Tracker for the mu2e Experiment at Fermilab

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Why μ→e?

See Rob Kutschke's talk for more

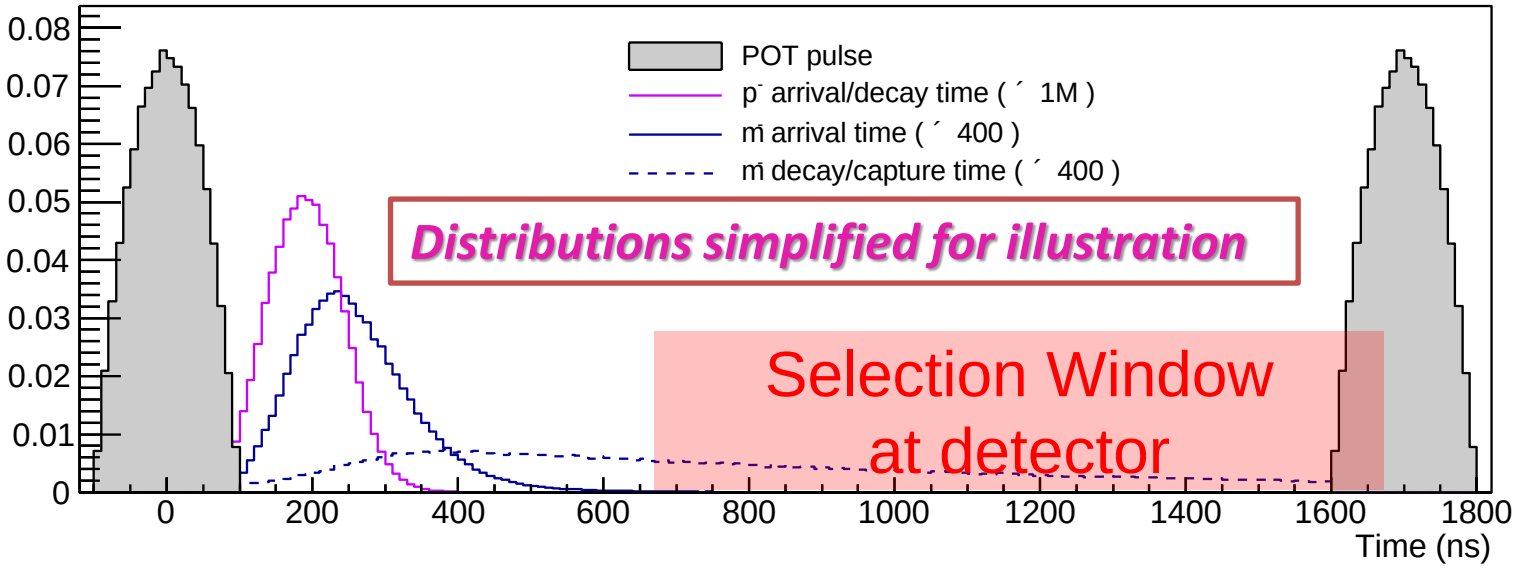
- Muons captured on a target to form a muonic atom
- 40% undergo the normal decay while in orbit (DIO)
  - LOTS of electrons at $\mathrm{E} < m_{\mu}/2$ … with a small tail to higher E
- 60% capture on the nucleus, causing a nuclear breakup
  - p, n, γ produced in the breakup
- We are looking for a small fraction of neutrinos-less conversions

  $$\mu^{-}N \rightarrow e^{-}N \ \ldots$$
- Signature: Mono-energetic electrons
  - 105MeV, depending slightly on nucleus
- Rate in standard model is very low (BR ~10^{-54})
- A signal indicates physics beyond the standard model

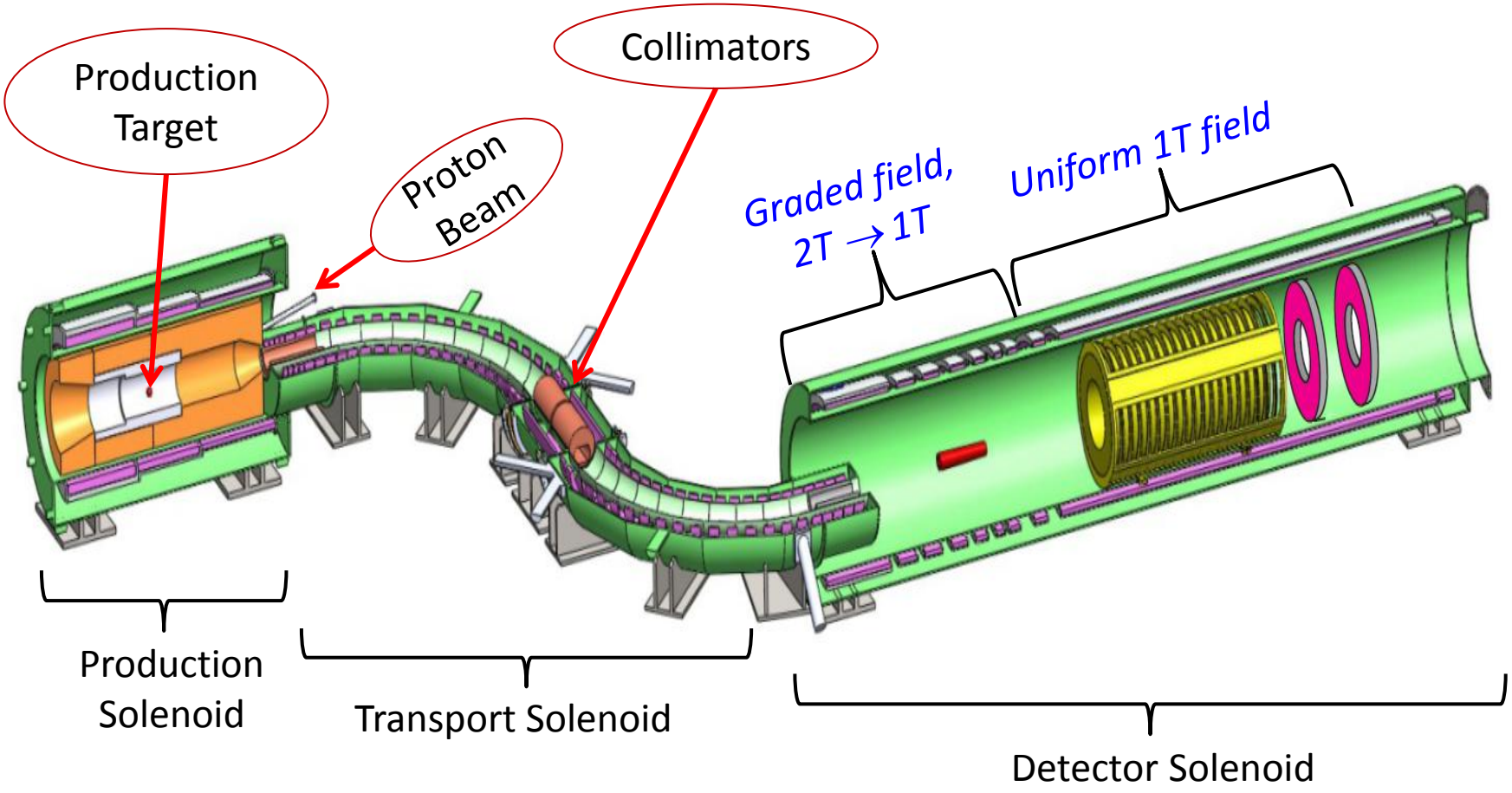
Why mu2e?

Far from the first such search! So how do we do better?

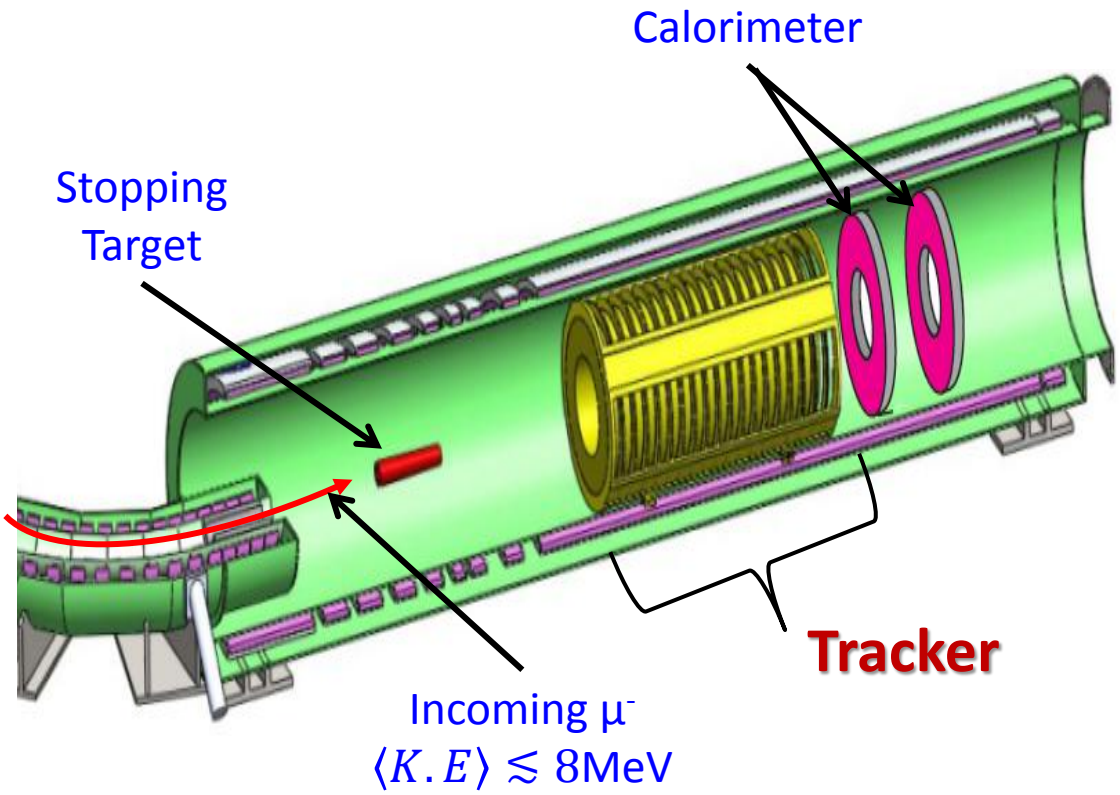
- More intense beam
- Pulsed beam with excellent extinction (fraction of protons out of time)
- Expect $10^4\times$ better than previous limit



Beam Line

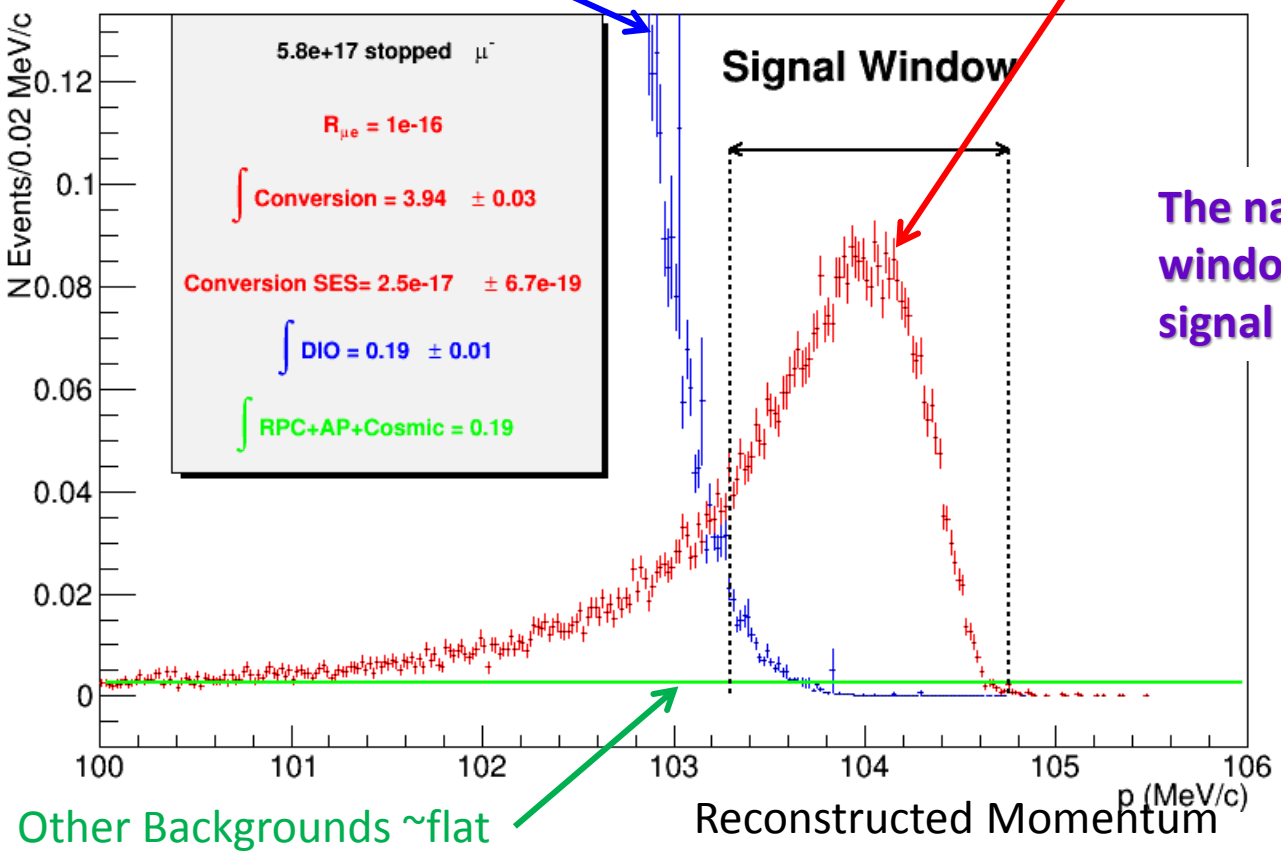

Production Target
Collimators
Proton Beam
Graded field, 2T → 1T
Uniform 1T field
Production Solenoid
Transport Solenoid
Detector Solenoid

Detector Solenoid



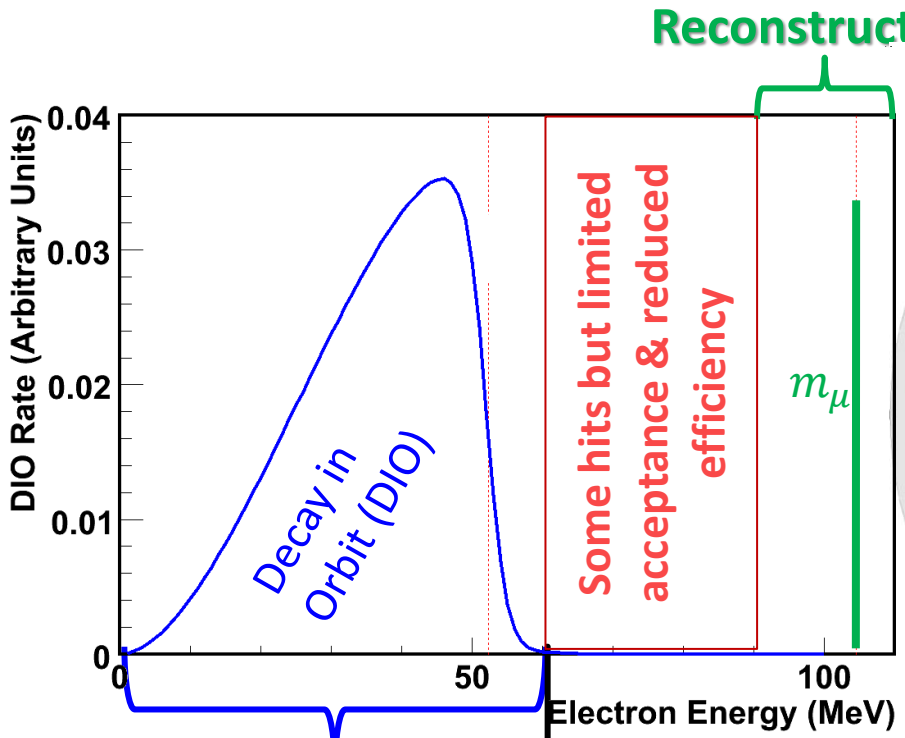
Cosmic Ray Veto (CRV, not shown) surrounds detector solenoid and much of the transport solenoid.

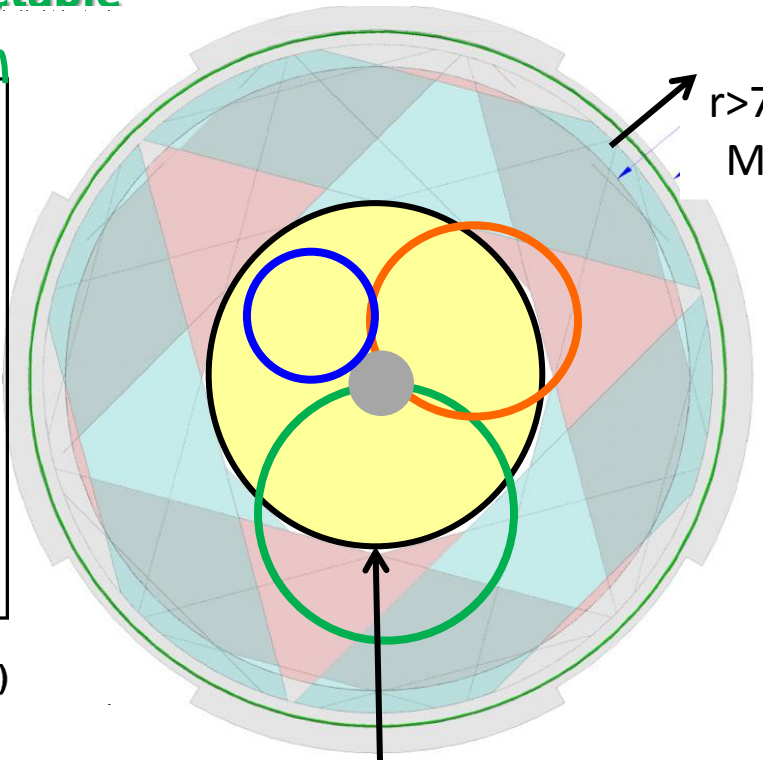
Importance of Resolution



The narrower the signal window, the better the signal to background

Why annular?


Reconstructable
DIO Rate (Arbitrary Units)
0.04
0.03
0.02
0.01
0
0
50
100
Electron Energy (MeV)
Decay in Orbit (DIO)
Some hits but limited acceptance & reduced efficiency
m_μ
No Hits

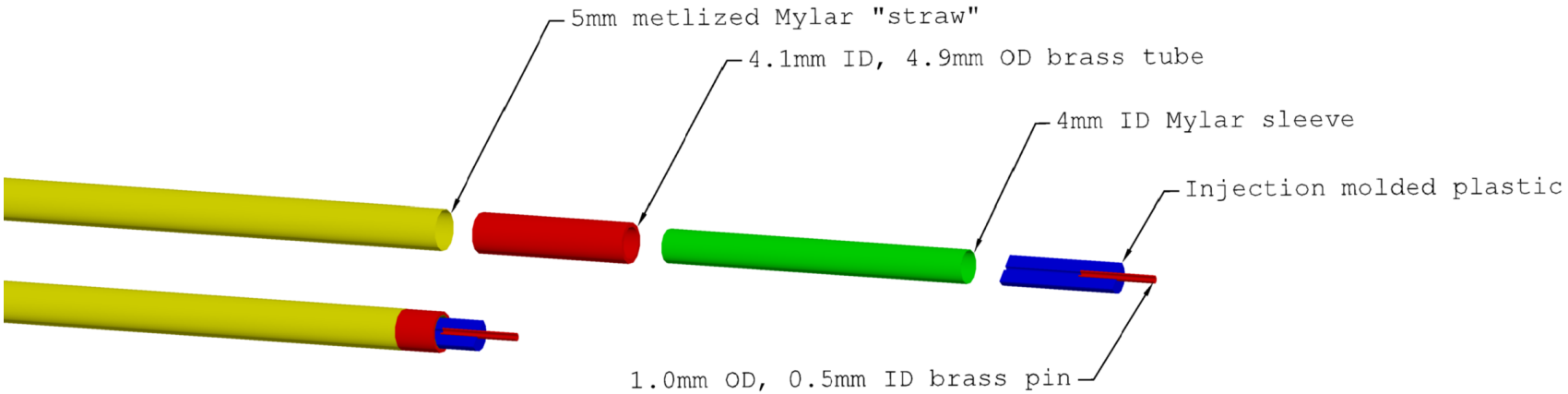

r>700mm:
Mass OK
Minimum mass at r<380mm
→ Vacuum

Tracker Design

- No mass at r<380mm
  - Ambient vacuum
    → Detector most handle ~15psi pressure differential
- Very light active region, 400<r<700mm
  Partial coverage for 380<r<400mm
- Light, inactive region for 700<r<720mm to reduce hits from photon conversion and stopped neutrons decaying
- Move mass out to r>720mm
- Selected Solution: Straw tracker
  - 18 **Stations** distributed along beam direction
    Optimization of number of stations in progress
  - A Station has 2 **Planes**.
  - A Plane has **Panels** with varying rotation for stereo reconstruction
  - Each Panel has 96 **Straws** of varying length

Straw

- 5mm OD, 15µm thick metalized Mylar tube as cathode
  - Metalized on inner & outer surface
  - 400Å Aluminum outer surface
  - 400Å Aluminum + 200Å Gold inner surface
  - 25µm gold-plated tungsten wire as anode



Leak Tests

Conventional methods

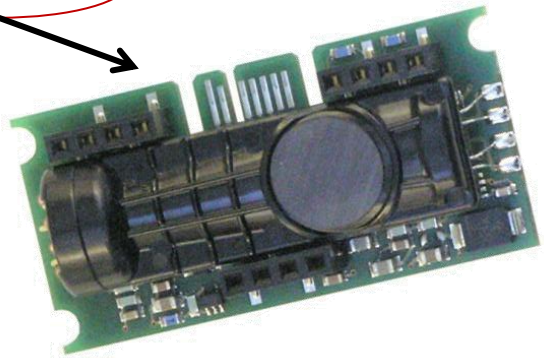
- In air, straw at 15psig
  - Test time: several days
- In vacuum, straw at 15psia
  - Measures exactly what we want
  - Test time >1day
  - Test setup too expensive to make many
- Can do large batches but lose sensitivity

Using CO2 sensor

- CO2 leaks through plastic faster than most gases
- Fill straw with Ar-CO2 (80:20), purge test vesel with N2, and monitor CO2 level
- Test time to required sensitivity: <1hour
- Test setup cost: <$100, can have many setups
- Needs to be calibrated against vacuum method

CO_2 Leak Test

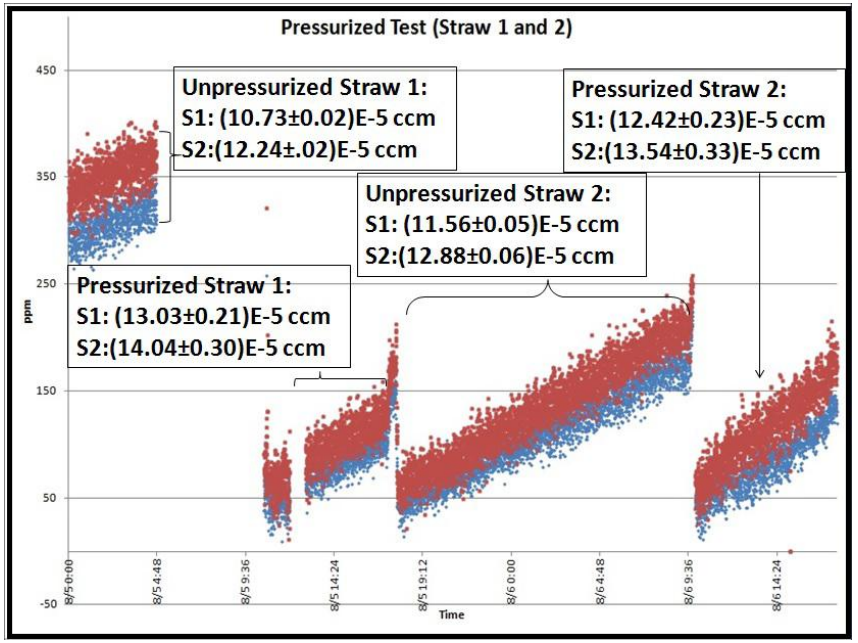
Container for CO_2 sensor and circulation fan



Copper pipe for straw
Another in back (not seen) for circulation

CO_2 Leak Tests

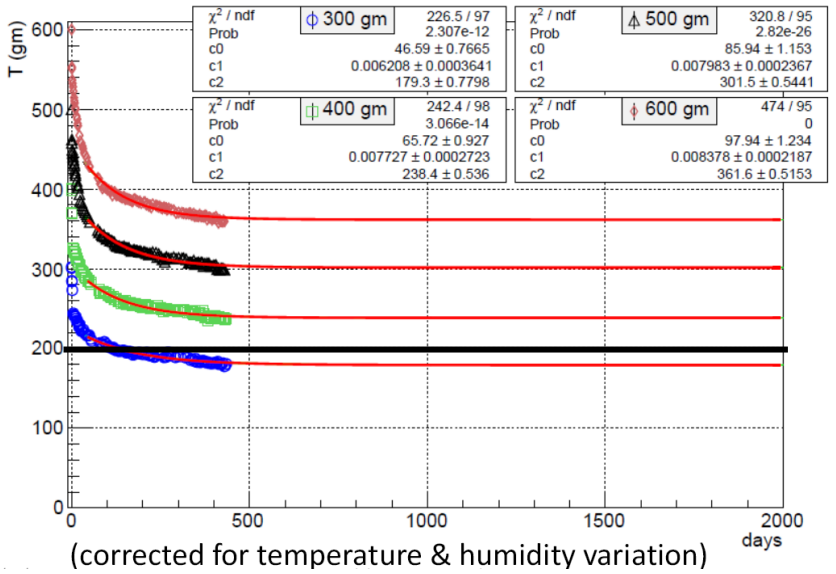
- Sample results for straws with and without being pressurized
- Leak rates well below limit of 3.5e-4 ccm



Straw Creep

- Like all plastics, the Mylar straws creep: loose tension over time
- Our best fit, extrapolated to several years, shows detector is fine (over 200g) indefinitely if we install at 700g tension

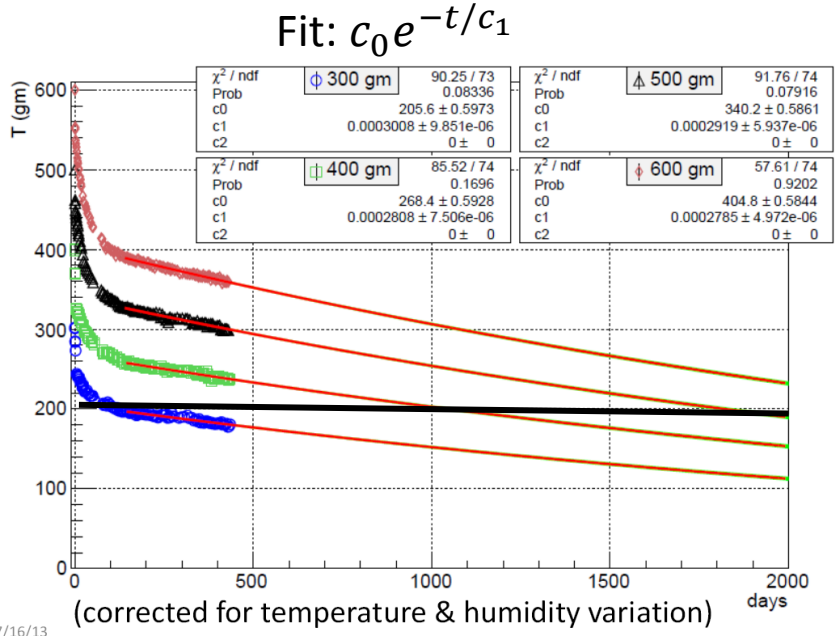
Fit: $c_0 e^{-t/c_1} + c_2$



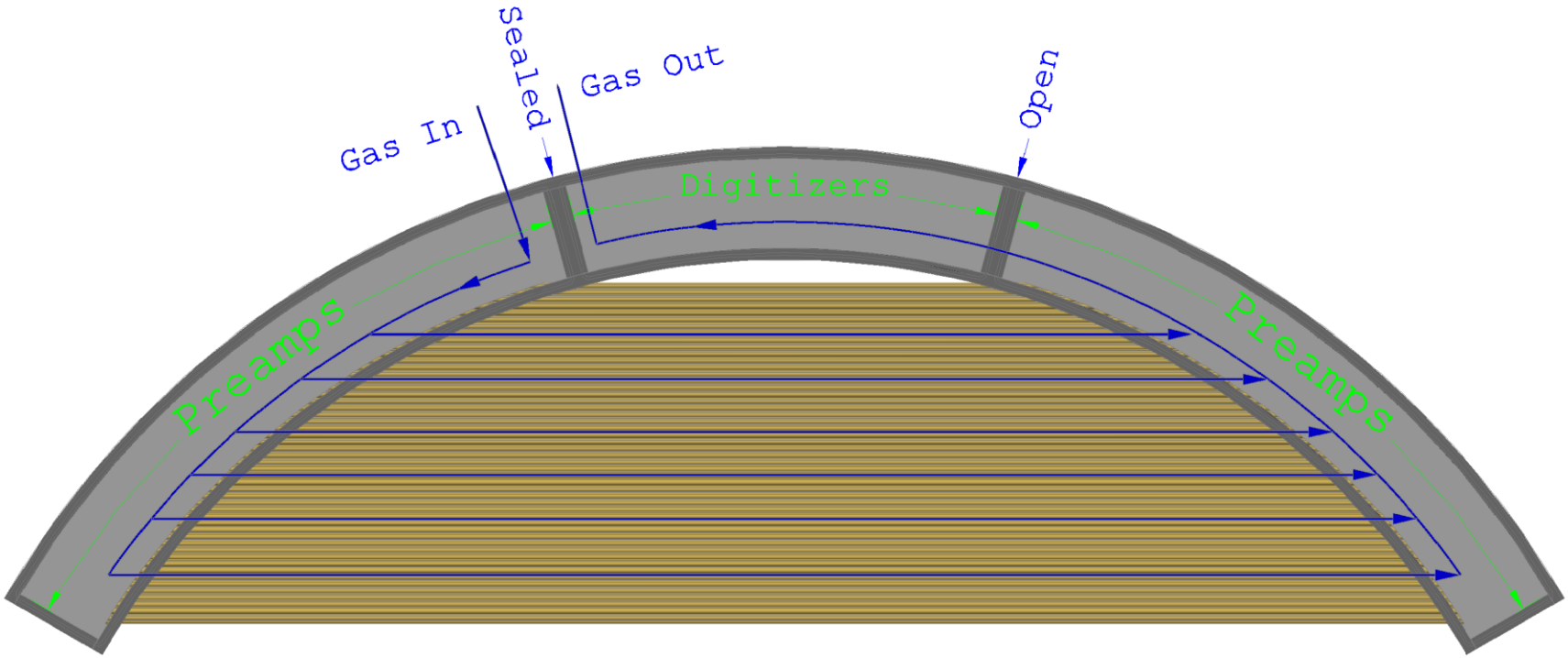
(corrected for temperature & humidity variation)

Straw Creep

- Extrapolation from <1year to many years is tricky
- Alternative fits indicate a lifetime of >6years
- Fine for mu2e … maybe not mu2e-II
- Alternative: Add a stiffening carbon fiber line radially across the panel



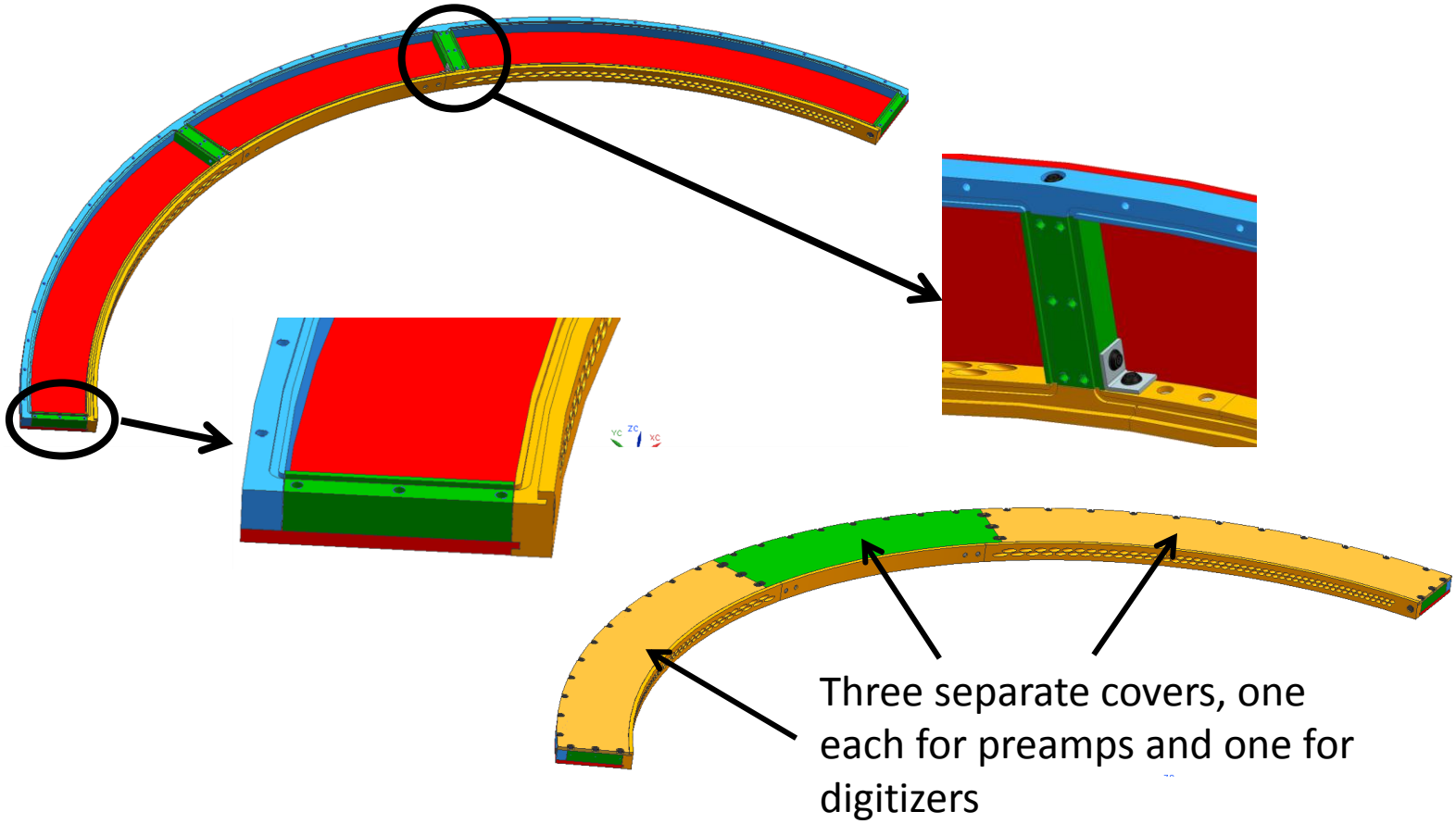
Panel



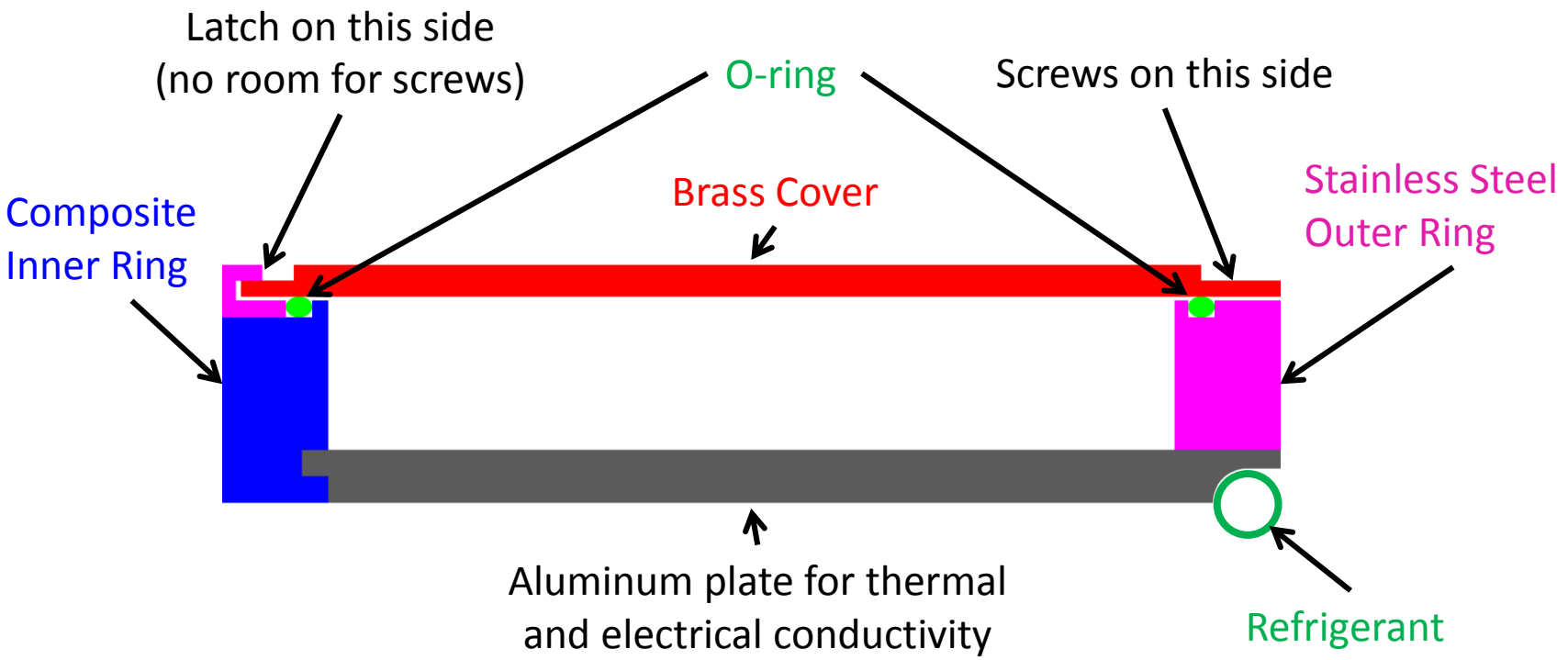
- All electronics are in drift gas to simplify cooling
- Preamps to be tested for gas contamination, and may need coating
- Digitizers are in the exhaust gas → don't need to worry about outgassing
- Digitizer region can be accessed while operating straws
  (not in the vacuum, of course)

Gas Manifold

- Gas tight while allowing access to electronics



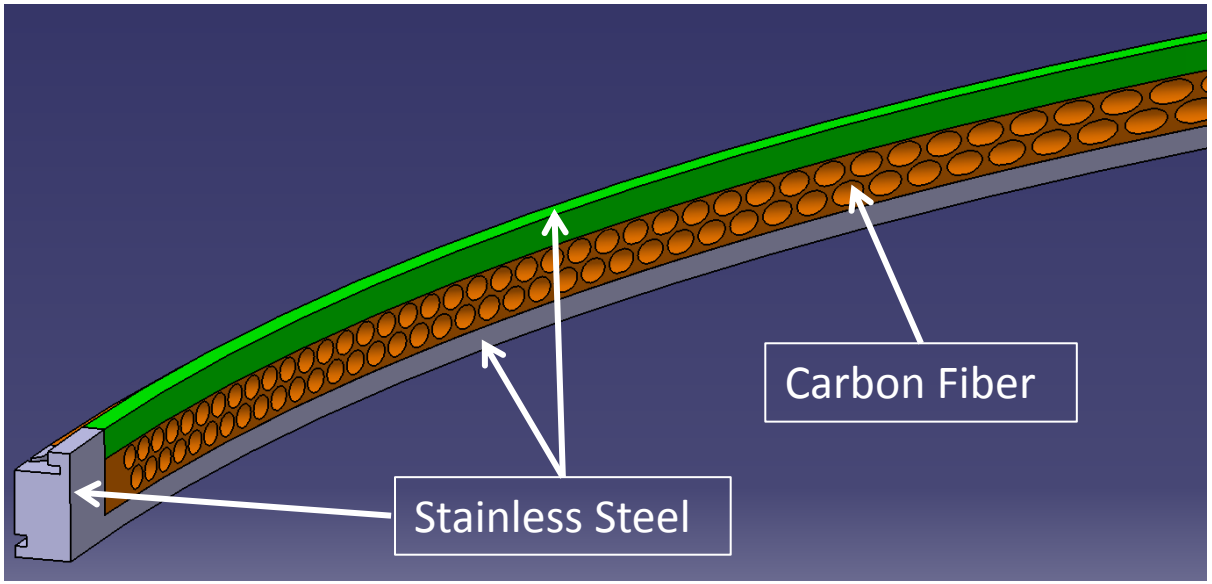
Gas Manifold

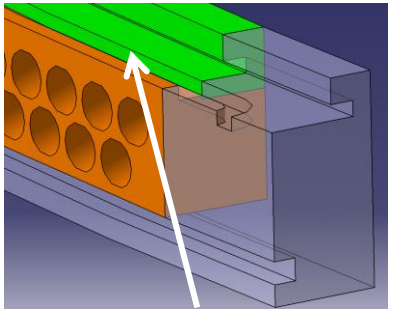


- Prototype had <0.24ccm leak rate
- Small compared to allowed total of 7ccm

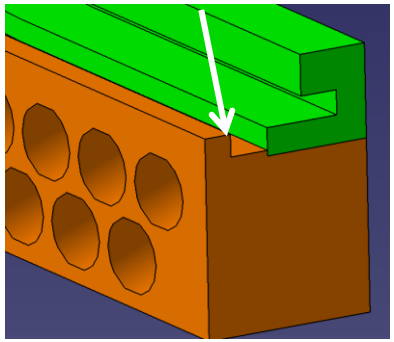
Gas Manifold Inner Ring

- 96 straws/panel ×6 panels/plane × 36 planes
  → ~20K straws → 40K precision holes
- Alternative: Mold the holes in carbon fiber



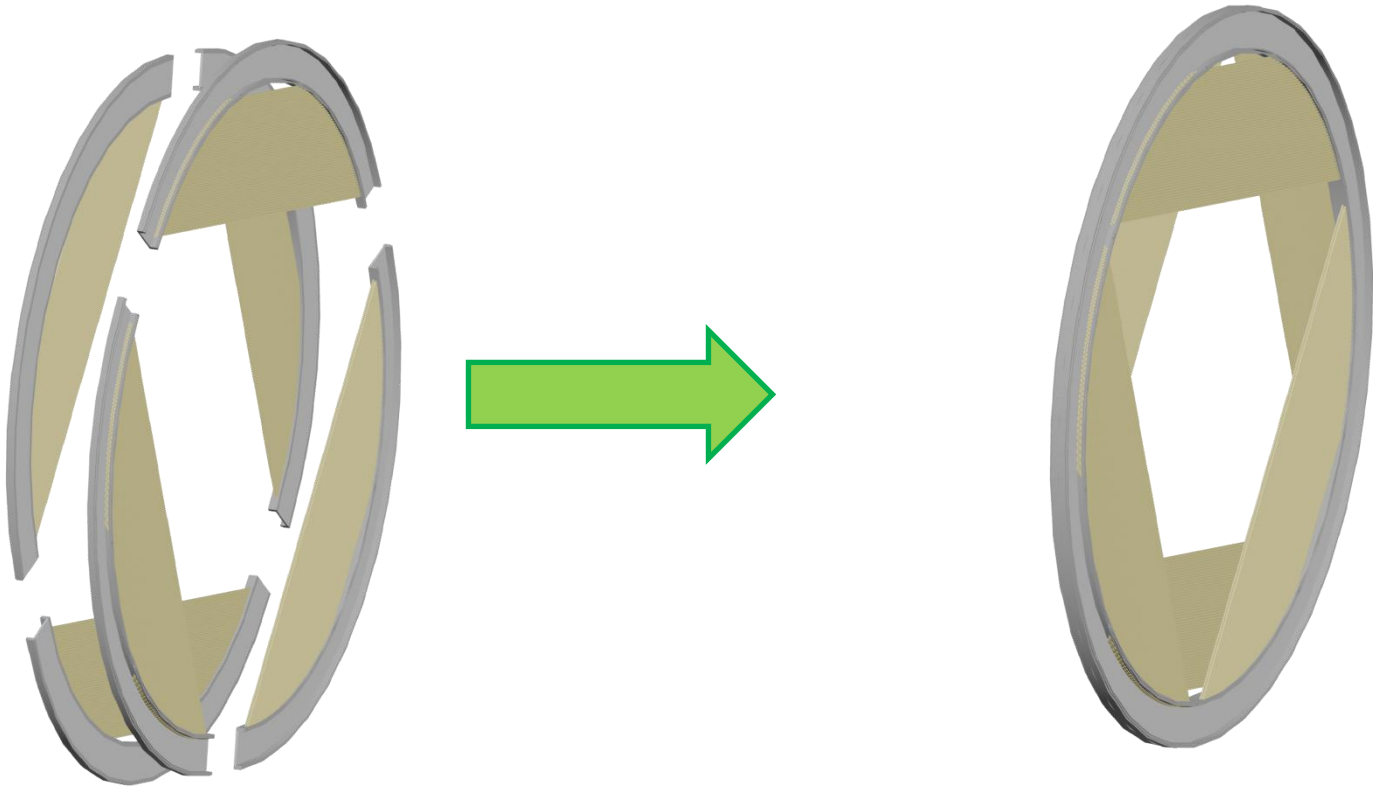


O-ring groove

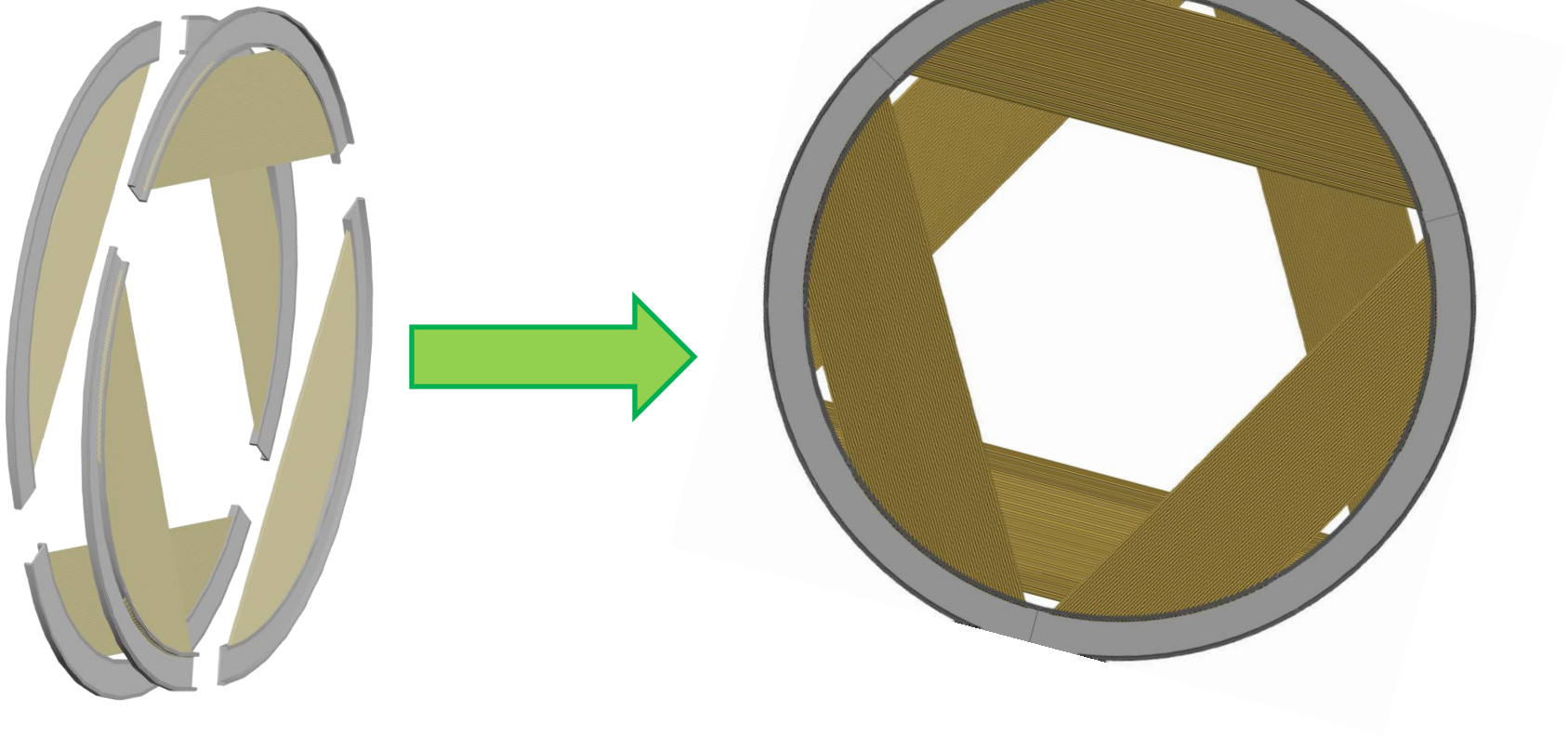


Plane

- Self-supporting panels assemble into a plane

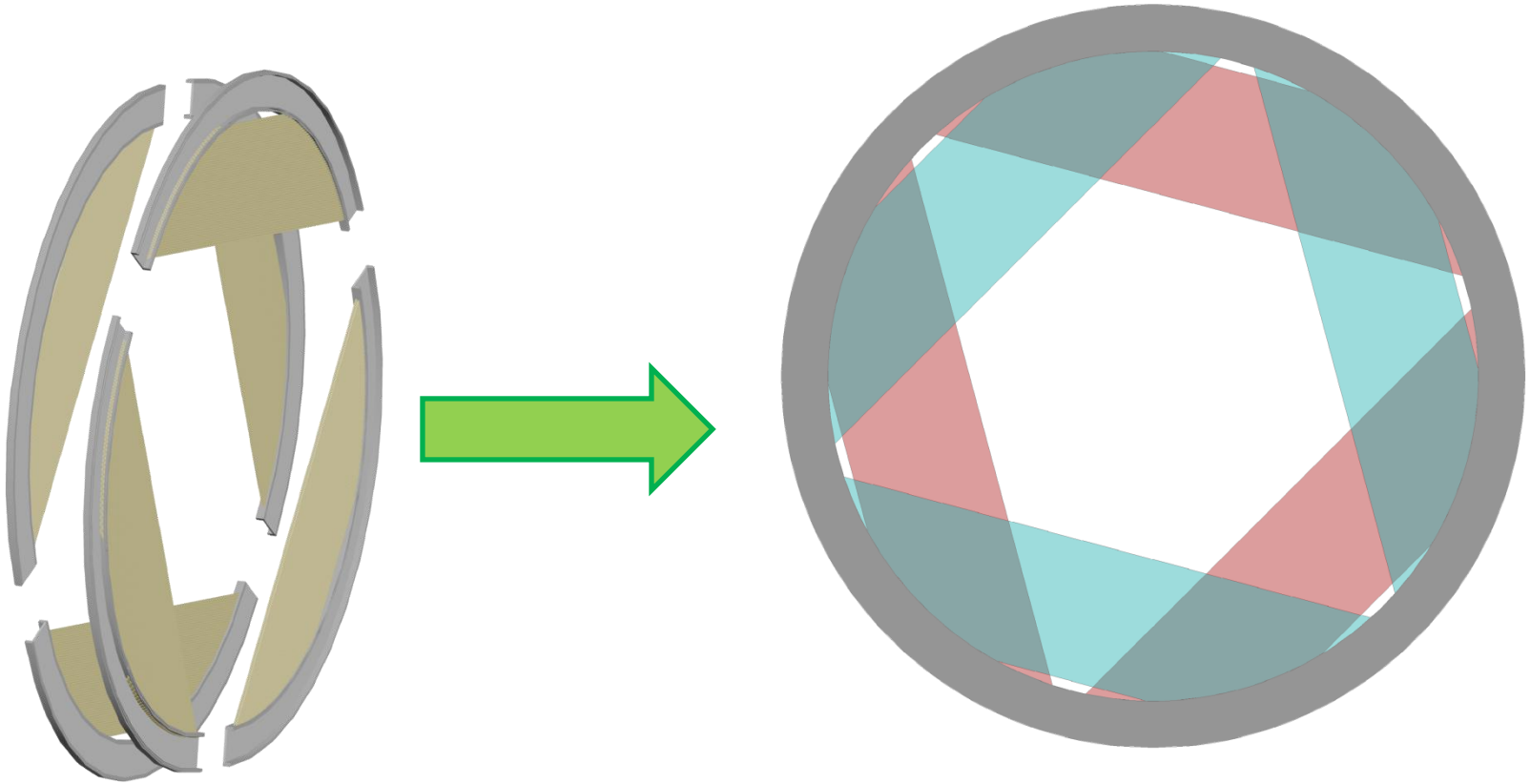


Plane



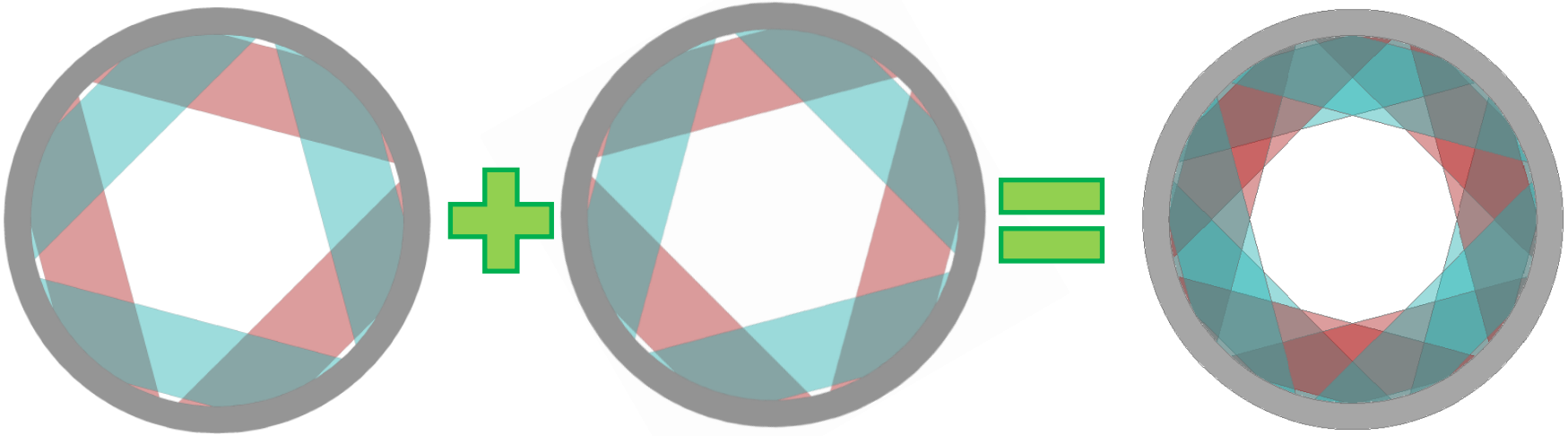
Plane

- Switch to simpler representation



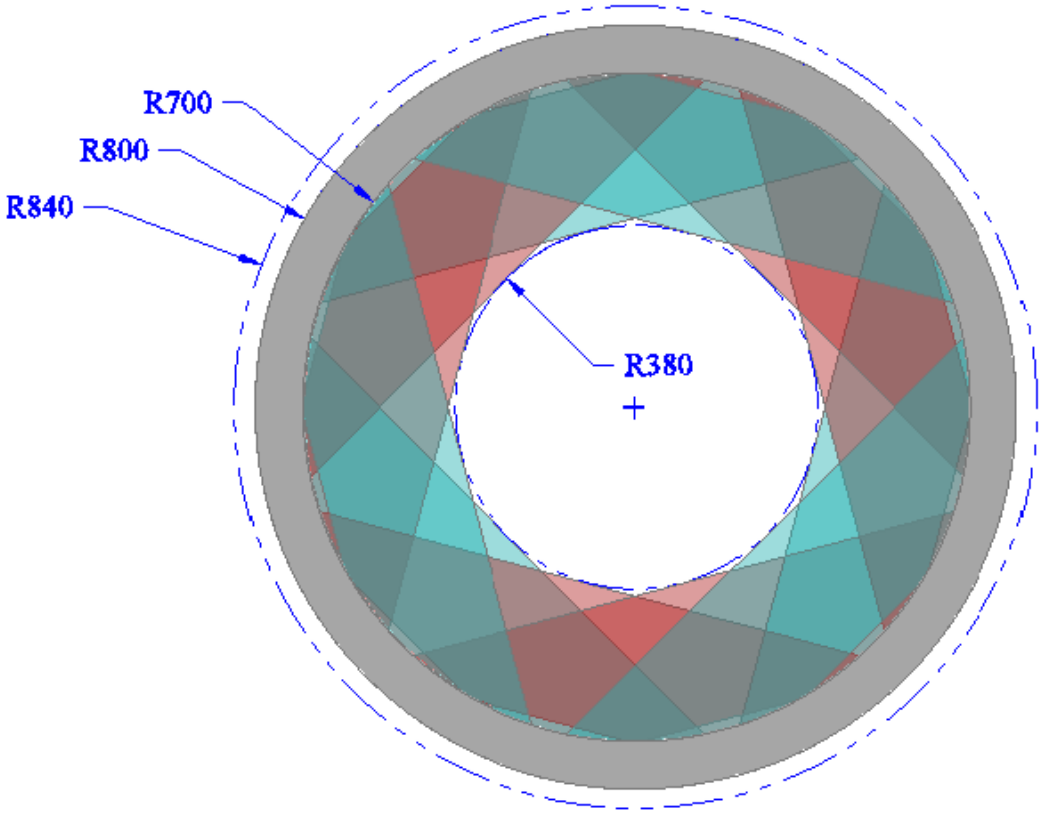
Station

- Two planes back-to-back



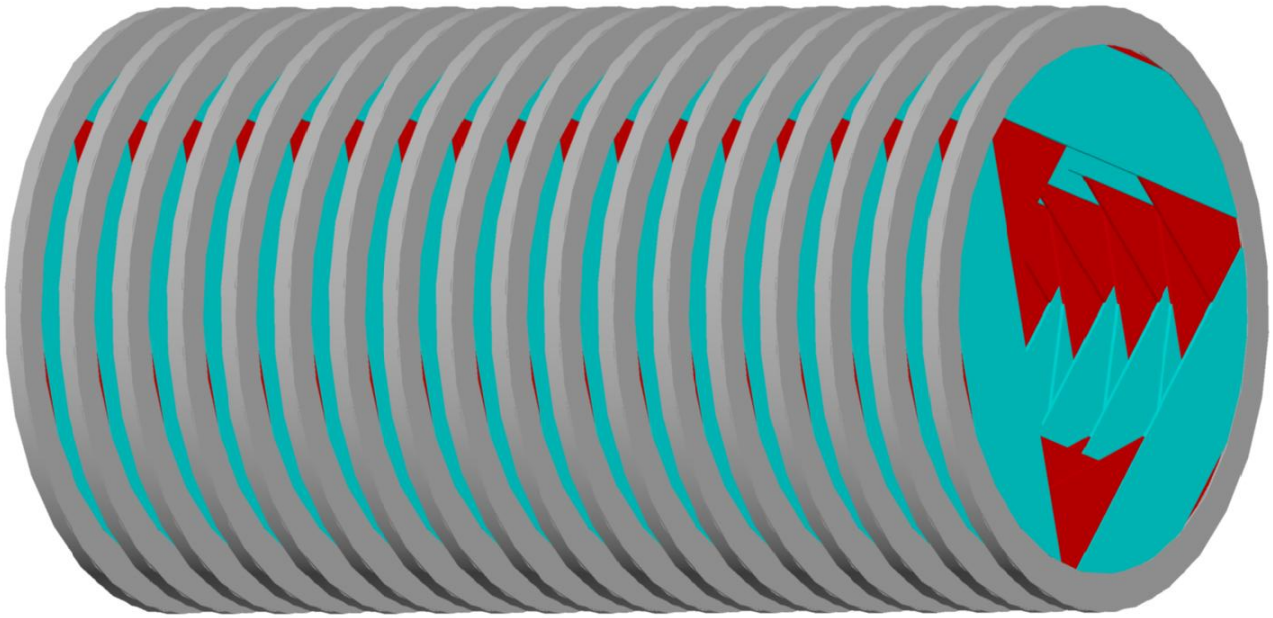
Station

Optimal Stereo order still under study



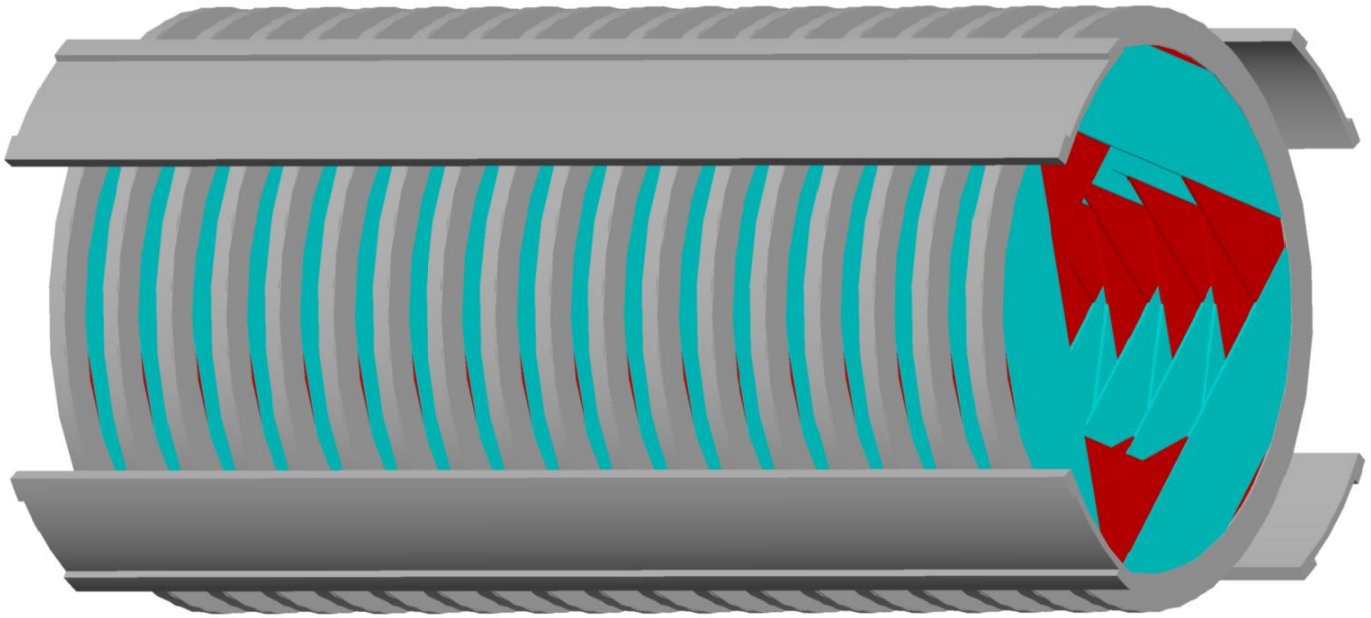
Tracker

- 18 stations
  tentative … optimal number being studied



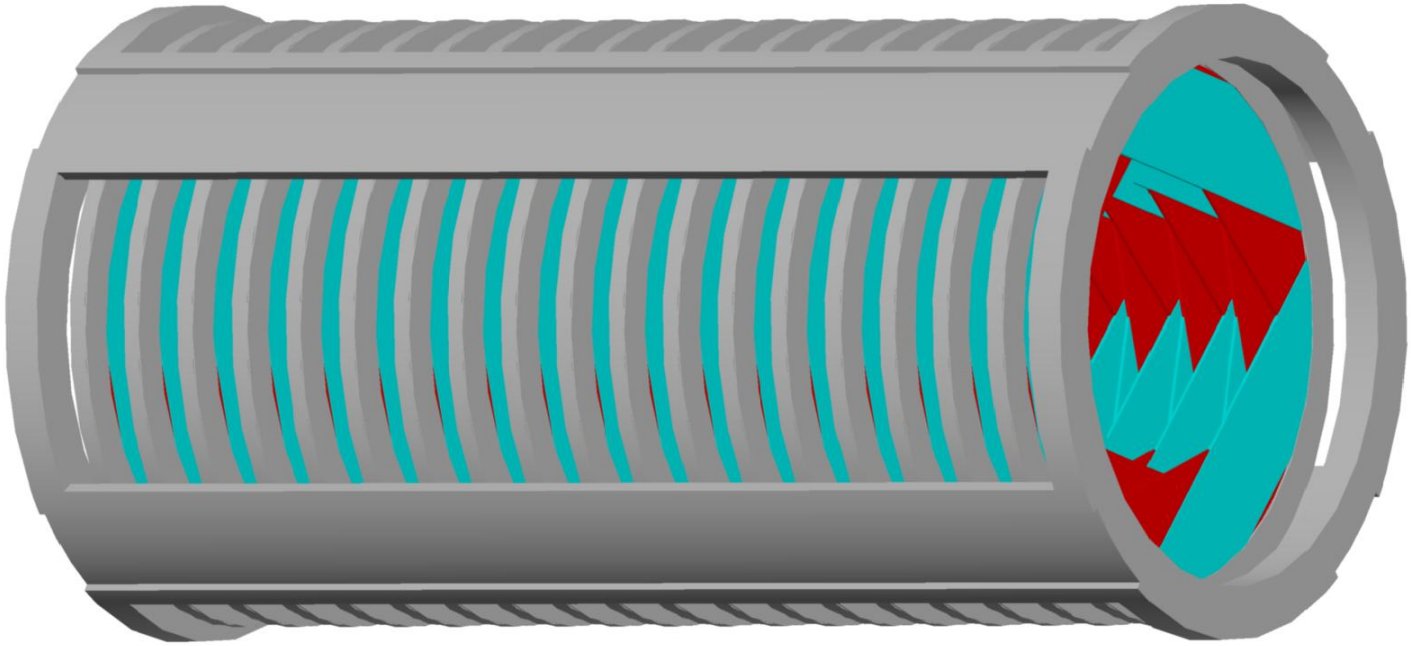
Tracker

- 18 stations + Support Structure



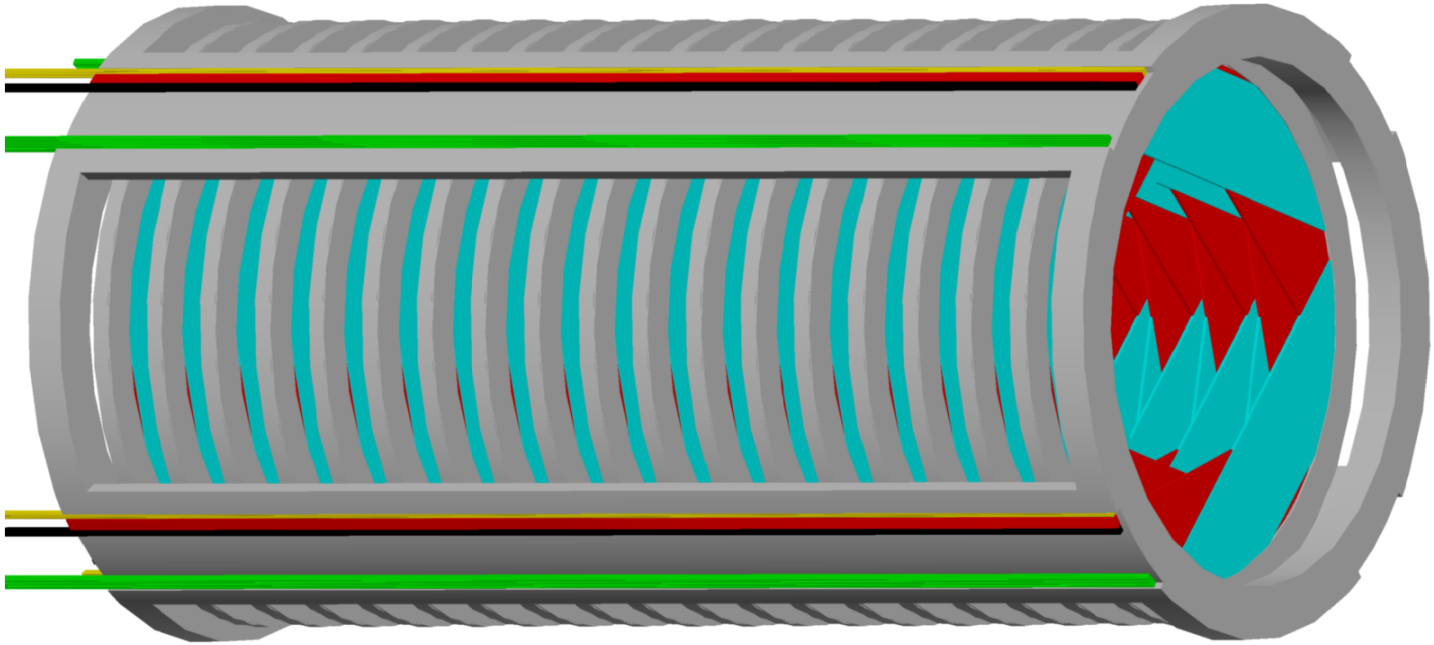
Tracker

- 18 stations + Support Structure

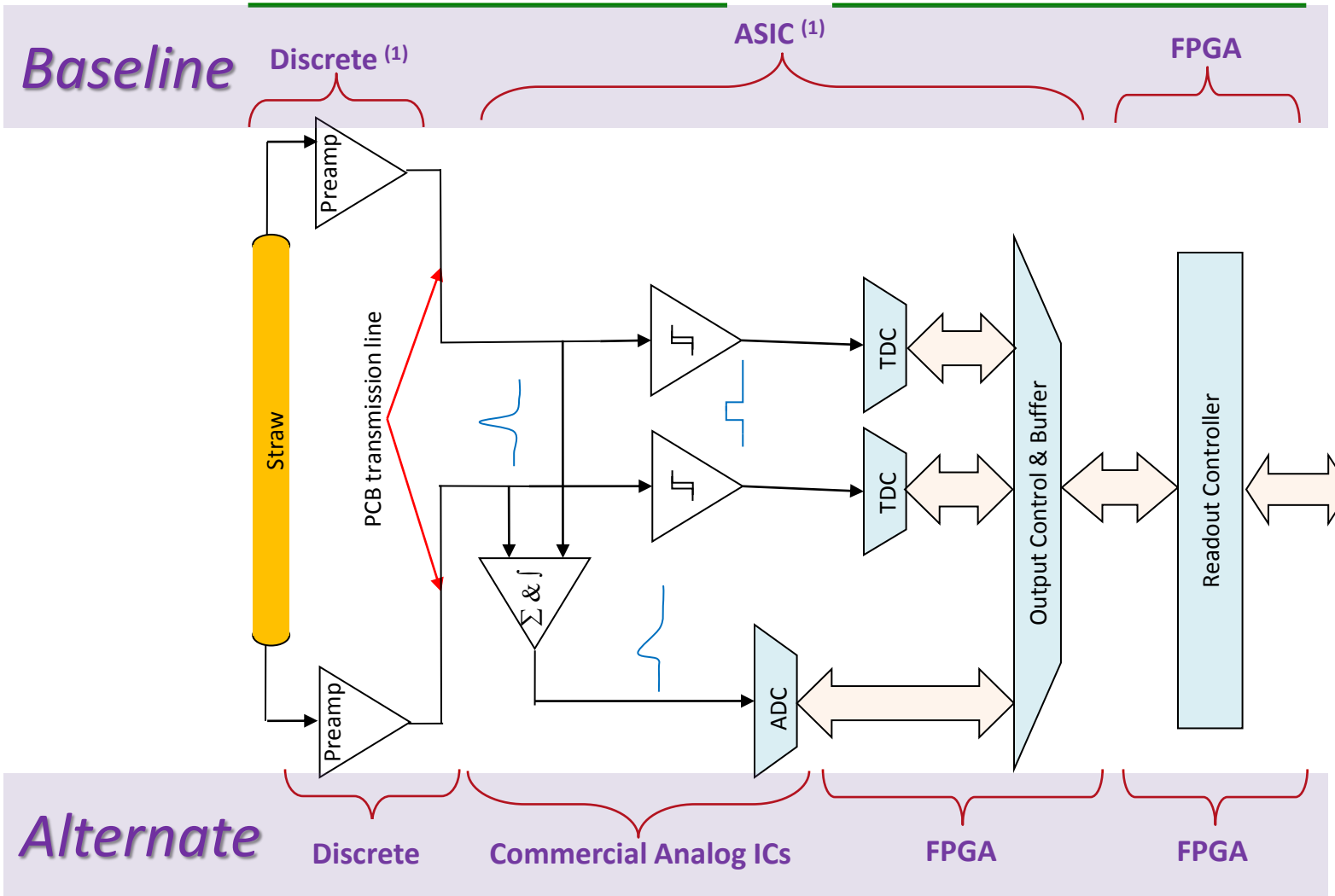


Tracker

- 18 stations + Support Structure
- Support beams also serve as cable trays

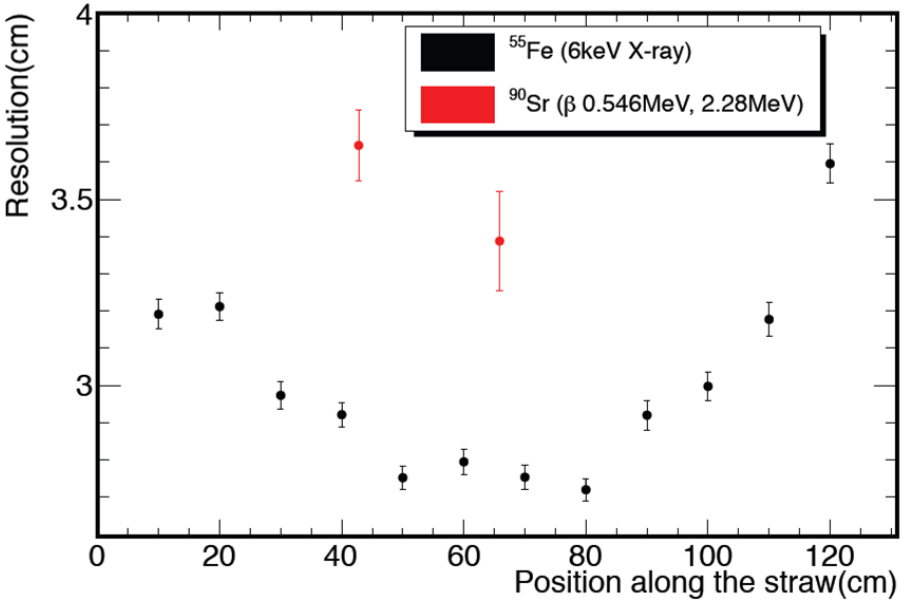


Front End Electronics



Time Division

- Use difference in signal arrival time at straw ends to estimate position along wire
- Resolution much worse than stereo (<1mm)
- Needed for stand-alone pattern recognition (not using calorimeter for timing)



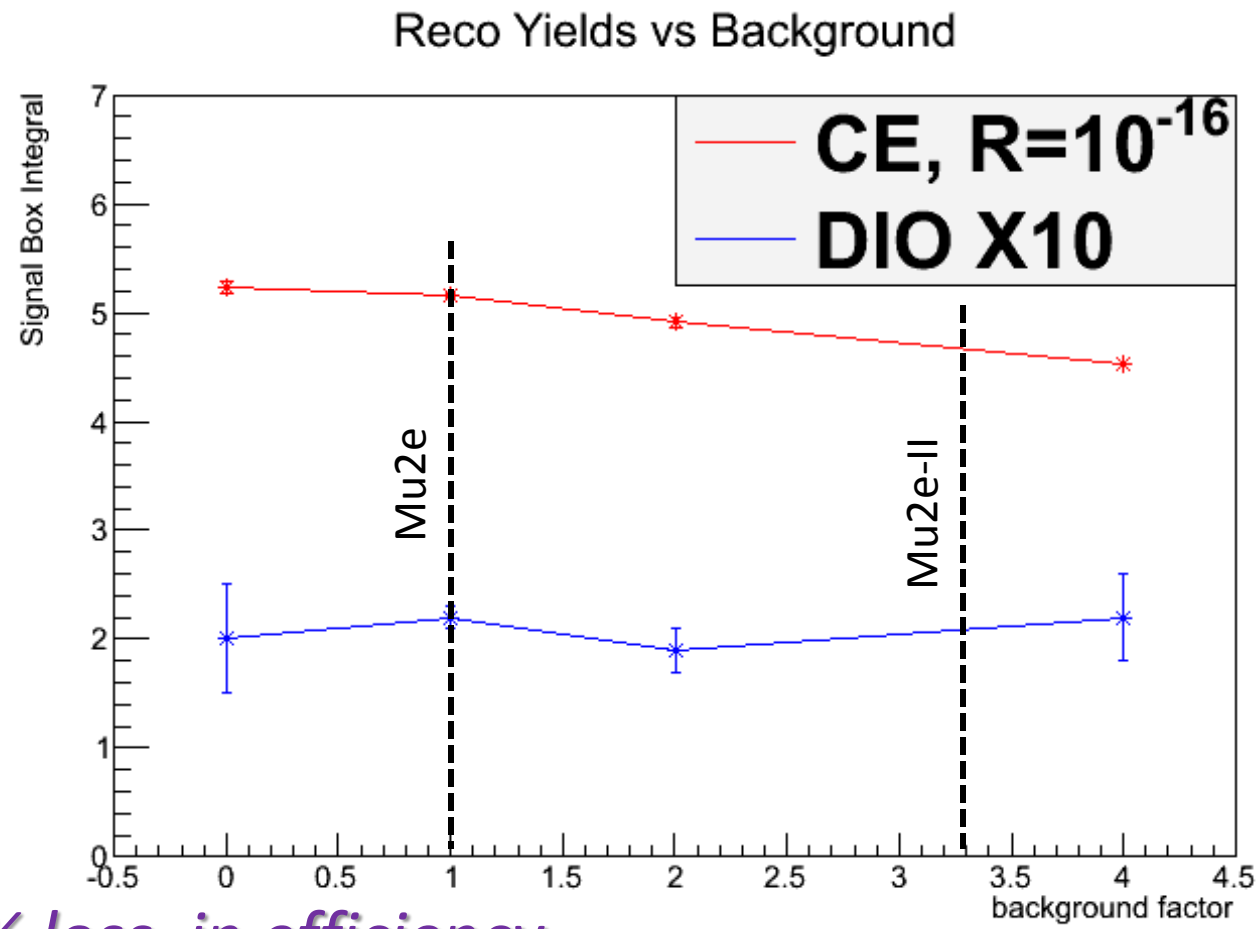
Difference caused by noise and large pulses from ^{55}Fe, while ^{90}Sr pulses are close to what we expect.

Continuing to work on reducing noise to bring the two closer together

Mu2e Tracker & Project X

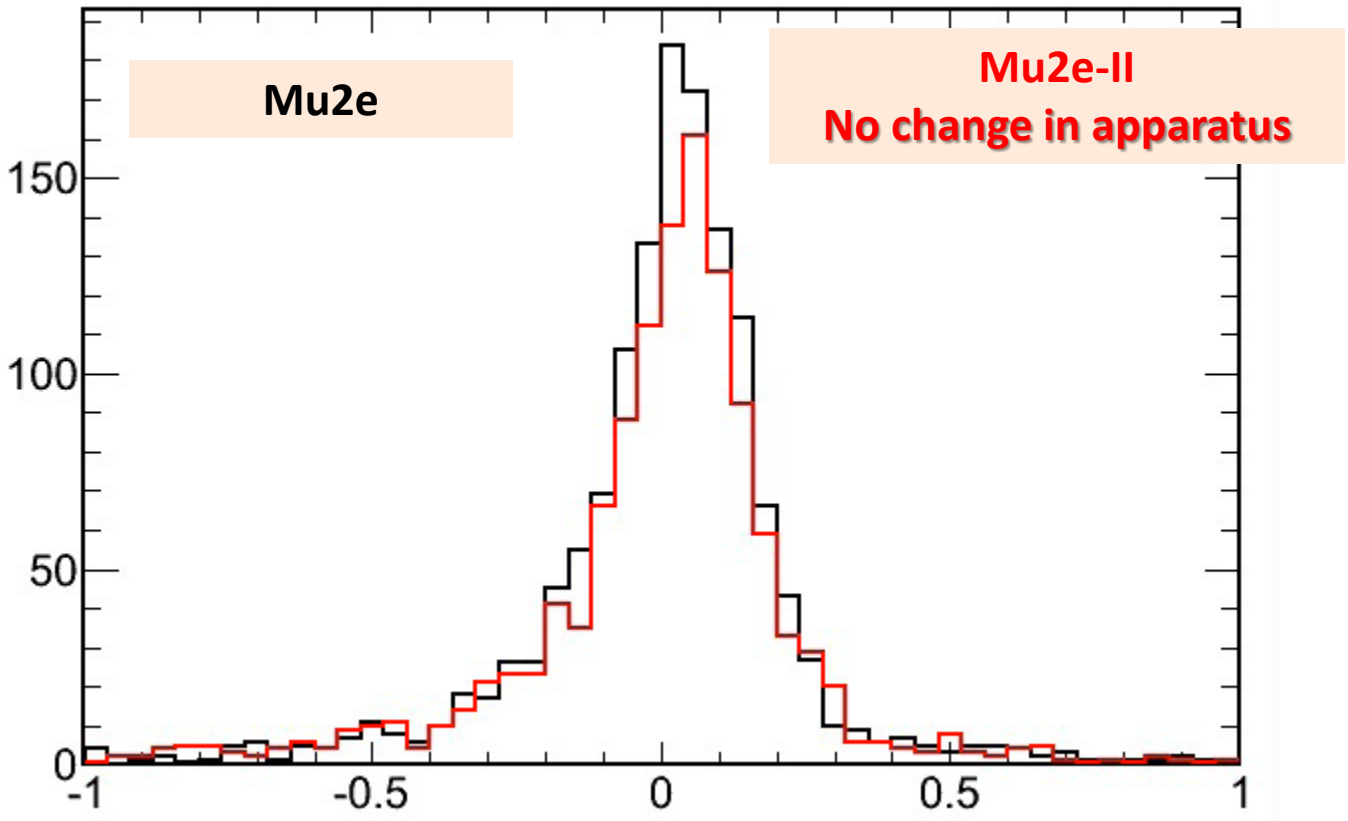
- Mu2e-II: 10× rate increase
  - 3× instantaneous rate
    - Affects performance directly (higher occupancy)
    - Can study via simulations
      Already studied up to ×4 background rates as part of understanding mu2e robustness
  - 3× duty factor
    - No direct affect on performance
    - Concern is radiation damage (aging)
- Mu2e-III: 100× rate increase
  - Unlikely this tracker can survive

Efficiency



<5% loss in efficiency

Resolution



*Loose cuts … **not** resolution used for most analysis*

Key point: No significant change

Rebuild

- Thinner walls
  - 8μm instead of 15μm
  - Less scattering
  - Fewer conversions & δ-rays
- Run sub-atmospheric
  - 8μm unsafe for 15psid
  - Fine for 8psid
- Side benefit: shorter ion drift time
  - Less space charge

- Cannot operate at nominal gas density in air
- Harder to test
- But … by then we'll have more experience

Summary

- Mu2e has a tracker design well suited for operation starting ~2019
- For mu2e-II, the detector is expected to continue to operate adequately, but rebuilding with thinner straws may be better
- Mu2e-III will require an entirely different design