475.04 Solenoid System

Michael Lamm
L2 for Solenoids
10/21/2014

Solenoid Team

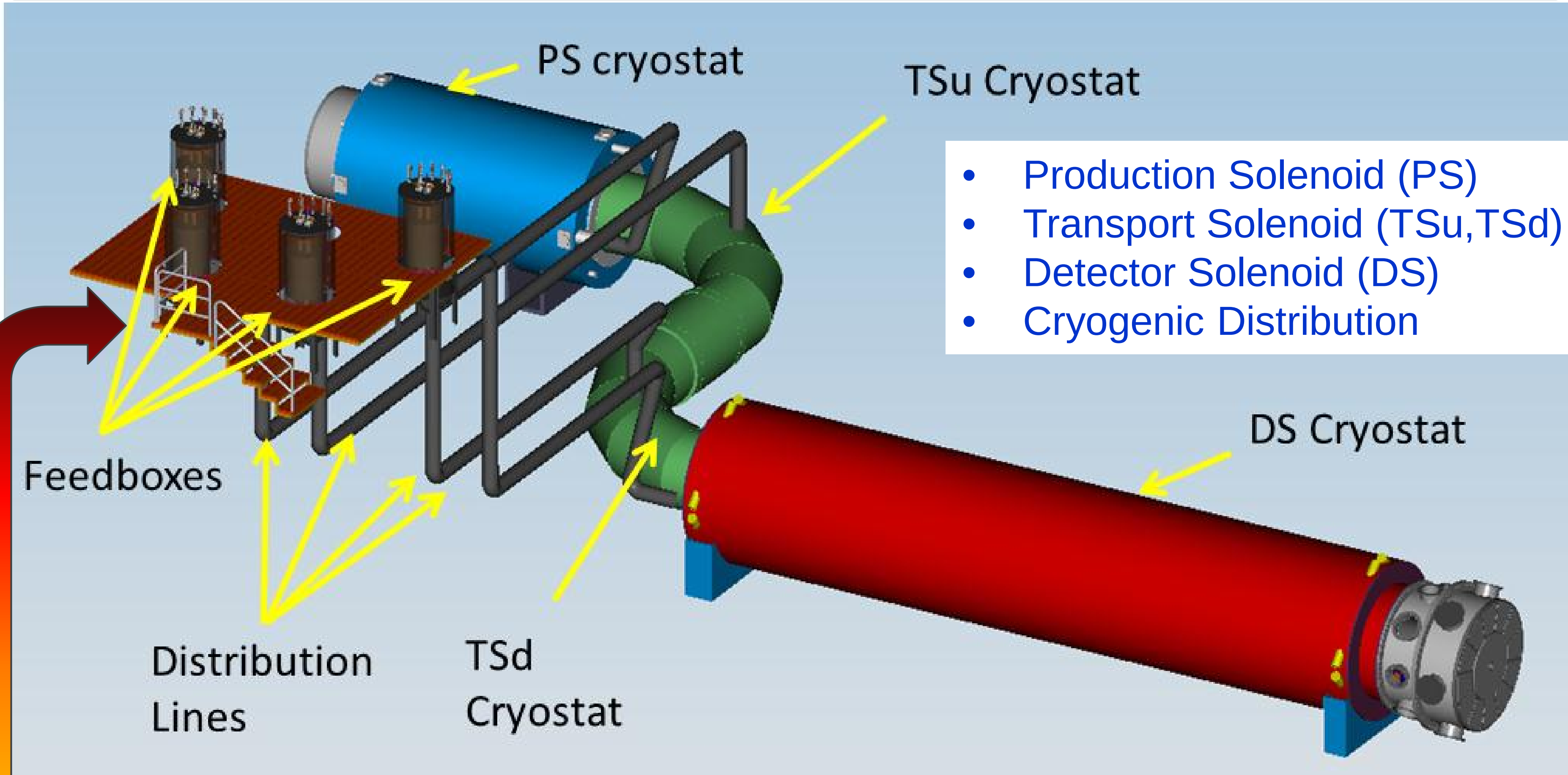
- Michael Lamm - L2 Manager
  - 25 years of experience in superconducting magnet technology. Management roles in several magnet projects including USLHC and LARP. Project manager for the Superfluid Vertical Magnet Test Facility.
  - Head of Magnet Department in Technical Division for 10 years where my job was to allocate resources and match skills to requirements
- Tom Page – Solenoid Project Engineer since January 2010
  - 15 years engineering experience in magnet technology
  - USLHC IR Quad cryostats, interconnects and integration
  - HINS Project Engineer: overall layout, power lead design, Radio Frequency Quad Procurement Oversight
- Strong local technical team on all phases of project; important collaboration with INFN Genova

Scope for Solenoids

Provide integrated magnetic system for Mu2e experiment included required support infrastructure and interfaces to the Muon Campus. Primary Deliverables:

- **Three superconducting solenoids**
  - Production Solenoid
  - Transport Solenoid
  - Detector Solenoid
- **…and support infrastructure**
  - Cryogenic Distribution System
  - Power Supply System along with magnet controls and monitoring
  - Magnetic Field Mapping System
  - Installation and Commissioning of these deliverables

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 is being built in industry**
  - Final engineering design done by industry based on detailed requirements and specifications and reference design.
  - Contract awarded after competitive bid process
    - Award based on “best value”, price only one element
  - QA/QC including travelers, cold test at Vendor and final acceptance at Fermilab
- **TS is being designed/built “in house”**
  - Cryostat, coil module assemblies and mechanical supports built by outside vendors
  - Final assembly and test at Fermilab
- **Cryo Distribution components fabricated in industry**
  - Final design Fermilab
- **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.

- Science Driven Requirements mu2e-docdb-4381
- 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

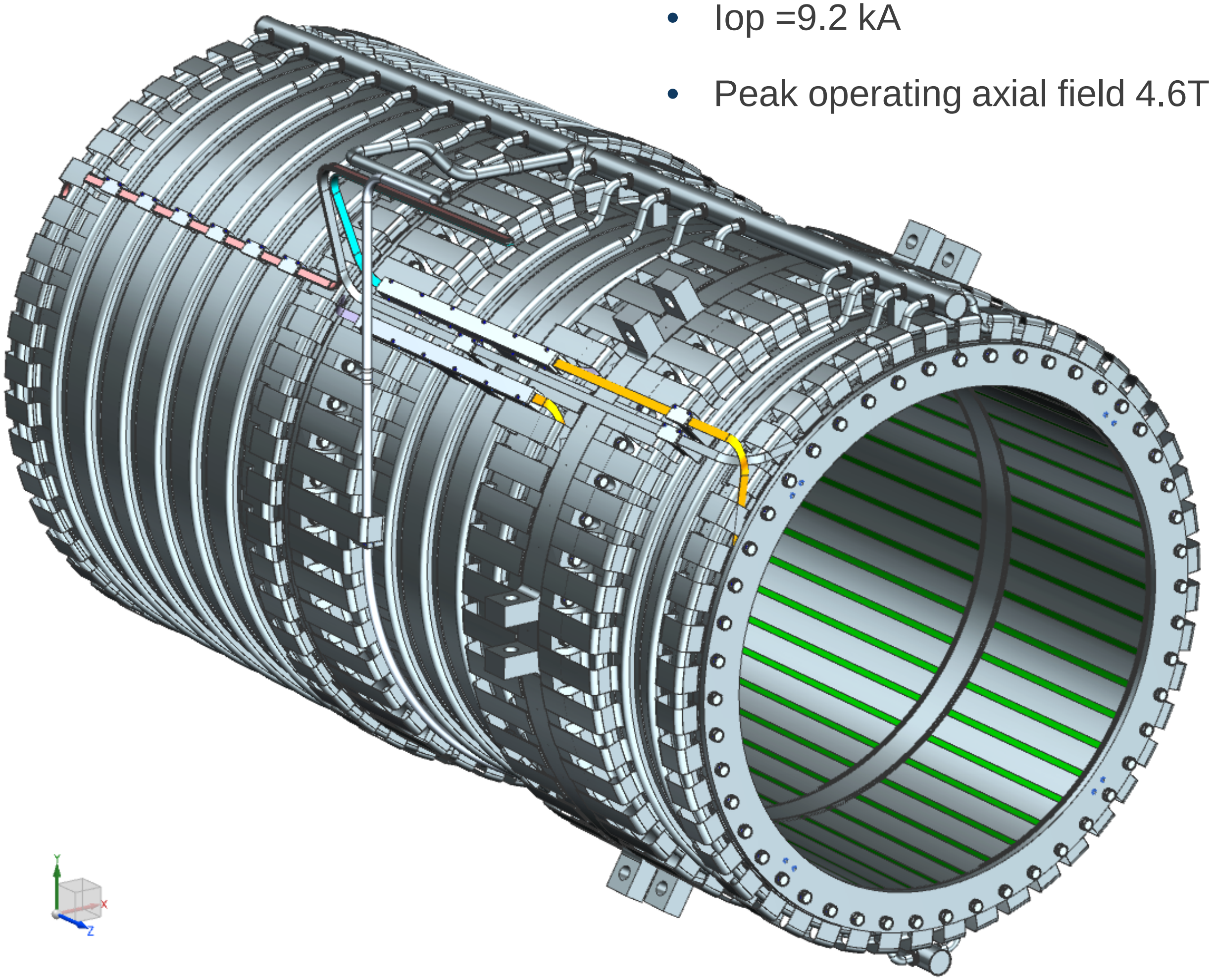
- Magnetic field requirements, described in the TDR and in supporting documents, are complex. Generally speaking field must meet the following:
  - Straight Sections
    - Negative monotonic axial gradient to prevent trapped particles. (potential source of backgrounds)
  - Toroidal Sections
    - Matched 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

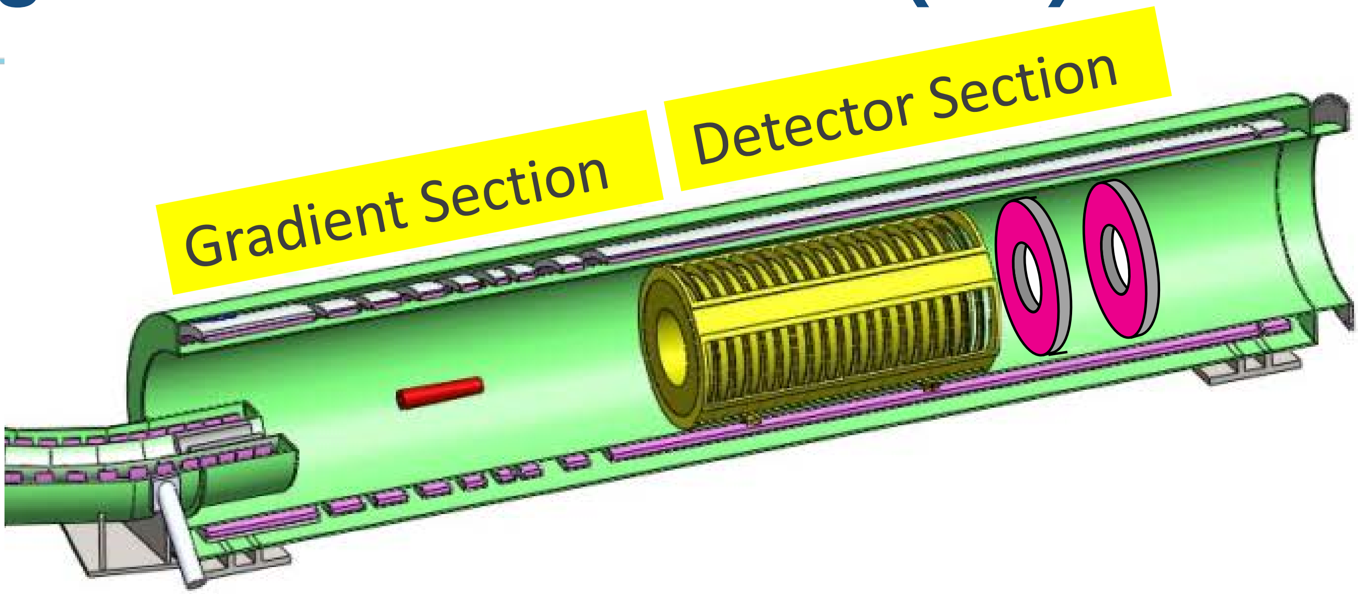
Design: Production Solenoid (PS)

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



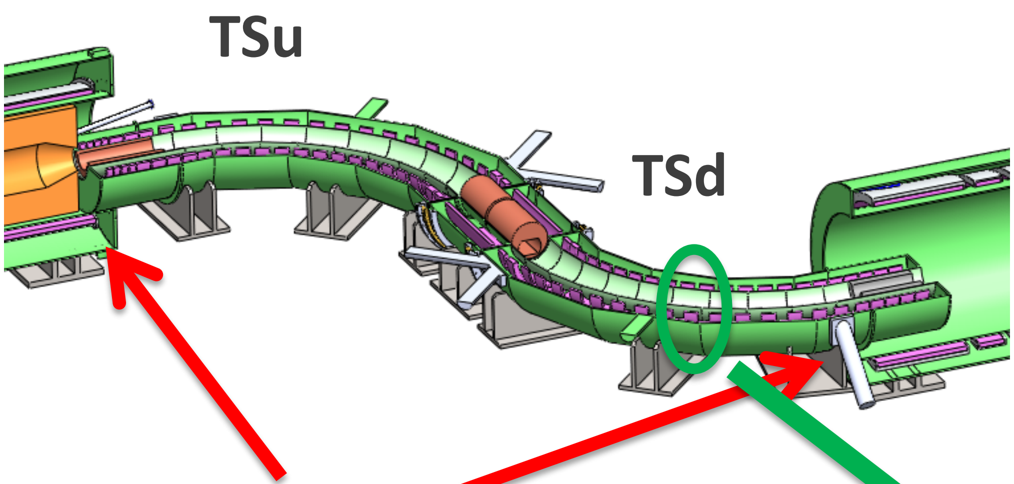
- PS consists of three coil modules with 3-2-2 layers of the same Al-stabilized cable wound in the "hard way";
- Each module has an outer support structure made of Al 5083-O to manage the forces;
- The shells are bolted together to form a single cold mass assembly.
- The coil modules are installed inside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

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
- **Fabrication technology similar to PS**

Design: Transport Solenoids (TS)



Two cryostats TSu and TSd

Separate cryogenic lines

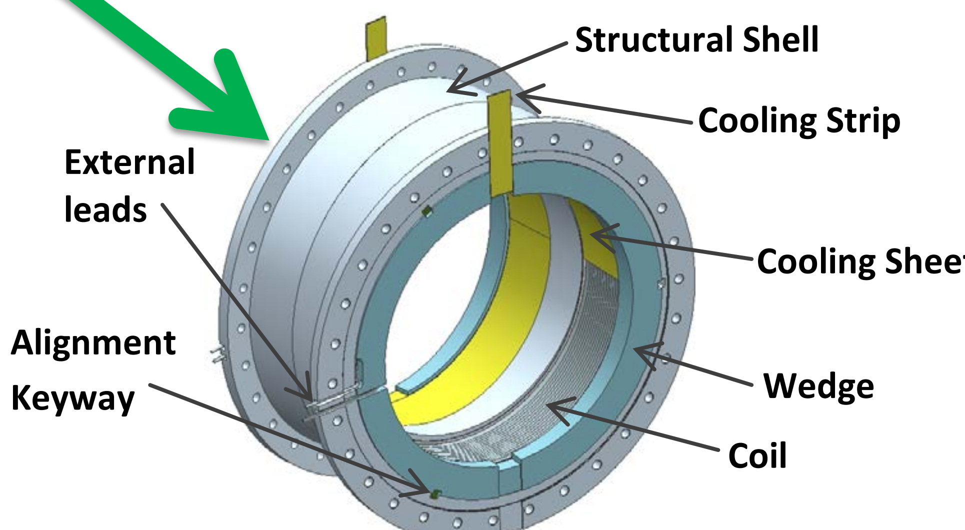
Separate power system

52 short solenoid coils
Typically 2 coils per module

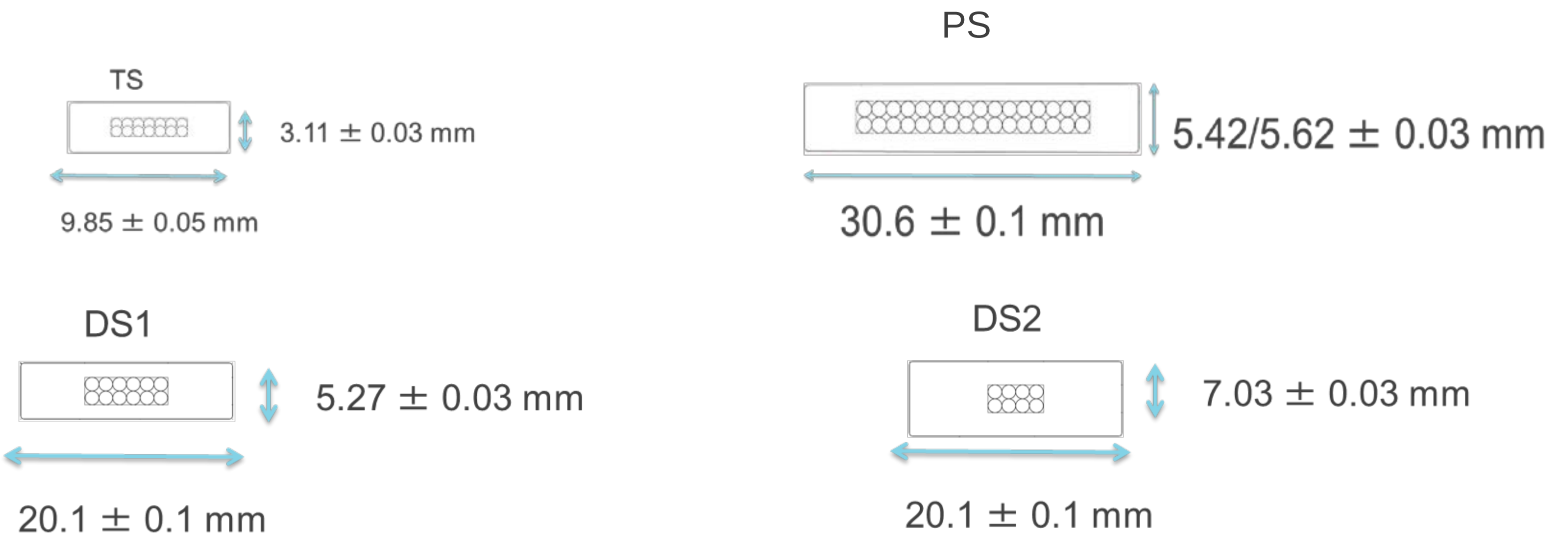
Mechanical and Magnetic interface
with PS and DS

Once bolted together defines coils
placement➔magnetic field

Modules will be built in Industry



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
- **Prototype conductor program successfully completed, production program in progress**

Improvements 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
  – Decision about cooling scheme for TS and DS
- 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

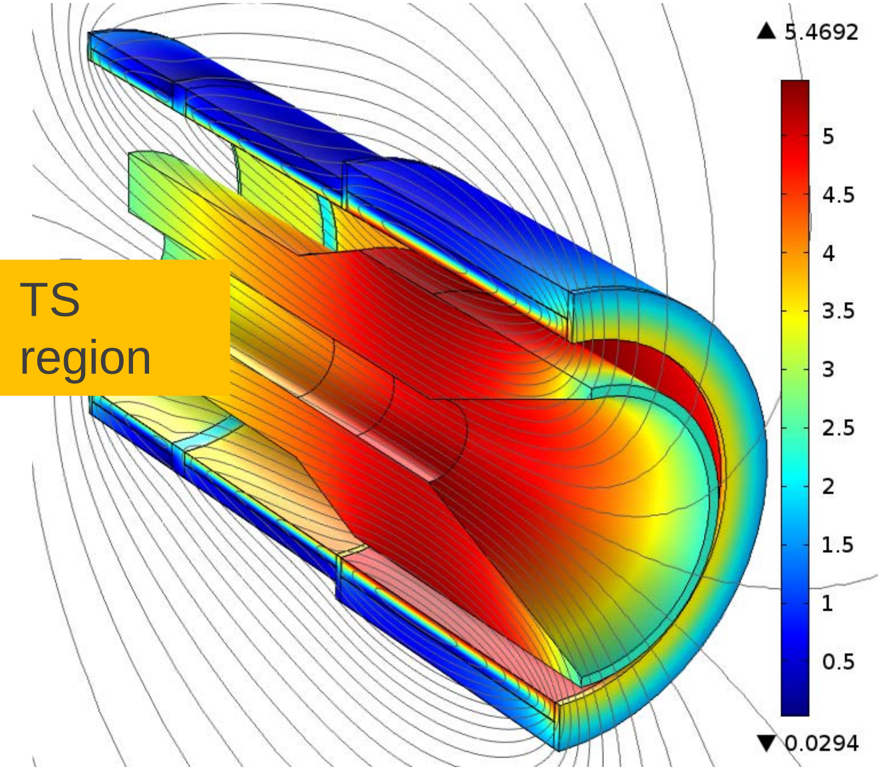
POST CD1:

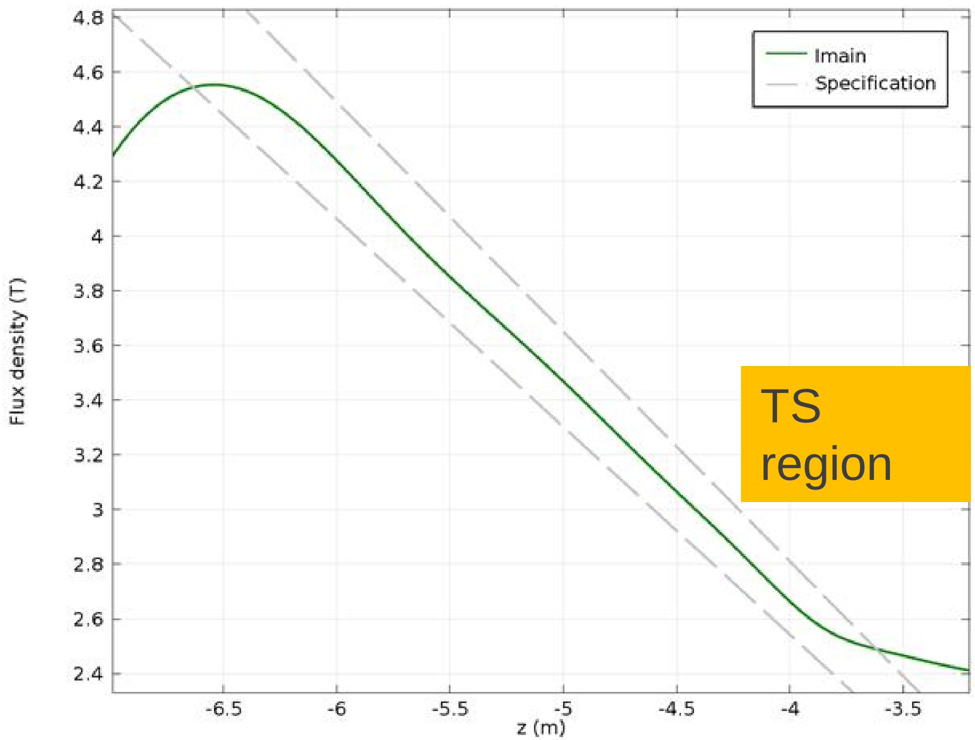
- Decision for DS to employ Thermal Siphon cooling is largely driven by value engineering (see next slide)
  - Allows for similar coil and feedbox fabrication & design
  - Allows vendors to fabricate both magnets with similar tooling
- We will recycle gently used Tevatron power supplies and extraction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

Downselects

- DS and TS cooling scheme decision
- Subject of an Internal review June 26-27, 2013
  - Reviewers: Philippe Bredy (CEA), Bertrand Baudouy (CEA), Joel Fuerst (ANL) and Kurt Kempetz (Chairman, FNAL)
- 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

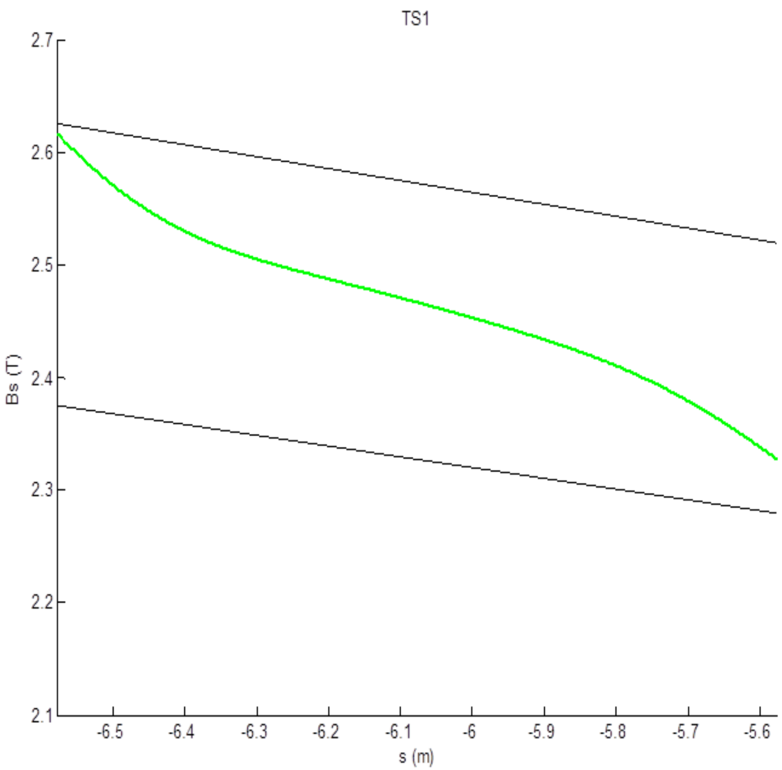


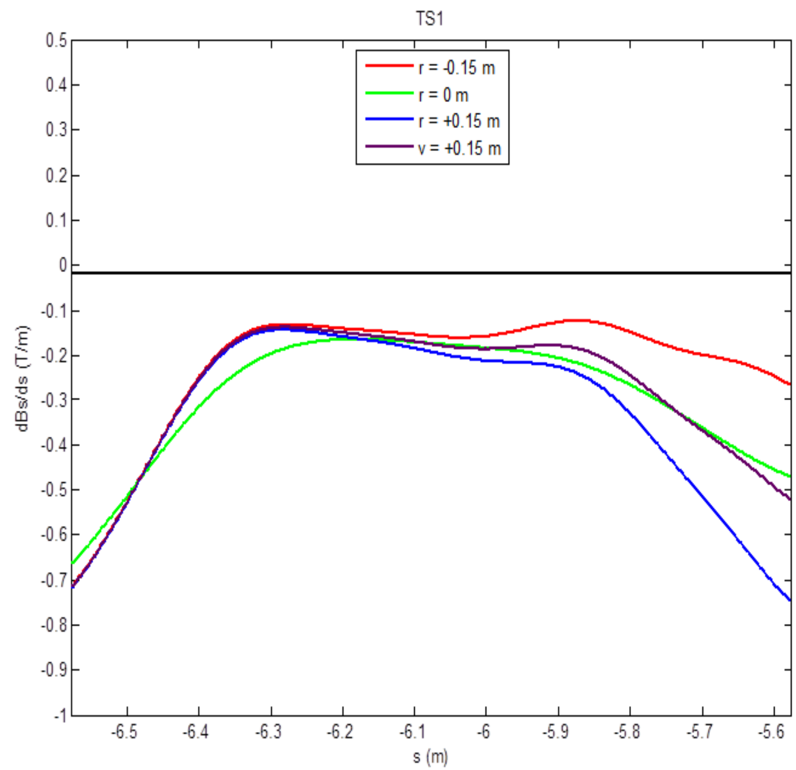


- Field analysis performed including Heat and Radiation Shield (left plot) made of high-resistivity bronze (magnetic permeability of 1.04).
- Nominal field even with HRS (as shown in right plot) meets specification (dashed lines)

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> (example shown below which includes field contributions from adjacent Production Solenoid)

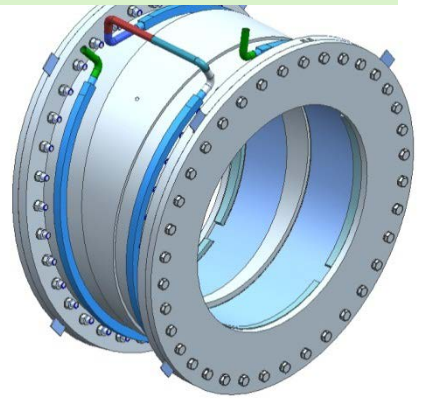




TS Prototype Coil Module Col

Scheduled completion: October 2014

INFN GENOVA and Fermilab

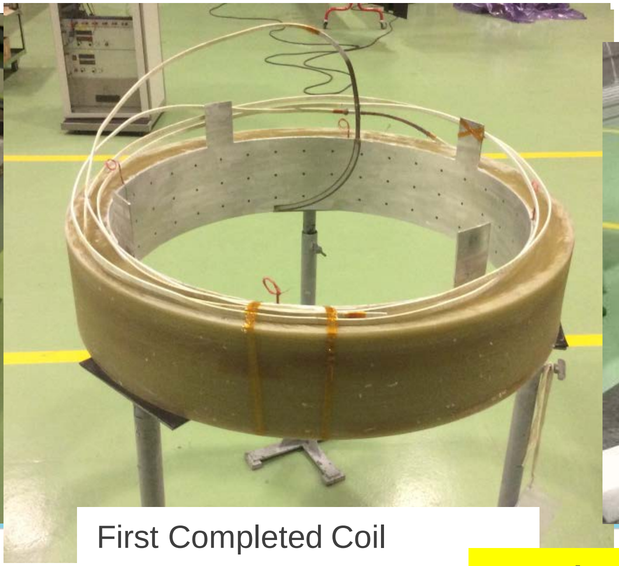


Computer model of coil module

Outer support cylinder casting pre-machined

Machined shell ready for inspection

Coil winding Mandrel

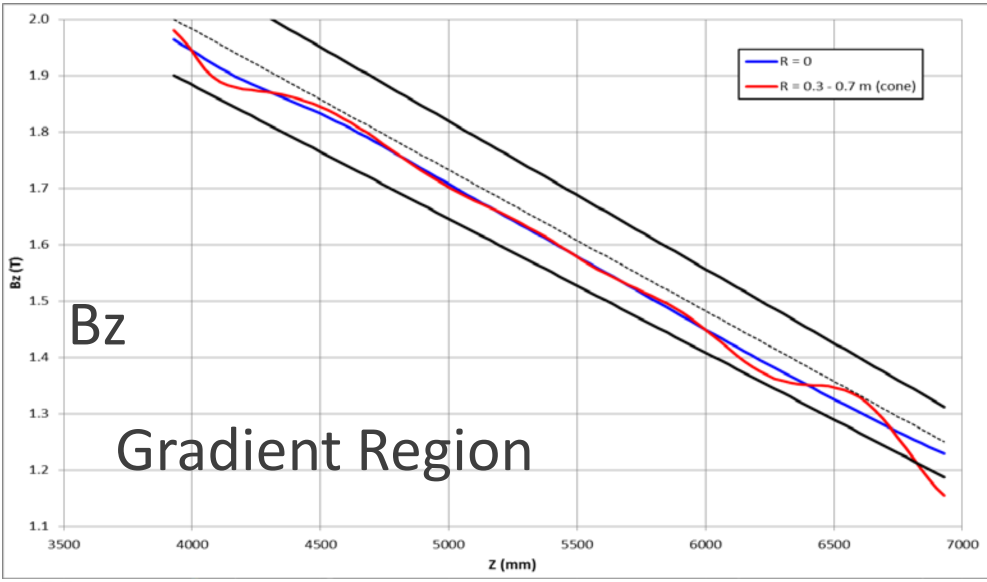


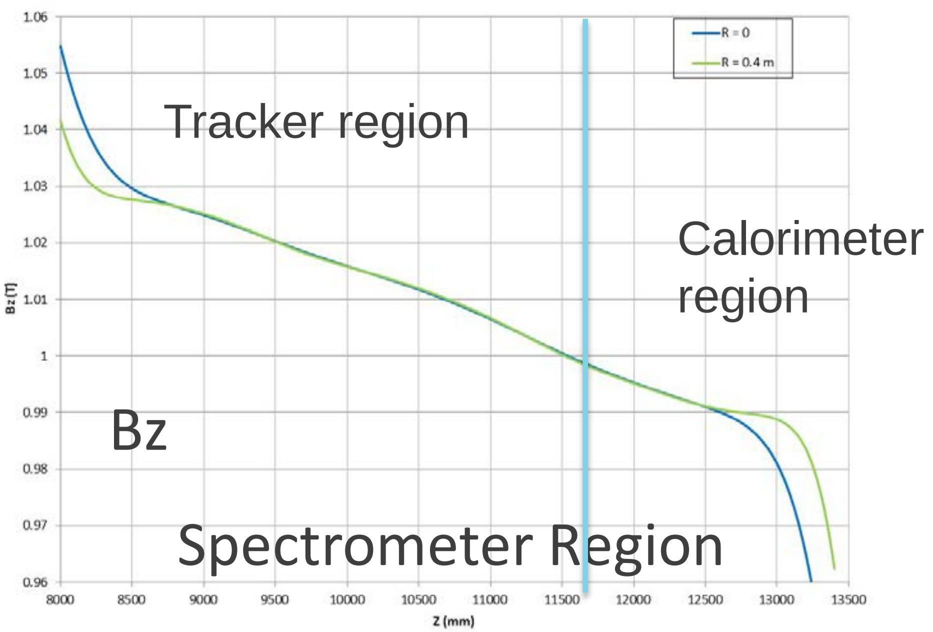
First Completed Coil

Second Completed Coil

Proprietary Assembly tooling not shown!

Performance: DS Magnetic Field





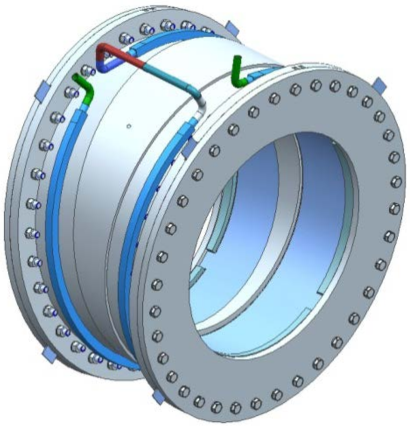
- Gradient Region: Black lines represent the limits for the field uniformity (dB/B) using the gradient of -0.25 T/m.

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

Meets Requirements

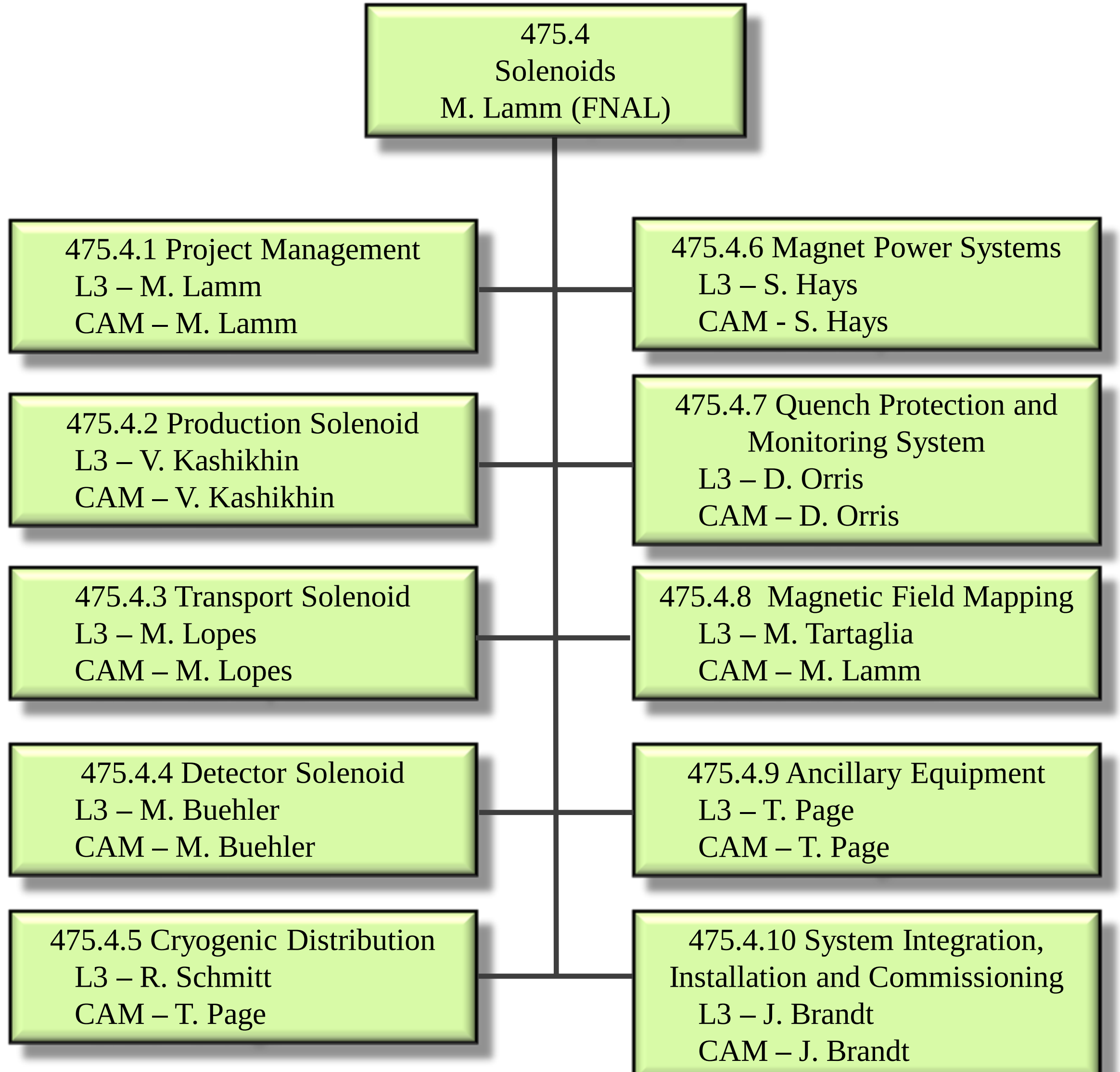
Fermilab

Request CD3 approval for TS coil modules



- TS coil modules will be fabricated in industry. There are 27 modules, with 1 or 2 (mostly) superconducting solenoid rings.
- Coil module design is quite advanced, as evidence by the progress made on the TS prototype coil. Large fraction of the drawings have been completed, remaining amount of work well understood.
- We would like to place a contract for production coil modules fabrication by Spring 2015. This will keep the TS fabrication on schedule and from delaying the entire project (TS is on critical path)
- To do this, we need to receive CD3 approval for the coil modules during this CD2/CD3b review cycle.
- In the breakout session, we will make our case to award CD3 approval
  – Status of the coil module design, but also present the considerable design analysis on the TS cold mass (magnetic, thermal, mechanical) and the TS cryostat.
  – Plans for final design and prototype testing

L2 Solenoid Organization



Technical Procurement Leads

-Vito Lombardo for Conductor

-Tom Page for PS/DS

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
- We are exercising option to perform cold full power test at Vendor facility

Integration and Interfaces

- Solenoids have external interfaces to the Muon Beamline, Conventional Construction, Muon Campus Cryo AIP, DAQ
  - Through muon beamline, interfaces with CRV and detectors
- Internal interfaces between solenoids, with cryo system, power system, quench protection and slow monitoring.
- Internal and external interfaces identified and described in Solenoid Interface document, available on Review site (docdb #1470).
- Participation in bi-weekly integration meetings
  - Jeff Brandt, our Integration L3 works closely with Mu2e integration team
  - Formal sign-off between owners of all external interfaces as part of final design requirements.
- Interfaces understood and under control.

Risks

Solenoid risks are delineated in the Mu2e Risk Register (docdb 4320). Risks cover all major deliverables; also risks associated with integration and installation. Risks are understood and under control.

Risk Statistics:

- 41 Solenoid risks in risk registry
  - All risks mitigated to the extent possible
  - 32 active threats
    - 2 high
    - 9 medium
  - 1 opportunity
  - 9 retired risks
- There is a breakout session talk dedicated to this important topic

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

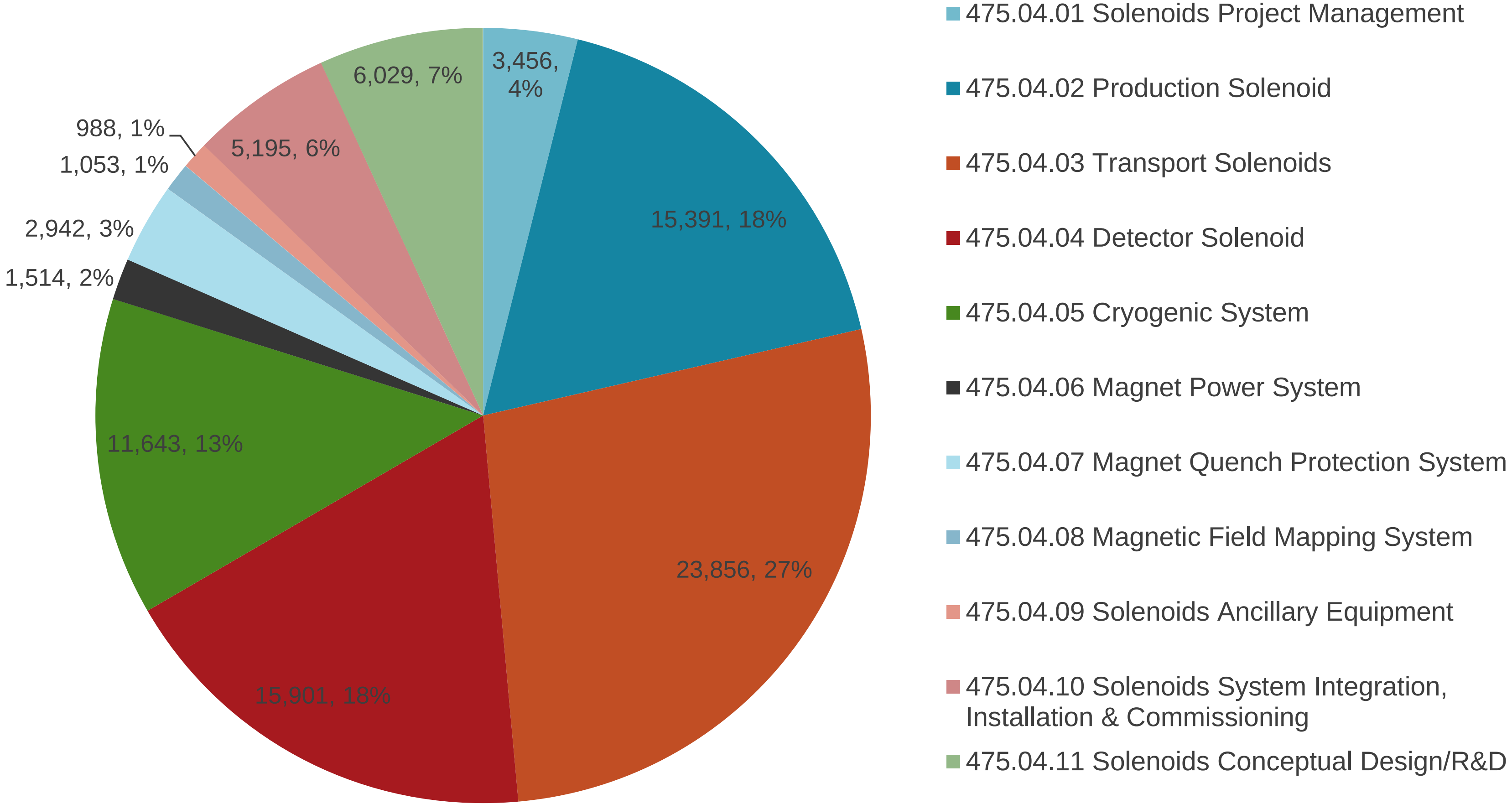
Quote in hand + change order contingency

	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency on (on remaining budget)	Total Cost
475.04 Solenoids						
475.04.01 Solenoids Project Management	610	2,846	3,456	500	21%	3,956
475.04.02 Production Solenoid	13,065	2,326	15,391	2,116	15%	17,507
475.04.03 Transport Solenoids	12,459	11,397	23,856	7,830	41%	31,686
475.04.04 Detector Solenoid	13,729	2,172	15,901	2,290	15%	18,191
475.04.05 Cryogenic System	5,221	6,405	11,626	4,003	38%	15,628
475.04.06 Magnet Power System	919	596	1,514	390	32%	1,905
475.04.07 Magnet Quench Protection System	745	2,197	2,942	991	39%	3,933
475.04.08 Magnetic Field Mapping System	339	715	1,053	448	43%	1,501
475.04.09 Solenoids Ancillary Equipment	316	672	988	423	44%	1,411
475.04.10 Solenoids System Integration, Installation & Commissioning	548	4,647	5,195	1,870	39%	7,065
475.04.11 Solenoids Conceptual Design/R&D	680	5,349	6,029		0%	6,029
475.04.99 Risk Based Contingency				3,455	-	3,455
Grand Total	48,629	39,322	87,950	24,316	34%	112,266

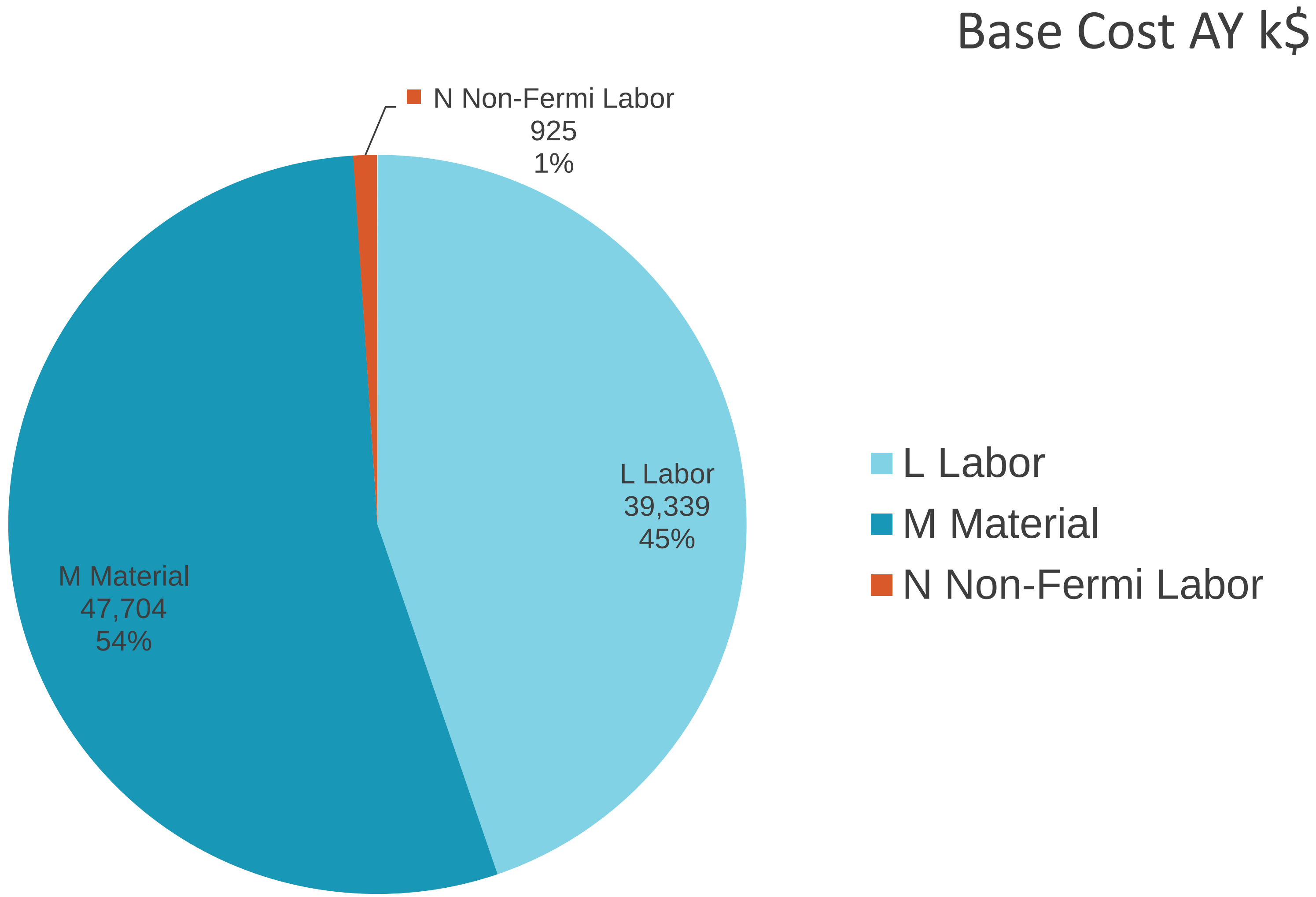
"Request for Information"
Nonbinding quotes only

Cost Breakdown by L3

Base Cost AY k$



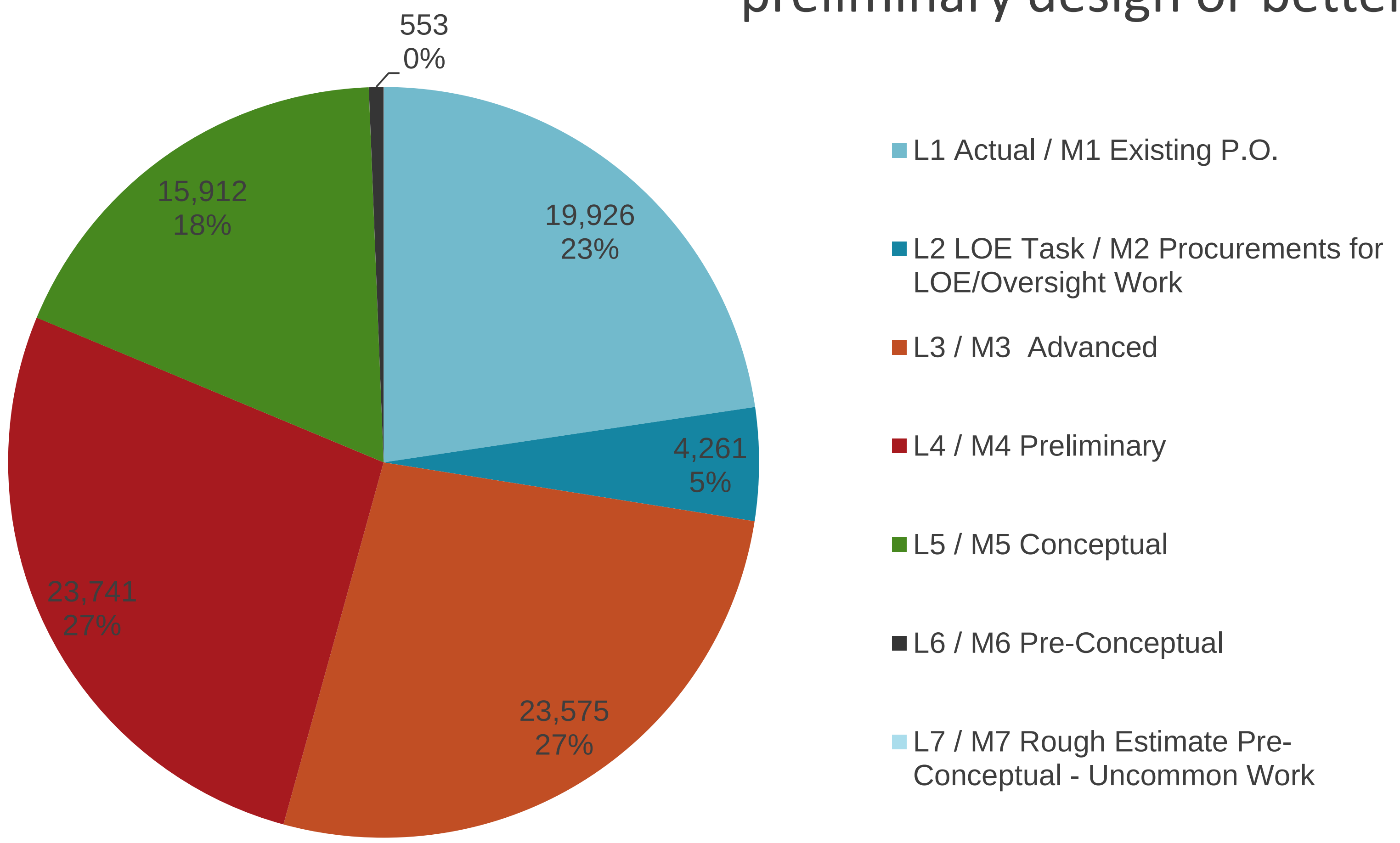
Cost Breakdown Labor vs. Material



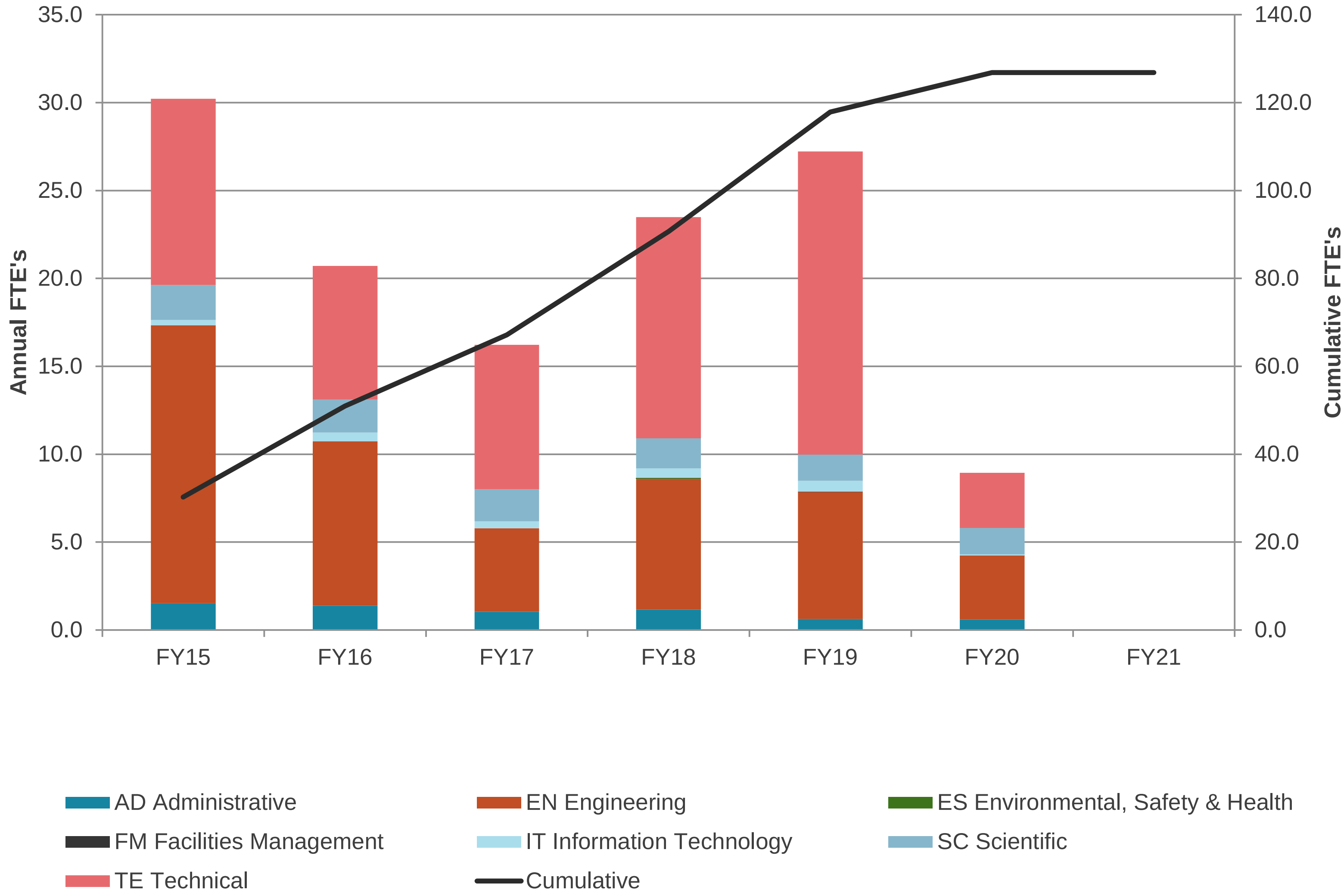
Quality of Estimate

Base Cost AY k$

82% of cost estimates are preliminary design or better



Labor Resources by FY

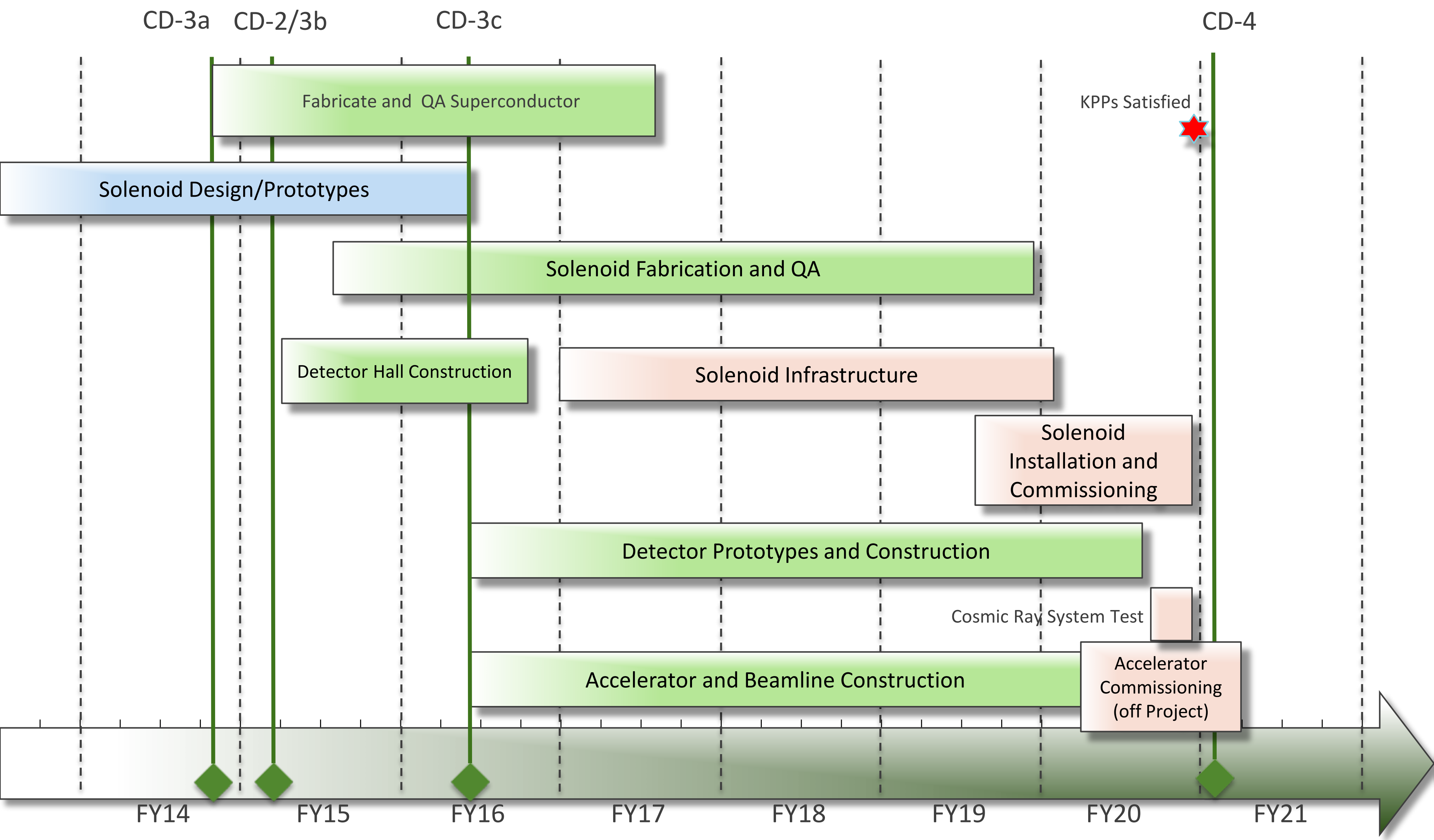


Major Milestones

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

Activity ID	Activity Name	Date	Milestone Description
47504.2.051655	T5 - PO issued for PS Final Design	10/27/2014	Fermilab approves vendors final PS magnet design. Fabrication cannot start without this milestone.
47504.4.051365	T5 - PO issued for DS Final Design	10/27/2014	PO issued for DS Final Design
47504.3.2.2.000230	T5 - Design of TS Cold Mass completed	11/3/2014	Design and documentation are ready to prepare for bid package.
47504.3.2.3.021467	T5 - PO issued for TS module fabrication	4/16/2015	PO issued for module fabrication
47504.3.3.2.011360	T5 - Final Design of TS Cryostat Complete	11/2/2015	Design and documentation are ready to prepare for CD-3.
47504.1.3.001010	T5 - Solenoids receives CD-3c approval	2/23/2016	Line Item PED funds released by DOE.
47504.2.051725	T5 - PS magnet Construction authorized	2/24/2016	Fermilab approves vendors final PS magnet design. Fabrication cannot start without this milestone.
47504.4.051450	T5 - DS construction authorized	2/24/2016	DS construction authorized
47504.10.002900	T5 - Cryo plant Operational (by GPP)	7/17/2017	Cryoplant Operational (by GPP)
47504.10.000950	T5 - Building ready for Solenoid installation	8/7/2018	Mu2e Experimental Hall is complete and ready for installation of Mu2e solenoid system and components.
47504.2.051890	T4 - Production Solenoid ready for installation	2/11/2019	Production Solenoid ready for installation.
47504.3.4.1.001840	T4 - TSu magnet ready for installation	3/4/2019	Transport Solenoid (upstream) magnet ready for installation
47504.4.051610	T4 - Detector Solenoid magnet ready for installation	7/16/2019	Detector Solenoid magnet ready for installation
47504.3.4.2.001630	T4 - TSd magnet ready for installation	10/11/2019	Transport Solenoid (downstream) magnet ready for installation
47504.10.005950	T5 - Solenoid system installation complete and ready for cooldown	4/9/2020	Solenoid system and supporting equipment is installed and magnets are ready to be cooled down to 4.5 K.
47504.10.006850	T5 - On Project Solenoid Commissioning complete	9/29/2020	Key Performance Parameter: Solenoid system has been cooled down and powered and demonstrated to run at nominal field strength.

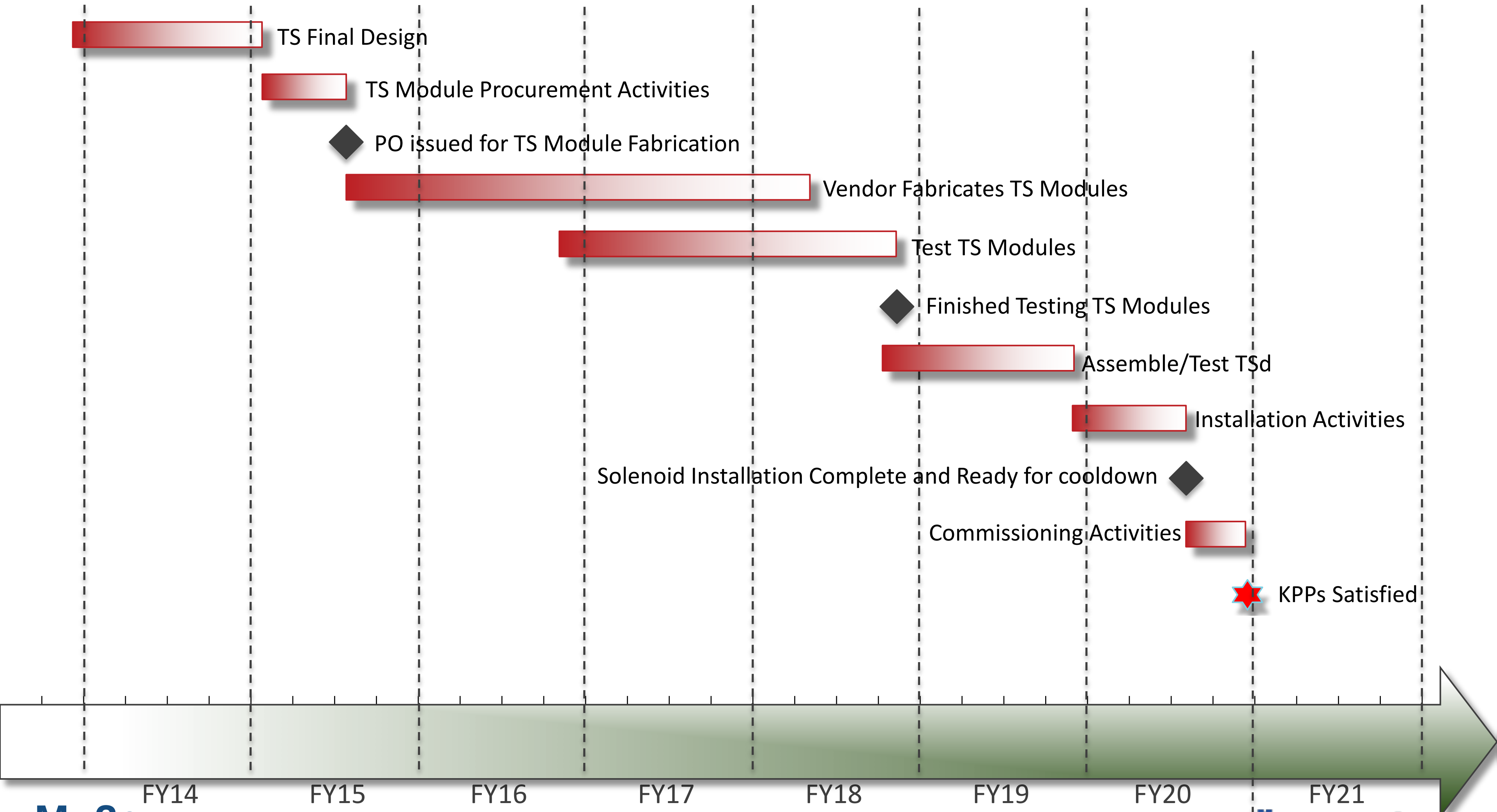
Schedule



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

Critical Path

TS is on the critical path for most of the project, PS/DS not far behind….



Breakout Session Talks

In addition to having dedicated talks on each Level 3 deliverable, (PS, DS, TS, Cryo distribution….) there will be presentations on the following topics:

- Solenoid Procurement Strategy
- Update on Conductor Procurement since CD3a
- Lessons learned from past and present magnet procurements
- Solenoid Risk analysis
- Expanded TS technical presentation because of the CD3 coil module request

Summary

- Solenoid designs are well understood and meet requirements
- Cost estimates for the Solenoids are complete
  - Over 80% of the cost understood at the Preliminary Design level or higher
  - Risk are understood, mitigated to the extent possible and are under control.
- All interfaces are identified and defined
- Resource needs understood
- ES&H and Quality embedded into all aspects of the Project
- We have responded to all recommendations from previous reviews
- We are well along on the procurement of the major components of the Solenoids:
  - Have initiated long lead time conductor orders
  - Have selected PS and DS vendor, final stages of contract negotiations
  - On track to place orders for TS coil modules
    - Asking for CD3 approval for a Spring 2015 procurement
- Solenoids are ready for CD-2