WBS 475.04.07 Quench Protection and Monitoring

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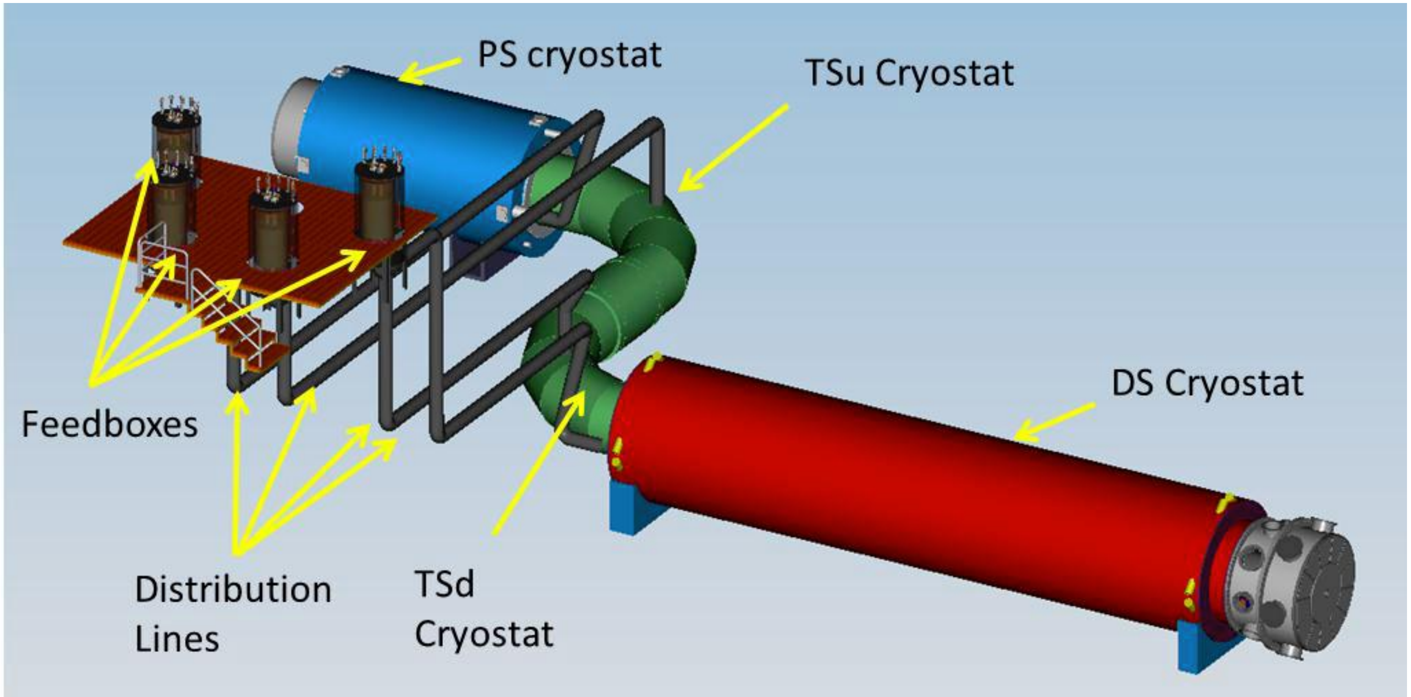
Quench Protection Requirements

- 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 is complicated by the mutual coupling between the independently powered magnets. As individual magnets are ramped, the changing magnetic fields will induce voltages in the other magnets that, if not taken into account, can cause false quench detection events.

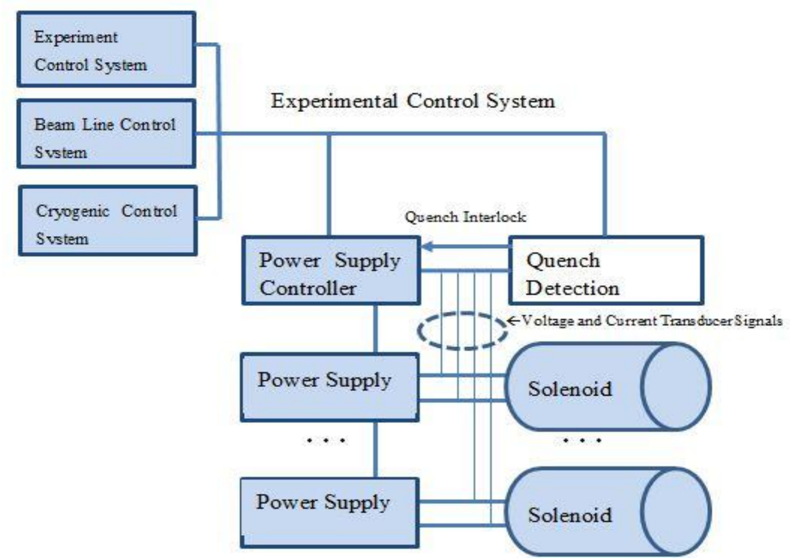
Quench Detection Requirements



- 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)
- Design for High Reliability (minimize false quench triggers)
- 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 quench characteristics for each of the magnets are listed below:

	Units	PS	TS	DS
Longitudinal Quench Velocity	m/s	4.20	4.20	4.80
Radial Quench Velocity	m/s	0.05	0.04	0.13
Axial Quench Velocity	m/s	0.08	0.06	0.10
Response Time	s	0.6	0.8	1
Threshold	V	0.5	1	1
Peak Resistive Voltage	V	112	16	170
Peak Temperature	K	69	47	55

Quench Protection Design

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

Parameter	Unit	PS	TSu	DS
Operating temperature	K	<5.1	5.0	4.7
Design operating current	A	9200	1730	6114
Peak field in coil	T	4.96	3.4	2.15
Inductance	H	1.58	4.77	1.4
Cold mass	tons	10.9	13	10
Dump Resistance	Ohms	0.059	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 verify the detection sensitivity and response times required for the design of the quench detection system using the same simulation tool
    - Studies include quench development versus fractional Iq

Quench Protection Design

- It was determined that the threshold voltages and response times are well within the capabilities of the quench detection system design:
  - Required threshold voltages of 0.5V-1.0V – expect sensitivity <50mV
  - Required response times of 0.6s-1.0s – expect response <5ms
- A 1/3 coil bucking scheme is expected to be implemented
  - This scheme will allow quenches to be detected even if they develop symmetrically between two bucked segments
    - The 1/3 bucking scheme: Seg1-Seg2, Seg1-Seg3, Seg2-Seg3
    - Segments will be chosen to optimize inductive balance
  - The following is a table of bucking segments chosen for initial study:

Magnet	Segment 1	Segment 2	Segment 3
PS	Layers 1-2	Layers 3-4	Layers 5-7
TSu	Coils 1-11	Coils 12-18	Coils 19-25
TSd	Coils 26-33	Coils 34-39	Coils 40-47
DS	Coils 1-3	Coils 4-7	Coils 8-11

Quench Protection Design

- The 1/3 bucking scheme will also improve bucked errors due to voltages from coupled coils
  - A 12x12 mutual inductance matrix (based on a 792 layer model) was generated to determine coupled voltages for the 4 magnets
  - The following table lists magnet ramp rates that will induce bucking errors due to coupled inductive voltages at 10% quench thresholds:

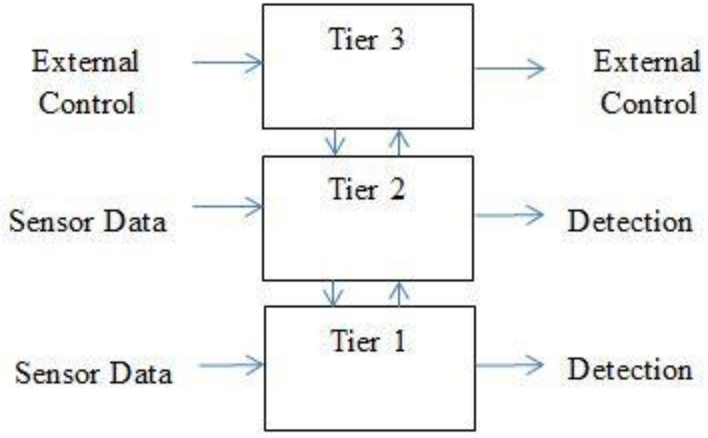
Magnet	Nominal Current	Quench Threshold	Bucked Segments	Bucked Voltage Error (Mutual Induc. Voltages not Subtracted)			
PS	9200	0.5	PS 1-2	0.000	-0.003	0.000	0.000
			PS 2-3	0.000	-0.023	0.000	0.000
			PS 3-1	0.000	0.018	0.000	0.000
TSu	1730	1.0	TSu 1-2	0.090	0.000	-0.005	-0.001
			TSu 2-3	0.005	0.000	-0.100	-0.002
			TSu 3-1	-0.099	0.000	0.100	0.003
TSd	1730	1.0	TSd 1-2	0.002	0.080	0.000	-0.005
			TSd 2-3	0.001	0.003	0.000	-0.069
			TDs 3-1	-0.003	-0.100	0.000	0.099
DS	6114	1.0	DS 1-2	0.000	0.000	0.028	0.000
			DS 2-3	0.000	0.000	0.006	0.000
			DS 3-1	0.000	-0.001	-0.038	0.000
			Solenoid Ramped	**PS**	**TSu**	**TSd**	**DS**
			Ramp Rate (A/sec)	1.55	0.37	0.45	1.25
			Ramp Time (Minutes)	98.92	77.93	63.93	81.52

Quench Protection Design

- The quench detection system will be capable of rejecting inductive voltages from mutually coupled solenoid coils
  - Bucking out the voltages from coupled coils will allow the magnets to be ramped simultaneously at a much greater ramp rate
    - An FPGA 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 and can be used for QP system tests
  - A prototype quench detection system that rejects coupled voltages will be parasitically tested during a test of the mu2e TS prototype solenoid at the Fermilab Solenoid Test Facility (SolTF)
  - System identification used to measure coupling coefficients

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 (AQD) 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 (AQD) for redundancy
    - The Test Stand was commissioned in 2013
    - Testing of the MICE Coupling Coil Solenoid (L=596H) was successfully completed in May, 2014
- HTS power leads have been extensively tested to 10.15kA in TD using a similar FPGA / AQD based quench detection system

QP Improvements Since CD-1

- Incremental changes have been made to the QD architecture for greater reliability and sensitivity of quench detection
- Improvements have be made to the coil bucking design including subtraction of mutual inductive voltages
- Developed an FPGA based quench simulator that will be used for quench detection modeling and validation tests of the completed QD system
- Slow logging of the magnet instrumentation will be controlled by an independent PLC, which will be integrated/interfaced with the cryogenic and experiment's DAQ and controls

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 – improve on existing designs
  - 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

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

QP Performance

- 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
- The quench detector performance will be validated using a real-time simulator
  - A simulator that models the operation of the four magnetically coupled magnets and the coupled inductive voltages has been implemented in an FPGA and tested
- When a quench is detected, all magnets will be de-energized

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

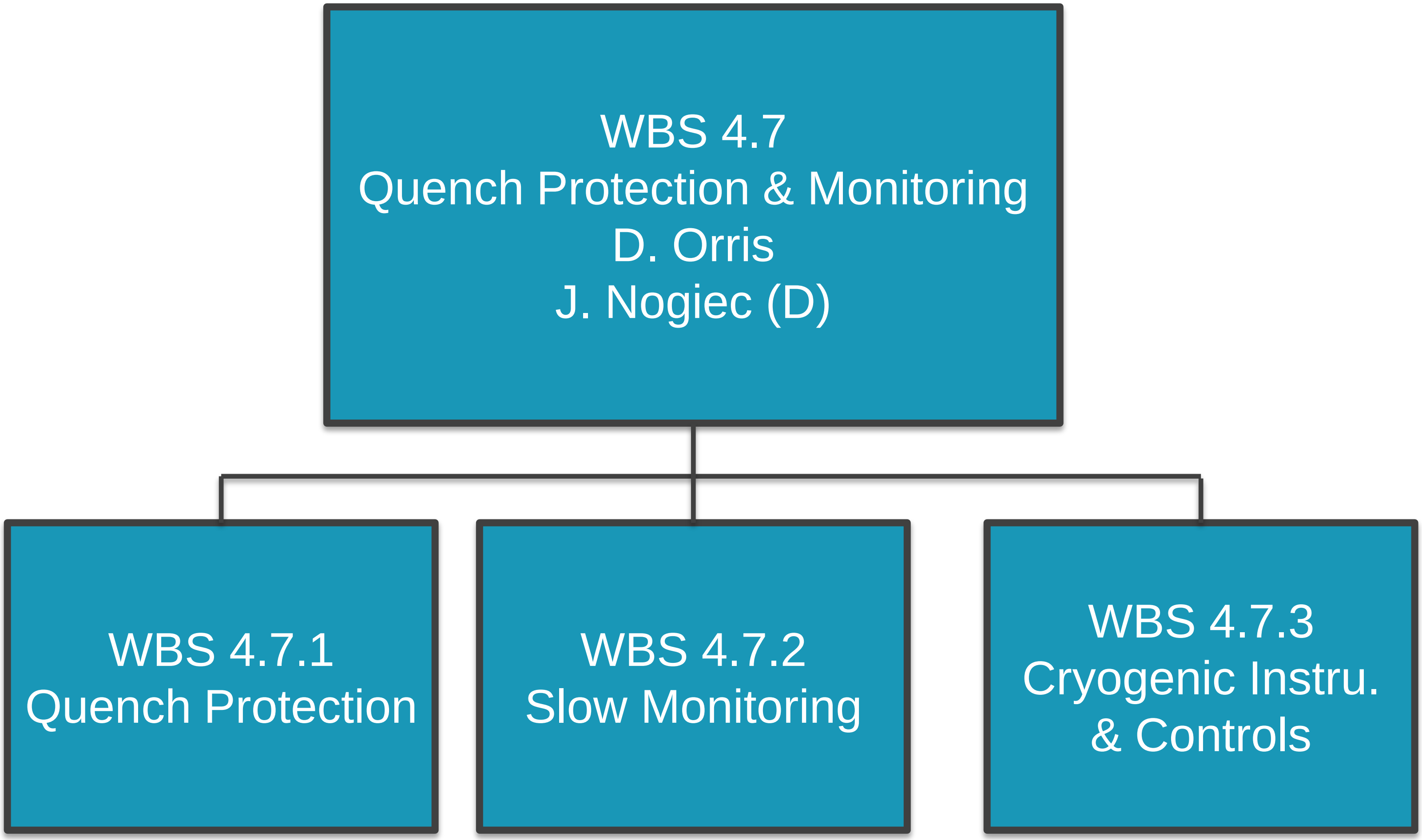
QP Quality Assurance

- 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 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

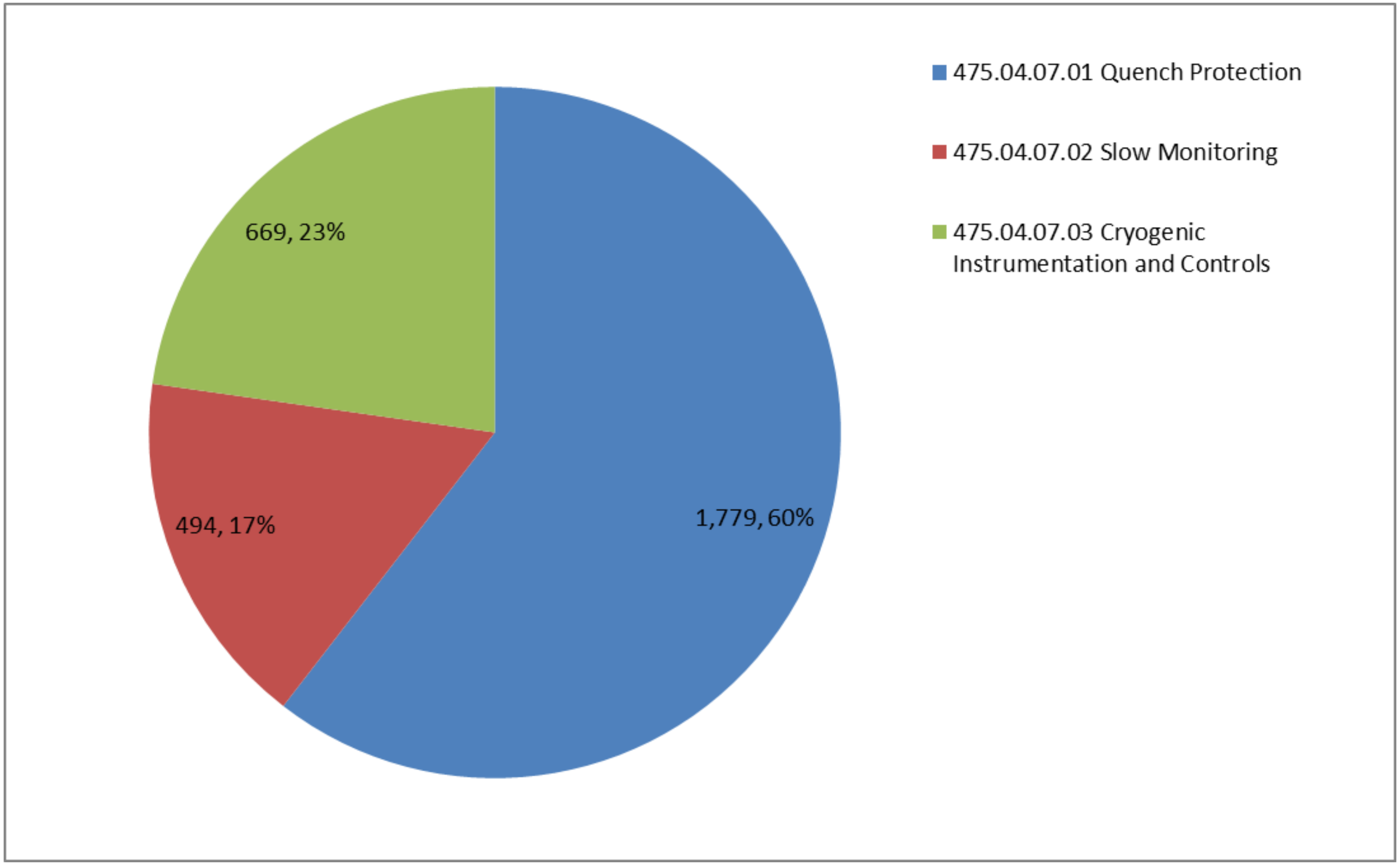
- The final product will have solenoid voltage tap cabling that carries voltages up to 600V (when the dump is fired). These cables are terminated in a relay rack to the inputs of isolation amplifiers. Since these cables may be accessible to personnel during powered operation, steps will be taken to prevent 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).

QPM Organizational Breakdown



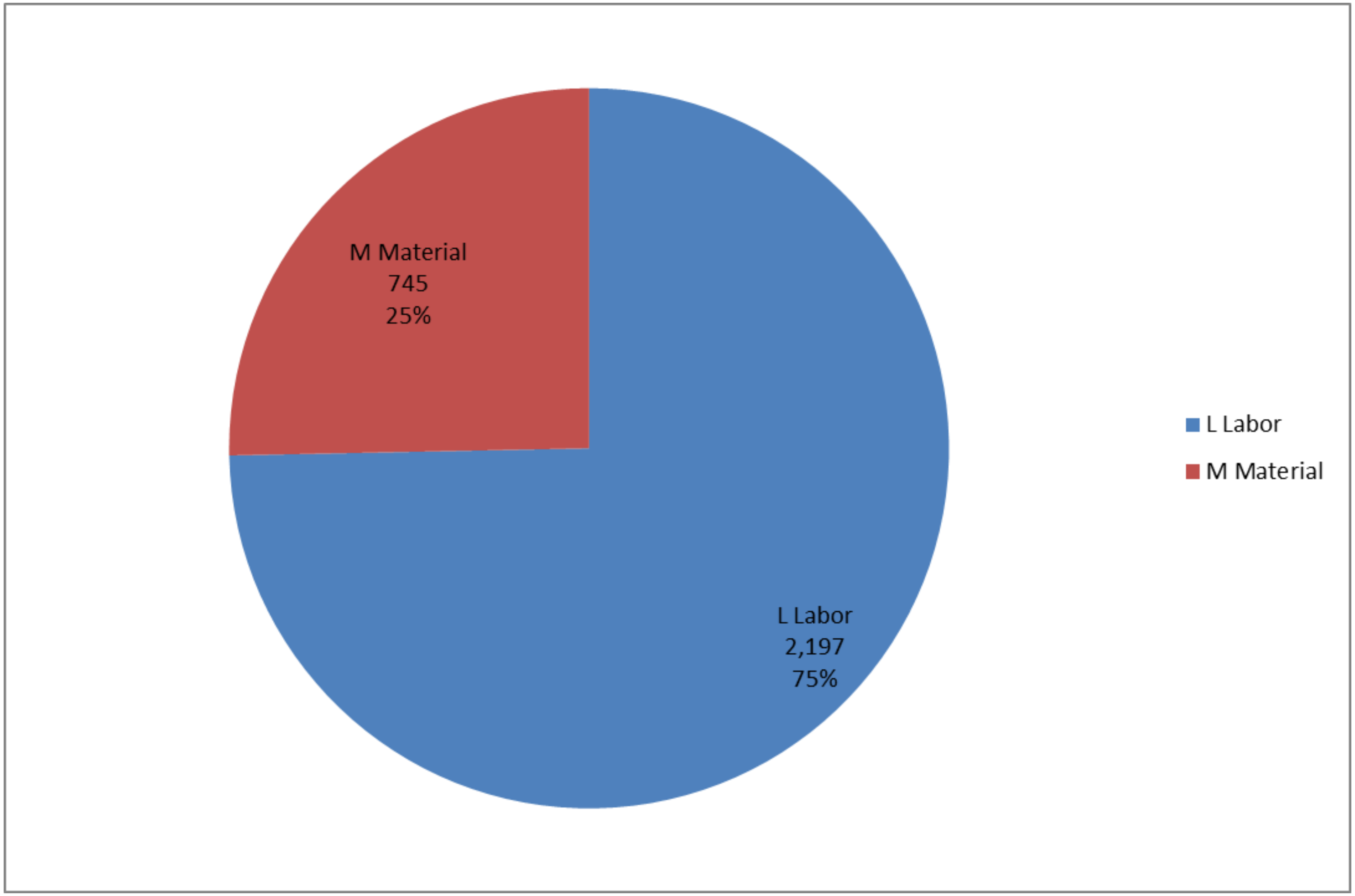
QPM Cost Distribution by L4

- Base Cost by L4 (AY $k)



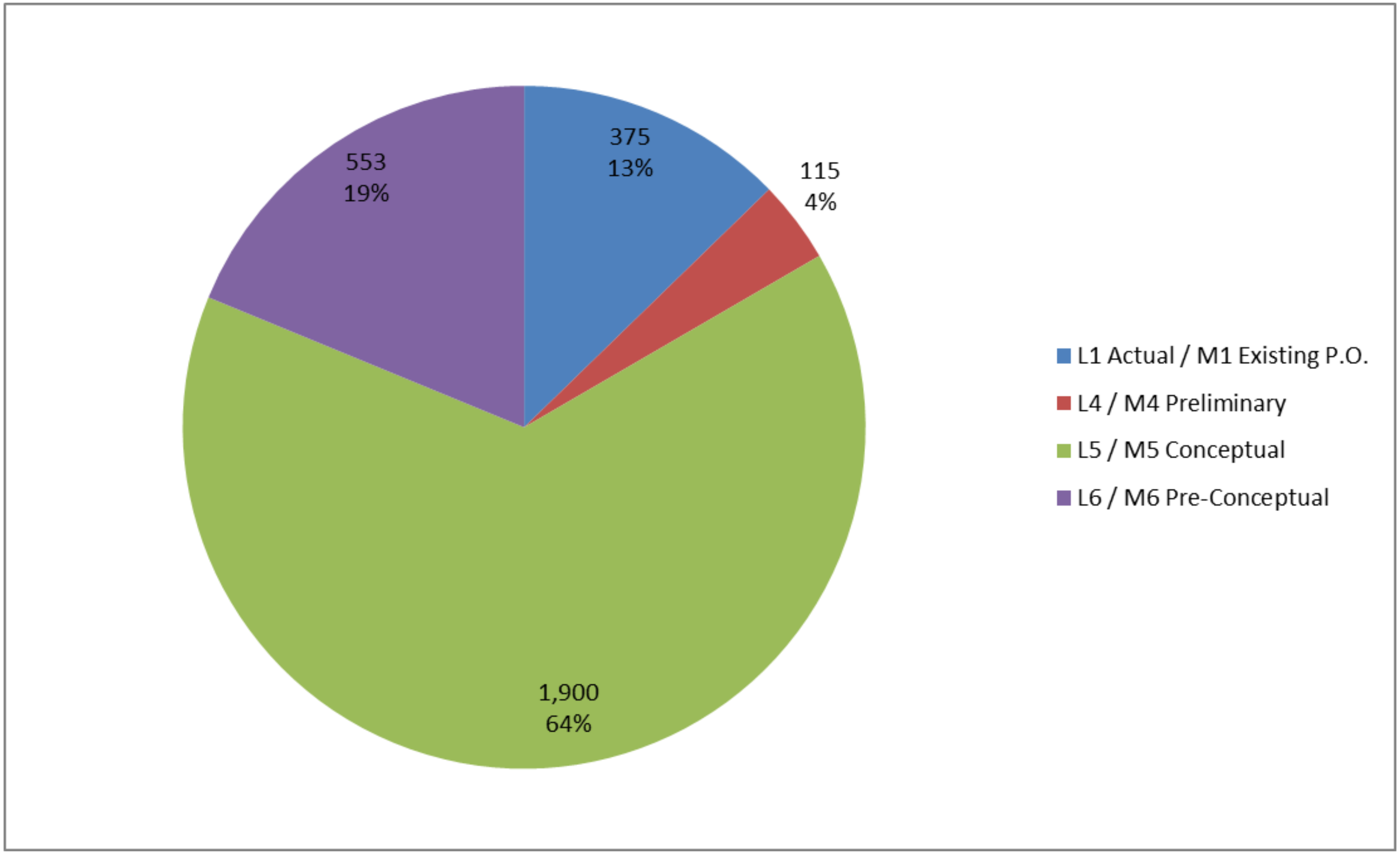
QPM Cost Distribution by Resource Type

- Base Cost (AY$k)



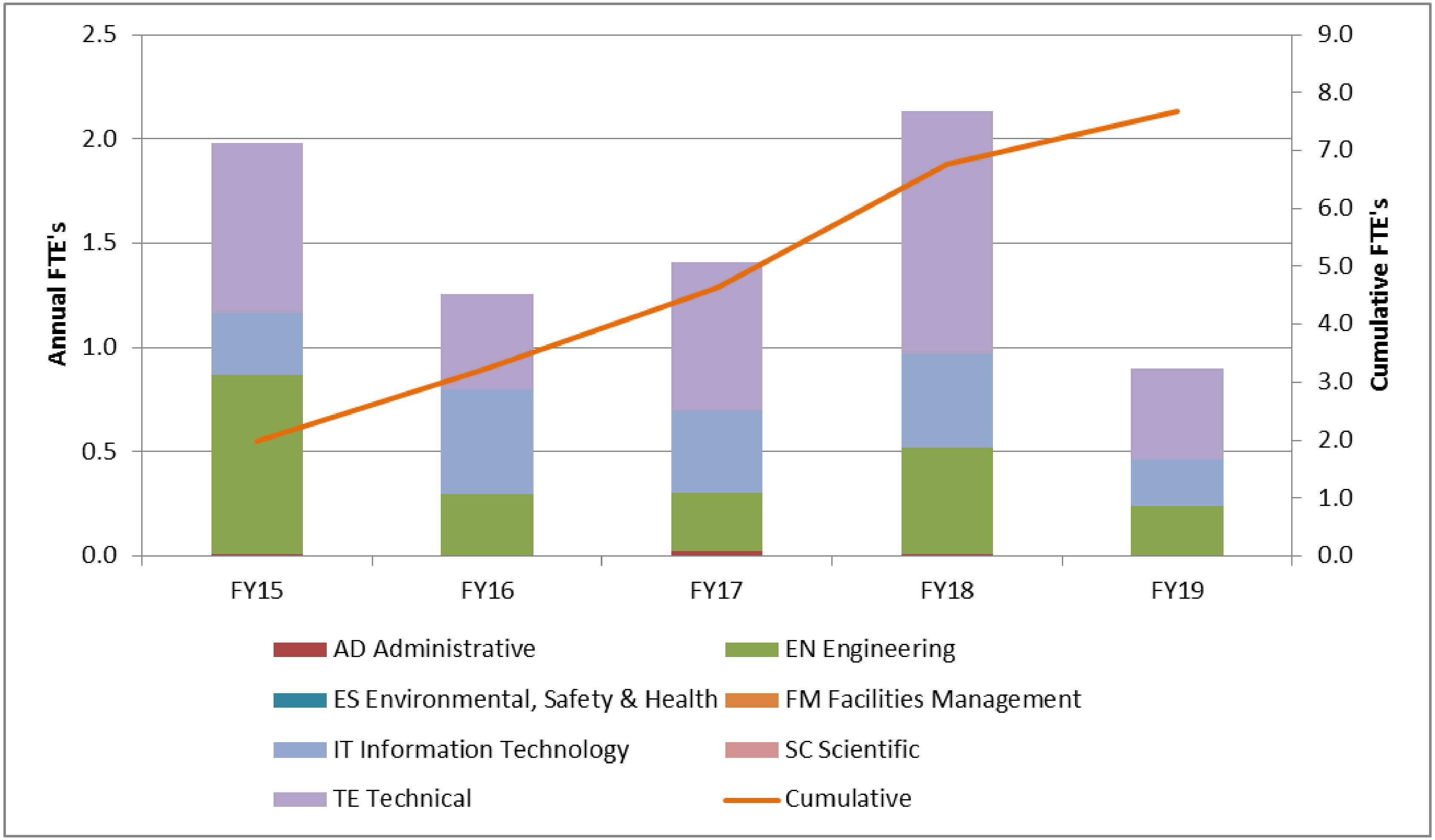
QPM Quality of Estimate

- Base Cost by Estimate Type (AY K$)



QPM Labor Resources by FY

- FTEs by Discipline



QPM Cost Table

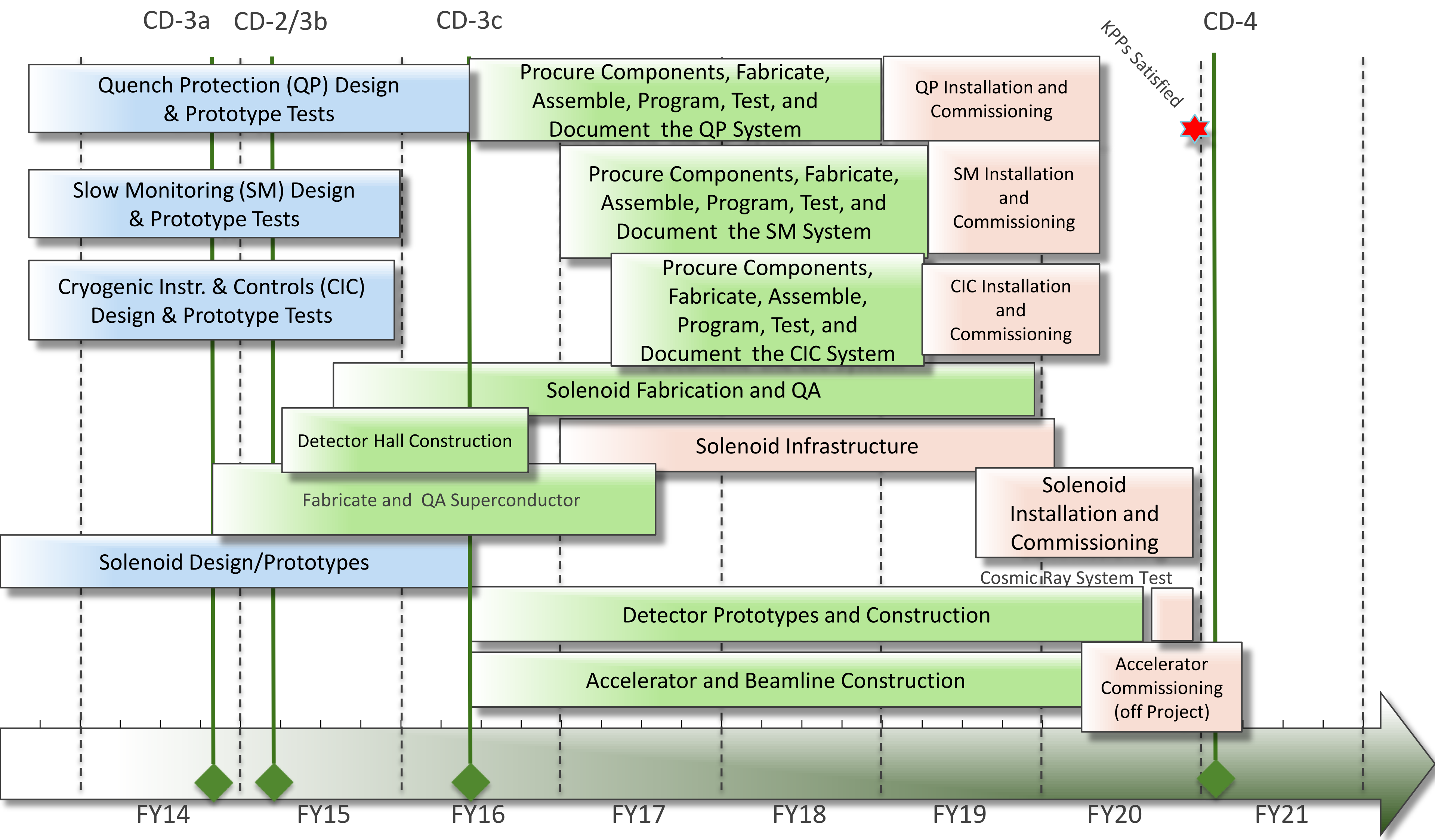
- WBS 4.7 Quench Protection & Monitoring (AY K$)

	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency on (on remaining budget)	Total Cost
475.04.07 Magnet Quench Protection System						
475.04.07.01 Quench Protection	215	1,564	1,779	609	41%	2,388
475.04.07.02 Slow Monitoring	246	248	494	174	36%	668
475.04.07.03 Cryogenic Instrumentation and Controls	284	385	669	208	37%	877
Grand Total	745	2,197	2,942	991	39%	3,933

Major Milestones

- Complete the Detailed Engineering & Software design for Quench Detection – 04/07/2016
- Perform Preliminary Quench Protection Integration Tests – 12/26/2018
- Completion of slow monitoring detailed engineering design – 4/1/2015
- Completion of preliminary slow monitoring integration tests – 9/18/2018
- Completion of cryo controls detailed engineering design – 4/3/2015
- Completion of preliminary cryo controls integration tests – 12/19/2018

Schedule


CD-3a
CD-2/3b
CD-3c
KPPs Satisfied
CD-4
Quench Protection (QP) Design & Prototype Tests
Procure Components, Fabricate, Assemble, Program, Test, and Document the QP System
QP Installation and Commissioning
Slow Monitoring (SM) Design & Prototype Tests
Procure Components, Fabricate, Assemble, Program, Test, and Document the SM System
SM Installation and Commissioning
Cryogenic Instr. & Controls (CIC) Design & Prototype Tests
Procure Components, Fabricate, Assemble, Program, Test, and Document the CIC System
CIC Installation and Commissioning
Solenoid Fabrication and QA
Detector Hall Construction
Solenoid Infrastructure
Fabricate and QA Superconductor
Solenoid Installation and Commissioning
Solenoid Design/Prototypes
Cosmic Ray System Test
Detector Prototypes and Construction
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Summary

- The magnet quench protection requirements are well within the capabilities of the quench detection system
- QP based on heterogeneous design architecture with redundancy
- Bucking 1/3 magnet coil sections will improve quench detection reliability.
- Subtracting coupled coil voltages will minimize bucked errors, allowing the magnets to be ramped much faster.
- The quench protection system is largely based on commercial hardware. The design is similar to the heterogeneous combination of digital and analog quench detection systems used for the superconducting magnet test stands in TD
- A preliminary design of a quench detection system that can reliably detect mu2e solenoid quenches is well understood. The QPS is ready for the next phase of design.