NOvA Project

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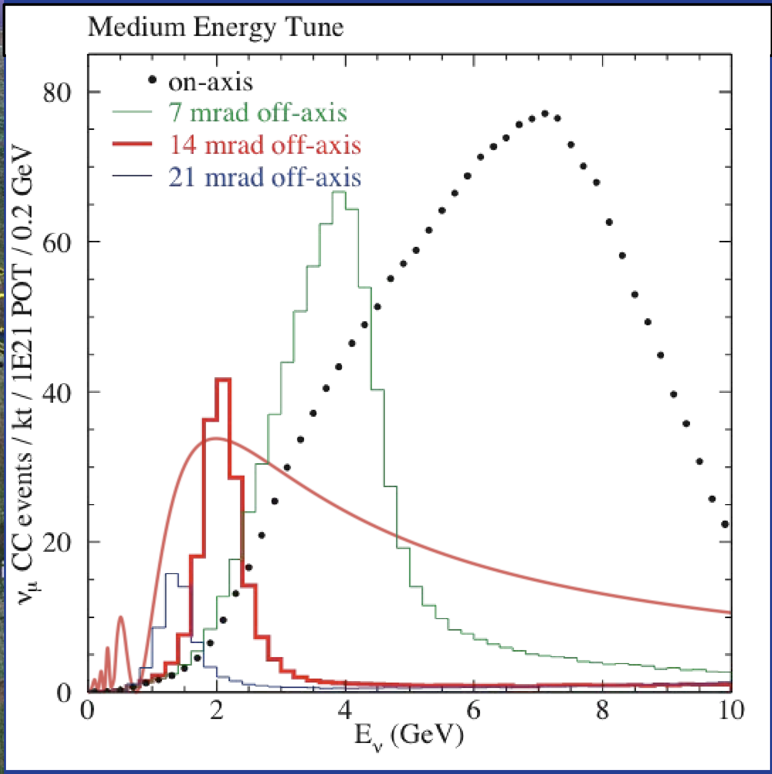
Fermilab Annual Science and Technology Review
September 5-7, 2012

U.S. DEPARTMENT OF ENERGY

Fermilab

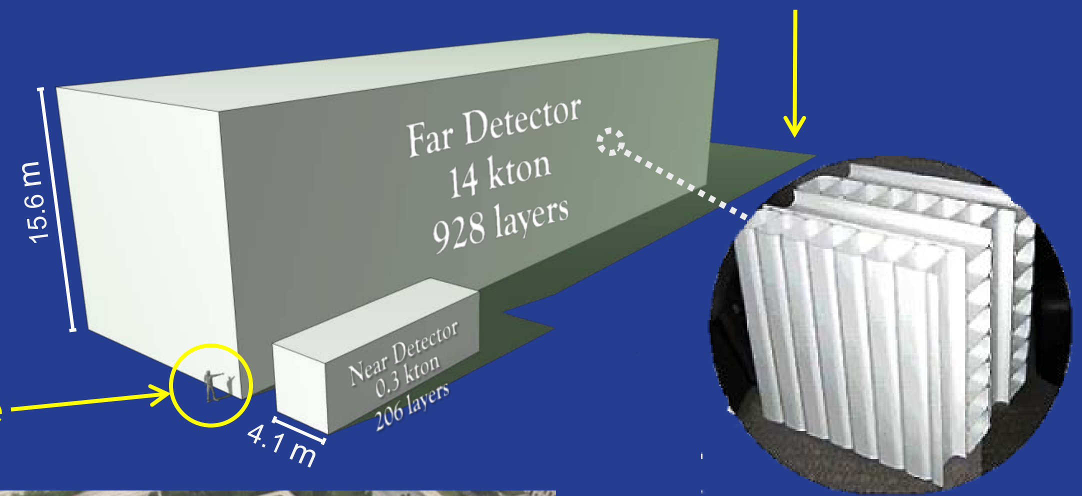
NOvA baseline and beam

- 810 km baseline, Fermilab to Ash River, Minnesota
- ν_μ narrow band beam at ~ 2 GeV re-using the NuMI beam with the detector 14.6 mrad off-axis to the NuMI beamline
  - This is at the peak of the atmospheric oscillation

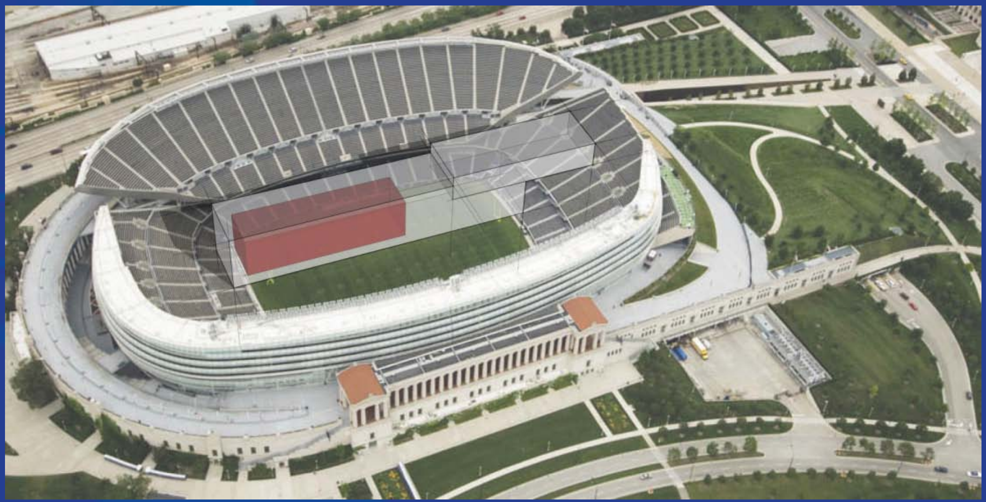


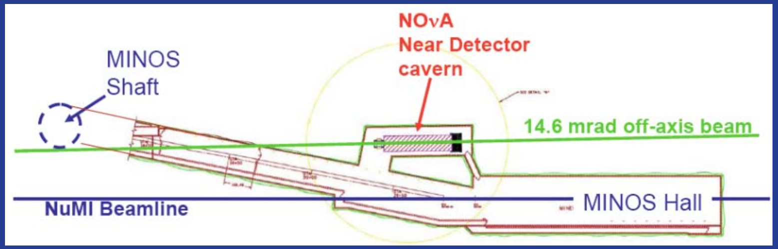
NOvA Near and Far Detectors

- 14 kt Scintillator / PVC (64% / 36%) Far Detector
- 0.33 kt Scintillator / PVC Near Detector at Fermilab
- Identical construction: Alternating X & Y layers of PVC cells



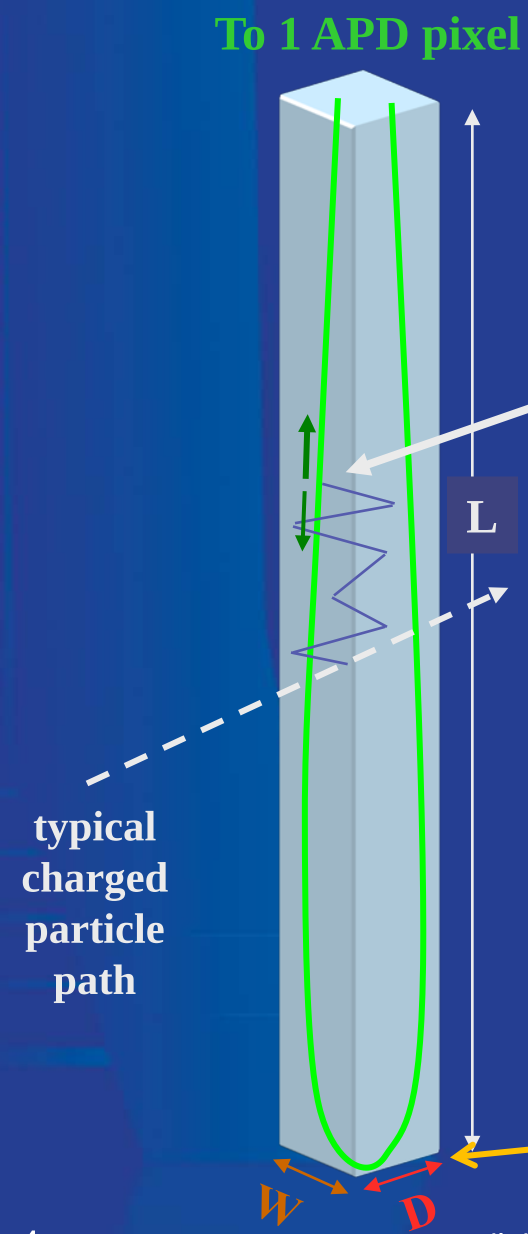
Note person for scale



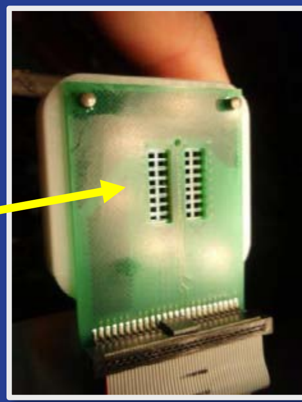


Plan view 300 ft underground

NOvA Basic Detector Element



- Liquid scintillator in a highly reflective PVC plastic cell -- PVC is 15% TiO_2
  - Passage of charged particles through scintillator creates light
  - Light bounces off reflective PVC walls until captured in a thin wavelength-shifting fiber
    - Typically light hits fiber within ~ 50 cm of particle path, ~ 8 reflections
  - The fiber is U-shaped and both ends terminate in one rectangular pixel of a 32-pixel avalanche photodiode (APD)



- Simple construction, just repeat 344,064 times
  - Cells are 15 m long (so they just fit in a 53 ft semi-trailer truck)
  - For vertical cells, pressure from liquid scintillator is 19 psi at bottom

NOvA Physics: Large $_{13}$ is good for NOvA

We should see just about the largest signals we had ever hoped for.

- Four Oscillation Channels
  - $\rightarrow {}_{e}$, $\bar{\ } \rightarrow \bar{\ }_{e}$ … appearance
  - $\rightarrow$, $\bar{\ } \rightarrow \bar{\ }$ … disappearance
  - Using $\rightarrow {}_{e}$, $\bar{\ } \rightarrow \bar{\ }_{e}$:
    - Measure $_{13}$ via $_{e}$ appearance
    - Determine the mass hierarchy
    - Search for CP violation
    - Determine the $_{23}$ octant
  - Using $\rightarrow$, $\bar{\ } \rightarrow \bar{\ }$:
    - Atmospheric parameters, precision measurements of $_{23}$, $|\Delta m^2|$.
      - *Exclude* $_{23} =$ /4 ?
    - Over-constrain the atmospheric sector

- Additional neutrino oscillation results are possible using
  - NOvA + results from T2K
  - NOvA + results from reactor experiments
- We will also use the narrow band 2 GeV off-axis beam for
  - Measurement of ν cross sections at the NO A Near Detector
  - Sterile neutrino searches
  - The narrow band beam gives a lower background from neutral current events of higher energy
- And we can detect
  - Supernova neutrinos

NOvA Collaboration (34 institutions, 138 physicists)

- Argonne
- U of Athens
- Caltech
- Fermilab
- Harvard
- Indiana
- Iowa State
- Lebedev Physical Inst. , Russia
- Michigan State
- Minnesota, Duluth
- Minnesota, Twin Cities
- Institute for Nuclear Research, Moscow
- South Carolina
- Southern Methodist
- Stanford
- Tennessee
- Texas at Austin
- Tufts
- Virginia
- Wichita State
- College of William and Mary

- Additions in the last Year (13 inst, 21 physicists)
- Czech Republic Group:
  - Institute of Physics of the Academy of Sciences of the Czech Republic, Prague
  - Charles Univ in Prague
  - Czech Technical Univ, Prague
- India Group:
  - Banaras Hindu Univ, Varanasi
  - Univ of Delhi
  - Indian Institute of Technology, Guwahati
  - Indian Institute of Technology, Hyderabad
  - Univ of Hyderabad
  - Univ of Jammu
  - Panjab Univ
- Univ of Minnesota, Crookston
- Univ of Cincinnati
- Univ of Sussex, UK

- New International Fellow at Fermilab
  - Jaroslav Zalesak, Institute of Physics, Prague, Czech Republic

NOvA Project CD-4 Deliverables

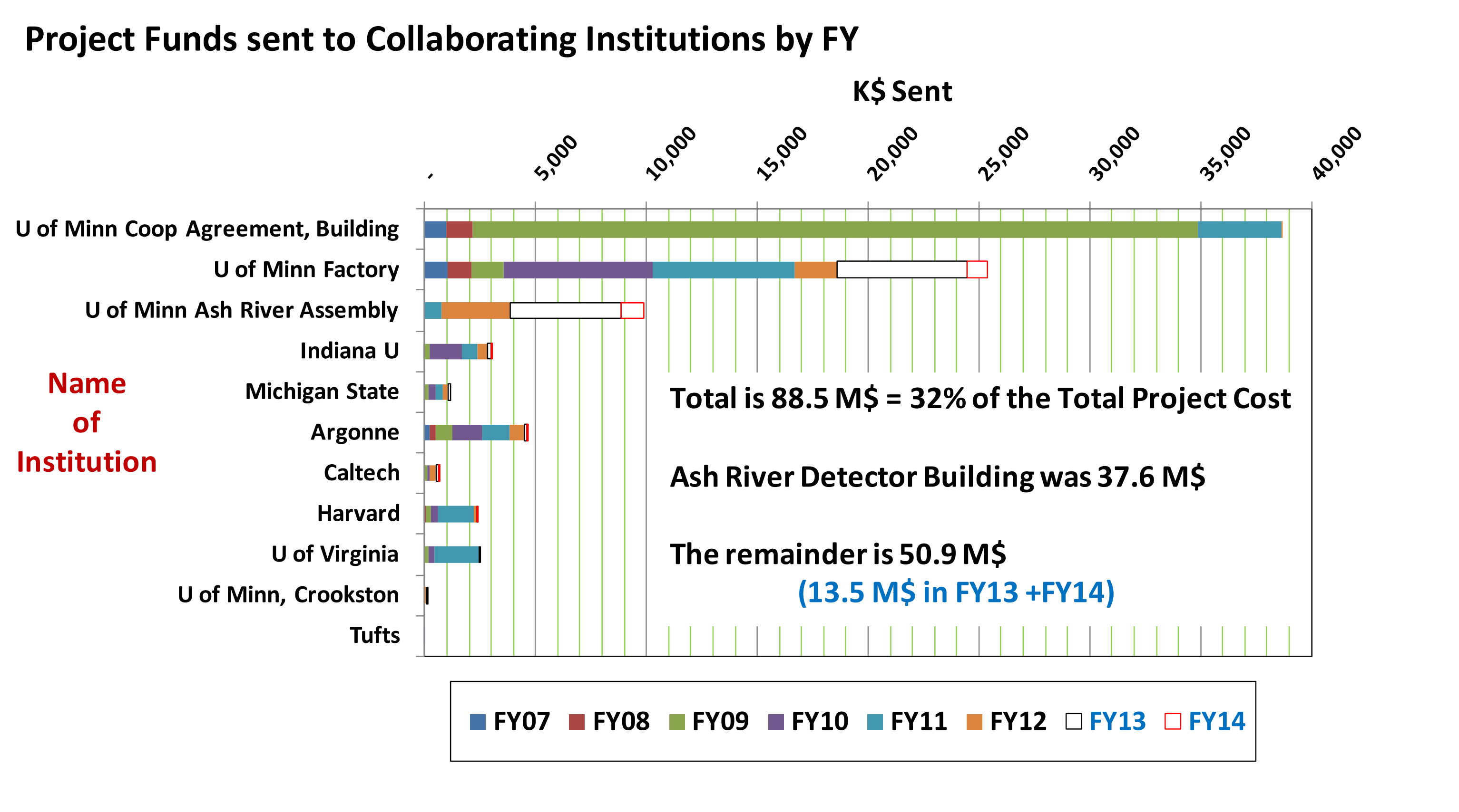
- Upgrade the Fermilab accelerator complex proton source from pre-NOvA 320 kW to a source capable of 700 kW
  - Paul Derwent is covering this in the parallel Accelerator breakout.
  - The accelerator shutdown for NOvA began in May, 2012 and is projected to finish on schedule late March, 2013.
- Build a new Far Detector Hall
  - At Ash River, Minnesota near the US-Canada border
  - The building was completed in 2011.
- Build a 14 kiloton Far Detector at Ash River
  - Detector construction started on July 26, 2012.
- Build a 222 ton Near Detector
  - Which will be underground at Fermilab in the MINOS tunnel
  - Cavern Construction began on August 14, 2012
- R&D goal: Integration Prototype Near Detector
  - Continues data taking on the surface near the MINOS Service building

Institutional contributions by Project WBS Level 2

- Accelerator and NuMI Upgrades
  - **Fermilab,** U Texas Austin
- Site and Building
  - **Fermilab, U of Minnesota**
- Scintillator
  - **Indiana U**, Fermilab
- Fiber
  - **Michigan State U**, U Texas Dallas
- PVC Extrusions
  - **ANL**, Fermilab
- Extrusion Modules
  - **U of Minnesota**
- Electronics
  - **Caltech, Harvard, U of Virginia**, **Indiana**, Fermilab, Tufts U, Minnesota
- Data Acquisition
  - **Fermilab**, Minnesota, Indiana, South Carolina, Tennessee
    U of Minnesota Duluth, U of Minnesota Crookston
- Detector Assembly at Ash River
  - **Fermilab, ANL, Minnesota,** Southern Methodist

Crude attempt to indicate scope of work by font size for this review

Work at Collaborating Institutions funded by the NOvA Project



- Accelerator work (50.3 M$) and all large procurements are done from Fermilab
  - Scintillator, Waveshifting fiber, PVC resin, PVC extruding, APDs, DAQ electronics, Near Detector, Near cavern

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What the Project needs from the Collaboration

- Complete the funded Project work
  - Substantial parts of the Detectors still to come.
    - Faculty, post-docs, graduate students are NOT on-project
- Operate shifts in a Fermilab Control Room during Detector Outfitting and Commissioning
  - Startup this Fall, ~ November
    - Probably only 2 shifts, leave commissioned section running overnight
- Operate the Ash River Detector Hall
  - This is a continuing / new DOE Cooperative Agreement with the University of Minnesota
    - FY13 estimate = 780 K$
      - Power and Propane are the big parts (~400 K$).
        - Not well known since only have data from one year of operation with no detector.

The Ash River Detector Hall is complete

- Bare ground in June 2009,
  Hole in the ground + Service Building in June 2010,
  Beneficial Occupancy in April 2011,
  Dedicated April 27, 2012.

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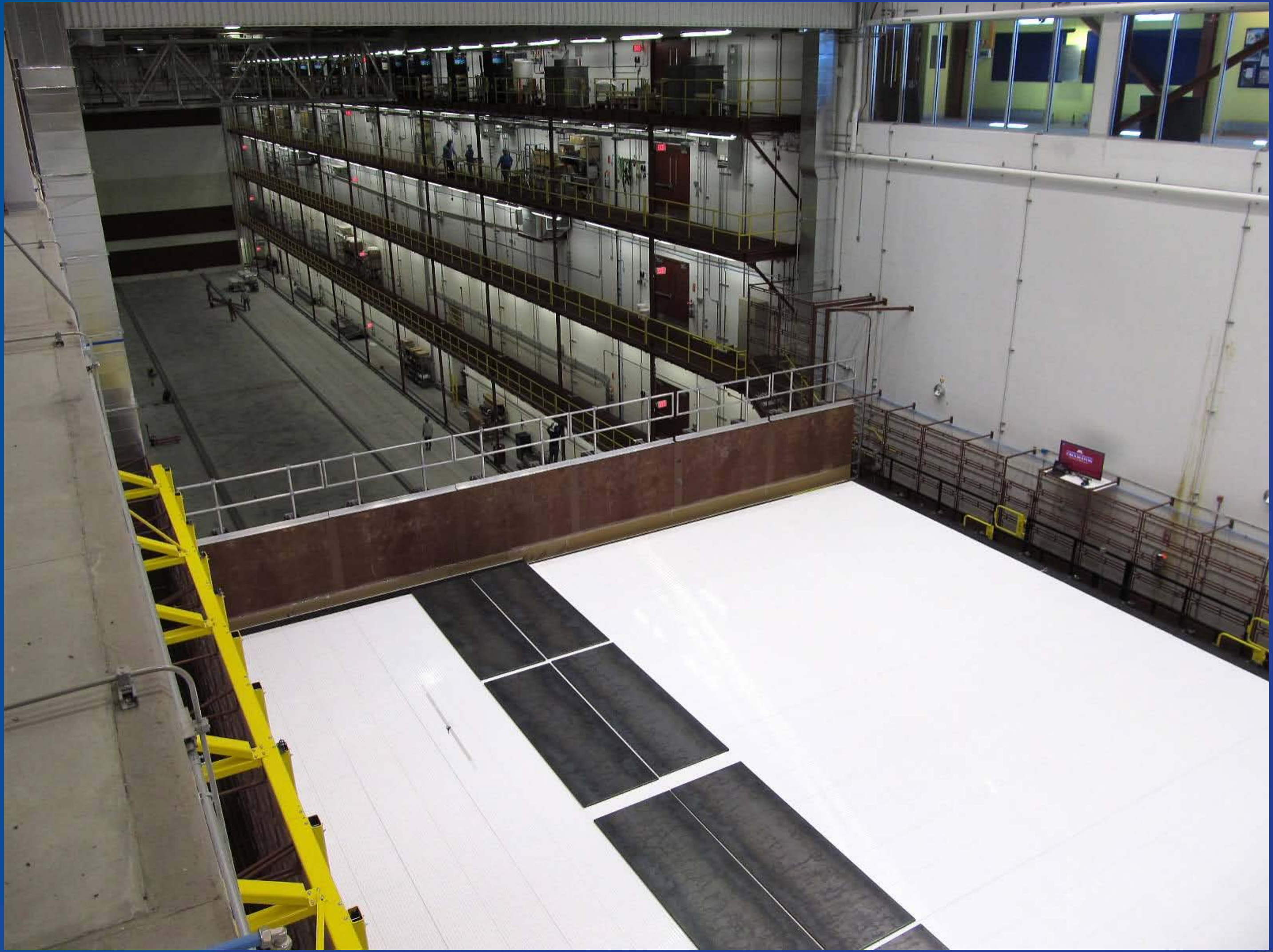
Now installing the NOvA Far Detector in the Hall

- Block assembly table (Pivoter) in place, racks on catwalks
- A crew of 40 Full time Technicians is in place and working 2 shifts



Construction of the NOvA Near Detector Hall has begun

- Mobilization and Site Preparation is complete.
  - Power, Cables moved from E to W wall during June.
- Removed shotcrete at tunnel entrance on Aug 14.
  - Excavation by Hoe Ram started deeper on Sept 3.
- Install ramp for Roadheader, Sept 4 – 11.
- Roadheader excavation in full production ~ Sept 12.

August

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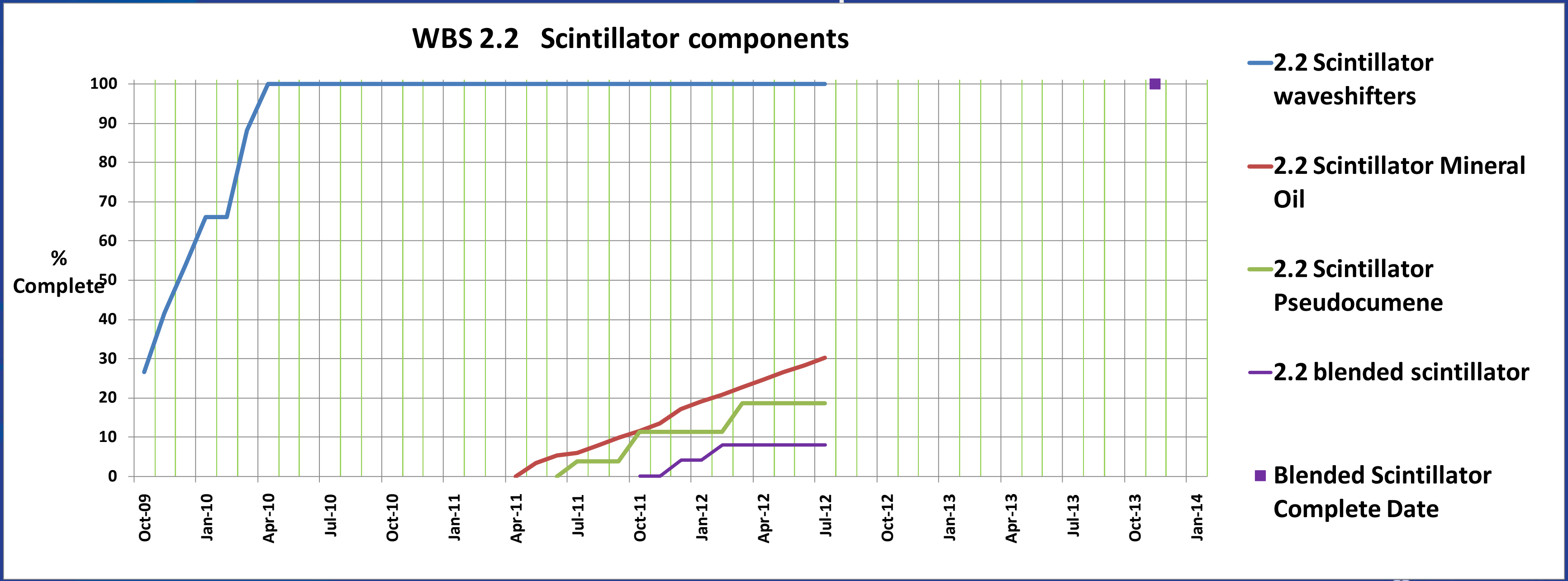
Scintillator Status (We blend our own)

- We need 2.8 M gallons of scintillator
  - 2.65 M gallons of mineral oil, delivered by railcar from Louisiana
  - 155,000 gallons of pseudocumene, delivered by ISO tanks from China
  - Waveshifters: PPO and bis-MSB (we own enough for the full experiment)
- We do Fluor blends (pseudocumene + waveshifters) then mix that in a separate tank with mineral oil to make scintillator at Wolf Lake, Indiana
  - 5% Fluor Mix: waveshifter powders into 300 gallons of pseudocumene to start
  - Then add into 6,000 gallon tank of pseudocumene
  - Then add into 120,000 gallon tank of mineral oil & blend with pulsed Nitrogen
  - 5 % pseudocumene + 95% mineral oil

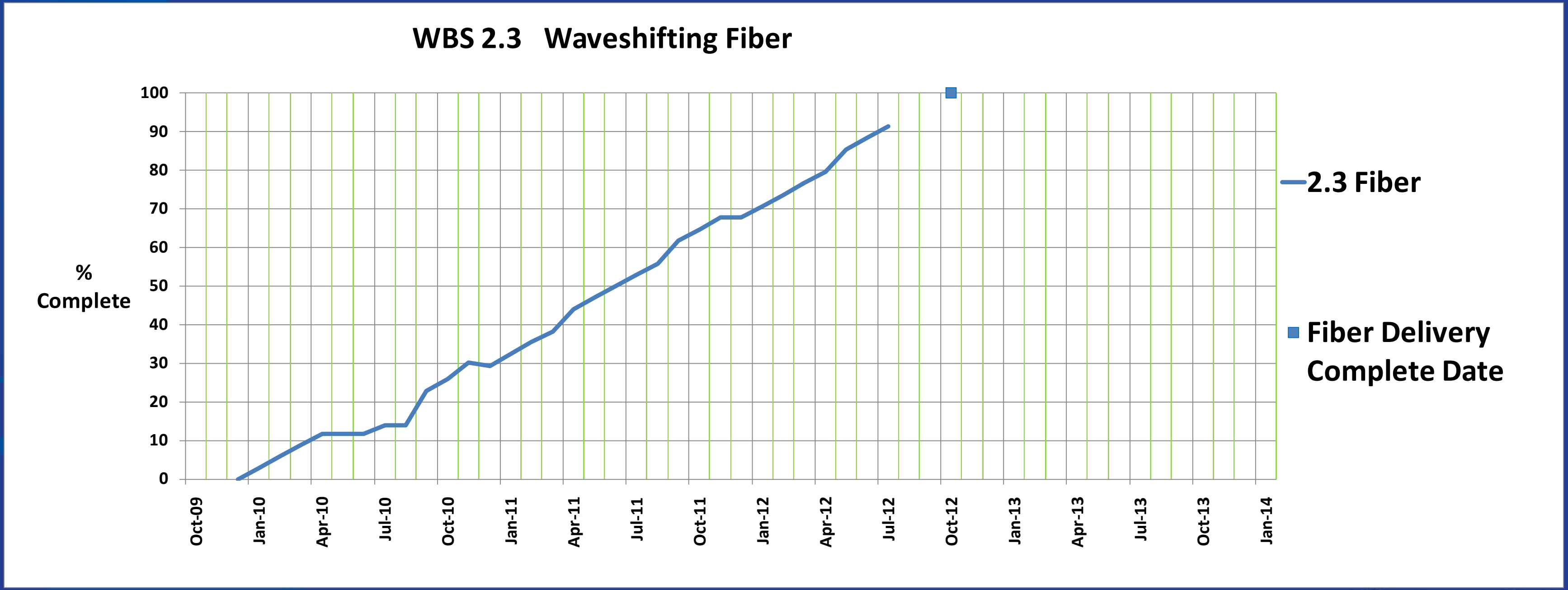
Scintillator Status

- Our two scintillator storage tanks are now full: 227,000 gallons = 2.4 blocks (the full detector is 28 blocks)
  - We can't blend any more until some moves to Ash River in ~November.
- We have a 600,000 gallon buffer tank for mineral oil.
  - ~ Full at 586,000 gallons. This is 30% of the total required, so the risk due to oil prices is reduced. We can ride out approximately 6 months of high prices with our buffer volume if needed.
  - We have 2 tankers as a buffer for pseudocumene, 1 more on order



Wavelength-shifting Fiber Status (from Kuraray, Japan)

- We have 11,130 km of fiber or 91% of the total needed.
  - Still on schedule to complete as planned.
- An assessment of the waste rate in the Minneapolis factory is in progress.
  - Initial start-up waste was ~ 5%.
  - Ongoing production waste is fluctuating in the range of 2 - 3%.
  - The plan was 4% waste overall



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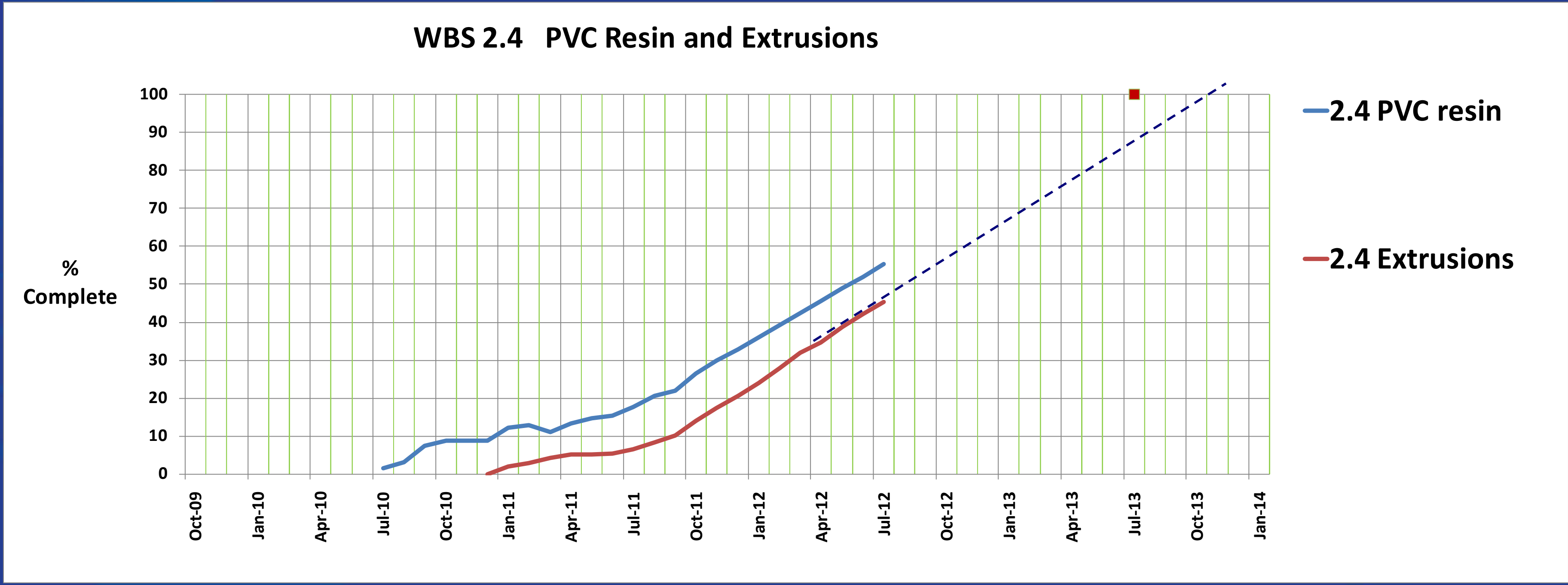
PVC Extrusions (Extrutech, Manitowoc, WI)

- We have ~10,101 extrusions of the 21,504 required (47%)
  - Vendor's 6x24 operations reduced to 5x24 since we are out of storage space in Minneapolis. Rented additional space in Manitowoc in June.
- Our schedule assumes 6% scrap & that's about what we have seen since production started in October 2011.
  - This does not include 2% due to 6" QA samples at end of each 51' extrusion
- Have saved about 1/8th of the 6% "waste" for the Near Detector
  - Only a couple of parameters out of spec & OK for less vertically challenged detector



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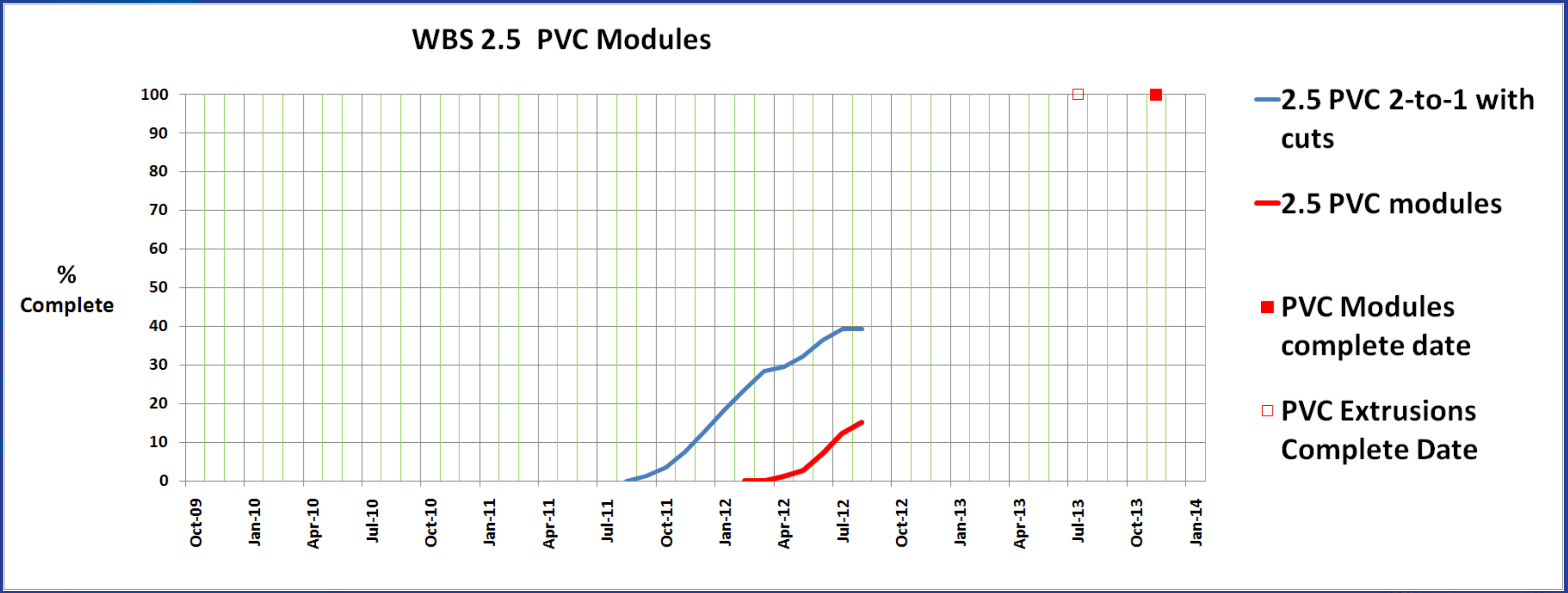
PVC Modules (constructed in Minneapolis, Minnesota)

- Module assembly in Minneapolis is divided into two parts:
  - 2–to–1 assembly of 2 extrusions into one module + cut to length
  - Final assembly with fiber loops, fiber manifold & optical connector, endcap & all seals + pressure test
- 4,369 2-to-1s are done out of 10,752 needed. (41%).
- 1,681 good final assembly modules are done out of 10,752 needed (15%)
  - Steady state rate needs to be 27.5 good modules per day & we are at that rate
- The scrap rate rate is 2-3% (goal is 2%). Saving scrap for Near Detector.



PVC Modules: Scenes from the Minneapolis Factory

- 150,000 sq ft warehouse. 70 – 200 students.

Production floor

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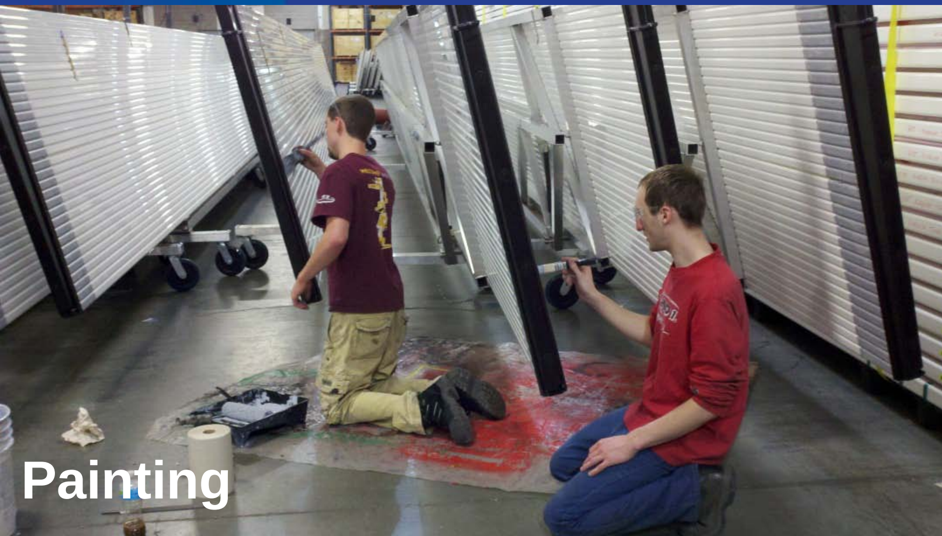
PVC Modules: Scenes from the factory

PVC Modules Scenes from the factory – Final Stages



Painting

Stacking finished modules

Closed module fiber testing,

MSU tester w red LED + phototransitor at end of loop

Packing

Shipping, 450 truckloads

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Electronics / DAQ

- 32 channel Hamamatsu Avalanche Photodiode (APD) on each PVC Module
  - APD cooled to -15C with thermoelectric cooler (TEC)
    - TEC Controller (TECC) board
  - Heatsink removes heat with chilled water system
- 32 channel Front End Board (FEB-4) on each PVC module

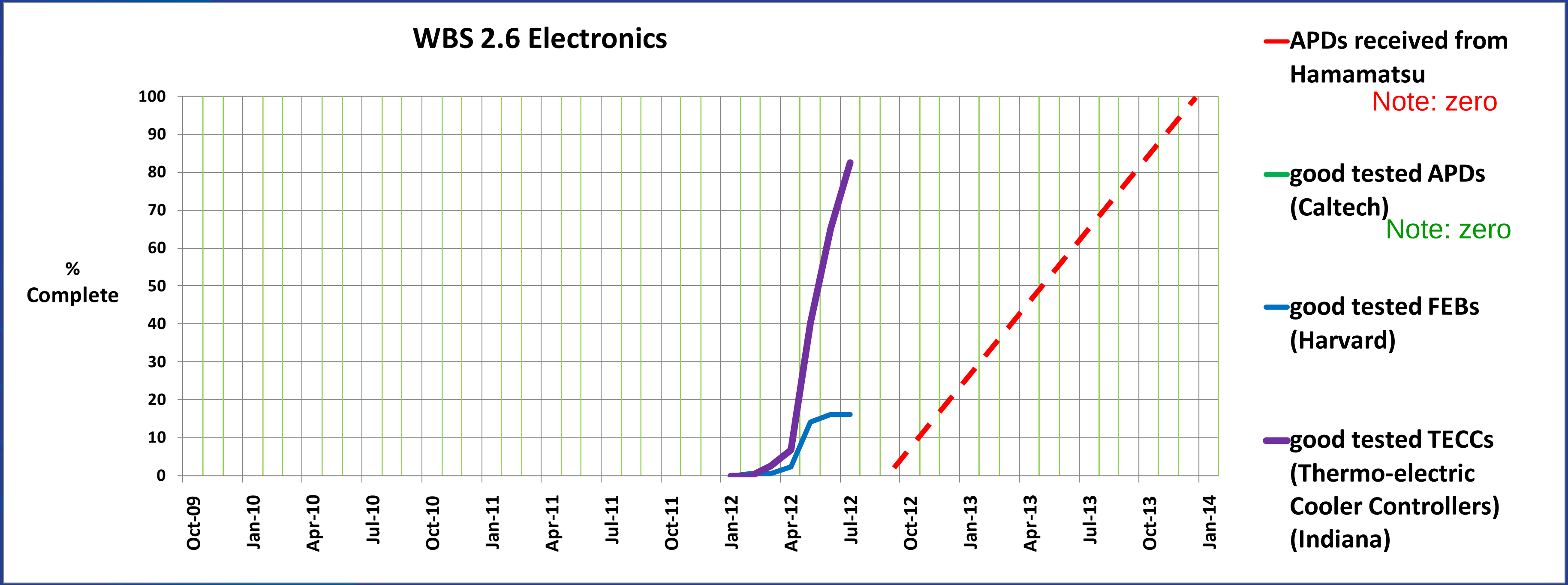
- 64 FEBs read out by a Data Concentrator Module (DCM)
- Timing relative to beam spill via GPS and Timing Distribution Units (TDUs)
- Ethernet to commercial CPUs and disk.

APDs

- We have added moisture controls following APD failures with our prototype Near Detector last year.
  - Our problem is 10,752 cold spots at -15C distributed over 20,000 square feet on one side of and the top of the detector
  - Belt: Dry air system keeps each APD volume at dew point below -25C
  - Suspenders: Protective coating for each APD – Silicone or Parylene. Prevents APD damage / death if water does get to the cold area.
- Results so far favor Parylene coating
  - 12 micron thick, vacuum deposition process, covers all sides uniformly, light loss is 5%, no aging observed
  - 100% of Parylene tested on prototype Near Detector continue to work, only 90% of Silcone have survived.
- Our order of 12,000 APDs from Hamamatsu has been executed and they will start deliveries of 150-200 per week at the end of September.

Electronics

- APDs, deliveries start in late September
- Front End Boards (FEBs), (Harvard)
  - 4171 delivered of 11,132 needed.
  - 1813 pass all tests (in progress, not pass rate), so 16% done
- Thermo-electric Cooler Controllers, (Indiana).
  - 9183 pass all tests, so 82% done



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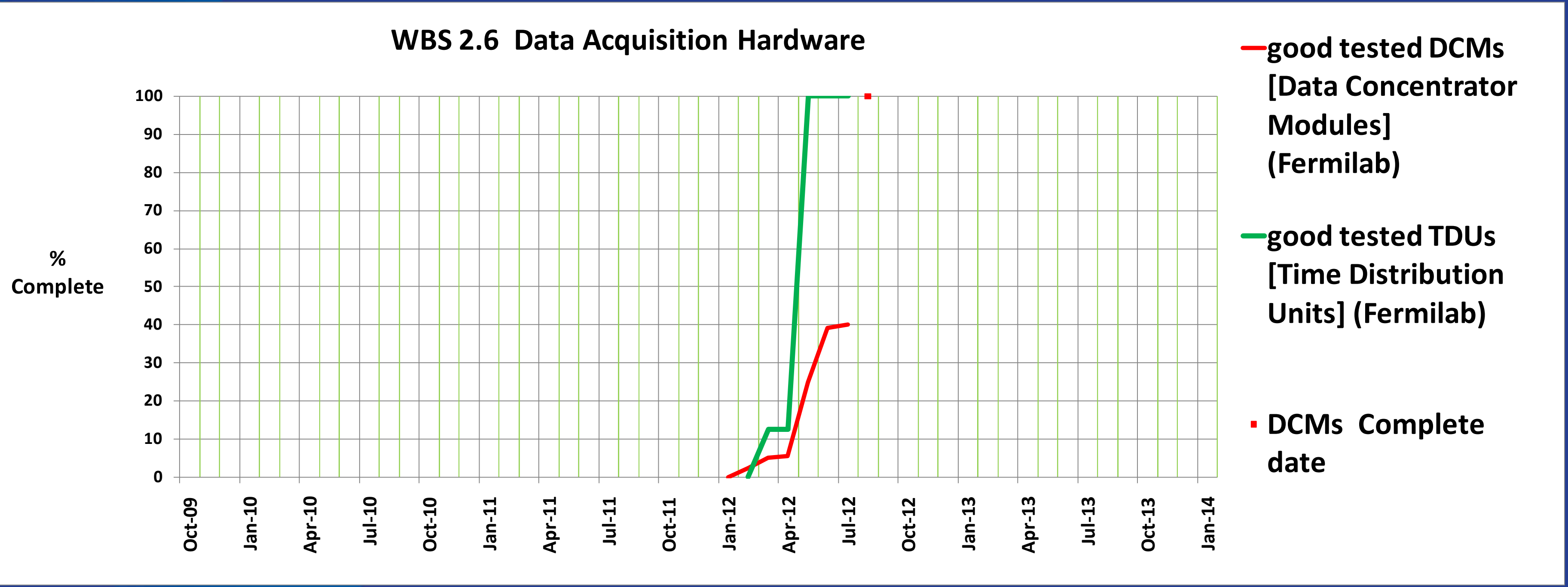
DAQ Hardware

- Data Concentrator Modules (DCMs) (Fermilab)
  - Now have 80 final boards completely tested of 200 required, 40%
- Timing Distribution Units (TDUs)
  - 2 Types, Master (2 required at Ash River) & Slave (30 required at Ash River)
  - Have them all, all tested



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Block Pivoter completed at Ash River

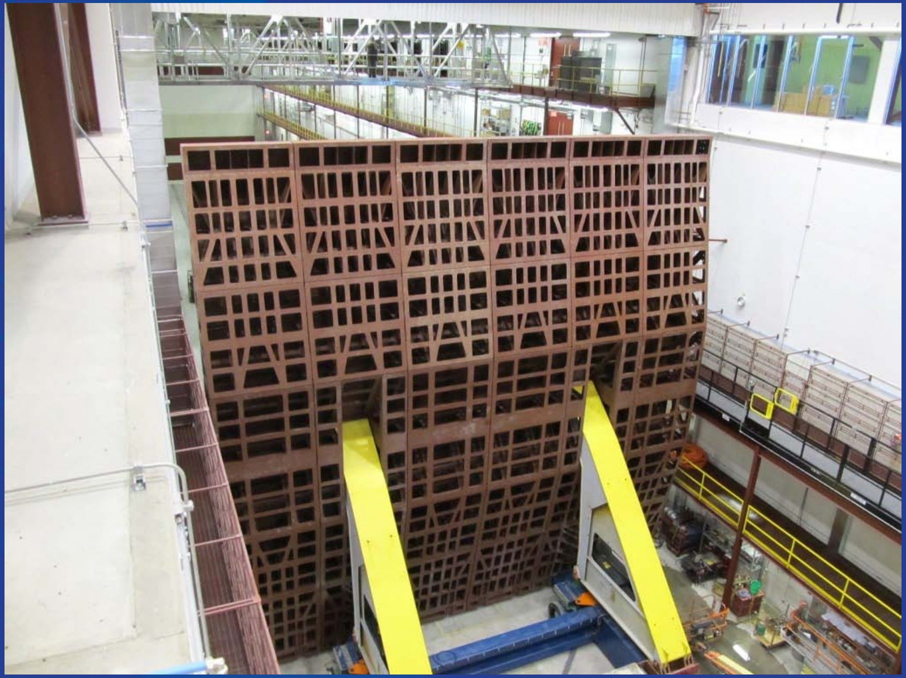
- Assembly during January – April, 2012

Base,
Counterweights,
Upper
Weldments
& pivot point

Assembly
Table

Pivoter: All 30 table sections in place

- 3300 bolts torqued to specification
- Table shimmed level to ± 8 mm
- 1st pallets in place
- Build 32 layers of 12 PVC Modules each on table = 1 block, then repeat 28 times



Pivoter Commissioning & Test Drive

- “Mock-block” exercise the week of 4 June
  - Defined block volume with a simple unistrut outline

- The table top, with “mock block” was rotated to vertical
  - Moved to the south end of the hall
    - Clearances checked to catwalks, OK at 6”,
    - 2” to East in assembly area
    - Found and fixed 2 interferences at the south wall.

Other Assembly Equipment

Lifting Fixture

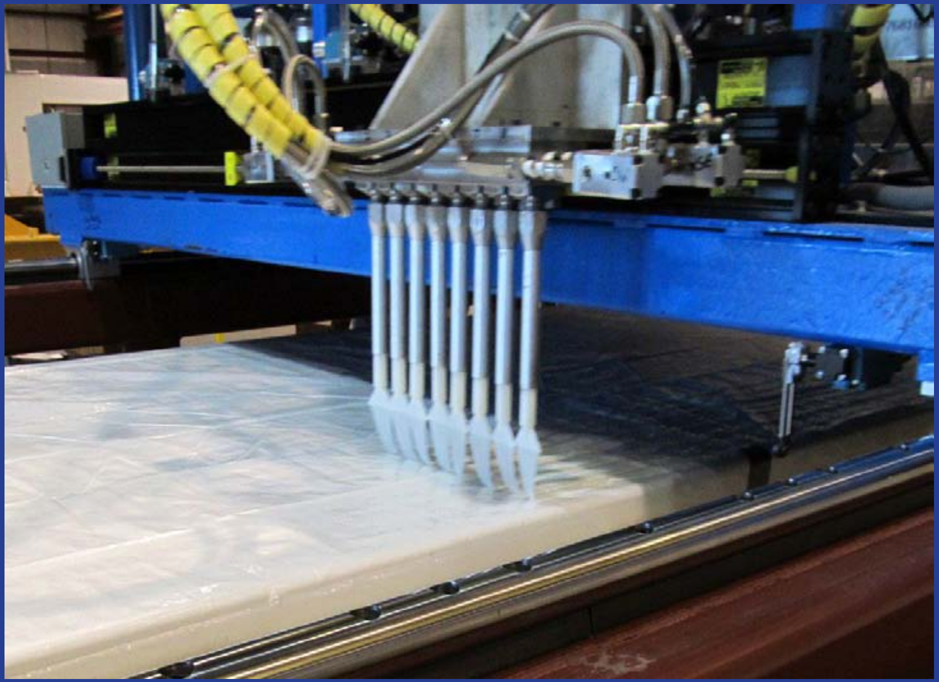
PVC Modules

Adhesive Dispenser

Alignment Poles

- Assembly area, viewed from the south

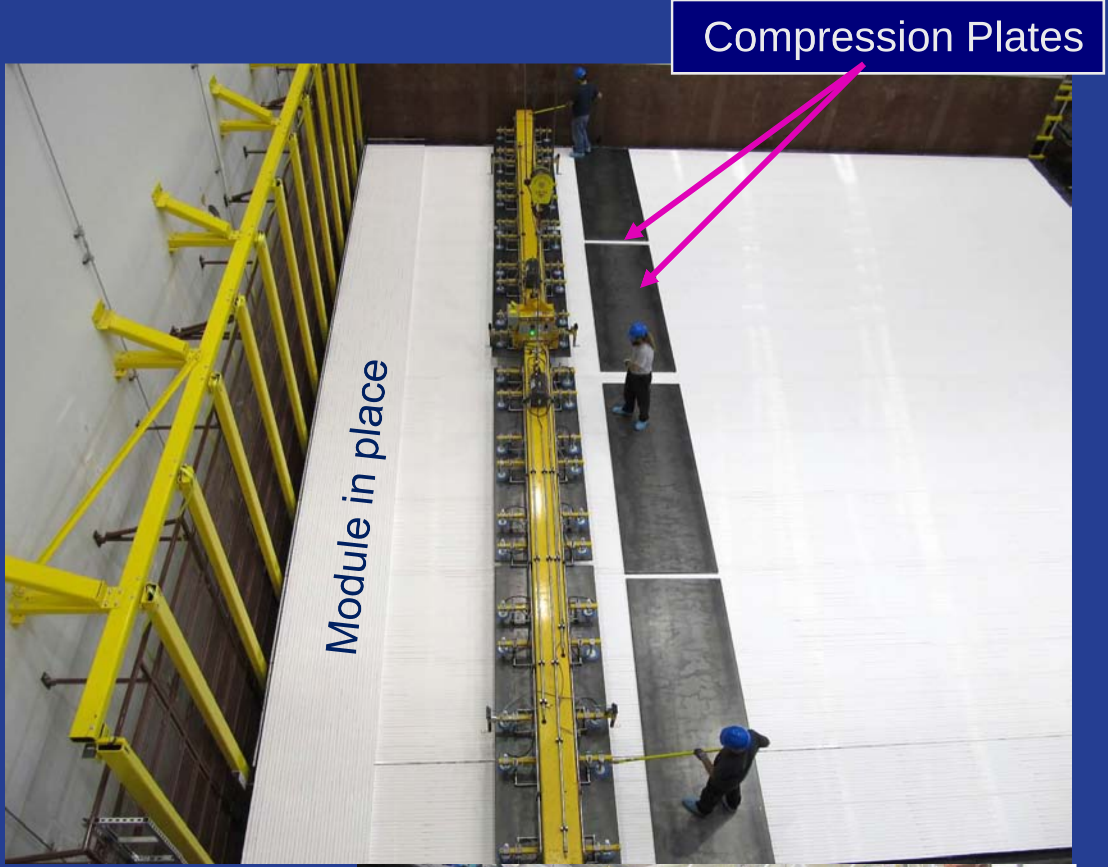
Adhesive Dispenser



- PVC Module is rotated within the dispenser
- Adhesive dispensing
  - 8 simultaneous beads, 4 passes per module
- Vapor level tests were performed week of 26 Mar.
  - Methyl Methacrylate (1 – 2 ppm) well below 50 ppm maximum allowed.
  - %LEL barely measurable, no special Fire response is needed.

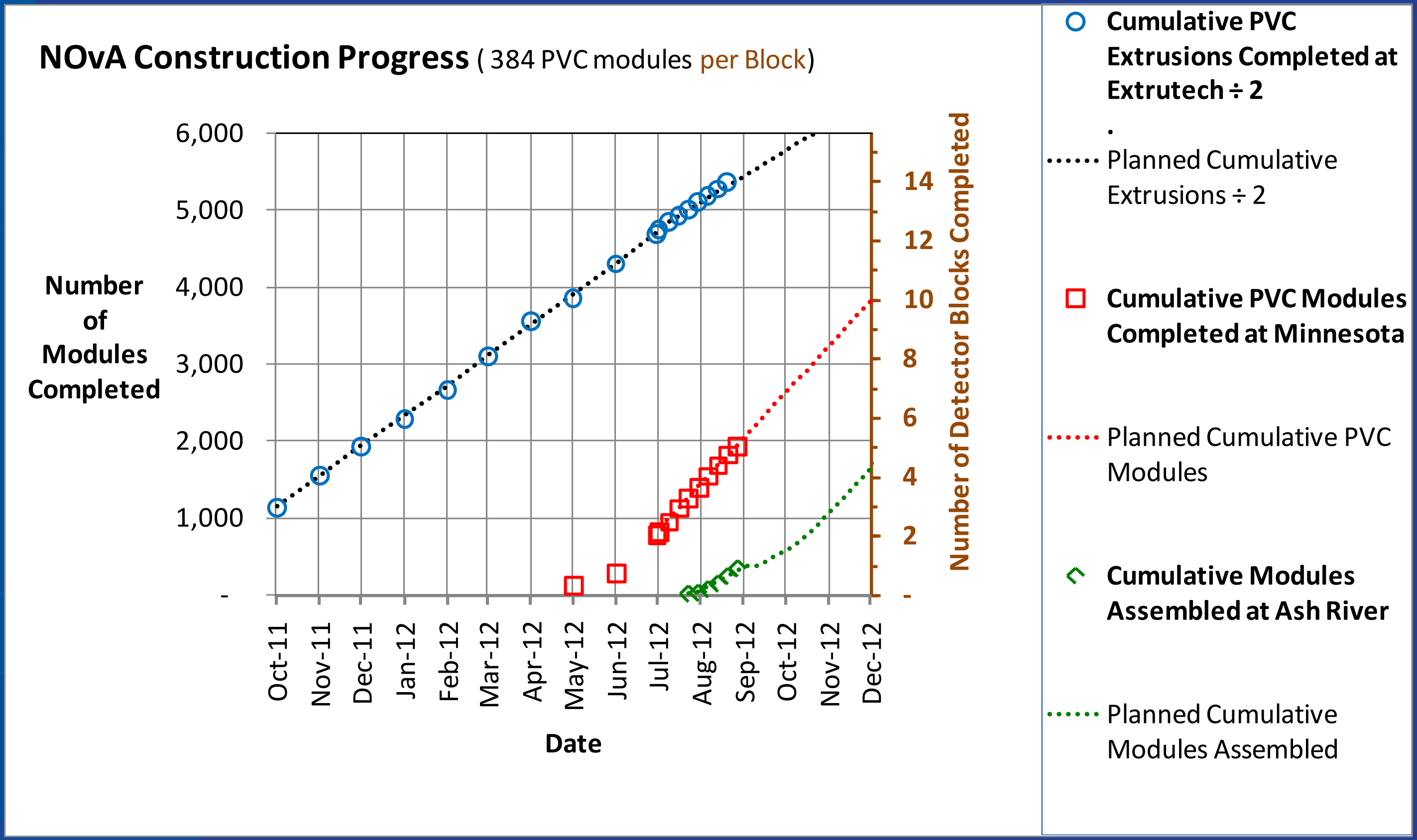
Assembly has begun !

- First vertical layer placed on 26 July.
- First horizontal layer glued on 1 Aug.
  - Switched to a stronger adhesive -- New adhesive arrived on 31 July.
  - Also roughing up each layer for better adhesion.
- 29 layers completed 30 August. (32 layers per block)
  - No module failures were created by the roughing process.(leak test, fiber inspection)



Cumulative Production

- Extrusions well ahead, throttling back, lack of storage space
- PVC Module factory has made 5 detector blocks of modules
- Ash River assembly into detector blocks started, ramping up



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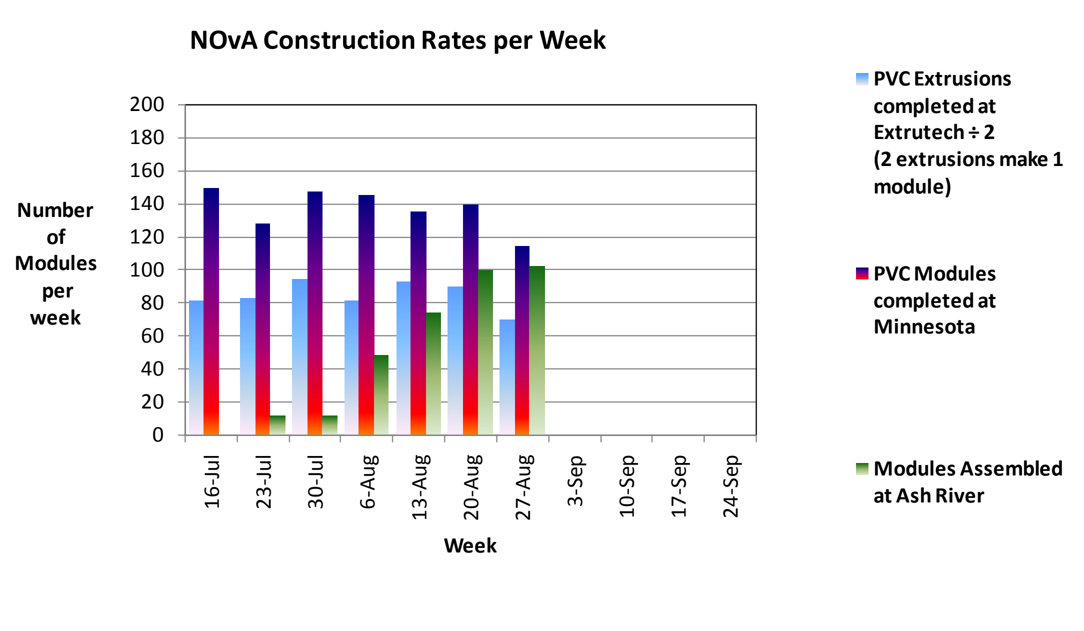
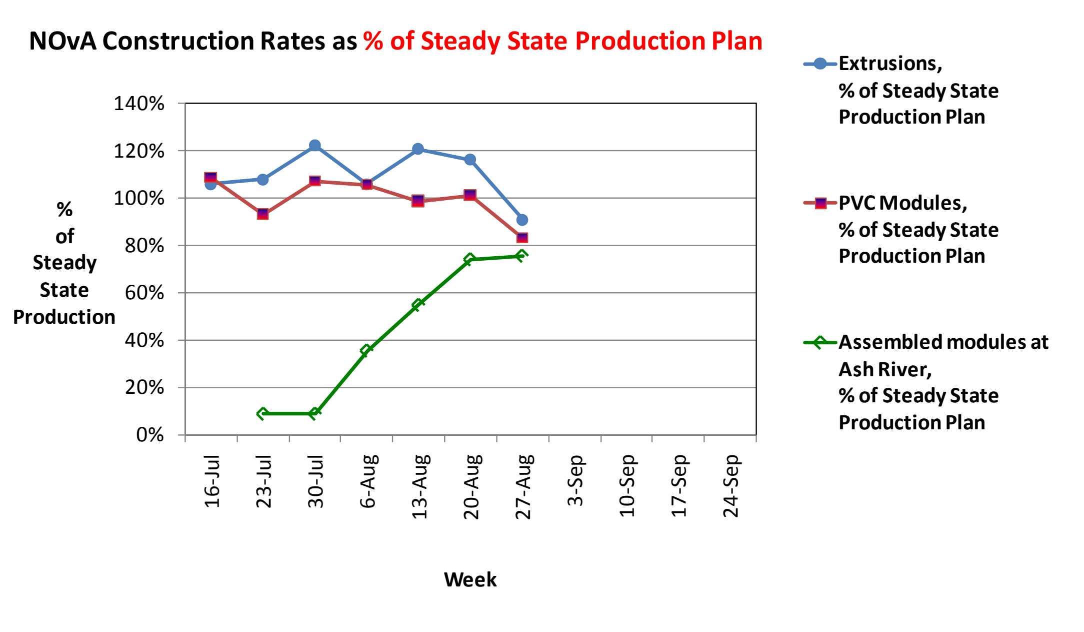
Weekly Production Rates: Extrusions, PVC Modules, PVC Blocks





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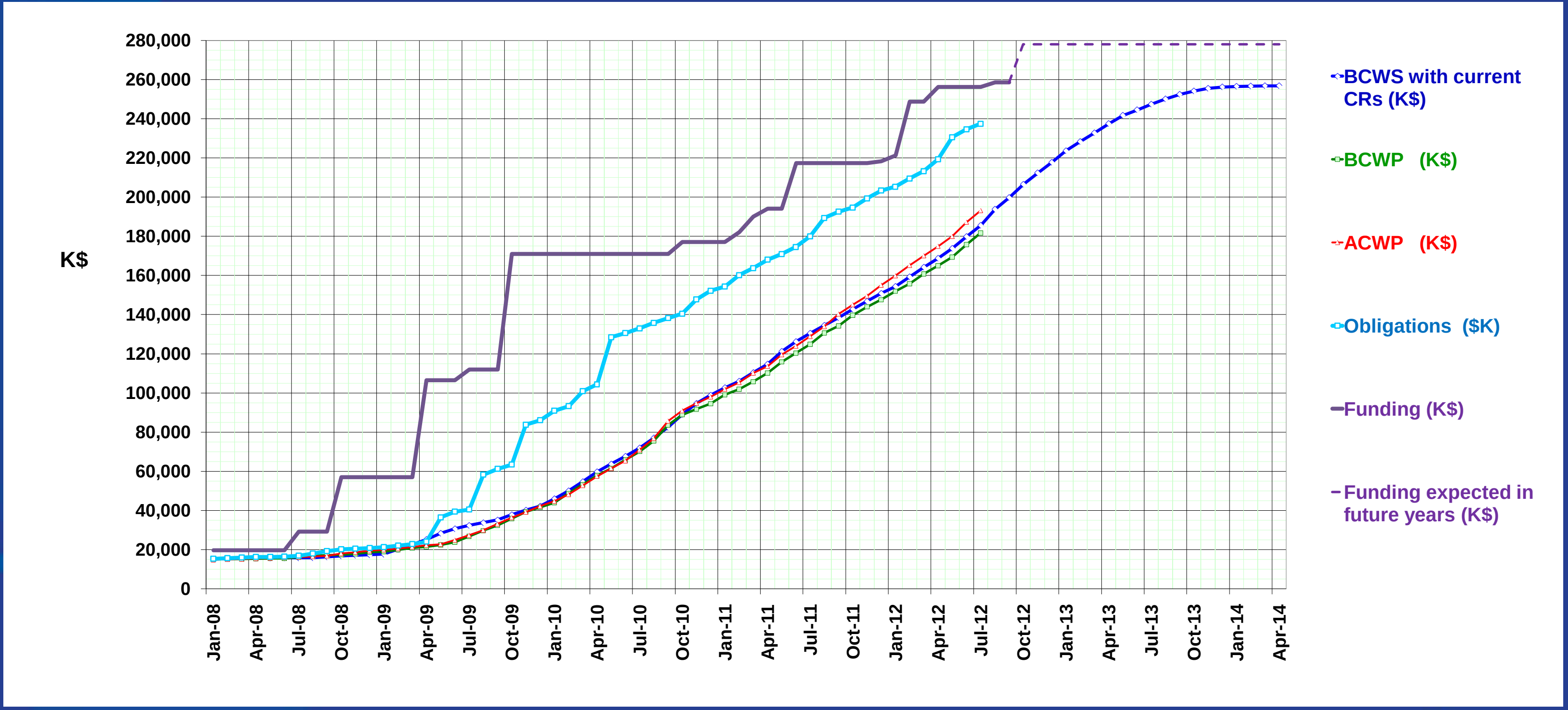
Project Progress: Financial Status

- Our Total Project Cost is 278 M$
- As of July 2012 have obligated 237 M$, costed 182 M$
  - The project is 92% obligated and 71% complete (% of BCWP) vs 46% complete at last S&T Review
- Basic data in Funding, Obligations, BCWS, BCWP & ACWP,
  - BCWS = Budgeted cost of work Scheduled
  - BCWP = Budgeted cost of work Performed
  - ACWP = Actual cost of work Performed

SPI=0.980, CPI=0.941



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Project Contingency

- Our TPC(Total Project Cost) is 278 M$
- Our current EAC (Estimate at Completion) is 266.8 M$.
- So we currently have 11.2 M$ of contingency.
  - This is 15% of the remaining work.
    - Remaining Work = Estimate at Completion – Costs to date
- But, we have obligated a large amount ahead of actual costs
  - 237 M$ obligated, 182M$ costed
  - So a fair amount of the Remaining Work is already in purchase orders and the costs are known rather well.
  - Our 11.2 M$ of contingency is 38% of the Remaining Obligations
    - Remaining Obligations = (Estimate at Completion – Obligations to date)
- The truth is somewhere between 15% and 38%
  - Since we have identified risks and contingency needs not yet in the schedule.

Project Schedule

- By March 2013 when the accelerator shutdown is scheduled to end, we expect to have 4 – 6 blocks (2 – 3 kilotons) working.
- By Oct 1, 2013 we expect to have ~ 16 blocks (~ 8 kilotons)
  - And the accelerator commissioning should be approaching the 700 kW goal
- In about May – July 2014, the full 14 kiloton detector is expected to be operational.
  - The date will depend on the rate of assembly at Ash River
  - We should know this rate by about November of this year.
- Our schedule contingency to CD-4 is about 6 months with 26 months to go. This is 24% schedule contingency.

SUMMARY

- **The NOvA Project continues to make good progress.**
  - **Every part of the Project, both accelerator components and detector components are now in production and being installed.**
  - **The first detector block at Ash River is nearly done ! Only 27 more to go!**
- The project has sufficient funding and adequate contingency.
- A DOE Office of Science Independent Project mini-Review (Lehman) was held on August 14.
  - "The committee determined that the project's cost and schedule impacts and related risks for the major outstanding issues have been properly identified and quantified…"
  - "Critical production and assembly activities have been initiated …. However, steady state production trends have not been established. The next four months will be critical in determining project success."
  - The Draft Review report is attached for reference.

Backup slides

August 14 Lehman mini-Review Summary page 1

OPA (SC-28) Mini - Review Summary
Department of Energy/Office of Science Review of the
NuMI Off-Axis ν Appearance Experiment (NOνA) Project

Review Date: **August 14, 2012**
Location of Project: **Fermilab**
Committee: **5 Members, 5 Observers**
Program Manager: **Ted Lavine**
Federal Project Director: **Pepin Carolan**
Acquisition Executive: **Pat Dehmer, SC-2**
Current Critical Decision: **CD- 3**

NOνA PROJECT STATUS as of August 14 2012		
Project Type	MIE / Cooperative Agreement	
CD-1	Planned: 5/2007	Actual: 5/2007
CD-2	Planned: 10/2008	Actual: 9/2008
CD-3	Planned: 3a – 2/2009 3b – 10/2009	Actual: 3a – 10/2008 3b – 10/2009
CD-4	Planned: 11/2014	Actual:
TPC Percent Complete	Planned: 68.1%	Actual: 69.6%
TPC Cost to Date	$187.1M	
TPC Committed to Date	$233.5M	
TPC	$278M	
TEC	$204.2M	
Contingency Cost (w/Mgmt Reserve)	BAC: $19.9 M EAC: $10.0 M	BAC: 24% to go EAC: 11% to go
Contingency Schedule on CD-4	6 months	24%
CPI Cumulative	0.~~98~~ 94	
SPI Cumulative	0.~~94~~ 98	

SUMMARY
A Department of Energy/Office of Science (DOE/SC) mini-review of the **NuMI Off-Axis ν Appearance Experiment (NOνA)** project was conducted via televideo on August 14, 2012. The review was chaired by Daniel R. Lehman, Director, Office of Project Assessment, SC. **The purpose of this review was to evaluate the current status of the project, especially in light of two outstanding technical issues.**

The Committee found that the NOνA project is progressing. **With respect to one of the outstanding technical concerns, the wave shifting fiber breakage issue,** the Committee noted that the Quality Assurance (QA) approach taken to address the fiber damage issue appears to be comprehensive and has resulted in a mitigating strategy and path forward for the project. On the second issue, the **failure of the Avalanche Photo Diodes (APDs), the project team continues to actively address the APD issues.**

1. **TECHNICAL**

The NOνA project team has focused on investigation of issues identified during the May 2012 Doe/SC min-review. These include the surface coating of the APD and the integrity of optical

August 14 Lehman mini-Review Summary, Page 2

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fibers in the detector modules during assembly and transport. The project continues to actively address the APD issues. The project also encountered a problem with the adhesive used in block construction, and has addressed this expeditiously.

With regards to the APD failure issue, silicone- and parylene-coated APDs operated in a dry environment have demonstrated 80-90% survival rates over a period of weeks to months. Although the measured quantum efficiency of parylene-coated APDs is about 5% less than silicone-coated APDs, the parylene coating is more uniform, and applied to more of the APD surface. Based on a small sample, the parylene-coated devices also appear to survive cold operation better. NOvA should continue to seek and engage experts in the field who could provide guidance on APDs.

Further investigation of the fiber damage problem has been carried out. In order to check on damage in shipment, three round trips of modules were made in May 2012. Comparison of status before and after shipping has provided reassurance that module shipping is not the source of the fiber damage. Module autopsy was unsuccessful because the act of gaining access to the fibers in modules invariably damaged the fibers. Since light transmission through a damaged fiber is typically about 90%, the team adopted the strategy of replacing single fibers during construction since implementing the fix and consequent QA entails small effort. Modules with single damaged fibers will be used in the most downstream blocks.

The project reacted promptly to the fiber damage issue. It has identified a path forward that is reasonable given the project completion constraints. The project team should continue to monitor whether fiber 'damage' worsens with time.

The Block Pivoter surface has been flattened to specification, and the device has been tested successfully. Congratulations to the project on completing this key task!

Difficulties were encountered with the structural epoxy used in constructing the blocks. Two fixes were adopted: roughen the surface of appropriate parts of the modules with Scotch Brite/sandpaper to ensure greater adhesion; adopt use of an alternate epoxy on the advice of the manufacturer. Shear strength tests indicate success in meeting requirements. The roughening process at Ashe River, performed on finished modules, has not damaged the fibers or introduced leaks. The extra effort needed for surface processing appears to be acceptable.

Responding to the structural adhesive issue cost several weeks of schedule. The response to the problem is reasonable. Although the surface roughening has not caused any module damage, e.g. fiber breakage or new leaks, the project team should continue to watch for possible problems. The team might consider performing, in parallel with construction, accelerated lifetime tests of the adhesive.

Recommendation

1. **Test the first ~100 final, production APD assemblies in a dedicated setup in order to validate the production parts, or find early signs of failure.**

2. COST, SCHEDULE and FUNDING

The Committee determined that the project's cost and schedule impacts and related risks for the major outstanding issues have been properly identified and quantified and there appears to be no unidentified outstanding risks related to cost and schedule requiring high-level management

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attention. The project team has undertaken a quantitative analysis to evaluate potential future contingency needs and mitigation strategies, including preliminary decisions dates, to recover cost contingency. The Committee remained concerned with the continued cost and schedule contingency use trends. Without continued, diligent contingency management, the remaining cost contingency may be insufficient to complete the project.

At this time, NOvA is approximately 70 percent complete. Cost and schedule performance to date remains satisfactory. The project has used $4.6M in contingency between May 2012 and July 2012 reducing current project contingency to approximately $10M (11% based on current EAC to go). Based on the project team's analysis, potential cost contingency requirements range from approximately $6M-$12M. The project team identified approximately $3M-$6M in known or possible cost contingency savings. The project is no longer pursing any additional increases in project scope and plans to process a change request to remove Block 29 from the Far Detector. Since the May 2012 DOE/SC mini-review, schedule contingency has decreased from 8 months to 6 months (24%).

Critical production and assembly activities have been initiated and several important early critical path milestones have been met albeit after several months delay. However, steady-state production and assembly performance trends have not been established. The Committee noted that the next four months will be critical in determining project success.

Recommendations
None.

3. MANAGEMENT

The Committee noted that the QA approach taken to address the fiber damage issue appears to be comprehensive and has resulted in a mitigating strategy and path forward for the project.

The Committee recommended that Fermilab evaluate the necessity of applying the Laboratory's increased General and Administrative (G&A) rates to the NOvA project, as it is not unusual for projects at other locations to be granted reduced rates or have the existing rates "grandfathered" for the term of the project.

It was also observed that the additional attention by senior Laboratory management has been beneficial to the project.

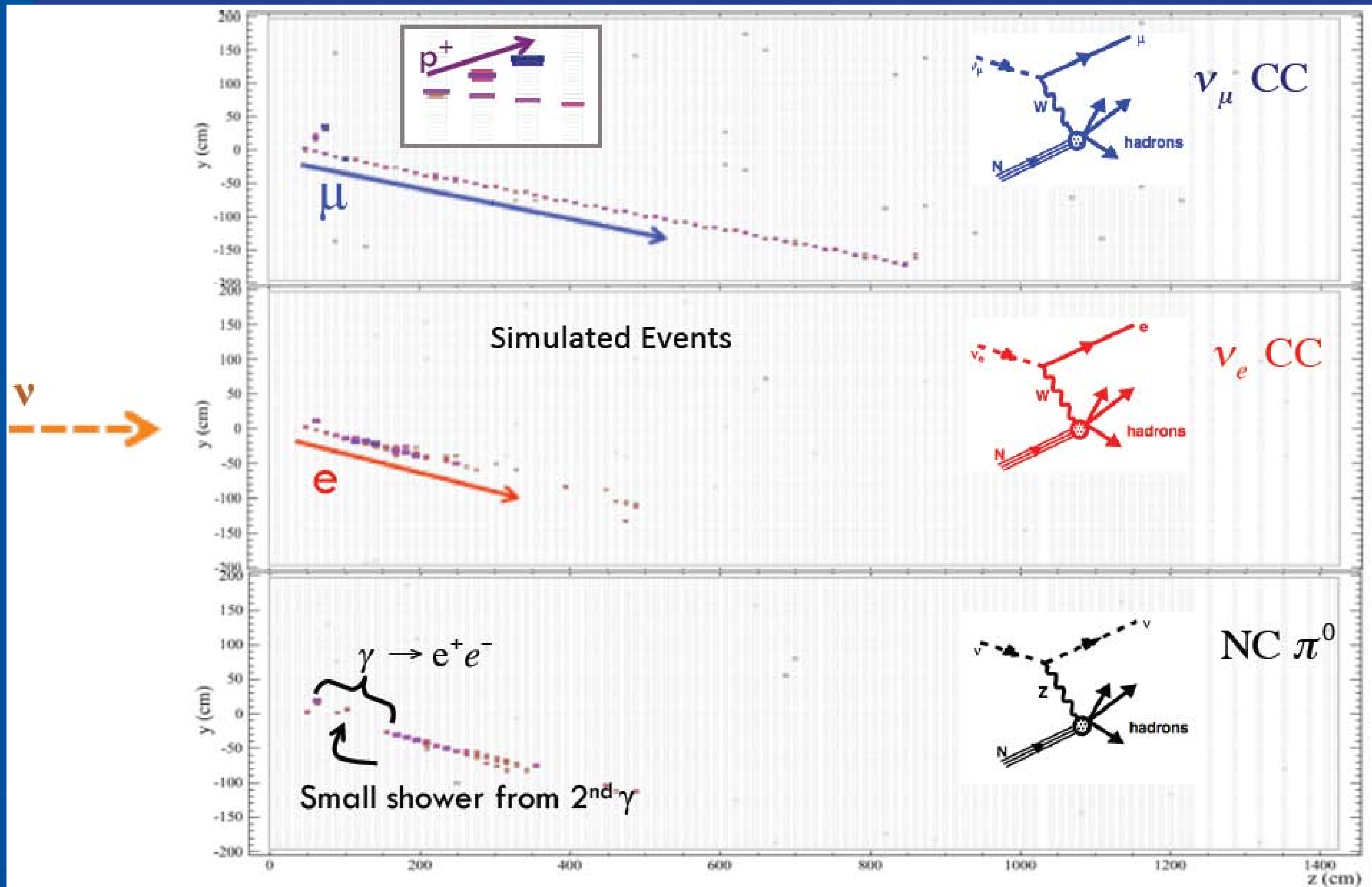
The Committee also suggested that the spare parts that were originally to be covered or reimbursed off project should continue to be handled that way

Recommendations:

2. **Initiate a weekly "update" on the major activities on the project to the program office. This should include the metrics/progress on the project.**
3. **Schedule a mini-review for November 20, 2012.**

Prepared By: Kurt Fisher, SC-28
Date: August 15, 2012

Distinguishing Neutrino Events in NOvA



- 41 – 48 % efficiency of identifying ν_e CC events while limiting NC background rate to 0.1%

$\nu_\mu \rightarrow \nu_e$ Oscillations in Long Baseline Experiments

Long-baseline $\nu_\mu \rightarrow \nu_e$ experiments have the potential to simultaneously measure θ_{13}, δ_{CP}, sign(Δm_{31}^2), sign(θ_{23}-45°):

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2 +$$

$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$

$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$a = G_F N_e \sqrt{2} \simeq (4000 \text{ km})^{-1}$ eg, in NOvA: $aL \simeq 0.23$

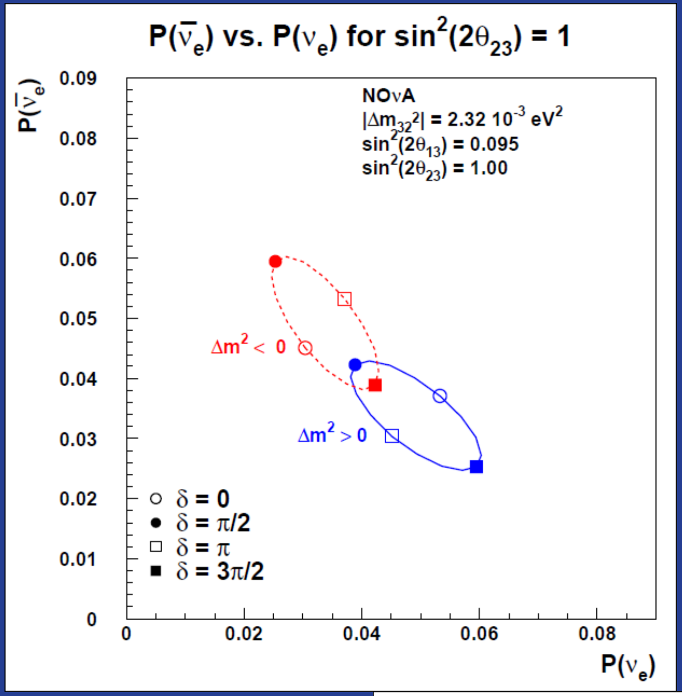
NOvA Measurements

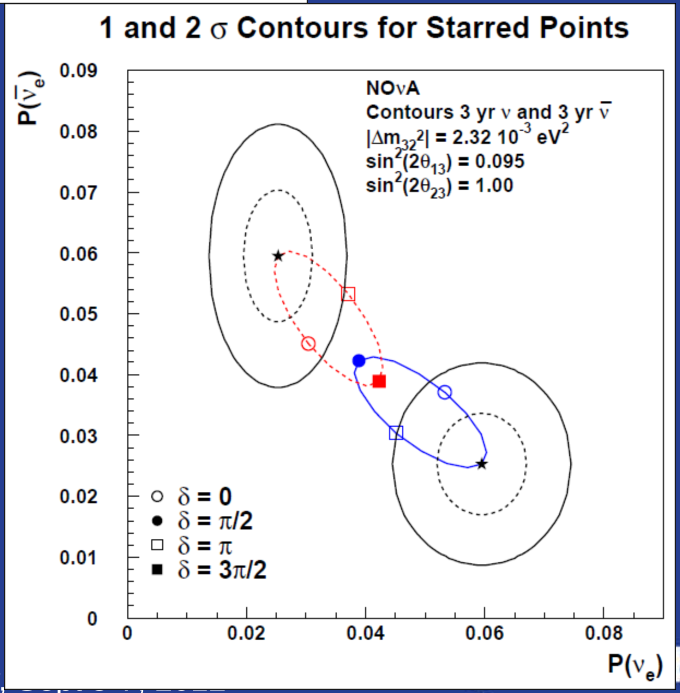
- The strategy in NOvA is to compare the oscillation probability of

  $\nu_\mu \rightarrow \nu_e$

  and

  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

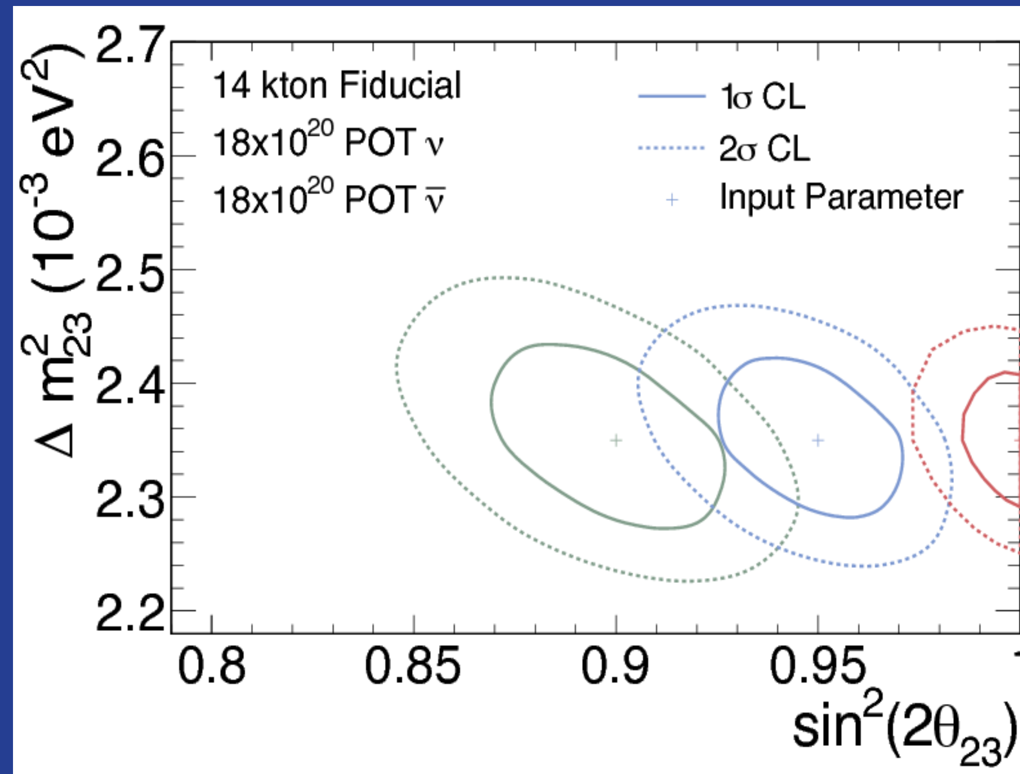




NOvA: $\sin^2(2\quad_{23}) \neq 1$?

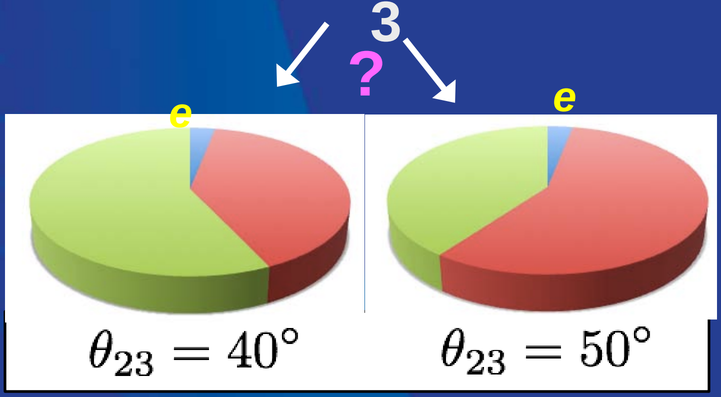
- Example NO A contours
  for three test points

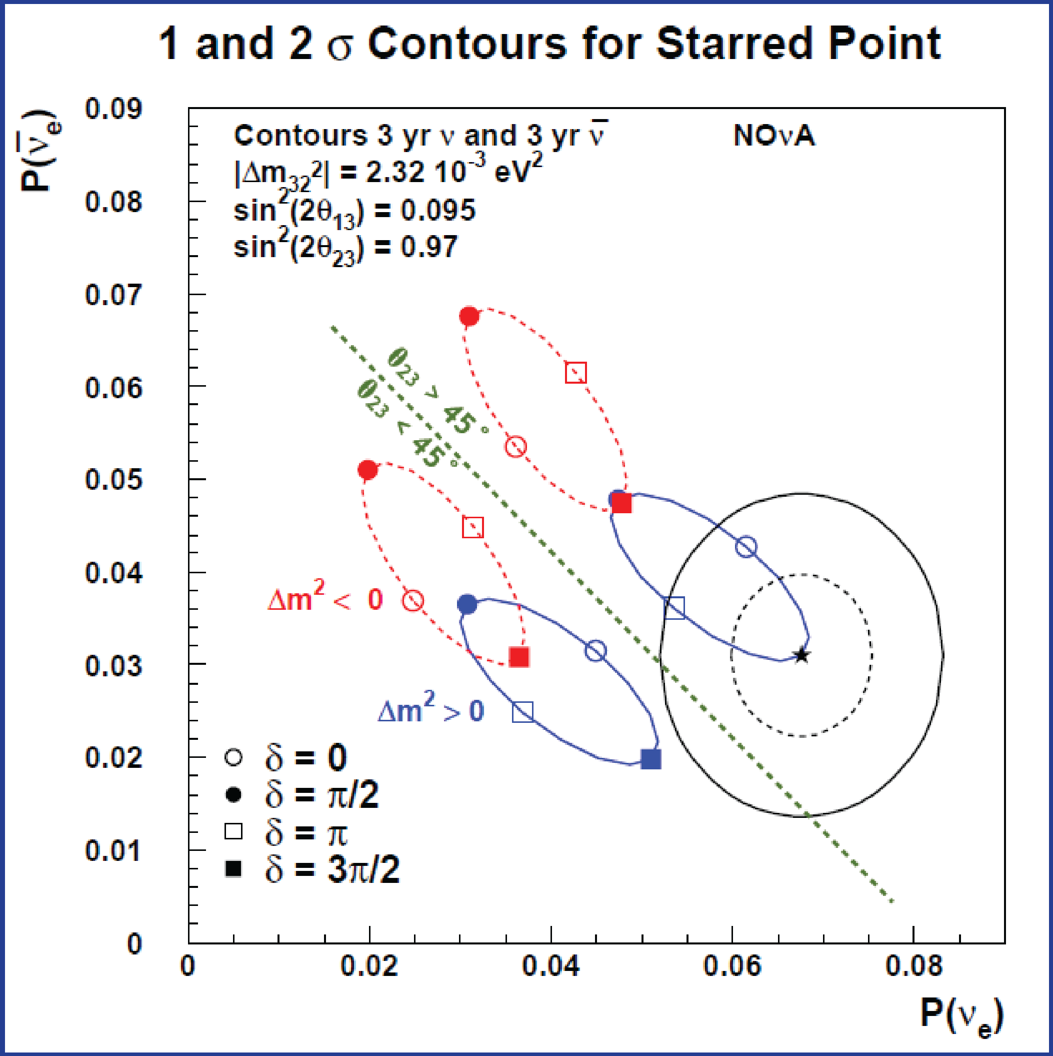
- 4% energy resolution for the QE sample.
- Inclusive   CC sample should be background-free



NOvA Measurements

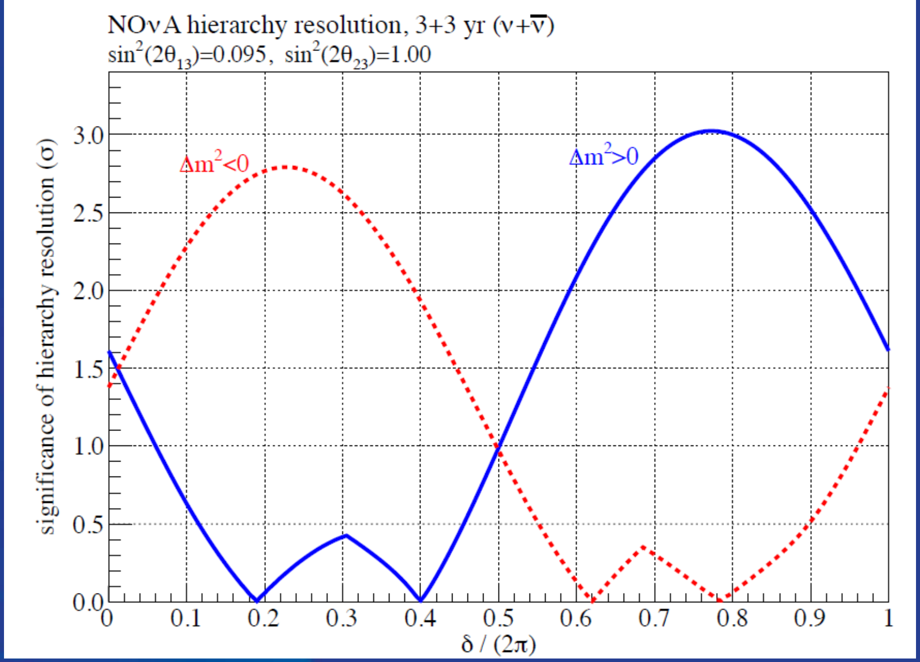
- If θ_{23} is non-maximal, then we also have the capability of determining the octant; this tells us whether or not ν_μ couples more strongly to ν_2 or ν_3.



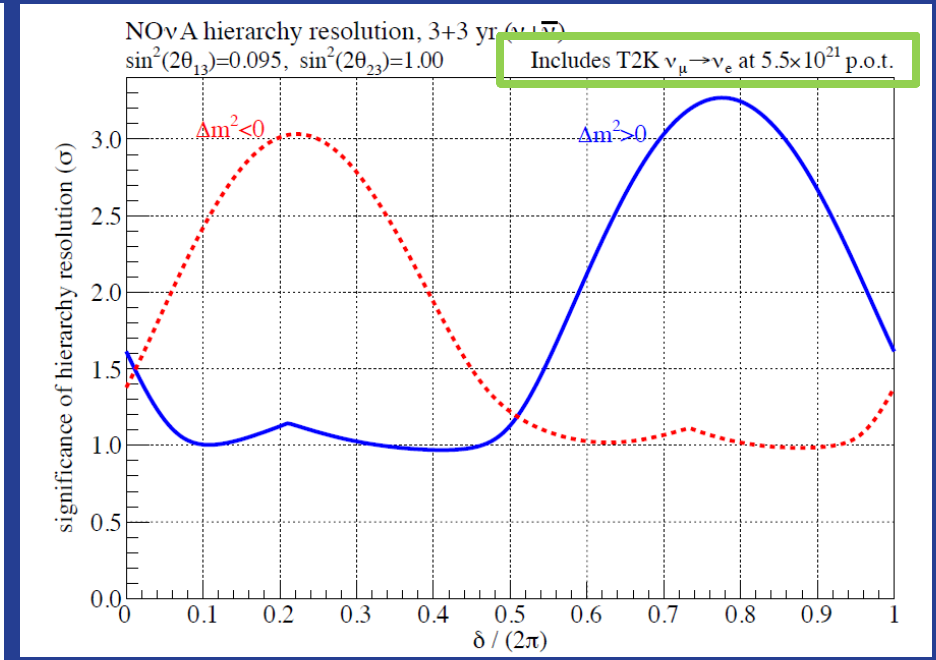


NOvA Resolution of the Mass Hierarchy

- NOvA alone

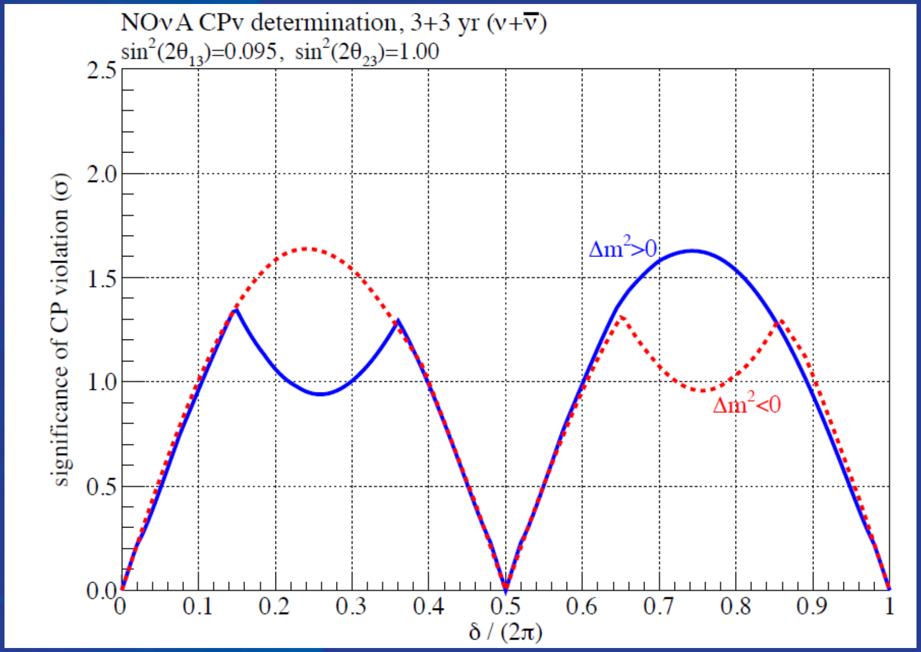


NOvA with T2K

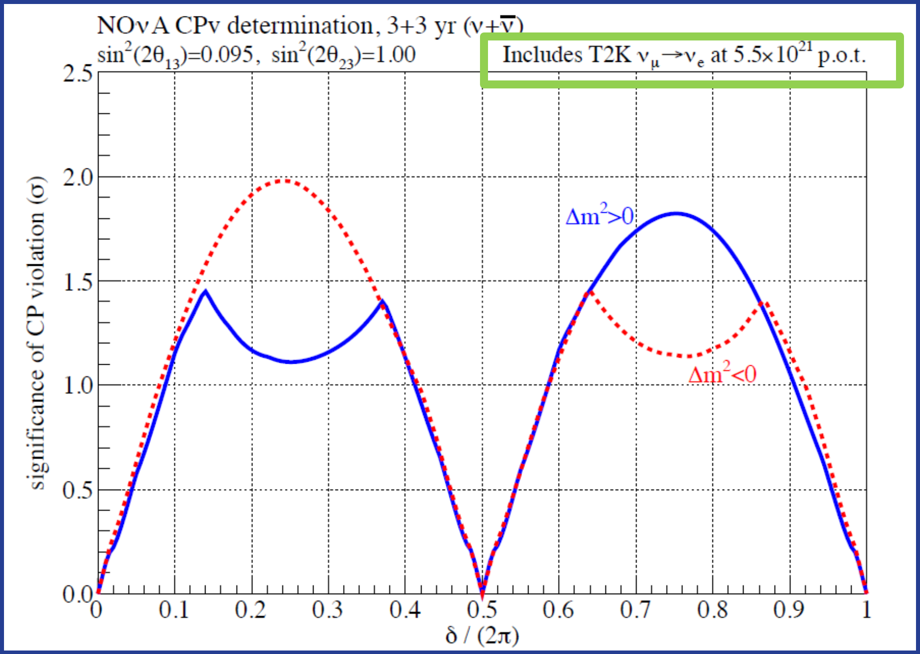


NOvA Measurement of CP-violation

- NOvA alone



NOvA with T2K



What NOvA can do in various θ_{13} scenarios

- **$\sin^2(2\theta_{13}) \approx 0.1$**
  - Determine the mass ordering for half of the δ space at the 1-3 σ level; combining with T2K, determine the mass ordering for the other half of the δ range at 1-2 σ level.
  - Exclude about half of the δ space at the 1-2 σ level.
  - Combining with Daya Bay, determine whether ν_3 couples more strongly to ν_μ or ν_τ at the 2 σ level if $\sin^2(2\theta_{23}) < 0.97$. (See G. Feldman talk at P5, Feb 2008)
- No Longer Relevant values:
- **$\sin^2(2\theta_{13}) \approx 0.06$**
  - Determine the mass ordering for half of the δ space at the 1-2 σ level; combining with T2K, determine the mass ordering for the other half of the δ range at 1-2 σ level.
  - Exclude about half of the δ space at the 1-2 σ level.
  - Combining with Daya Bay, determine whether ν_3 couples more strongly to ν_μ or ν_τ at the 2 σ level if $\sin^2(2\theta_{23}) < 0.94$. (See G. Feldman talk at P5, Feb 2008)
- **$\sin^2(2\theta_{13}) \approx 0.03$**
  - Determine the mass ordering for a quarter of the δ space at the 1 σ level.
  - Exclude about half of the δ space at the 1-2 σ level.
- **$\sin^2(2\theta_{13}) \approx 0.01$**
  - See a signal at the 1-3 σ level, confirming weak signals seen in other experiments.