The Mu2e Tracker

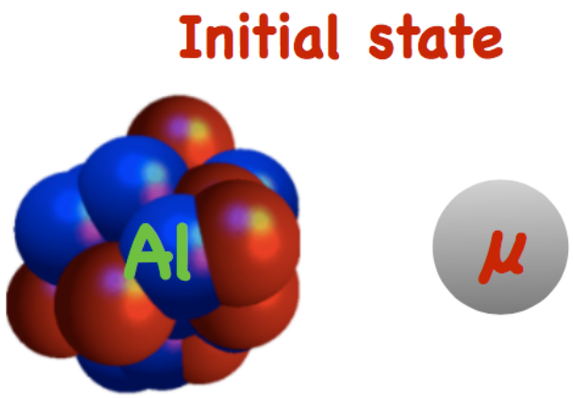
Jason Bono on behalf of the Mu2e Collaboration

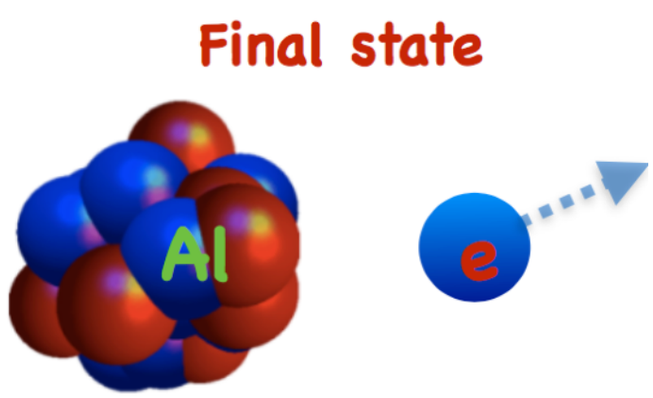
Symposium and Memorial in Honor of Marj Corcoran

Rice University, April 26, 2017

Mu2e in a Slide

- Mu2e will search for the neutrino-less conversion of a muon into an electron within the vicinity of a nucleus, $\mu N \rightarrow eN$
  - Unprecedented sensitivity: 10,000-fold improvement on the world's best!
- Mu2e will have sensitivity to a multitude of New Physics phenomena with mass scales up to 10,000 TeV
  - Far beyond the mass scales accessible at colliders
- Mu2e could discover Charged Lepton Flavor Violation
  - Thereby providing unambiguous evidence of physics beyond the Standard Model
- Regardless of the outcome, we will ultimately help guide future experimental and theoretical developments in HEP

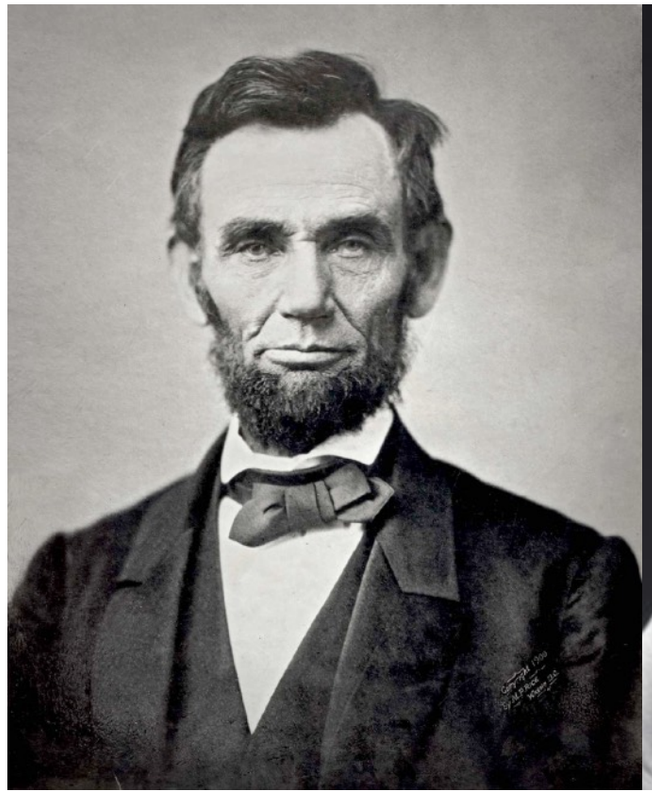




Venerable Opinions

Marj believed in Mu2e

"We shall nobly save, or meanly lose, the last best hope of earth."

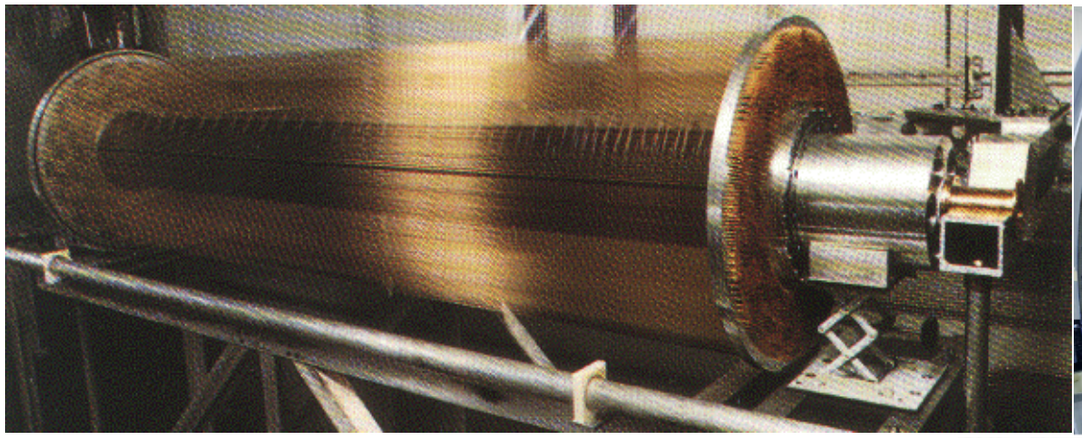
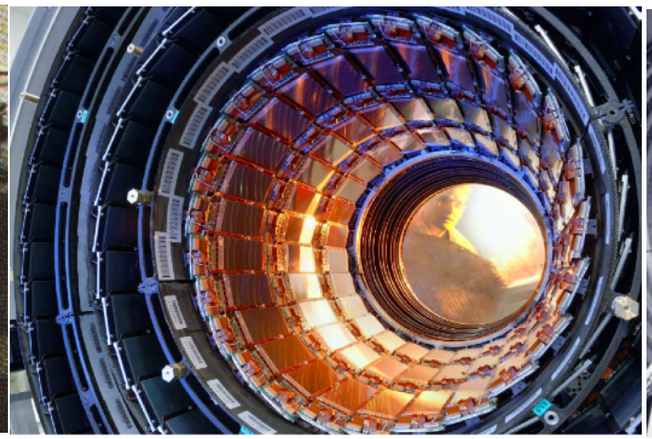
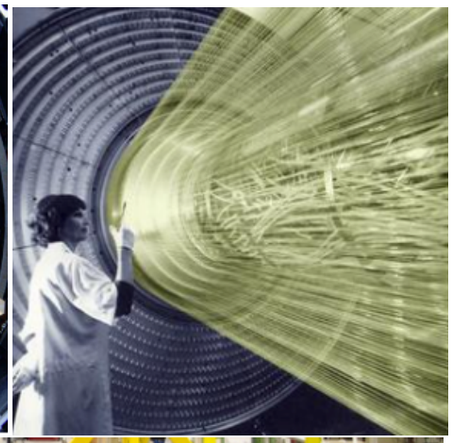


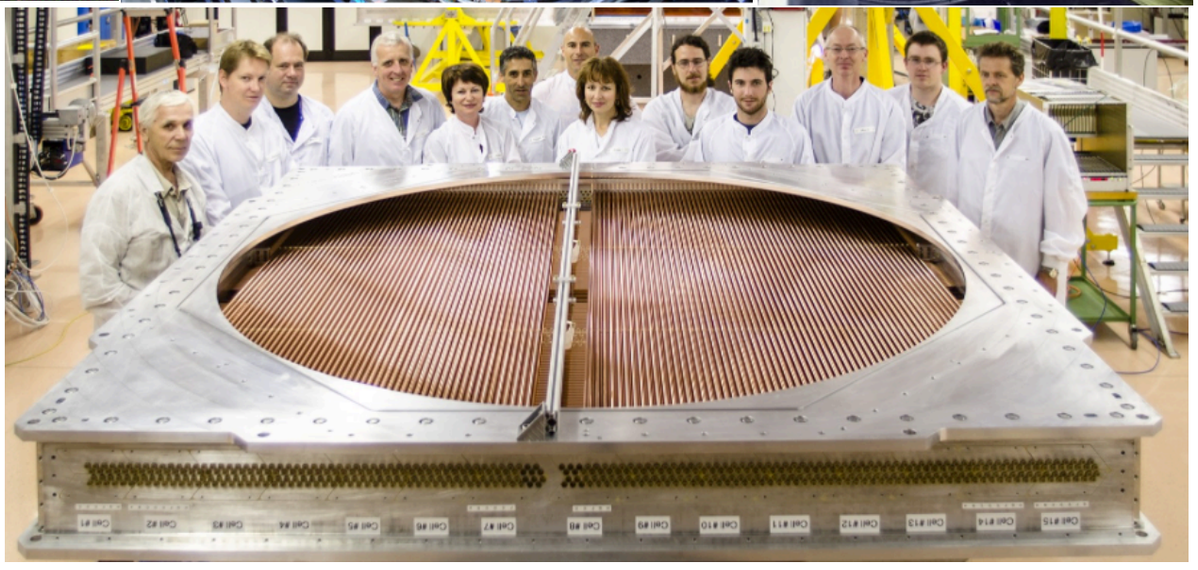
"Mu2e is MY last best hope for uncovering New Physics!"

And she made enormous contributions to the experiment

What's a Tracker?

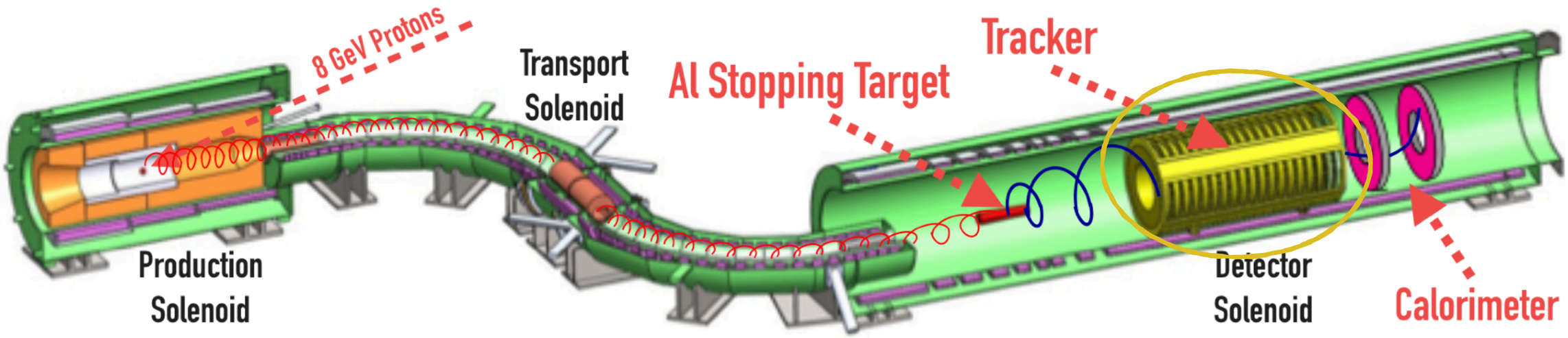
- A tracker is a detector that can measure the trajectory of a particle, usually without significantly altering it
  - This ultimately gives us knowledge of the particle's momentum/energy
    - In general, $d\mathbf{p}/dt = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$


The Mu2e Tracker

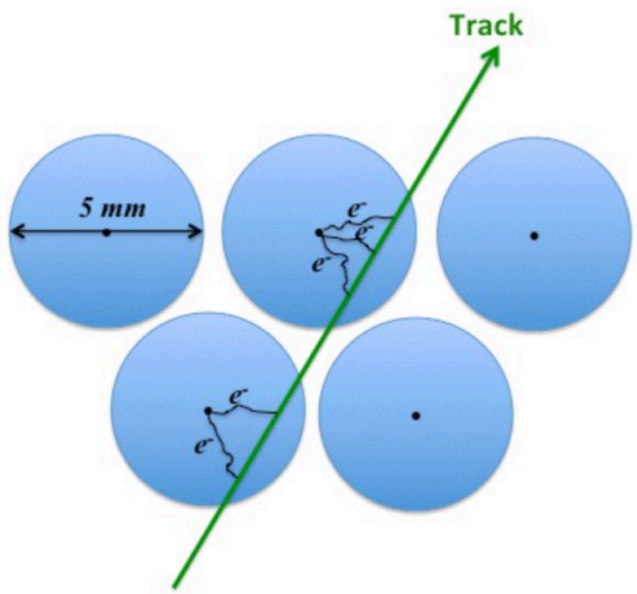
- In Mu2e, the conversion electrons move in a helix
  - p = 105 MeV
  - $p_\perp$ = qRB
- The Mu2e Tracker is designed to efficiently detect conversion electrons
  - While also not detecting most of the background
  - In early 2010, Marj held the Mu2e Collaboration Meeting at Rice, where much of the groundwork for the current detector design was established



The Mu2e Tracker: Design

Goal: efficiently detect conversion-electrons & reject background!

- 20,000 metalized mylar straw-tubes, filled with Ar:CO_2, running perpendicular to the B-field, in an ambient vacuum
  - 15 μm wall thickness
  - The gas alone is ~7% of the mass in the tracking region!
  - 0.5- 1.2 m long
  - Al: 500 Å inside and out. Au: 200 Å inside
- In each straw is a 25 μm gold plated tungsten wire
  - Held at ~1500 V
- The straws will be grouped into “panels” of 96
  - Total of 216 panels, grouped into 36 sextuples known as planes
  - 30 degree panel rotations help with stereo output

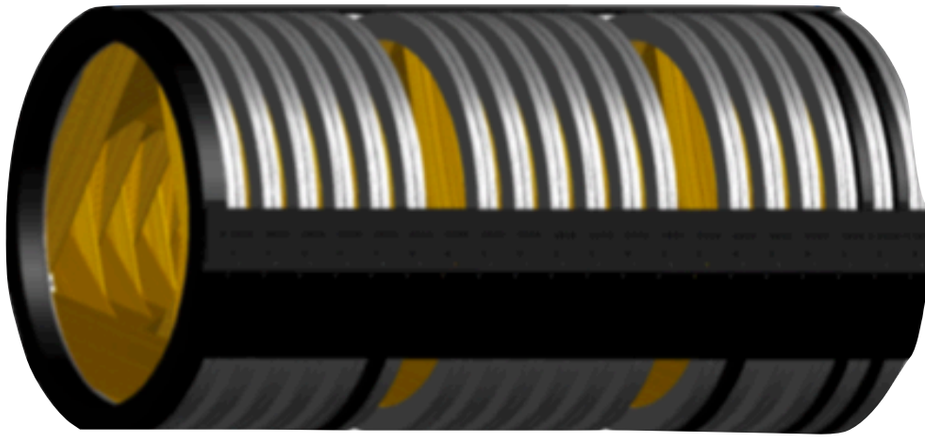


A straw next to a pencil

A photo of a panel

A plane

~ 10 ft



The entire tracker

A Few Requirements

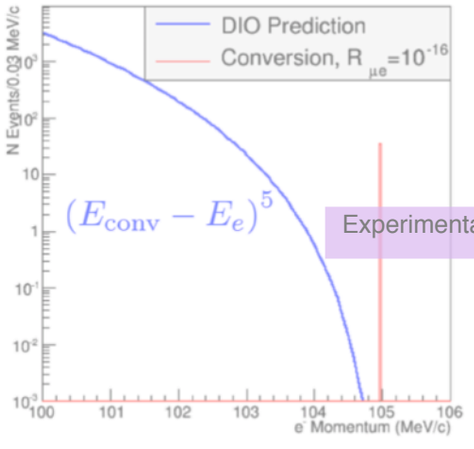
- Minimize energy loss and scattering
  - In other words, be ultra lightweight!
- Operate in vacuum (10^{-4} torr)
  - For reference, 10^{-3} torr is the U.S. definition of space flight
  - No one has ever built such a large, lightweight, tracker capable of operating in vacuum!
- Reliable: 10 year lifetime, etc.
  - This is more difficult than it might sound, particularly because of the other requirements

Marj helped a lot with these!

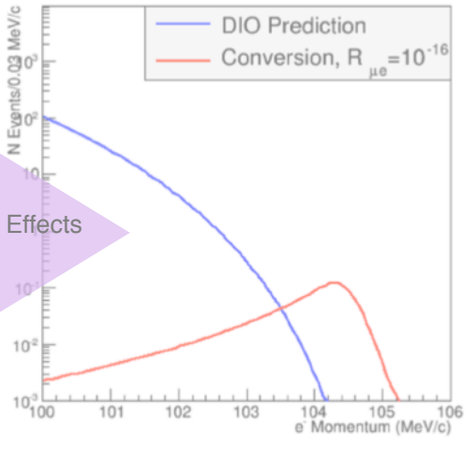
- Other requirements will not be discussed
  - (Acceptance)x(Reconstruction efficiency) > 20% @ 105 MeV/c
  - Momentum resolution $\sigma < 0.2\%$ @ 105 MeV/c
  - Blind to low momentum background

these too, but we wont be covering them!

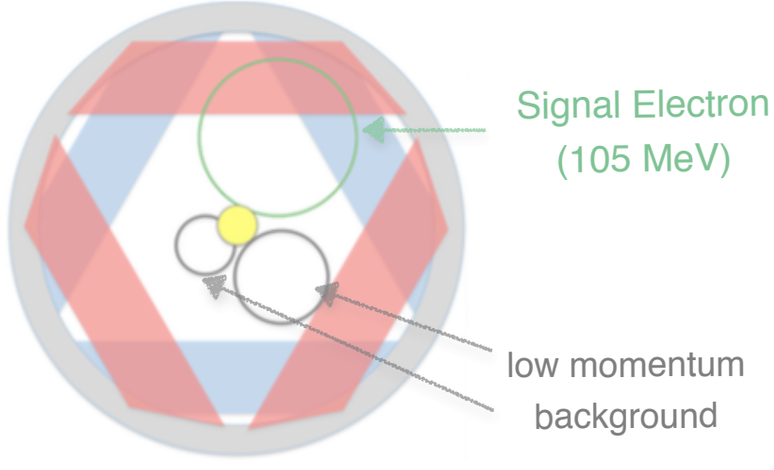
Perfect Experiment



Efficiency + ΔE + Resolution

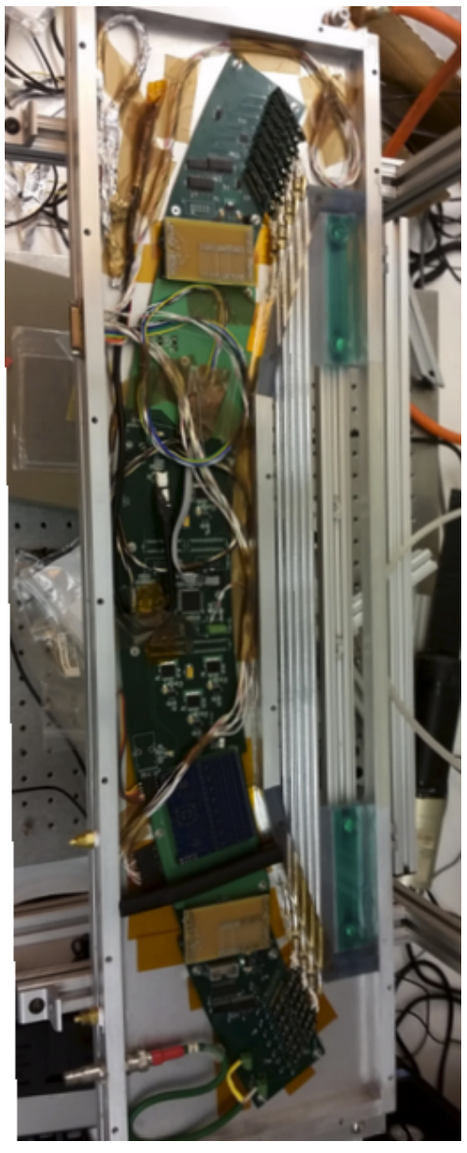


Experimental Effects

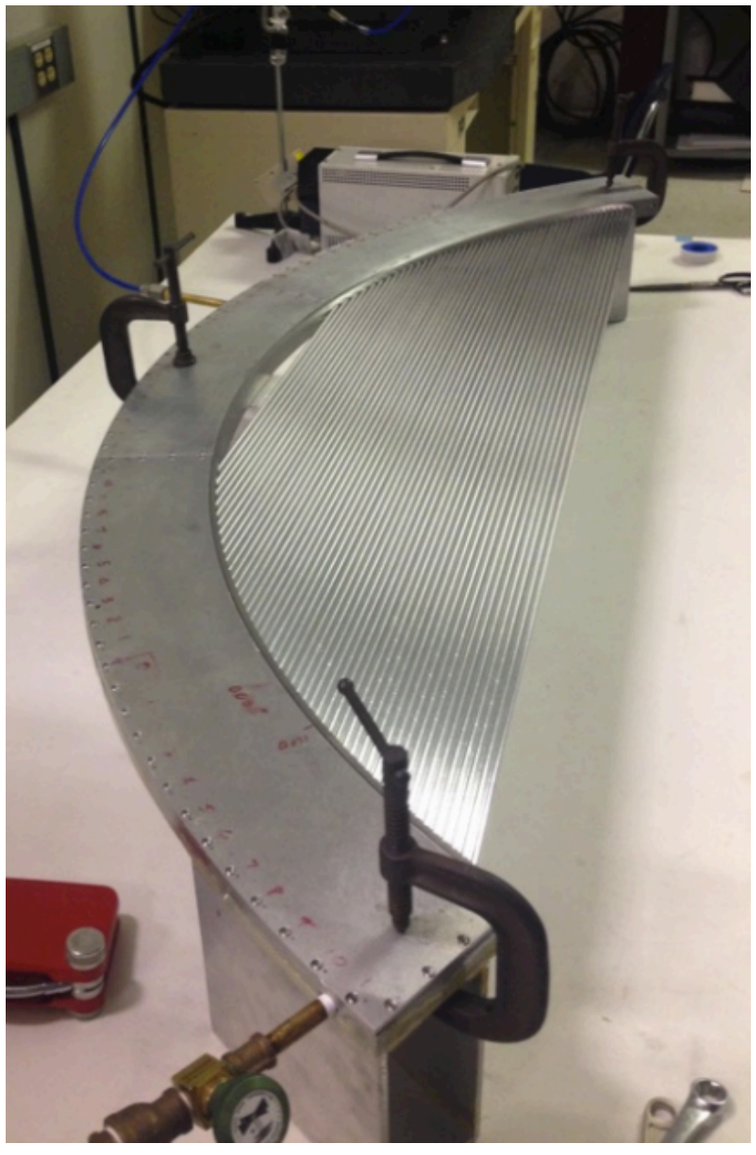


Recent Tracker Prototypes

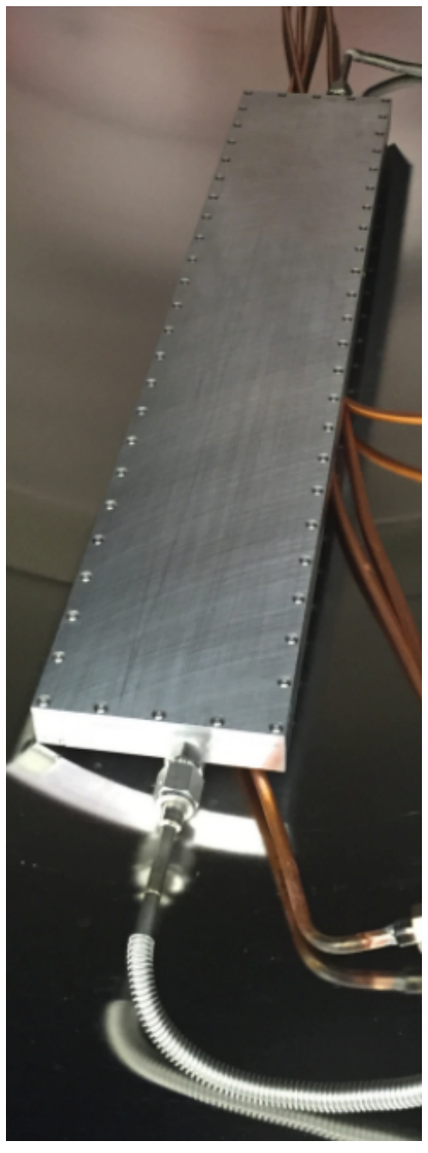
8-Straw Prototype



Full Panel V1.5



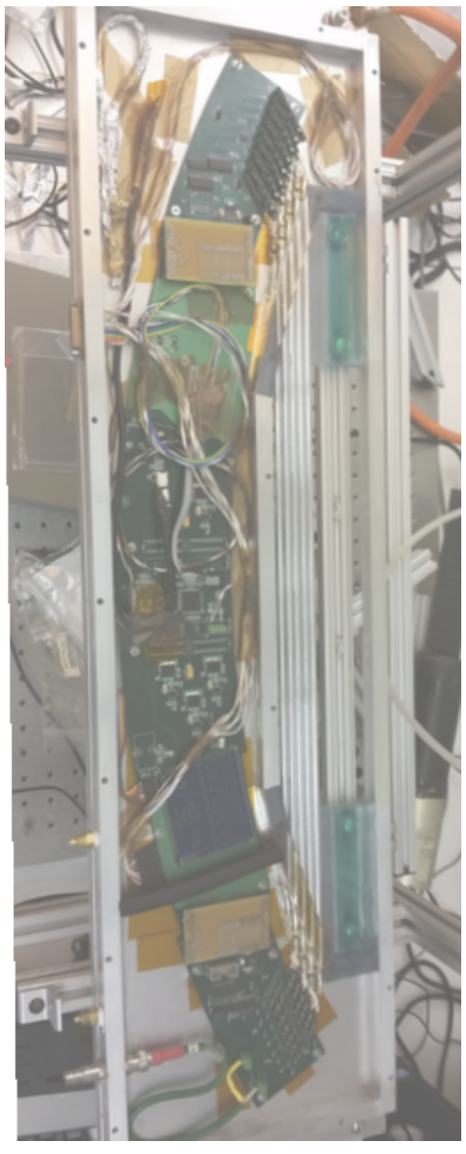
Rectangular Prototype 2



Early 2015 — Completion Date — Mid 2017

Recent Tracker Prototypes

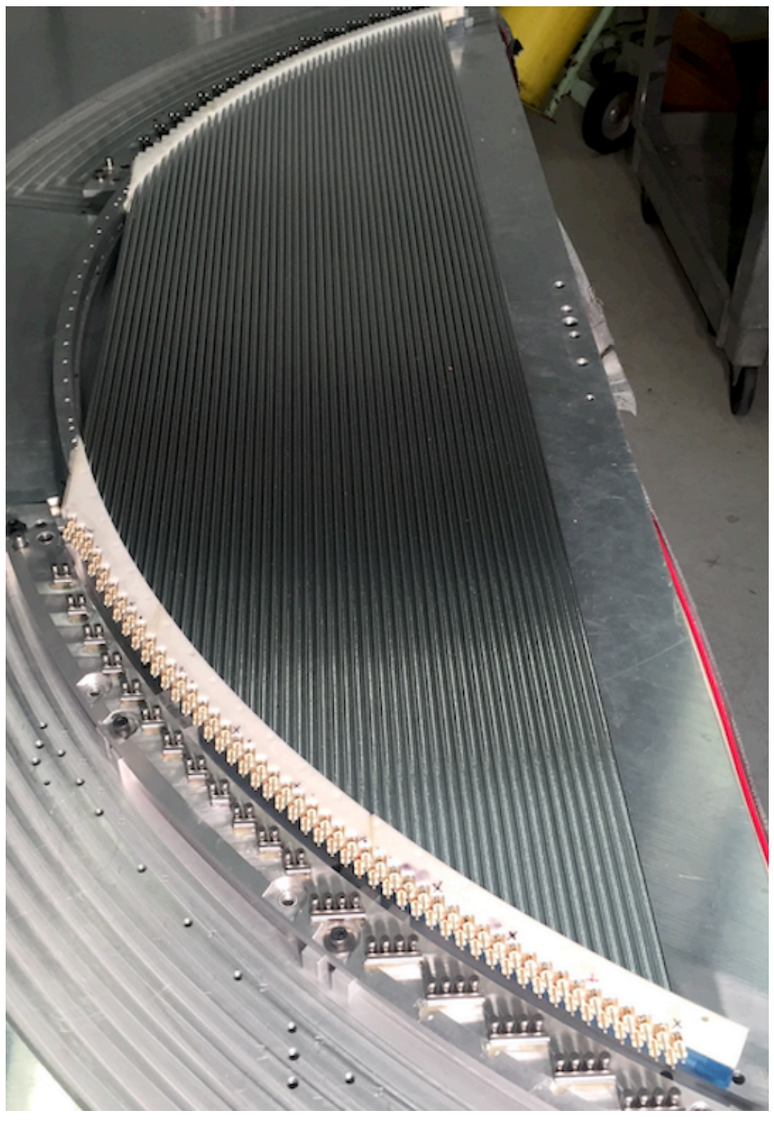
8-Straw Prototype



Full Panel V1.5

Rectangular Prototype 2

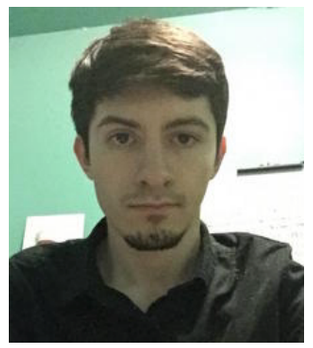
Full Panel V2.5



Early 2015 — Completion Date — Mid 2017

Meeting The Vacuum Requirement

- There are 20,000 straws which collectively must leak less than 6 cm^3/min
  - total surface area > $3x10^6$ cm^2 with ~1 atm of differential pressure (Ar:CO_2)
  - straws are delicate and we need to test each one!
- Vacuum measurements are time consuming
  - and in fact testing 20K straws this way would be impossible
- As it turns out, CO_2 permeates through mylar at least 10x faster than Argon[1,2]
  - any chemists in the audience? Email me!
- We can exploit this last point by using CO_2 sensors within specialized chambers!
  - like most things in science, this was a collaborative effort
  - but Marj took the idea, and with her students, developed it into a viable testing method which is being used now
    - Rice undergraduate #1: David Rivera (currently UPenn)
    - Rice undergraduate #2: Lauren Yates (currently MIT)



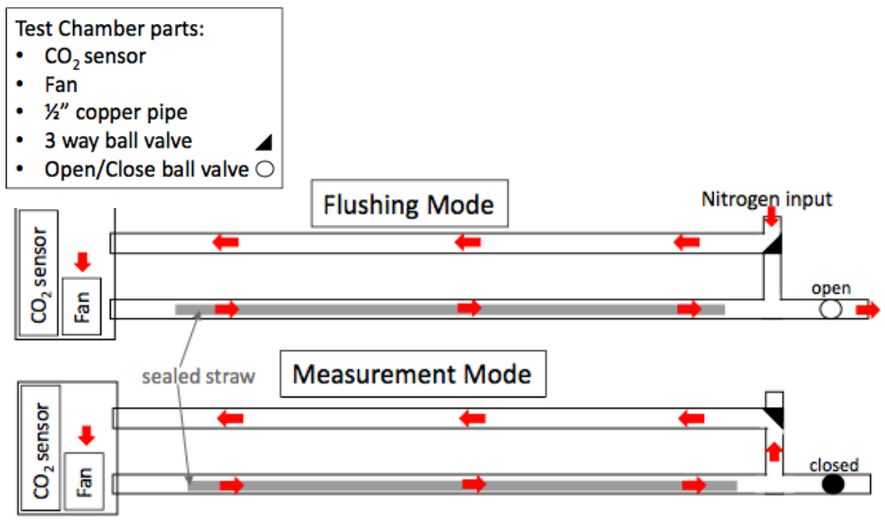
1: http://usa.dupontteijinfilms.com/informationcenter/downloads/Chemical_Properties.pdf

2:Brookhaven preprint BNL-4892, published in Journal of Vacuum Science and Technology A, vol 12, Issue 4

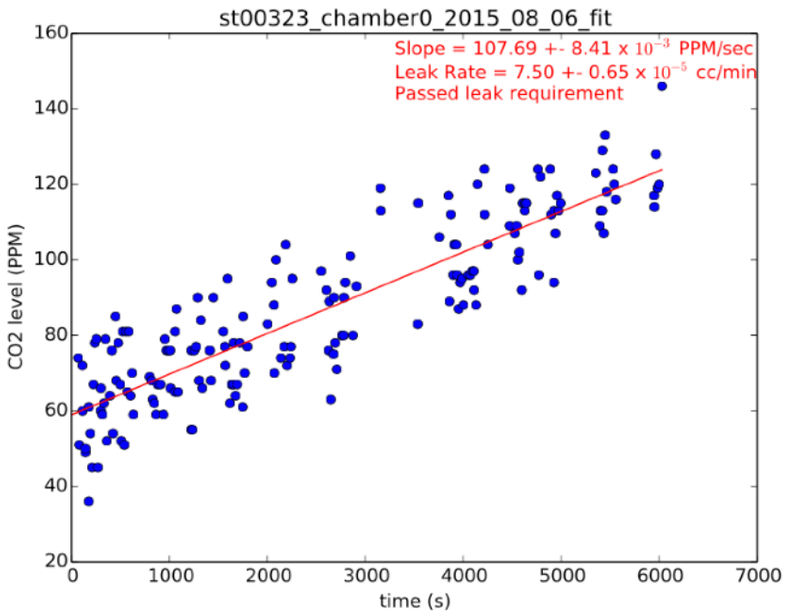
Meeting The Vacuum Requirement: A Novel Approach

How to test 20,000 straws for leaks?

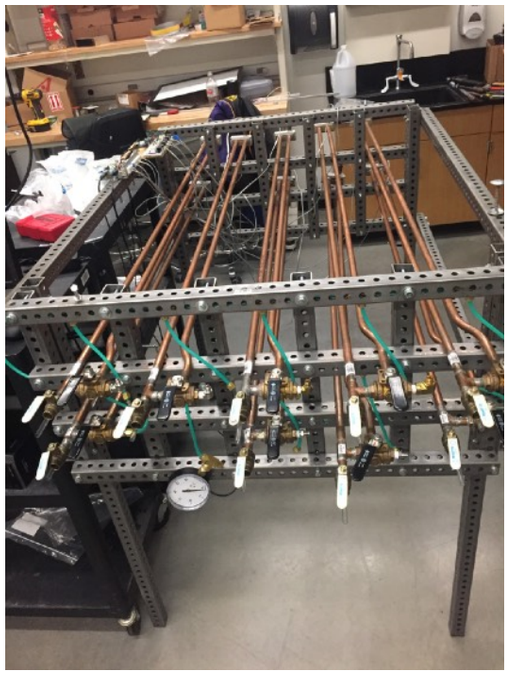
- Our CO_2 chambers are cost effective, efficient, and scalable!
  - insert a straw (inflated with CO_2)
  - purge the residual CO_2 with nitrogen
  - close the valves
  - collect data on the CO_2 rate of rise
  - script tells user when uncertainty is low enough to conclude pass/fail
  - takes about an hour per straw
- Currently have 10 operational chambers at UMN
- Our technology is being adopted elsewhere



Schematic of CO_2 chamber in both modes



An example of the CO_2 rate of rise from a straw

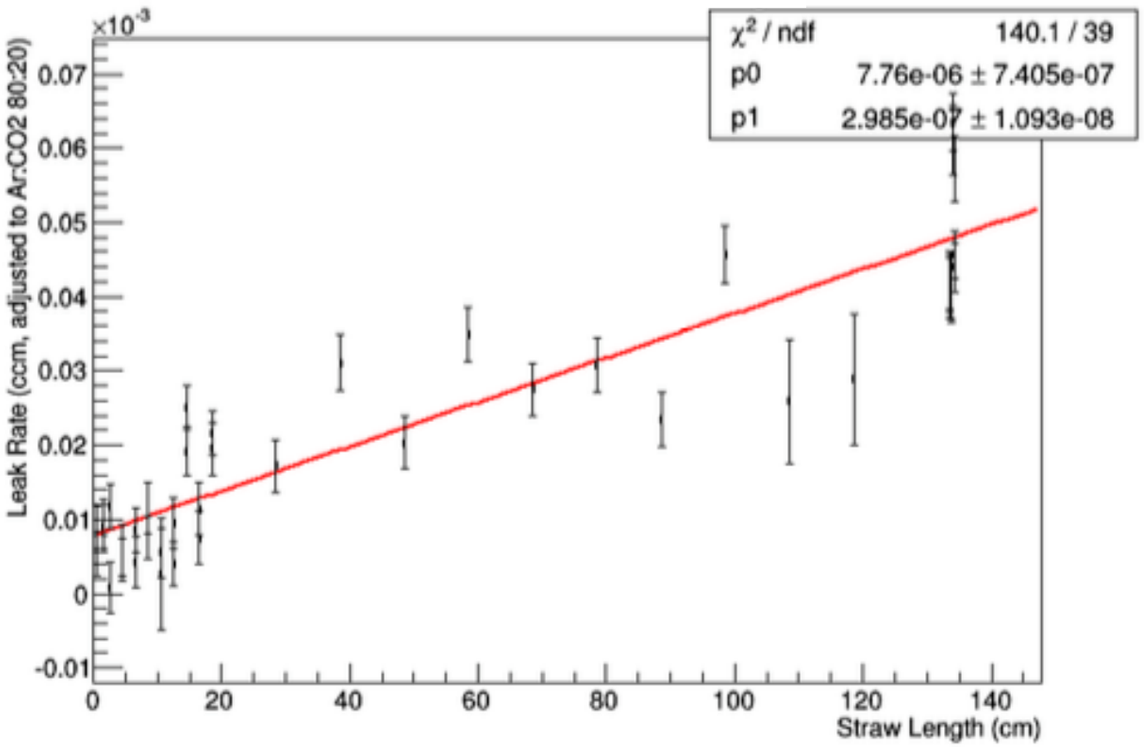


CO_2 Chambers at UMN

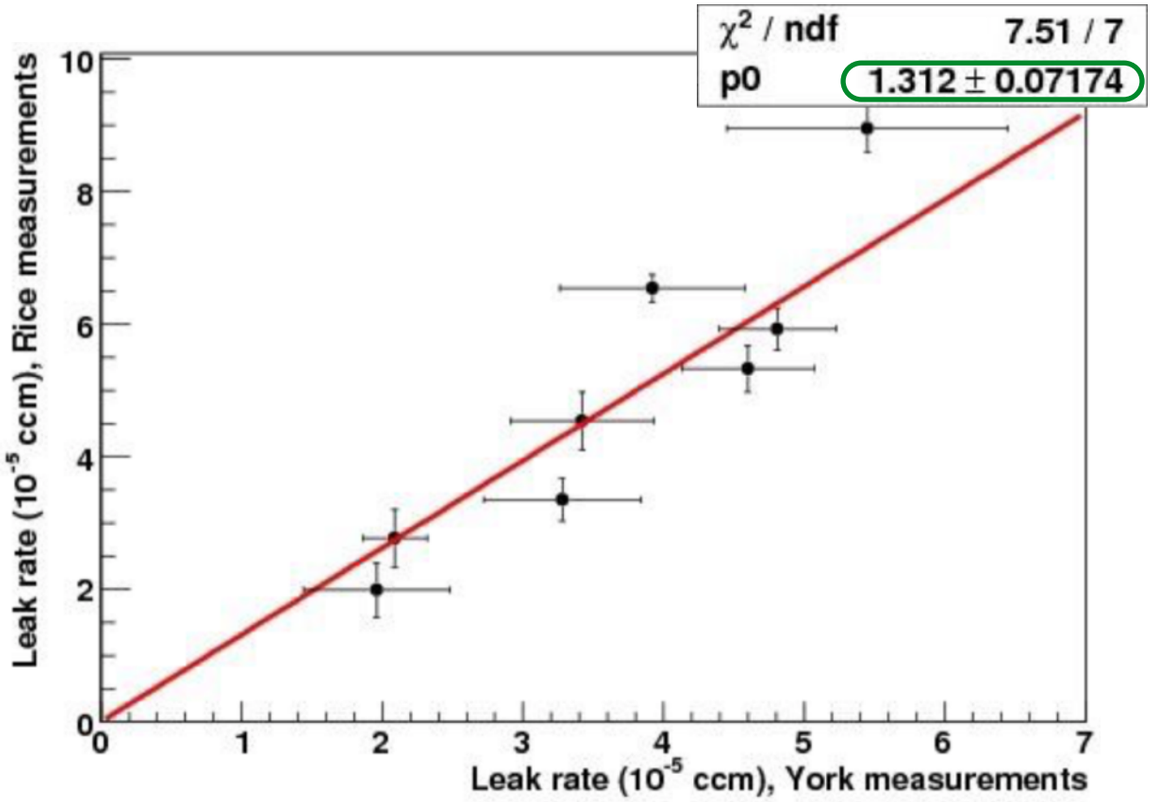
Meeting The Vacuum Requirement: A Novel Approach

- Marj also played a leading role in studying the systematics
  - time dependent end-piece contribution
  - background leak rate of chamber
  - uncertainty in Ar/CO_2 relative leak
  - etc.
- No time for details!

Leak Rate vs Straw Length

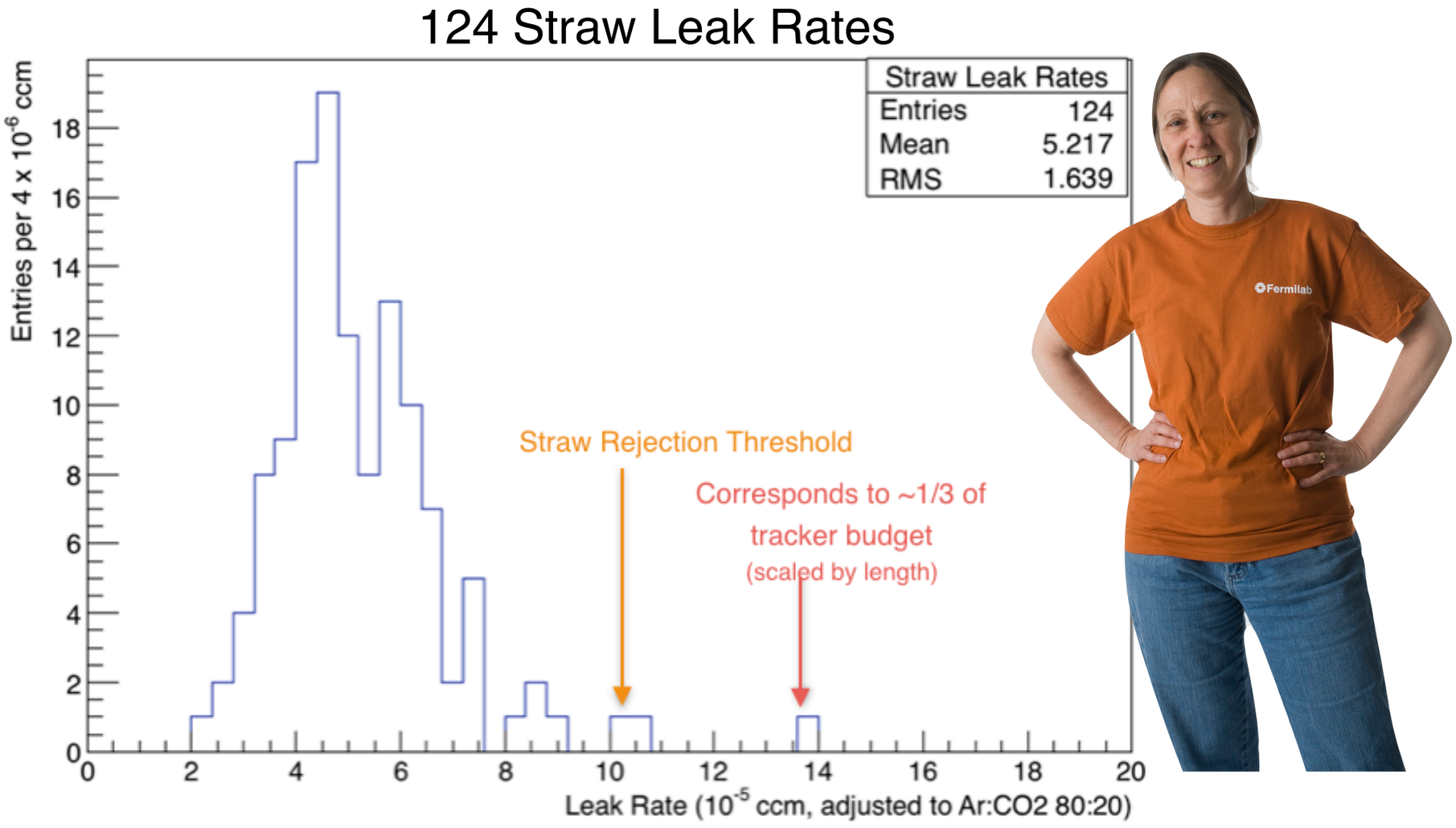


CO2 Measurements vs Vacuum Measurements



So Far, Our Straws Look Good!

- Scaling for length, the plot below indicates that the straws only spend 1/8th of the entire tracker leak budget!
  - This is good news, because the straws are expected to constitute the majority of the total outgassing + leak rate budget



Tracker Lifetime: The Problem

- For a number of reasons, we must position the straws to within ~ 150 μm and we need to keep them straight!
  - Around 3 newtons of tension keeps them straight enough for our purposes
  - But the straws stretch over time, relaxing the tension!
  - This gradual strain is known as “creep,” and most materials do it
  - Want as much tension as necessary but as little as possible
  - We need a way to monitor straw tension!
  - This is another area where Marj made major contributions

A “sagging” straw with zero tension

Creep is partially responsible for tectonic shifts

Tracker Lifetime: Vibrational Motion of Straws

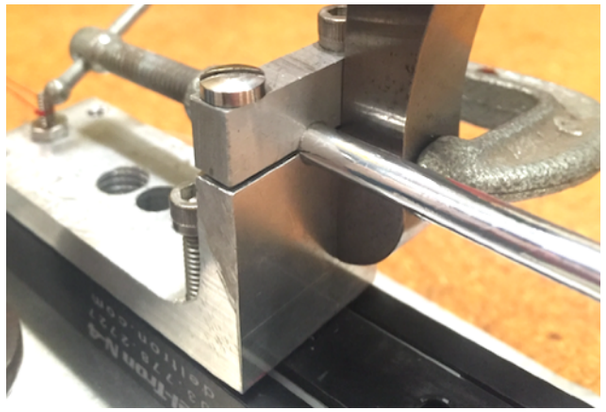
$$\mu \frac{\partial^2 y(x,t)}{\partial t^2} = T \frac{\partial^2 y(x,t)}{\partial x^2} - B \frac{\partial^4 y(x,t)}{\partial x^4}$$

B = Bending Stiffness
$\boldsymbol{\mu}$ = Linear Mass Density
T = Tension

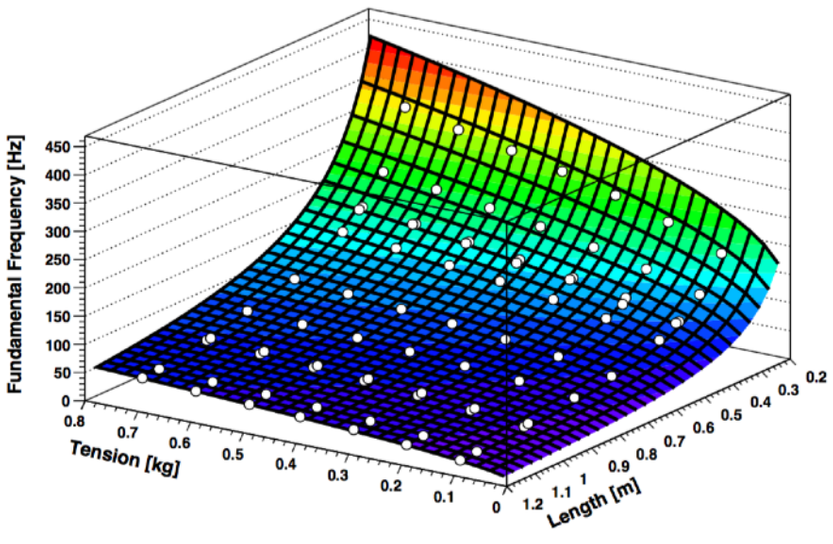
$$\mathcal{K} \equiv \sqrt{\frac{g}{\mu}} \quad \mathcal{C} \equiv \sqrt{\frac{B}{\mu}}$$

Boundary Condition 1

$$f_1 = \frac{\mathcal{K}}{2L}\sqrt{m} + \frac{\mathcal{C}}{L^2}$$

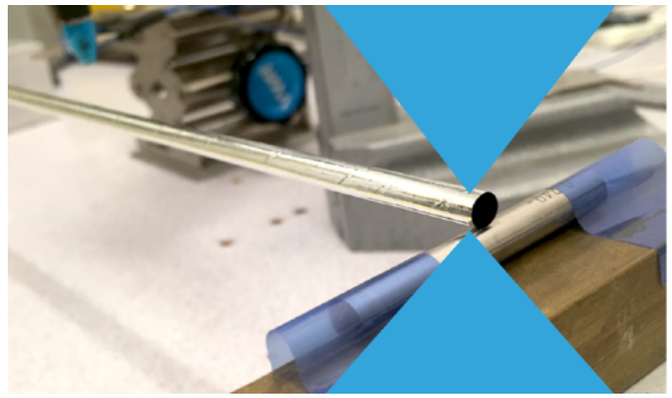


"Perfectly Glued"

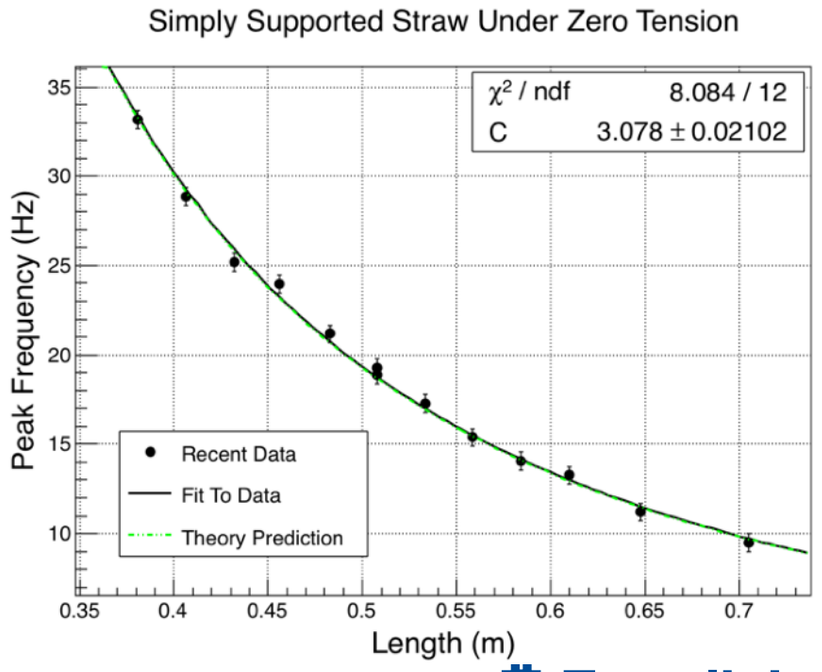


Boundary Condition 2

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}\sqrt{\frac{n^2\pi^2 B}{TL^2} + 1}$$



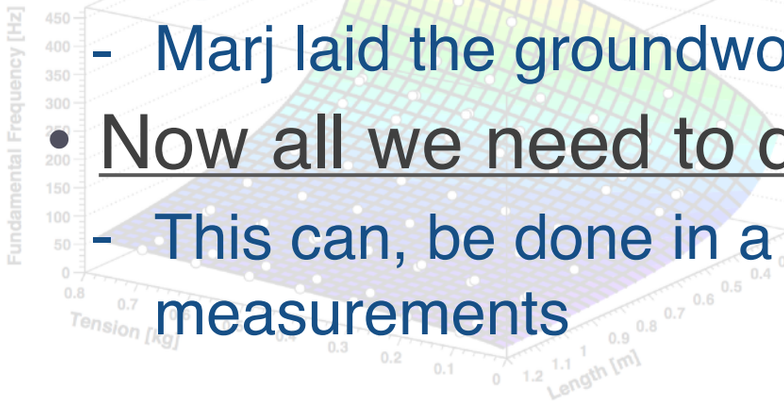
"Perfectly Pinned"



Tracker Lifetime: Vibrational Motion of Straws

- There are many ingredients to the solution
  - Obtain the correct differential equation
  - Apply appropriate boundary conditions
  - Stretch of the straw changing its density and stiffness
  - Metallization layer affecting the stiffness
  - Oxidation of the metallization layer!
  - Mass of air inside the tubes
  - Mass of air outside the tubes! “virtual mass”

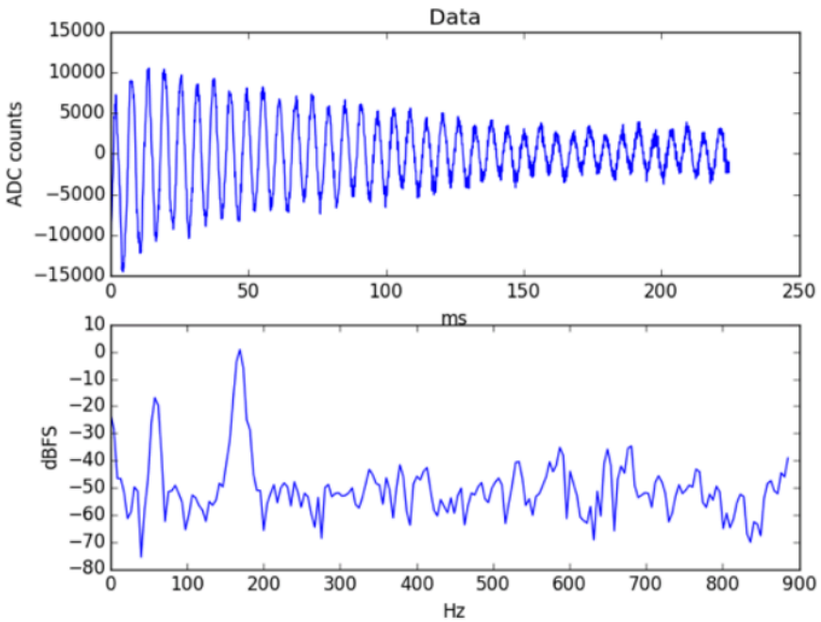
- In short, we now have an understanding of the vibrational properties of our straws at the % level
  - Marj and her student collected the original data, without which we would have never figured out the relationship
  - Marj laid the groundwork on the modeling side as well
- <u>Now all we need to do is measure the frequency to get tension!</u>
  - This can, be done in a much wider set of circumstances than “direct” tension measurements



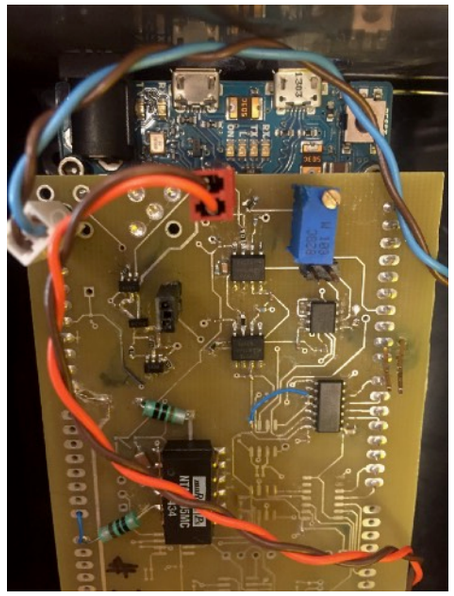
Tracker Lifetime: Magnetic Plucking

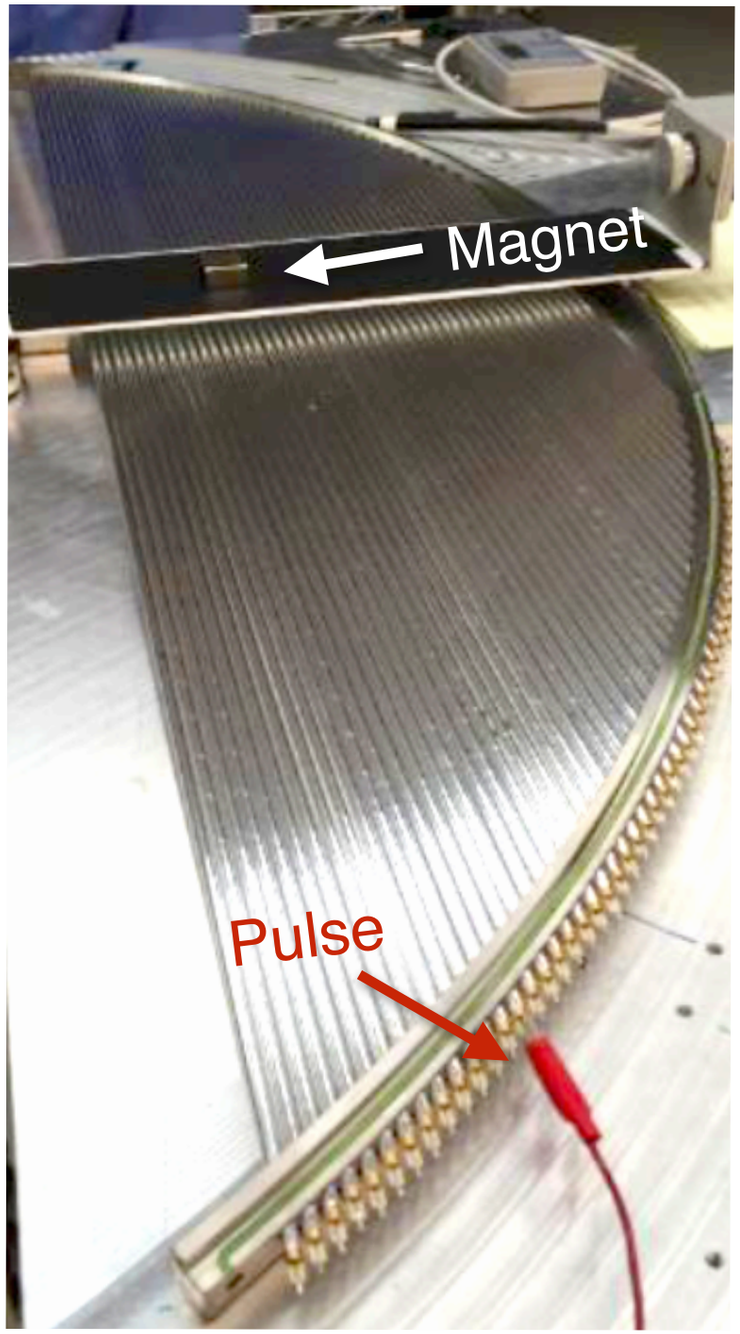
1. Send a current pulse of a few ms through a straw in a magnetic field
2. **F** = I**L**x**B** deflects the straw
3. Straw vibrates in the B-field, inducing AC current
4. The peak frequency = straw natural frequency!

- Once again, many people worked on this
  - And once again, Marj and her students played a leading role in making it work
    - Improved the circuit
    - Improved the code
    - Empirically discovered a signal optimization using pulse-width and worked out the physics to explain why it works



A typical signal


The circuit board

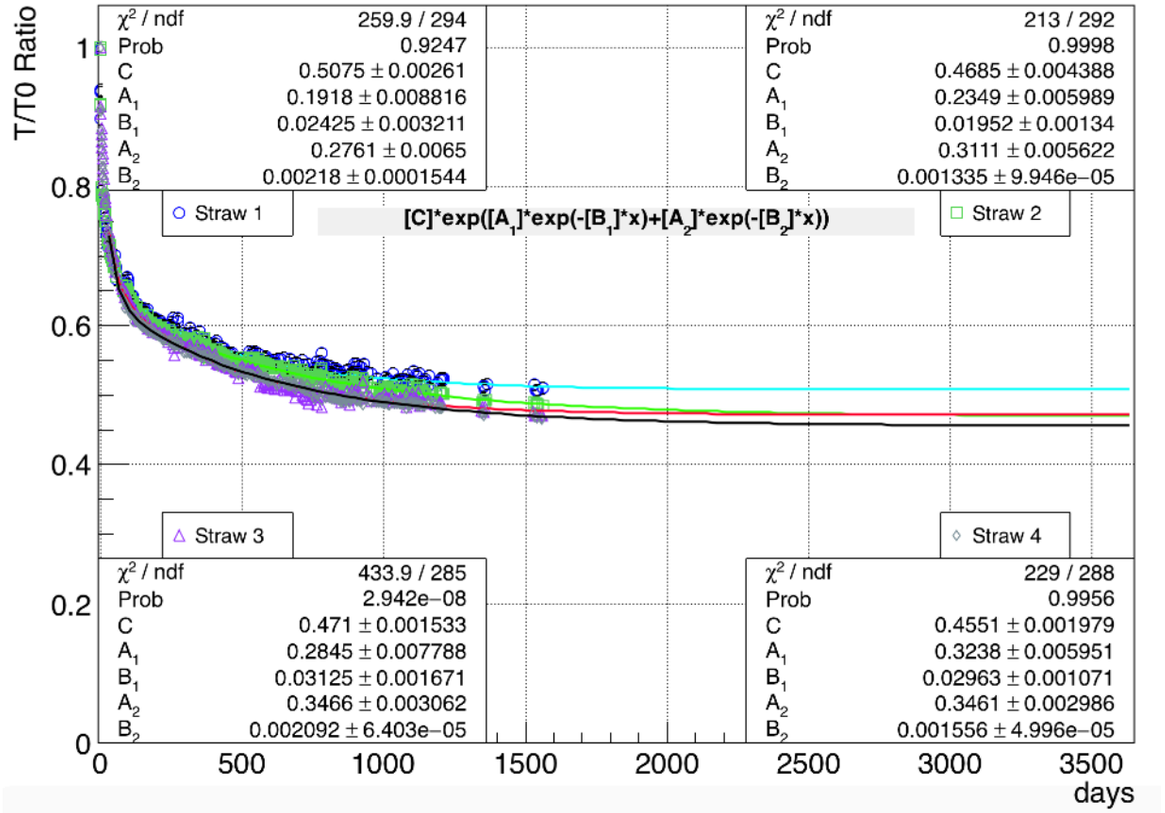


Measuring tension on a prototype panel

Tracker Lifetime: Tension Relaxation Data

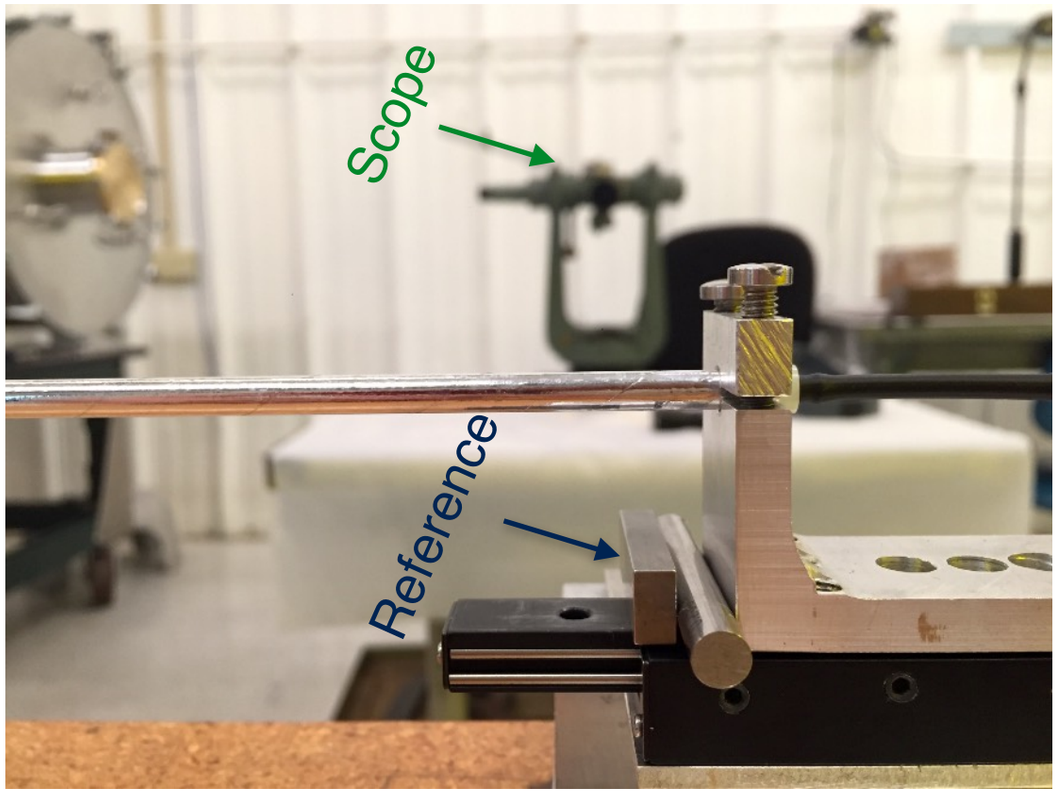
- Using the magnetic plucking technology, Duke collected frequency vs time data for 4 straws
  - All straws identical length with “glued” boundary conditions
  - Different tensions: approximately 3, 4, 5, and 6 newtons for straws 1, 2, 3, and 4, respectively
- We can produce the below tension plot by using our frequency-tension relationship
- The fitting function is physically motivated but can’t be discussed here.
- We learned that regardless of the initial tension, the straws should drop to around 45% thereof in ten years
  - So if the straws need ~3 newtons to stay straight, we just set the initial tension to ~6.7 newtons!
  - We worry about damage after ~10 newtons, so we have some margin

Tension Relaxation

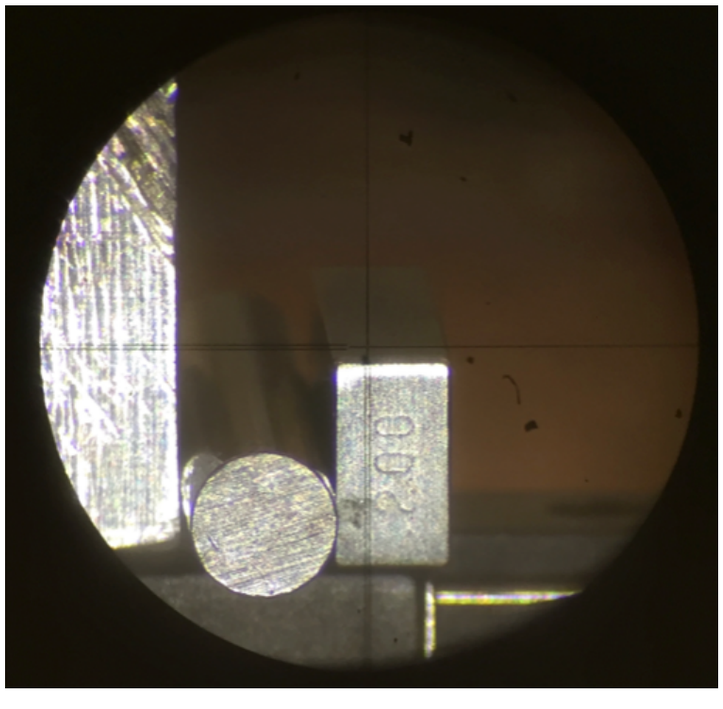


Tracker Lifetime: Setting the Straw Tension

- One could set the straw tension directly
  - e.g. via servo motor pulls the straw with tension feedback
  - But there are many problems with this approach
- Better to place the ends of every straw in the same place every time
  - Need to know the spring constant for straws
    - Marj played a primary role in determining this



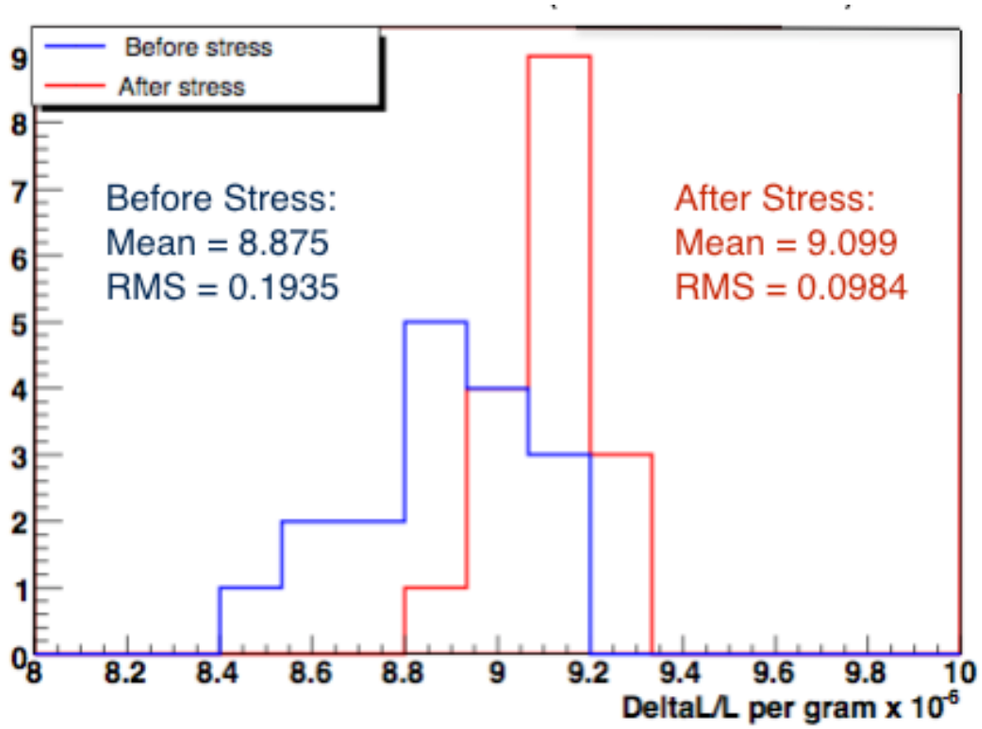
Straw on a low-friction slider



Reference viewed by the scope

Tracker Lifetime: Setting the Straw Tension

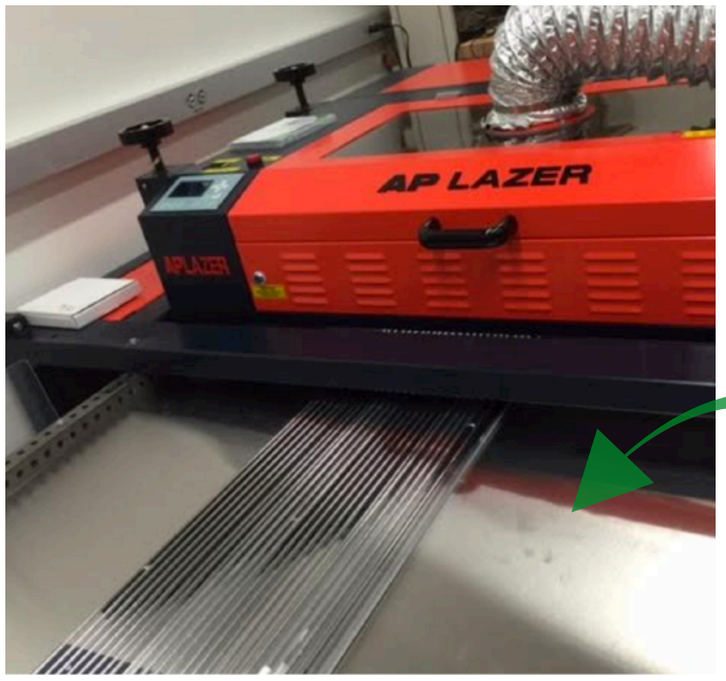
- One could set the straw tension directly
  - e.g. via servo motor pulls the straw with tension feedback
  - But there are many problems with this approach
- Better to place the ends of every straw in the same place every time
  - Need to know the spring constant for straws
    - Marj played a primary role in determining this



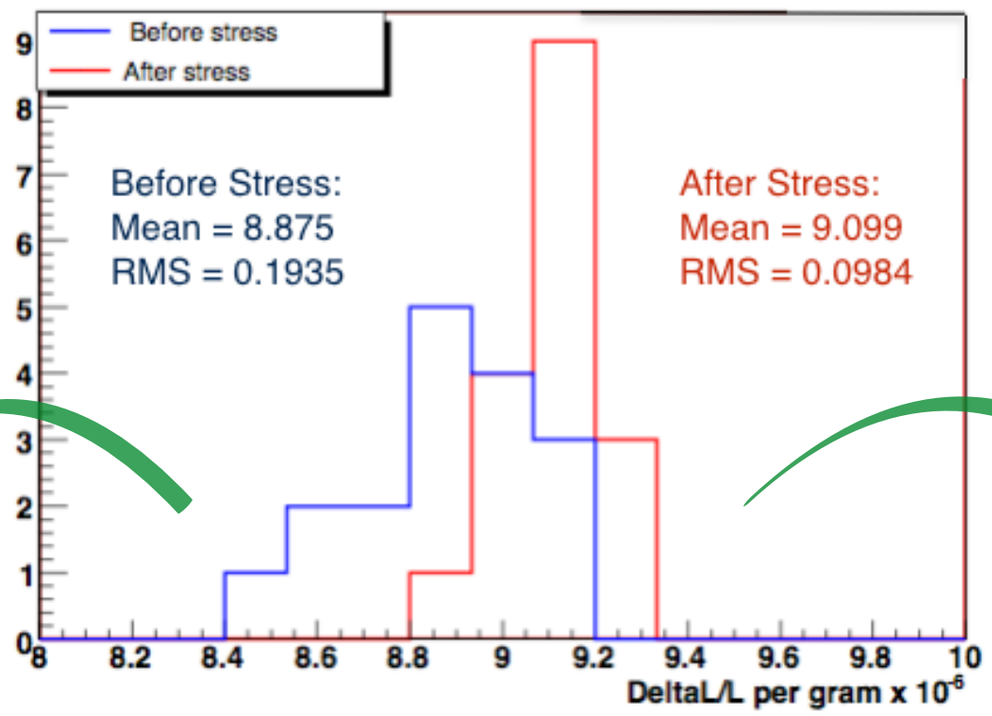
The spring-constant distribution for Mu2e straws

Tracker Lifetime: Setting the Straw Tension

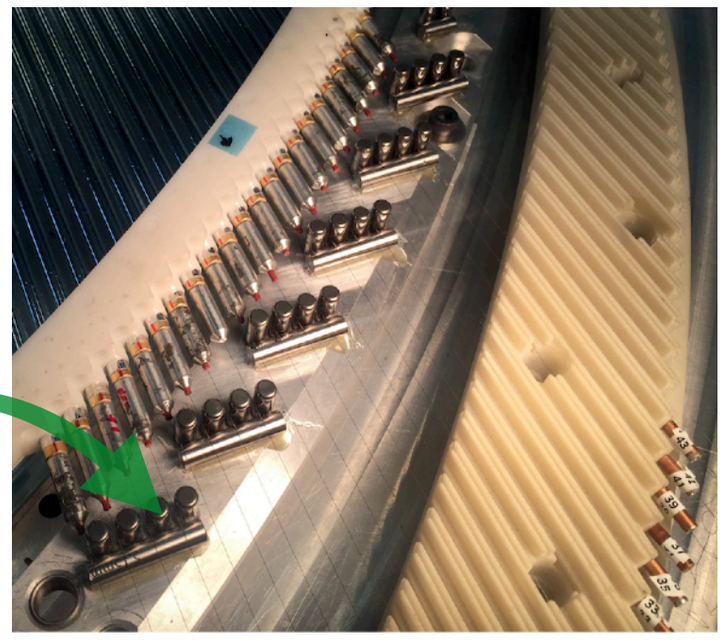
Tensioning 20,000 straws just got a lot easier!



Laser cutting the straw



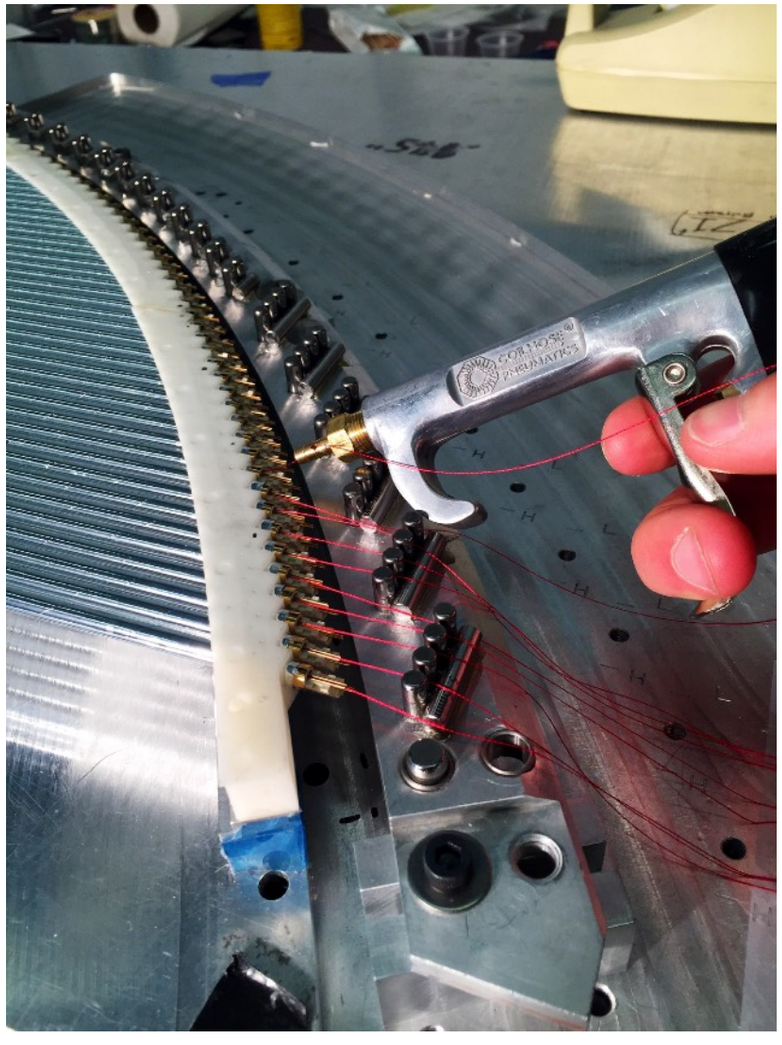
The spring-constant distribution for Mu2e straws

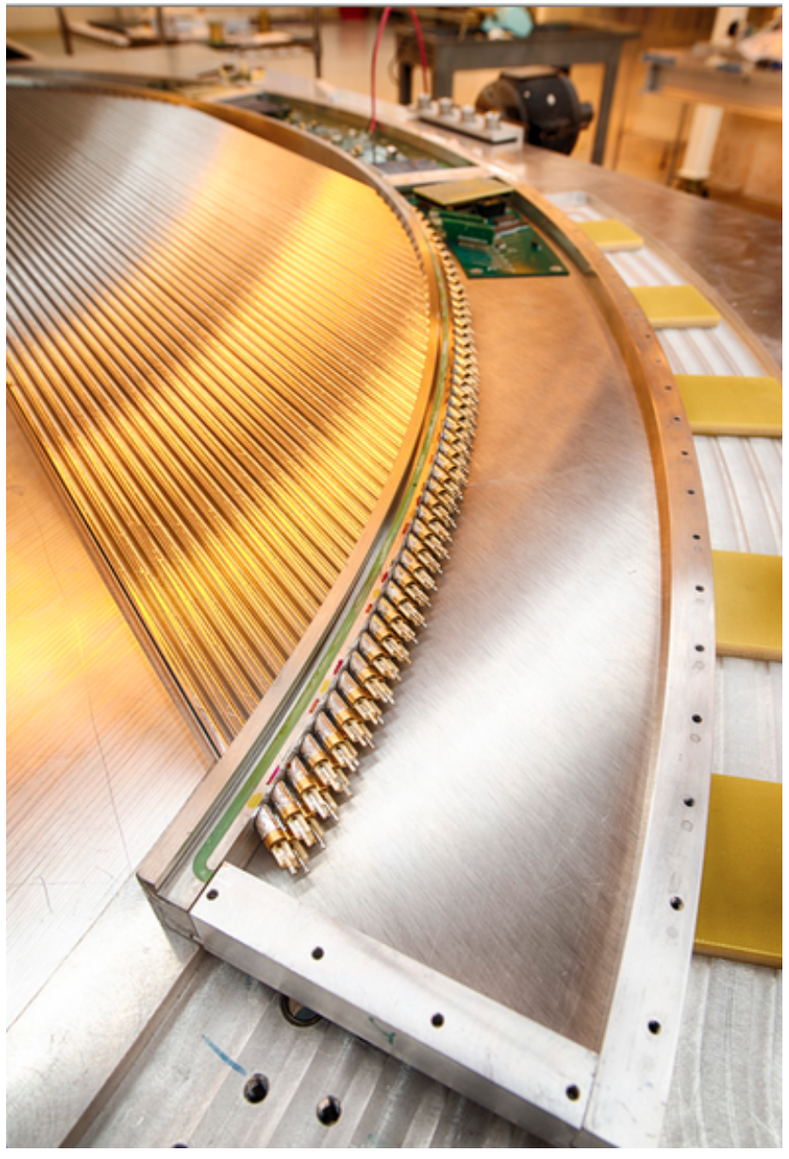


Straws being tensioned via “fixed length”

Tooling for Production

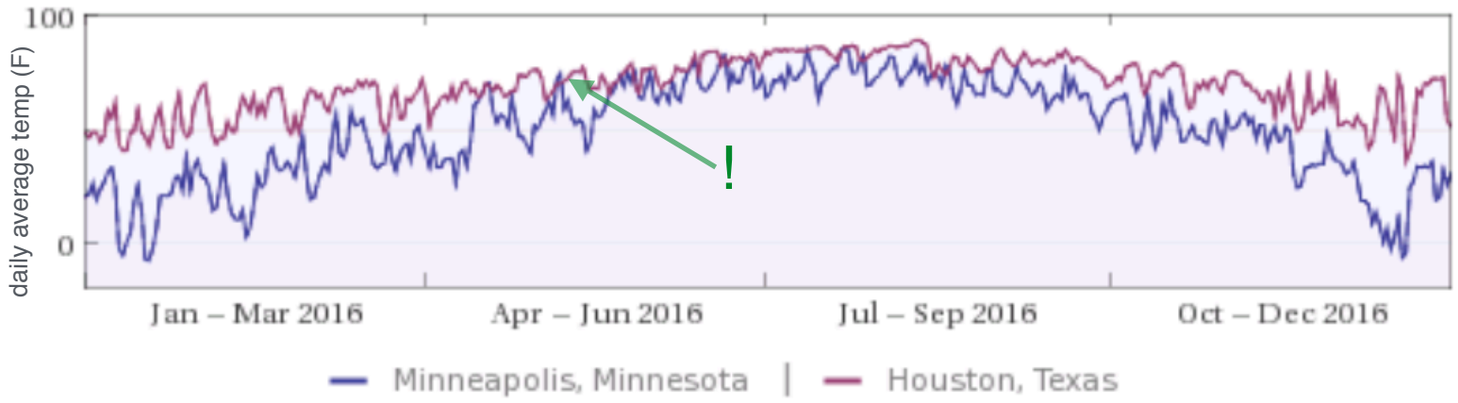
- Marj also contributed greatly to the development of tools needed to build the tracker reliably and economically
  - but there is no time to cover this…

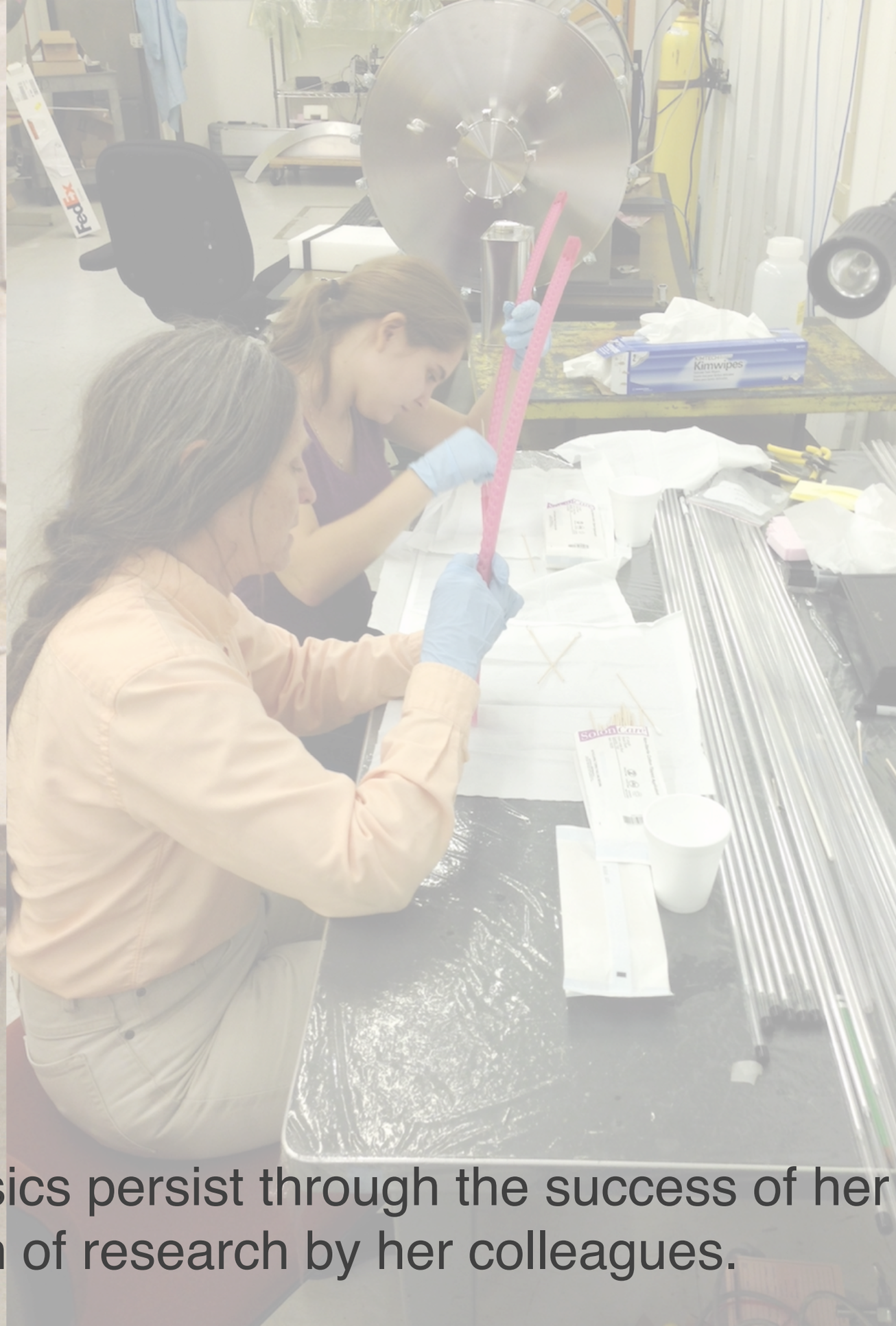




Transfer of Rice's Responsibilities

- Panel construction is moving to UMinn
  - They are considered leaders in Experimental Particle Physics
  - They built the NOvA detectors
  - They have great facilities





Marj’s contributions to Particle Physics persist through the success of her students and the continuation of research by her colleagues.