# Mu2e DOE CD-2 Review: Resonant Extraction L3

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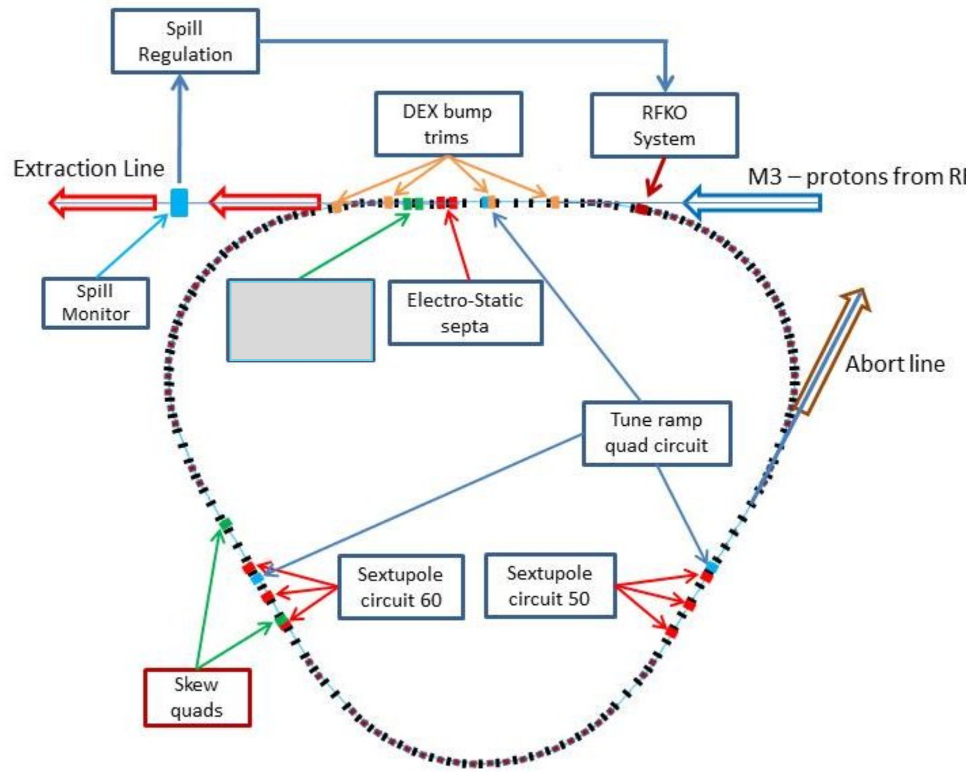
Resonant Extraction L3 Manager
10/22/2014

# WBS 475.02.05 Resonant Extraction System

**The scope of the Resonant Extraction Systems includes:**

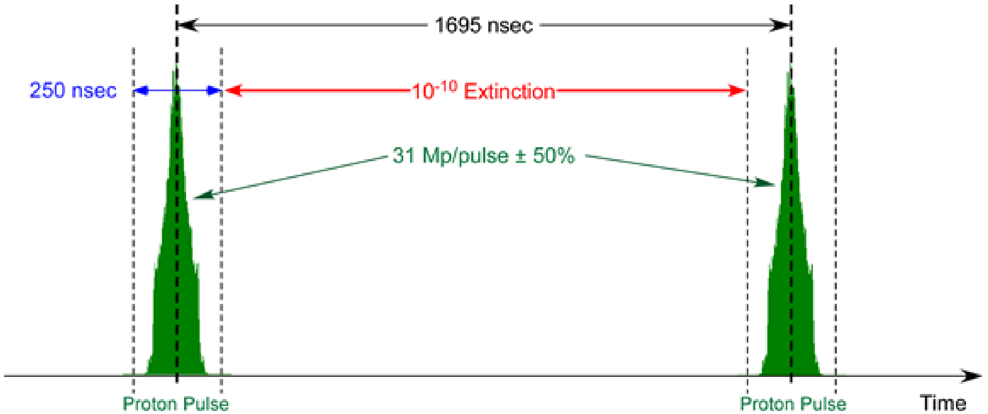
1. Development of the physics model
2. Design, fabrication and installation of:
   - Tune quad magnets (3)
   - Sextupole magnets (6)
   - Dynamic bump correctors (4)
   - Skew quad magnets (2)
   - Electro static septa (2)
   - Spill Monitor (1)
   - RFKO system (1)
   - Spill regulation electronics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




Map of Resonant Extraction elements in the Delivery Ring (L=505m)

# 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 | $3.1\times10^{7}$ | protons |
| Maximum Delivery Ring Beam Intensity | $1.0\times10^{12}$ | protons |
| Instantaneous spill rate | $18.5\times10^{12}$ | protons/sec |
| Average spill rate | $6.0\times10^{12}$ | 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 | % |

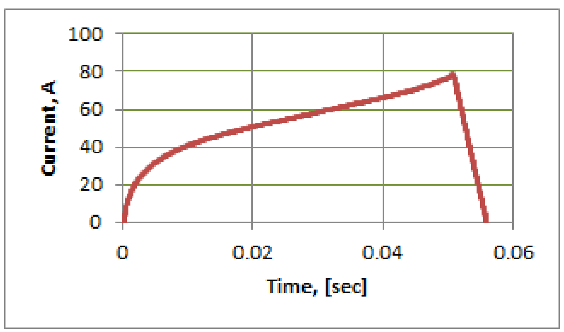
- Design

# Design: Main Magnets and Power Supplies

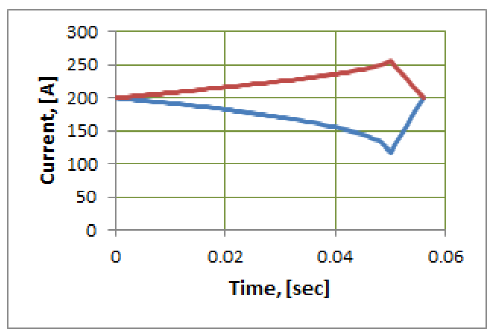
Derived requirements/specs for 3 families of specialized magnets to drive the slow extraction

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

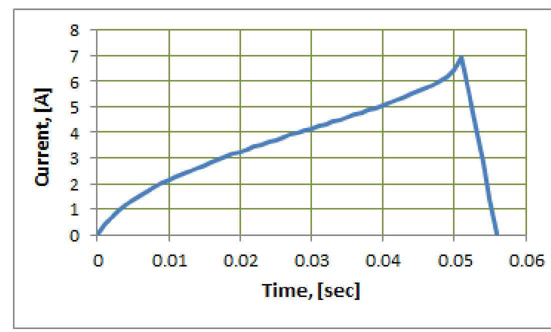
| Magnet | Quantity | Integrated gradient excursion | Base* Current, [A] | Max Current Excursion, [A] | Max supply Current [A] | Max dI/dt [A/sec] | Regulation accuracy, % | Regulation stability | Curve accuracy | Ripple, % |
|---|---|---|---|---|---|---|---|---|---|---|
| Tune Quad | 3 | 0.2 T | 0 | 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)**

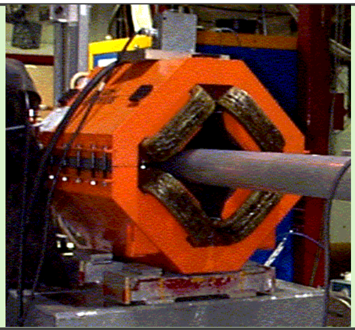
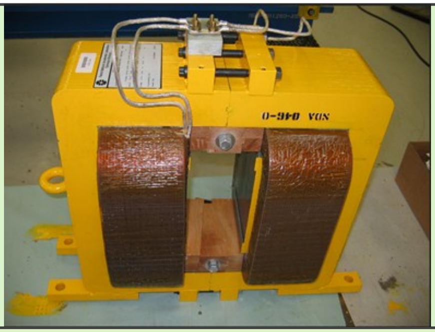



**Sextupole ramp curve I(t)**




**DEX bump ramp curve I(t)**

# Design:  Solution for Magnets and PS

<table>
<tr><th>Tune quad magnets : CQA</th><th>Sextupole magnets :   ISA</th><th>Dynamic bump trims: NDB</th></tr>
<tr><td></td><td>
</td><td></td></tr>
<tr><td>Cooling Ring magnets, available in abundance.<br><br>Some refurbishing may be needed.</td><td>Existing design of Main Injector sextupoles.<br><br>Spare magnets are not available – will be built.</td><td>Debuncher style correctors.<br><br>Available in working conditions</td></tr>
<tr><td colspan="3">Power supplies<br>for all magnet types will be built on the basis of the Booster switch-mode 65A 180 V units</td></tr>
<tr><td>2 units in parallel<br>3 independent  bulk supplies;</td><td>6 units in parallel to provide 300A current for each circuit</td><td>Split magnet coils in 2;<br>Upgrade bulk supply to 350V with higher voltage FETs and filter module</td></tr>
<tr><td colspan="3">Status:  building PS prototypes and testing magnets with representative ramps will complete the Final design for magnets and their power supplies.</td></tr>
</table>

# Design: Electrostatic Septa

## Design considerations for ESS:

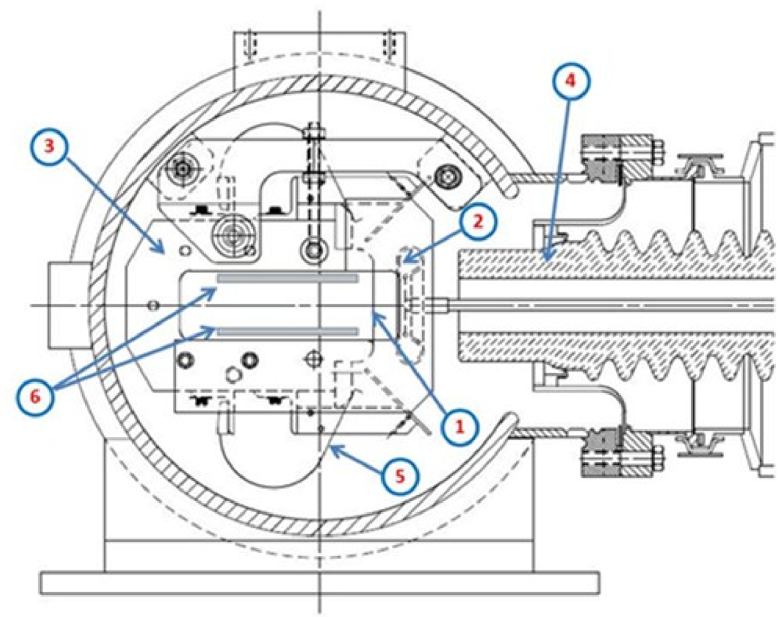
1. Foils instead of wires (advantages!)
2. Rad levels → Minimize service time in tunnel and maximize septa lifetime
3. 2 septa straddle the focusing quad Q203

## Main technical challenge:

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

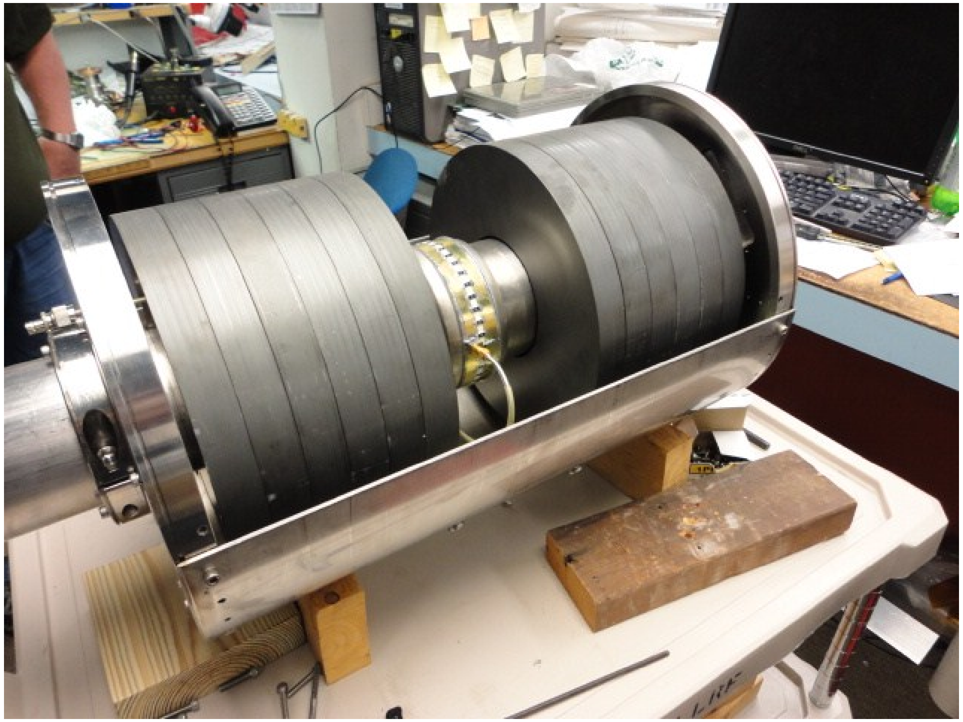
## Using prior experience:

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



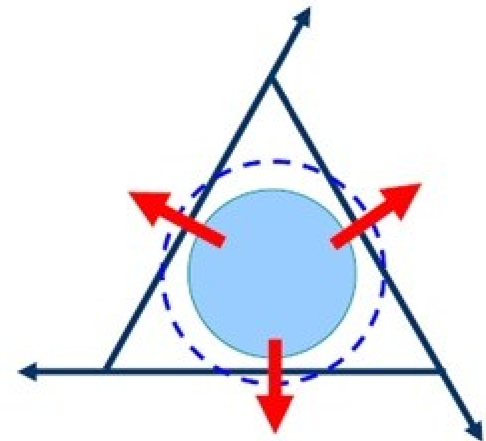
# Design: Spill Monitoring

- 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.



# Design: RF Knock-Out

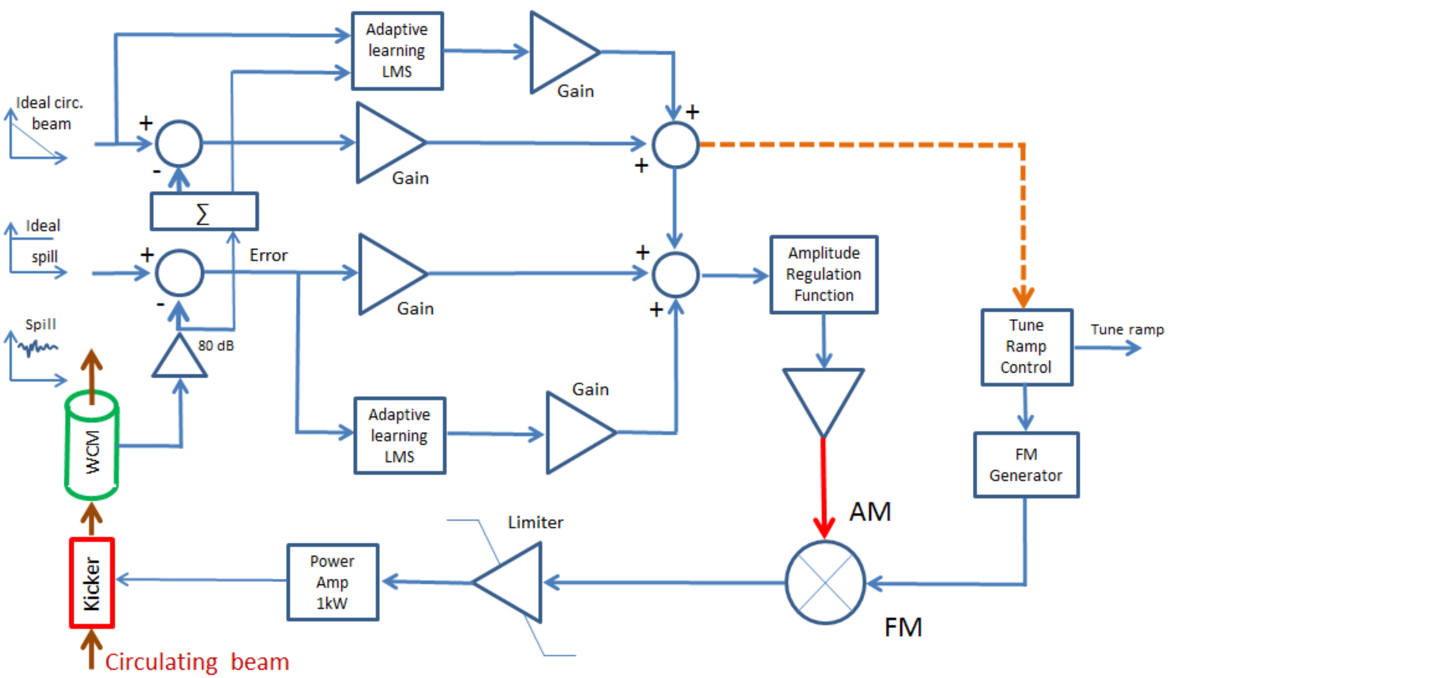
- Fast ripples on the spill rate will be regulated with the RF Knock-Out method that employs transverse heating of the beam.
- Kicker waveform is FM-ed to cover the beam betatron frequency spread.
- AM is provided by the regulation logic



- Reuse old Tevatron damper kicker as the RFKO device.
- RFKO beam heating rates have been measured with beam
- The kicker has been identified, prepped and tested with the beam: **Ready for use.**

# Design: Spill regulation electronics

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



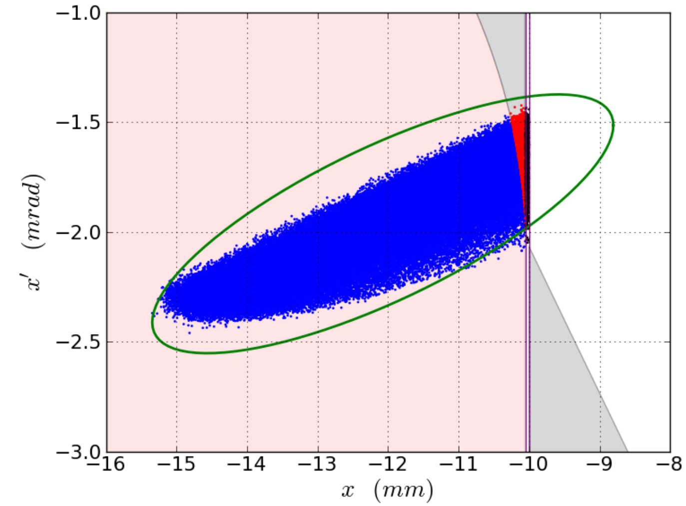

*Currently we are doing prototyping in order to validate design solutions.*
*This will complete the Final Design of Spill Regulation Electronics*

# Performance

- Physics Design
- ESS R&D

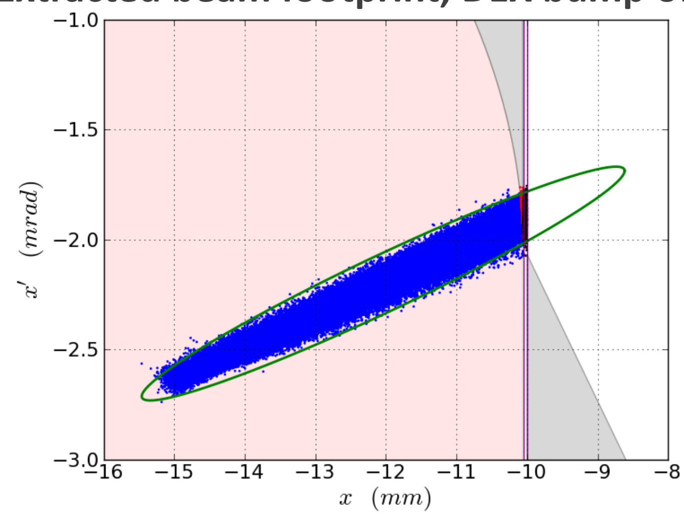
# Performance: Synergia tracking simulations

- **Synergia – state of the art tool**
  - Model improved since CD1
  - All features: DEX, RF, RFKO, aperture, ramping
  - Full spill
  - Substantially sped up




**Extracted beam footprint, DEX bump off**

- **Main results:**
  - Main parameters verified and optimized through the entire spill
  - Performance consistent with earlier ORBIT simulations and physics model; no showstoppers within known physics
  - RFKO process - heating rates consistent with expected



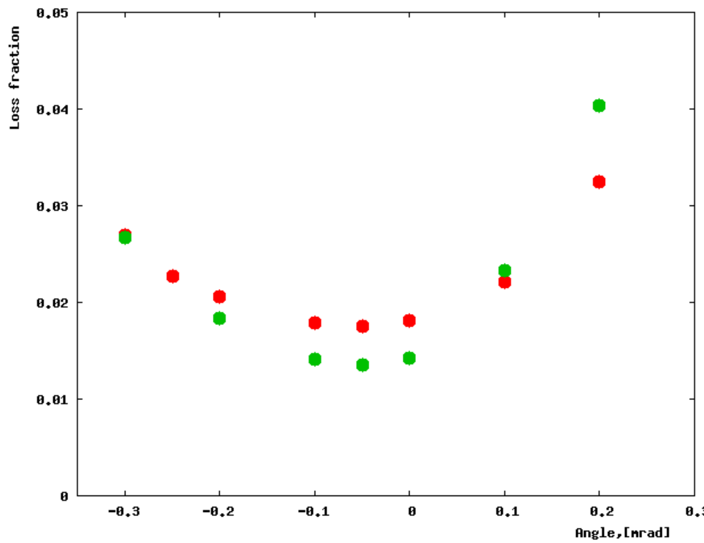

**Extracted beam footprint, DEX bump on**

*Status: Complete*

# 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 advantage over foils in terms of losses
  - ✓ Fine alignment is important
  - ✓ Performance can be improved by making septa asymmetric
  - ✓ Using a pre-scattering diffuser reduces losses further

Losses vs beam angle.

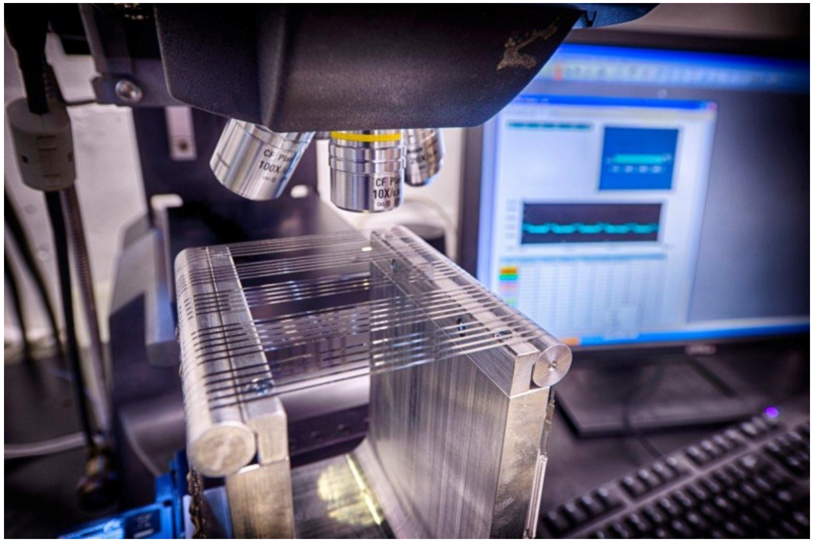


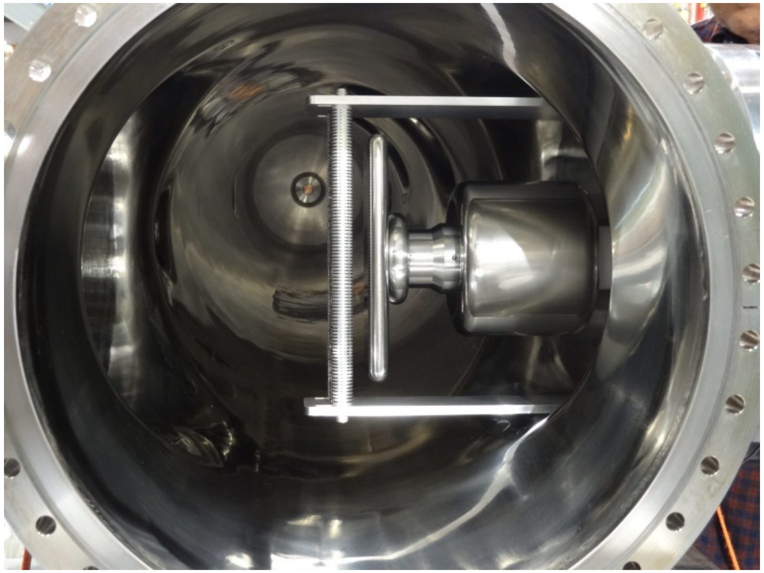

Red- 100μ wires; Green- 50μ foils

*Status: Complete*

# Performance: ESS studies

1. FEA field calculations:
   - ✓ Determined optimal geometries with foils and electrodes
2. Prototype-I:
   - ✓ Built a prototype to study mechanical properties, techniques for clamping, stretching, measuring.
   - ✓ Developed a strategy to achieve good performance
3. Prototype-II for HV testing in vacuum:
   - ✓ Testing cave is made available and ready
   - ✓ Old Tevatron separator vessel reused to house the structure
   - ✓ Stage-0 prototype structure fabricated and tests are in progress





*Status: in progress*

- Essential Project information

# Changes since CD-1

- *Magnetic septa* have been moved out from our scope as a synergy with g-2 project
- Added new scope to improve performance:
  - *Dynamic bump*
  - *Skew quadrupole magnets*
- Change in the extraction geometry: *flipped direction* as part of integration plan with the Muon Campus

# Value Engineering since CD-1

- Used synergy with Main Injector operations in preparations of the septa testing cave at the NWA building.

- 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

- 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

- QA standards and guidelines
  - Fermilab Integrated QA Program – esh-docdb#2469
  - Fermilab Engineering Manual
  - QA Management Plan for Mu2e Experiment - mu2e-docdb# 677
- 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

# Risks

- 6 risk items considered:
  - 1 absorbed in the BL
  - 1 realized
  - 1 mitigated by an external project (AIP)
  - 2 risks transferred to operations

- Presently only one item in the Risk Registry (opportunity)

| RR index | Risk/ Opportunity | Impact | Probability | Point estimate | Status |
|---|---|---|---|---|---|
| 203 | Opportunity to reuse existing spare sextupoles | Cost | L | $164k | **Current** |

# ES&H

- Radiation hazard during operations and service
- Tunnel hazards during installation

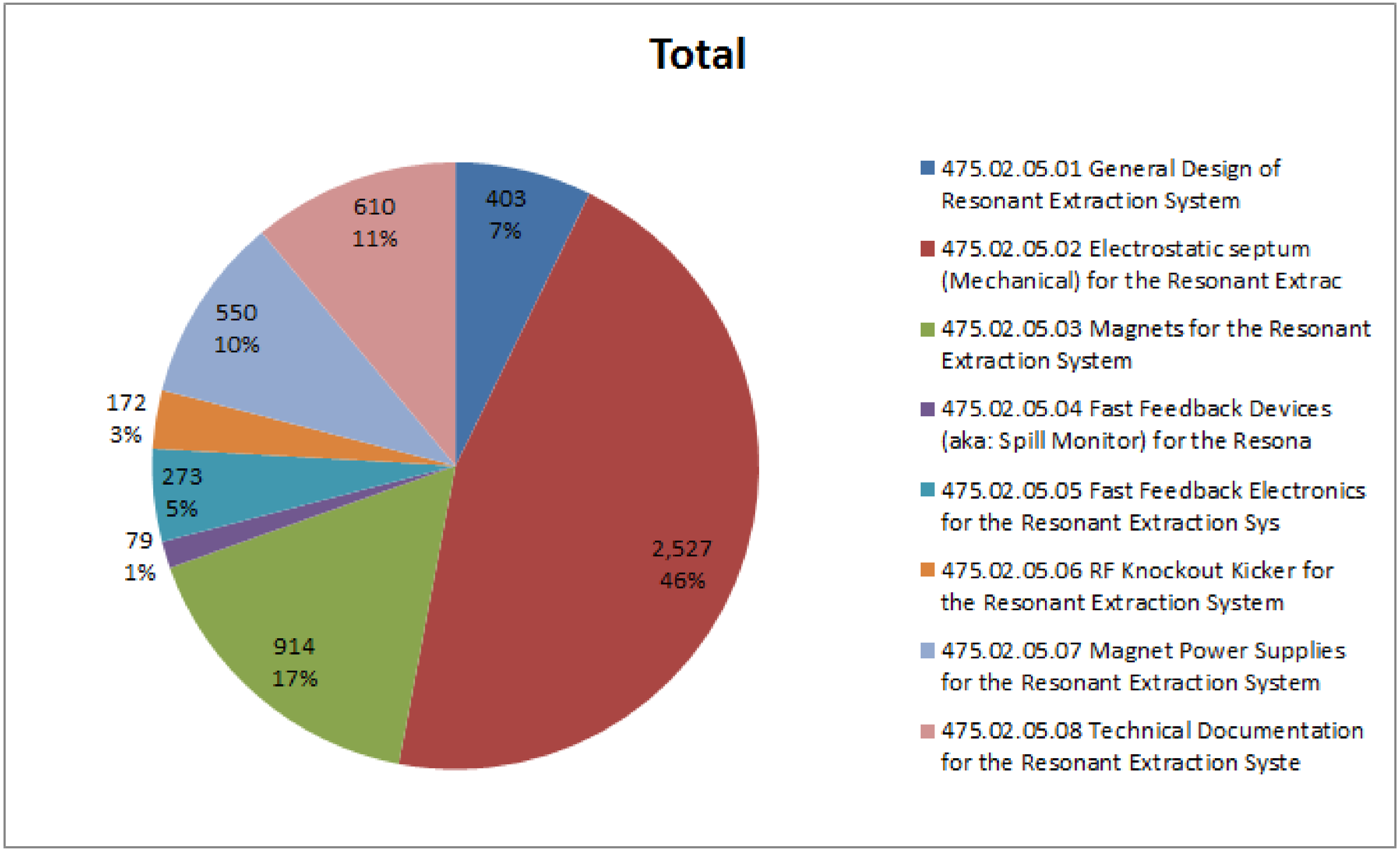
- Specific hazards in the prototype testing area (UV and HV):
  - Testing cave is interlocked and operation protocol is included in the AD operations procedures.
  - LOTO procedure has been written and approved with AD ES&H

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

- Cost & Schedule

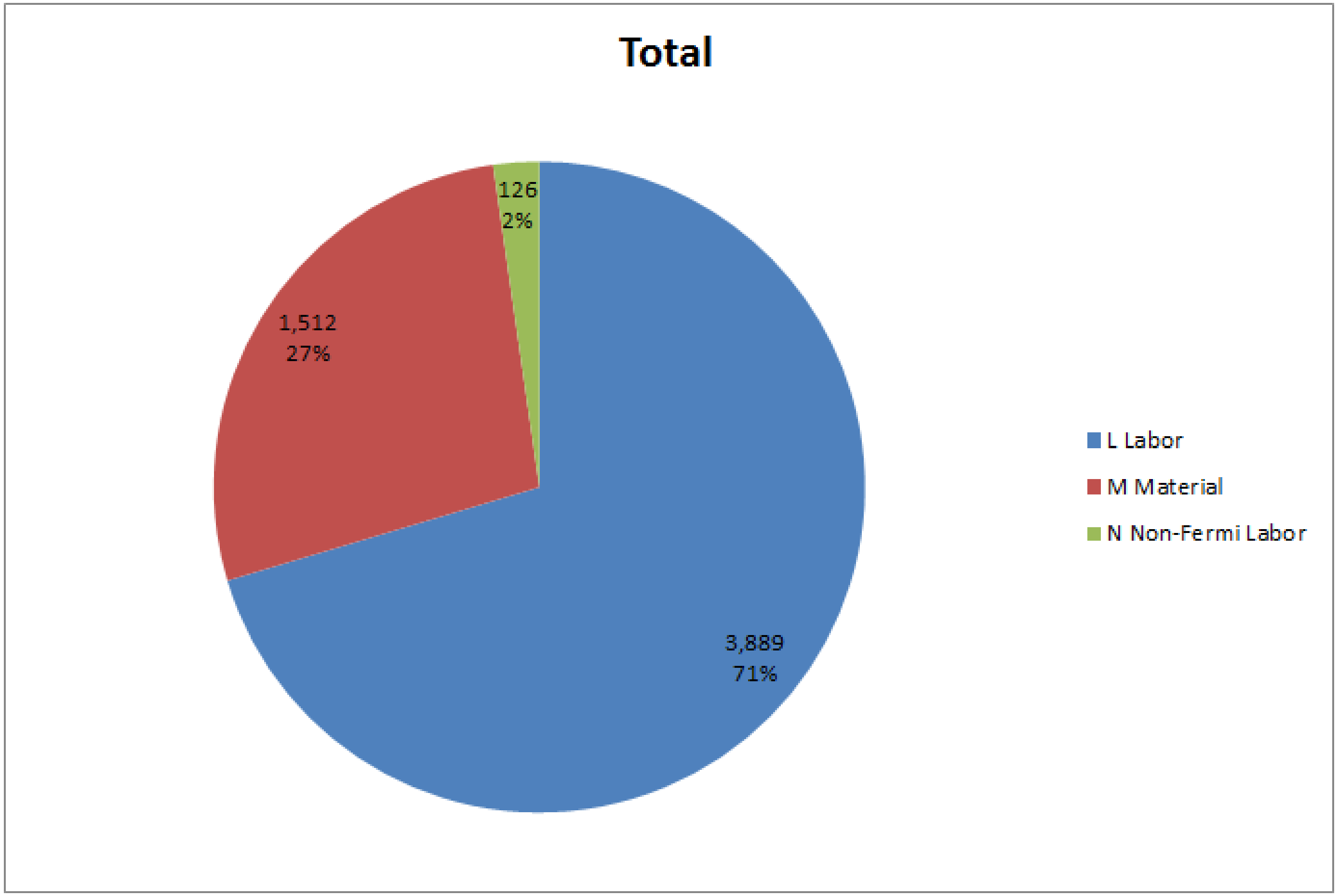
# Cost Distribution by L4

Base Cost by L4 (AY $k)

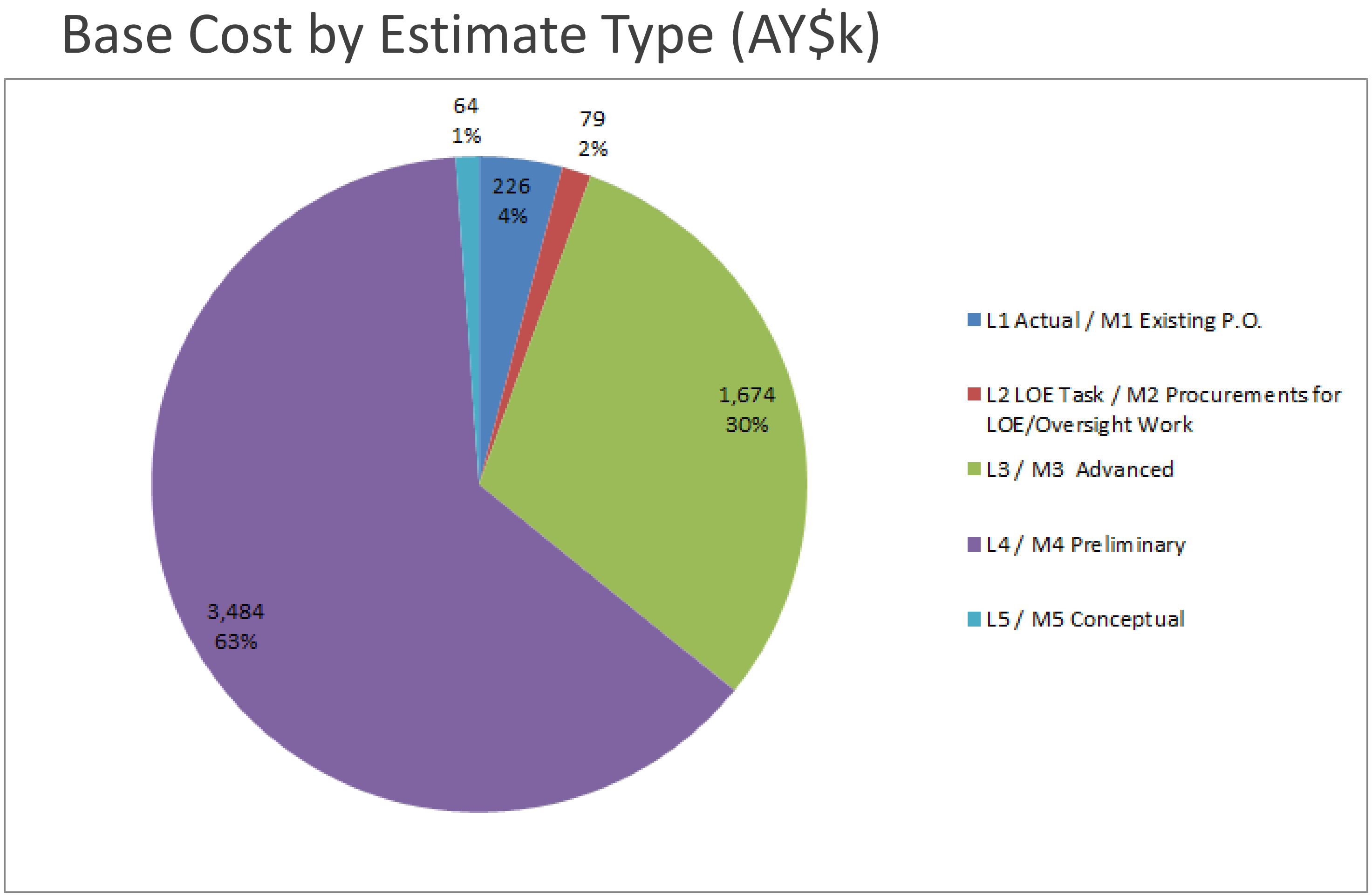


# Cost Distribution by Resource Type

Base Cost (AY $k)



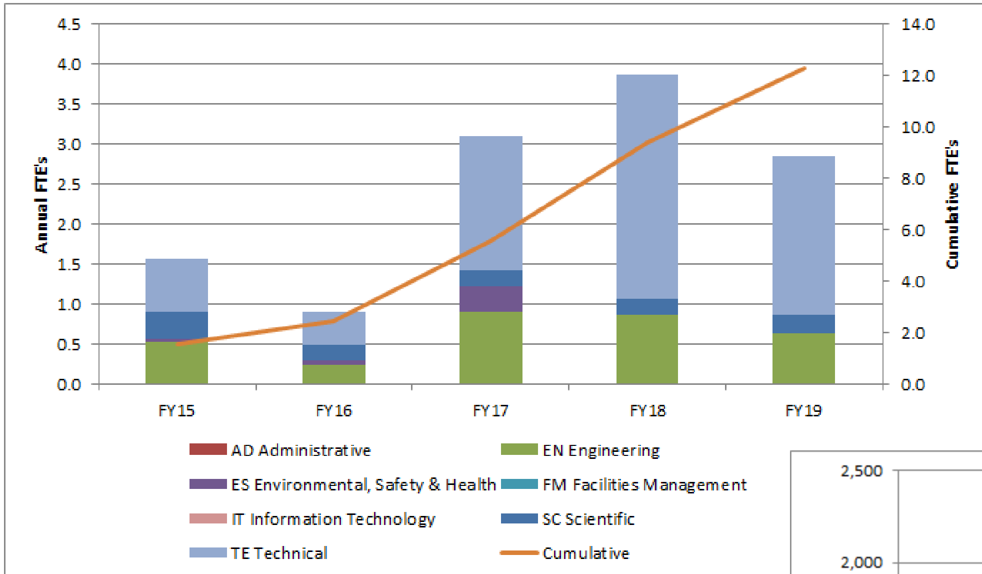
# Quality of Estimate



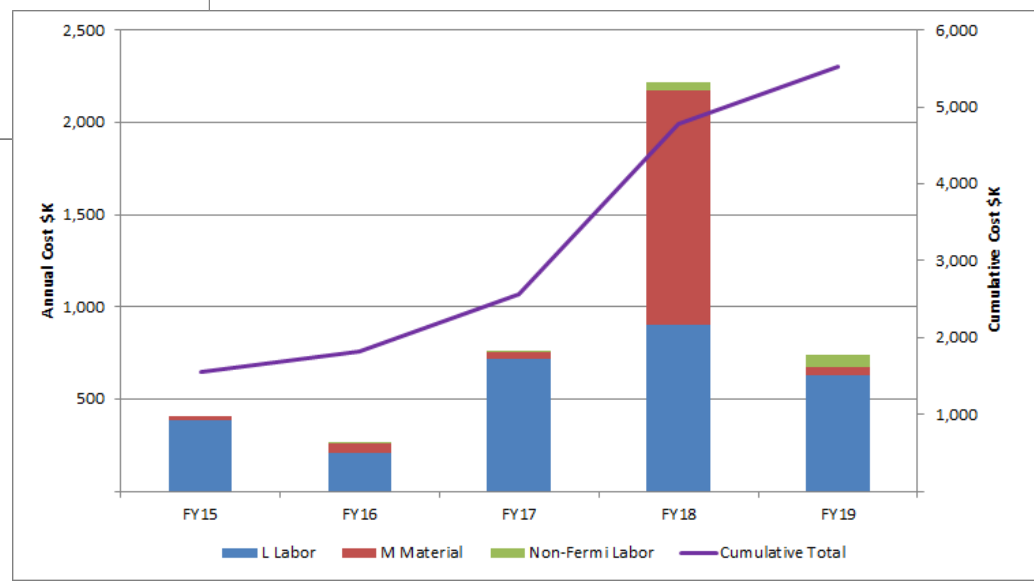

99% of estimate is at Preliminary level or better

# Labor Resources

## FTEs by Discipline




## Labor/Material breakdown



# Cost Table

WBS 2.5 Accelerator Resonant Extraction System

Costs are fully burdened in AY $k

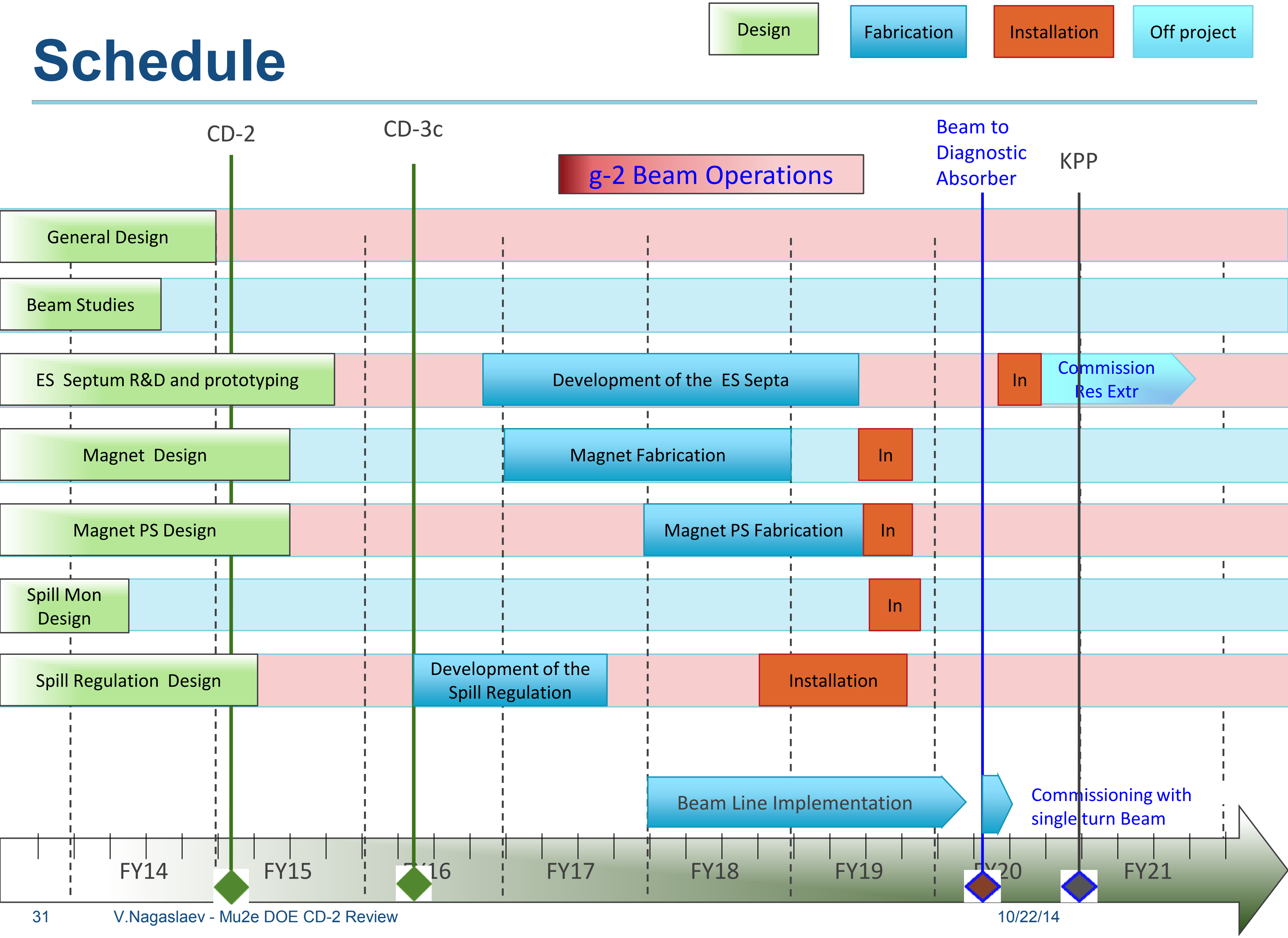
| | Base Cost (AY K$) | | | | | |
|---|---|---|---|---|---|---|
| | M&S | Labor | Total | Estimate Uncertainty (on remaining budget) | % Contingency on (on remaining budget) | Total Cost |
| 475.02.05.01 General Design | | 403 | 403 | 15 | 143% | 418 |
| 475.02.05.02 Electrostatic septum (Mechanical) | 528 | 1,999 | 2,527 | 939 | 41% | 3,466 |
| 475.02.05.03 Magnets | 594 | 320 | 914 | 237 | 26% | 1,152 |
| 475.02.05.04 Fast Feedback Devices (aka: Spill Monitor) | 15 | 65 | 79 | 14 | 30% | 93 |
| 475.02.05.05 Fast Feedback | 40 | 233 | 273 | 81 | 41% | 354 |
| 475.02.05.06 RF Knockout Kicker | 143 | 29 | 172 | 60 | 35% | 232 |
| 475.02.05.07 Magnet Power Supplies | 317 | 232 | 550 | 132 | 26% | 682 |
| 475.02.05.08 Technical Documentation | | 610 | 610 | 137 | 30% | 747 |
| Grand Total | 1,638 | 3,889 | 5,527 | 1,616 | 35% | 7,143 |

# Major Milestones

Total 53 tier-5 milestones in the MS dictionary
14 most significant in the table below

| | | |
|---|---|---|
| 47502.05.001020 | T5 - Septum Technology Choice Complete | 12-Dec-12 |
| 47502.05.03.000500 | T5 - Resonant Extraction Magnet Design Complete | 26-Feb-14 |
| 47502.05.01.001070 | T5 - Milestone: Beamline Studies Complete | 18-Apr-14 |
| 47502.05.05.001105 | T5 - Resonant Extraction Fast Feedback Electronics Design Complete | 24-Nov-14 |
| 47502.05.07.000500 | T5 - Resonant Extraction Magnet Power Supply Design Complete | 27-Feb-15 |
| 47502.05.02.001215 | T5 - Resonant Extraction Electro-Static Septum Design Complete | 22-May-15 |
| 47502.05.001050 | T5 - DOE CD-3c Accelerator Resonant Extraction Approval | 24-Feb-16 |
| 47502.05.03.2.001020 | T5 - Start of Resonant Extraction Harmonic Sextupole Magnet Fabrication | 3-Oct-16 |
| 47502.05.03.2.001095 | T5 - Resonant Extraction Harmonic Sextupole Magnet Fabrication Complete | 29-Jan-18 |
| 47502.05.03.001000 | T5 - Resonant Extraction Magnet Installation Complete | 30-Oct-18 |
| 47502.05.07.001000 | T5 - Resonant Extraction Magnet Power Supply Installation Complete | 13-Dec-18 |
| 47502.05.02.001315 | T5 - Resonant Extraction Electro-Static Septum Assembly Complete | 11-Jul-19 |
| 47502.05.02.001318 | T5 - Start Resonant Extraction Electro-static Septum Installation | 12-Jul-19 |
| 47502.05.02.001350 | T5 - Installation of Electrostatic Septum Modules Complete | 13-Sep-19 |

# Schedule


Design
Fabrication
Installation
Off project
CD-2
CD-3c
g-2 Beam Operations
Beam to Diagnostic Absorber
KPP
General Design
Beam Studies
ES Septum R&D and prototyping
Development of the ES Septa
In
Commission Res Extr
Magnet Design
Magnet Fabrication
In
Magnet PS Design
Magnet PS Fabrication
In
Spill Mon Design
In
Spill Regulation Design
Development of the Spill Regulation
Installation
Beam Line Implementation
Commissioning with single turn Beam
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

# Summary

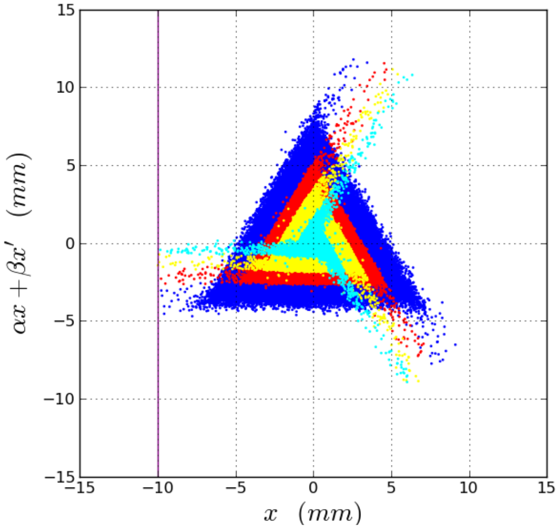
- Resonant Extraction Systems Preliminary Design is complete
- Design of the Resonant Extraction meets the requirements
- The final studies are underway with the high confidence of success
- Cost and schedule estimates are well understood and ready to establish the baseline

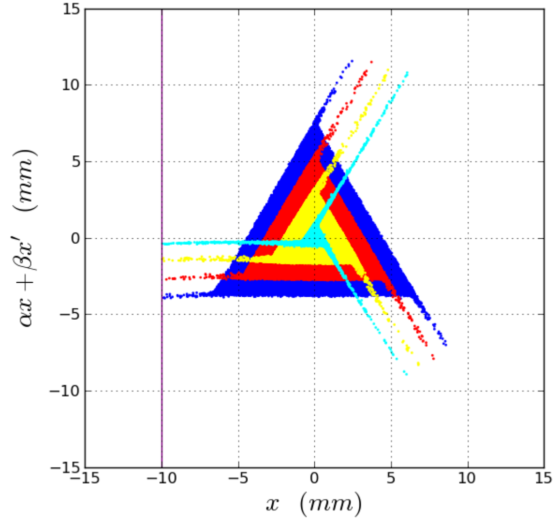
# Backup slides

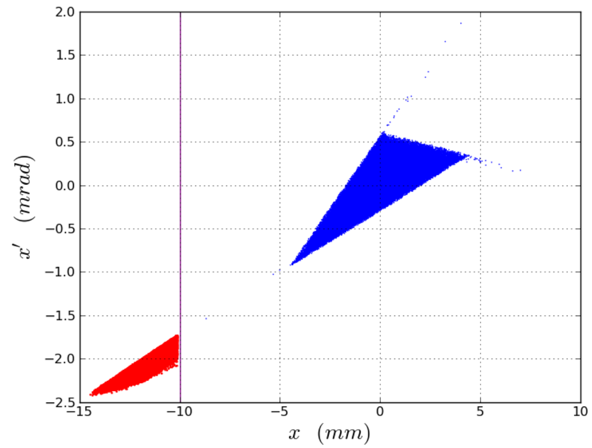
# Organizational Breakdown

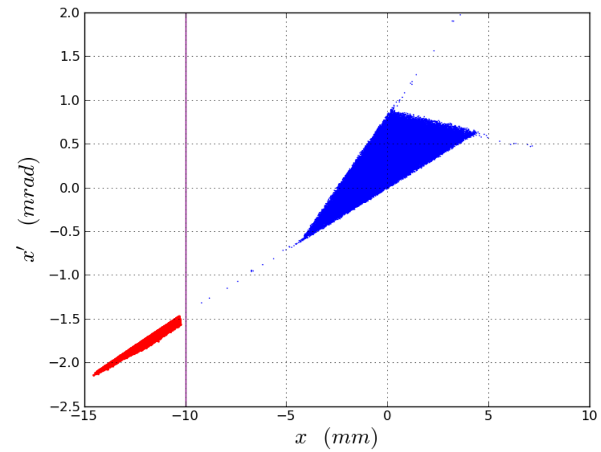
- Key people in the subproject:
  - V. Nagaslaev, AD, L3 Manager
  - C. S. Park, CD, L3 Deputy Manager, Synergia
  - D. Tinsley, AD, Sr. Mechanical Engineer, ESS design
  - P. Prieto, AD, Sr. Electronics Engineer, Spill Controls
  - G. Krafczyk, AD, Sr. Electrical Engineer, Power Supplies
  - TJ Gardner,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

# Phase space diagrams



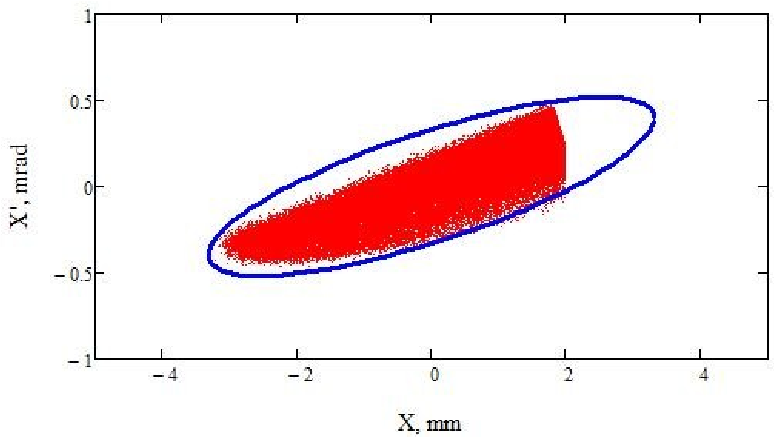



# Extracted beam footprint

$\beta_n := 10 \qquad \alpha_n := -1.2 \qquad \varepsilon_n := 1.1$

$$xe_k := \sqrt{\beta_n \cdot \varepsilon_n} \cdot \cos(\varphi_k) \qquad xep_k := \sqrt{\frac{\varepsilon_n}{\beta_n}} \cdot \left(\sin(\varphi_k) - \alpha_n \cdot \cos(\varphi_k)\right)$$

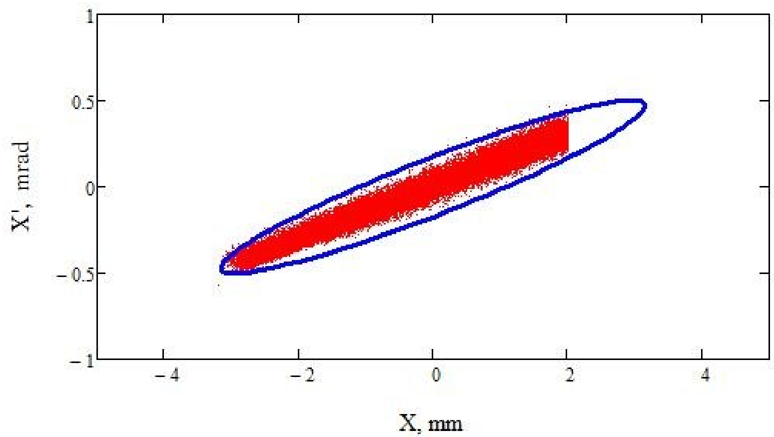
$$\frac{\text{sampleFilter}(\text{Xnobump}, \beta_n, \alpha_n, \varepsilon_n)}{\text{rows}(\text{Xnobump})} = 0.999$$




$\beta_b := 18 \qquad \alpha_b := -2.7 \qquad \varepsilon_b := 0.55$

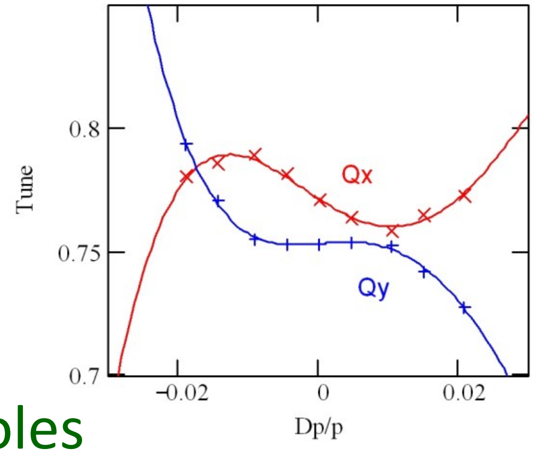
$$ye_k := \sqrt{\beta_b \cdot \varepsilon_b} \cdot \cos(\varphi_k) \qquad yep_k := \sqrt{\frac{\varepsilon_b}{\beta_b}} \cdot \left(\sin(\varphi_k) - \alpha_b \cdot \cos(\varphi_k)\right)$$

$$\frac{\text{sampleFilter}(\text{Xbump}, \beta_b, \alpha_b, \varepsilon_b)}{\text{rows}(\text{Xbump})} = 0.999$$



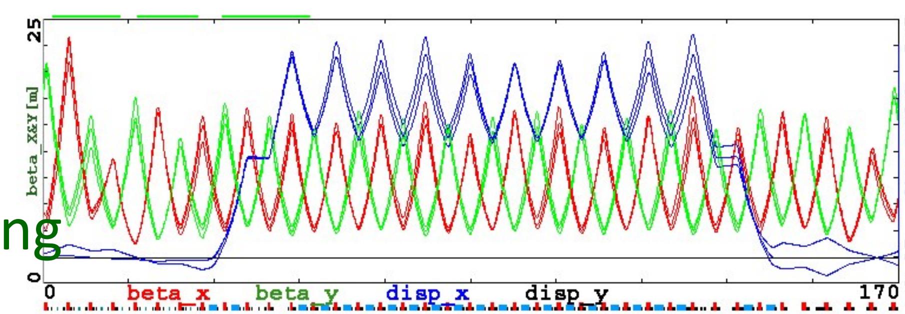
# Optics of the Debuncher: chromaticity

Chromaticity:




- Large momentum spread
- 2 families of sextupoles in arcs
- Tunes vs $\Delta p/p$
- Fit: 6- and 10-pole harmonics in dipoles
- Included in the model

Chromaticity of functions




No problem for injection matching
No dynamic aperture limitation

# Risks

- Presently only one item in the Risk Registry (opportunity)

| RR index | Risk/ Opportunity | Impact | Probability | Point estimate | Status |
|---|---|---|---|---|---|
| 203 | Opportunity to reuse existing spare sextupoles | Cost | L | $164k | **Current** |
| 025 | Need to ramp Delivery Ring sextupoles | Technical | M | -- | Mitigated in BL |
| 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 by AIP |
| 022 | High Beam Loss | Technical, Schedule | M | -- | Transferred |
| 012 | Mu2e beam commissioning delayed. | Schedule | L | -- | Transferred |

# Tune space