Temporary Muon Spectrometer

Tom LeCompte, L2 for TMS

LBNF16-17 February 2021

Who I Am

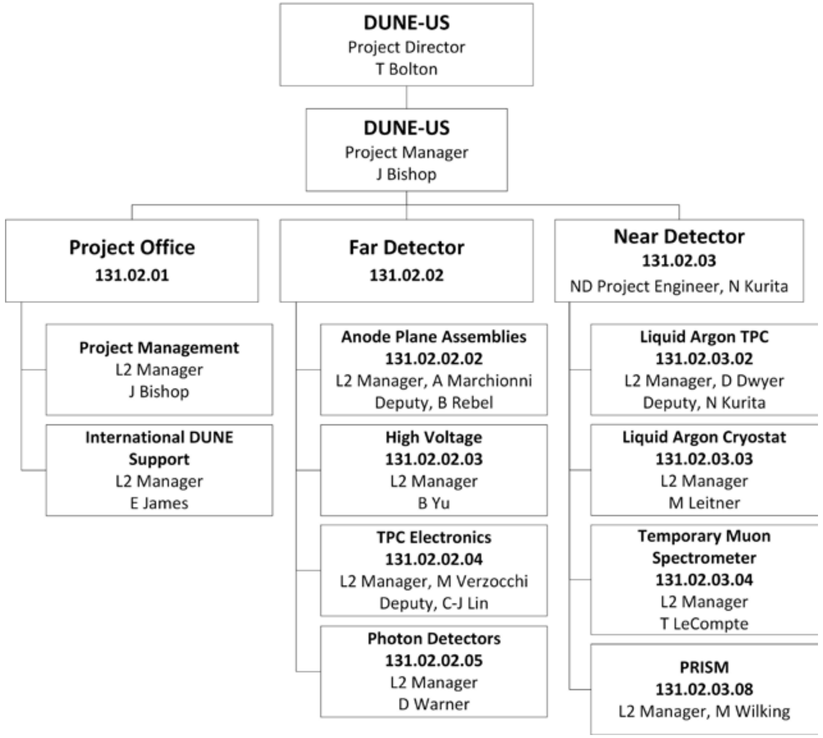
- Member of DUNE since June 5th
- Level 2 for Muon Spectrometer and
  Technical Lead for the Multi-Purpose Detector pre-Consortium.
  - In place since this became part of the project at the end of April
- Experience Includes
  - FNAL E-705 (@Proton West), CDF, STAR (BNL), ATLAS (CERN) and CTEQ
  - Physics Coordinator of ATLAS (first one with beam) and STAR
  - CDF Run II Upgrade Project Level 2 for muons
  - (Re-) Designed STAR's EM Calorimeter
  - Two years at DOE in the Washington DC area

Outline

- TMS Overview
- Schedule Updates (“What’s New”)
- Principles of Operation
- Magnet and Magnetics
- Energy Measurements
- Electronics Update
- Stereo Tracking
- QA/QC and Spares
- Installation
- Prototyping
- Summary

Your comments are always valued and appreciated. I have identified some areas throughout the talk with a gold star where your advice would be especially helpful to me.

Who We Are



DUNE-US
Project Director
T Bolton

DUNE-US
Project Manager
J Bishop

Project Office
131.02.01

Project Management
L2 Manager
J Bishop

International DUNE Support
L2 Manager
E James

Far Detector
131.02.02

Anode Plane Assemblies
131.02.02.02
L2 Manager, A Marchionni
Deputy, B Rebel

High Voltage
131.02.02.03
L2 Manager
B Yu

TPC Electronics
131.02.02.04
L2 Manager, M Verzocchi
Deputy, C-J Lin

Photon Detectors
131.02.02.05
L2 Manager
D Warner

Near Detector
131.02.03
ND Project Engineer, N Kurita

Liquid Argon TPC
131.02.03.02
L2 Manager, D Dwyer
Deputy, N Kurita

Liquid Argon Cryostat
131.02.03.03
L2 Manager
M Leitner

Temporary Muon Spectrometer
131.02.03.04
L2 Manager
T LeCompte

PRISM
131.02.03.08
L2 Manager, M Wilking

This talk

We intend a university-lab partnership model modeled on MINOS

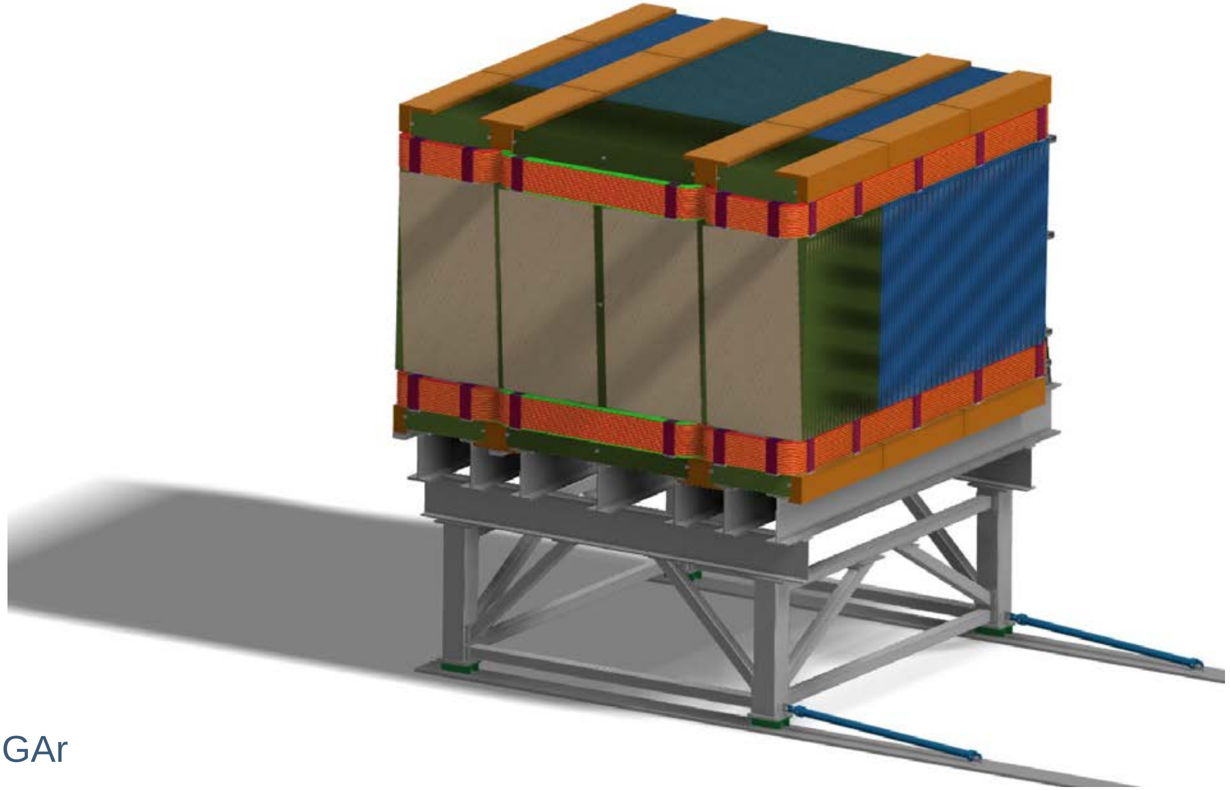
Interested institutions

Subproject engineer is Vic Guarino (Argonne)

- Level 3 managers are Hugh Gallagher (Tufts) and Mat Muether (Wichita State)
- During construction:
  - Infrastructure, steel and magnets
  - Electronics
  - Construction sites A, B and C

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
  - Steel thickness 15 mm (front 40 layers) or 40 mm (back 60 layers)
- Entirely DUNE-US scope
- Sits between ND-LAr and SAND
- Designed to support early physics
  - Measures muons – is not capable of the low energy program of ND-GAr
  - Intended to operate up until ND-GAr is delivered
  - Requires some flexibility on our part as the international situation evolves
  - Nevertheless, this is a device sufficient for initial physics we can build for a known cost and schedule sufficient for initial physics.



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

Based on well-established technologies – intended to be very low-risk by design

Why A TMS?

- DUNE’s long-term intent is to build the detector described in the CDR, including a high pressure gas TPC downstream of the LAr TPC (ND-GAr) 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 that 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?”

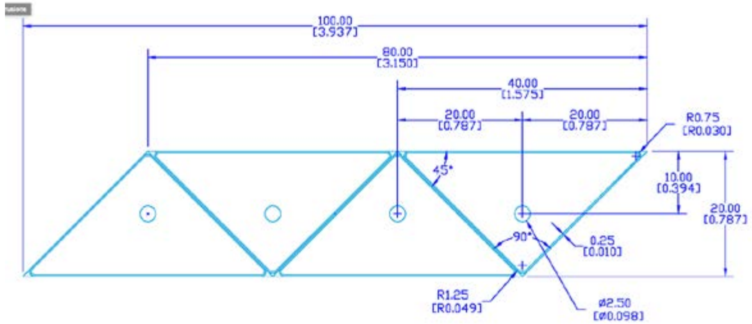
- What’s New?
- We have a go/no-go date: mid-2026
  - This has us waiting 782 days from a technically limited schedule to start
  - We will of course monitor how this data is influenced by various developments
  - Getting this date late by 50% is more damaging to DUNE than getting the cost wrong by 50% (although both are bad)
- TMS is the baseline – the path we are on. This date is the last possible date to change this.

ND-GAr “Lite”

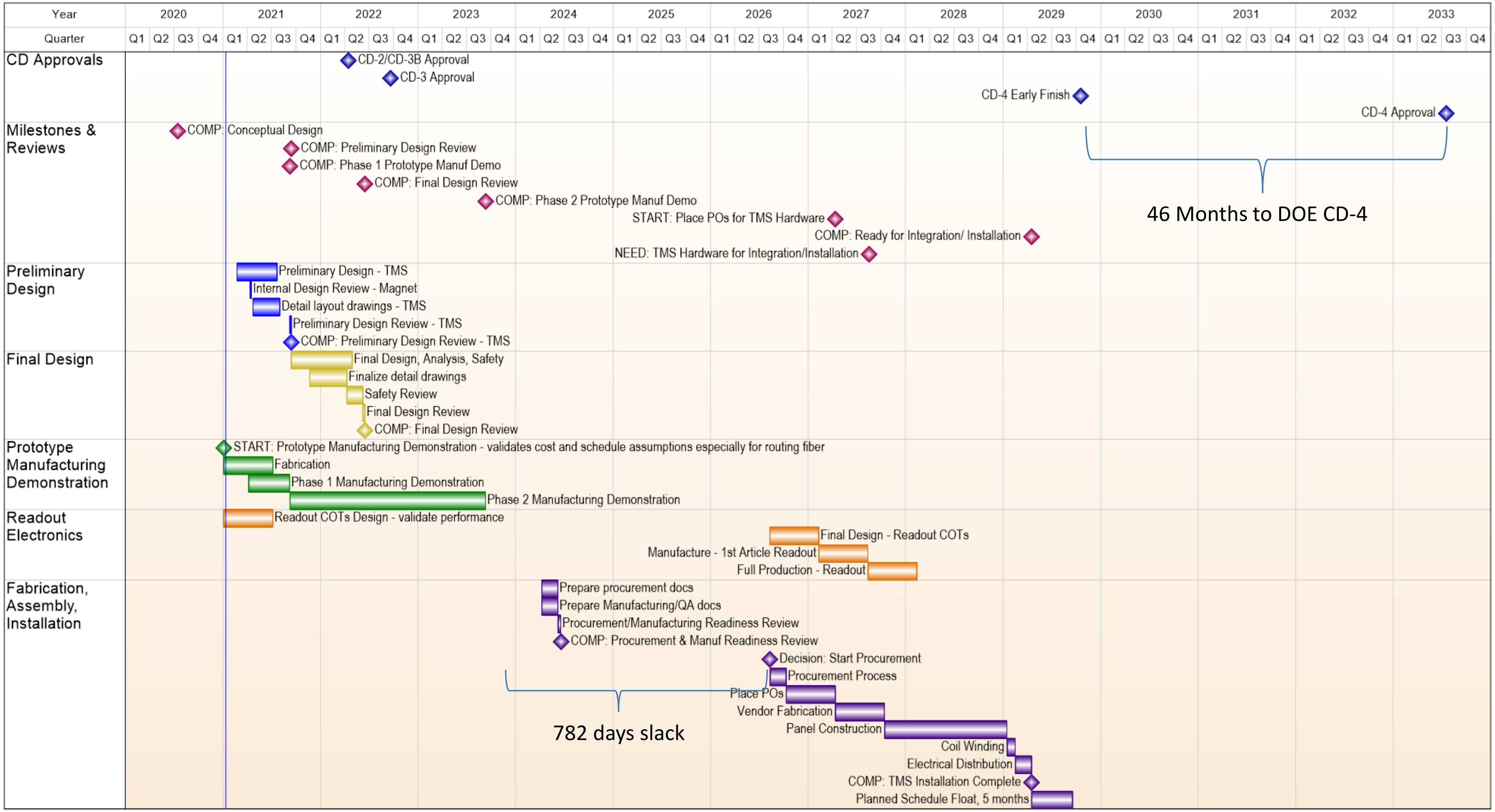
- If ND-GAr will arrive in time, we won’t build an iron range stack. Why would we want to?

- What if we only had the resources for the solenoid?
  - We would build that, as opposed to a range stack, along with a MINERvA-like scintillator tracker
  - The better performance is not the decision driver; it’s that it leaves us better positioned for the full ND-GAr when it happens
    - Chris Marshall will discuss the performance implications

- We need to accurately determine the time to build the muon spectrometer in order to know the latest possible decision date
  - We don’t want to lock ourselves into a less-capable design by doing this too early
  - We don’t want to have an incomplete detector by doing this too late



More Detailed Schedule



46 Months to DOE CD-4

782 days slack

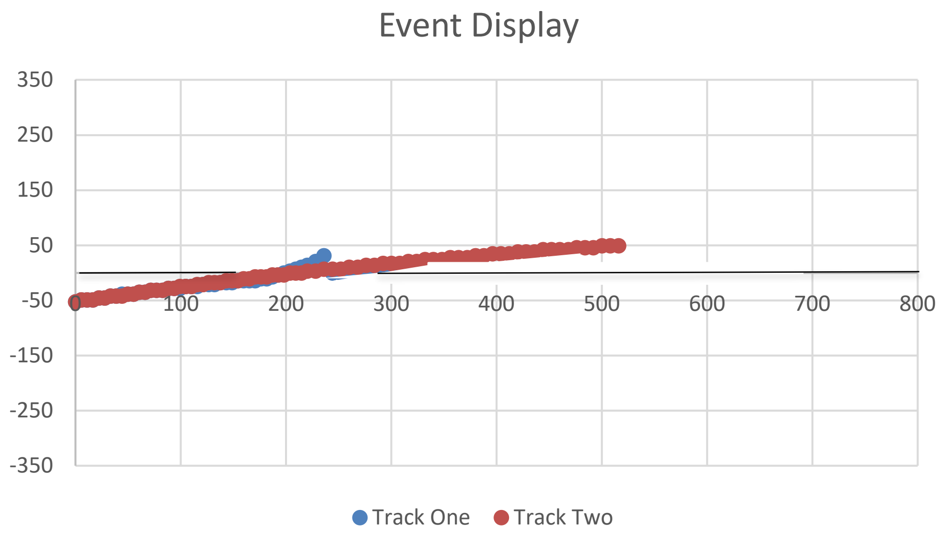
Baselining Decisions

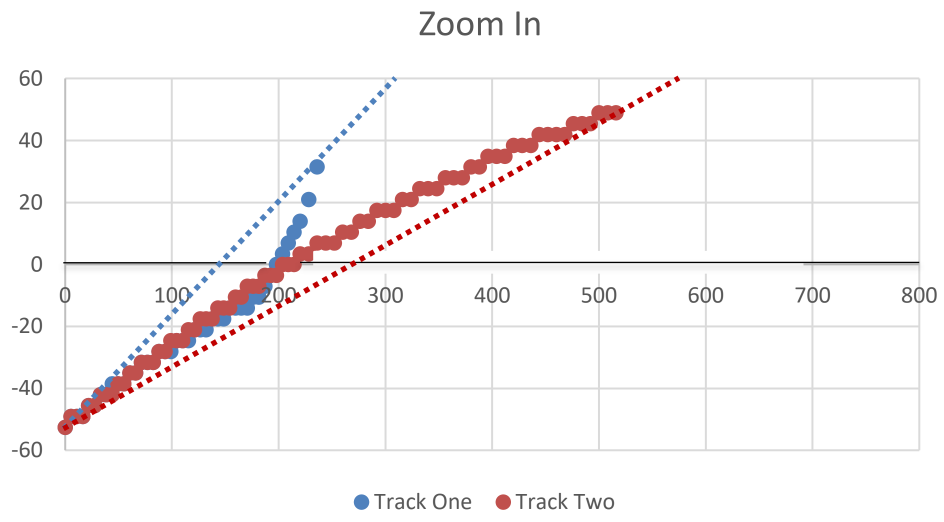
- We’ve made a number of decisions that may not be optimal so baselining can go forward.

- We have written the alternatives for 11 of them down along with what it would take to change our minds:

- Example: *Change WLS Fiber Diameter*
  - *Description: Change the WLS fiber diameter from the present 1.4 mm to a different radius. Other common radii are 1.5 mm, 1.2 mm, 1.0 mm and 0.8 mm.*
  - *Intended benefits: Reduced cost (smaller), improved performance by increased light (larger)*
  - *Other changes: may have implications for groove or hole co-extrusions. Affects all the downstream optics.*
  - *What would change our mind: A design showing a smaller diameter would work and be a net cost savings, or alternatively that a larger diameter would provide physics impact (beyond just “more light”) commensurate with the cost increase. This physics impact is probably demonstrated via simulations.*

TMS “Event Displays”

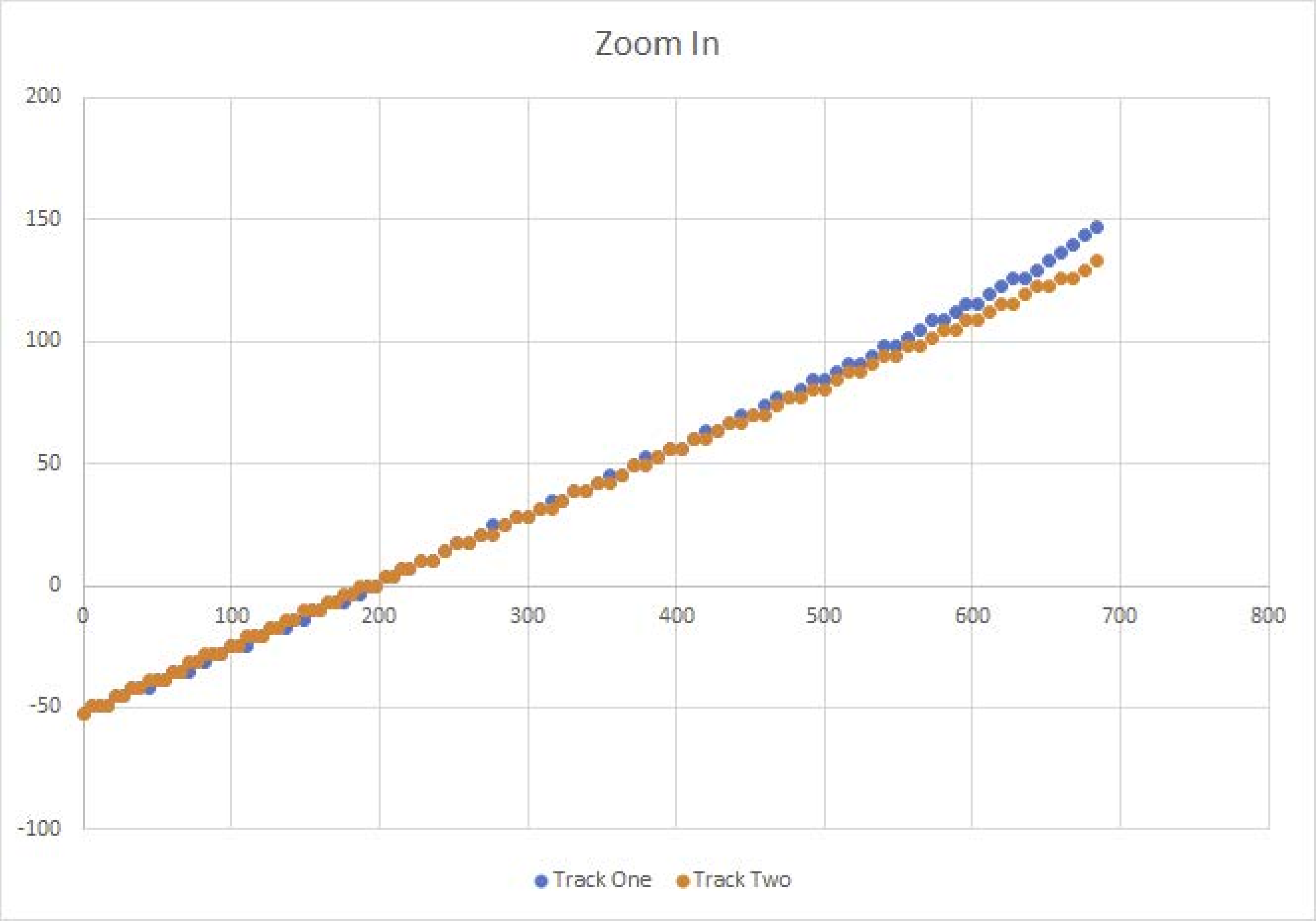




- Blue is a 1 GeV μ^+, Red is a 3 GeV μ^-.
- Range is visibly different
  - A factor 3 in material, which is not a factor of 3 in distance (steel is thicker in back)
- Sagittae are in opposite directions (good)
  - Their magnitude is not proportional to 1/p (more in two slides)

Caveat: These are not actual event displays. These are Excel-level, but incorporate magnetic bend, multiple Coulomb scattering, a Landau-like energy loss, and counter granularity. Geometry is purely vertical. If it helps, think of these as “artists conceptions”.

TMS At High Momentum



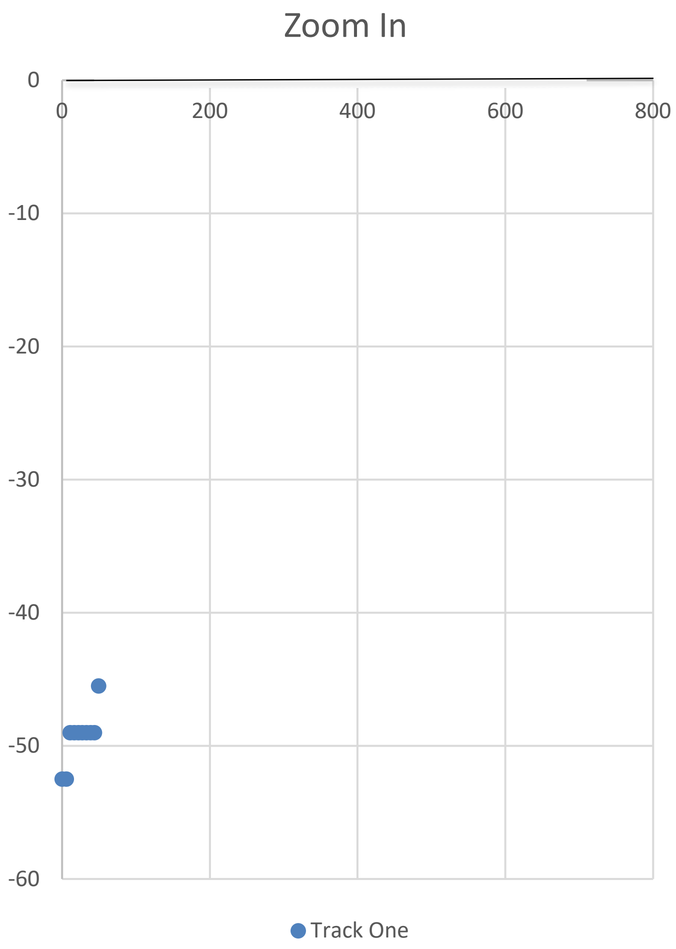
- Blue is a 5 GeV μ^+, Orange is a very high momentum μ.
- At 5 GeV, we have pretty good charge ID.
- Note that the track starts curving late – once p < 1 GeV or so.
  - One could say TMS measures the charge of ~1 GeV muons. The more energetic the muon is initially, the deeper in the stack this happens

TMS Spectrometry

- We measure momentum via range, not curviture

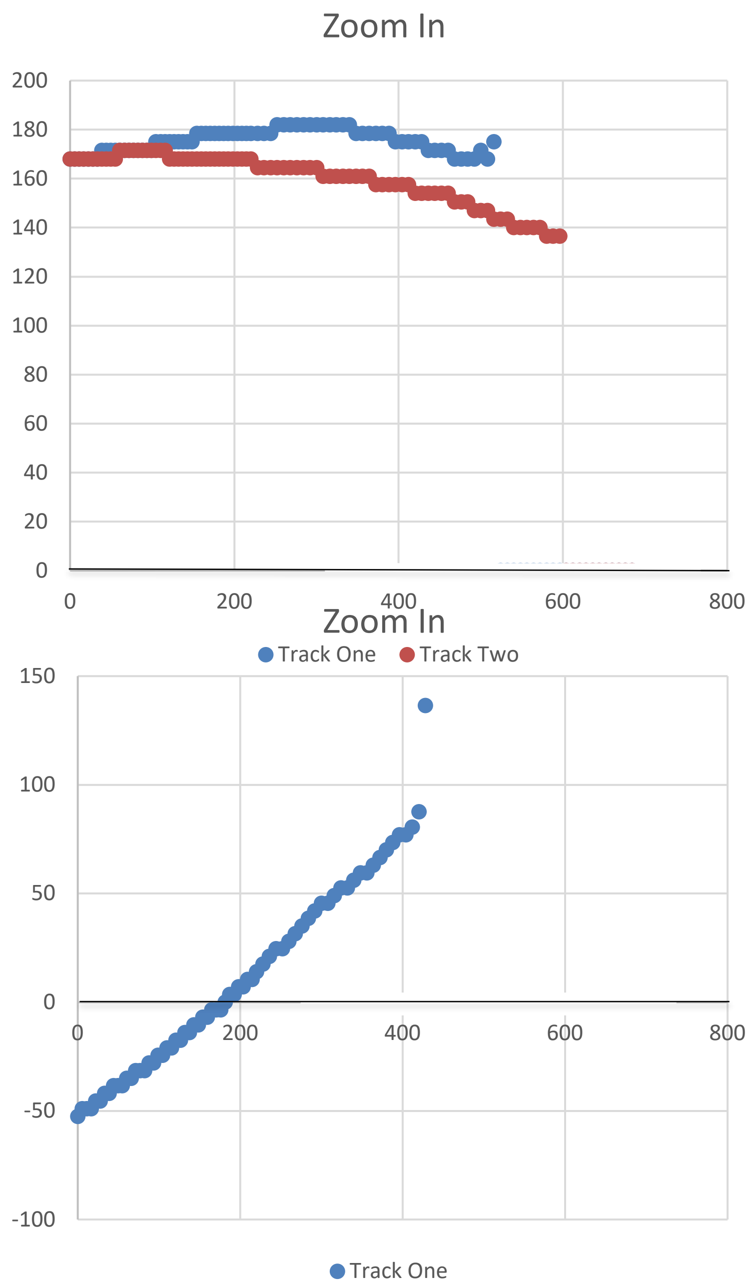
- Sagitta magnitude is roughly constant with p
  - 1/p bend per layer, but the number of layers is proportional to p – near cancellation
  - Where in the stack the sagitta occurs does in fact measure p

- Charge identification gets *better* at high p.
  - There are simply more hits
  - Bend goes as N, multiple scattering goes as √N.



A 200 MeV muon. It's charge is not discernable.

Some Oddball Events



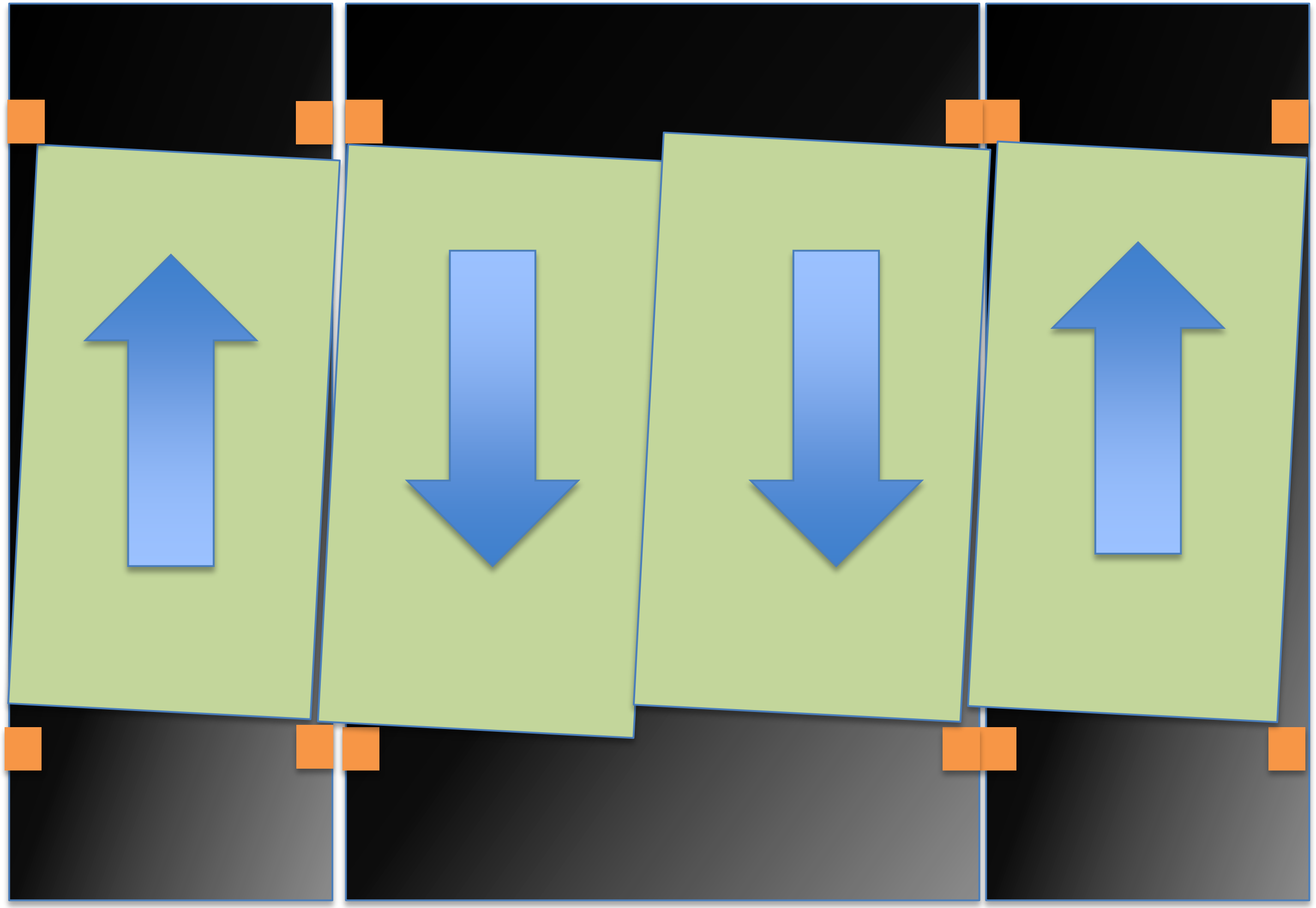
- The blue track is a “swimmer”. It crosses the field reversal boundary (twice) which reverses its bend.
- The charge is still distinguishable from the oppositely charged red track, which has the wrong charge to swim.
- The last hit is significantly displaced from the rest of the track.
  - Almost certainly happens more in the model than in real life, but at the end of the track the muon has low energy and we all know low energy particles do weird things.

Magnet I

Why do we do it this way? It keeps the field in the liquid argon low. The field is returned through the counter-coils to limit fringing.

(Dipole on the inside, sextupole on the outside)

We've been drawing the field like this →



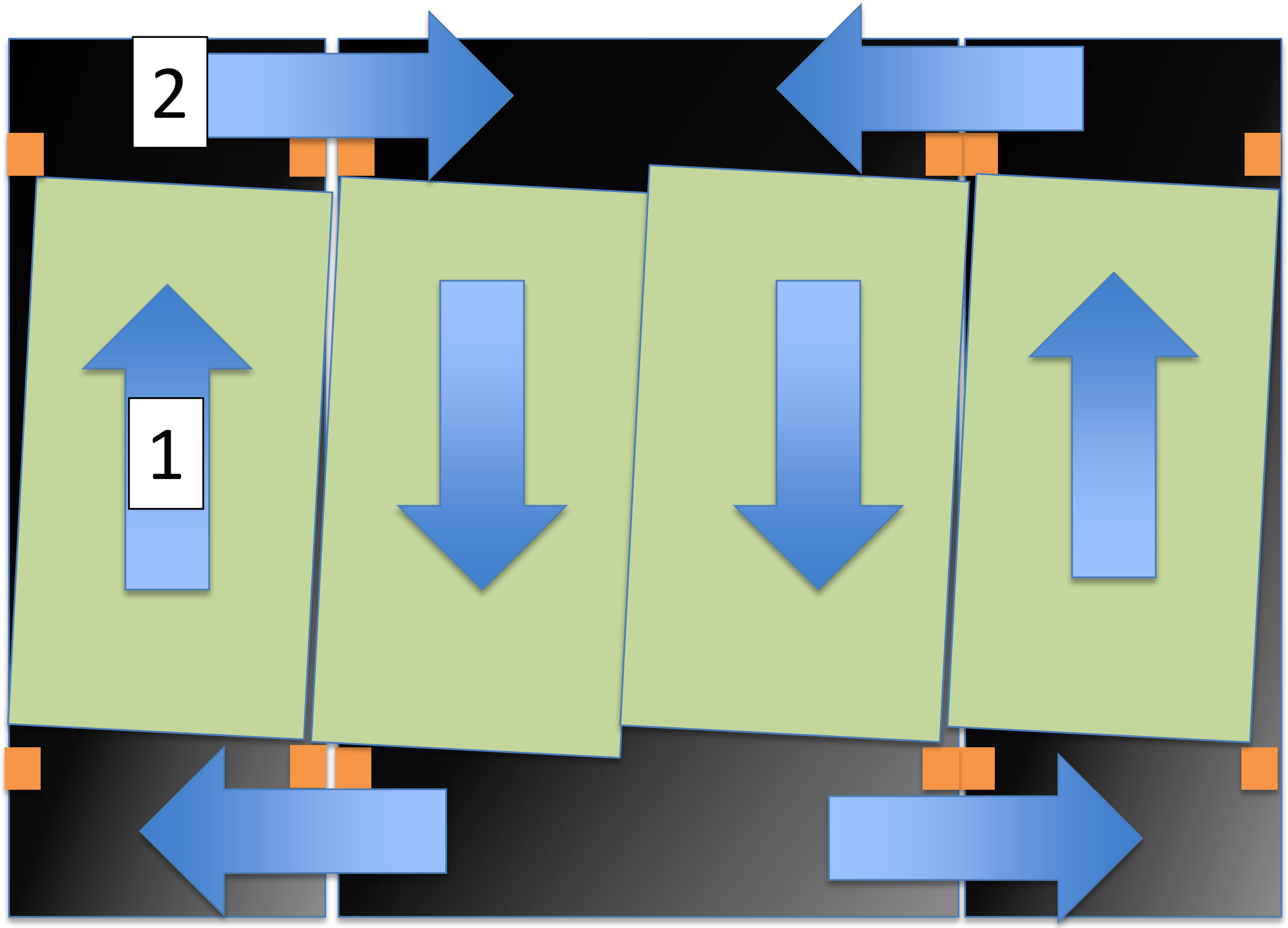
Magnet II

- …but this is more complete
- There is a relationship between the field and the geometry of regions 1 & 2:

$$B_1 = \frac{h_2}{w_1} B_2$$

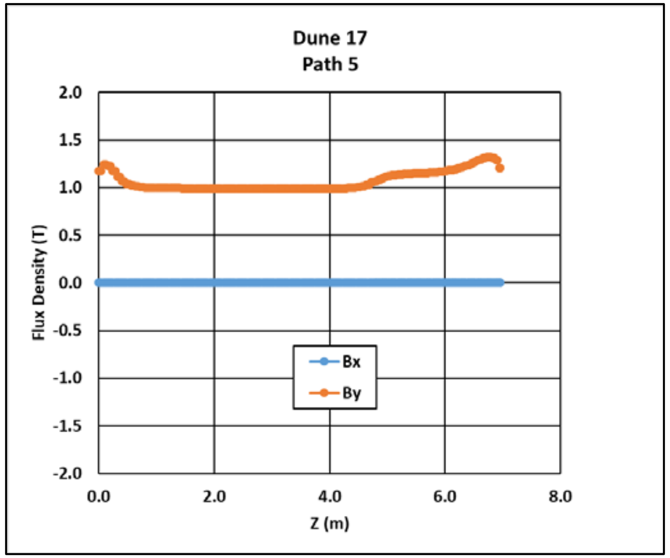
$$(\nabla \cdot B = 0)$$

- Saturating the iron in Region 2 gives a magnetic field of 1.0-1.1 T in Region 1 (where we measure muons)



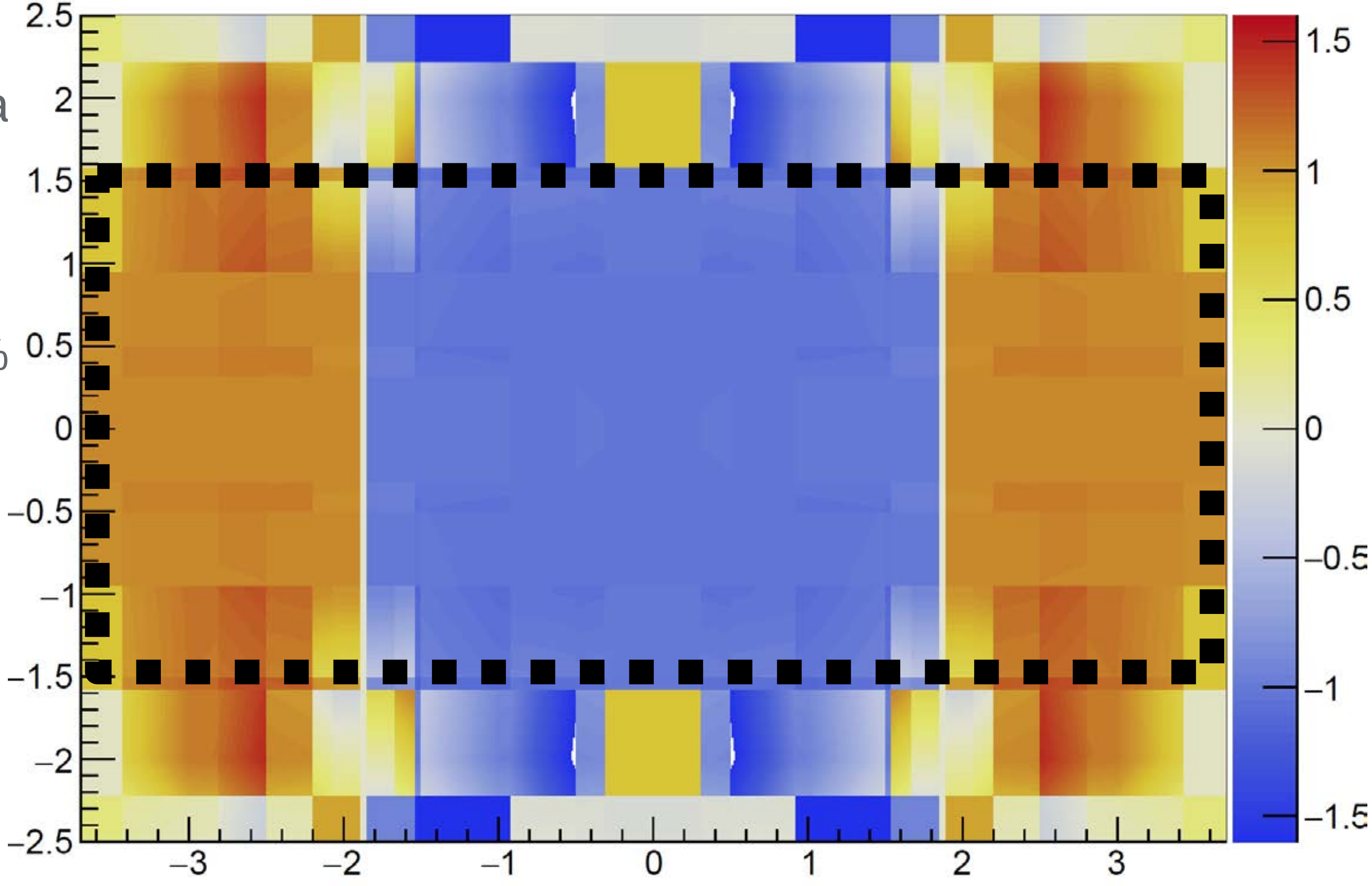
Magnetic Field

- The finalized steel geometry produces a lower B but (on average) higher B_y than our previous design.
  - The field is more uniform (less tilt). Standard deviation in the x-y direction is 6%



B vs. z from ANSYS
at single (x,y)

Average B_y through the stack



x-y (front) view

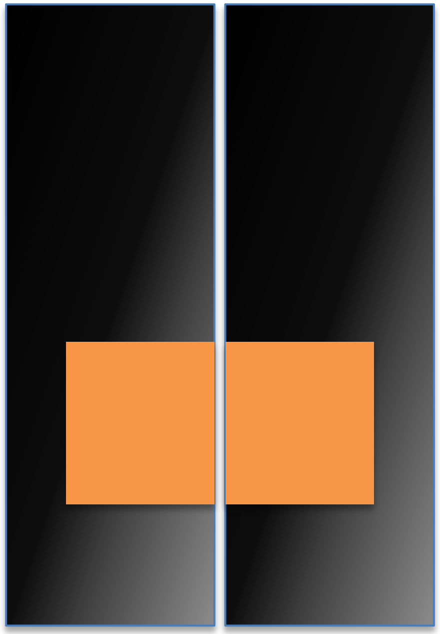
Black dashed line indicates active area

Magnetic Field Implications

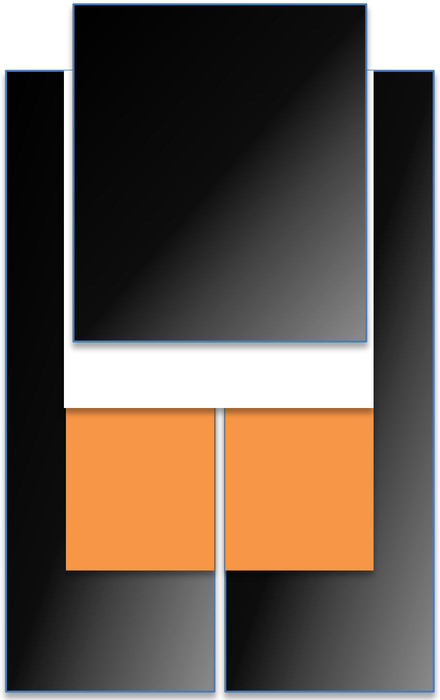
- All that top (& bottom) steel doesn't technically need to be there.
  - $B_1 = \frac{h_2}{w_1} B_2$ just means that we need a lot of air to compensate
  - But if we did this, we would introduce extreme sensitivity to the exact steel geometry
  - The height (about two feet) is chosen to balance field strength with steel weight/cost and more importantly, steel flatness.

- How the coils are cooled matters
  - Increasing the coil notch size increases the area of Region 1 and decreases it in Region 2: lowers the useful field
  - Water cooling requires space for water; air cooling requires space for air
  - In general, water cooling allows 4-5x the current per unit of copper

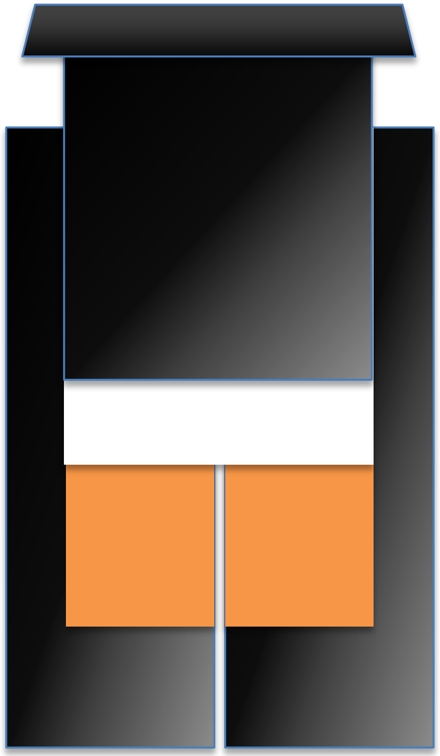
And About That Coil Notch…



Installing coils
this way is really
hard.



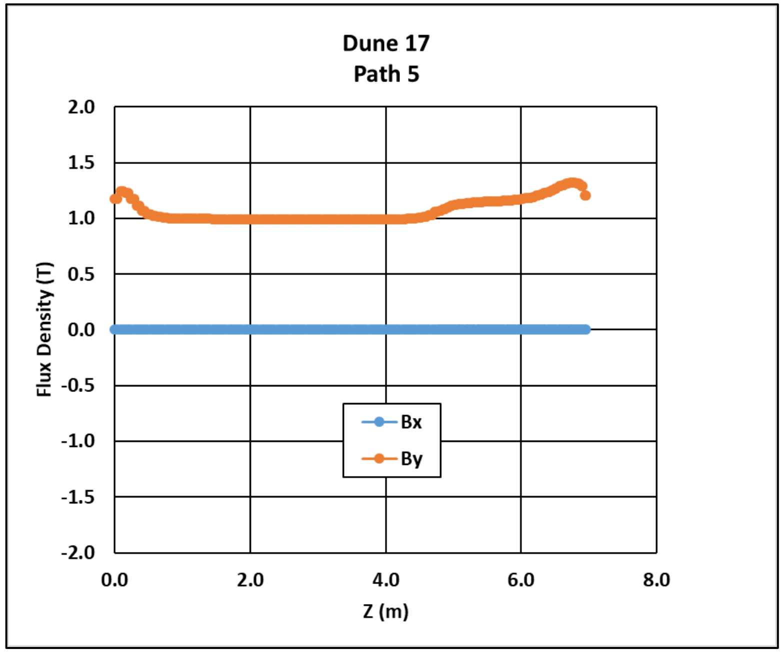
Plan is to cut notches in
the steel and fill the notch
with a long beam after
installing the coils.



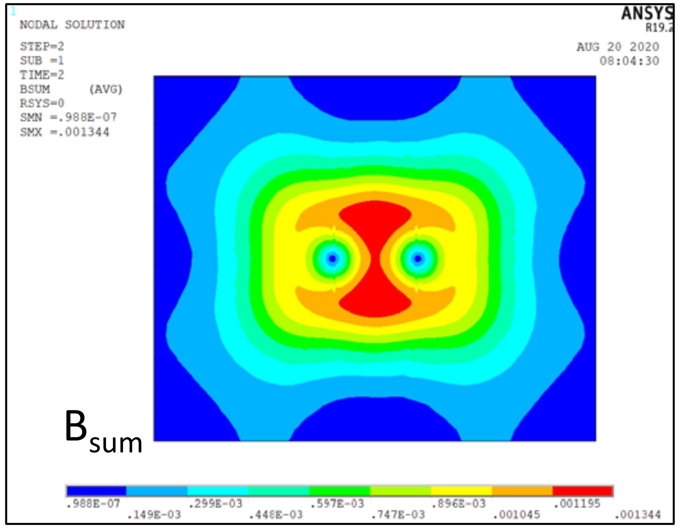
Because air gaps are
inevitable, the beam
needs a “cap” to contain
the field lines

Magnetic Field In z

- The magnetic field is slightly larger in the front than the back of the stack. This is good – we need the field in the front more than in the back.
  - Charge assignment is hardest for low energy muons
  - Every muon goes through the front. Not so for the back.



- The magnetic field in the liquid argon is very low indeed (< 15 gauss in the model)
  - Probably lower than it has to be
  - Probably driven by manufacturing tolerances more than the design (~100 guass)

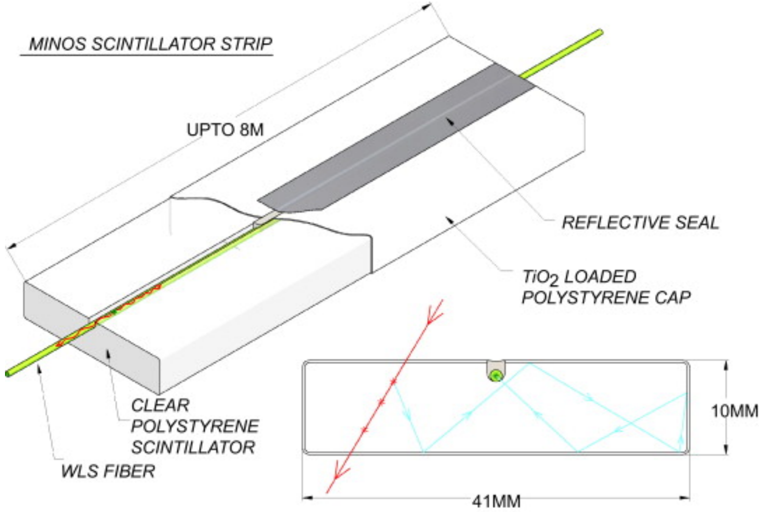


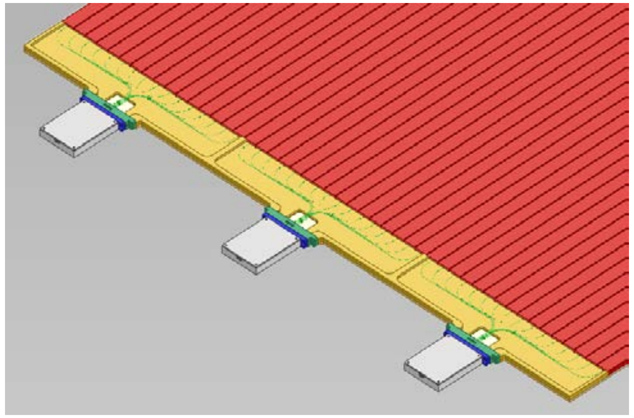
Magnetic Field Final Comment

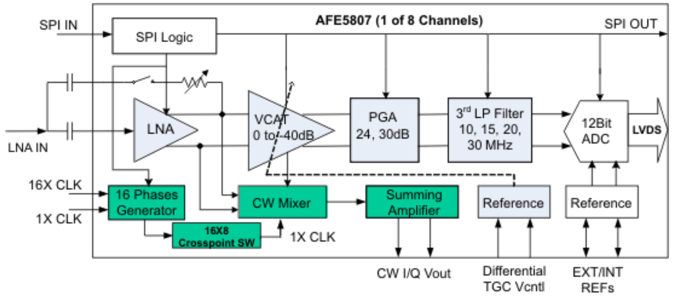
- This magnet is unique.
- I will be more comfortable once it’s gone through a review (I am organizing that)
  - Wide panel of experts from FNAL, ANL APS, JLab, etc.
    - In some ways it looks more like a light source undulator than a traditional analysis magnet
  - Before June would be better than after

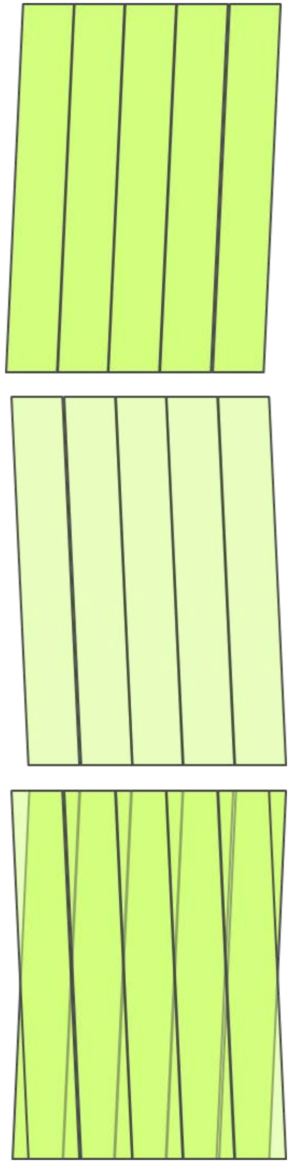
Detector Design Overview

- 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
  - Single bucket (under 19 ns) time resolution



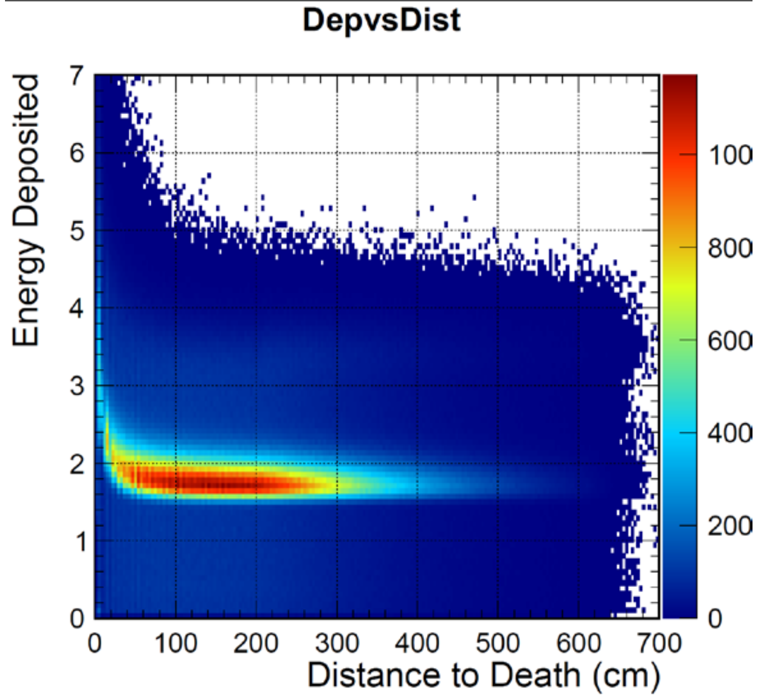


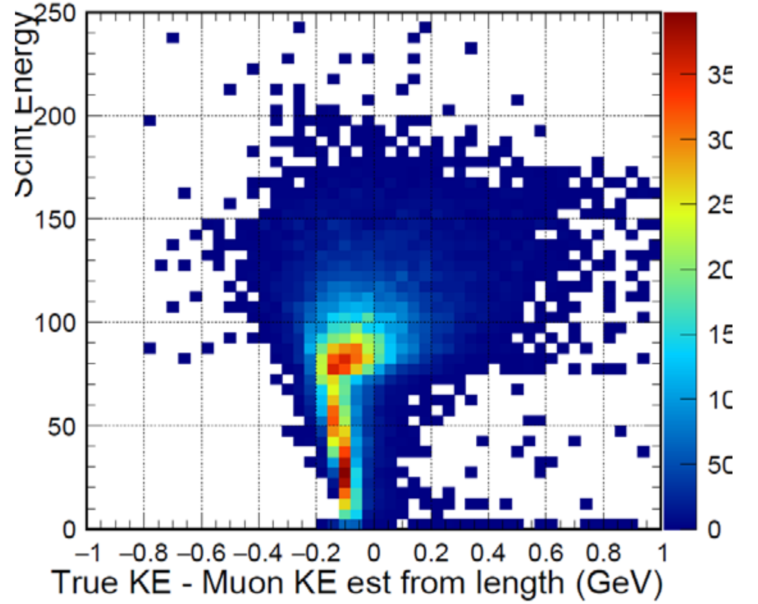




The Story Of Energy I

- Originally, we intended a yes/no signal – measuring only position
- The front-end chip includes a 12-bit ADC “for free” – why not use it?
- What for?
  - As a calorimeter, this device is probably so-so: ~15%/√E. However, preliminary Geant studies suggest it is correlated (but not simply) with energy via track length. Might reduce tails.
  - We can see the $1/\beta^2$ term in the Bethe-Bloch formula over the last few hits
    - Might improve track fit near the stopping point
  - In the ~10% of time the muon stops in the scintillator, we can see the Bragg peak
- How good does this have to be?





The Story Of Energy II

- We expect a number of photoelectrons per m.i.p. in the low or mid 20’s.
  - This is from scaling from other experiments, and not our own simulations. Nevertheless, it’s not 10 and it’s not 50.

- This assumes we use our baseline 1.4 mm WLS fiber
  - Why 1.4? Mu2e has a recent purchase, and because of our costing rules on contingency, it will appear cheaper than 1.2mm.

- If we just wanted position, we could go to thinner fiber and/or make other cost-saving choices.

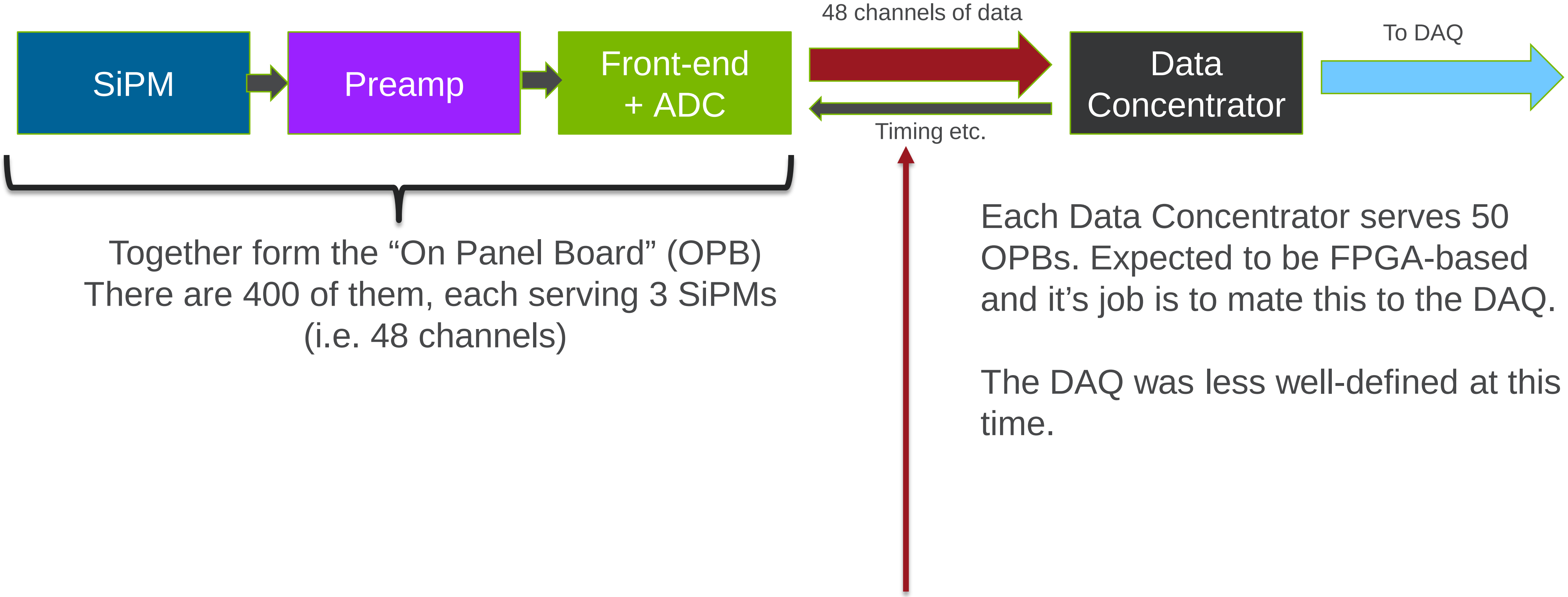
- My opinion: energy will not substantially improve our momentum resolution. It may, however, help us reduce tails and identify problematic tracks. But **we want to understand this better**.

Electronics Strategy

- 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 had an EE and a designer spend one FTE-week creating a Bill Of Materials-level estimate, after which they stopped
- We learned a lot from this exercise, and I would to repeat it every year.
  - It has been particularly helpful with mechanical integration
    - For example, envelopes

Electronics Changes

- Our original design looked something like this



Together form the “On Panel Board” (OPB)
There are 400 of them, each serving 3 SiPMs
(i.e. 48 channels)

Each Data Concentrator serves 50 OPBs. Expected to be FPGA-based and it’s job is to mate this to the DAQ.

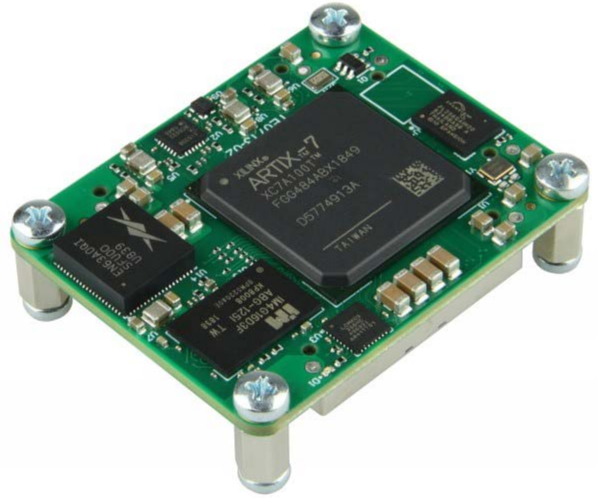
The DAQ was less well-defined at this time.

This data run is a few (2-3) meters

Electronics – Back From The Engineers

- The single FPGA concept was eliminated
  - The Data Concentrator FPGAs needed to be big to handle all the inputs
  - But there wasn't much work for the FPGA to do, so a lot of the chip was unused → uneconomical

- The new concept is to split this into two parts
  - A Xilinx Artix-7 FPGA on the Panel
    - Does zero suppression on the panel
    - Panel communications becomes serial over DisplayPort cables rather than parallel
  - A Xilinx Zynq-7 FPGA on the Data Concentrator
    - FPGA with a built in ARM Cortex-A9 CPU
      - This chip is powerful enough to run Linux



Electronics – Back From The Engineers Part II

- Not everyone was enthusiastic about the AFE5807 front-end chip, but everyone thought it would work
  - Single-ended input with no common mode rejection – potential for noise
  - We should keep this in mind when the time comes
  - Also, when the time comes there will likely be a version that can run at 106 MHz (Main Injector frequency is 53 MHz)

- The estimate did not specify what goes on which boards, but it appears that the low voltage is generated at the DCs and sent to the OPBs. The DisplayPort cable can't handle this many different voltages
  - A separate cable is needed, probably with DIN or DSUB connectors (never use the same connector twice on the same unit!)

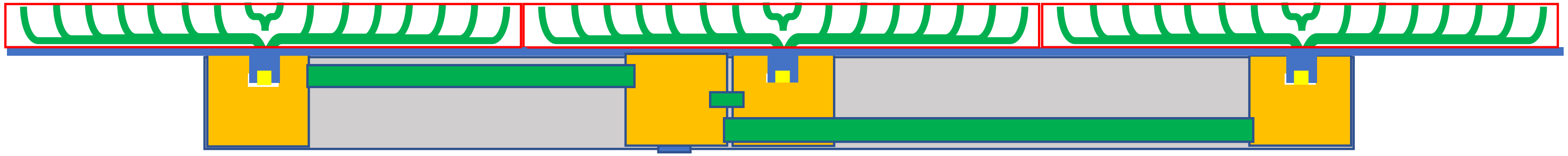
DisplayPort

DIN

D-SUB

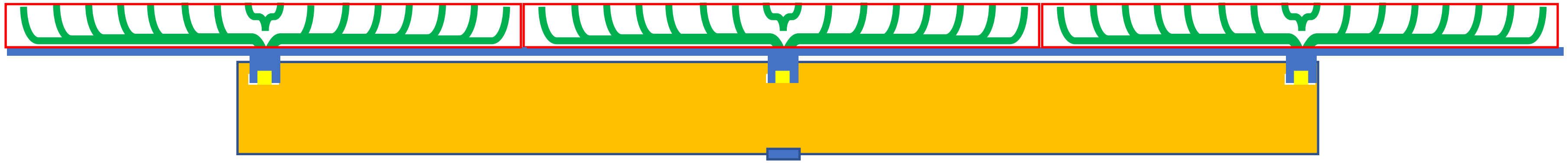
These are in the dollar to few dollar range.
These are commodities – can easily get from Newark, Mouser, DigiKey etc.

Electronics – Mechanical Interface

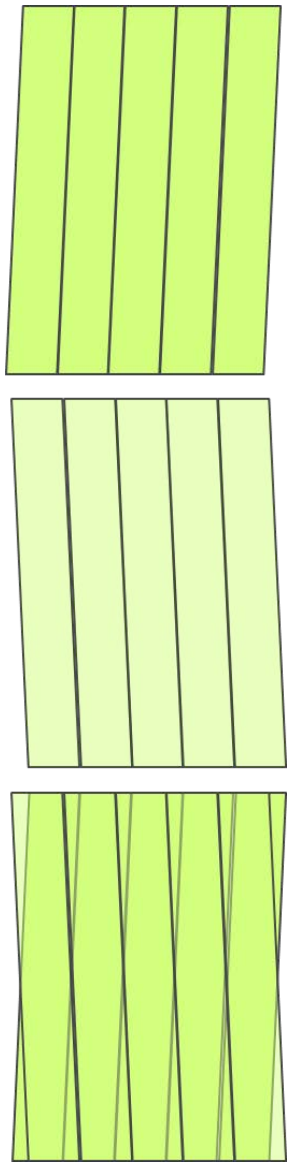


- Each SiPM now gets its own board in a light-tight box with two 8 channel front-end chips
- Signals (LVDS) collected via ribbon cables to a common board
- The whole thing sits inside covers – protection plus reduces light (box in a box)

- A single board is very expensive (33-36” > 24”) and requires *extreme* precision



Stereo



- The magnet has a vertical field and so a horizontal bend
- Most of the measurement is therefore in the x-direction
  - Granularity in x is ~3.5 cm
  - Resolution in y is σ ~ 45 cm for a $\pm 3^{o}$ tilt

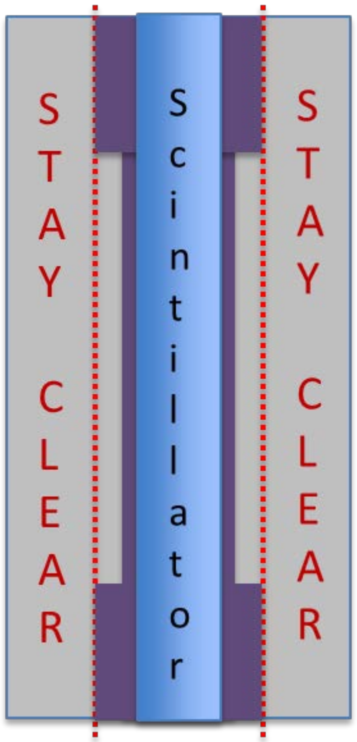
- Would dedicated x and y planes be better?
  - Reducing the number of x planes reduces our charge identification ability, especially at low momentum where this is hardest
  - It would improve the pattern recognition (stereo is weaker than orthogonal)
    - At low power, multiplicities are at their lowest and pattern recognition is easiest
    - Muons of interest have a LAr track which will be extrapolated to TMS
    - My opinion: I am less worried about pattern recognition and more concerned about distinguishing muons that exit out the top or bottom from ones that stop. Here we will rely on the LAr track and possibly the energy measurement at each hit.

SiPM Update

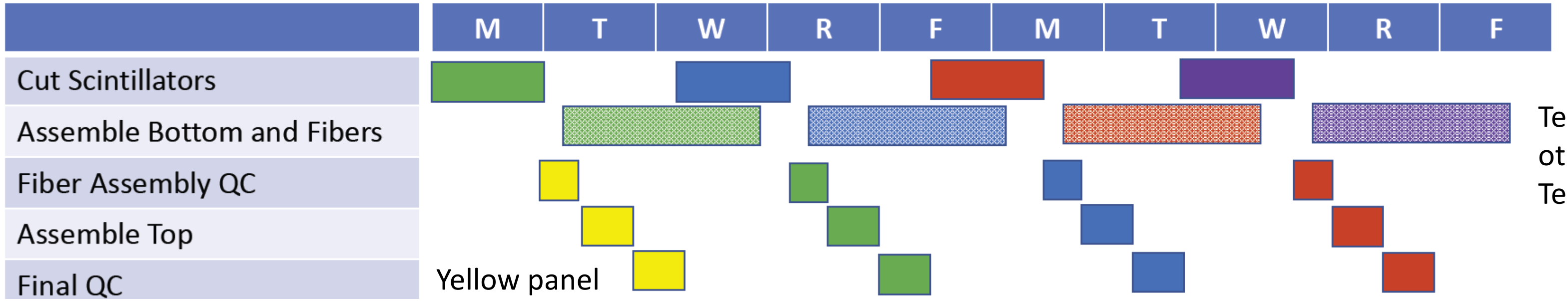
- We built the design around the 16 channel Hamamatsu S13361-2050AE-04
  - A 4x4 array of 2 mm x 2 mm elements
- This device is not in the present catalog (since ~January) although the 64-channel variant is
  - We didn’t expect this exact device to stay available forever, but we did expect there would be *some* 4x4 array of 2 mm x 2 mm SiPM available. (This was a failure of imagination on my part) There are a wide variety of 3 mm x 3 mm SiPMs, available including a 4x4 array.

- For now, we’re prototyping based on the 3 mm x3 mm 4x4 (S13361-3050AE-04)
  - A 13mm SiPM does not leave much room in a 20mm envelope.
- We are revisiting the question of individual vs. array SiPMs
  - Originally made this decision based on cost
  - It is unclear that the cost reduction is still substantial with the larger device
  - There are no savings if you can’t buy the part

QA/QC and Spares



- Most QA/QC is done using “un-costed scientific labor” (students & postdocs)
  - Steel flatness & thickness
    - Only acceptance testing in the plan – we could do more
      - If the steel is flatter than the spec, we would probably reduce the plate separation (and therefore density) in the front (upstream/east) of the detector and improve our charge i.d.
  - Detector Panel QA/QC
    - About half of Team Two’s time is spent in QC activities



Team One – other tasks are Team Two

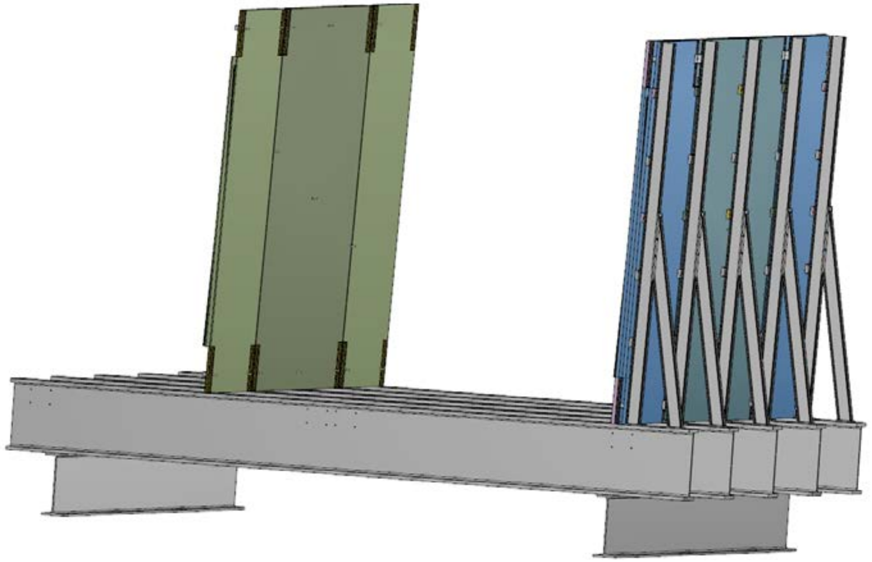
Yellow panel from previous week

Each color represents a module

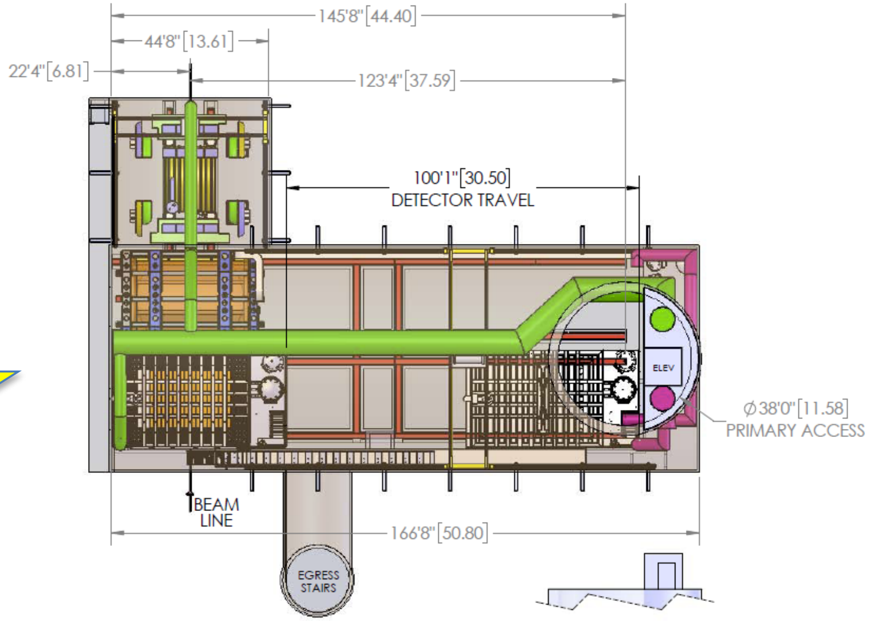
- We have 0% spare modules (and no LED flashers) in the plan
  - A consequence of cost-cutting

Installation

- First we build the supports (6-8 weeks)
- Then we build up the layers, back (west) to front
  - Three steel sheets + four panels per day
  - Run cosmic rays overnight before doing the next layer
- Then 4 weeks to install the six magnet coils



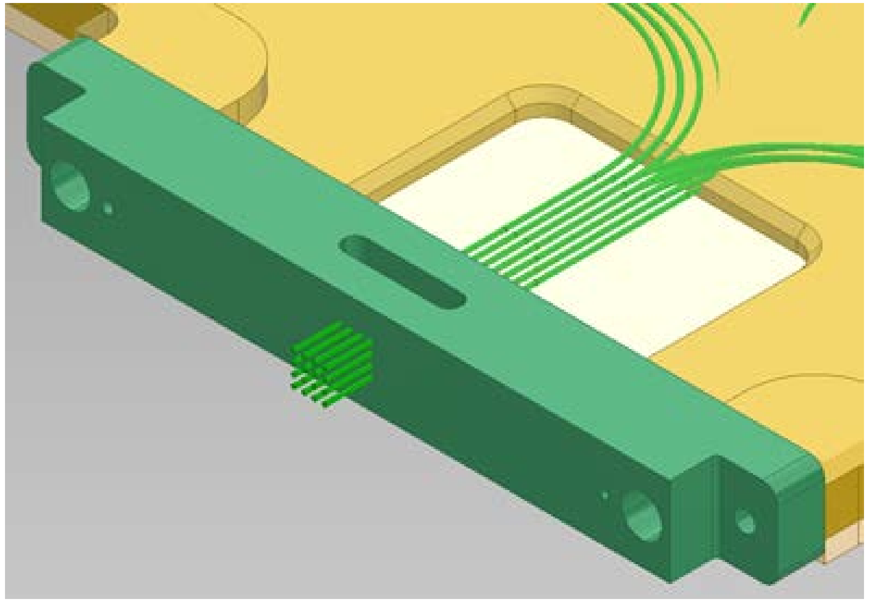
The schedule assumes there is no crane or shaft contention. This is likely not the case. This will move the need-by date and thus the go/no-go decision date earlier. Installation meetings have started to work this through.

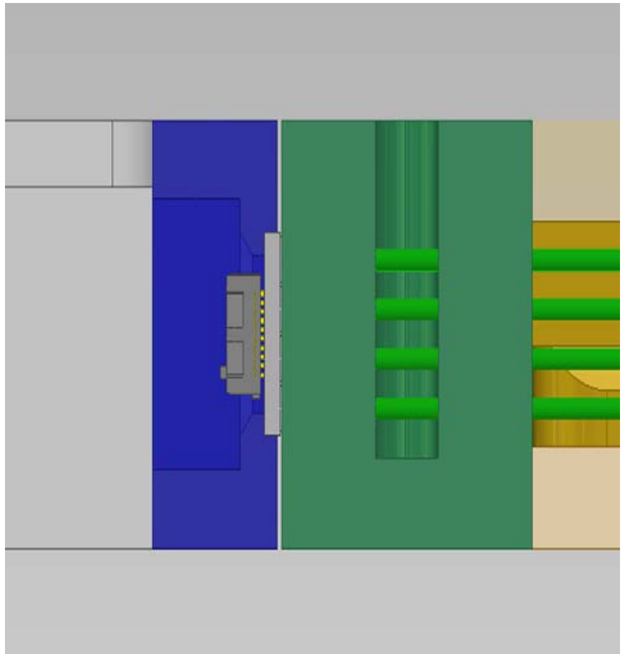


Prototype 1 (I)

We are starting by prototyping the fiber and optics separately from the scintillator. When we are satisfied with these pieces, we can combine with scintillator. (We don't have an infinite amount of scintillator)

- Purely Mechanical
  - Doesn't even use scintillator: mocks it up with clear fiber in a fixture
- Sixteen "channels" (one SiPM-array equivalent)
- Intended to:
  - Test fiber routing (yellow piece)
  - Test Fiber Guide Bar concept (green piece)
  - Test SiPM mounting concept (blue piece + leaf springs)
  - Refine our construction time estimates

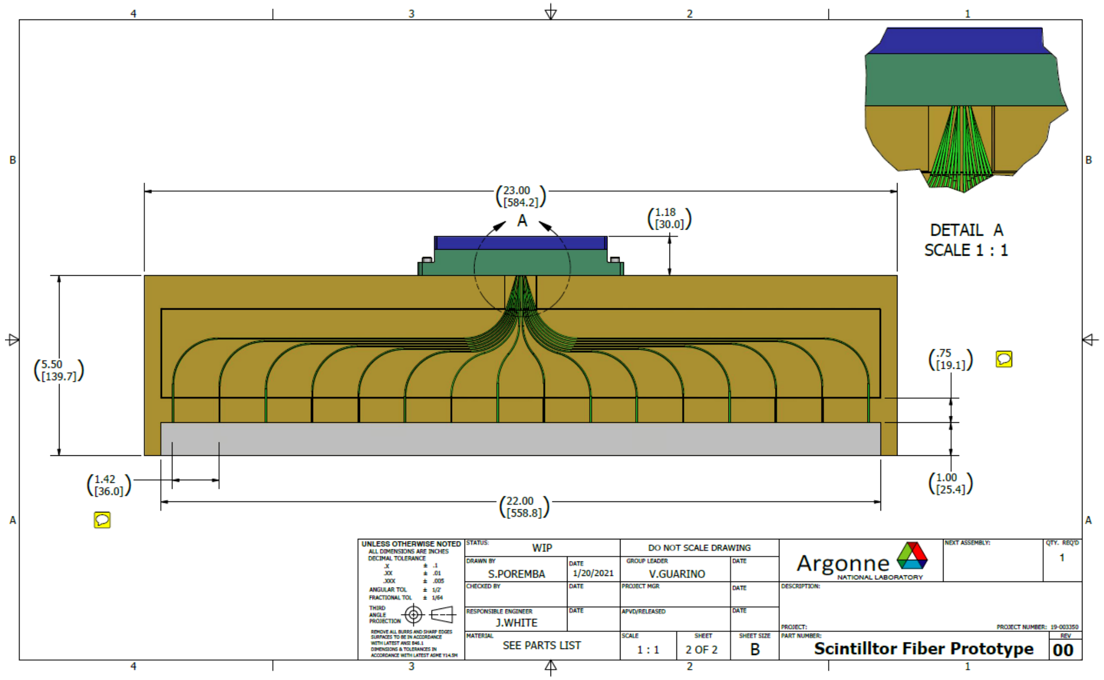




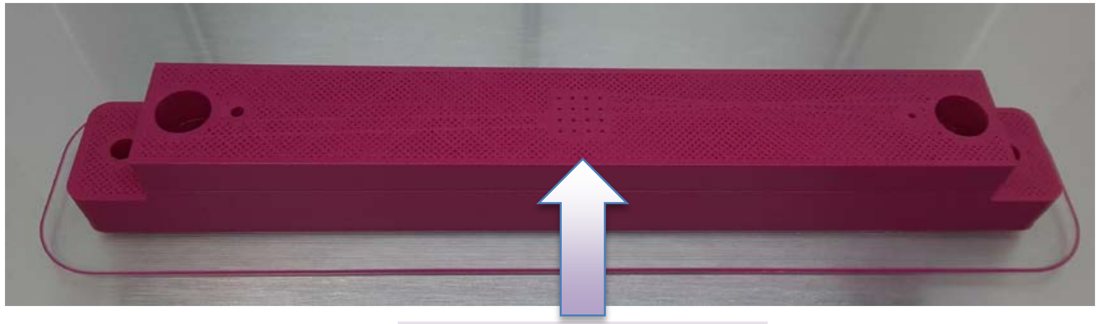
Prototype 1 (II)

- We’ve finally started (Many Covid delays)

- The 3-D printed fuchsia piece is green in the drawing. In real life we anticipate machined Delrin, but for fast prototyping, you can’t beat it.
  - Also 3-D printing lets us quickly test modifications. What if it were longer? Shorter? Taller? etc.



UNLESS OTHERWISE NOTED	STATUS:	DO NOT SCALE DRAWING		NEXT ASSEMBLY:	QTY. REQ'D
ALL DIMENSIONS ARE INCHES DECIMAL TOLERANCE .X ± .1 .XX ± .01 .XXX ± .005 ANGULAR TOL ± 1/2' FRACTIONAL TOL ± 1/64 THIRD ANGLE PROJECTION	WIP				1
	DRAWN BY S.POREMBA	DATE 1/20/2021	GROUP LEADER V.GUARINO	DATE	
	CHECKED BY	DATE	PROJECT MGR	DATE	DESCRIPTION:
	RESPONSIBLE ENGINEER J.WHITE	DATE	APVD/RELEASED	DATE	PROJECT: PROJECT NUMBER: 19-003350
REMOVE ALL BURRS AND SHARP EDGES SURFACES TO BE IN ACCORDANCE WITH LATEST ANSI B46.1 DIMENSIONS & TOLERANCES IN ACCORDANCE WITH LATEST ASME Y14.5M	MATERIAL SEE PARTS LIST	SCALE 1 : 1	SHEET 2 OF 2	SHEET SIZE B	PART NUMBER: Scintilltor Fiber Prototype REV 00



Holes for fibers

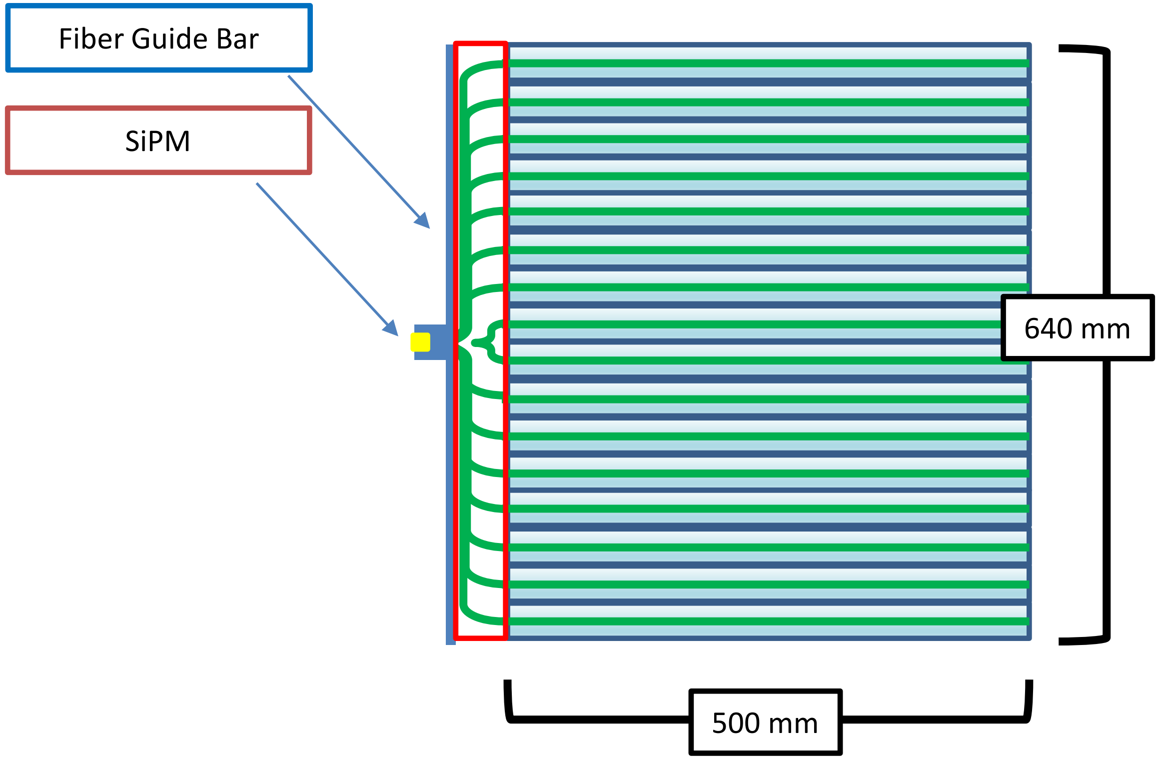
Prototype 2 & Beyond

- Prototype 2
  - A forty-eight “channel” (one panel) version of Prototype 1
  - Also purely mechanical and using fixtured clear fiber
  - Does Prototype 1 scale up?
  - Does the production time scale up?

- Future prototypes
  - Each prototype should set out to answer specific questions
  - We have a little 1.5mm WLS fiber in hand. The baseline uses 1.4 mm fiber.

Working Prototypes?

- We have the ability and the materials to build something like this.
  - 16 channels, 1/3 x 1/6 scale.
- Commercial readout exists for about $2000.
  - 20 Lemo outputs
    - 16 single channel amplified outputs
    - 4 Four-channel sums
- The 16 channels wouldn't necessarily need to be identical
  - E.g. glued vs. non-glued, groove vs. hole



Summary

- We continue to progress towards baselining
  - I won’t say there weren’t speedbumps, but these are of the normal pain-in-the-neck varieties, not showstoppers
  - We don’t expect showstoppers because we deliberately chose a mature technology

- Electronics design is much more mature

- Prototyping is off the ground

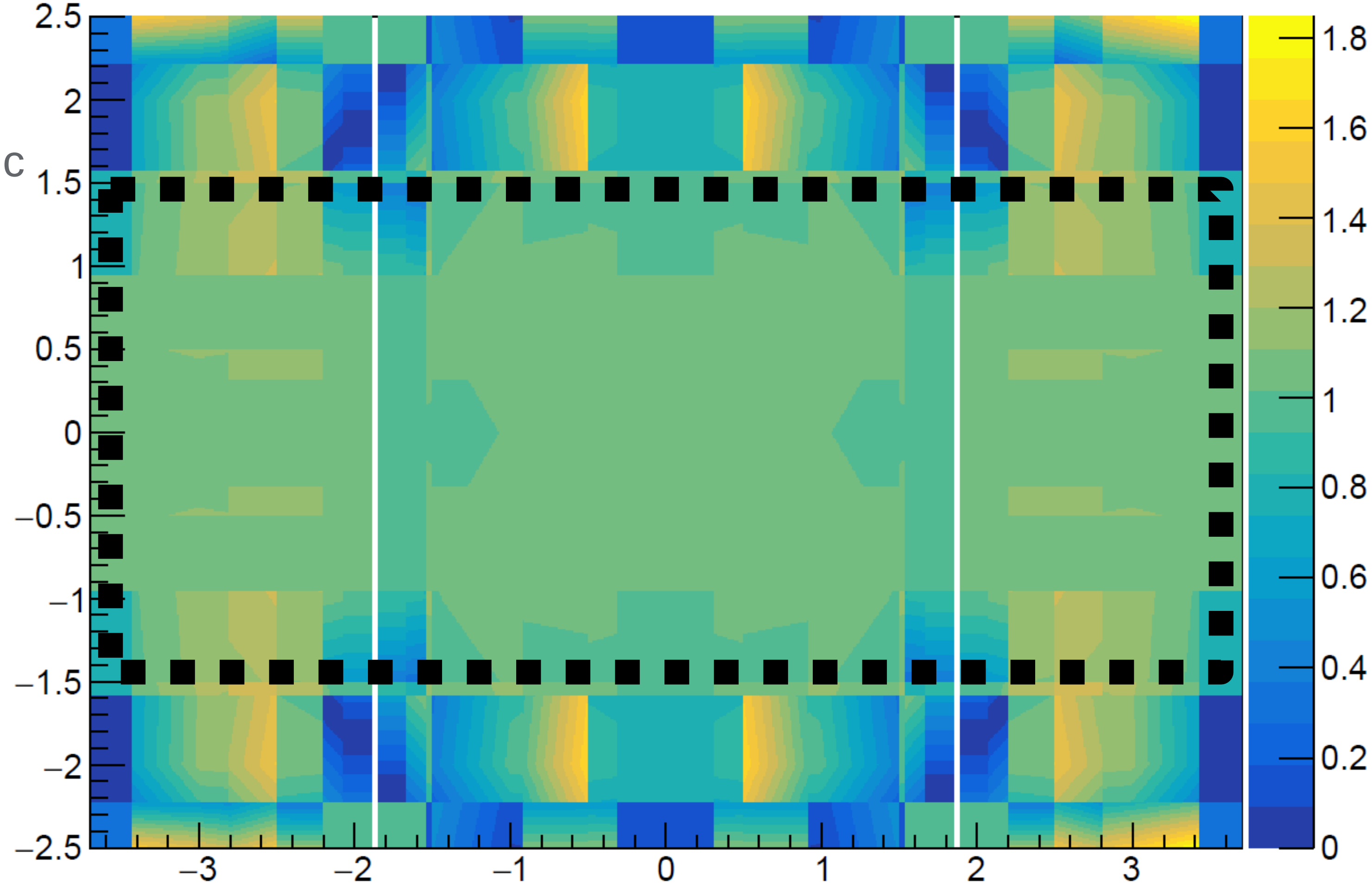
- We believe this device is buildable and will enable the DUNE Day One physics program

Backup

Magnetic Field

- This is the same plot as before, only plotting the absolute value of the magnetic field in the y-direction.
- This better shows the degree of uniformity.

x-y (front) view

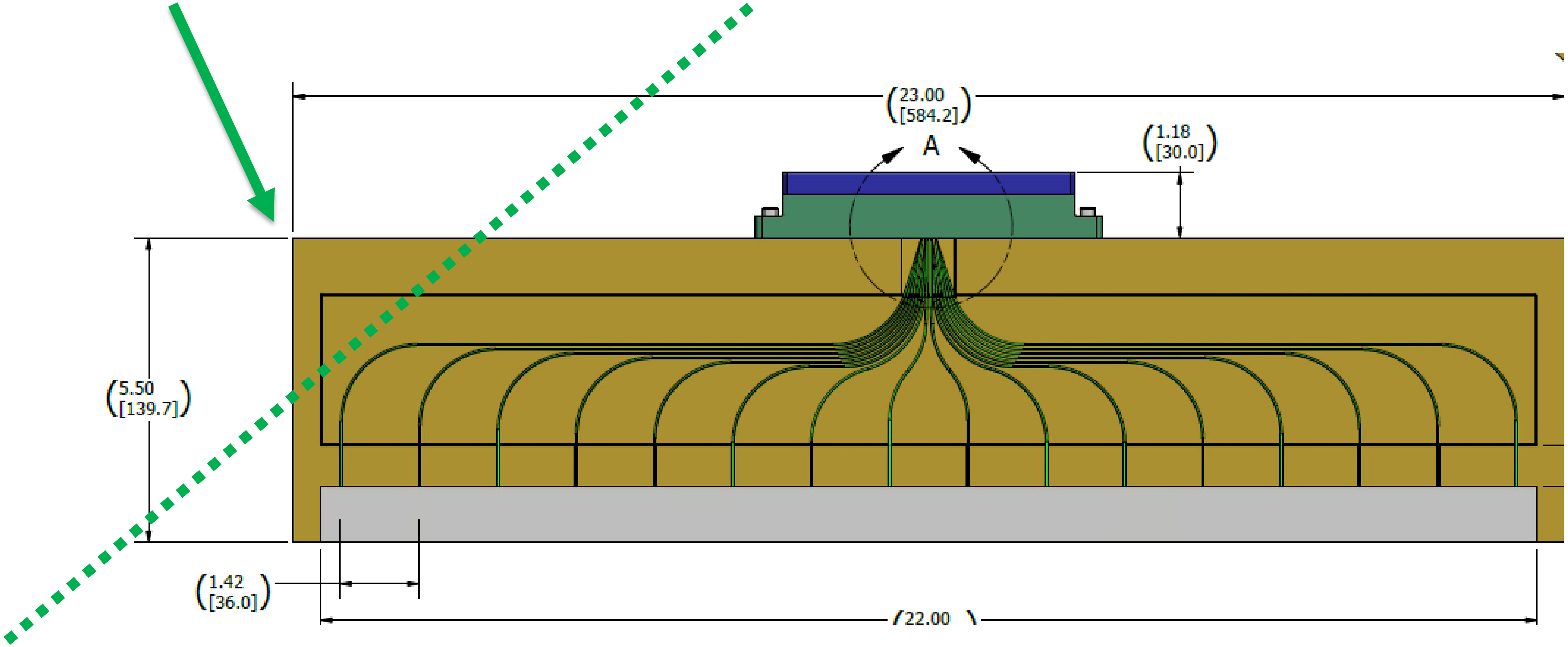


$\int |B_y| dz$ shown

Black dashed line indicates active area

Mechanical Interference

This corner has zero stay-clear with the magnet coil.
We may have to cut some corners (literally)



Interfaces with Other Elements

- 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)

- PRISM
  - The detector weighs too much for four Hilmans to accommodate
    - We are redesigning the base to support the TMS on six columns, rather than four
  - There is a small risk that the rails will become magnetized
    - This slows motion because it adds a demagnetization step
    - We are adding mounting points for additional return steel
    - Adding this steel or not would be an Ops Program decision

Issues to address in advance of CD-2

- Complete the PDR
  - Aside: it’s a good indicator of the progress we have made since July. We have designs where we had concepts.

- Complete the interface documents

- Make the tasks in P6 more fine-grained
  - Operationally, that means taking the Excel and Project files I have been using to manage this and load them into P6.

- Internal review of the magnet by magnet experts (FNAL, ANL APS, JLab…)
  - This magnet is unique (size, field directions)
  - Internal means I am asking for (and arranging) it
  - Reviews keep pushing this later

- While counter prototyping is not strictly necessary for baselining, I have launched it already
  - It will obviously inform the process
  - It will also help the team cohere

Overall Schedule & Milestones

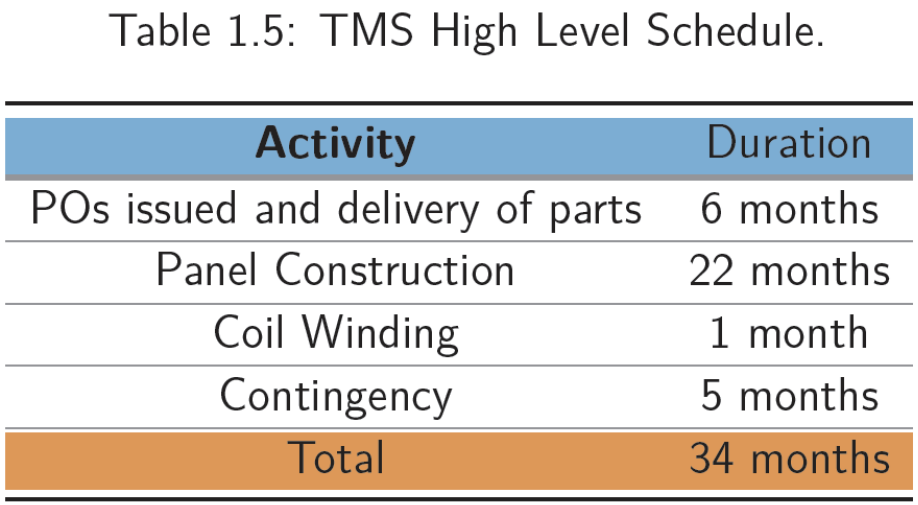


Table 1.5: TMS High Level Schedule.

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

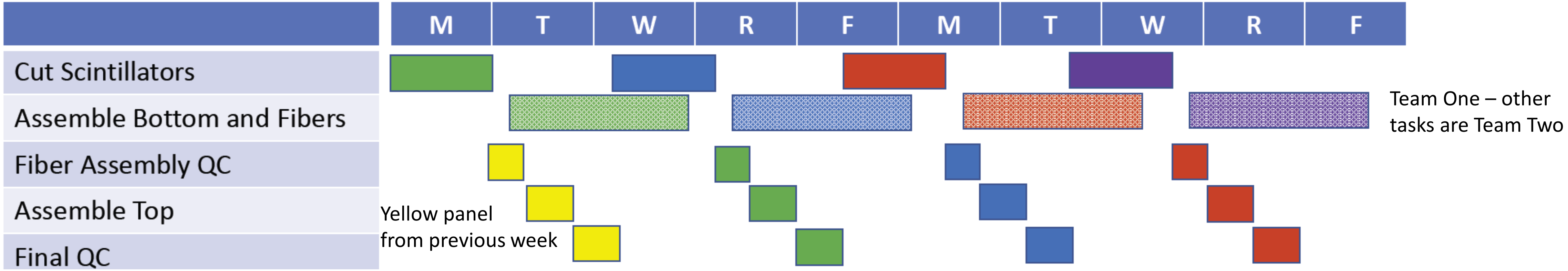
Our most significant milestone is the Decision Date: the last day possible to wait for ND-GAr.

Now that we have calculated that, our next step is to set up lower-level milestones registered to that one.

- Decision date is Day One less **34 months**
- Based on the schedule on the next 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.

Individual Site Schedule



M T W R F M T W R F

Cut Scintillators

Assemble Bottom and Fibers

Fiber Assembly QC

Assemble Top

Final QC

Team One – other tasks are Team Two

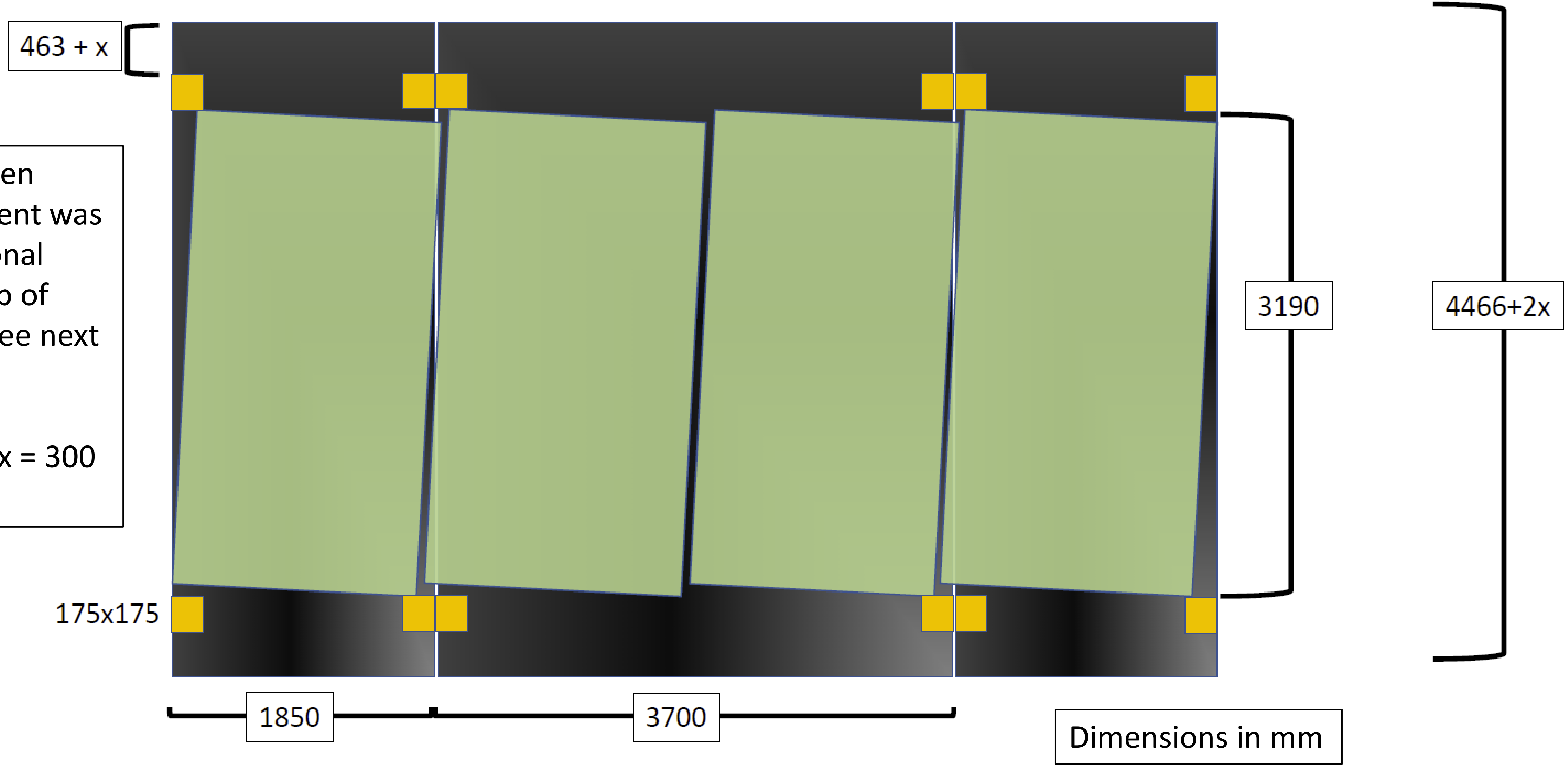
Yellow panel from previous week

Each color represents a module

- Based on the 51 individual and summary tasks (details in PDR) in making a panel, we calculate
  - It takes a week (+ 2 days glue curing time) to make a module
  - Each site can make 2-2.5 panel 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

Dimension Decisions



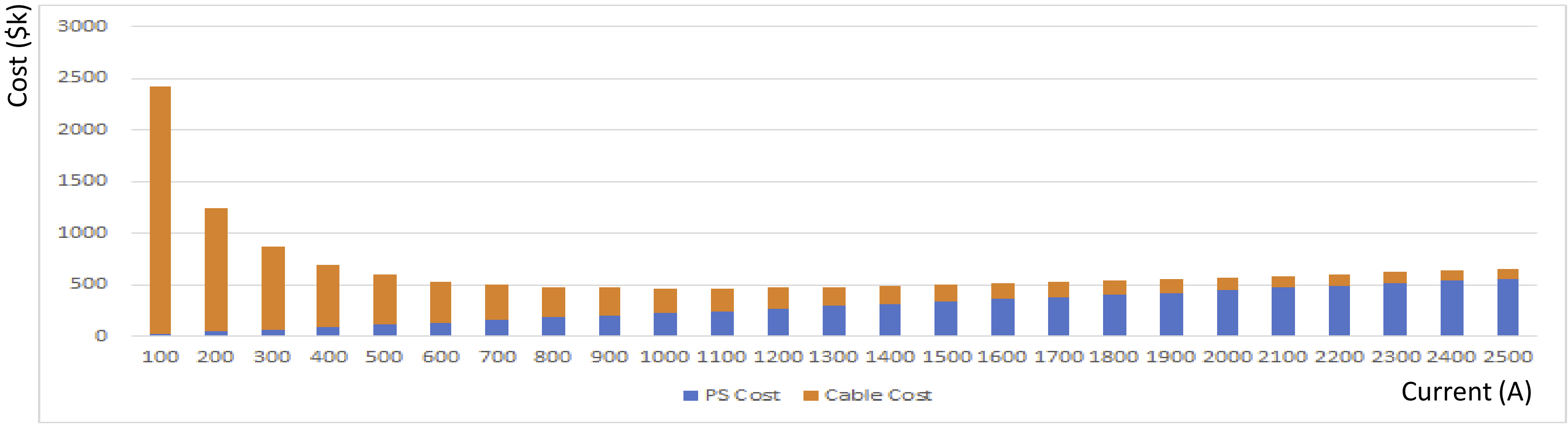
The last open measurement was “x”, additional steel on top of detector (see next slide).

Settled on x = 300 mm.

Dimensions in mm

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 is not ready today, so it's a future Opportunity

Prototyping & Other Studies

- Construction Time and Motion
- Magnet Value Engineering
- Signal Cables and Noise
- Steel Plate Thickness Optimization
- Fiber Hole Placement
- Fiber Attachment to SiPM
- 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?

Scintillator Prototyping

- Our plan was to start with undoped polystyrene. This had two problems:
  - Much less lab access than we planned for
  - This handles very differently from scintillator. It's not the doping; it's the TiO_2 coating.
- We have obtained some non-physics grade scintillator from Fermilab
  - 103 strips (4 cm x 1 cm, edge/MINOS groove) – 4 meters long
  - 58 strips (4 cm x 1 cm, center/mu2e hole) – 1.5 meters long
  - No shortage of materials (enough for 264 counters) – no need to start with undoped plastic
  - A working 16-channel 1/3 scale (1m long) panel is now an option
- Our first prototype is being constructed now
  - Intended to study fiber path from scintillator to SiPM
  - No scintillator, clear fiber, 16 channels

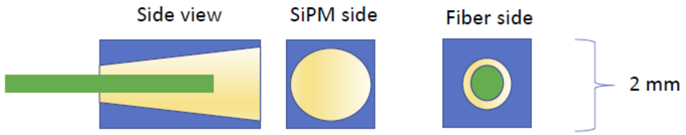
Fiber-SiPM Coupler

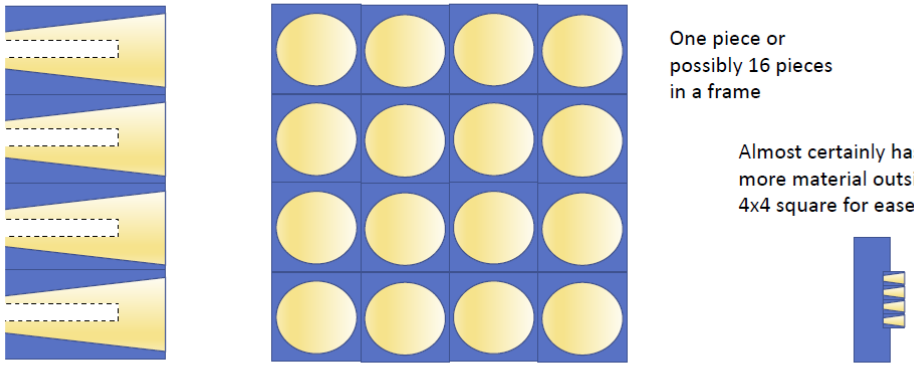
- The most time-consuming part of panel assembly is attaching the fibers to the SiPMs
  - These SiPMs are really *really* small
  - They have sixteen even smaller things (WLS fibers) attached to them.
  - These fibers are constrained at the opposite end as well (they are glued into the scintillator)

- 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.





One piece or possibly 16 pieces in a frame

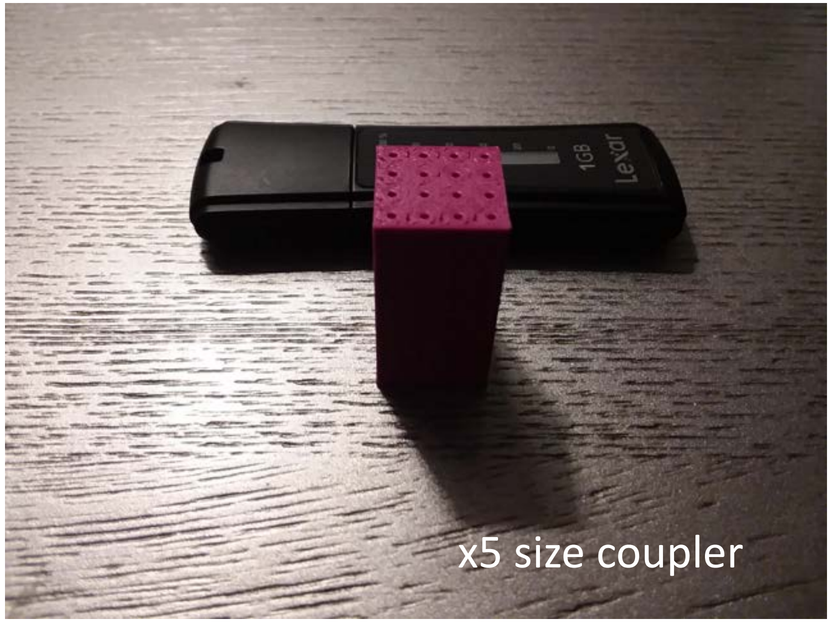
Almost certainly has more material outside the 4x4 square for ease of handling

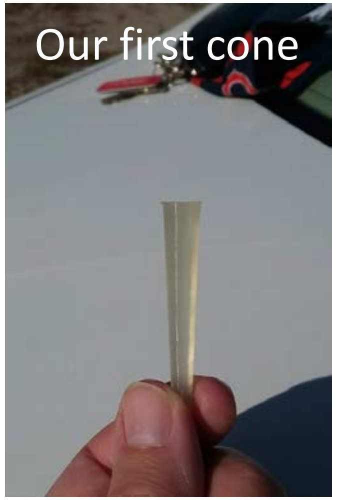
Potential to save several months of construction time.

3D printed Coupler Prototypes

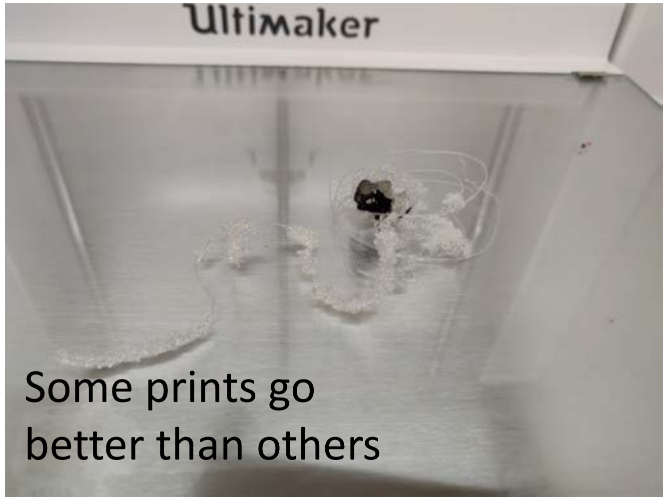

What is possible in industry

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


x5 size coupler


Our first cone


Our best cone


Some prints go better than others


It works!

Tables from PDR

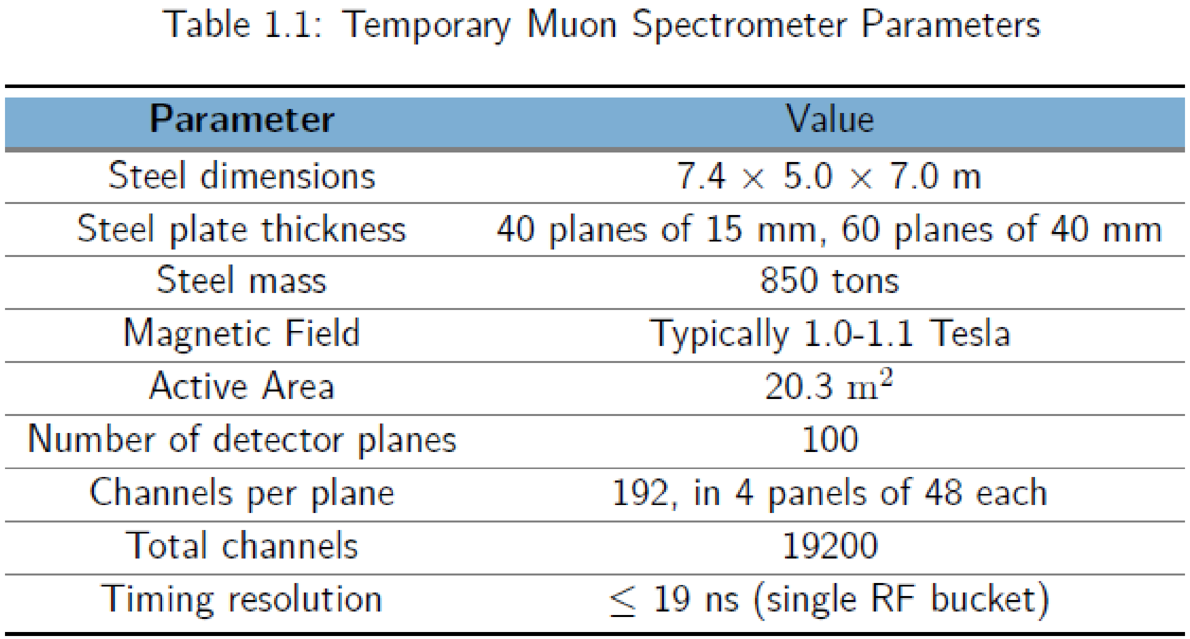


Table 1.1: Temporary Muon Spectrometer Parameters

Parameter	Value
Steel dimensions	7.4 × 5.0 × 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	$20.3\ \mathrm{m}^2$
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)

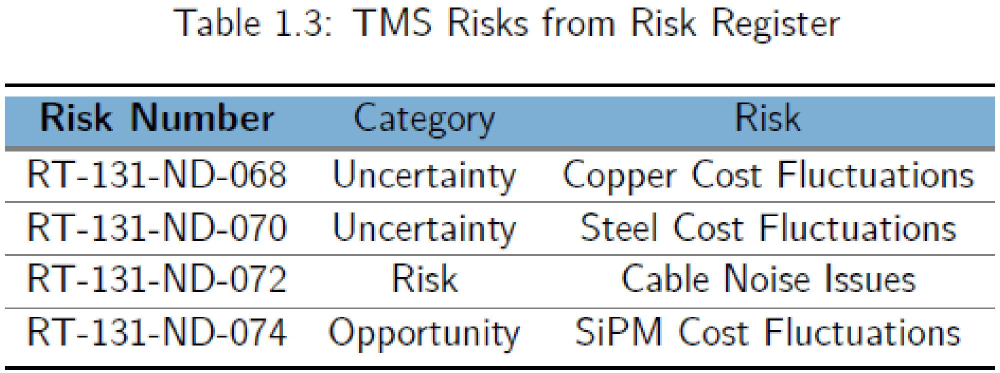


Table 1.3: TMS Risks from Risk Register

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

Documented Design Alternatives (at Present)

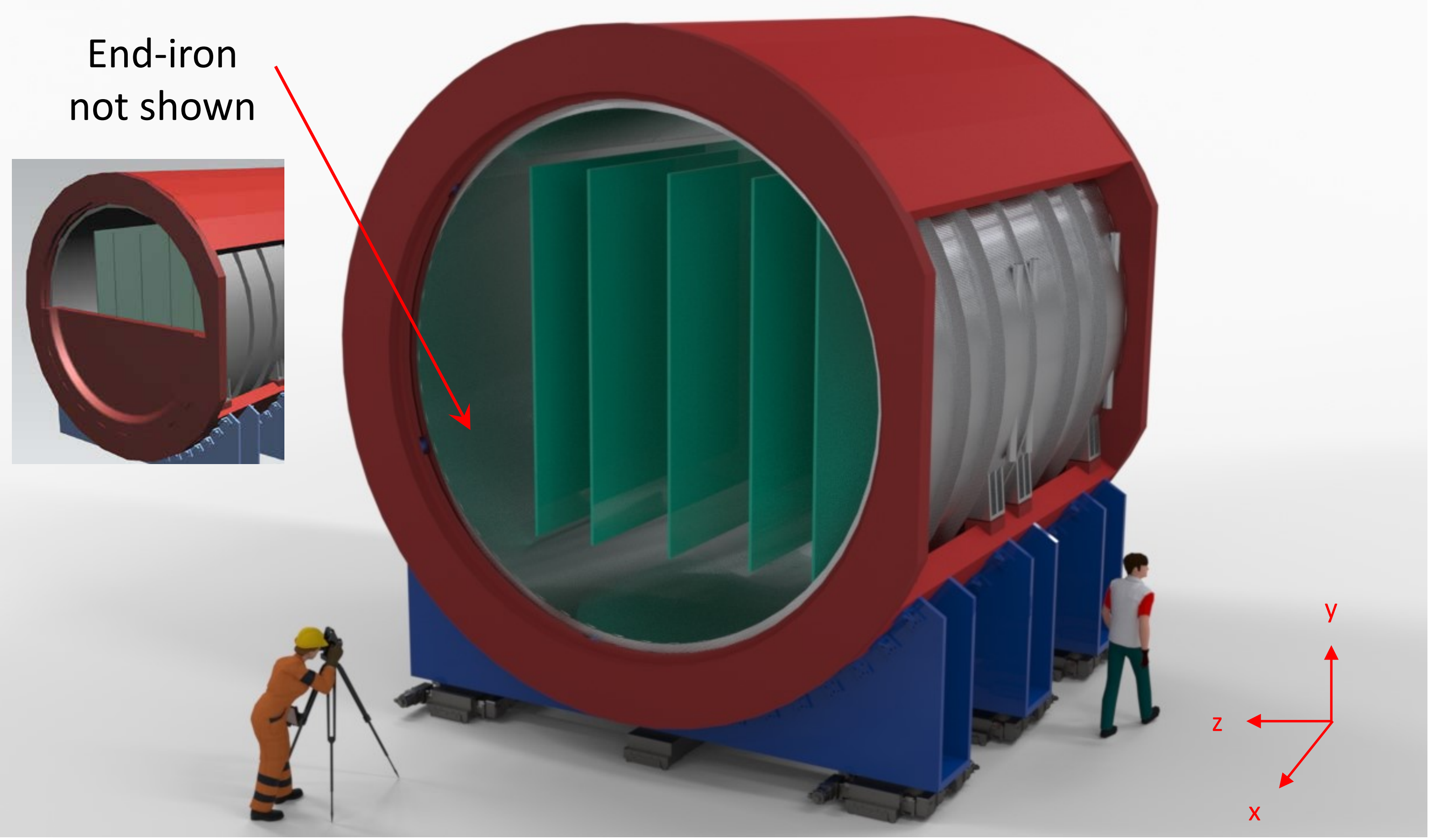
- Water Closed-Loop Cooling the Coils
- Change WLS Fiber Diameter (in main body of talk)
- Include 3D-printed Diffuser/Coupler
- Scintillator Fiber Hole
- Move On-Panel Boards Off-Panel
- Move DC functionality to OPBs
- Switch to Single-Channel SiPMs
- Orthogonal Tracking
- TMS yz-tilt
- Calibration and Monitoring
- Steel Thickness Distribution

We've taken some decisions so we could write the PDR.

If better alternatives exist, we can switch to them. But we have to demonstrate they are better. This should not be an unreasonably high bar. It will keep us from flip-flopping.

The earlier we decide to change, the easier it will be.

ND-GAr lite design status



ND-GAr lite:

- Full magnet system
  - Coil(s)
  - Return iron
- Scintillator tracker
  - Minerva-like scintillator planes
    - Triangle: 4 cm base, 2 cm height
    - 5 planes: 6 m long X 5 m tall
      - Spacing to be optimized
    - X-Y readout