Mu2e CD-2 Review: Resonant Extraction L3

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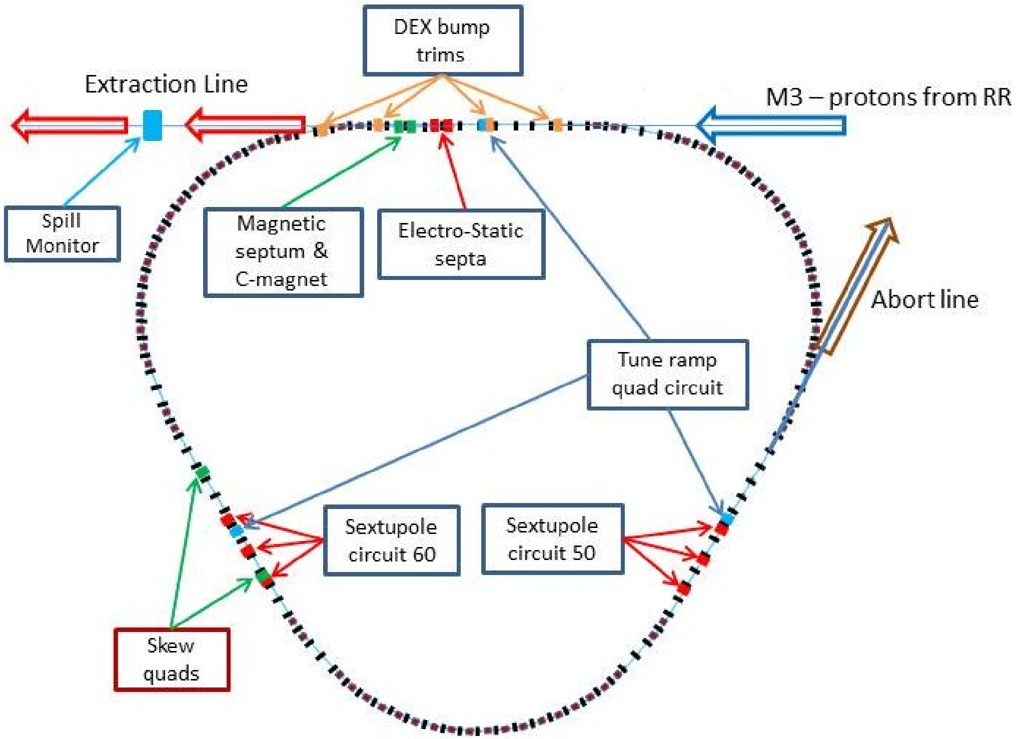
Resonant Extraction L3 Manager
7/8/2014

WBS 475.02.05 Resonant Extraction System

The scope of the Resonant Extraction Systems includes:

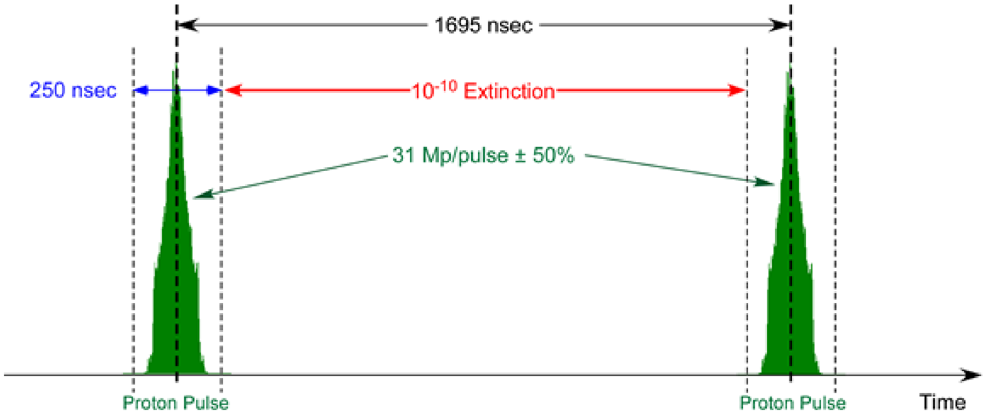
1. Development of the physics model
2. Design, fabrication and installation of:
   - Tune quad magnets (3)
   - Sextupole magnets (6)
   - Dynamic bump correctors (4)
   - Skew quad magnets (2)
   - Electro static septa (2)
   - Spill Monitor (1)
   - RFKO system (1)
   - Spill regulation electronics (1)



Map of Resonant Extraction elements in the Delivery Ring

Requirements

Slow extraction preserves the time structure of the proton beam circulating in the Delivery Ring



Time structure of the proton beam on target

Mu2e Proton Beam Requirements (doc-1105)

	Parameter	Design	Limit
★	Length of slow spill period	54 ms	>20 ms
★	Average intensity per pulse on target	31 Mp	<50 Mp
★	Maximum variation of pulse intensity on target	<50%	<50%

Design: Delivery Ring Spill Parameters

Parameter	Value	Units
MI Cycle time	1.333	sec
Number of spills per MI cycle	8	
★ Number of protons per micro-pulse	3.1×10^7	protons
★ Maximum Delivery Ring Beam Intensity	1.0×10^{12}	protons
Instantaneous spill rate	18.5×10^{12}	protons/sec
Average spill rate	6.0×10^{12}	protons/sec
Duty Factor (Total Spill Time ÷ MI Cycle Length)	32	%
★ Duration of each spill	54	msec
Spill On Time per MI cycle	497	msec
Spill Off Time per MI cycle	836	msec
Time Gap between 1st set of 4 and 2nd set of 4 spills	36	msec
Time Gap between spills	5	msec
★ Pulse-to-pulse intensity variation	±50	%
★ Extraction efficiency	98	%

Organizational Breakdown

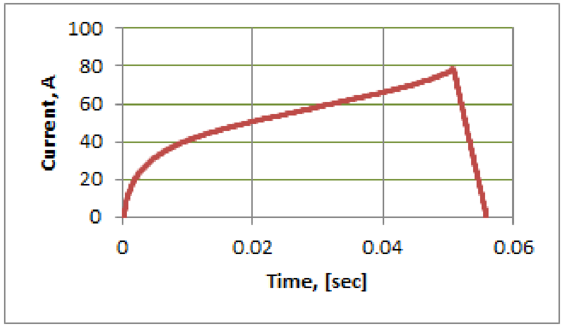
- Key people in the subproject:
  - V. Nagaslaev, AD, L3 Manager
  - C. S. Park, CD, L3 Deputy Manager, Synergia
  - D. Tinsley, AD, Sr. Mechanical Engineer, ESS design
  - P. Prieto, AD, Sr. Electronics Engineer, Spill Controls
  - G. Krafczyk, AD, Sr. Electrical Engineer, Power Supplies
  - TJ Gardner, TD, liaison for magnet production

Design: Magnets and Power Supplies

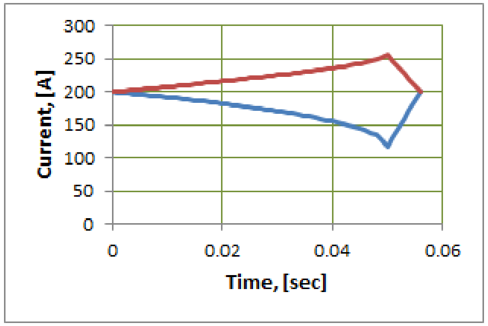
Derived requirements/specs for 3 families of specialized magnets to drive the slow extraction

1. **Sextupole magnets**
2. **Tune ramp quad magnets**
3. **DEX – dynamic bump correctors**

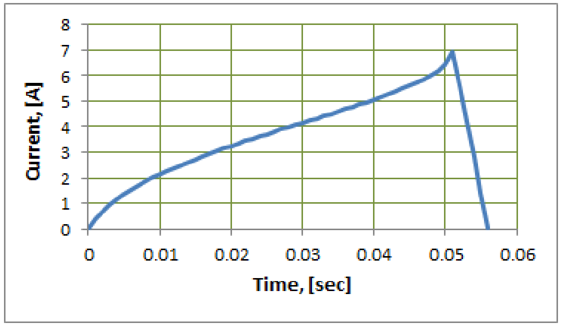
Magnet	Quantity	Integrated gradient excursion	Base* Current, [A]	Max Current Excursion, [A]	Max supply Current [A]	Max dI/dt [A/sec]	Regulation accuracy, %	Regulation stability	Curve accuracy	Ripple, %
Tune Quad	3	0.2 T	0	80	100	16,000	<0.5%	<0.5%	<0.5%	<0.05%
Sextupoles	6	32 T/m	200	+-80	300	16,000	<0.5%	<0.5%	<0.5%	<1%
DEX trims	4	0.014 Tm	ND	14	+-40	2,800	<1%	<1%	<1%	<1%



Tune quad ramp curve I(t)

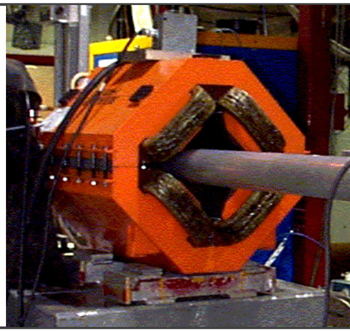
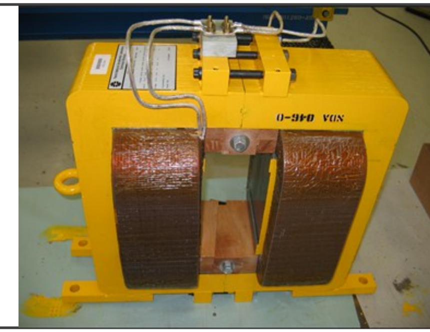


Sextupole ramp curve I(t)



DEX bump ramp curve I(t)

Design: Solutions for magnets and PS

Tune quad magnets : **CQA**	Sextupole magnets : **ISA**	Dynamic bump trims: **NDB**
		
▪ *R* = 0.012 Ω ▪ *L*= 2.16 mH ▪ I_{DC}= 0 ▪ I_{AC}= 80 A	▪ *R* = 0.015 Ω ▪ *L*= 2.6 mH ▪ I_{DC}= 200 A ▪ I_{AC}= 80 A	▪ *R* = 0.45(0.225) Ω ▪ *L*= 0.42(0.105) H ▪ I_{DC}= ND ▪ I_{AC}= 14 A
Power supplies for all magnet types will be built on the basis of the Booster switch-mode 65A 180 V units		
2 units in parallel 3 independent bulk supplies;	6 units in parallel to provide 300A current for each circuit	Split magnet coils in 2; Upgrade bulk supply to 350V with higher voltage FETs and filter module
Common status: building PS prototypes and testing magnets with representative ramps will complete the Final design for magnets and their power supplies.		

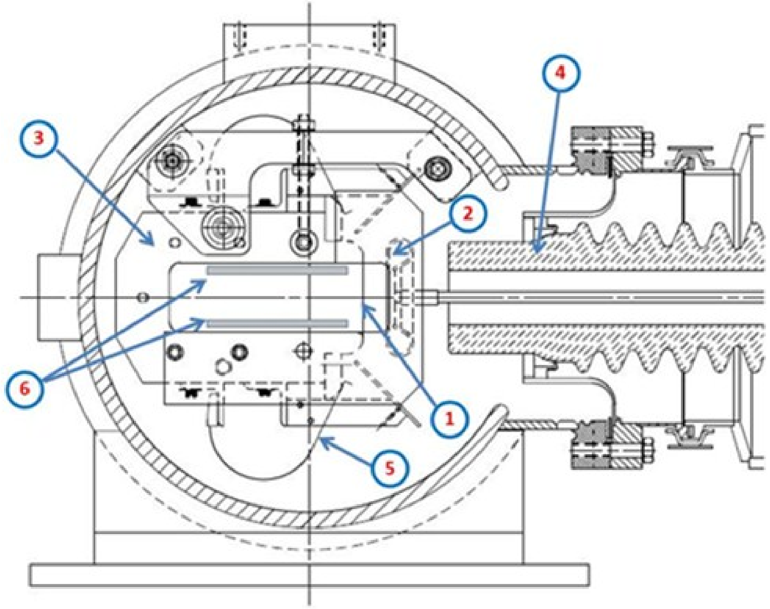
Design: Electrostatic Septa

Design considerations for ESS:

1. Foils instead of wires
2. 2 septa straddle the focusing quad Q203
3. Maximize lifetime
4. Minimize service time in tunnel
5. Space constraints

Main challenges:

1. Strive to achieve HV>100kV
2. Vacuum conditions in Delivery Ring

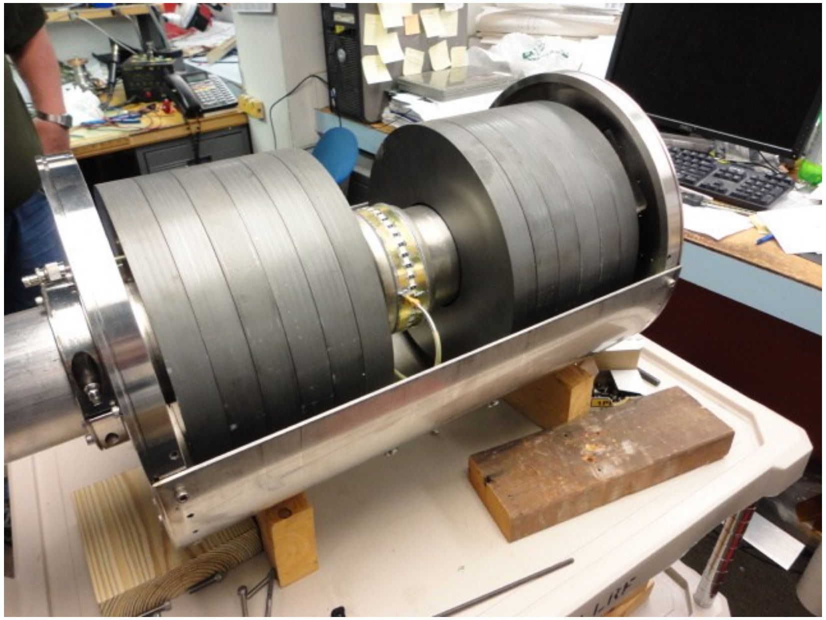


Prior experience:

1. Building ESS for MI at FNAL
2. Building ES Separators for Tevatron
3. Other labs experience with ESS

Design: Spill Monitoring

- Fast spill rate monitoring is required for effective regulation. A WCM Spill Monitor prototype has been built and tested.
- This device will be used as a working module - no new fabrication is needed.
- We will also use the UEM (Upstream Extinction Monitor, WBS 475.02.08.03.1) as an additional spill monitoring device.



Design: RF Knock-Out

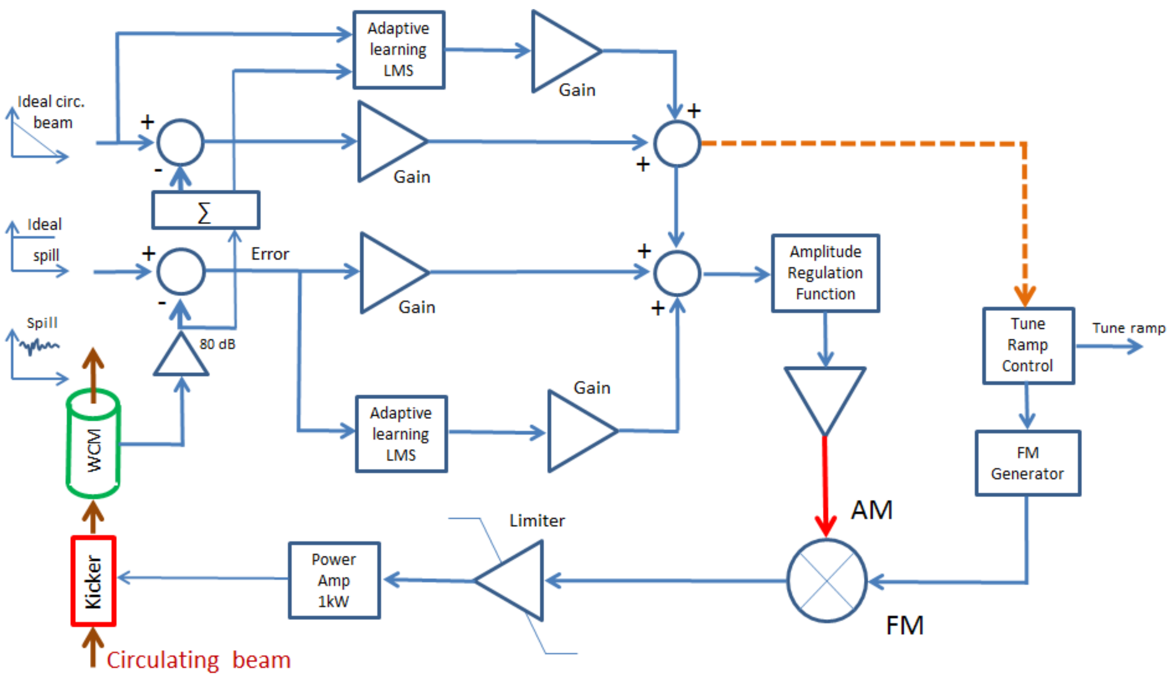
- Fast ripples on the spill rate will be regulated by the RF Knock-Out method that employs transverse heating of the beam.
- Old Tevatron damper kicker will be reused as the RFKO kicker.
- Kicker waveform is FM to cover the beam betatron spread and AM to modulate the spill rate

- The kicker has been identified, prepped and tested with the beam.

- Ready for use.

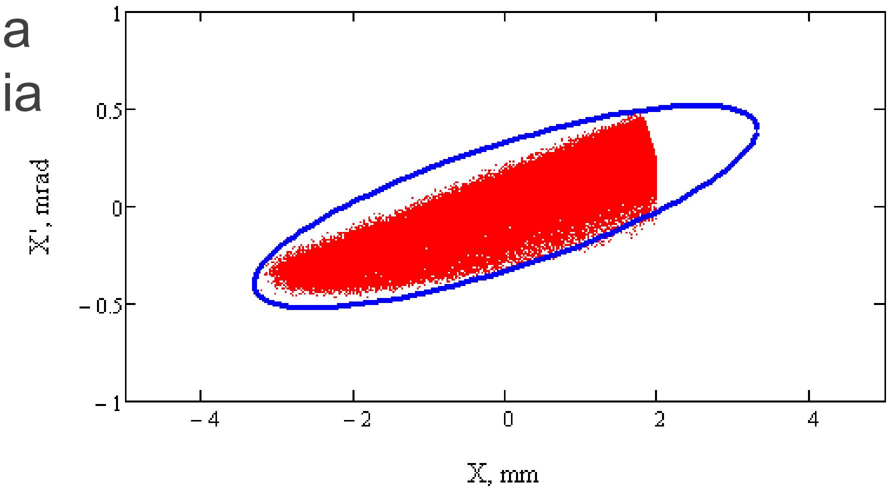
Design: Spill regulation electronics

- Regulation logics is realized in the MVME5500 processor
- Slow regulation (feedforward) to the tune quad ramp
- Fast regulation (feedback) to the RFKO kicker

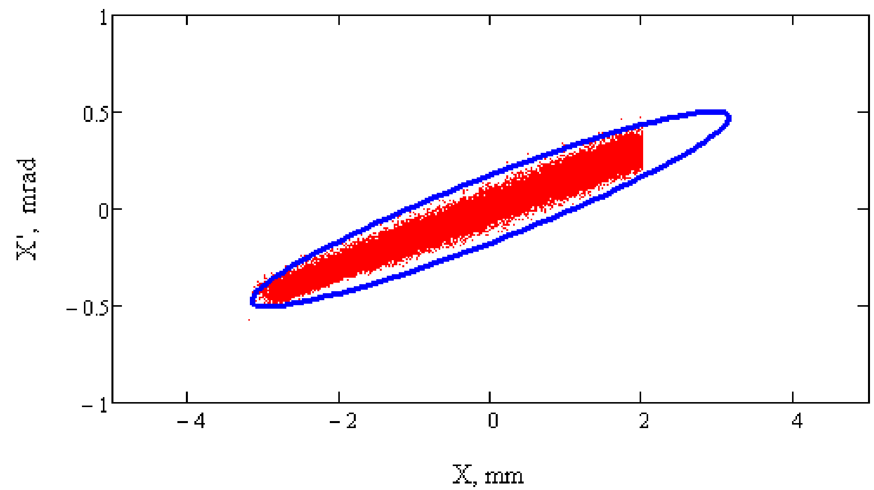


Performance: Synergia tracking simulations

- Since the CD-1 review we've made a number of enhancements in Synergia tracking model:
  - RF fields;   RFKO fields
  - DEX bump with ramping
  - Tune ramping; full spill tracking
  - Aperture definition
  - Substantial speed up
- Main outcome include:
  - Extracted beam footprint
  - DEX bump optimization
  - RFKO heating rates consistent with expected
  - Performance consistent with earlier ORBIT performance and no known physics observed to impact performance



Extracted beam footprint, DEX bump off



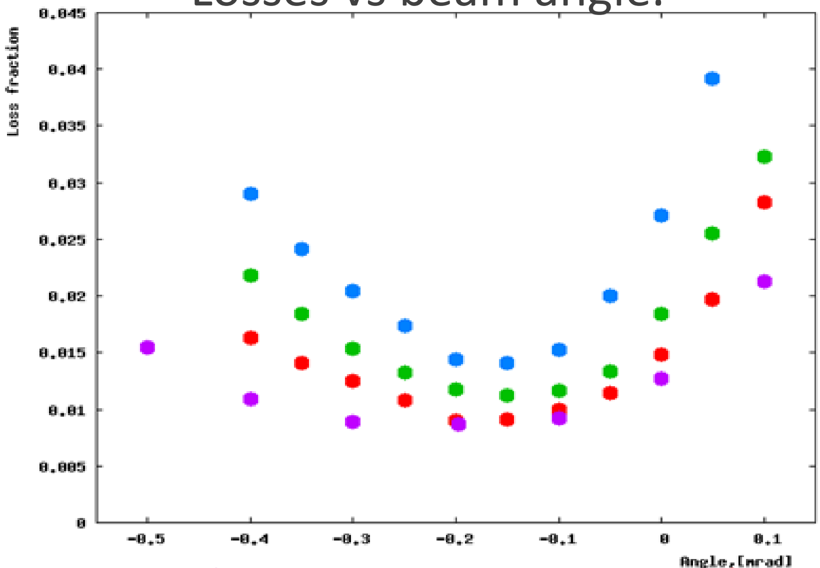
Extracted beam footprint, DEX bump on

Performance: MARS tracking simulations

- Tracking extracted beam with MARS code:
  - ✓ Tracking particles in media and DC fields
  - ✓ Detailed calculations of interaction with materials
  - ✓ Radiation levels, Residual activation, Energy deposition, etc
  - ✓ Essential for beam loss calculations and geometry optimization

- Main outcomes include:
  - ✓ Wires do not have apparent advantage over foils
  - ✓ Optimal beam angle to septum is nonzero
  - ✓ Optimal ratio of two septa lengths is 1:2
  - ✓ Pre-scattering diffuser may reduce losses by 20-30%

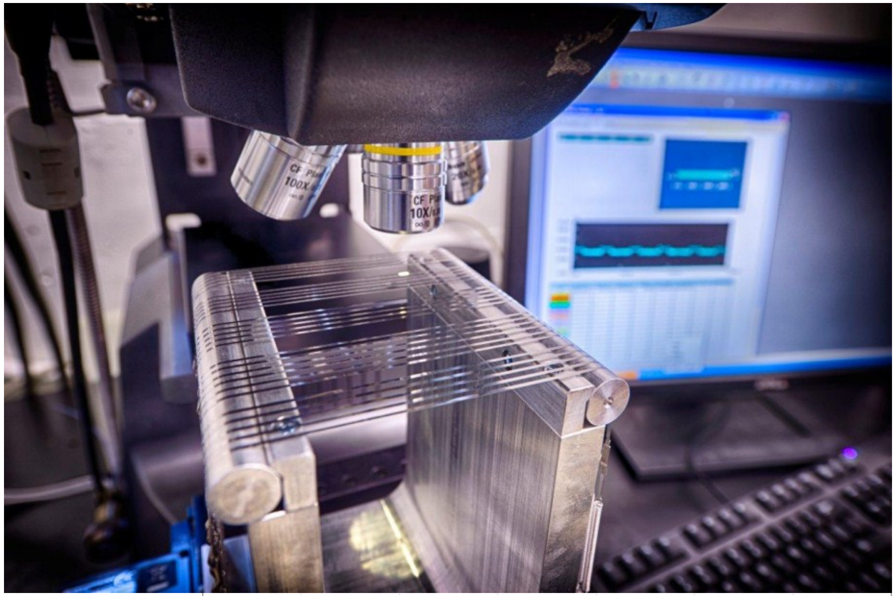
Losses vs beam angle.

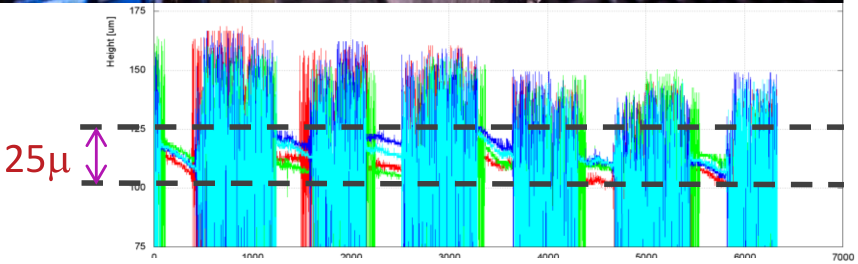


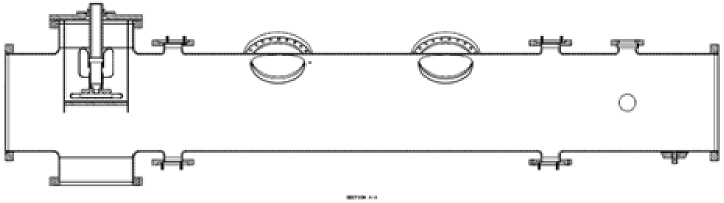
Purple- 100μ wires; Red- 50μ foils

Performance: ESS studies

1. Foil prototype:
   - Built a prototype to study mechanical properties, techniques for clamping, stretching, measuring.
   - Used laser profilometer to measure the foil plane flatness.
   - Developed a strategy to achieve good performance
2. FEA field calculations:
   - ✓ Studied optimal geometries with foils and electrodes
   - ✓ Concluded with foil spacing limitation at s<2.6mm
3. Prototype-II for HV testing in vacuum:
   - ✓ Finishing parts fabrication for stage-0
   - ✓ Testing cave is ready for use







Changes since CD-1

- *Magnetic septa* have been moved from our scope to g-2.
- Added new scope:
  - *Dynamic bump*
  - *Skew quadrupole magnets*
- Change in the extraction geometry: *flipped direction*

Value Engineering since CD-1

- Used synergy with Main Injector operations in preparations of the septa testing cave at the NWA building. This cave is ready now for the prototype testing.
- Use the prototype WCM as a working instrument
- Reuse existing hardware:
  - ✓ Old style Tevatron damper kicker as RFKO kicker
  - ✓ CQA magnets for tune ramping
  - ✓ NDB magnets for Dynamic Bump
  - ✓ TeV separators for the HV/vac prototyping

Downselects

- The choice of the machine resonance for the slow extraction has been finalized in favor of the third integer one.
- Selection has been made for use of foils in the ESS instead of wires. Milestone has been met.

Remaining work before CD-3

- Finish tracking simulations with Synergia and MARS
- Complete ESS prototyping studies with HV in vacuum
- Fabricate prototypes of power supplies for each type of ramped magnets and complete magnet testing with representative ramps
- Develop a prototype of the timing module for spill regulation and complete its testing.

Quality Assurance

- Design Level QA
  - Design analysis tools (simulations, FEA)
  - Prototyping, performance tests
  - Beam studies
  - Reviews, reports, communications
- Fabrication and installation QA
  - Built in process QA (written procedures, travelers)
  - Personnel training
- Commissioning QA (off project)
- QA standards and guidelines
  - QA Management Plan for Mu2e Experiment - mu2e-docdb# 677
  - Fermilab Integrated QA Program – esh-docdb#2469
  - Fermilab Engineering Manual

Risks

- Presently only one item in the Risk Registry (opportunity)
- Several more have been considered and (pre-)mitigated

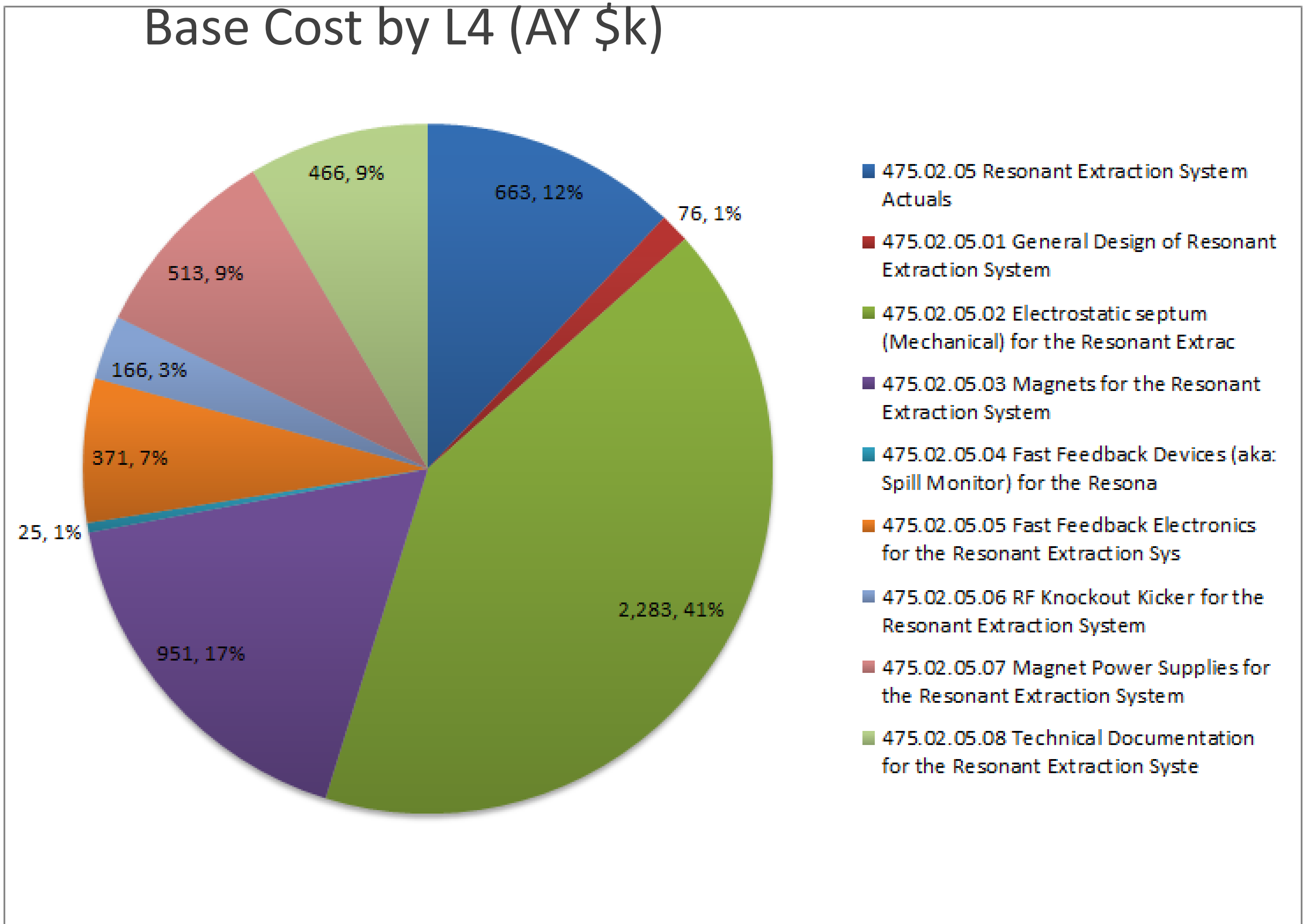
Index in RR	Risk/ Opportunity	Impact	Probability	Point estimate	Status
	Opportunity to reuse existing spare sextupoles	Cost	L	$164k	Current
022	High Beam Loss	Technical, Schedule	M	--	Transferred
012	Mu2e beam commissioning delayed.	Schedule	L	--	Transferred
025	Need to ramp Delivery Ring sextupoles	Technical	M	--	Mitigated, Retired
024	Inability to locate and reuse tooling for ESS	Cost	M	ND	Realized
023	Inacceptable amount of beam left in the DR	Technical	L	--	Mitigated, Retired

ES&H

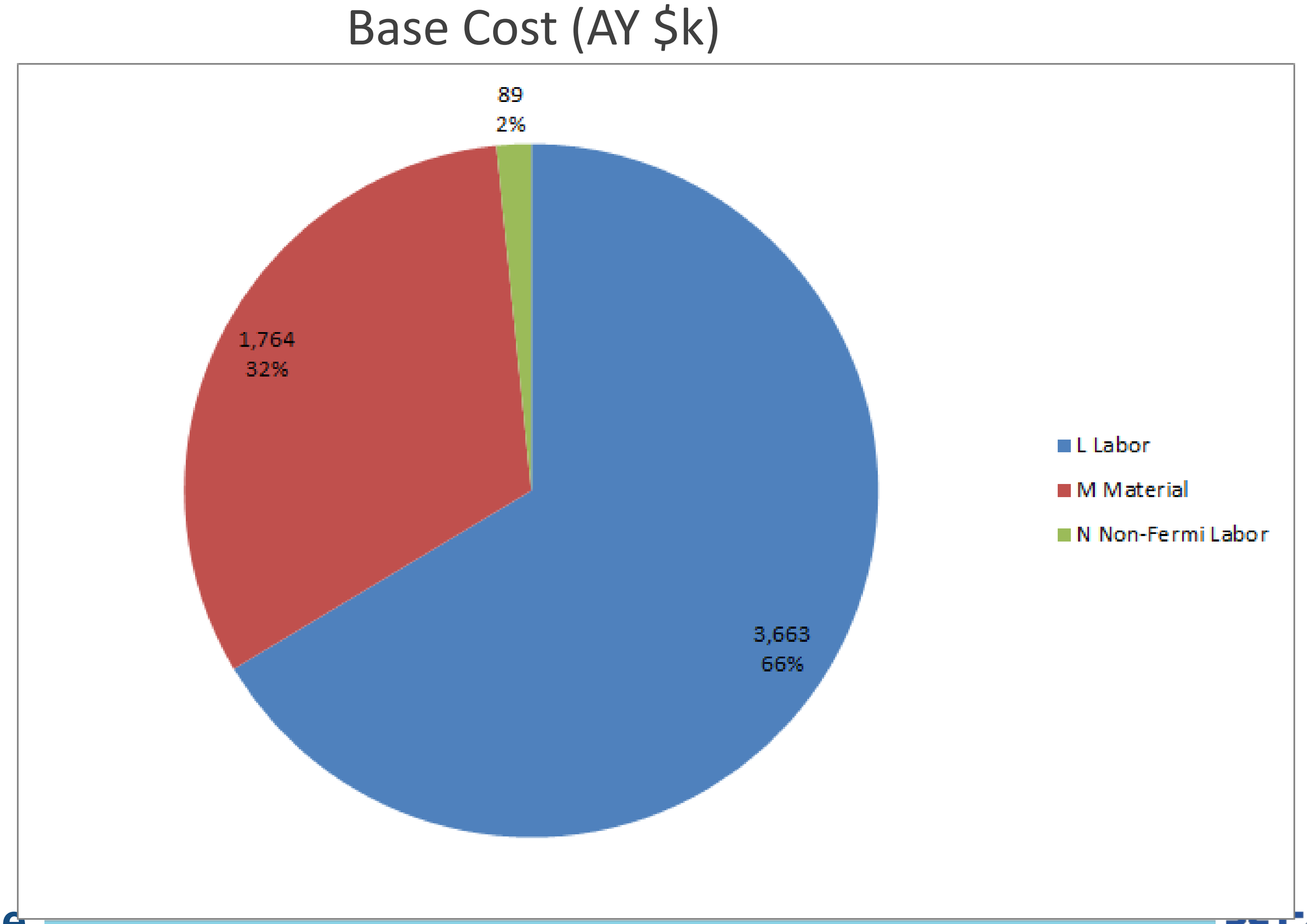
- Radiation hazard during operations and service
- Tunnel hardware specific hazards during operation
- Tunnel hazards during installation

- These hazards are all discussed in the Mu2e Hazard Analysis Report (Mu2e-doc-675).
- Fermilab Environment, Safety and Health Manual (FESHM)

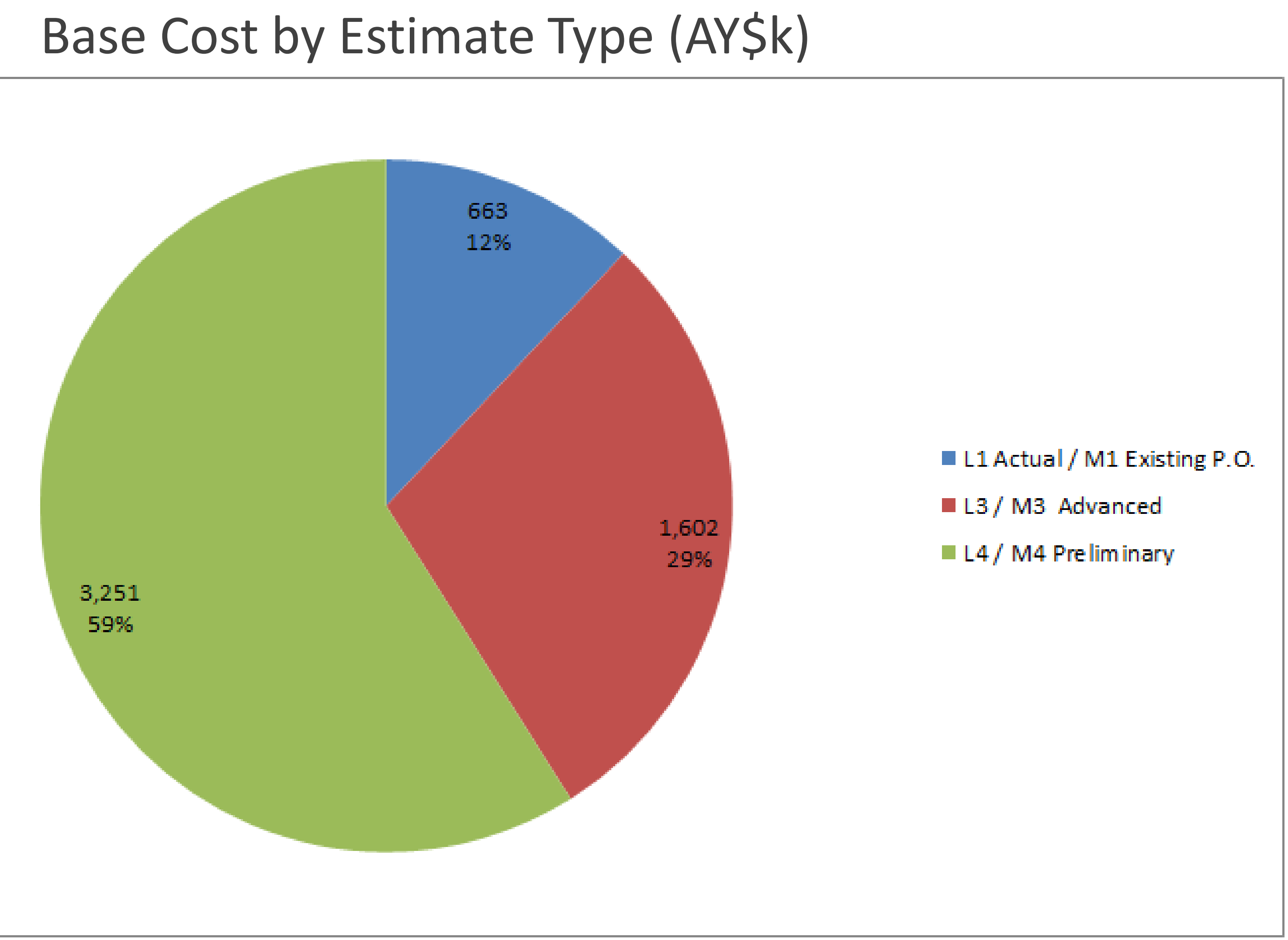
Cost Distribution by L4



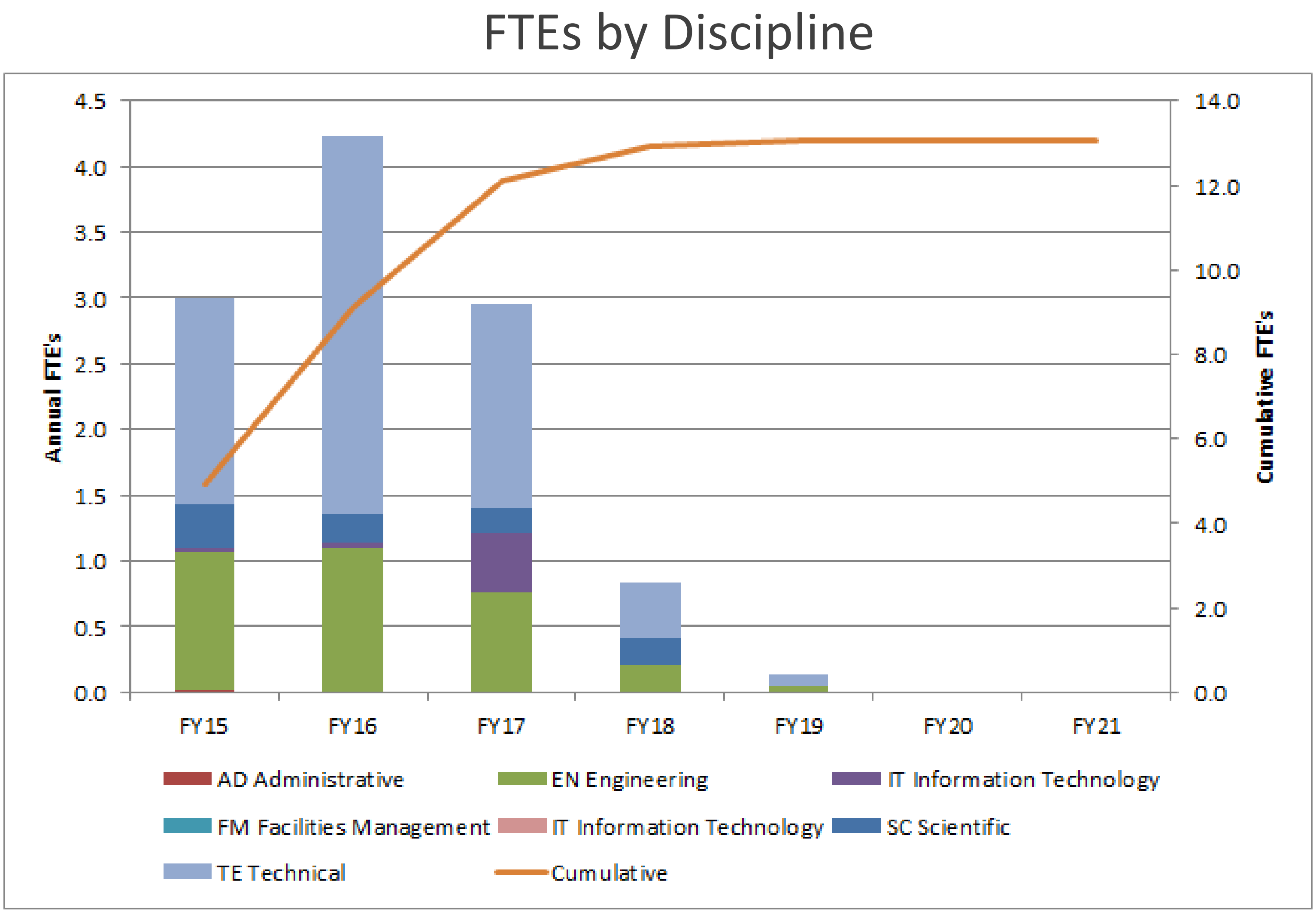
Cost Distribution by Resource Type



Quality of Estimate



Labor Resources



Cost Table

WBS 2.5 Accelerator Resonant Extraction System

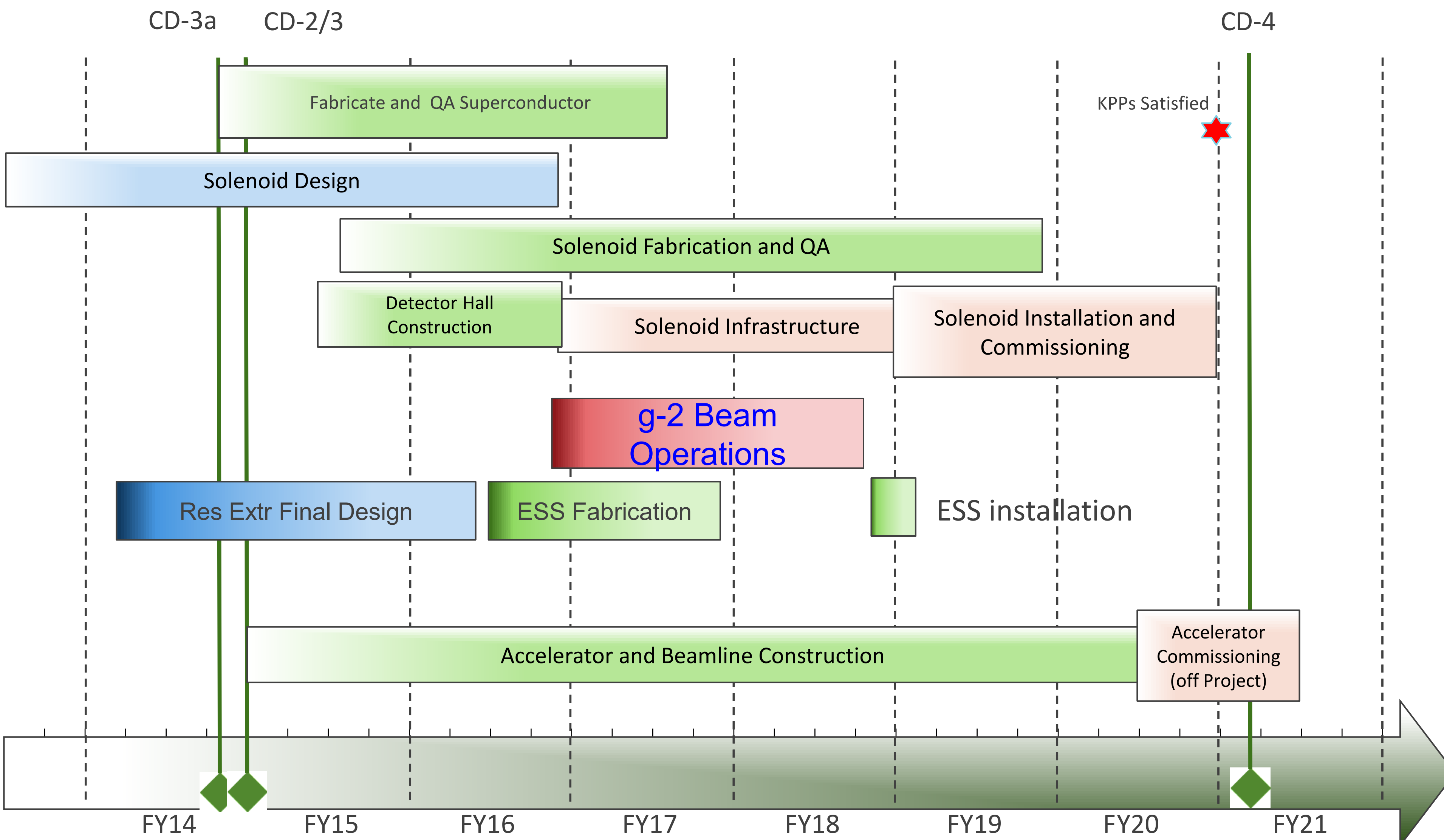
Costs are fully burdened in AY $k

	Base Cost (AY $)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining costs)	% Contingency on ETC	Total Cost
475.02 Accelerator						
475.02.05 Resonant Extraction System						
475.02.05 Actuals	14	649	663			663
475.02.05.01 General Design		76	76	15	20%	92
475.02.05.02 Electrostatic septum (Mechanical)	496	1,788	2,283	913	40%	3,197
475.02.05.03 Magnets	794	157	951	278	29%	1,230
475.02.05.04 Fast Feedback Devices (aka: Spill Monitor)	5	20	25	7	30%	32
475.02.05.05 Fast Feedback Electronics	83	288	371	116	31%	487
475.02.05.06 RF Knockout Kicker	139	27	166	58	35%	224
475.02.05.07 Magnet Power Supplies	322	191	513	131	26%	645
475.02.05.08 Technical Documentation		466	466	130	29%	596
Grand Total	1,853	3,663	5,516	1,649	34%	7,165

Major Milestones

47502.05.001010	Resonant Extraction System Conceptual Design Complete	06/28/2012
47502.05.001020	Septum Technology Choice Complete	12/12/2012
47502.05.001030	Resonant Extraction System Preliminary Design Complete	3/10/2014
47502.05.01.001070	Beam line Studies Complete	4/18/2014
47502.05.001040	Resonant Extraction System Final Design Complete	3/2/2016
47502.05.001050	DOE CD-3 Accelerator Resonant Extraction Mini-Review Approval	3/17/2016
47502.05.001060	Resonant Extraction System Implementation & Close-out Complete	9/4/2018

Schedule



CD-3a
CD-2/3
CD-4
Fabricate and QA Superconductor
KPPs Satisfied
Solenoid Design
Solenoid Fabrication and QA
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
g-2 Beam Operations
Res Extr Final Design
ESS Fabrication
ESS installation
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

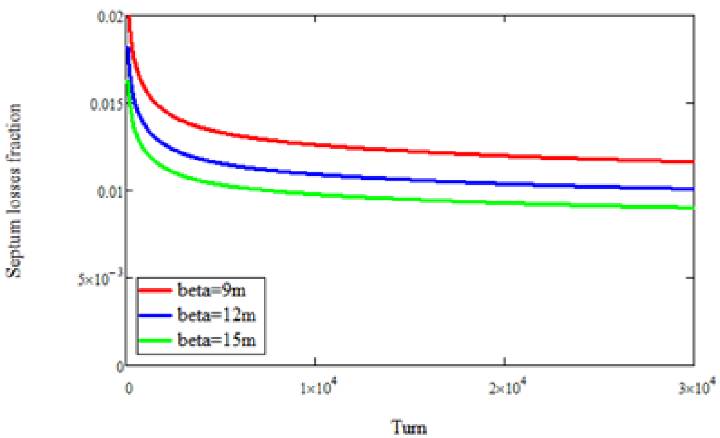
Summary

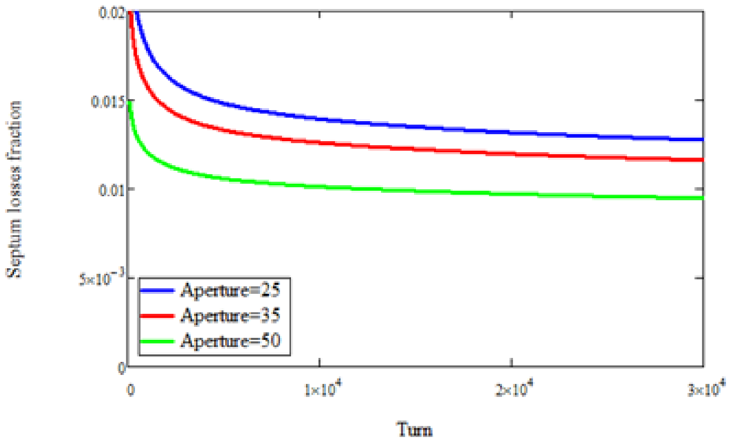
- The Resonant Extraction Design is in most part at a high level of maturity.
- The final studies are underway with a high confidence of success
- The most challenging part of the design remains to be the Electrostatic septum. This is a very complicated design with a high uncertainty in both cost and schedule.
- Resonant Extraction Systems Preliminary Design is ready
- Cost and schedule estimates are well understood and ready for the baseline

Backup slides

Performance: General Design

- The conceptual theory background (mu2e-docdb-556) was further extended in (mu2e-docdb-3472) into an analytical model that can be used for calculations of the extraction efficiency as a function of time and various machine parameters, such as acceptance, initial beam emittance, and Twiss functions.

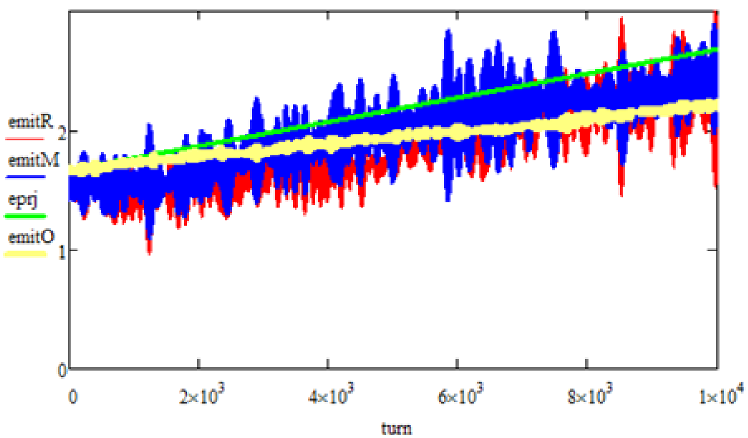




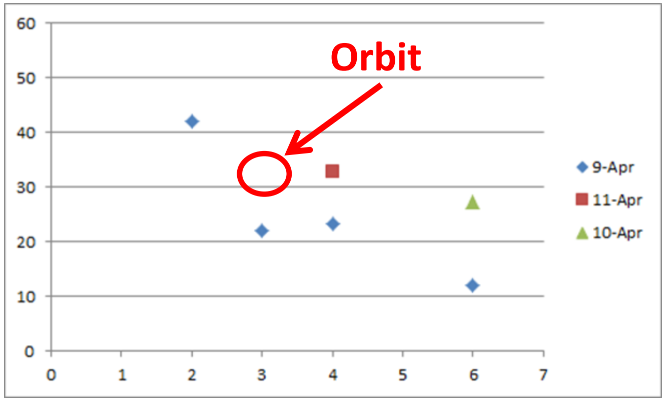
Beam losses at extraction as function of time (turn#), for different values of septum beta-function and machine acceptance.

Performance: Beam studies

- Limited beam time was made available in spring 2014 for the 8GeV proton beam studies in the Debuncher ring.
- Main goal for our studies was to confirm the emittance growth rates due to heating beam with RFKO.
- Hard failure in the Accumulator ring did not allow us to completely finish the studies, however there is a good confidence that rates measured agree with models and simulations.



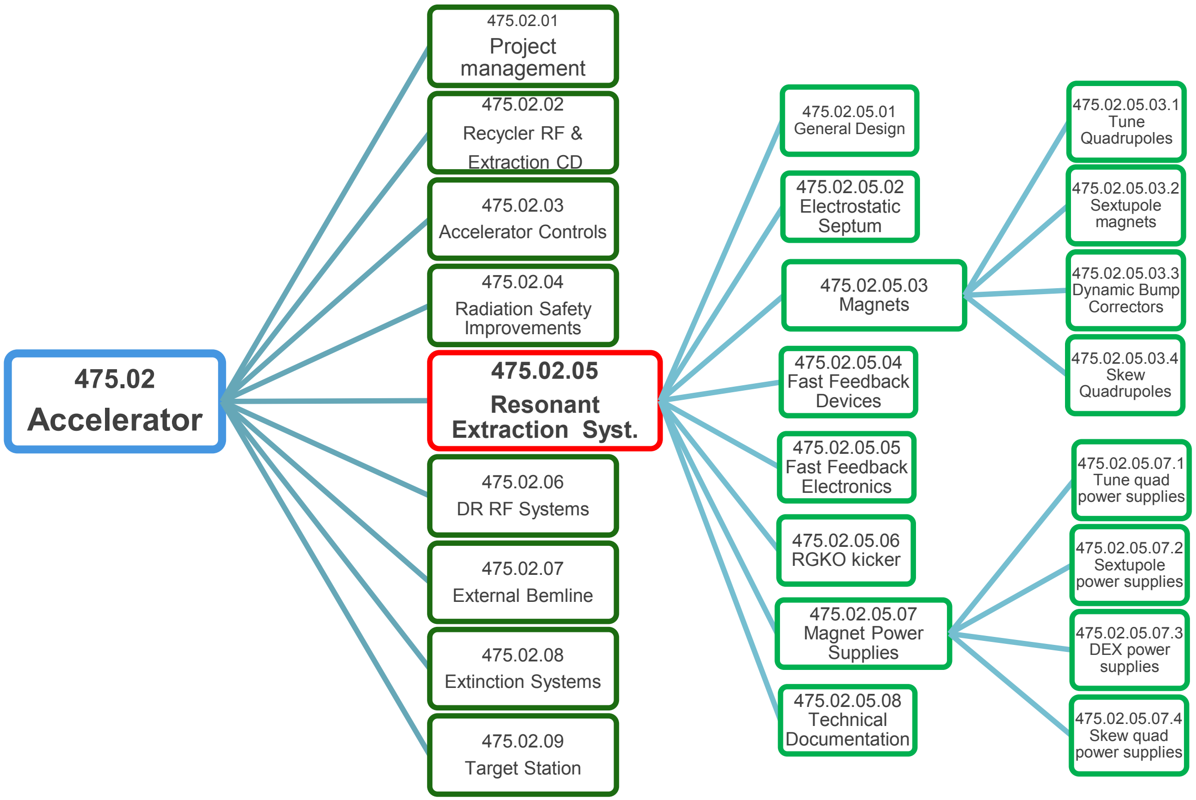
Beam emitance growth with time by different sources;   Yellow - ORBIT



Emitance growth vs FM width [kHz]; shown comparison with ORBIT

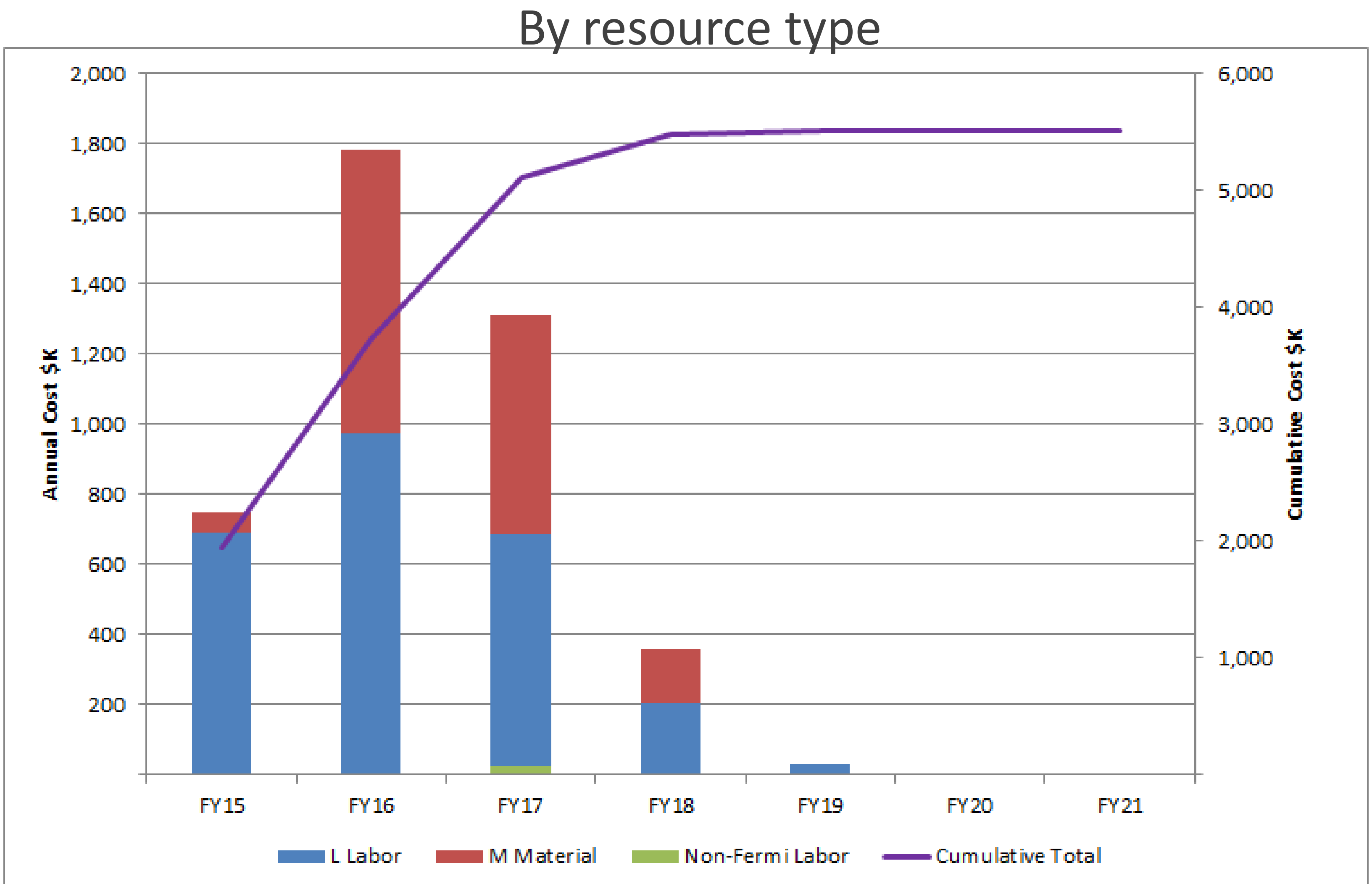
WBS 475.02.05 Resonant Extraction System (WBS)

L3 Manager - V. Nagaslaev L3 Deputy Manager - C.S. Park



- 6 CTC accounts at level 4
- 8 CTC accounts at level 5

Resources


By resource type
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
Annual Cost $K
6,000
5,000
4,000
3,000
2,000
1,000
Cumulative Cost $K
FY15
FY16
FY17
FY18
FY19
FY20
FY21
L Labor
M Material
Non-Fermi Labor
Cumulative Total