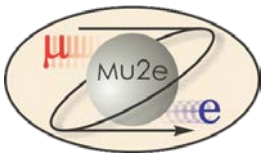
Fermilab

Transport Solenoid System



Michael Lamm

L2 for Solenoids

02/04/2015

Outline

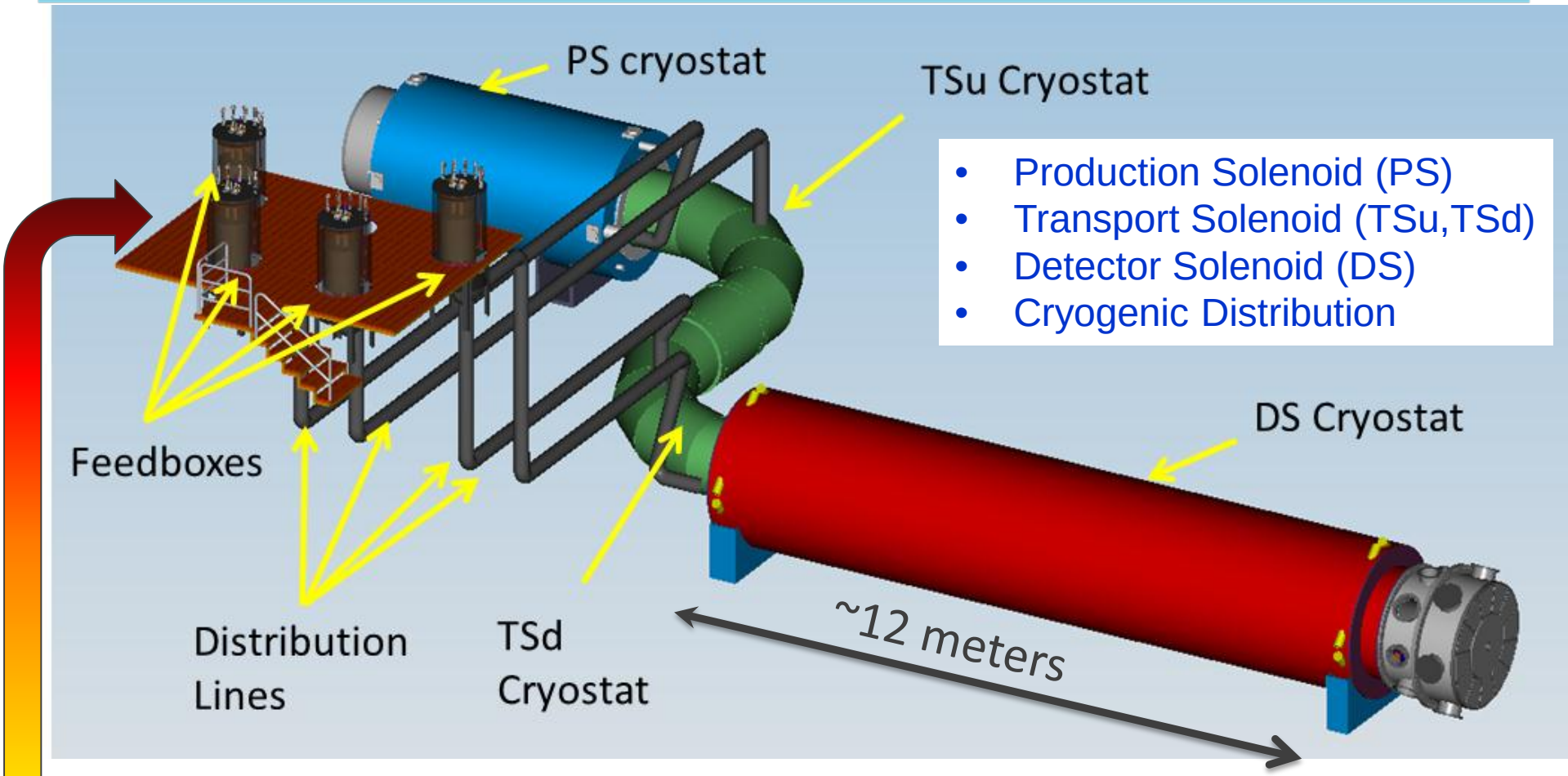
- Introduction
  - Mu2e Solenoid Scope and Organization
- Transport Solenoid Module Overview
- Transport Solenoid Agenda Topics
  - TS Module Design Review/Final Design Status
  - TS Prototype Module Status, Test and Acceptance Plan
  - TS Module Procurement and Fabrication Readiness
- Summary

Introduction: Scope for Solenoids

Provide integrated magnetic system for Mu2e experiment. Includes 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, quench protection, controls and monitoring
  - Magnetic Field Mapping System
  - Installation and Commissioning of these deliverables

Introduction: Mu2e Solenoid Scope

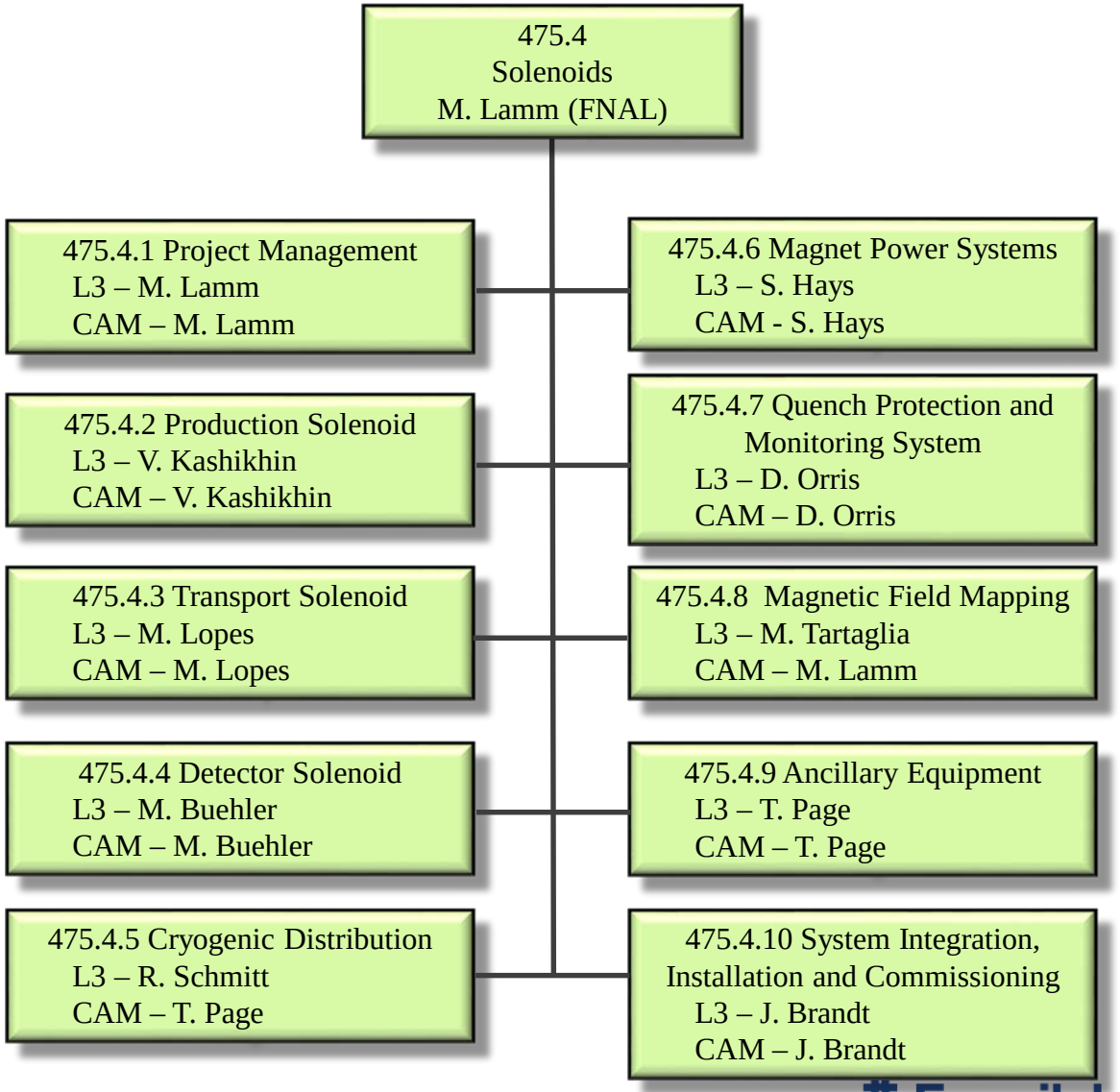


- Production Solenoid (PS)
- Transport Solenoid (TSu,TSd)
- Detector Solenoid (DS)
- Cryogenic Distribution

- Cryo distribution box
- Power Supply/Quench Protection

- Field Mapping
- Ancillary Equipment
- Installation and commissioning

Introduction: L2 Solenoid Organization



Procurement Leads

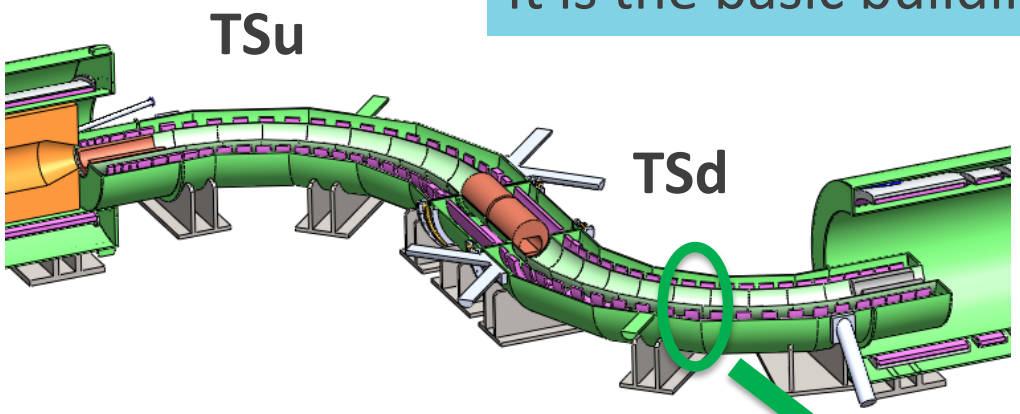
-Vito Lombardo for Conductor

-Tom Page for PS/DS

-M. Lopes/G. Ambrosio of TS

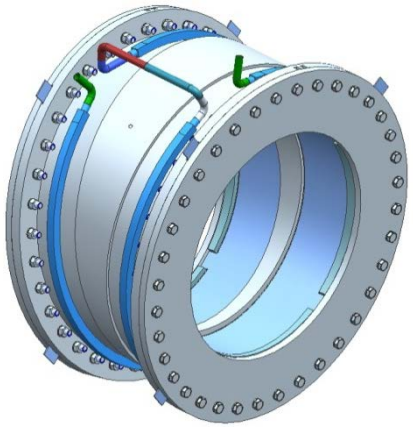
TS Module Overview

It is the basic building block of Transport Solenoids

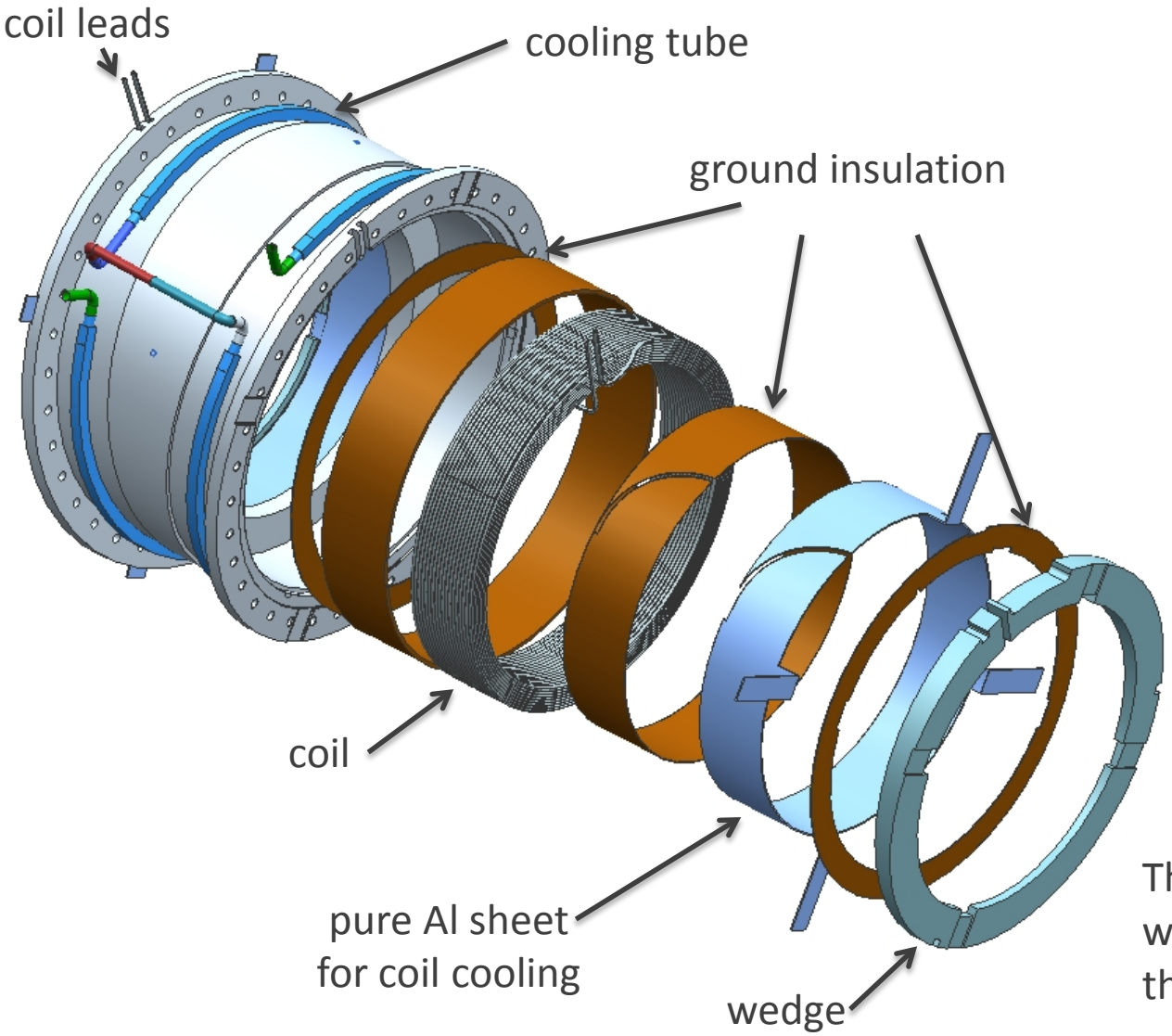


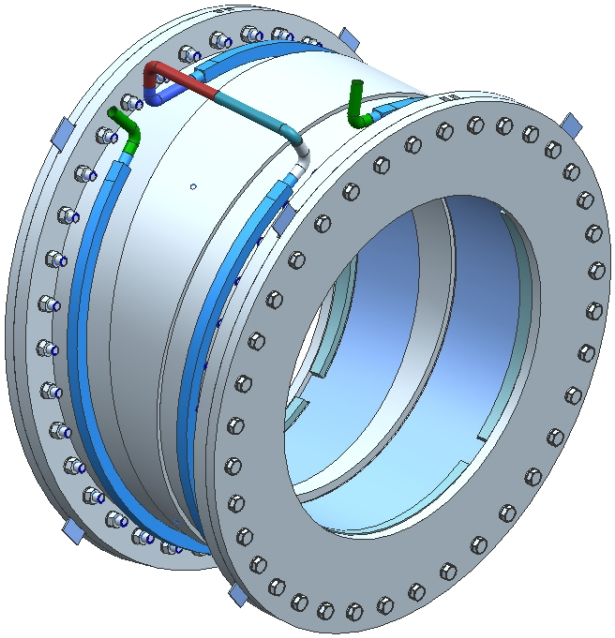
- Typically 2 superconducting solenoid rings per module
- Outer aluminum support shell
- Coils indirectly cooled with LHe
- 27 modules in total
  - 13 in TSu
  - 14 in TSd

- Modules bolted together to form required “S” shaped geometry. Geometry defines the magnetic field
- Modules will be built in Industry



Design – TS Module





The coils are epoxy impregnated with the ground insulation and the Al sheet.

Transport Solenoid Agenda Topics

1. TS Module Design Review/Final Design Status
2. TS Prototype Module Status, Test and Acceptance Plan
3. TS Module Procurement and Fabrication Readiness

1. TS Module Design Review/ Final Design Status

TS Module Final Design

Design has been analyzed in detail and reviewed

- Documented in presentations, in Mu2e Technical Design Report, and in analysis-specific reference design documents
- Subject of a Independent Technical Design Review in December 2014

Design is very robust

- Large superconductor Ic and temperature safety margin
- Exceeds magnetic field quality requirements over a wide range of mechanical tolerances
- Substantially exceeds mechanical stress requirements under all operating and failure scenarios
- Robust thermal design provides coils with large temperature margins over a wide range of operating conditions

Design validated through prototype TS module testing

Load Line Show Large Operating Margins

With 5.1 K operating temperature

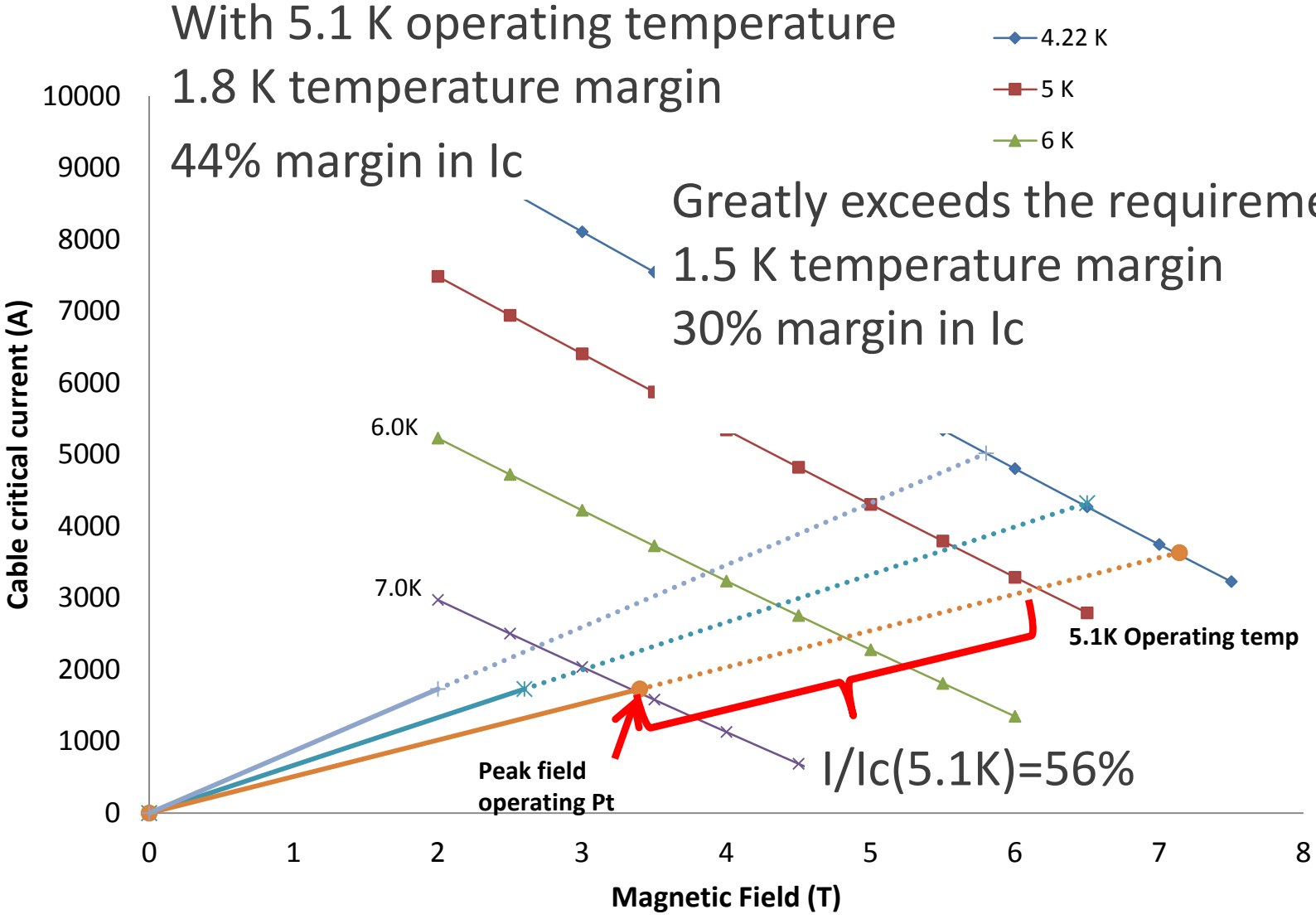
1.8 K temperature margin

44% margin in Ic

Greatly exceeds the requirements of:

1.5 K temperature margin

30% margin in Ic



Structural Analysis

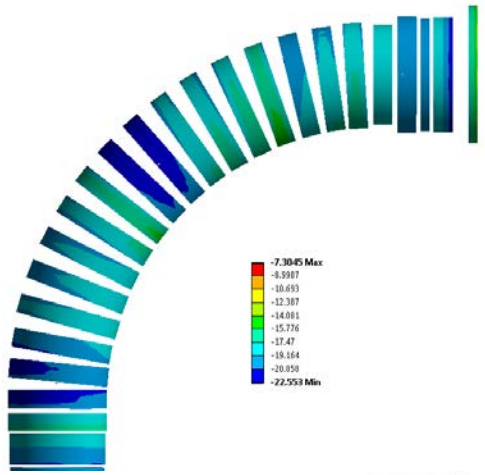
COIL STRESSES WELL BELOW REQUIREMENT: 40 MPa (max)

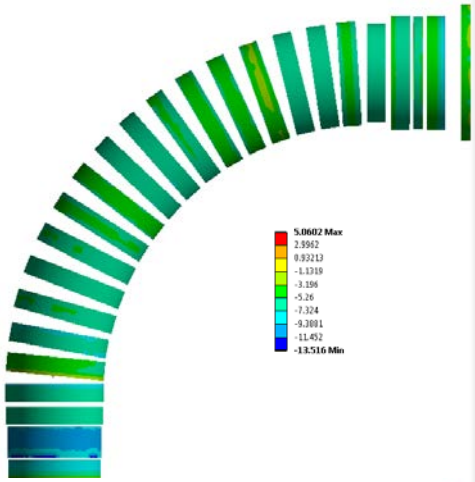
Hoop stress

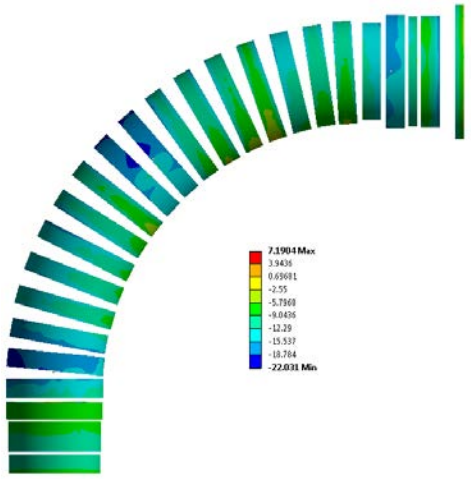
Axial stress

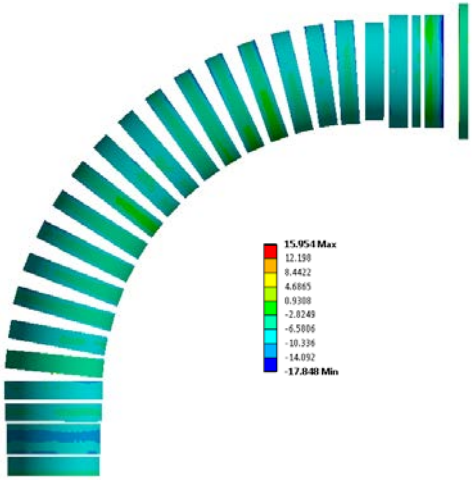
Cool down

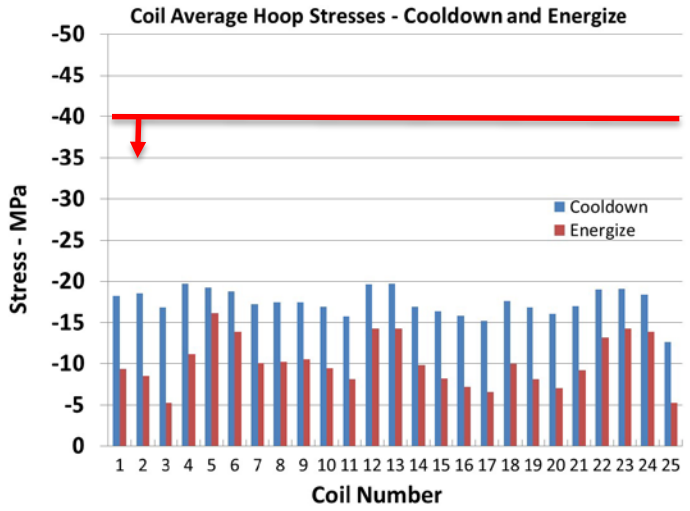
Energize

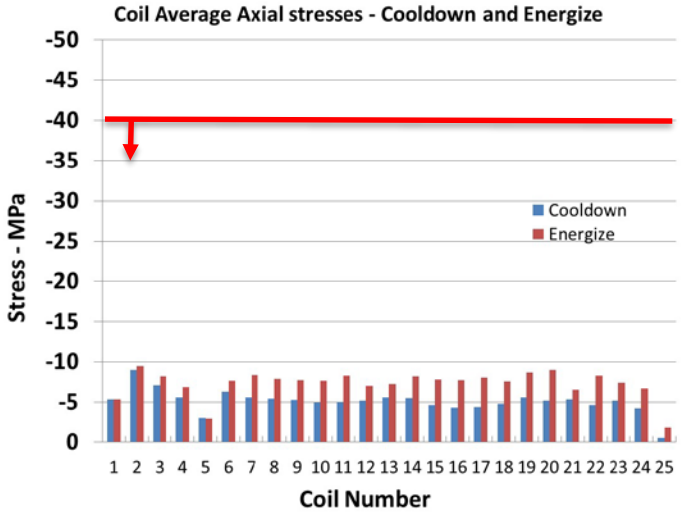






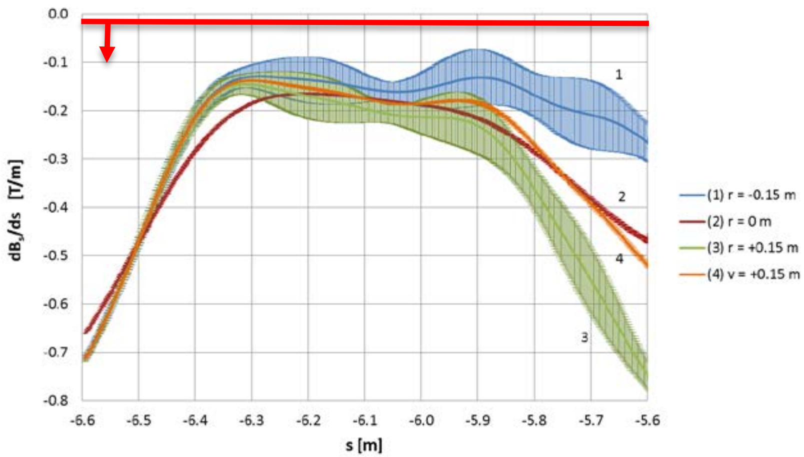


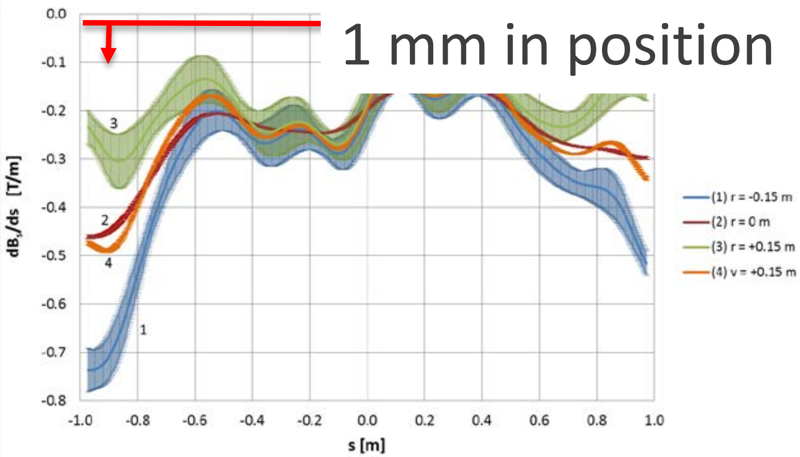


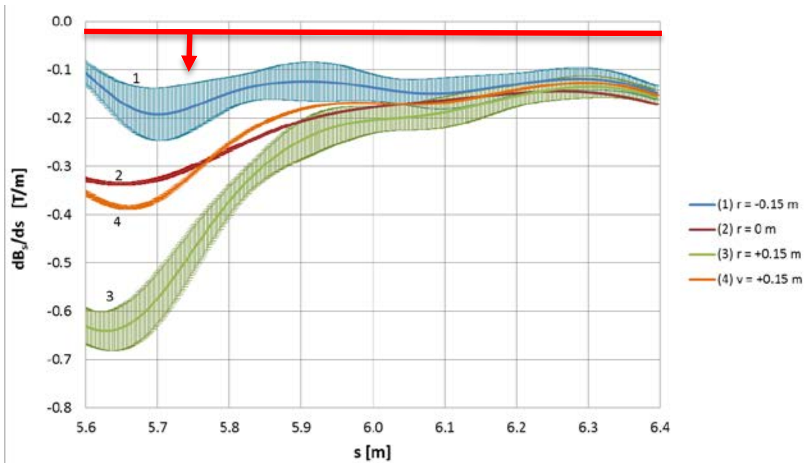


Coil Tolerance Studies

Typical tolerances:
3 mr in angle
1 mm in position



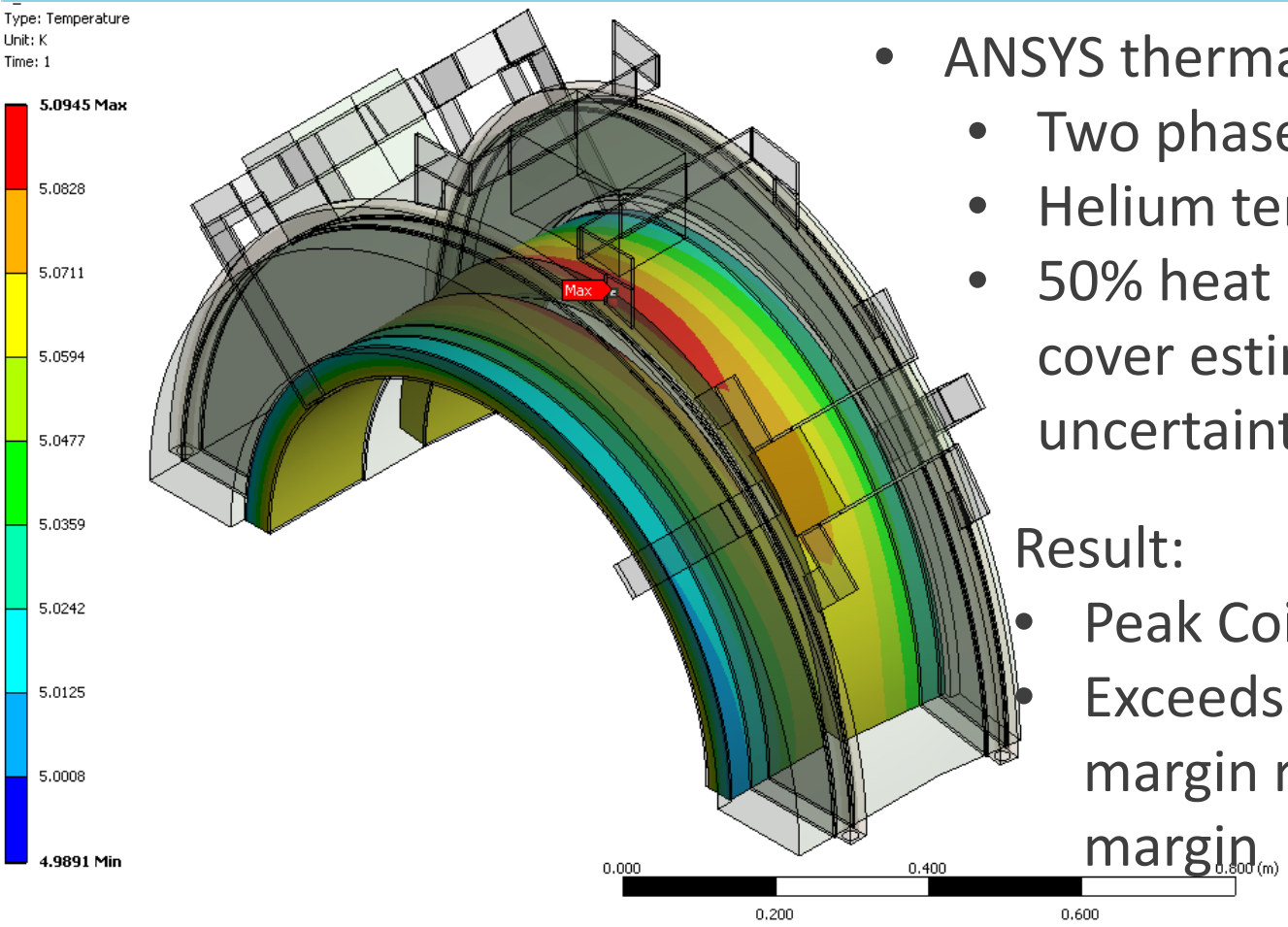




Error type	Maximum error	Maximum longitudinal gradient (T/m)		
		TS1	TS3	TS5
Radial	10 mm	-0.072	-0.072	-0.083
Radial	2 mm	-0.114	-0.106	-0.115
Vertical	10 mm	-0.103	-0.082	-0.104
Longitudinal	10 mm	-0.023	-0.009	-0.060
Longitudinal	2 mm	-0.111	-0.096	-0.109
Pitch	10 mrad	-0.120	-0.092	-0.116
Pitch	2 mrad	-0.124	-0.112	-0.12
Yaw	10 mrad	-0.108	-0.086	-0.105
Yaw	2 mrad	-0.121	-0.107	-0.119

Exceeds negative gradient requirement even with large coil tolerances

Cooling Scheme Analysis



- ANSYS thermal model assuming
  - Two phase flow
  - Helium temperature 4.85K
  - 50% heat load added to cover estimated heat load uncertainty

Result:

- Peak Coil temperature <5.1 K
- Exceeds 1.5 K temperature margin requirement by wide margin

Meets/exceeds temperature and heat load requirements over the entire range of running conditions.

Coil Splice R&D and Analysis

- Splices will need to be performed at the Vendor as well as at Fermilab as part of the magnet assembly
- High quality splices are key to the success of the magnet
- We conducted an extensive coil splice R&D program
- Splice criteria
  - Low resistance, mechanical robustness, reproducibility, minimal superconductor degradation
- Numerous splices performed and tested
- Results: two methods meet all our requirements
  - Rutherford to Rutherford solder
    - Aluminum stabilizer chemically removed
  - Ultrasonic Welding
    - Our samples made from commercially available machine
    - Excellent reproducible results

Coil Splice R&D and Analysis II

- All splices both at the vendor and at Fermilab will undergo a rigorous Quality Assurance process and Quality Control program
- Method of splice
  - Splices performed at Fermilab will use the ultrasonic weld method
  - TS Module fabrication vendor may chose either of our approved methods, but as part of our procurement specification:
    - Vendor must assume responsibility for splices
    - Must demonstrate that they can meet our specification

Note: all vendor splices will be cold tested prior to final assembly, as part of our TS module test program

TS Module Design Review

- **We held an Independent Design Review on December 5th to assess our progress**
  - Reviewers from outside Mu2e project
    - Mike Anerella (BNL)
    - Joel Fuerst (ANL)
    - Jim Kerby (ANL)
    - John Tompkins (FNAL)
  - Asked to comment on manufacturability
  - Asked to comment on cooling scheme
  - Asked to comment on status of design/drawings leading to an April procurement.

Agenda from Independent Design Review

Presentations

Title	Presenter	Start Time
Introduction to Mu2e	M. Lamm	9:00 am
Transport Solenoid Overview	M. Lopes	9:20 am
Cooling Scheme	S. Cheban	11:10 am
Cold Mass Fabrication	D. Evbota	11:40 am
TS Coil Modules Procurement Specification	M. Lopes	12:10 pm
TS Prototypes	G. Ambrosio	12:30 pm

- Requirements
- Structural Analysis
- Magnetic Analysis
- Splice Analysis

- Cryogenic design
- Cryogenic interfaces

- Solid Model
- Cold Mass assembly
- Mechanical interfaces

http://mu2e.fnal.gov/public/project/reviews/TSCoilModuleTDR%20/TSCoilModuleReview.shtml

Independent Design Review Recommendations

#	Recommendation	Assigned to	Status	Response and comments to be edited prior to launch
1.	Complete all drawings and sign off all pertinent technical calculations before the start of the Acquisition Oversight Committee.	Daniel Evbota	Ongoing	We presented a full set of drawings for one coil module for their consideration at the 1/26/2015 AOC meeting. All drawings are complete and signed off by February 4, 2015 review date. Technical Calculation sign off is nearly completed.
2.	Make a technical list comparing what will be tested with the prototype, and what will not be tested, relative to the full implementation. Modify test plans or the risk table, as appropriate.	Giorgio Ambrosio, Mau Lopes, Michael Lamm	Complete	The biggest issue is the magnetic forces which come from operating of all Mu2e coils under all possible operating conditions. We will only approximate these conditions by testing the prototype to 120% of the operating current and testing with reverse polarities. This gap in test coverage is considered small but is covered in the Mu2e risk register.

Independent Design Review Recommendations

#	Recommendation	Assigned to	Status	Response and comments to be edited prior to launch
3.	Perform a thorough peer review (inspection of all assumptions, material properties and thermal properties, inspection of ANSYS models, etc.) or repeat all thermal analyses to check results of maximum coil temperature under operating conditions.	Rich Schmitt, Sergei Cheban, Grzegorz Tatkowski	Ongoing	Thermal analysis is being repeated and will cover the expected system cooling and coil operating scenarios including cool down. Much of this analysis has been completed and documented. Final document will then be peer reviewed.
4.	Complete splice design and include this as part of the build to print portion of the procurement.	Mau Lopes	Complete	Splices will be performed at the magnet vendor and on site. We will provide a specification for the splice and give the vendor two options for the splice method. It will be the responsibility of the vendor to demonstrate that they can reliably make splices that meet our spec

Independent Design Review Recommendations

#	Recommendation	Assigned to	Status	Response and comments to be edited prior to launch
5.	Consider revising helium line connections to be welded stainless steel with commercial stainless steel to aluminum transitions or equivalent. If this is not practical establish early testing of proposed aluminum helium piping system in magnet configuration (i.e., connected to a large thermal masses) at cryogenic conditions. If there is any concern about the durability of Al/Al field welds at the cooling tube joints, consider implementing Al/SS transition elements to allow SS/SS field welds.	Dan Evbota, Mau Lopes	Ongoing	Plan is twofold. We will perform a series of bench tests to validate our baseline design. We will also test these connections during the prototype: First with LN2 shock test and then during the magnet cool down and heater induced quench. If necessary we will require the vendor to adapt these Al/SS transition elements
6.	Heavily instrument the prototype in all coil areas, along exiting coil leads and at helium line entrance and exit locations (with intermediate points as possible)	Darryl Orris, Mau Lopes, Giorgio Ambrosio	Complete	Prototype will be heavily instrumented in all coil areas. Instrumentation includes strategically placed thermometry, spot heaters for quench initiation, acoustic quench sensors, strain gauges and of course voltage taps. Instrumentation plan is being executed.

TS Module Design Review Conclusion

- Many useful comments and recommendations
  - We are incorporating them into our plans
- 6 recommendations to be addressed
  - 3 have been completed
  - 3 are ongoing
    - Will be completed in the next few weeks, well before construction readiness review

2. TS Prototype Module Status, Test and Acceptance Plan

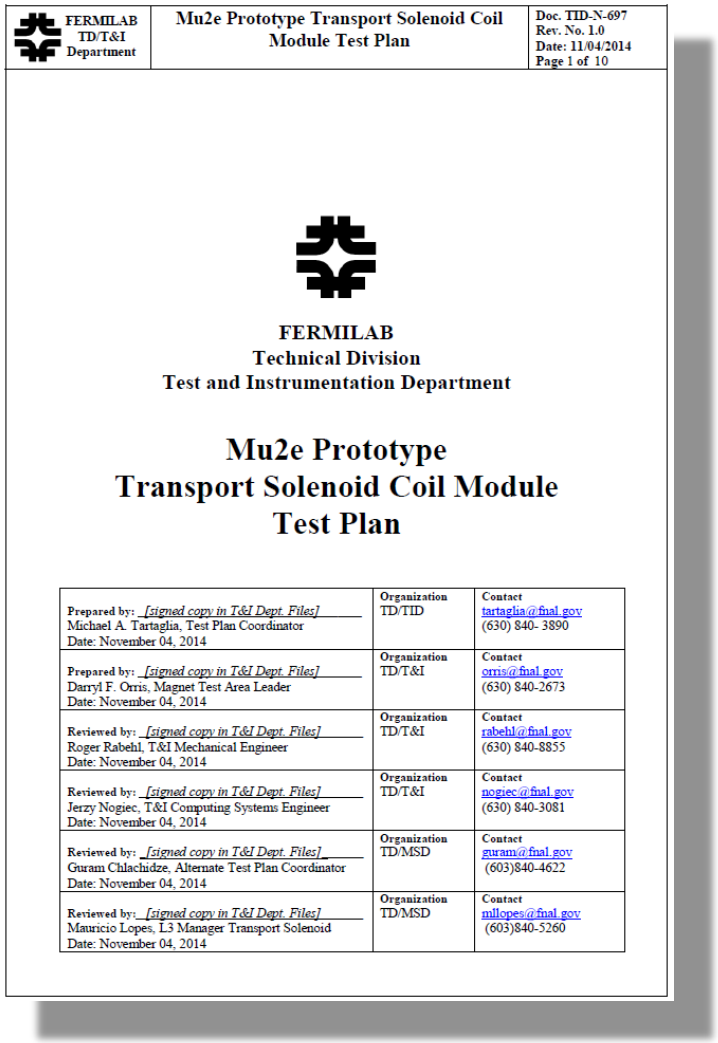
TS Prototype Module Status

- Successful prototype fabrication completed at ASG (Genoa)
- Delivered to Fermilab on December 23, 2014
- Preparing prototype for Test Facility
  - Completed room temperature mechanical, electrical and magnetic acceptance tests
  - Prepared magnet leads for Rutherford-Rutherford splice connection to test stand
  - Installing additional instrumentation as per December 5th review recommendation

Test and Acceptance Plan Status

- Test Plan for Prototype Complete
- Prototype Module Acceptance Plan Complete
- Executing Acceptance Plan

Test Plan for Prototype



FERMILAB TD/T&I Department | Mu2e Prototype Transport Solenoid Coil Module Test Plan | Doc. TID-N-697 Rev. No. 1.0 Date: 11/04/2014 Page 1 of 10

FERMILAB
Technical Division
Test and Instrumentation Department

Mu2e Prototype
Transport Solenoid Coil Module
Test Plan

Prepared by: *[signed copy in T&I Dept. Files]* Michael A. Tartaglia, Test Plan Coordinator Date: November 04, 2014	Organization TD/TID	Contact tartaglia@fnal.gov (630) 840- 3890
Prepared by: *[signed copy in T&I Dept. Files]* Darryl F. Orris, Magnet Test Area Leader Date: November 04, 2014	Organization TD/T&I	Contact orris@fnal.gov (630) 840-2673
Reviewed by: *[signed copy in T&I Dept. Files]* Roger Rabehl, T&I Mechanical Engineer Date: November 04, 2014	Organization TD/T&I	Contact rabehl@fnal.gov (630) 840-8855
Reviewed by: *[signed copy in T&I Dept. Files]* Jerzy Nogiec, T&I Computing Systems Engineer Date: November 04, 2014	Organization TD/T&I	Contact nogiec@fnal.gov (630) 840-3081
Reviewed by: *[signed copy in T&I Dept. Files]* Guram Chlachidze, Alternate Test Plan Coordinator Date: November 04, 2014	Organization TD/MSD	Contact guram@fnal.gov (603)840-4622
Reviewed by: *[signed copy in T&I Dept. Files]* Mauricio Lopes, L3 Manager Transport Solenoid Date: November 04, 2014	Organization TD/MSD	Contact mllopes@fnal.gov (603)840-5260

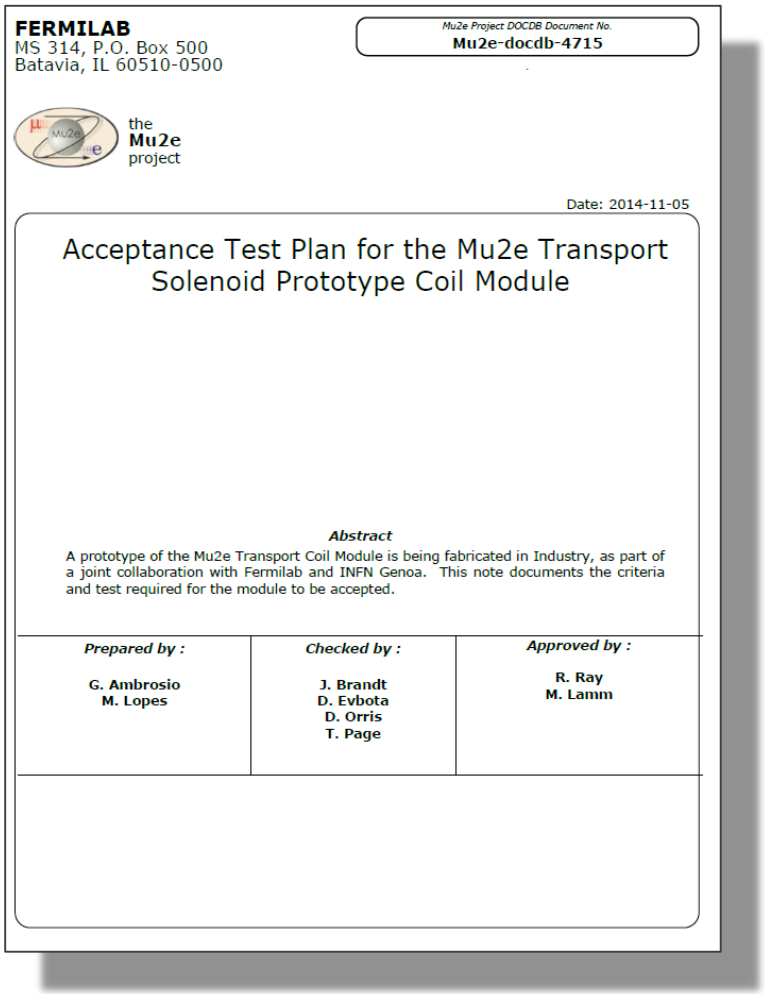
Features

- Controlled document
- Follows well established test facility procedures
- Follows acceptance plan
- Includes additional tests that can not be easily tested in production mode

Test Plan for Prototype complete

Similar plan for production modules has been developed

Acceptance Plan for Prototype



FERMILAB
MS 314, P.O. Box 500
Batavia, IL 60510-0500

Mu2e Project DOCDB Document No.
Mu2e-docdb-4715

the Mu2e project

Date: 2014-11-05

Acceptance Test Plan for the Mu2e Transport Solenoid Prototype Coil Module

Abstract

A prototype of the Mu2e Transport Coil Module is being fabricated in Industry, as part of a joint collaboration with Fermilab and INFN Genoa. This note documents the criteria and test required for the module to be accepted.

Prepared by :	*Checked by :*	*Approved by :*
G. Ambrosio M. Lopes	J. Brandt D. Evbota D. Orris T. Page	R. Ray M. Lamm

Features

- Acceptance Procedure
- Acceptance Criteria
  - Requirements
  - Reference
  - Procedure
  - Procedure Summary

Prototype acceptance plan complete

Similar plan for production modules

Acceptance Test Examples

3.4 ROOM TEMPERATURE MAGNETIC MEASUREMENTS

Requirements:	The axis with respect to fiducials installed on the OD of the shell will be measured using a stretched wired system. The measurements will be done at room temperature. Each coil will be individually powered using a current of 30 A. The axis of each coil must be within 0.2 degrees with respect to the nominal axis
Reference:	Mu2e Technical Design Reference Document TS coil tables [1]
Procedure:	Procedure for Aligning Solenoid Magnets using the Vibrating Wire Technique with the Single Stretch Wire (SSW) System [6]
Procedure summary:	SSW measurements of magnetic axes of each coil to external fiducials.

3.6 COLD POWERING TEST

3.6.1 NOMINAL COLD POWERING

Requirement:	Coils shall reach 2100 A (120% of nominal current) with less than 5 quenches per coil
Reference:	Mu2e TDR [1]
Procedure:	TS Prototype Test Plan [3]
Procedure summary:	Test performed in SolTF, following standard test procedures for superconducting magnets

Acceptance Status by Test Category

- ✓ Dimension validations: Dimensions of the module must be within tolerances.
- ✓ Cooling tube leak and pressure tests
- ✓ Room temperature electrical tests
- ✓ Room temperature magnetic measurements
- Electrical tests at LHe temperatures
- Module tests at full power
- Room temperature tests after LHe tests.

All test performed to date pass with flying colors!

TS Prototype Coil

TS Prototype Coil in the News!

Fermilab Today — Friday, Jan. 23, 2015

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Calendar

[Have a safe day!](#)

Friday, Jan. 23

9 a.m.-5 p.m.
ELBNF Proto-Collaboration Meeting

3:30 p.m.
Director's Coffee Break - WH2XO

4 p.m.
Joint Experimental-Theoretical Physics Seminar - One West
Speaker: Eun-Joo Ahn, Fermilab
Title: Surprising Results on the Composition of the

Feature

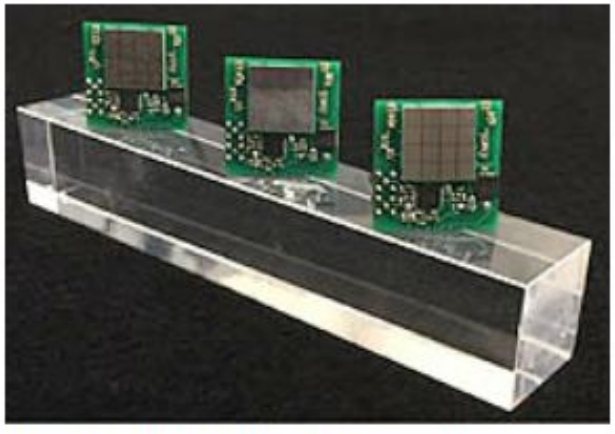
Mu2e polishes off prototype module for transport solenoid

From left: Giorgio Ambrosio, Mau Lopes, Michael Lamm and Daniel Evbota show off the prototype coil module for the Mu2e transport solenoid. The prototype, here mounted on a test stand, will be one of 27 like pieces that guides muons to their target. *Photo: Reidar Hahn*

Mau Lopes has never waited as anxiously for a package as he did for the

Frontier Science Result: Muon g-2

New detectors for the Muon g-2 experiment



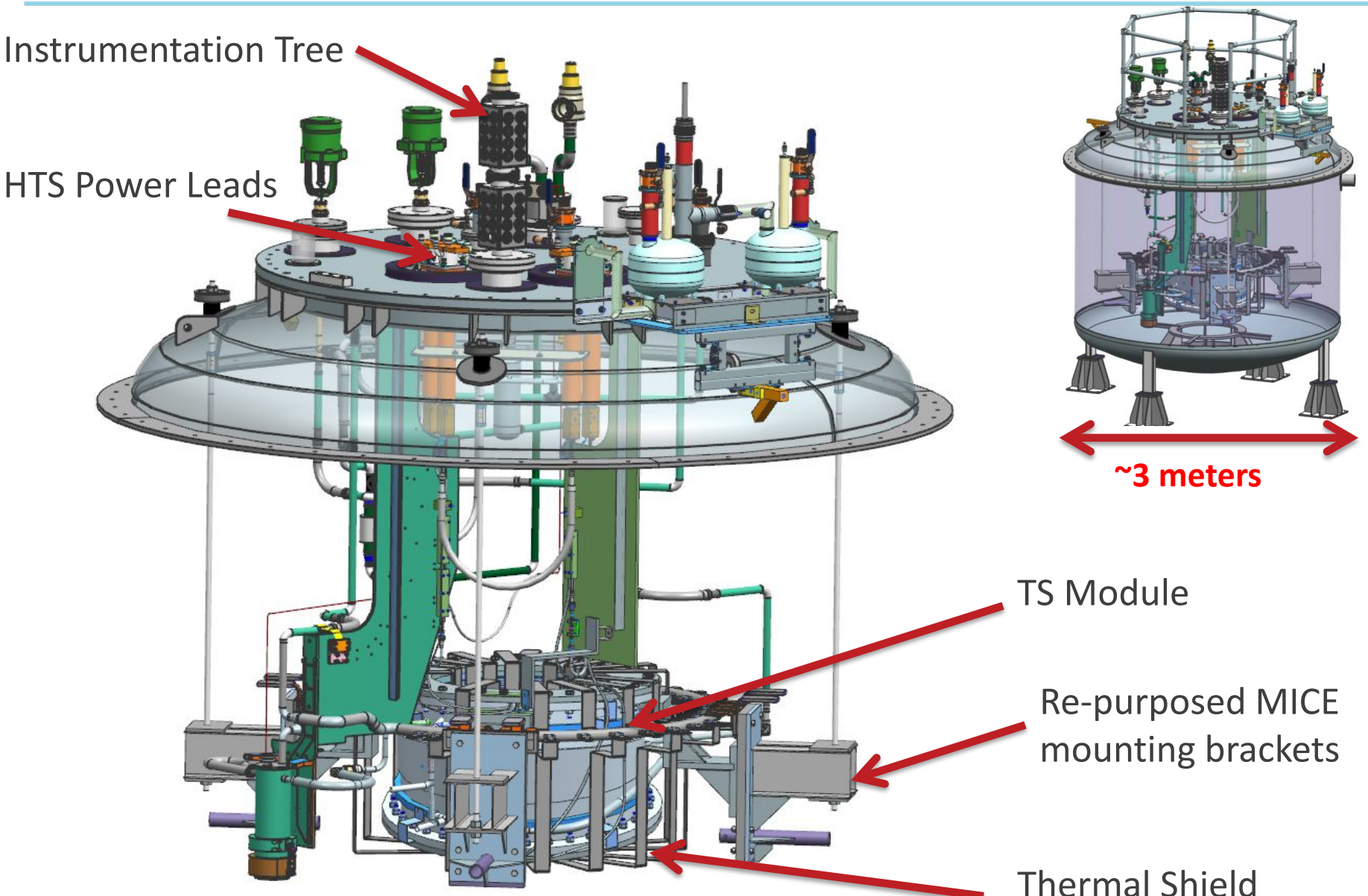
Members of the Muon g-2 collaboration at Fermilab are developing this lead fluoride crystal, 14 centimeters long, and the large-area SiPMs for the experiment's detector. They will help scientists measure more precisely the energies of particles from decaying muons, as well as the decay time of the particles.

The Muon g-2 experiment at Fermilab is

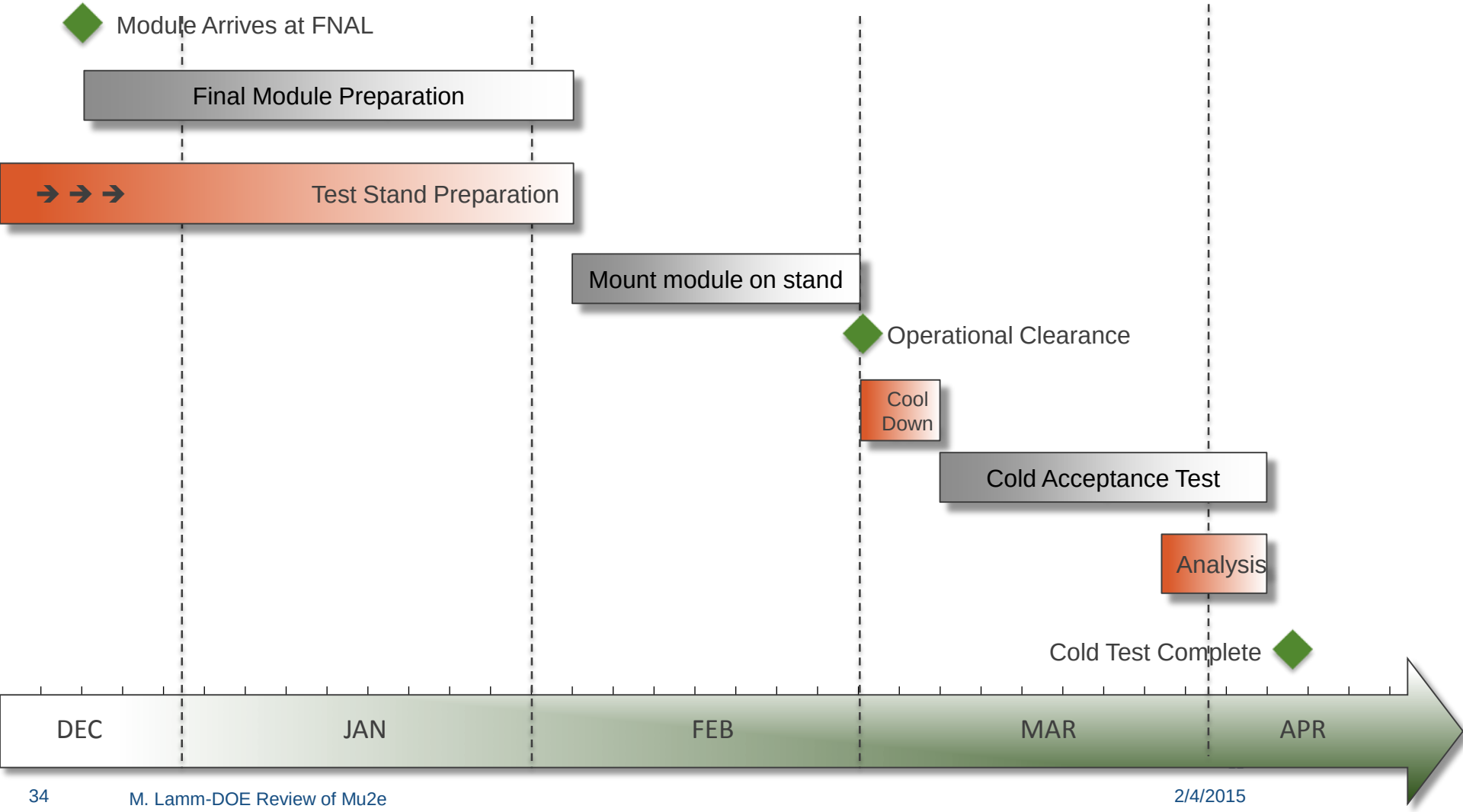
TS Facility Preparation Continues

- Significant progress made ahead of TS module delivery
  - Modify infrastructure for HTS power leads
  - Power supply with quench protection and extraction
  - Thermal shield
  - Mechanical supports to hang “elbow shaped” module from test facility top plate
- Facility is now ready to accept TS prototype module

3-D Model of TS Prototype in the Test Facility



TS Prototype Module Schedule



3. TS Module Procurement and Fabrication Readiness

Status of Procurement

1. Drawings Complete and signed off: Over 300 drawings!
2. Procurement Specification Completed
3. Reference Documents Complete
4. Assembly procedure complete
5. 1-4 presented to AOC on January 26, 2015
   - Individual committee members file reports with recommendations
   - All recommendations will be addressed prior to readiness review

Presented here is the plan for procurement

Request for Proposal Documents

Similar to successful Production and Detector Solenoid procurements. Working closely with Fermilab Procurement to assemble documentation for bid package

- Procurement-Generated Documents
  - Terms and Conditions
  - Warranties
  - Bid options
    - For example opportunity to bid on TSu/TSd or both
- Mu2e-Generated Documents
  - Reference Design Reports
  - Procurement (Technical) Specifications
  - Drawings and 3-D Models

Procurement Specification

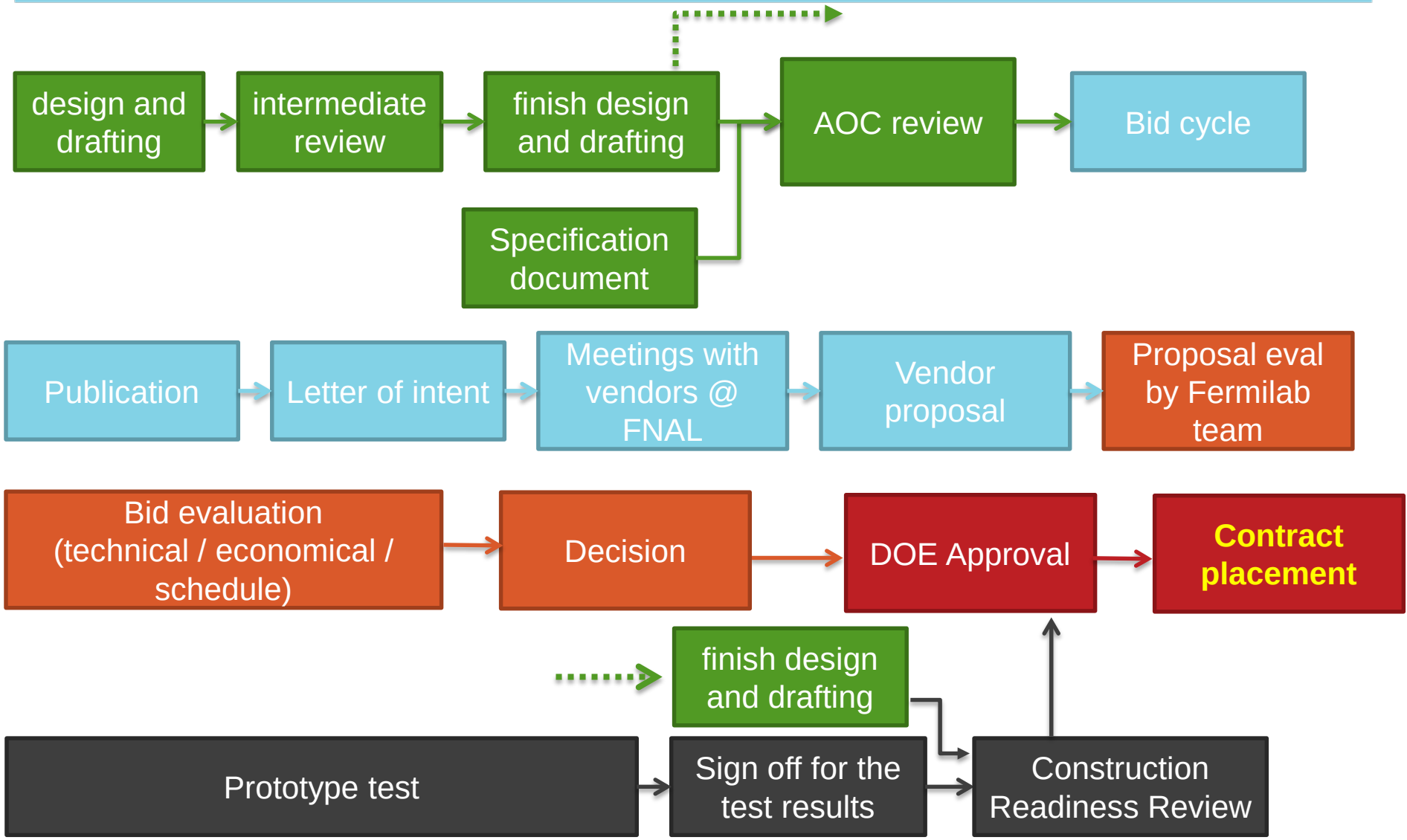
Using guidelines from Fermilab Engineering Handbook, the procurement specification documentation:

- Describes scope of work.
- Lists “technical requirements”
  - Reference to drawings
- Includes a responsibility matrix to define Buyer vs. Seller responsibilities
- Lists required codes and standards
- Lists documents to be supplied by vendor in bid package
- Lists materials and documents that we will supply to vendor
- Describes documentation that vendor must deliver with completed modules
- Spells out QA plan requirements

Bid Cycle

- 8 week bid cycle.
- Begin: Procurement places offering on Procurement Web Site, advertise on FED BIZ OPS, notify known vendors
- After two weeks - Vendors must formally respond that they are interested in bidding (we will limit future communications to vendors who respond).
- Week 3 - Invite interested/selected vendors to Fermilab for a one day information session
- Require vendor questions to be submitted by the end of week 6.
  - We want to avoid last minute request for clarifications that would delay bid cycle
  - Lesson learned from PS/DS bid campaign
- Proposals will be collected by Procurement, cost information separated from technical proposal, in preparation for technical evaluation

Road map for the TS module procurement



Summary

- Solenoid Designs are well understood and meet requirements
- TS Module design complete. It is robust and well documented.
- Successful External Independent Design Review in December.
- TS Module Prototype evaluation proceeding. Excellent results thus far.
- Procurement of TS Coil Modules is following a course similar to the successful Mu2e Conductor and PS/DS
  - Organized procurement with well defined requirements and responsibilities and evaluation plan.
  - We have benefited from “lessons learned” from previous and ongoing procurements (as presented in detail at the October CD2/CD3b review)
  - Is a minimal risk to the project
- Ready for CD3b
- On track for approval to procure in April following a successful prototype test.