Fermilab

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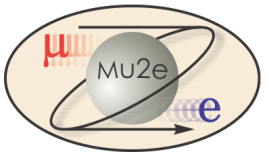
Mu2e Progress



Ron Ray
Mu2e Project Manager
6/24/15

Outline

- Introduction
- Project Milestones
- Simulations
- Recent Progress
- Project Performance
- Summary

Introduction

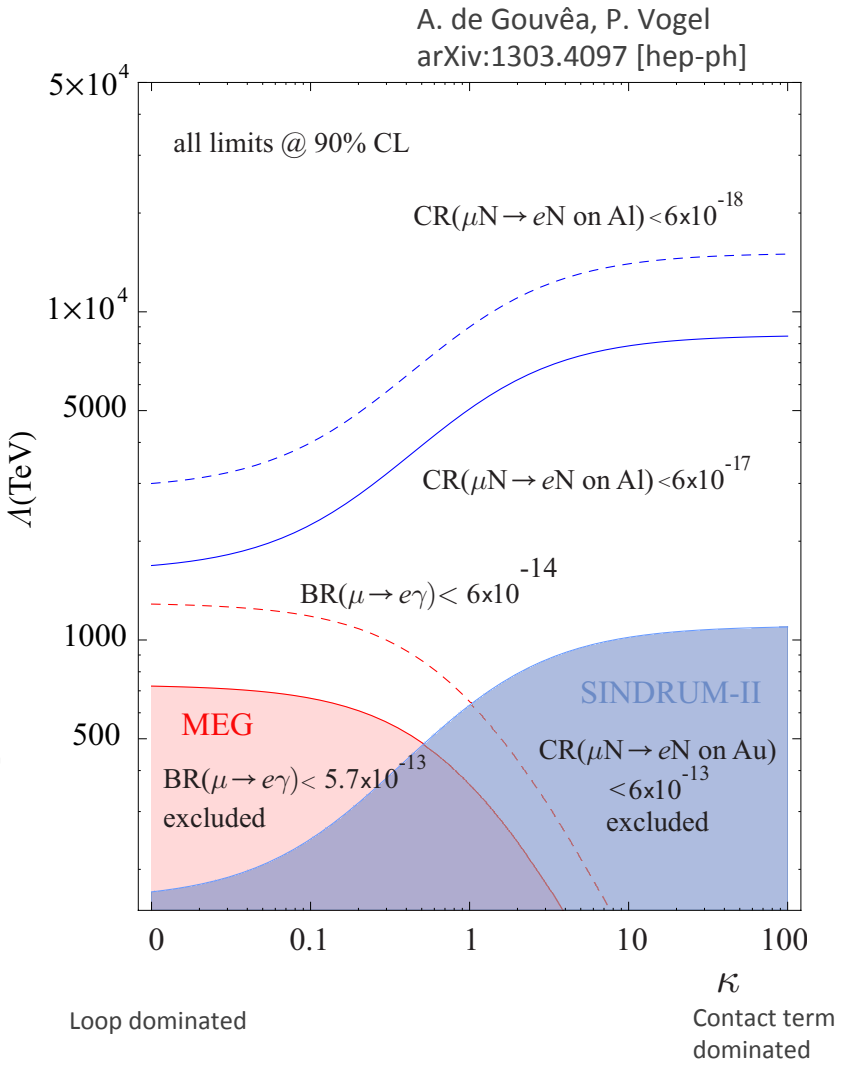
- Mu2e is a compelling discovery experiment with sensitivity to a broad range of new physics
  - Reach extends to 10^4 TeV, beyond the reach of any current or planned accelerator.
- Synergistic part of the overall muon program at Fermilab
  - Nearly realized Muon Campus enables 2 world-leading muon experiments for significantly less than the cost of the individual experiments.
- Mu2e Project recently baselined at $274M TPC.
- Unequivocal guidance from P5
  - “Complete the Mu2e and g-2 projects.”

Mu2e in a Nutshell

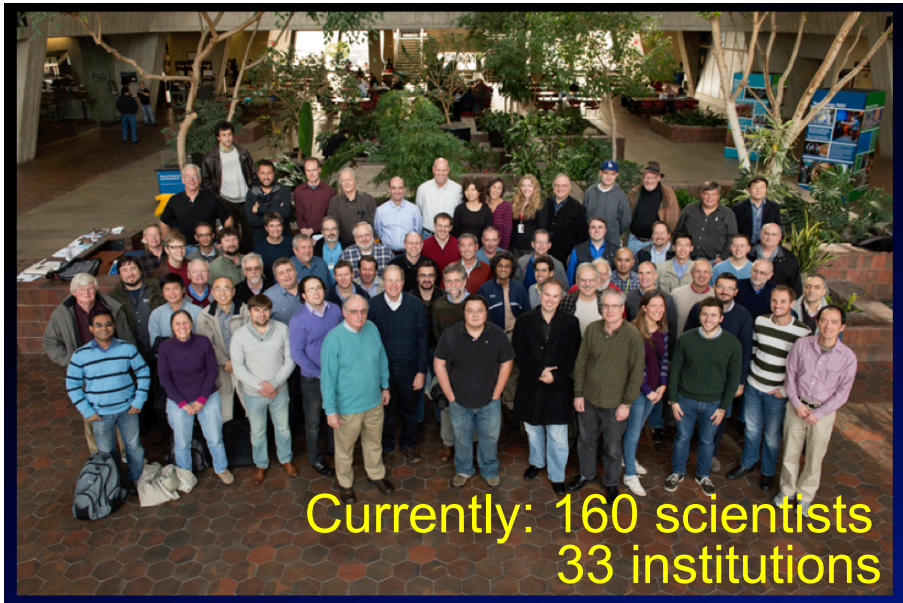
- Mu2e is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \rightarrow e^- N$
  - Most new physics models so far postulated provide new sources of flavor phenomena
  - Observation is unambiguous evidence for new physics.
- Target sensitivity has great discovery potential
  - Goal: Single-event-sensitivity of 3×10^{-17} (relative to ordinary μ capture)
  - Goal: <0.5 events background
    - Yields Discovery Sensitivity for all rates > few 10^{-16}
    - Factor of 10,000 more sensitive than existing measurement.
- Quark flavor is violated. Neutrino flavor is violated.
  - Both implied something profound about the underlying physics
  - Both garnered Nobel Prizes
- Mu2e enables a search for charged lepton flavor violation with unprecedented sensitivity that could prove to be equally profound.

Science Drivers

- Explore the unknown, new particles, interactions and physical principles (in the new P5 framework).
- Broad discovery sensitivity across all categories of new physics models
- Sensitivity to 10,000 TeV, well beyond any imaginable accelerator
- Sensitive to new physics at LHC energies that is suppressed by small mixing angles, loop factors
- Also sensitive to new physics at 10 TeV, beyond reach of LHC but within reach of 100 TeV pp collider.



Mu2e Collaboration



Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Kansas State University
Lewis University
University of Louisville
University of Minnesota
Muons Inc.
Northern Illinois University
Northwestern University
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

Helmholtz-Zentrum Dresden-Rossendorf

Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce and Università del Salento
Laboratori Nazionali di Frascati and Università Marconi Roma
INFN Pisa

Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of Nuclear Physics
Institute for Nuclear Research, Moscow

Mu2e Collaboration

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory

Added 30 collaborators and 8 institutions since the last PAC presentation (Jan 2014).

- Yale
- Minnesota
- ANL
- Kansas State
- Louisville
- Southern Alabama
- Novosibirsk
- Dresden

Helmholtz-Zentrum Dresden-Rossendorf

Laboratori Nazionali di Frascati
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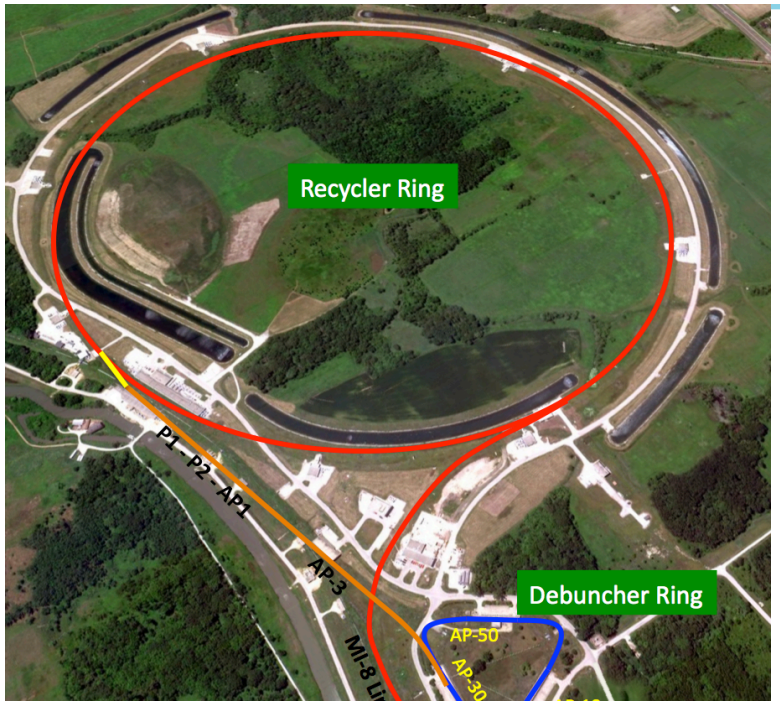
Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of Nuclear Physics
Institute for Nuclear Research, Moscow

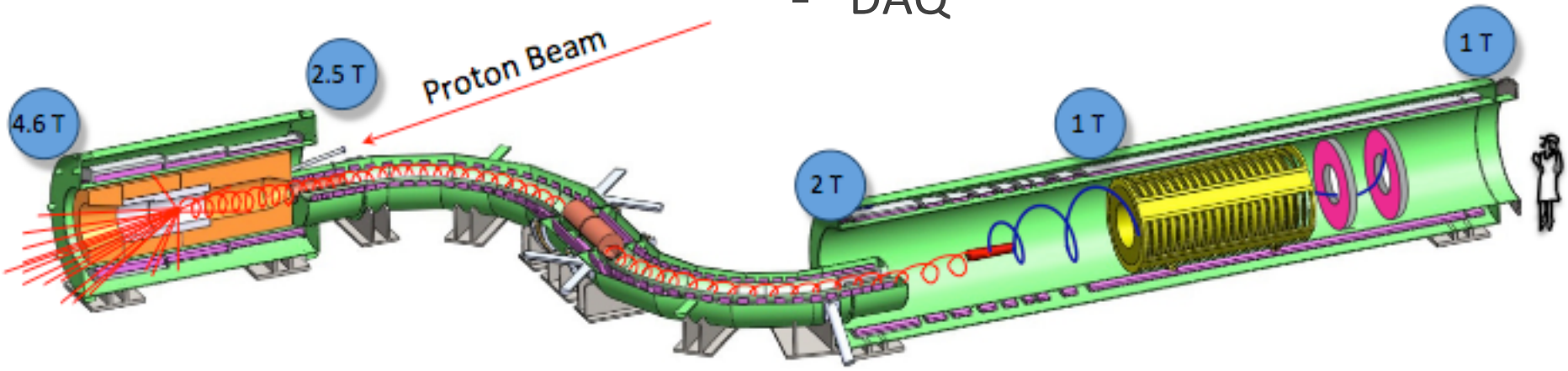
Northwestern University
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

Mu2e Project Scope



Mu2e Project scope includes

- New building to house experiment
- Modifications to accelerator
- Mu2e apparatus
  - Superconducting Solenoids
  - Tracker
  - Calorimeter
  - Cosmic Ray Veto (not shown)
  - DAQ

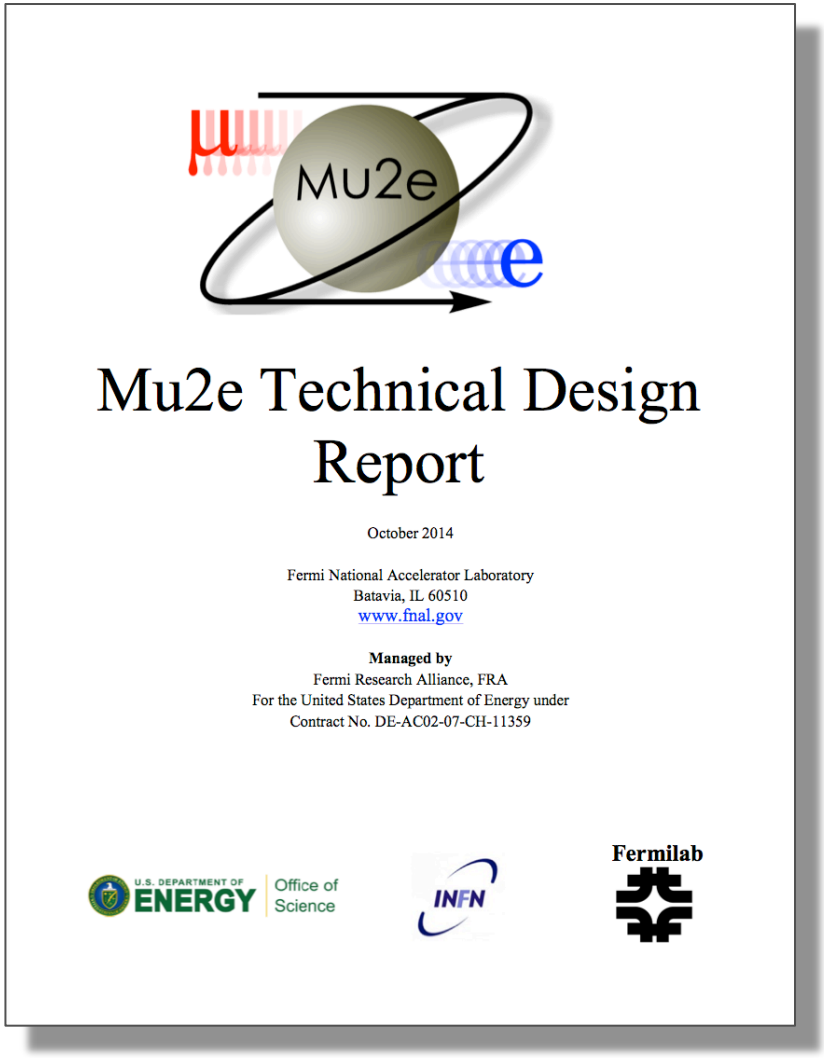


Project Milestones

- CD-0 approved in November 2009
- NEPA Categorical Exclusion in June 2012
- CD-1 approved in July 2012
  - Cost range of $200M-$300M
- CD-3a for long-lead solenoid conductor approved July 2014.
  - ~$6M of procurements following a year of R&D and prototyping
- CD-2 and CD-3b for the Detector Hall and Transport Solenoid Modules approved in March 2015.
  - TPC of $274M
  - CD-3b procurements ~$18M

Technical Design Report

- Completed as part of CD-2. Nearly 900 pages.
  - arXiv:1501.05241
- Detailed description of the Mu2e apparatus
- This apparatus
  - Meets the requirements
  - Achieves the physics goals of the experiment
  - Is robust.



CD-3c

- CD-3c is the next significant Project Milestone
  - Authorizes construction of the remainder of the Project scope.
- CD-3c approval scheduled for Summer of 2016.
  - Timed to keep the solenoids on schedule
  - Not all designs will be completed by then, but they will be very mature and the risk associated with the remaining design work will be small.
- Full suite of external design reviews scheduled prior to CD-3c reviews.

Scheduled Design Reviews

- Accelerator Instrumentation – Oct 2015
- Radiation Safety – Oct 2015
- Resonant Extraction – Aug 2015
- Delivery Ring RF – Aug 2015
- Beamline – Sept. 2015
- Extinction System – Aug 2015
- Target Station – Nov. 2015
- PS/DS 50% Design Review – Aug. 2015
- PS/DS Final Design Review – Jan. 2016
- Cryo feedboxes – Jan. 2016
- Solenoid Power System – Aug. 2015
- Solenoid Slow Monitoring – Aug. 2015
- Quench Protection – Jan. 2016
- Cryo controls – July 2015
- Tracker - 2016
- Calorimeter crystals – July 2015
- Calorimeter Final Design – Jan. 2016
- CRV – Jan 2016.
- DAQ – Jan 2016

Additional Independent Oversight

- Acquisition Oversight Committee for Solenoids has been in place for 2 years
  - (http://mu2e.fnal.gov/public/project/reviews/SolenoidAOC/index.shtml)
  - Group of world experts who provide occasional advice on solenoid design, acquisition, QA
- Technical Oversight Committees have also been put in place for the Tracker and Cosmic Ray Veto
- Working on oversight committees for Calorimeter and Accelerator.

Simulations

- GEANT4 with detailed geometry description including building, overburden, penetrations, detector elements, target supports, solenoid coils and cryostats.
- Physics list chosen to best describe HARP pion production data in relevant kinematic region. Utilize high precision list for neutrons < 20 MeV. Customized for muon capture/decay.
- Detailed hit-level tracker simulation includes effects of ionization drift in straws, gas amplification, signal transit, and electronic amplification, shaping, and digitization.
  - Also includes overlay of time-dependent accidental occupancy from unstopped beam, μ capture and decay, etc.
- Data-like reconstruction begins with simulated digitized output, forms hits, performs full pattern recognition and track fitting.

Simulations

- For CD-2 we completed a full, integrated set of physics studies with a full error analysis.

Table 3.4 from TDR

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.23 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.082 ± 0.018
	Total	0.36 ± 0.10

Simulations

Error analysis includes full analysis of systematics

Error analysis for DIO background

Effect	Uncertainty in DIO background yield	Uncertainty in CE single-event-sensitivity ($\times 10^{-17}$)
MC Statistics	±0.02	±0.07
Theoretical Uncertainty	±0.04	-
Tracker Acceptance	±0.002	±0.03
Reconstruction Efficiency	±0.01	±0.15
Momentum Scale	+0.09, -0.06	±0.07
μ-bunch Intensity Variation	±0.007	±0.1
Beam Flash Uncertainty	±0.011	±0.17
μ-capture Proton Uncertainty	±0.01	±0.016
μ-capture Neutron Uncertainty	±0.006	±0.093
μ-capture Photon Uncertainty	±0.002	±0.028
Out-Of-Target μ Stops	±0.004	±0.055
Degraded Tracker	-0.013	+0.191
Total (in quadrature)	+0.09, -0.07	+0.35, -0.29

Simulations

- Roadmap with milestones that bring us from where we are now to CD-3c to being ready for data taking.
  - Roadmap includes
    - alignment and calibration mock-up
    - data challenge to test the tools and workflows ahead of real data taking
- We are well ahead of the typical experiment at this stage but we feel that we have to be because of the complexity of the experiment.
- Based on these studies, we are confident this apparatus will allow us to achieve our physics goals.

Review of Mu2e Offline and Simulations

- March 5-6, 2015. Charge included:
  - evaluation of current offline computing infrastructure and tools, build and release tools, simulation tools, framework, database, workflow, workflow management, data management, and operations.
  - plan for developing the offline computing infrastructure, tools, and processes leading to Mu2e data taking.
- Review was generally positive:
  - "The current setup of the Mu2e infrastructure and tools are appropriate for the current... stage of the experiment"
  - "The experiment has done an excellent job in incorporating the tools provided by the Scientific Computing Division. They have integrated ART at a high level and the collaboration is using it in a productive fashion."
  - "There is good bi-directions communication with the experiment and [SCD]."
  - "The experiment should keep the engagement of non-experts a priority."
- https://fermipoint.fnal.gov/organization/cs/scd/coordinators/SitePages/Mu2E%20Review%20March%202015.aspx

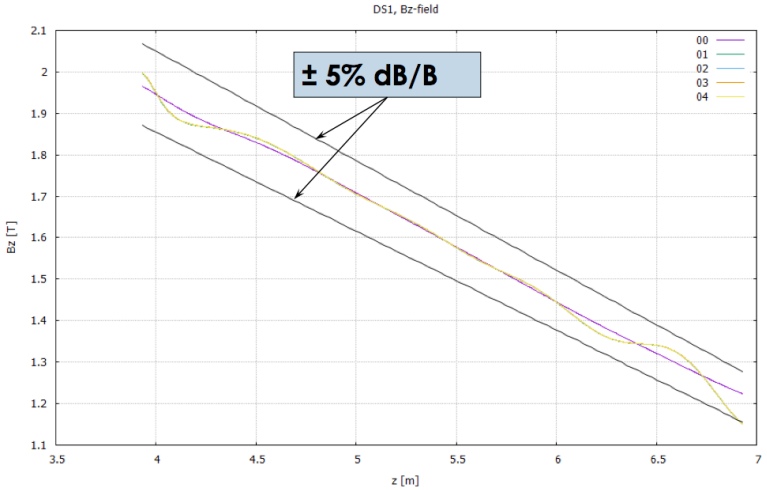
Recent Progress: Conductor Procurement

- Conductor procurement authorized by CD-3a.
- 4 different custom conductors required for the Mu2e solenoids
  - PS, TS, DS1, DS2
  - Developed during a 1 year R&D program with industry
- 75 km of Al-stabilized cable
- DS2 production order completed ahead of schedule
- DS1 and TS conductor in progress and ahead of schedule
- PS conductor on schedule.

TS	DS1	DS2	PS
14x0.67mm	12x1.466mm	8x1.303mm	32x1.466mm
Cable size:	Cable size:	Cable size:	Cable size:
9.85x3.11mm	20.1x5.27mm	20.1x7.03mm	30.1x5.42/5.62mm

Recent Progress: PS and DS

- Detailed reference design of DS and PS completed by Mu2e last year
- Final design and build contract placed with General Atomics in March 2015.
- Work on final design proceeding on schedule.
- Weekly phone meetings
- Face-to-face meetings every 6 weeks
- 50% design review in August
- Final design complete by December



Recent Progress: Transport Solenoid

- Prototype TS Module fabricated in Italy in collaboration with INFN
- Battery of warm tests performed upon delivery. Prototype meets or exceeds acceptance criteria thus far.


TS Coil Module prototype at Fermilab

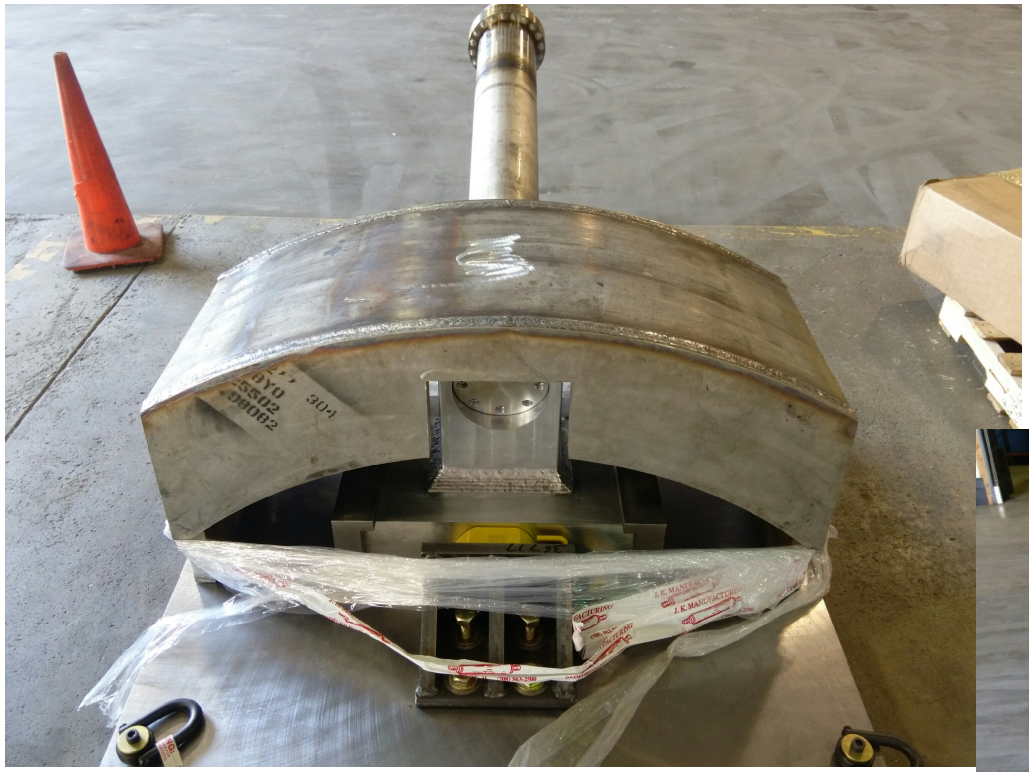
TS Module Prototype Cold Test

- Cold test of TS Module prototype being conducted in CHL.
- Mu2e and MICE invested in infrastructure in CHL
- MICE completed test last year.
- Mu2e cold test began in late April.

TS Module Prototype Cold Test

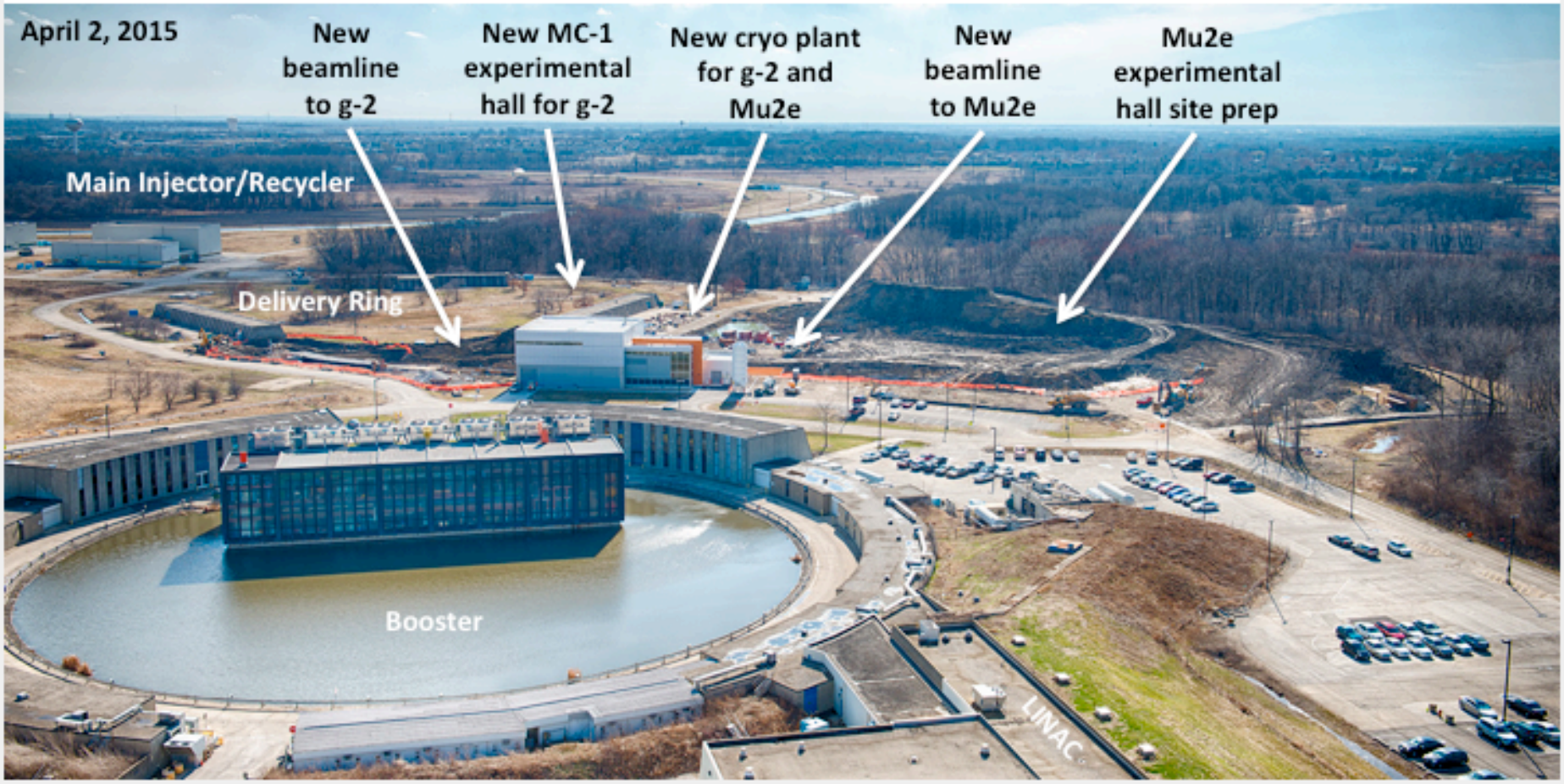
- Broken equipment in CHL delaying TS Module prototype cold test
  - Cold Box 1 – propylene glycol/water-to-helium leak in compressor C. Switch to Cold Box 2 and compressor A.
  - Cold Box 2 – repair turbine broken during Tevatron running.
  - Compressor A had a bad motor bearing that had to be replaced by an outside vendor. Work completed on June 18. Started compressor on June 19 and it sparked and died. Switch to compressor B which has high helium losses.
- This is now critical path.
  - Cannot procure TS Modules until we fully evaluate and review the prototype.
  - Lost 3 months of schedule contingency (1/8 of total schedule float).
  - One way to recover schedule is split TS production to 2 vendors.
    - Can save up to a year, but will cost between $1M - $3M.
      - Have to test twice as fast
    - 3 month delay will cost about $3M

Recent Progress: Transport Solenoid



TS adjustment rod prototype delivered

Muon Campus


April 2, 2015
New beamline to g-2
New MC-1 experimental hall for g-2
New cryo plant for g-2 and Mu2e
New beamline to Mu2e
Mu2e experimental hall site prep
Main Injector/Recycler
Delivery Ring
Booster
LINAC

Recent Progress: Detector Hall Construction

Detector Hall Construction authorized by CD-3b

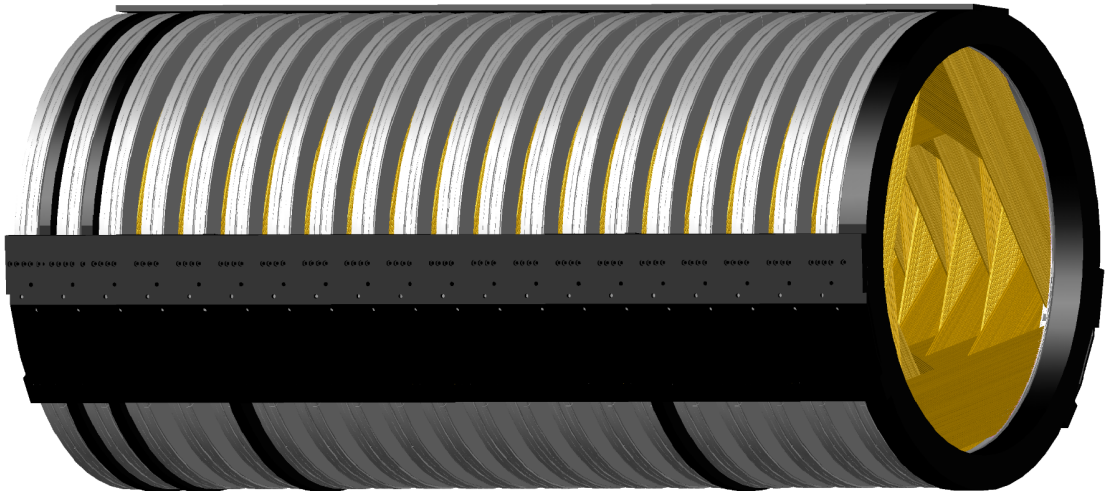
Recent Progress: Detector Hall Construction

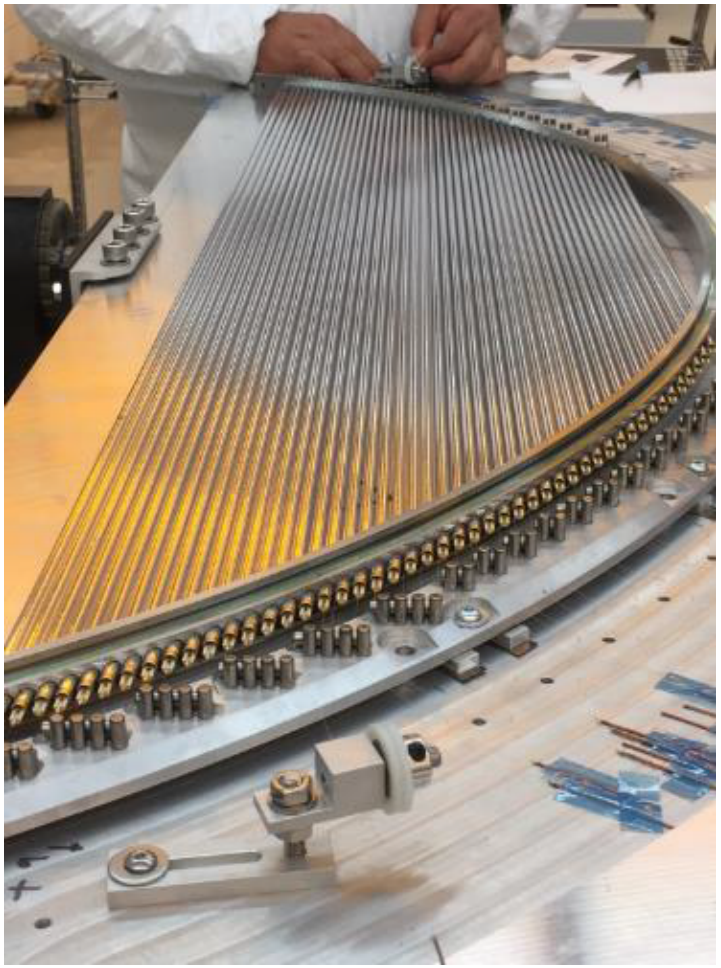
Recent Progress: Detector Hall Construction

Muon Campus Beamline

Recent Progress: Tracker Panel Prototype

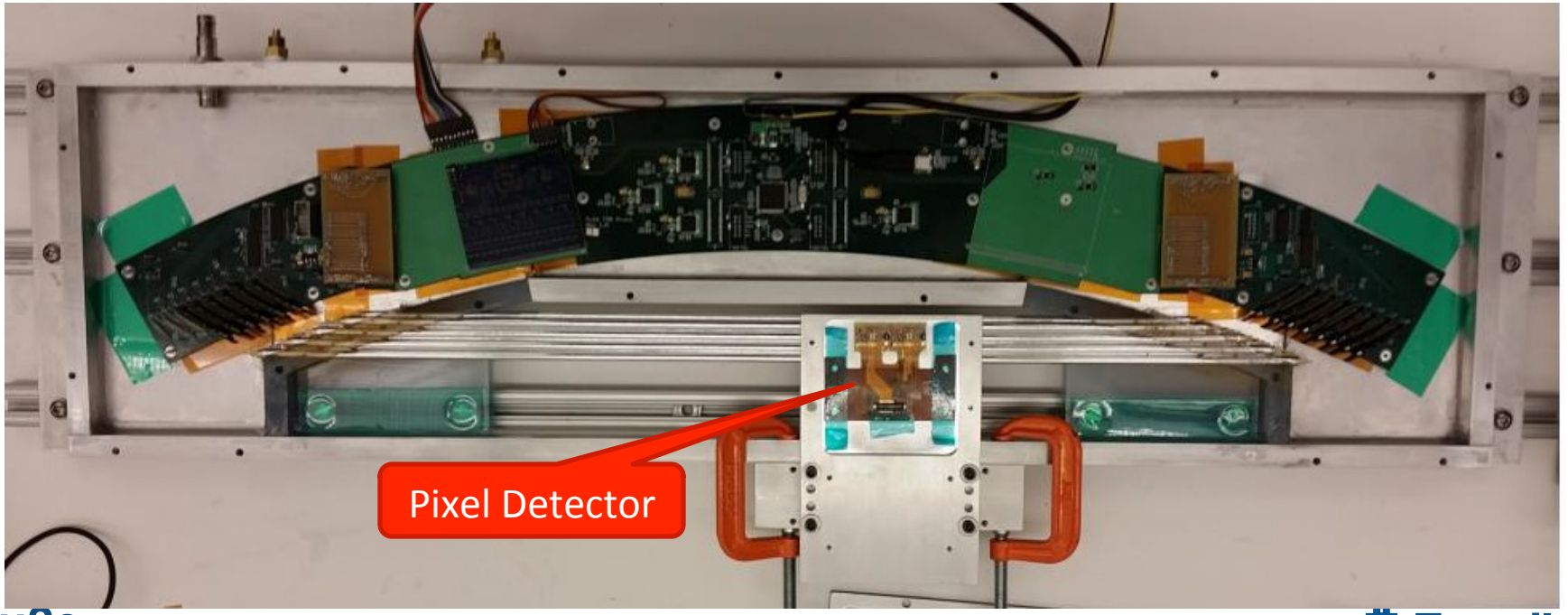
- Tracker panel ready for test in vacuum chamber.
  - DAQ pilot system and prototype readout controller will be used to read out data.





Recent Progress: Tracker

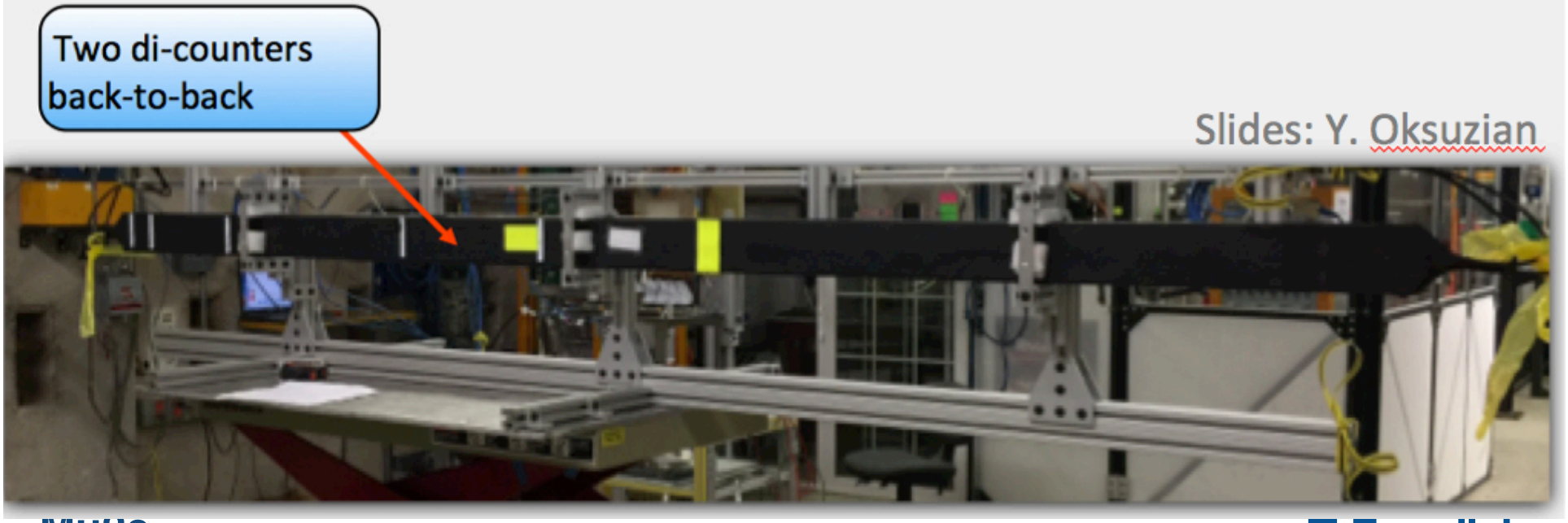
- 8-straw test panel of shortest straws exposed to low energy proton beam at 88-inch cyclotron at LBNL
  - 5 MeV and 10 MeV protons
  - Electronics tests, including cross-talk
  - Data analysis underway.



Recent Progress: CRV Beam Test

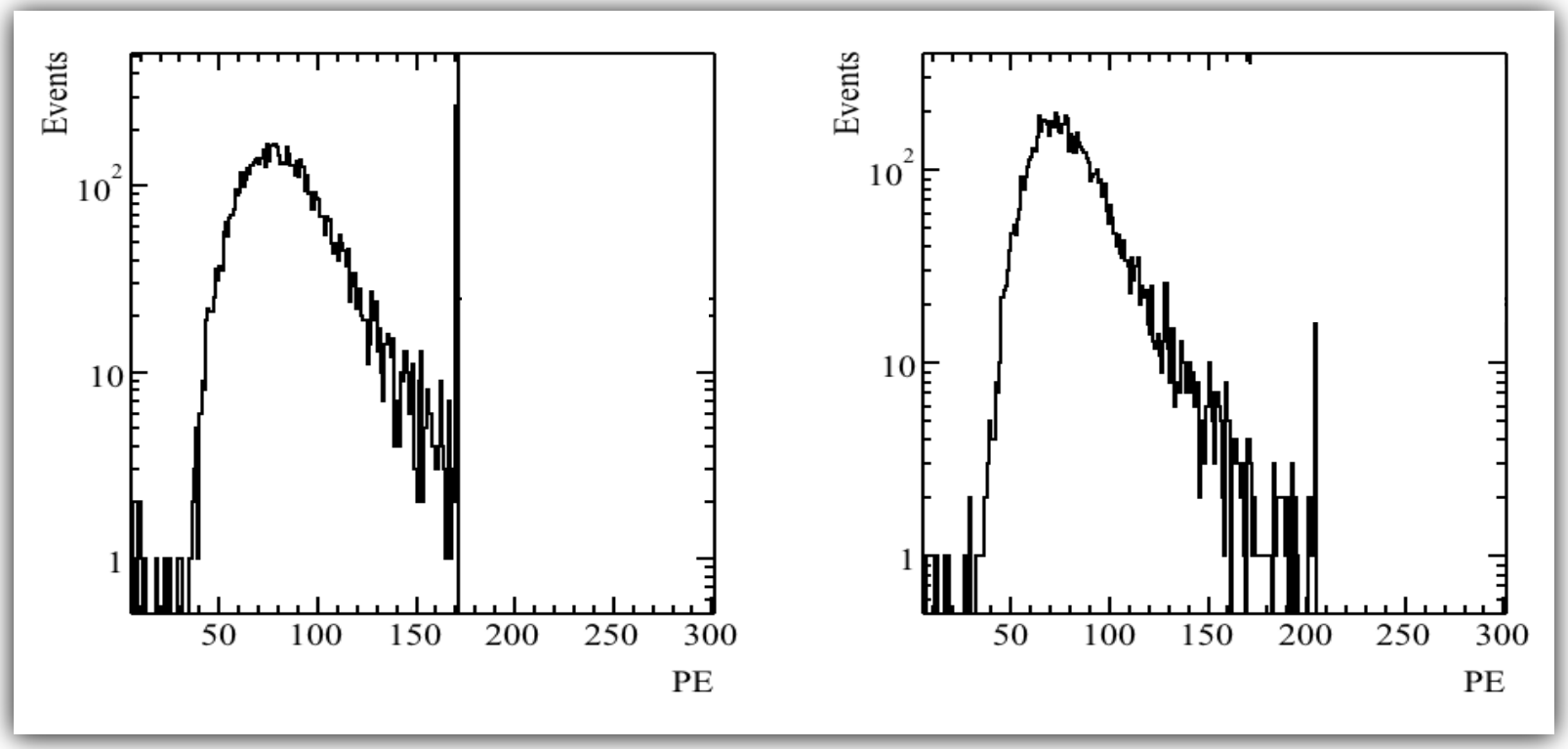
Measurements at Fermilab test Beam facility in May and June using 120 GeV proton beam.

- Absolute PE yields from 2 x 5 x 300 cm^3 and 2 x 6 x 300 cm^3 scintillation counters using 1.4 mm and 1.8 mm diameter WLS fibers
- Attenuation measurements
- Scans across cracks



Recent Progress: CRV Beam Test

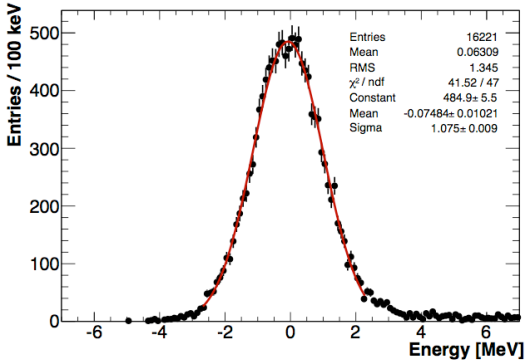
PE Yield (1.4mm Fiber)

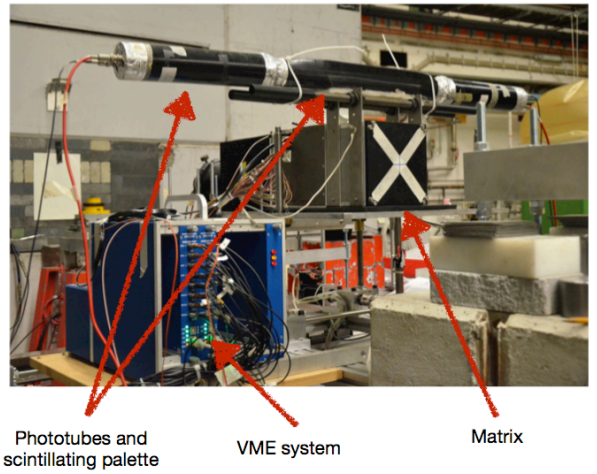


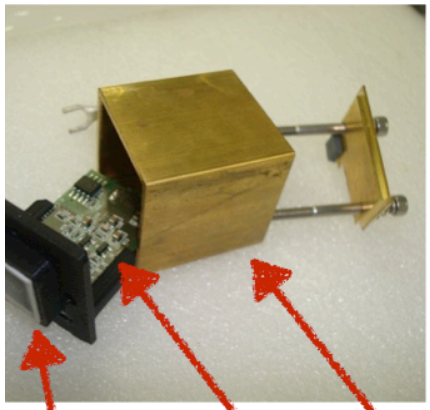
- Preliminary estimates of light yield are very promising, but final conclusion awaiting a more thorough understanding of the pixel cross-talk on the SiPMs.
  - Next generation of SiPMs will have significantly less cross-talk.

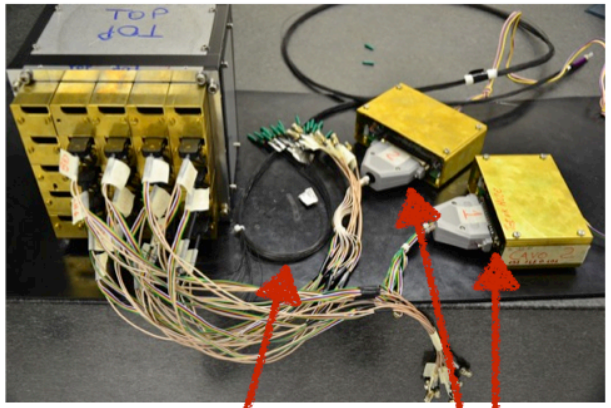
Recent Progress: Calorimeter Beam Tests

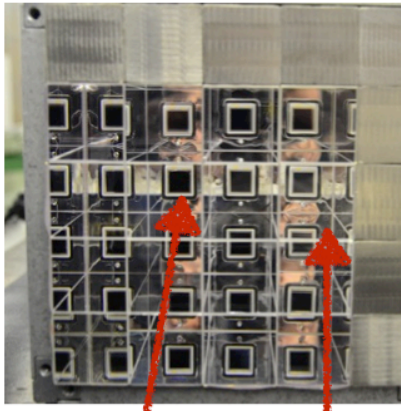
Numerous beam tests in Europe of LYSO, BaF2 and CsI crystals. Measurements of energy, position and timing resolution, longitudinal response. Radiation damage studies of crystals.





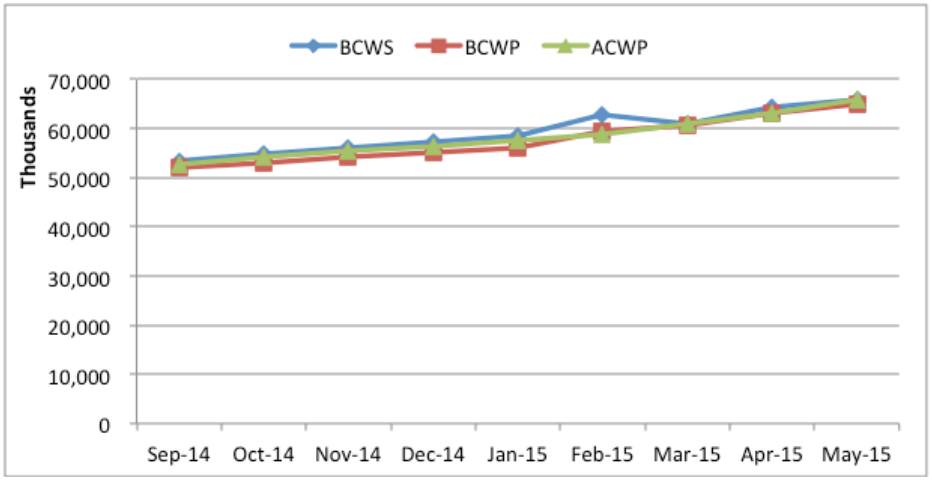


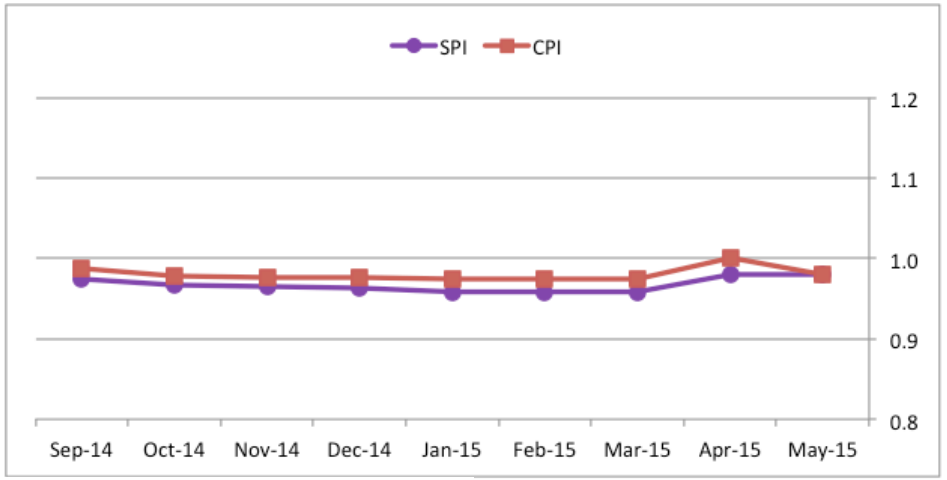


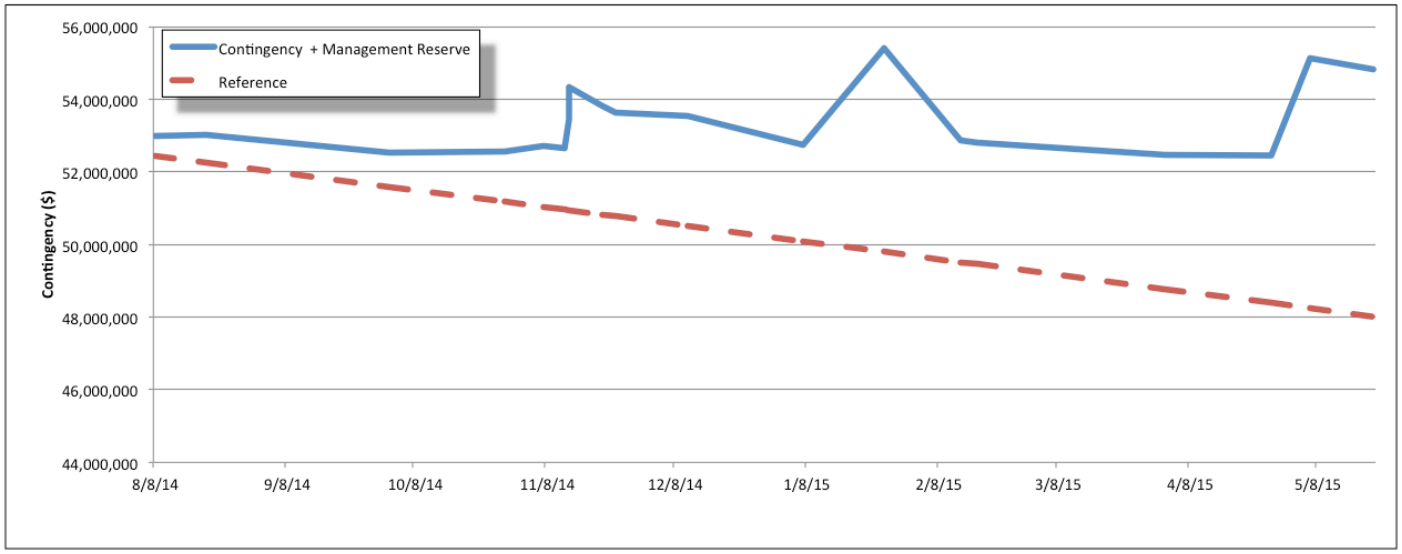


Project Performance

Total Project

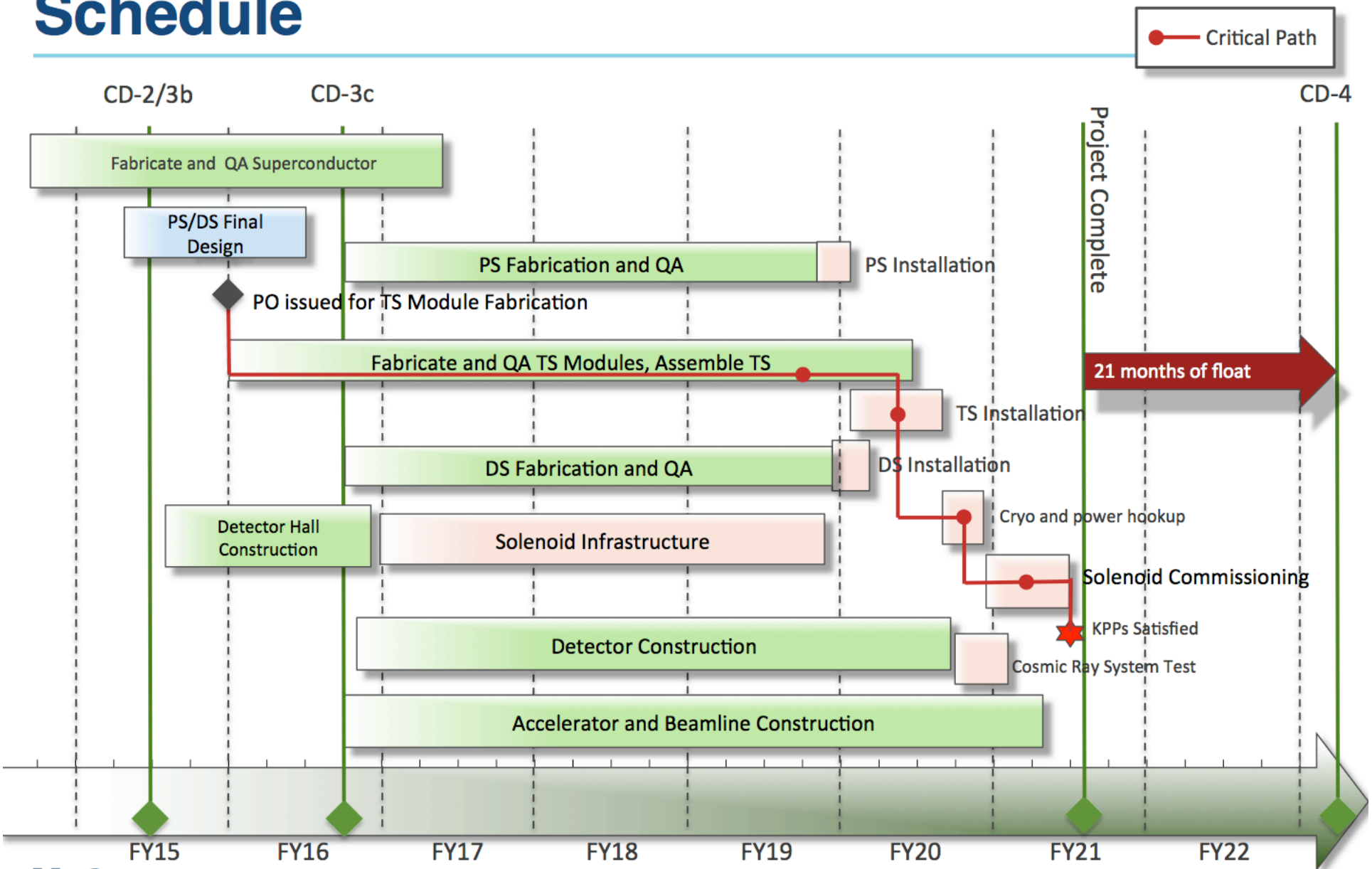




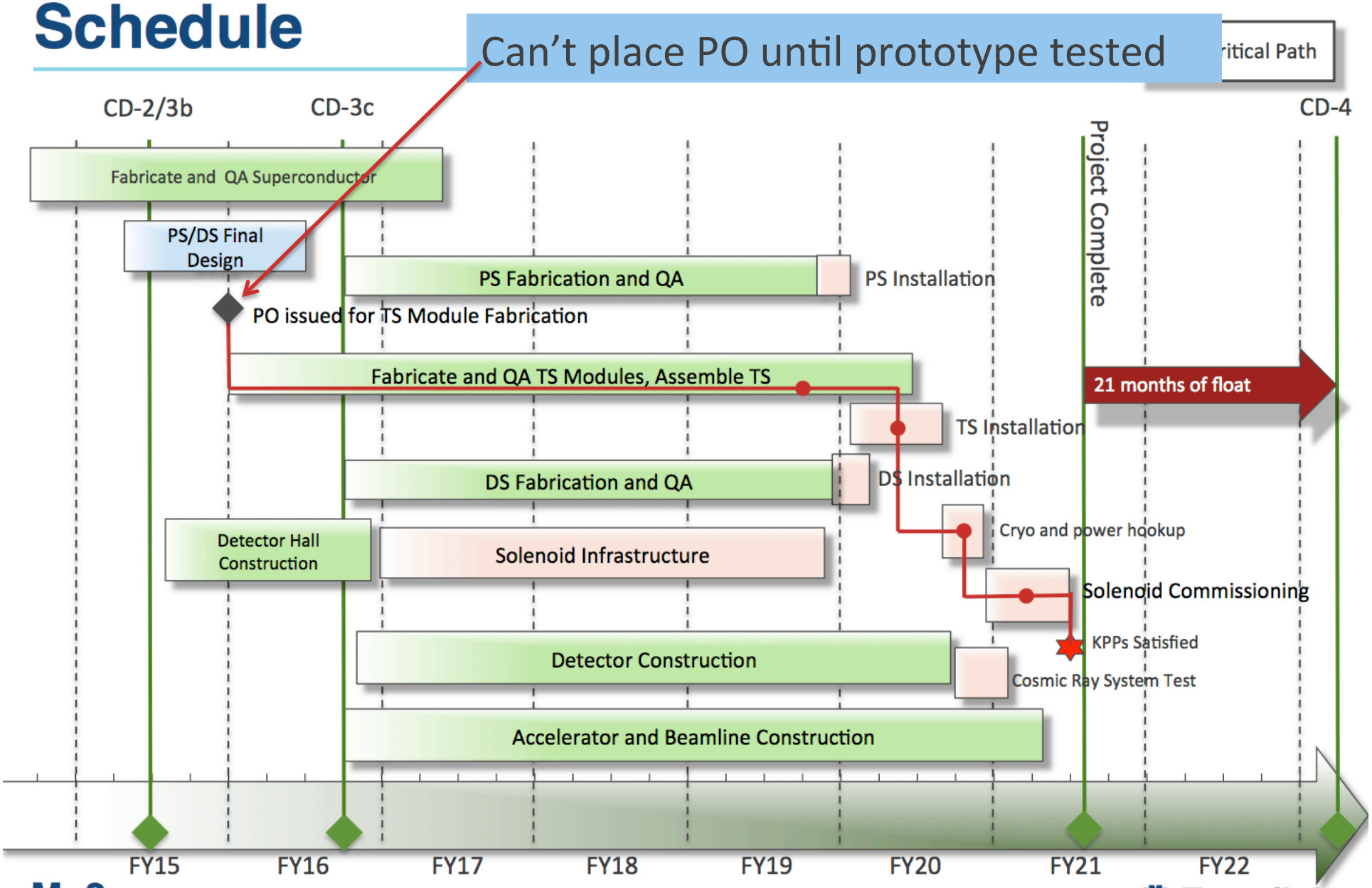


Mu2e has less contingency than NOvA, a more complex project and more back-loaded risks. Must manage contingency draw-down carefully.

Schedule


Critical Path
CD-2/3b
CD-3c
CD-4
Project Complete
Fabricate and QA Superconductor
PS/DS Final Design
PS Fabrication and QA
PS Installation
PO issued for TS Module Fabrication
Fabricate and QA TS Modules, Assemble TS
21 months of float
TS Installation
DS Fabrication and QA
DS Installation
Detector Hall Construction
Solenoid Infrastructure
Cryo and power hookup
Solenoid Commissioning
KPPs Satisfied
Detector Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22

Schedule


Can't place PO until prototype tested
itical Path
CD-2/3b
CD-3c
CD-4
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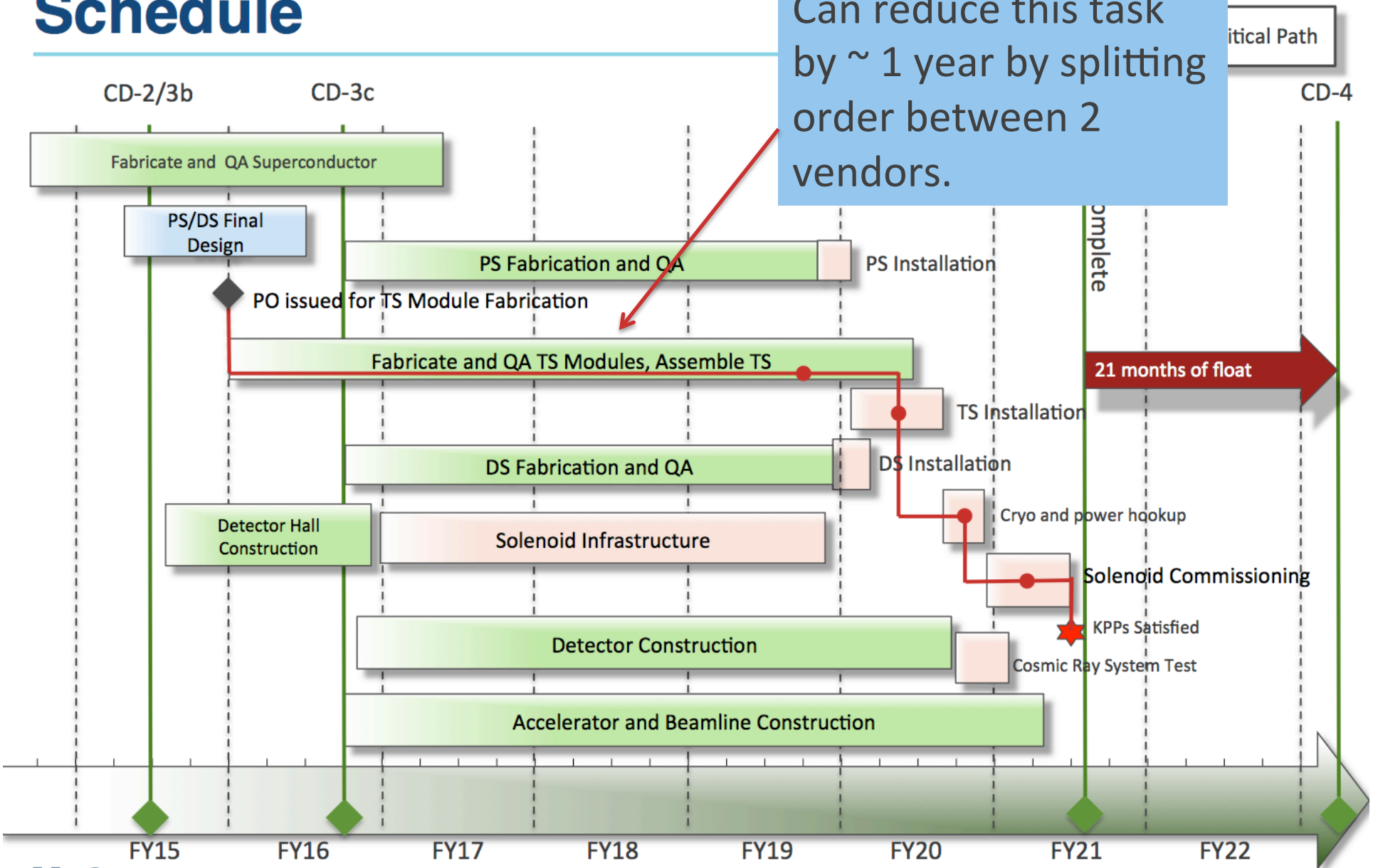
FY22

Schedule


Can reduce this task by ~ 1 year by splitting order between 2 vendors.
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CD-3c
CD-4
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Accelerator and Beamline Construction
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22

Summary

- CD-2/3b in April was a major milestone. CD-3c next summer.
- Good progress on all fronts
  - Detailed simulations give us confidence that the apparatus will satisfy the requirements. Indicate that we are not sitting on any performance ledges.
  - Prototypes of 3 major detector systems and DAQ constructed and being tested.
  - Detector Hall construction underway. Beneficial occupancy in about a year.
  - PS and DS final design at GA proceeding on schedule.
  - Struggling to get TS Module prototype tested.
- Significant level of independent, external review and oversight.
- Project performing well.