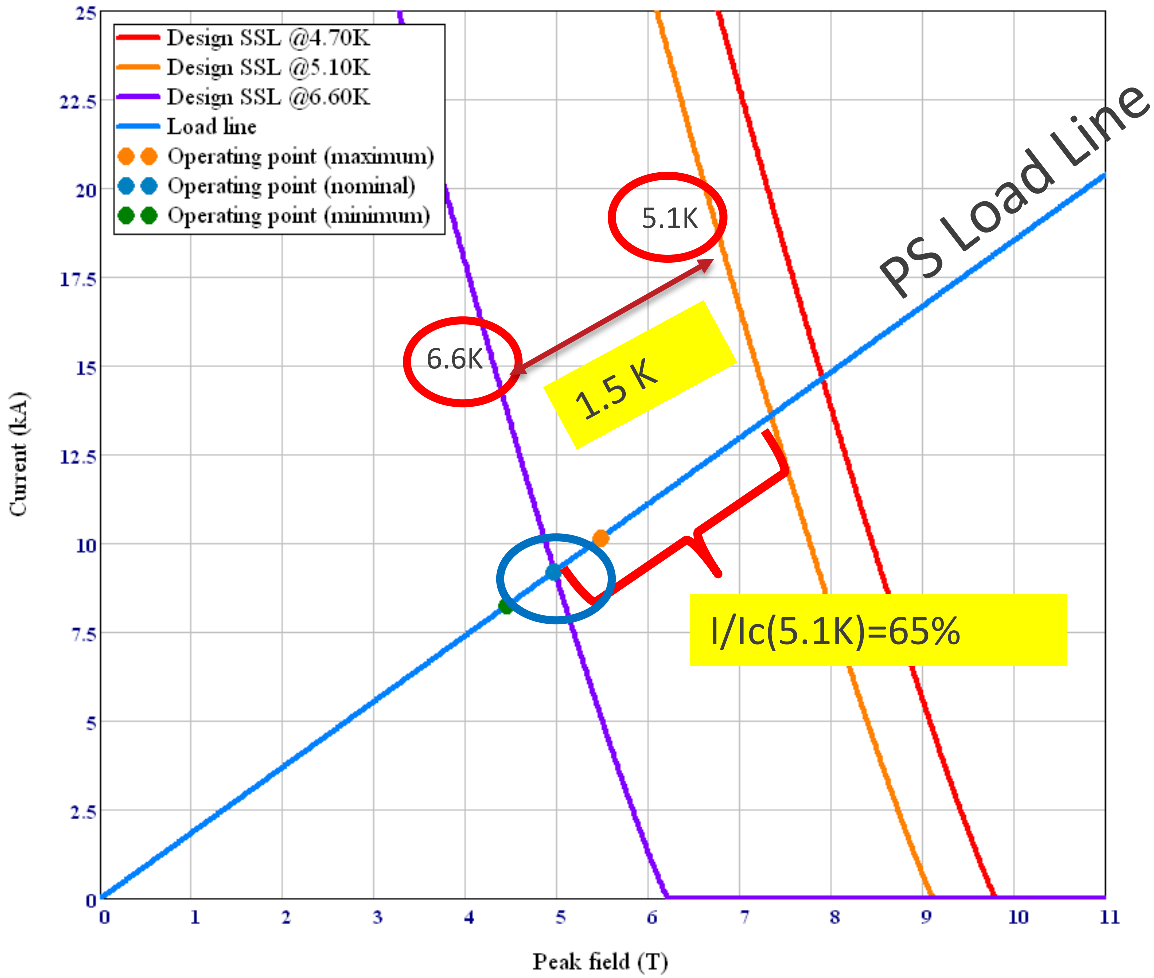
# Performance:  PS Magnetic field




- Center profile (right plot) is nominal field which meets specification (dashed lines)
- Different field profiles correspond to variation of the current by ±1 kA;
- Heat and Radiation Shield (left plot) is made of high-resistivity bronze (magnetic permeability of 1.04).

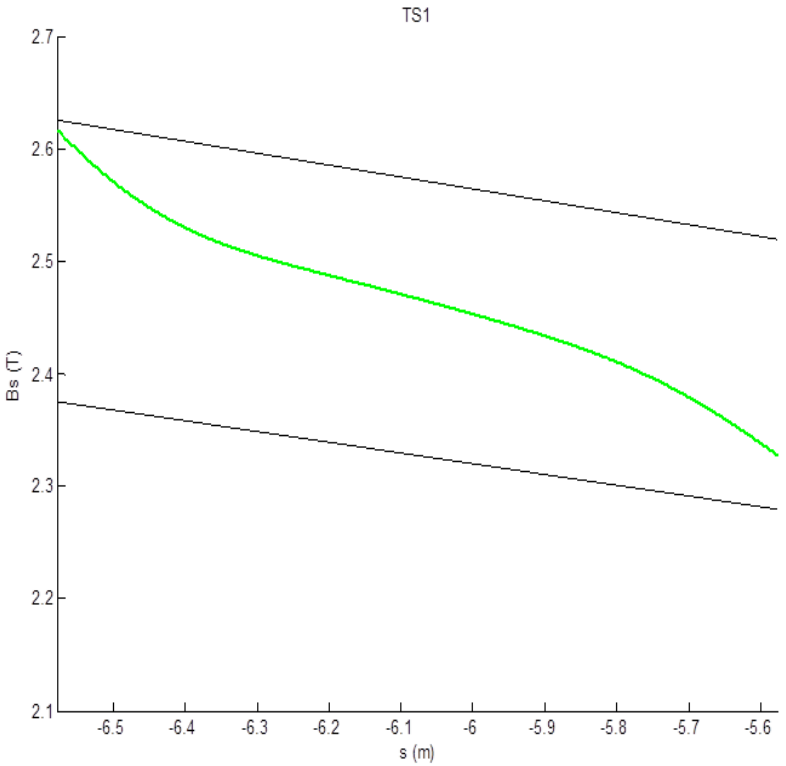
# PS Load line meets performance

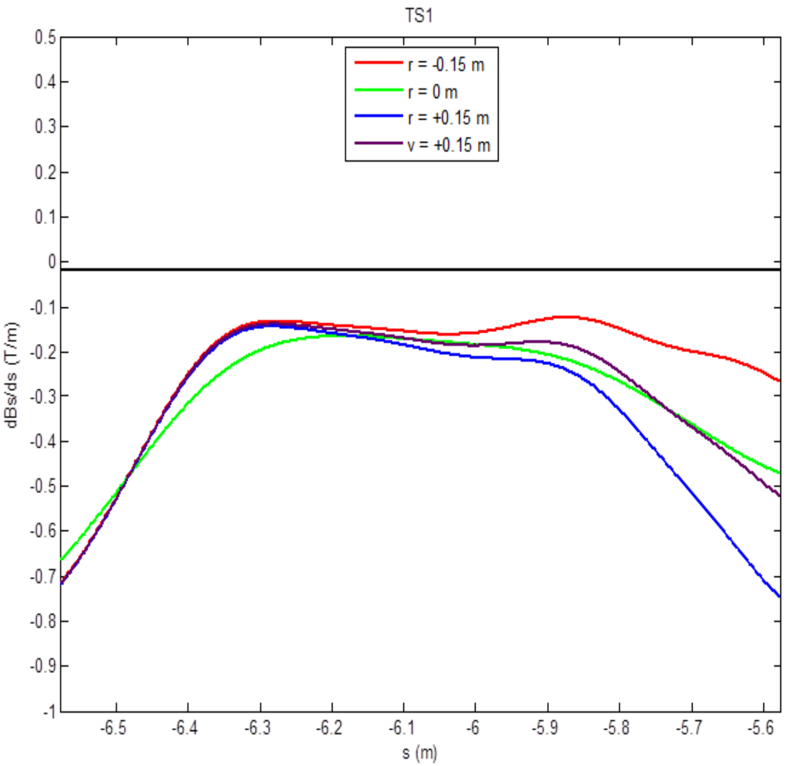



- Peak Coil temperature is 5.08K based on thermal analysis of PS coil with Heat and Radiation Shield
- From load line: 1.5 K thermal margin is maintained, Iop/Ic < 70% as required

# Performance TS Field Profile

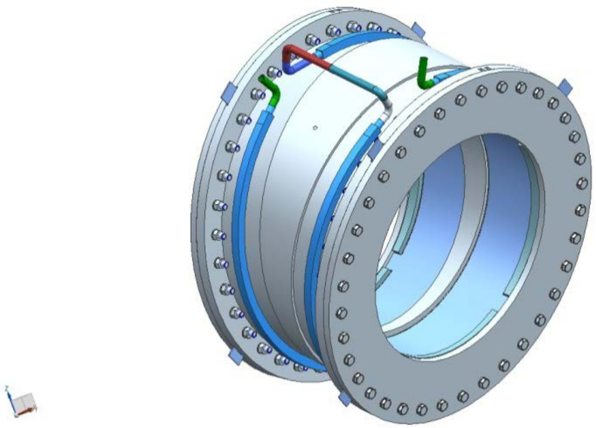
- Field specifications are complex
- Generally speaking require:
  - Negative axial gradients in straight sections to avoid trapped particles
  - Absolute fields within defined limits
- <u>Meets requirements</u>



# TS Prototype In Progress

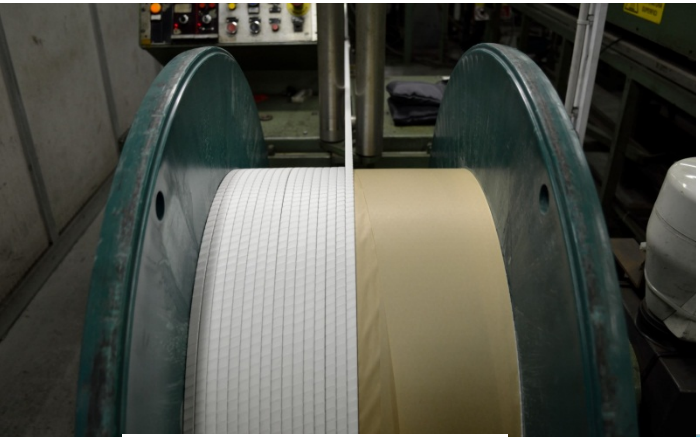
Scheduled completion: October 2014



Computer model of outer support cylinder

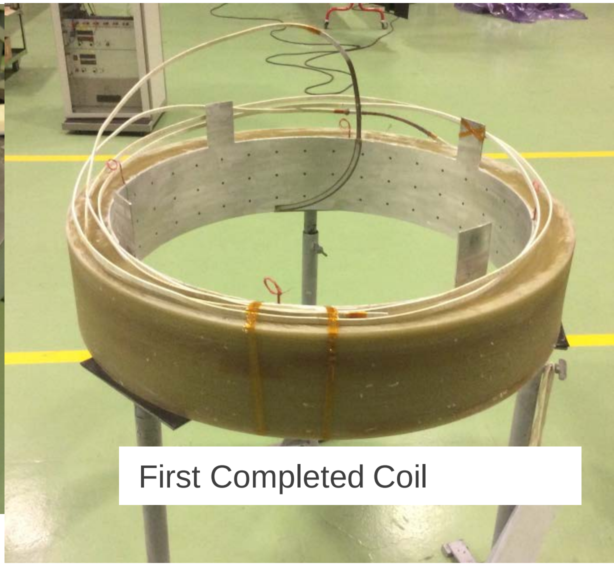
Outer support cylinder casting pre-machined

Machined shell ready for inspection



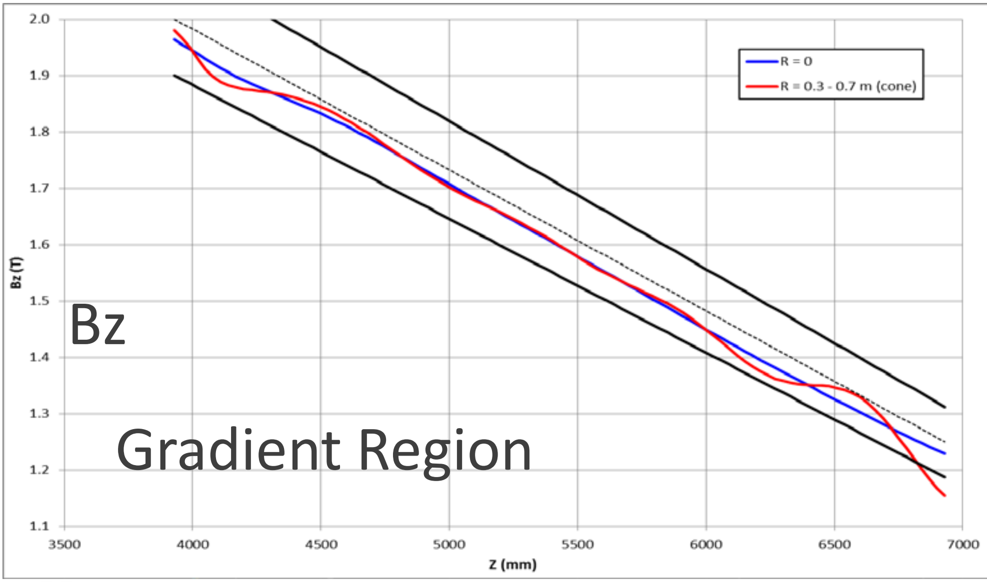
Cable Insulation

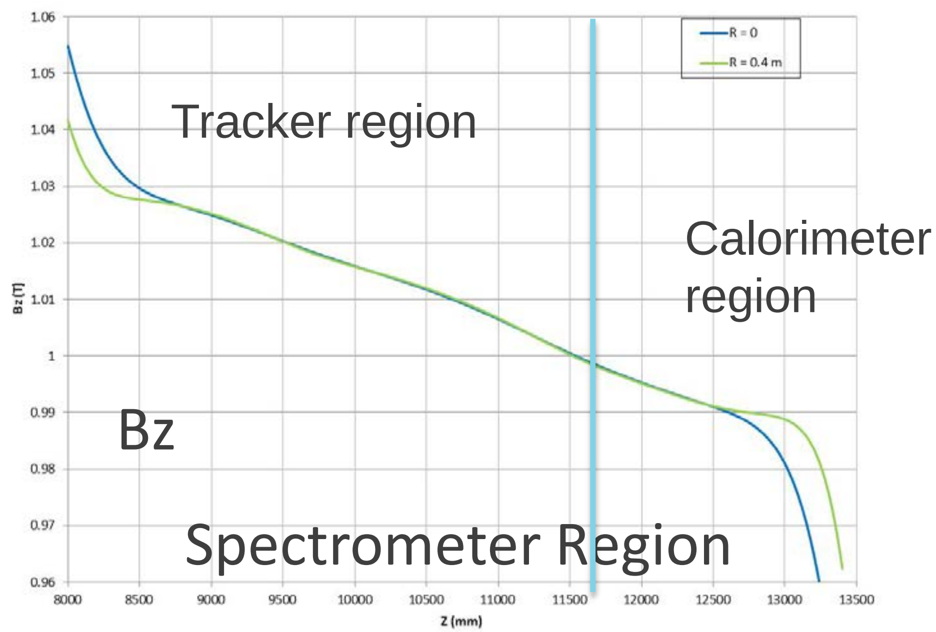

Assembly Mandrel



First Completed Coil

# Performance:  DS Magnetic Field




- Gradient Region: Black lines represent the limits for the field uniformity (dB/B) using the gradient of -0.25 T/m.

- Spectrometer Region: Field distribution in detector region for different radii.   Field is monotonically decreasing in tracker region for R≤ 0.4 m.

**Meets Requirements**

# Remaining work before CD-3

- Production and Detector Solenoid
  - We are very close to awarding contracts for final design.
  - Final design phase will last approximately 1 year.
- Transport Solenoid
  - Finish final design.
- Cryogenic Design
  - Complete final design of feedbox and cryo-distribution line
- Note: we recently completed a CD3a review for the Solenoid superconductor
  - DS orders have been placed
  - Waiting for DOE approval to place remaining orders
    - Approval expected on July 11th

# Solenoid Organization

**WBS 4 – Mu2e Solenoids**
Michael Lamm
Tom Page-Project Engineer

- **4.01 - Project Management**
  Michael Lamm
  Thomas Page – L2 Project Engineer
- **4.02 - Production Solenoid**
  Vadim Kashikhin
- **4.03 - Transport Solenoids**
  Mau Lopes
- **4.04 – Detector Solenoid**
  Marc Buehler
- **4.05 – Cryogenic Distribution**
  R. Schmitt
- **4.06- Magnet Power System**
  Steve Hays
- **4.07 - Magnet Quench Protection and Monitoring System**
  Darryl Orris
- **4.08 - Magnetic Field Mapping System**
  M. Tartaglia
- **4.09- Ancillary Equipment**
  (Tom Page)
- **4.10 - System Integration, Installation and Commissioning**
  Jeff Brandt

Vito Lombardo: Engineering oversight and coordination of superconductor acquisition and QA/QC

# Quality Assurance

We have completed the prototype phase of the superconductor. Embedded into the specifications are tests and hold points to assure that the conductors meet specifications. These principals have been built into the Procurement specifications for the large solenoids as outline below:

- QA Plan Essential Features
  - Traveler system
  - Testing embedded into fabrication process
    - Outline of test plan provided in Proc. Spec.
  - Hold points in fabrication at major milestones
  - Regularly scheduled meetings to discuss fabrication status/issues
  - Monthly EVMS-style reporting
  - Acceptance tests upon delivery at Fermilab
- Vendor was required to provide Preliminary QAP as part of bid package
  - QAP was one of the metrics for awarding contract.
- Vendor must provide full QAP at the end of “final design phase”
  - Including detailed test plan

# Risks

Solenoid risks are delineated in the Mu2e Risk Register (docdb 4320). Here are the most significant risks with mitigation:

- Sol-066: Critical Path delayed due to solenoid schedule delay
  - Close monitoring of vendors, QC built into schedule
- Sol-070: Interface problems with the solenoids
  - Close oversight/careful documentation of all interfaces
- Sol-080: Insufficient testing at the Vendor
  - Additional testing called out in procurement specs
- Sol-148: Solenoids must be installed through the PS hatch using a rented crane
  - Occurs if PS is delivered late. See Sol-066
- Sol-157: PS production conductor first article does not meet specifications
  - Close monitoring of vendor project, QC built into schedule

# ES&H Issues

- Cryogenic fluids
- Large Stored energy (~100MJ)
- High Currents (up to 10kA)
- Large voltages to ground during a quench (up to 600 V)
- ODH (liquid helium + LN2 for 80 K shields)
- Mechanical forces (>100 Tonnes of axial force between adjacent magnets, magnets are very heavy)
- Large volume vacuum systems (beam line + insulating)
- Stray Magnetic Fields (no return yoke)
- Access issues due to radiation from 8kW proton beam

**These hazards, common to Large Superconducting Magnet Systems, are discussed in the Mu2e Hazard Analysis document and Solenoid TDR chapter.**

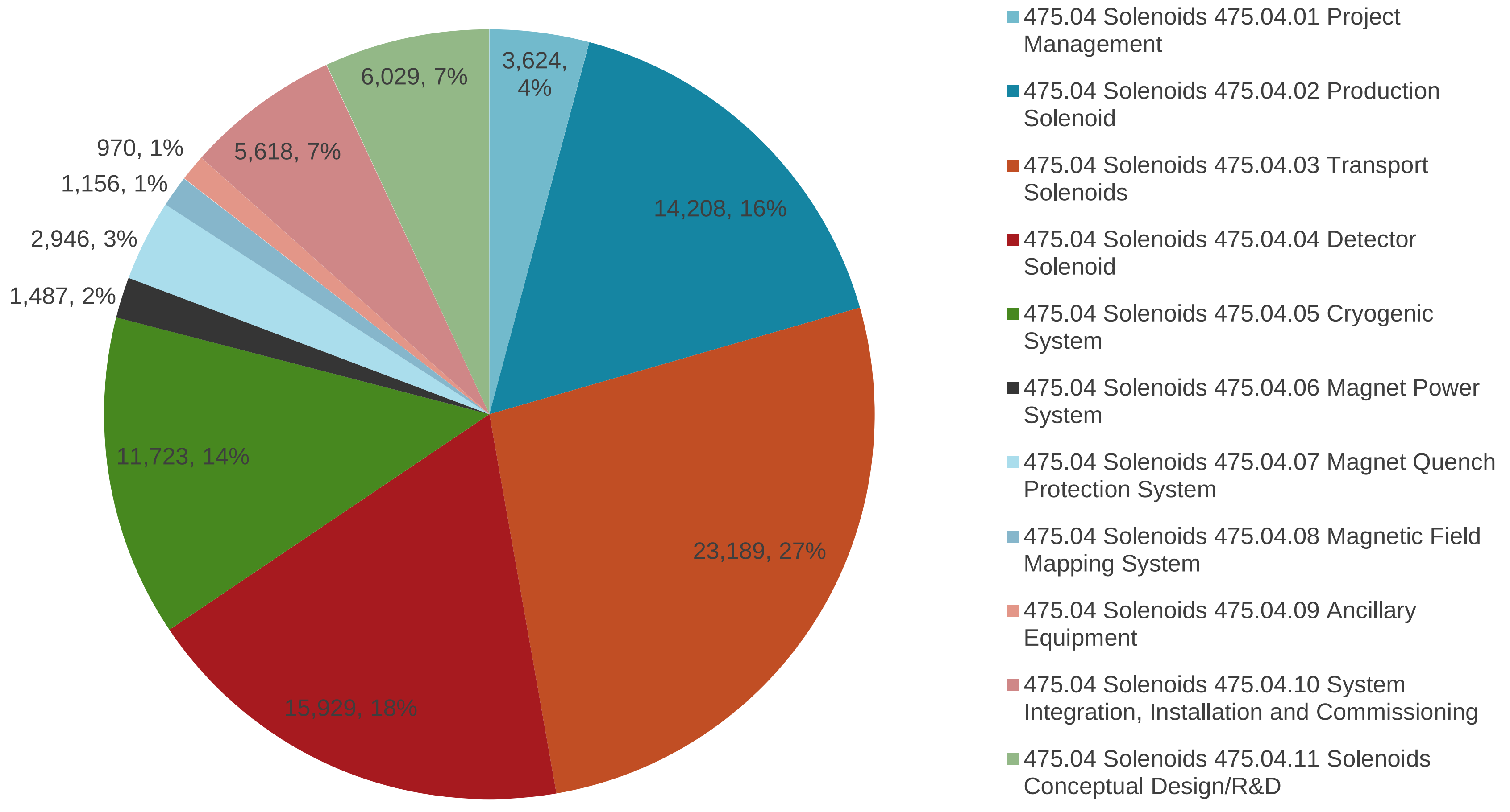
# Solenoid Costs by L3's

Base Cost AY k$

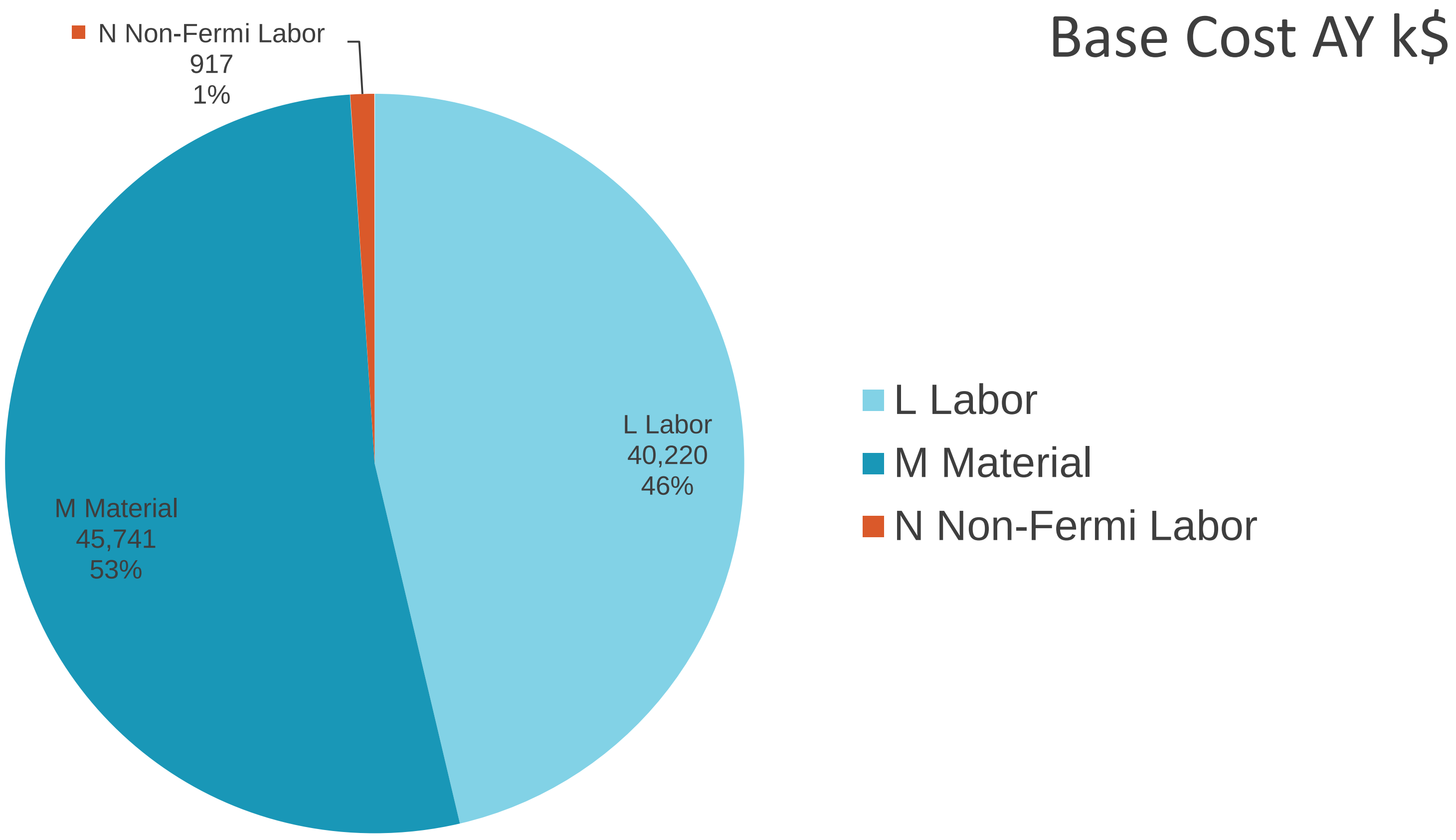
| | M&S | Labor | Base Cost | Estimate Uncertainty | % Contingency on ETC | Total |
|---|---|---|---|---|---|---|
| 475.04.01 Project Management | 632 | 2,992 | 3,624 | 533 | 21% | 4,158 |
| 475.04.02 Production Solenoid | 11,860 | 2,348 | 14,208 | 2,302 | 18% | 16,510 |
| 475.04.03 Transport Solenoids | 11,682 | 11,508 | 23,189 | 7,987 | 42% | 31,177 |
| 475.04.04 Detector Solenoid | 13,759 | 2,169 | 15,929 | 2,620 | 17% | 18,549 |
| 475.04.05 Cryogenic System | 5,165 | 6,558 | 11,723 | 4,122 | 38% | 15,844 |
| 475.04.06 Magnet Power System | 890 | 597 | 1,487 | 383 | 31% | 1,870 |
| 475.04.07 Magnet Quench Protection System | 726 | 2,220 | 2,946 | 1,055 | 41% | 4,001 |
| 475.04.08 Magnetic Field Mapping System | 430 | 726 | 1,156 | 501 | 44% | 1,657 |
| 475.04.09 Ancillary Equipment | 302 | 667 | 970 | 435 | 45% | 1,404 |
| 475.04.10 System Integration, Installation and Commissioning | 532 | 5,086 | 5,618 | 2,074 | 40% | 7,692 |
| 475.04.11 Solenoids Conceptual Design/R&D | 680 | 5,349 | 6,029 | 0 | | 6,029 |
| Risk Based Contingency | | | | 1196 | | 1,196 |
| Total | 46,658 | 40,220 | 86,878 | 23,208 | 32% | 110,086 |

# Cost Breakdown by L3

Base Cost AY k$

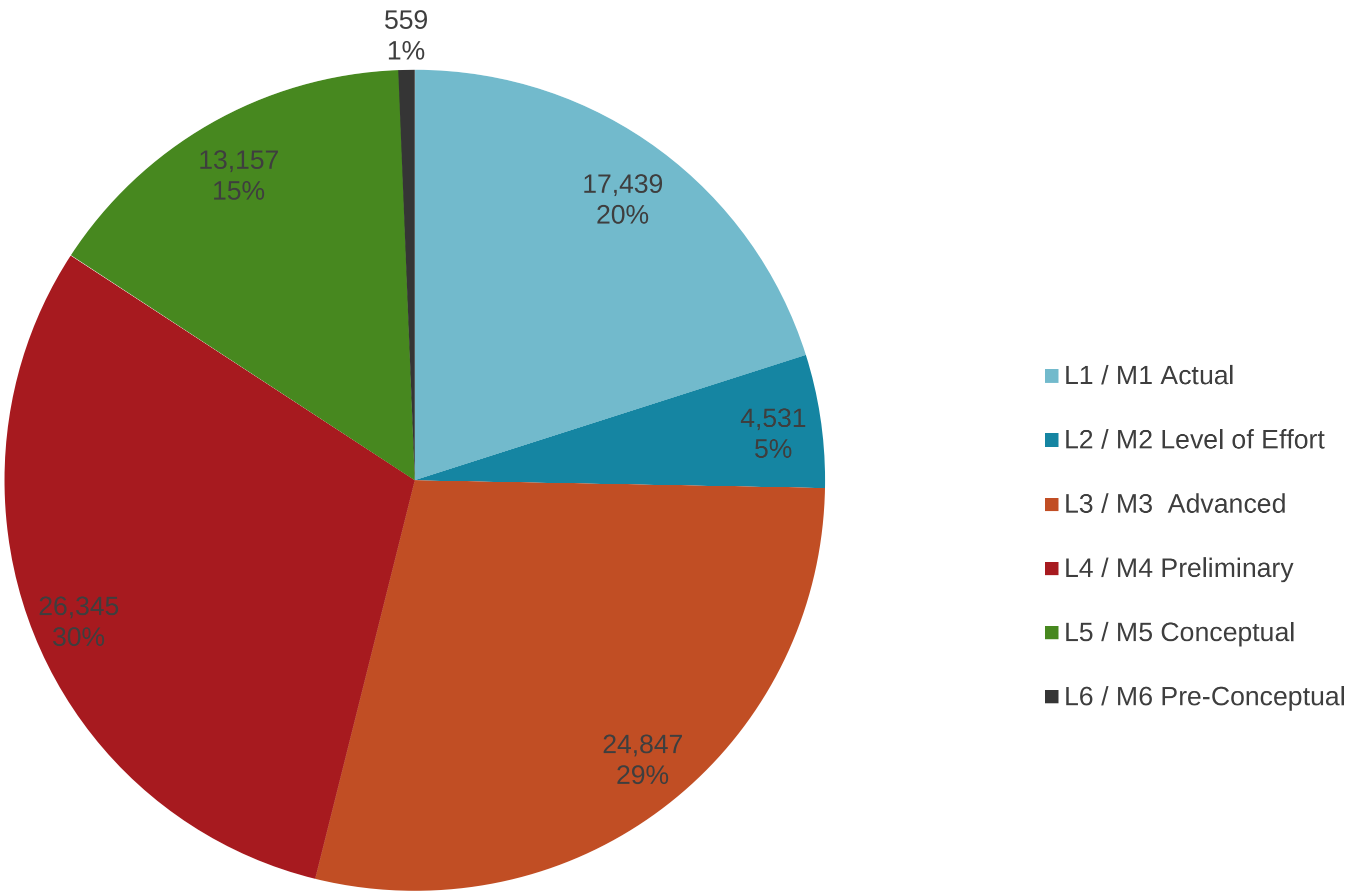


# Cost Breakdown Labor vs. Material

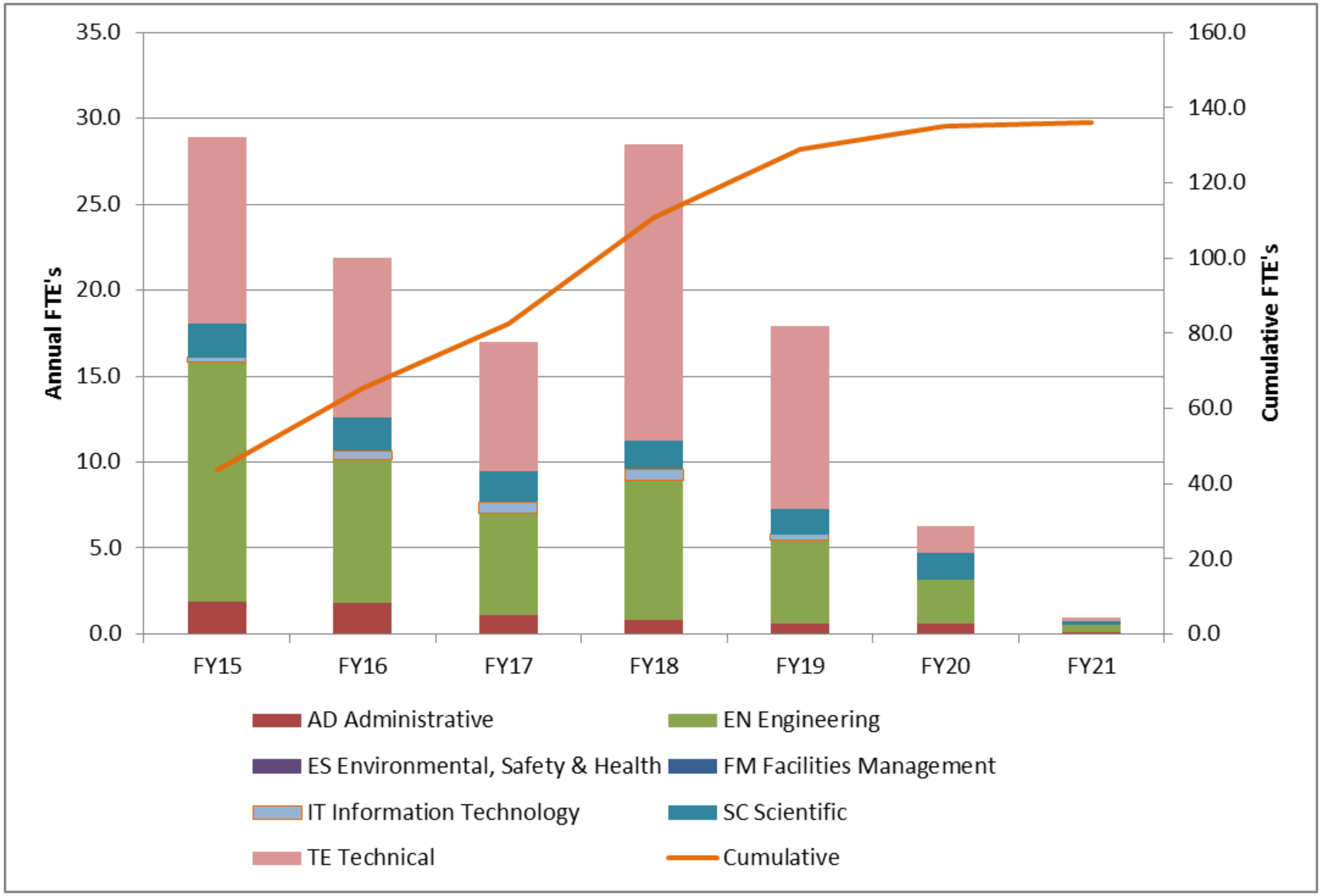


# Quality of Estimate

Base Cost AY k$



# Labor Resources by FY

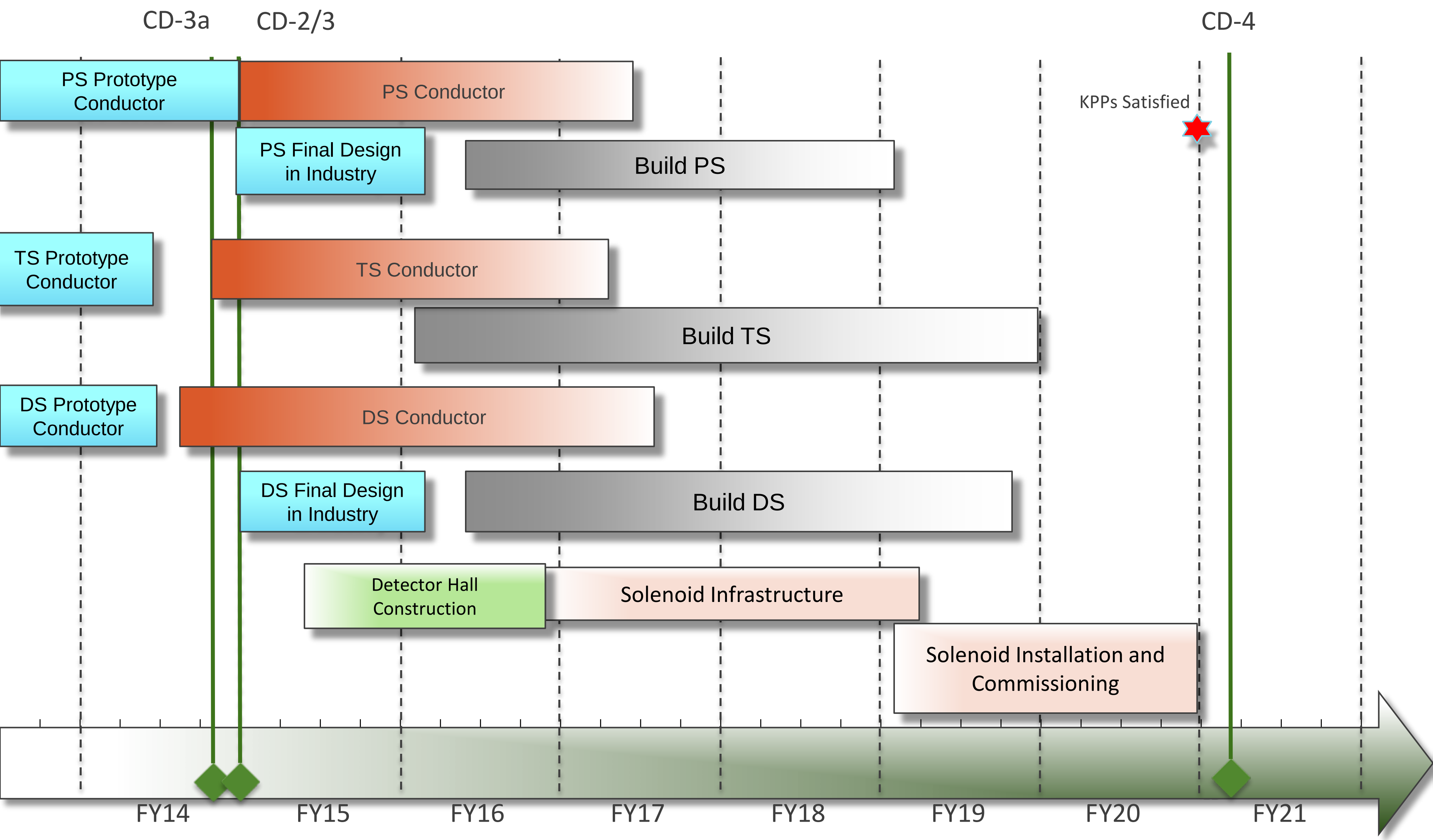


# Major Milestones

Complete set of Solenoid Milestones in Milestone Dictionary (Docdb-4301).

| Subproject | Activity ID | Milestone Name | Milestone Description | Milestone Tier | Milestone date |
|---|---|---|---|---|---|
| Solenoids | 47504.1.2.001105 | DOE Approval of CD-3a | Approval to order production lengths of conductor. | L3 | 6/24/2014 |
| Solenoids | 47504.2.051630 | Vendor for PS Final Design and Build selected | Vendor for PS Final Design and Build selected | L4 | 6/10/2014 |
| Solenoids | 47504.2.051890 | Production Solenoid ready for installation | Production Solenoid ready for installation. | L4 | 10/10/2018 |
| Solenoids | 47504.3.2.3.021450 | Vendor for module fabrication selected | Vendor for module fabrication selected | L4 | 2/25/2015 |
| Solenoids | 47504.3.2.3.021480 | TSu Modules Completed | TSu Modules Completed | L6 | 3/6/2017 |
| Solenoids | 47504.3.2.3.021488 | TSd Modules Completed | TSu Modules Completed | L6 | 1/17/2018 |
| Solenoids | 47504.3.4.1.001840 | TSu magnet ready for installation | Transport Solenoid (upstream) magnet ready for installation | L4 | 9/19/2018 |
| Solenoids | 47504.3.4.2.001630 | TSd magnet ready for installation | Transport Solenoid (downstream) magnet ready for installation | L4 | 9/6/2019 |
| Solenoids | 47504.4.051610 | Detector Solenoid magnet ready for installation | Detector Solenoid magnet ready for installation | L4 | 8/19/2019 |
| Solenoids | 47504.5.2.001336 | Vendor for Feed Boxes Fabrication selected | Vendor for Feed Boxes Fabrication selected | L6 | 8/9/2016 |
| Solenoids | 47504.10.000950 | Building ready for Solenoid installation | Mu2e Experimental Hall is complete and ready for installation of Mu2e solenoid system and | L5 | 5/2/2017 |
| Solenoids | 47504.10.002850 | Transfer line from Cryoplant to Mu2e Detector Building complete (by GPP) | Transfer line from Cryoplant to Mu2e Detector Building complete (by GPP) | L4 | 7/17/2017 |
| Solenoids | 47504.10.002900 | Cryoplant Operational (by GPP) | Cryoplant Operational (by GPP) | L4 | 7/17/2017 |
| Solenoids | 47504.10.005950 | Solenoid system installation complete and ready for cooldown | Solenoid system and supporting equipment is installed and magnets are ready to be cooled down | L2 | 3/5/2020 |
| Solenoids | 47504.10.006850 | On Project Solenoid Commissioning complete | Key Performance Parameter: Solenoid system has been cooled down and powered and demonstrated to run at nominal field strength. | L3 | 11/16/2020 |

# Solenoid Schedule



# Summary

- Solenoid Designs are well understood and meet requirements
- We are well along on the procurement of the major components of the Solenoids:
  – Have initiated long lead time conductor orders
    - DS production orders placed, TS and PS after CD3a approval
  – Final stages of selecting PS and DS vendor
  – On track to place orders for TS coil modules
- Cost and Schedule understood
- We believe we are ready for CD2 project baseline