Temporary Muon Spectrometer

Tom LeCompte

DUNE ND LBNC Interaction

3 December 2020

What This Talk Is About

- We have made a great deal of progress in the last 2-1/2 months
  - You have the PDR draft in your hands
  - We have made a number of decisions for baselining
    - In some cases we selected more mature and less performant options. We can revisit these decisions after baselining via Change Control. (That's what it's for – provided we can prove the change is better)
    - In the following slides I will discuss some of the options along with the baseline
  - We have a bottom-up construction schedule that agrees with top-down
    - Both are based on MINOS and mu2e experience, so the agreement is not unexpected

- Caveat: not all of the simulation has completely caught up with the design changes
  - However, we believe we are well beyond where we were in September, and that the qualitative conclusions are correct.

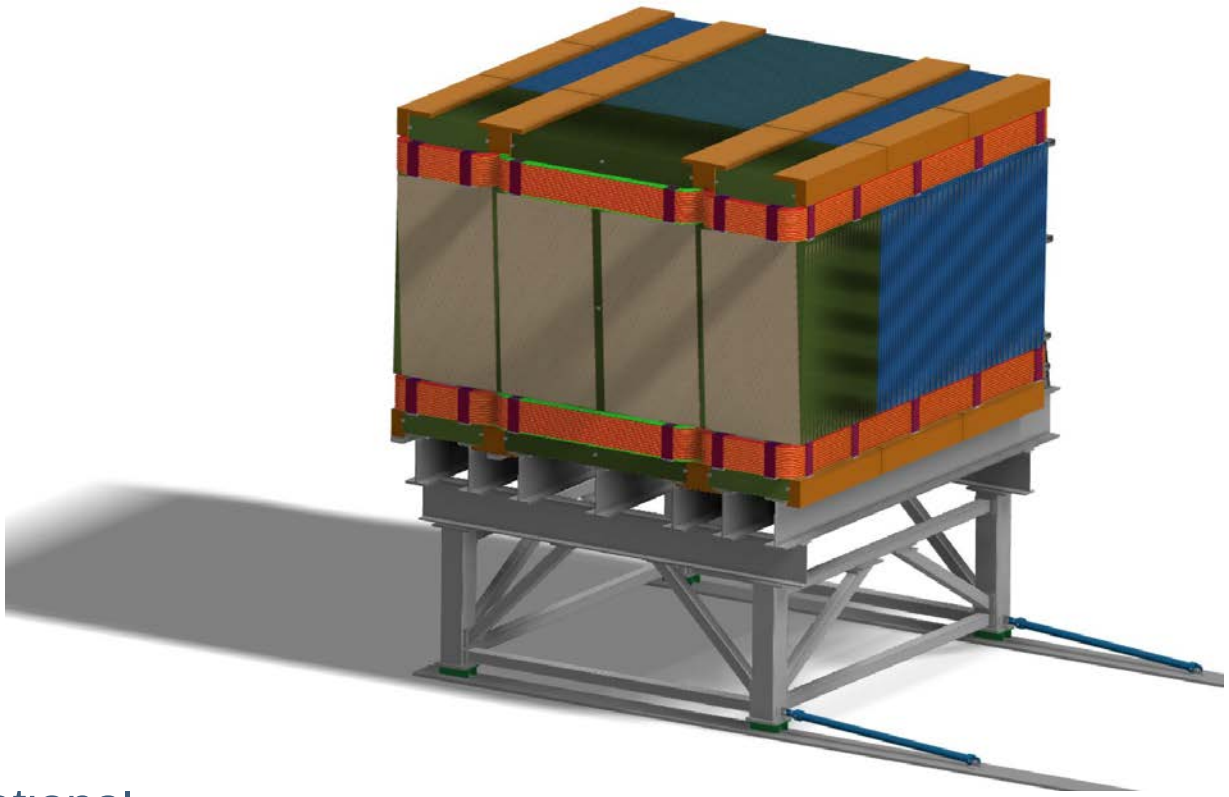
Outline

- Device Description
- Overall Strategy
- Construction Schedule
- Removal Schedule
- Design Decisions
  - Geometry and Dimensions
  - Scintillator
  - Magnet
  - Magnetic Field
  - DAQ
- Prototyping

Chris Marshall's talk will focus on performance. Mine will concentrate on design & production.

TMS Description

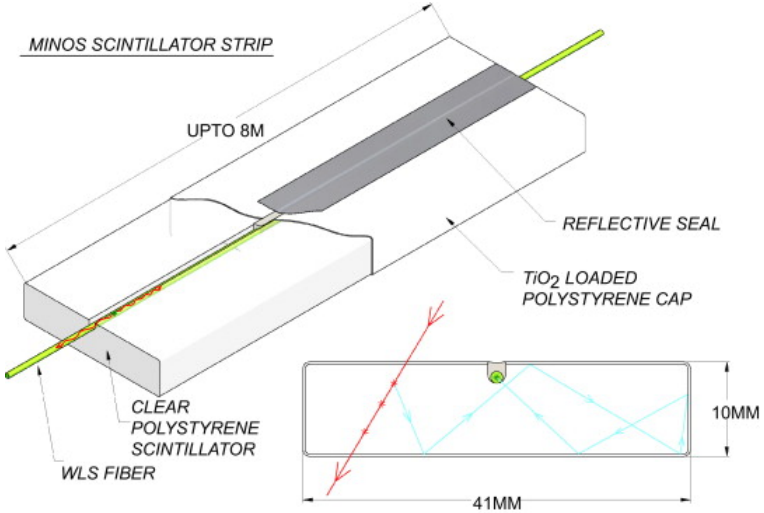
- A magnetized range stack with =100 layers
  - Face is the same size as the ND-LArTPC face
  - 192 scintillator slats (@ 3.5 cm wide) per plane
- Entirely DUNE-US scope
- Sits where ND-GAr will eventually go
- Intended to run until the ND-GAr is delivered
  - Requires some flexibility on our part as the international situation evolves
  - Nevertheless, this is a device we can build for a known cost (~$6M base) and schedule sufficient for initial physics.

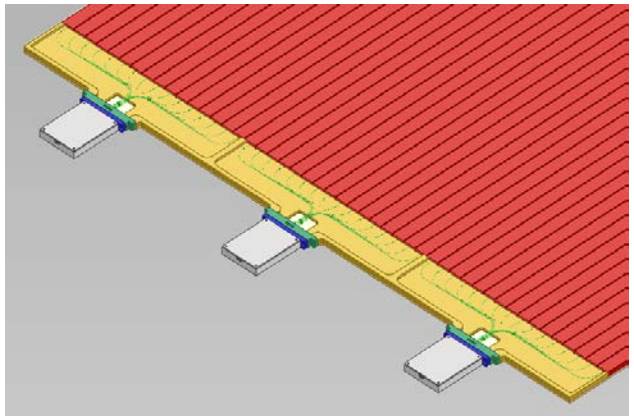


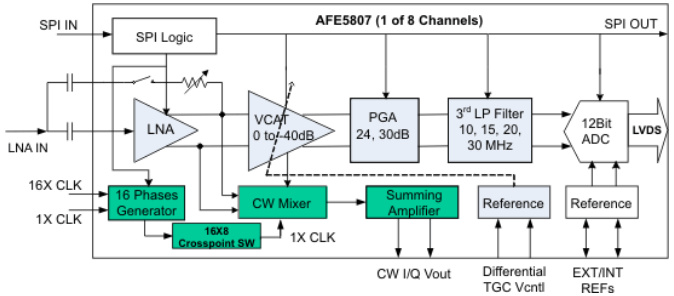
7.4m wide x 5.0 m tall x 7m deep
~850 tons

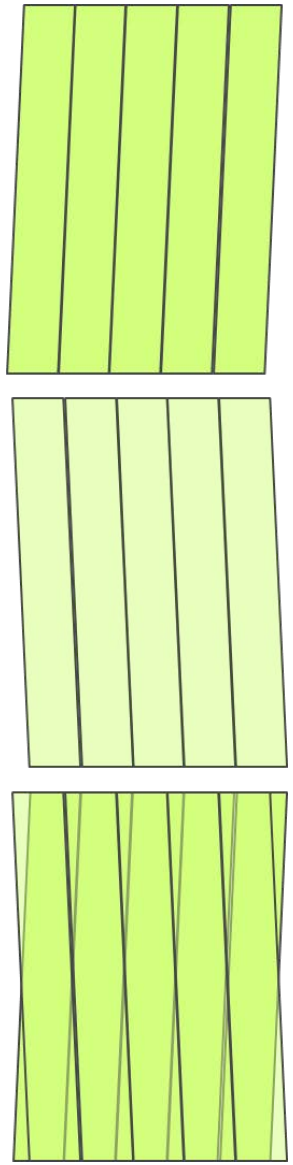
Detectors

- Design is MINOS/mu2e-like (co-extruded polystyrene)
- Each plane (of 100) has four panels (192 channels)
- Each panel is a self-contained box containing
  - 48 slats of scintillator 3.5 cm wide with Y11 wavelength-shifting fiber
  - SiPM, Front End-ADCs (based on Texas Instruments AFE5807 chip) and associated electronics
- Panels (which are rectangular) are tilted ±3º in alternating layers
  - Gets us ~45 cm resolution in y-direction
  - An inexpensive choice – but will be subject to pileup issues at 2.4 MW (Year 6).









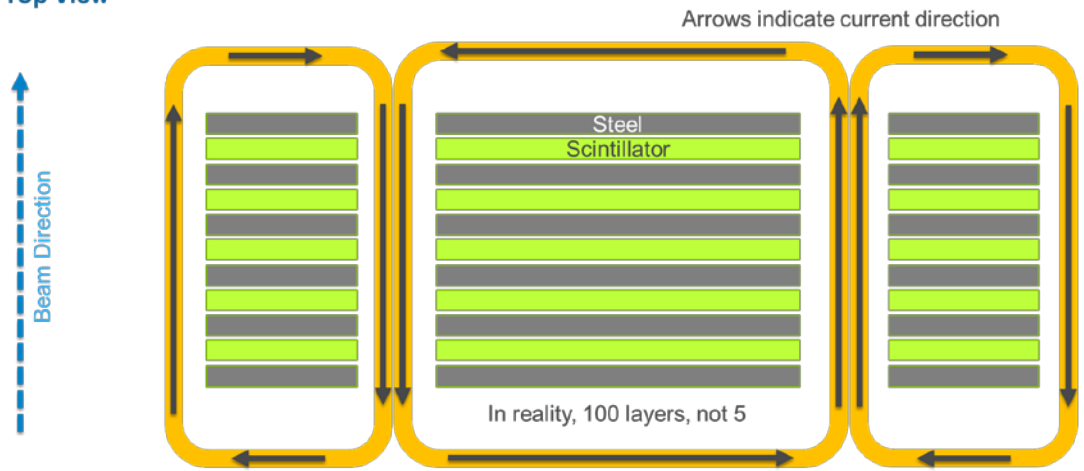
Magnet

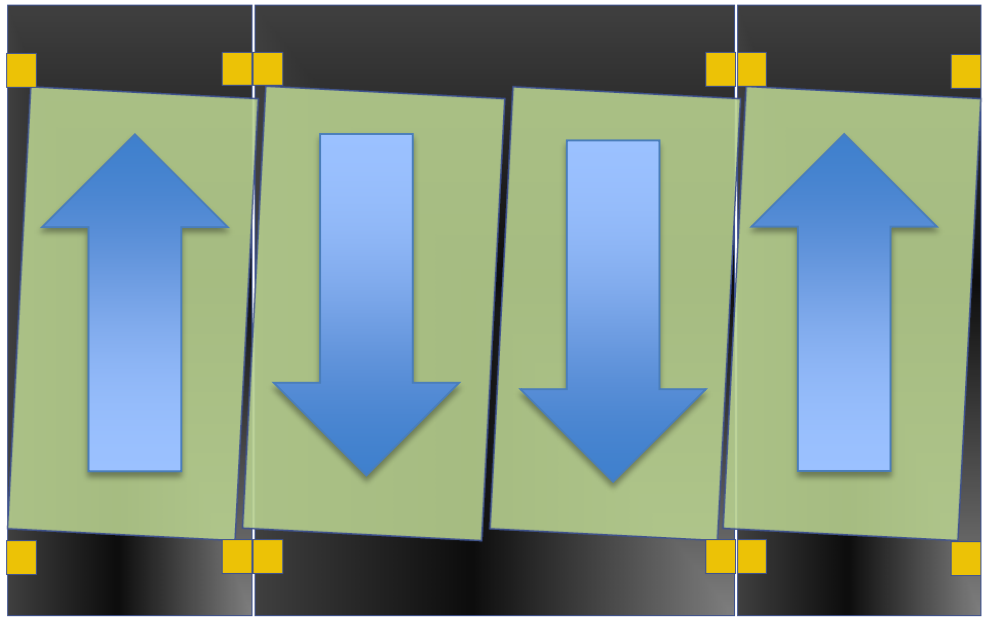
- The magnet measures charge, not momentum
- Each plate sees a dipole; outside it's a sextupole
  - 1.08 T inside but only a few Gauss at the edge of LArTPC
- Plan on 150 Amperes & 200 turns
  - Air-cooled 00 gauge cable

Coil Design

Top View

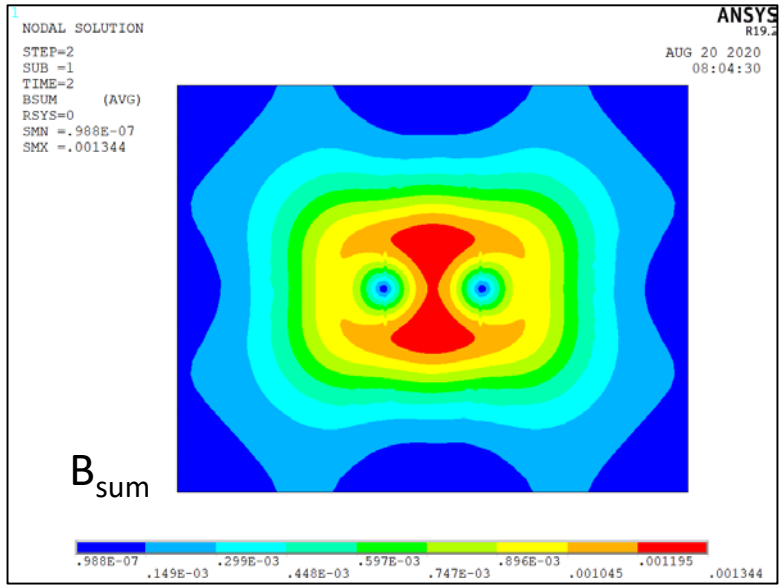
(current is reversed)





Magnetic field reverses in the different steel plates.

This is how we keep it low in the LAr.



B_{sum}

Magnetic Field at the closest part of the liquid argon

Strategy

- Get the TMS Baselined
  - Continue to advance the design, establish the interfaces and write the reports
- Understand the drivers of the go/no-go decision date
  - Monitor and adjust as necessary
- Ensure that the costs stay under control

- Rationale (from last LBNC meeting)
  - DUNE's intent is to build the detector described in the TDR, including a high pressure gas TPC downstream of the Lar TPC at the Near Detector site.
  - Resources to do this have not been fully identified at this time. We cannot guarantee we will be able to build this detector in time for Day One.
  - The collaboration has a strong desire to operate the experiment at the earliest possible time, a desire supported by the funding agencies. The US Department of Energy has agreed to adding a Temporary Muon Spectrometer, suitable for Day One measurements, to its scope.
  - If circumstances evolve so that we do not need this device, we would not build it – we would go straight to the permanent instrument. Therefore, the question we are working to is "when do we need to decide?" which is coupled to "how long does it take to build this?"

Strategy & Electronics

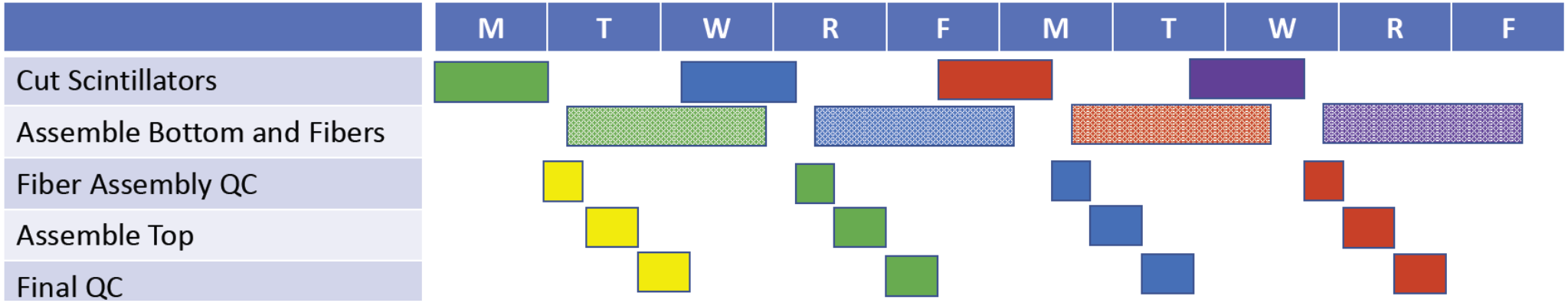
- We do not want to do the detailed electrical engineering now, as parts available today may not be optimal – or even available - when we need to purchase them. In that case we would end up having to do this over

- We have a EE and designer creating a BOM-level estimate, after which they will stop
  - Expected impact: base cost estimate won't move much, but contingency will come down

- We will revisit this in 2022

n.b. some off-Project research might prove relevant

Individual Site Schedule



- Based on the 51 individual and summary tasks in making a module, we calculate
  - It takes a week (+ 2 days curing time) to make a module
  - Each site can make 2-2.5 modules a week
  - This assumes two teams – one boxing the scintillator and routing the fibers, and the other preparing materials, finishing each box, and QC testing

- Our construction duration assumes two sites working 100%
- We intend to have three sites to account for a learning curve and to add some margin

Overall Schedule

Table 1.5: TMS High Level Schedule.

Activity	Duration
POs issued and delivery of parts	6 months
Panel Construction	22 months
Coil Winding	1 month
Contingency	5 months
Total	34 months

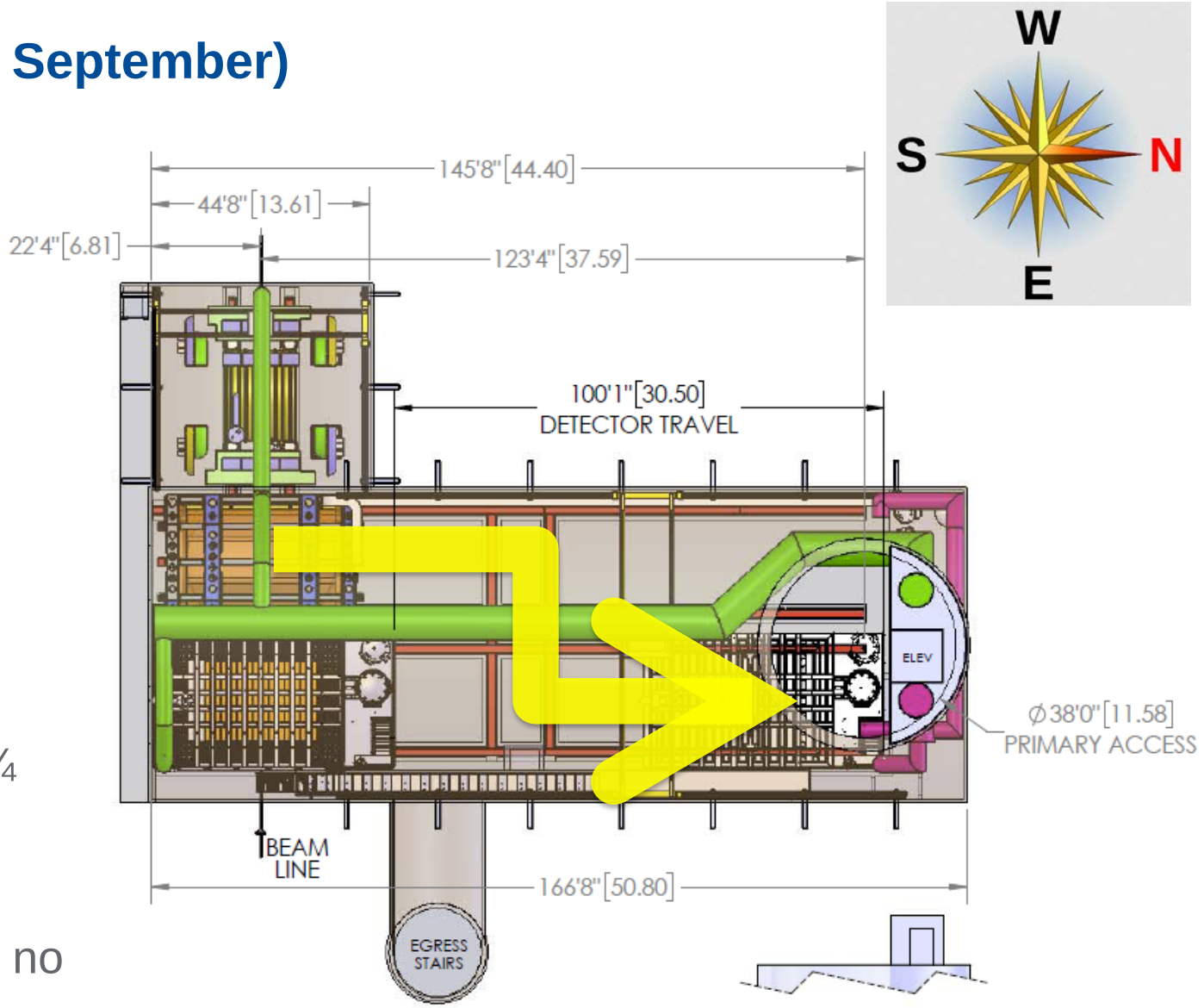
Decision date is Day One less **34 months**

- Go/no-go date is a T-34 months
- Based on the timescale on the last slide, we believe panel assembly takes 22 (± 3) months
- Purchase orders for half a million dollars take time. Some items (WLS fibers) can have long lead times
- Coil winding occurs after the last counter is installed
- We have included 20% contingency
  - With three sites, this may be generous. Or it may not. There are correlated risks, such as late parts delivery.

Reality is less black and white. One could push this back a month for $150,000 if one split the WLS order into two and buys 1/3 of it at T-34, but made the final decision at T-33. We fully understand the difference between the day we want to decide and the day we *must* decide.

Removal Schedule (A Question from September)

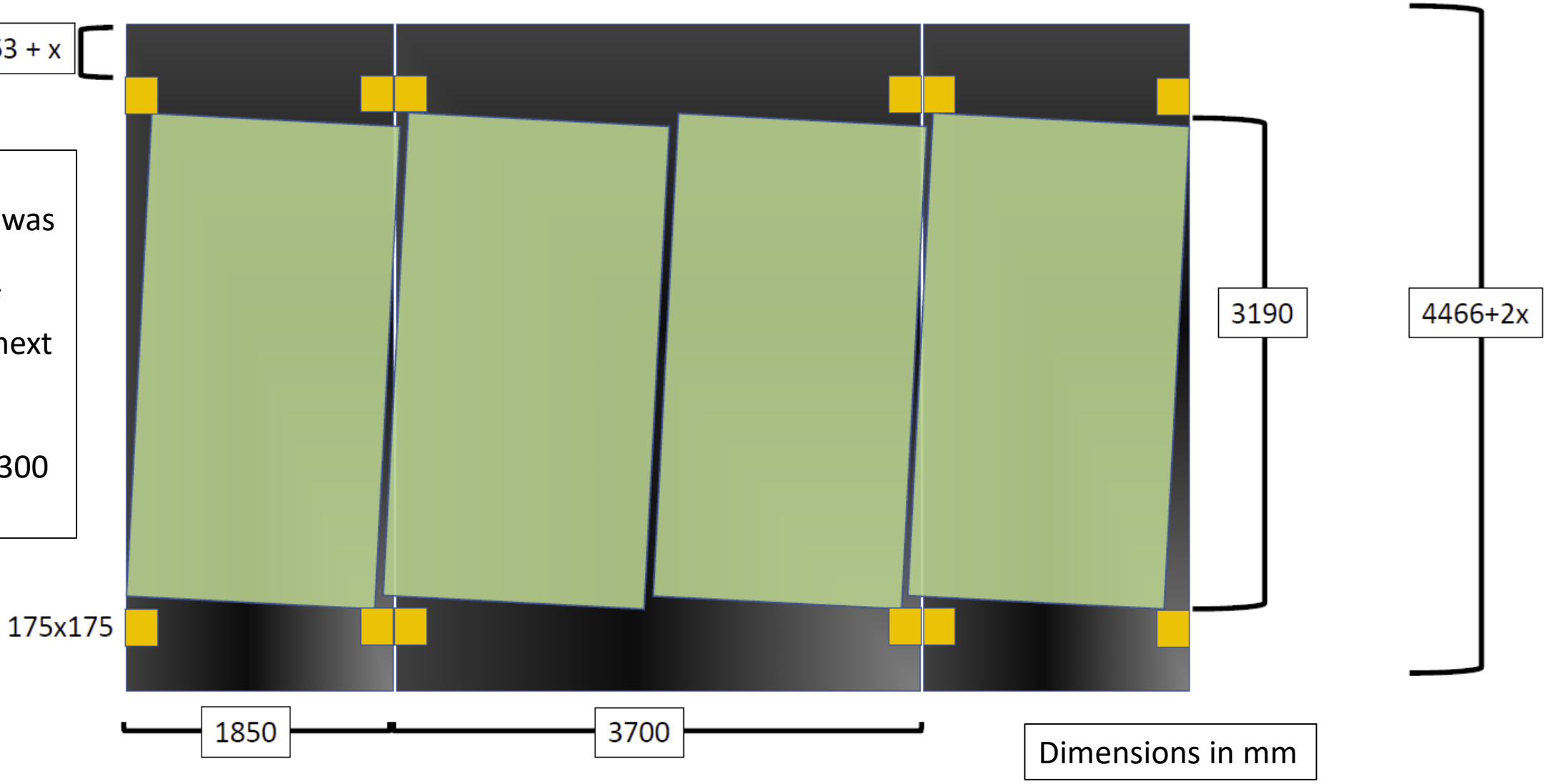
- When ND-GAr is ready the swap with TMS takes **two weeks without muons**
  - Dominated by cabling and uncabling time
- PRISM is used for N-S motion of both detectors
  - TMS moves to the East PRISM rails on temporary E-W rails. The SAND rails are too close together to use for this purpose
- During ND-GAr construction and TMS disassembly PRISM motion is limited to ¾ of maximum.
- This plan has assembly implications (e.g. no welding)



Dimension Decisions

The last open measurement was “x”, additional steel on top of detector (see next slide).

Settled on x = 300 mm.



Dimension Decisions II

- The “x” (which we should have called “y”) in the previous slide is set to 300 mm
  - This is advantageous for the magnetic field (see later slides)
  - Making the plates much taller and we start to run into other issues, particularly with steel flatness.

- Panel dimensions are 1695x3000 mm
  - The “3.5 cm” counters are 3.51 cm with 5mm on each side for the frame
  - This gives an active area of 20.22 m^2. (96.3% coverage)
    - This is 1.1% above our (proposed) Key Performance Parameter of 20 m^2

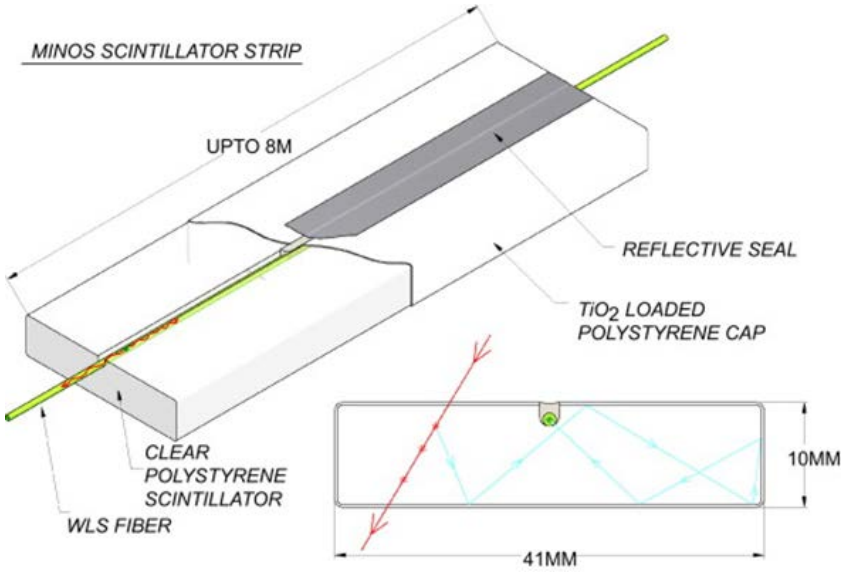
- We are moving to an “integration envelope” philosophy
  - Full disclosure – we have no interferences, but we have volumes touching (zero stay clear) at six points per plane.

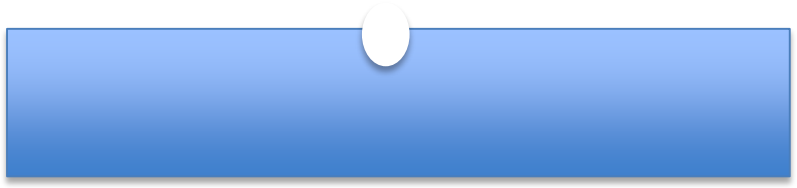
Scintillator Decisions

- Groove options:
  - MINOS-like: along the edge. Allows horizontal construction, but produces less light (theoretically – glue quality may be better)
  - mu2e-like: centered. Produces more light, but we need to get bubbles out of the glue (low viscosity glue, and probably inclining counters at this stage)

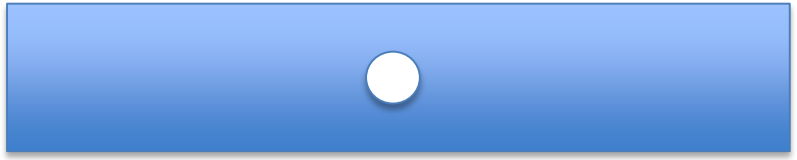
- Decision: baseline the MINOS-like (edge) design

- What would cause us to change this?
  - Successful prototyping of a centered-design counter, including
    - Getting the bubbles out
    - Construction time increase understood and minor
    - Acceptance of mu2e light yield studies (or conducting our own)





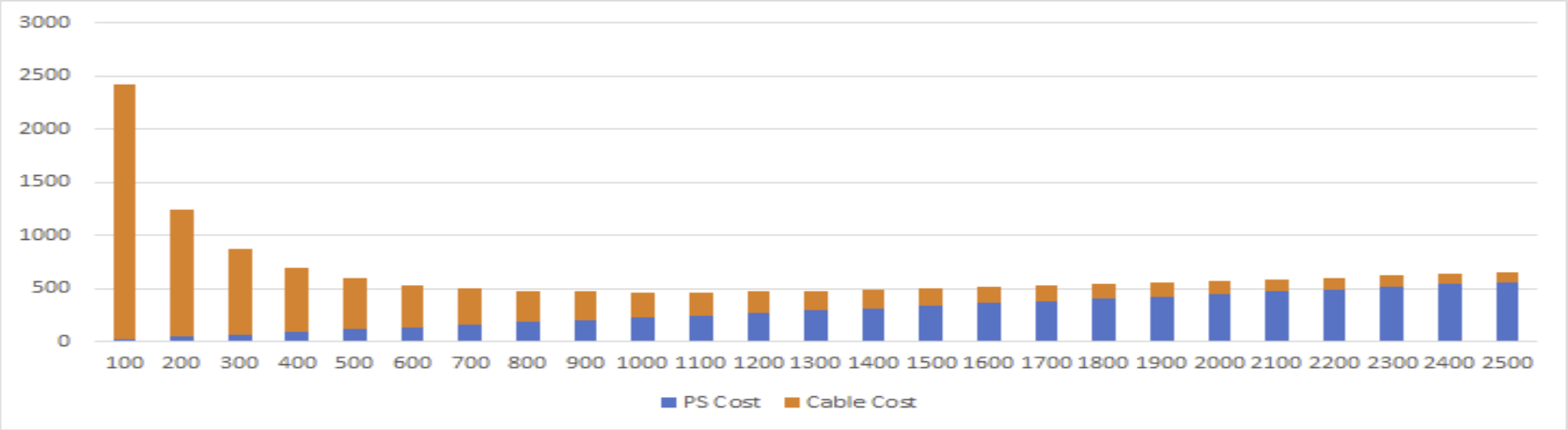
MINOS-like



mu2e-like

Magnet Design – A Value Engineering Perspective

- Wrapping a coil around a piece of iron is not the challenge.
- The challenge is do this for not a lot of money.



An (over-)simplified optimization model between the amount of copper and the power supplies needed to energize the magnet.

- In reality, we optimize on a multidimensional space
  - Coil material – drives current requirements
  - Power supply – drives coil requirements
  - Cooling – sets maximum power
  - Steel above & below panels – captures more flux
    - In principle, the least expensive way to get flux (20 ± 40% cheaper)

There will probably need to be another round of value engineering nearer to the construction date.

This can only improve things

Magnet Design - Cooling

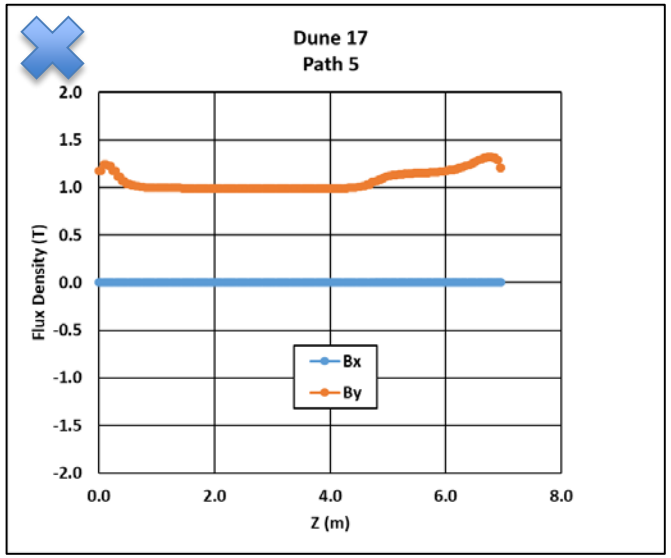
- We have flip-flopped between water and air cooling a number of times

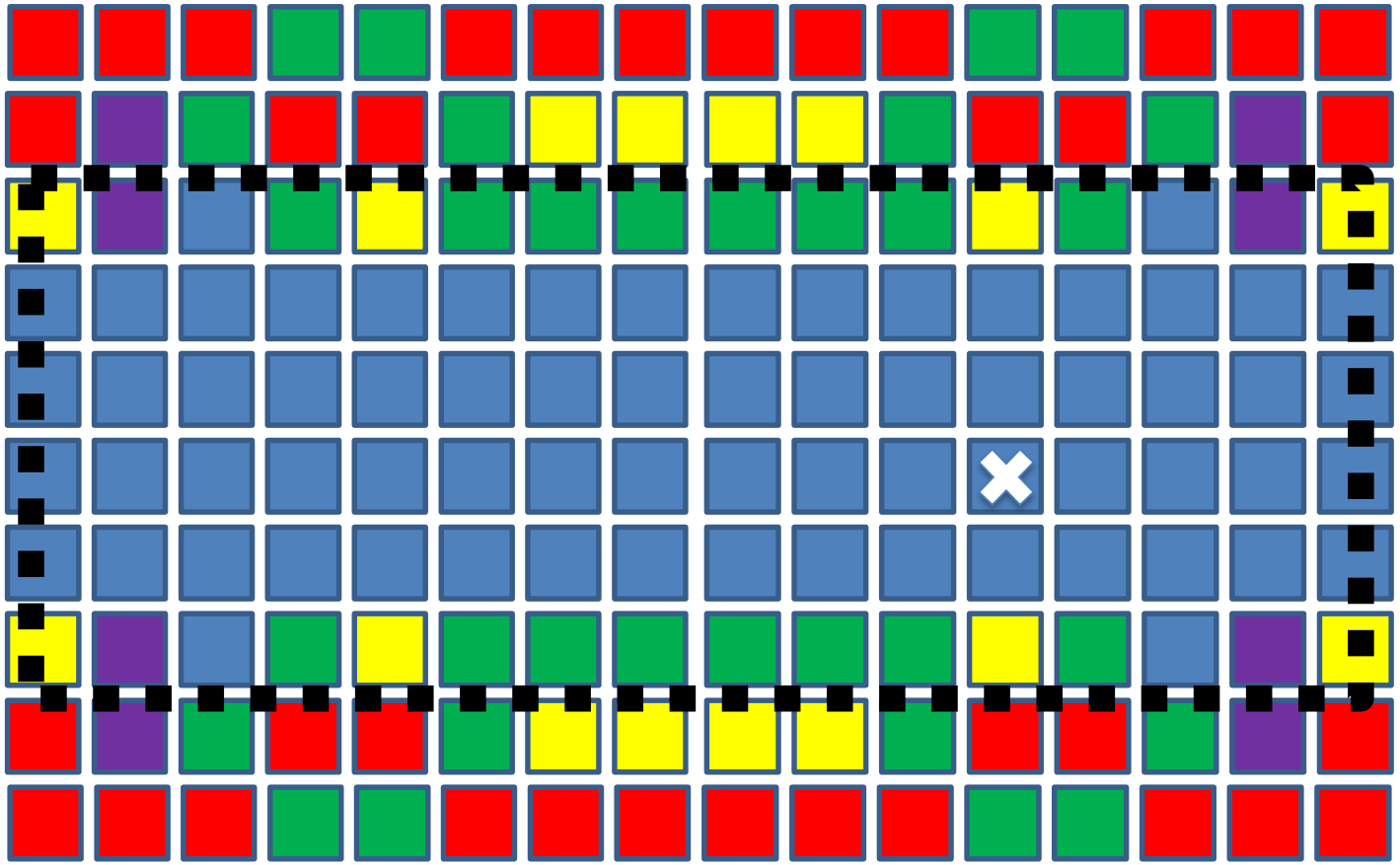
- The design we are moving forward with is air-cooled
  - Coil surface is 150F/65C or below

- Water cooling would allow ~4x the current in each coil
  - This means 4x the power (so a cost tradeoff there)
  - We are designing a closed-loop water cooling system
    - Coil heat is transferred to the water
    - Water heat is transferred to the steel
    - Steel heat is transferred to the air
    - Hall cooling ultimately removes the heat
    - This will not be defensible by January, so it's a future Opportunity

Magnetic Field

- The new steel geometry produces a lower B but (on average) higher B_y.
  - The field is more uniform (less tilt). Standard deviation in the x-y direction is 6%.
  - Non-uniform spots are near the coils, and top and bottom of the centerline.



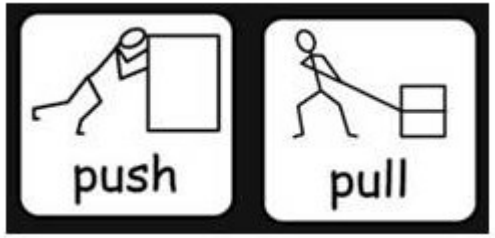


Black dashed line indicates active area

$\int B_y dz$ shown

>50% low	5-50% low	± 5%	5-10% high	>10% high

Interface with the DAQ



- Previously there was an issue with frequency mismatch
  - The DAQ preferred frequency was 62.5 MHz
    - Driven by desire for commonality with Far Detector where this drives the 2 GHz sampling time
    - Our events have a frequency of 53 MHz (Main Injector RF)

- We have agreed on a “push” architecture
  - The TMS will send TCP/IP packets or UDP datagrams to the DAQ via optical link
    - We are responsible for the socket; DAQ is responsible for the fiber
    - Packets include time stamps (to the nearest Main Injector RF bucket)
    - Packets do not have to be sent in chronological order – reassembly is DAQ’s responsibility
    - Neither side cares (or even knows) what frequency the other uses

- This is at the handshake agreement stage – interface documents are in preparation (next step)

Prototyping & Other Studies

- Construction Time and Motion
- Magnet Value Engineering (shown)
- Signal Cables and Noise
- Steel Plate Thickness Optimization
- Fiber Hole Placement (shown)
- Fiber Attachment to SiPM (next slides)
- Certainly more to come…

- Studies address four questions
  - Can we reduce the construction time or its contingency? That would allow us to make a later go/no-go decision.
  - Can we reduce the technical risk?
  - Can we improve the performance for fixed cost?
  - Can we reduce the cost?

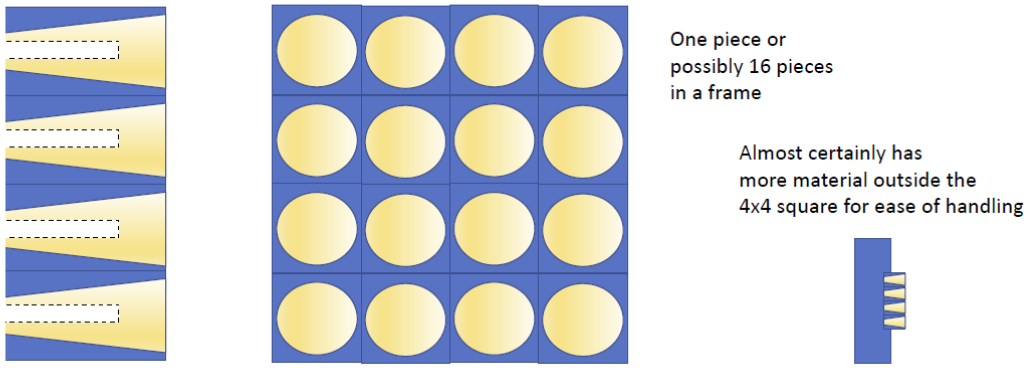
Fiber-SiPM Coupler

- The most time-consuming part of panel assembly is attaching the fibers to the SiPMs
  - These SiPMs are really *really* small
  - They have sixteen even smaller things (WLS fibers) attached to them.
  - These fibers are constrained at the opposite end as well (they are glued into the scintillator)

- Solution: 3-d print a combination fiber holder and light diffuser to attach to the SiPM.
  - In the drawing, the blue will be white and the cones will be Winston cone-shaped transparent/translucent
  - Simpler (and larger) prototype printing is going on (next slide)

SiPM is roughly the size of this (smaller than standard) die.

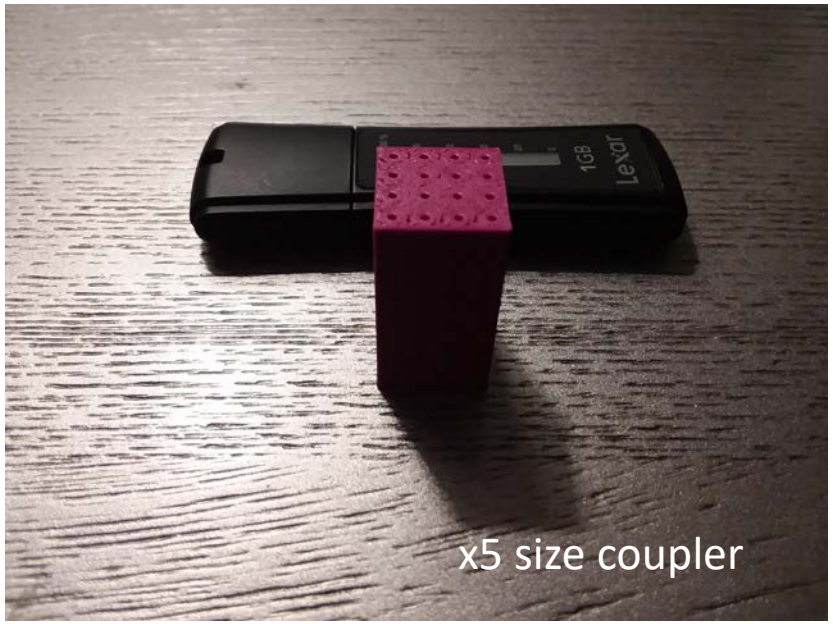
Compare with the penny and not standard dice.

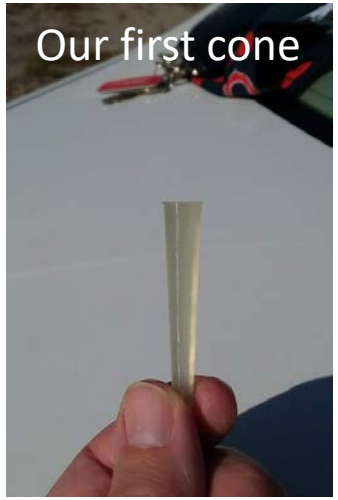


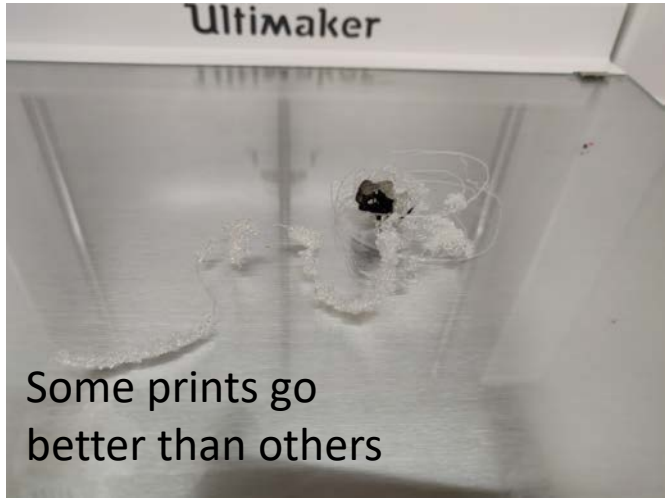
Potential to save several months of construction time.

3D printed Coupler Prototypes

- Plan:
  - Large (x5 in all dimensions) 16-channel model with no optical diffuser
  - Large single-channel optical cone
  - Combine….
  - …and shrink
  -







How Can the LBNC Help?

From September

- An endorsement (or not) of the general strategy:
  - Build this device only if we have to
  - Make that decision as late as we can
  - Find out how late “as late as we can” is as early as possible.

- An endorsement (or not) of the technical performance
  - Can we do Day One physics with this device? (We know it’s not fully optimized)
  - If you need more information, we would be happy to provide it.
  - It would be good if the DOE IPR panel (meets in January) knows what you think.

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Thanks!

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  - If you need more information, we would be happy to provide it.
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See Chris Marshall’s Talk

- Advice in general, but it would be especially valuable to hear your views on the strategy of
  - Making design decisions now
  - Baselining as soon as we can
  - Roll future improvements in through the change control process

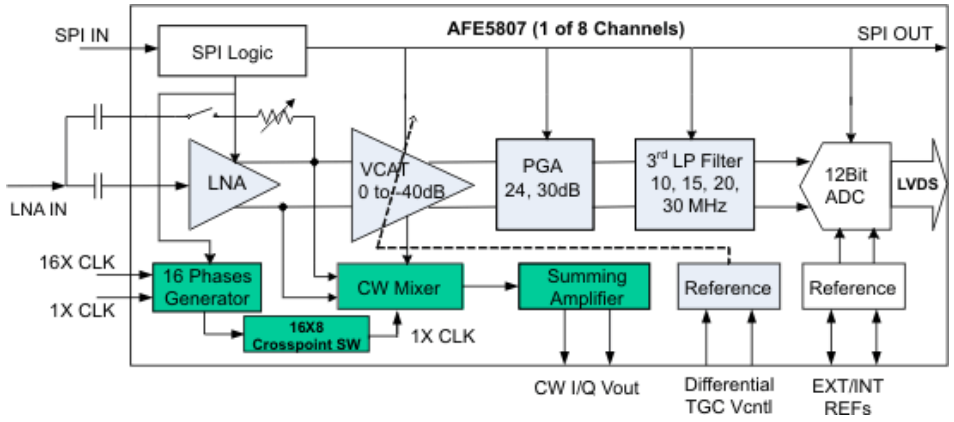
Summary

- This is a new subdetector, to ensure a robust physics program starting on Day One
  - This is only the second time you have seen it, but the design is significantly advanced from September
- This subdetector design is not anyone's first choice. But…
  - It will do the job for the initial physics goals
  - We are prepared to build it
  - We know how much it will cost
  - We know about how long it will take – and are working on knowing this better.
- Prototyping and design finalization work is ongoing

Backup

Subsystems: Scintillator Readout

- On-Panel Board (OPB)
  - Has three 16-channel SiPMs and six Texas Instruments AFE5807 analog front ends
    - Output is LVDS on shielded twisted pair (96c)
  - Also does low-voltage DC-DC conversion and distribution (SiPM + 3 voltages for front-end chip)
  - In an early stage of design (contingency is 75%)
- Data Concentrators
  - Eight FPGA-based units that accept OPB output , reformat it and send it on to the DAQ
  - In a very early stage of design (contingency is 99%)



Electronics cost is **$80/channel**.

We compared costs line by line with the mu2e CR veto – this is less expensive because 48 channels share a common low voltage system.

Tables from PDR

Table 1.1: Temporary Muon Spectrometer Parameters

Parameter	Value
Steel dimensions	$7.4 \times 5.0 \times 7.0$ m
Steel plate thickness	40 planes of 15 mm, 60 planes of 40 mm
Steel mass	850 tons
Magnetic Field	Typically 1.0-1.1 Tesla
Active Area	20.3 m^2
Number of detector planes	100
Channels per plane	192, in 4 panels of 48 each
Total channels	19200
Timing resolution	$\leq$ 19 ns (single RF bucket)

Table 1.3: TMS Risks from Risk Register

Risk Number	Category	Risk
RT-131-ND-068	Uncertainty	Copper Cost Fluctuations
RT-131-ND-070	Uncertainty	Steel Cost Fluctuations
RT-131-ND-072	Risk	Cable Noise Issues
RT-131-ND-074	Opportunity	SiPM Cost Fluctuations

Proposed Key Performance Parameters

Near Detector	Threshold KPP	Objective KPP
Near Detector System (WBS 131.02.03)	1) Deliver a LArTPC plus muon spectrometer with an average area density between LAr active volume and TMS active volume shown by calculations to be ≤ 150 g/cm^2 over 75% of the aperture (metal wall option for cryostat).	1) Deliver a LArTPC plus muon spectrometer with an average area density between LAr active volume and TMS active volume shown by calculations to be ≤ 100 g/cm^2 over 90% of the aperture (composite wall option for cryostat). 2) Deliver a muon spectrometer with performance verified by simulation of 98% muon charge separation for fiducialized muons in momentum range 0.5-5 GeV/c and muon energy resolution of 6% for fiducialized muons up to 4 GeV/c momentum.
TMS (WBS 131.02.03.04)	Fabricate components capable of detecting muons in a 16 m^2 area with at least 75% of the readout channels verified by component testing to be fully functional	Fabricate components capable of detecting muons in a 20 m^2 area with at least 98% of the readout channels verified by component testing to be fully functional.