WBS 475.04.07 Quench Protection and Monitoring

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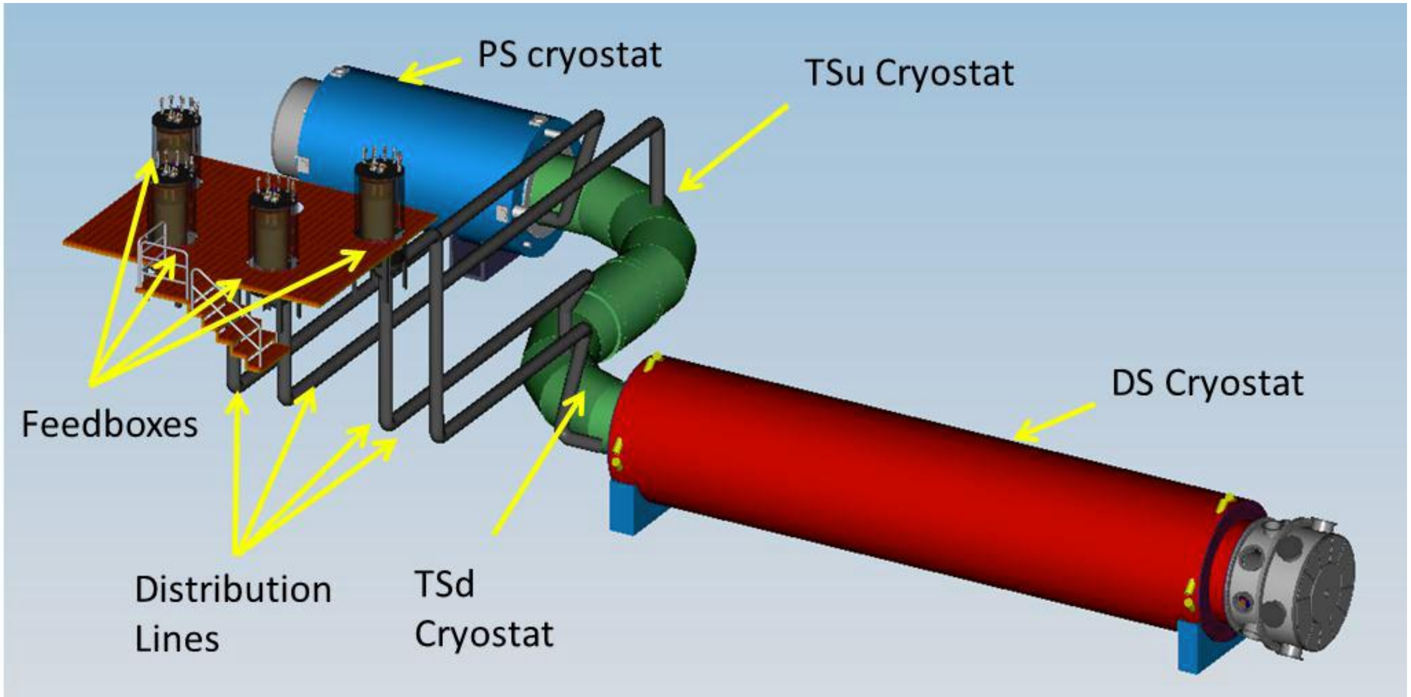
7/8/2014

Quench Protection Requirements

- The quench protection system is responsible for the safe operation (equipment and ES&H) of the Mu2e solenoids and associated power bus system.
- Monitors signals from sensors – typically voltage taps – installed on the mu2e solenoid coils, leads, and superconducting power bus and generates an interlock signal if the sensor signal exceeds a specified threshold. The interlock signal will trigger the ramp down of the power supplies and switch in the energy extraction circuit to remove stored energy from the magnet.
- The primary goal of the mu2e quench protection system is to reliably detect true quenches while the secondary goal is to minimize the number of falsely detected quenches.
- Quench detection of the mu2e solenoids is complicated by the mutual coupling between the multiple magnets. As individual magnets are ramped, the changing magnetic field will induce voltages in the other coils that, if not taken into account, can cause false quench detection events.

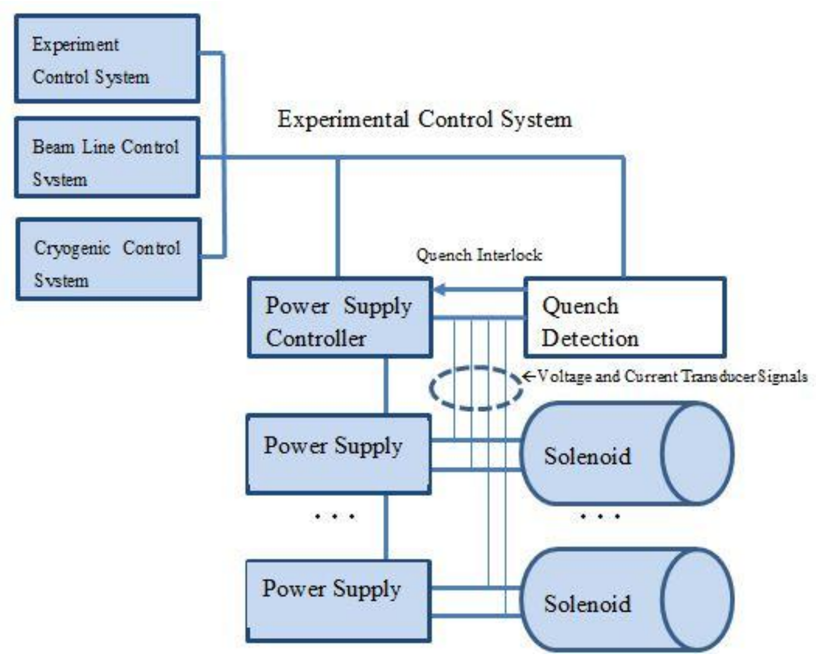
Quench Detection Requirements



- The Quench Protection Scope Includes:
  - The PS, TSu, TSd, & DS Solenoids
  - All Solenoid Superconducting Leads & Trim Bus
  - All the Superconducting Bus Bars (Distribution lines)
  - All the HTS Leads (Feedboxes)
  - & Resistance Threshold Detection of All Copper Leads (Feedboxes)

Quench Protection Requirements

- The Quench Protection System will Require Redundancy and Failsafe Design with Heterogeneous Subsystems
- Design for High Availability (Low Hardware Maintenance / Downtime)
- System Integration: The mu2e Quench Protection System must communicate with the Solenoid Power System, Cryogenic Controls, Quench DAQ, Experimental Controls, and Beam Line Controls.



Quench Protection Design

- Quench development in each of the mu2e solenoids has been simulated using both quench specific computer codes such QLASA and more general simulation packages such as COMSOL Multi-physics
  - The expected quench characteristics for each of the solenoids is listed below:

	Units	PS	TS	DS
Longitudinal Quench Velocity	m/s	4.78	4.20	4.80
Radial Quench Velocity	m/s	0.06	0.04	0.13
Axial Quench Velocity	m/s	0.04	0.06	0.10
Response Time	s	0.3	0.8	1
Threshold	V	0.5	1	1
Peak Resistive Voltage	V	330	16	170
Peak Temperature	K	90	47	55

Quench Protection Design

- Solenoid and power supply system parameters relevant to quench detection are summarized below:

Parameter	Unit	PS	TSu	TSd	DS
Operating temperature	K	<5.1	5.0	5.0	4.7
Maximum design current	A	9200	1730	1730	6114
Peak field in coil	T	5.48	3.4	3.4	2.15
Current fraction along load line at 4.5 K	%	63	58	50	45
Inductance	H	1.58	4.77	3.79	1.4
Stored energy	MJ	66.7	7.14	5.67	26.1
Cold mass	tons	10.9	13	13	10
E/m	kJ/kg	6.75	0.61	0.48	2.88
Dump Resistance	Ohms	0.059	0.340	0.340	0.050

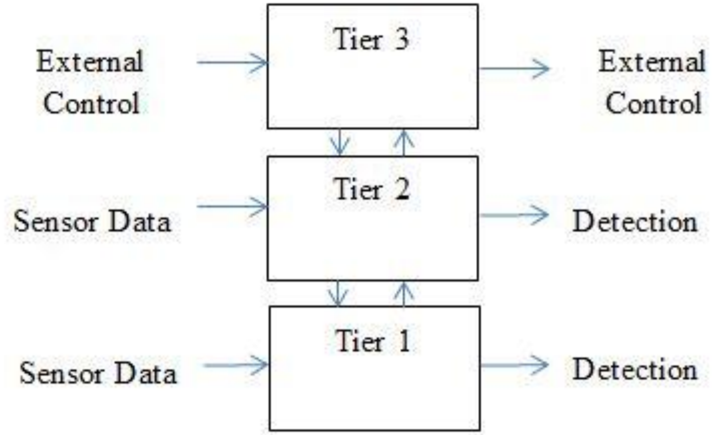
- The characteristic signals expected from quenches in each of the mu2e solenoids were modeled using QLASA quench detection simulation program written and maintained by INFN
  - This was done to determine the detection sensitivity and response time required for the design of the quench detection system

Quench Protection Design

- The threshold voltages and response times are well within the capabilities of the quench detection system design
- The quench detection system will also be capable of rejecting inductive voltages from mutually coupled solenoids
  - A simulator that models the operation of the four magnetically coupled solenoids and the coupled inductive voltages has been implemented in an FPGA and tested
    - Used to determine expected voltages from ramping magnetically coupled solenoids
    - The simulator could be incorporated into a quench detector to improve coupled voltage rejection
  - A prototype quench detection system will be parasitically tested during a test of the mu2e prototype solenoid at the Fermilab Solenoid Test Facility (SolTF)

Quench Protection Design

- Quench Detection System Architecture –
  - Redundancy ensures that quenches will be detected even in the event of single point failures and that any single point failure can be detected and corrected when they occur. The use of heterogeneous components minimizes the likelihood that undetected design errors will be duplicated in the redundant channels.
  - To ensure reliable detection of true quenches while remaining immune to false quenches, the mu2e quench detection system is organized into three heterogeneous redundant tiers shown below:



Quench Protection Design

- The quench protection system is modeled after existing systems designed and built in the Technical Division for testing superconducting magnets:
  - The Vertical Magnet Test Facility (VMTF) with its 30kA DC power system uses a Digital Quench Detection system (primary) running on a real-time operating system and an Analog Quench Detection system (secondary) for redundancy
    - In service since 1997
    - Tested LHC short magnets, High Field R&D magnets, LARP short magnets, etc.
  - Most recently, the new Fermilab Solenoid Test Facility (SolTF) uses a National Instruments C-RIO based Quench Detection System with FPGA / Real-Time for Digital Quench Detection and Analog Quench Detection for redundancy
    - The Test Stand was commissioned in 2013
    - Testing of the MICE Coupling Coil Solenoid (L=596H) was successfully completed in May, 2014

QP Changes since CD-1

- None

QP Value Engineering since CD-1

- The quench protection system will be based on designs similar to proven systems currently used in the TD Magnet Test Facility
  - Less expected risk of design issues that could cost more effort
- The quench protection system will be based mostly on commercial hardware with long term support
  - The exception are in-house built isolation amplifiers but the current design is mature and has been in service for several years

24/32 Channel Isolation Amplifier Box: Uses USB and Serial Peripheral Interface (SPI) Bus

QP Performance

- The quench detector performance will be validated using a real-time simulator
  - A simulator that models the operation of the four magnetically coupled solenoids and the coupled inductive voltages has been implemented in an FPGA and tested
- The threshold voltages and response times are well within the capabilities of the quench protection system design
- The quench protection system design incorporates redundancy by:
  - Instrumenting redundant quench sensors and wires from each device (magnet, bus, and leads)
  - Redundant isolation amplifiers and quench detectors

QP Remaining work before CD-3

- A prototype quench detection system will be assembled and tested parasitically on the prototype TS solenoid test at SolTF
- The detailed engineering design will be completed following the test of the prototype system

QP Quality Assurance

- Multiple mechanisms to ensure quality of design and implementation
  - Peer review
  - Independent coding of redundant systems
  - Extensive validation using real-time simulator
  - Validation against existing QP systems during multiple mu2e prototype and production magnet tests
  - Formal testing to relevant accepted industry standards
- Comprehensive validation against offline system models during commissioning of the final product
- Development team has extensive experience designing and developing quench protection systems, which have been in service for many years

QP ES&H

- The final product will have solenoid voltage tap cabling that carries voltages up to 600V (when the dump is fired). These cables are terminated in a relay rack to the inputs of isolation amplifiers. Since these cables may be accessible to personnel during powered operation, steps will be taken to prevent accidental exposure in accordance with the Fermilab Electrical Safety Program (FESHM 5040).
- Instrumentation rack power will also follow the Fermilab Electrical Safety Program (FESHM 5040).

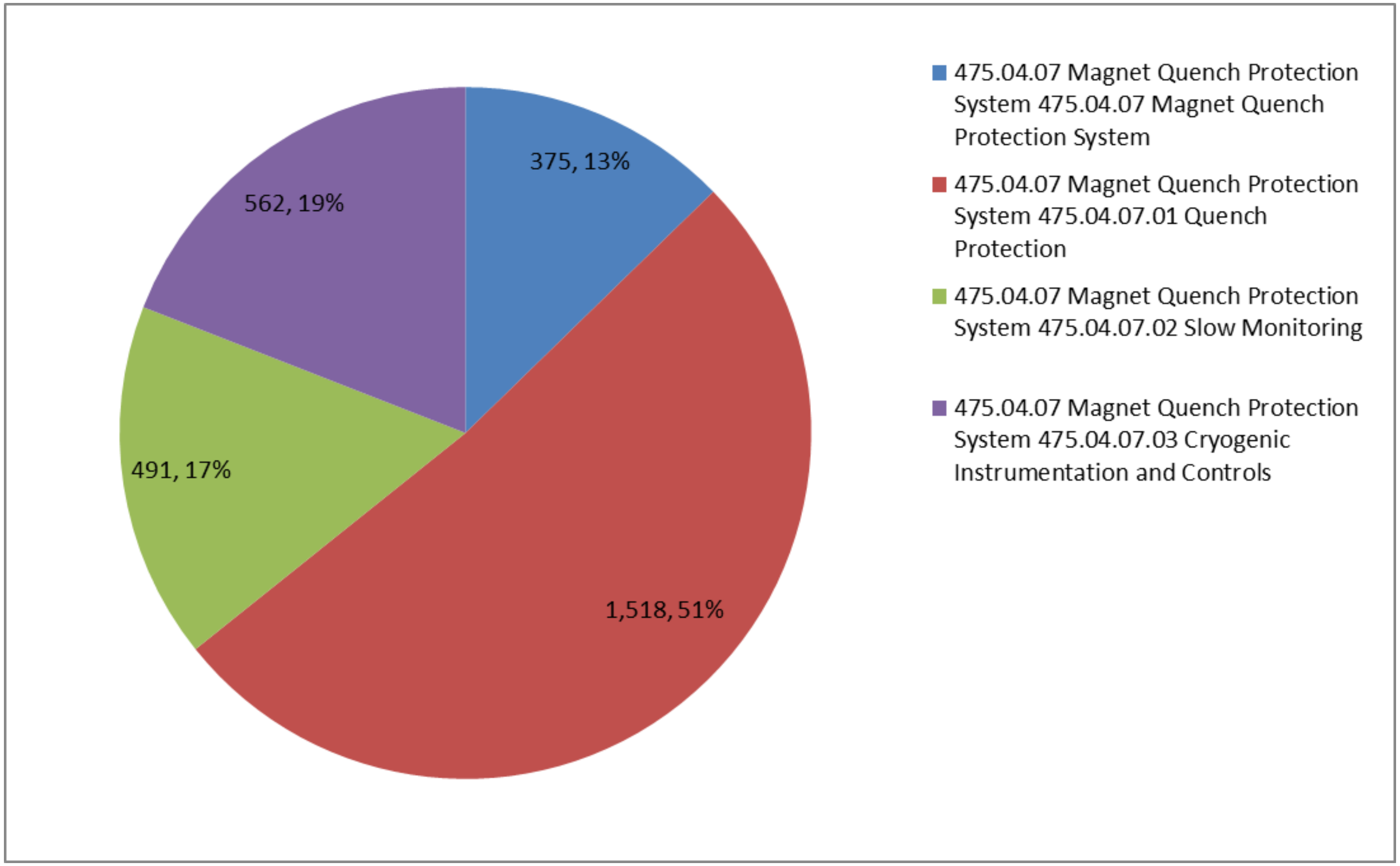
Cost Table

- Quench Protection & Monitoring Base Cost Table

	Base Cost (AY k$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining costs)	% Contingency on ETC	Total Cost
475.04 Solenoids						
475.04.07 Magnet Quench Protection System						
475.04.07 Magnet Quench Protection System Actu	2	373	375			375
475.04.07.01 Quench Protection	210	1,308	1,518	615	41%	2,133
475.04.07.02 Slow Monitoring	238	253	491	201	41%	693
475.04.07.03 Cryogenic Instrumentation and Contr	275	287	562	238	43%	800
Grand Total	726	2,220	2,946	1,055	41%	4,001

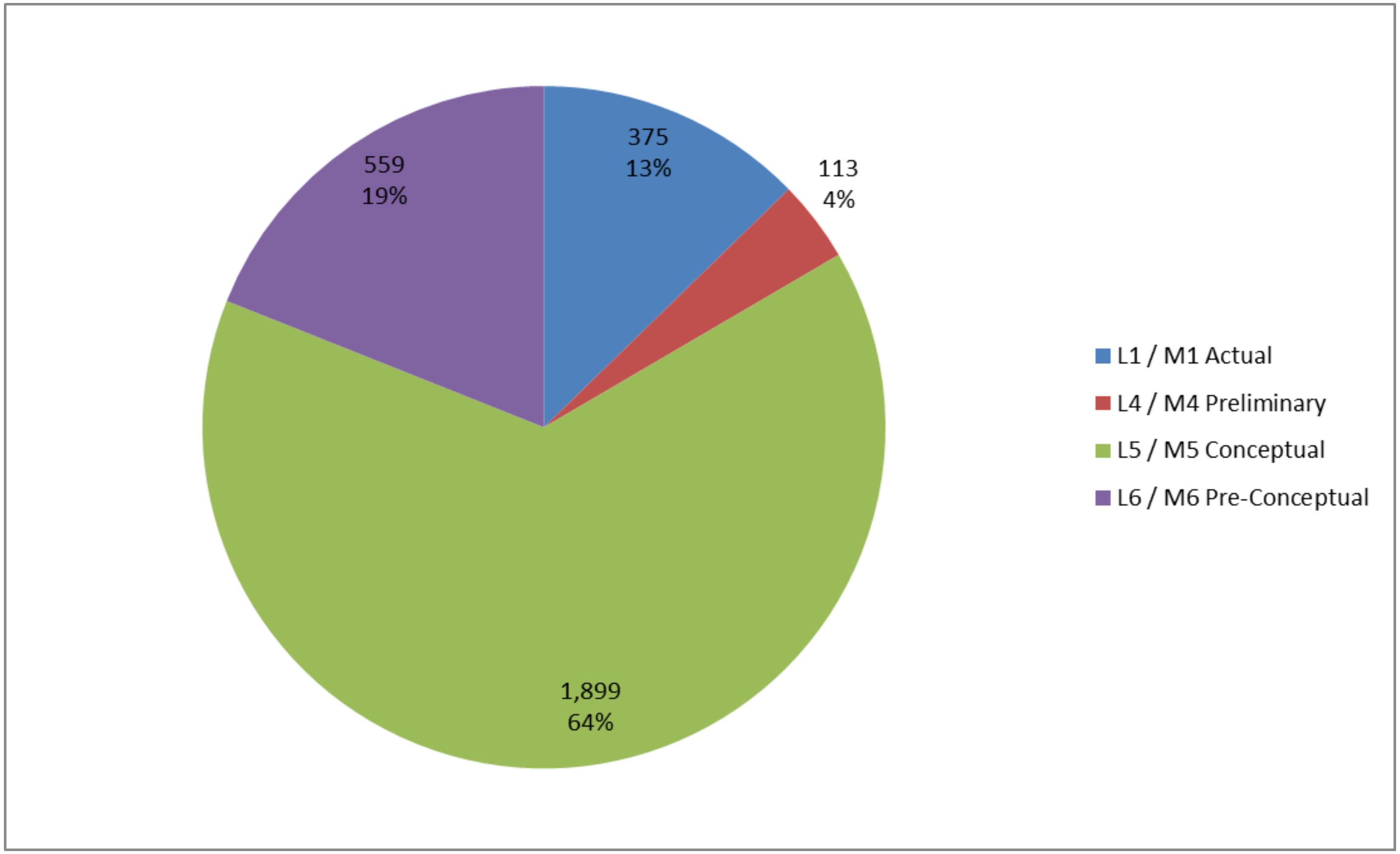
Cost Breakdown

- Quench Protection & Monitoring WBS Breakdown (AY K$)



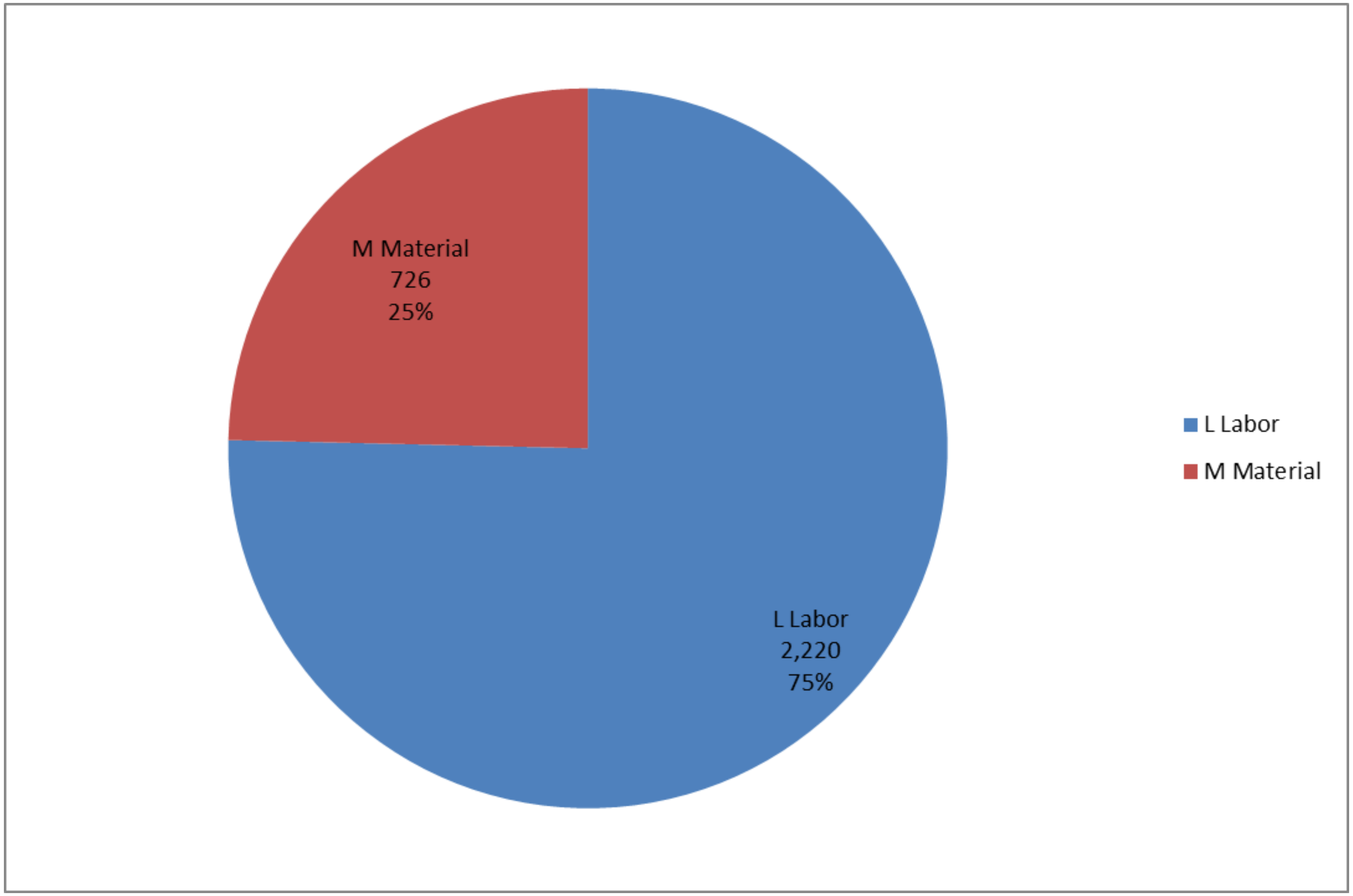
Quality of Estimate

- Quench Protection & Monitoring Quality of Estimate (K$)



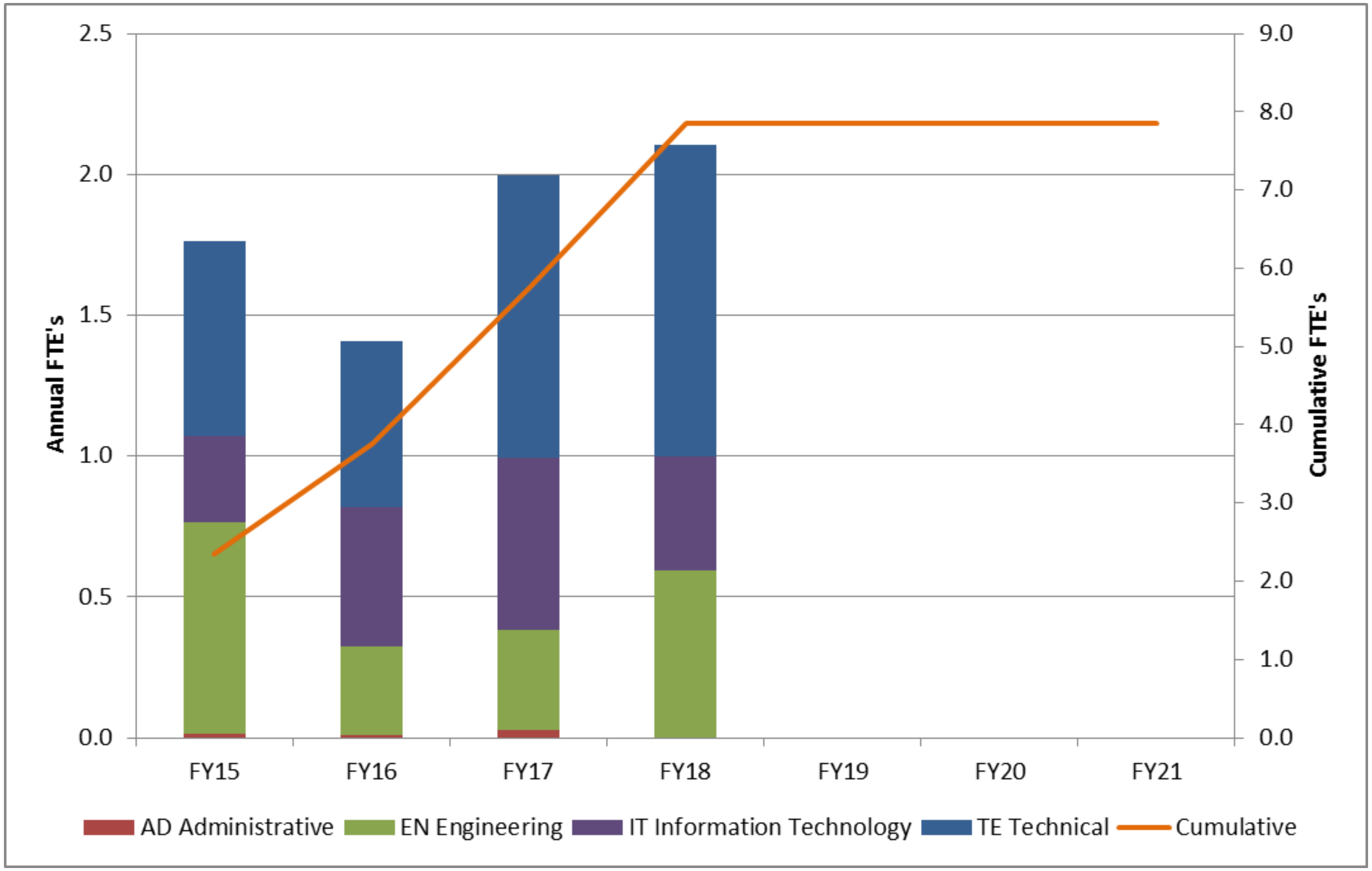
Resource Type

- Quench Protection & Monitoring Resource Type



Labor Resources by FY

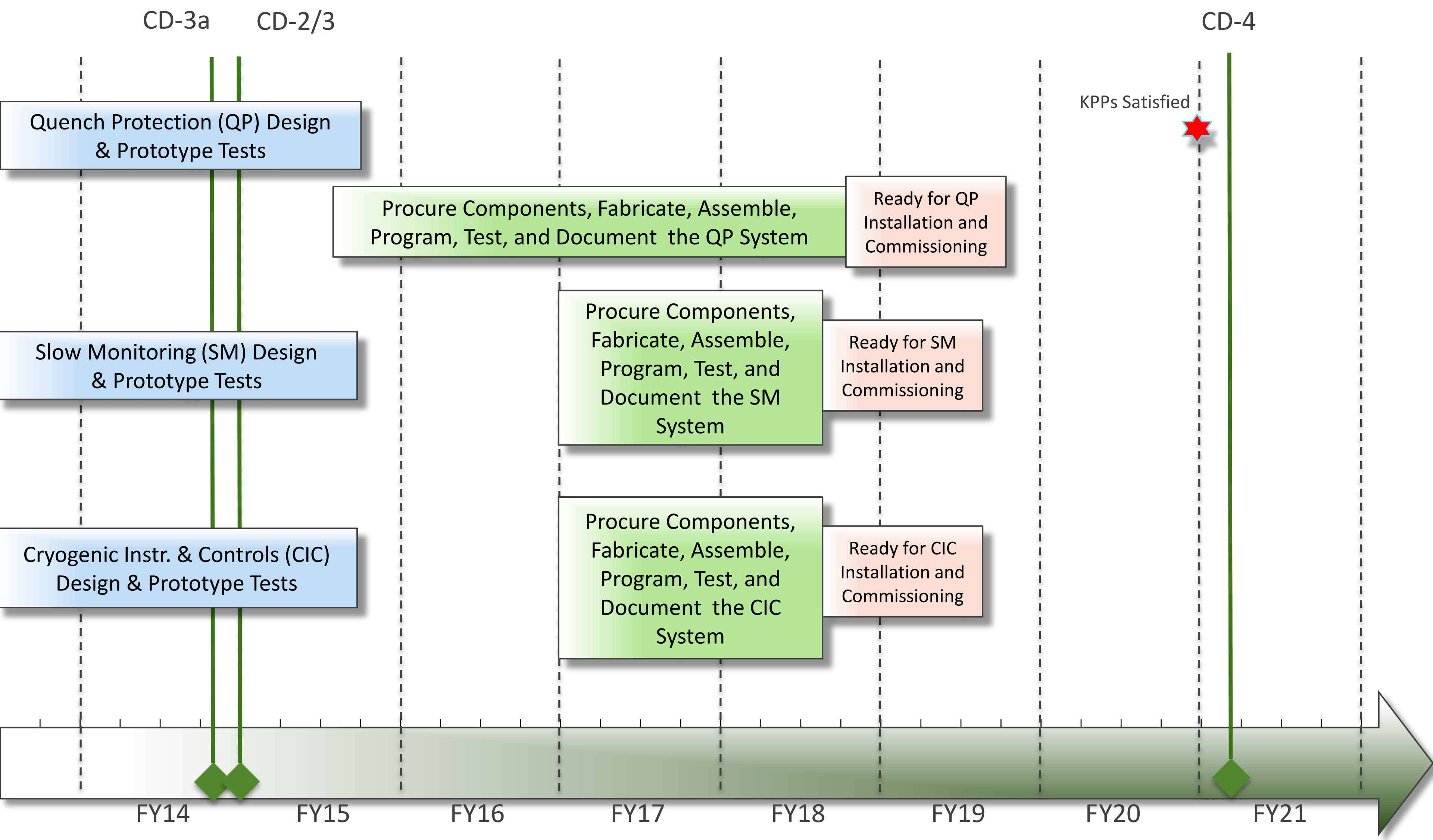
- Quench Protection & Monitoring FTE's by Discipline



Major Milestones

- Complete the Detailed Engineering & Software design for Quench Detection (02/25/2016)
- Perform Preliminary Quench Protection Integration Tests (08/02/2018)

Schedule



CD-3a
CD-2/3
CD-4
KPPs Satisfied
Quench Protection (QP) Design & Prototype Tests
Procure Components, Fabricate, Assemble, Program, Test, and Document the QP System
Ready for QP Installation and Commissioning
Slow Monitoring (SM) Design & Prototype Tests
Procure Components, Fabricate, Assemble, Program, Test, and Document the SM System
Ready for SM Installation and Commissioning
Cryogenic Instr. & Controls (CIC) Design & Prototype Tests
Procure Components, Fabricate, Assemble, Program, Test, and Document the CIC System
Ready for CIC Installation and Commissioning
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Summary

- The Quench Protection and Monitoring system includes the mu2e solenoid magnets and bus Quench Protection system, the mu2e solenoid Slow Logging system, and the Cryogenic Controls for the mu2e cryogenic distribution

- The quench protection system is largely based on commercial hardware and the design is similar to the heterogeneous combination of digital and analog quench detection systems used for the superconducting magnet test stands in TD

- The cryogenic controls and slow logging systems are also based on system design and operational experience of cryogenic controls systems for experiments and magnet testing at Fermilab

Slow Monitoring Requirements - Backup

- Provide Slow Monitoring of Solenoid Specific Instrumentation
  – Coil Splice Resistance Measurements – requires voltage isolation & high resolution
  – Readout of Cernox and Platinum RTDs to measure Solenoid Temperatures of:
    - Cold Mass temperatures
    - Warm-up & Cool-down temperatures
    - Supply& Return Temperatures
    - Shield temperatures
  – Strain Gauge readout of solenoid supports – full bridges using SG rosettes
  – RRR Resistance Readout – accurate measurement of aluminum witness samples
  – Displacement Sensors – of supports
  – Field Map Hall Probes
- Provide necessary accuracy and resolution for associated measurement
- Data archiving, trending, analysis

Slow Monitoring Design - Backup

- System based on existing designs for reading out large numbers of multiple sensors types for magnet testing in TD
- Using Commercial Hardware – Keithley Integrated DMM/Switch Instruments
  - Precision DMM with six slots for multiplexors – large number of channels
- Will use Siemens S7 PLC controller with warm backup
  - Same as the systems currently used at the Muon campus

SM Value Engineering since CD-1 - Backup

- Since the system is controlled by a Siemens S7 PLC controller, which will be used for other mu2e controls, it can be easily maintained by controls staff and spare controller parts can be shared
- The Slow Monitoring system is also based on designs similar to proven systems currently used in the TD Magnet Test Facility
  - Less R&D effort and less risk of design issues
- The Slow Monitoring system will be based mostly on commercial hardware with long term support
  - The exception are in-house built Current Sources but the existing design is mature and has been in service for several years in the Magnet Test Facility for SGs and RTDs

SM Remaining work before CD-3 - Backup

- The detailed engineering design for Slow Monitoring will be completed following the test of the prototype system

Slow Monitoring Quality Assurance - Backup

- Multiple mechanisms to ensure quality of design and implementation
  - Peer review
  - Formal testing to relevant accepted industry standards
- Development team has extensive experience designing and developing PLC Controls and Slow Monitoring systems
  - The PLC controls will be developed and implemented by PPD controls staff using the same controls hardware used on the Muon campus
  - The same Slow Monitoring hardware (minus the PLC) was recently used in the design of the Slow Monitoring system of the new Fermilab Solenoid Test Facility (SolTF) developed by TD

SM Major Milestones - Backup

- Complete the Slow Monitoring Detailed Engineering design (02/18/2015)
- Perform Slow Monitoring Preliminary Integration Tests (03/28/2018)

Cryogenic Controls Requirements - Backup

- Provide Controls for the Cryogenic Distribution System
  - ~160 Cryogenic Distribution Instruments
- Process control Process Variables (PVs) for Readout & Control include:
  - Differential Pressure Transducers – 6
  - Pressure Transducers – 26
  - Liquid Level – 7
  - Flow Meters – 8
  - Platinum Temperature Sensors – 25
  - Cernox Temperature Sensors – 39
  - Heater Control – 3
  - Valve Controllers – 47
- Provide necessary accuracy and resolution for associated measurement
- Provide PID Control Loops
- Interface with Quench Protection, Power System, and Experiment Controls

Cryogenic Controls Design - Backup

- Will use Siemens S7 PLC controller with warm backup
  - System based on proven design of existing systems at Muon Campus
  - Will easily integrate with other controls systems including the power system, slow logging, quench protection
- Using all Commercial PLC Hardware

CC Value Engineering since CD-1 - Backup

- The Cryogenic Controls will be based on designs similar to proven systems currently used on Muon campus
- The Cryogenic Controls system will be based on commercial hardware with long term support
- Since the system is controlled by a Siemens S7 PLC controller, which will be used for other mu2e controls, it can be easily maintained by controls staff and spare controller parts can be shared

CC Remaining work before CD-3 - Backup

- The detailed engineering design for Cryogenic Controls will be completed following the test of the prototype system

Cryo Controls Quality Assurance – Backup

- Multiple mechanisms to ensure quality of design and implementation
  - Peer review
  - Formal testing to relevant accepted industry standards
- Development team has extensive experience designing and developing PLC Controls
  - The PLC controls will be developed and implemented by PPD controls staff using the same controls hardware used on the Muon campus

CC Major Milestones - Backup

- Complete the Cryogenic Controls Detailed Engineering design (02/18/2015)
- Perform Preliminary Cryogenic Controls Integration Tests (03/28/2018)

QP Backup Slide (Performance)

- The following table shows the maximum current ramp rates required to keep the induced voltages on corresponding solenoids to 0.1 of V_{thresh} when no rejection of coupled inductive voltages:

Parameter	Solenoid Ramped			
	PS	TSu	TSd	DS
PS,V	1.106	0.030	0.001	0.001
TSu, V	0.103	0.954	0.099	0.005
TSd, V	0.005	0.099	0.758	0.096
DS, V	0.001	0.002	0.038	0.7
Ramp Rate (A/sec)	0.7	0.2	0.2	0.5
PS Max Current (A)	9200.00	1730	1730	6114.00
Ramp time (hours)	3.65	2.40	2.40	3.40

Numbers in RED are self-inductance Voltages

  - Higher ramp rates will be achieved by determining the mutual inductance coefficients and rejecting the associated voltages. This will be done in the digital quench detectors.
  - The quench detectors numerically solve differential equations for a system of coupled magnets in real-time.