A straw tracker for FCC-ee

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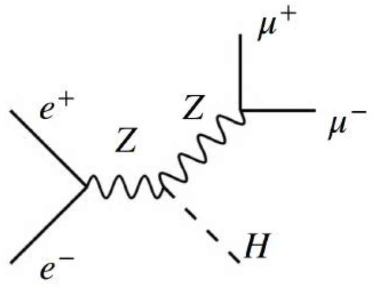
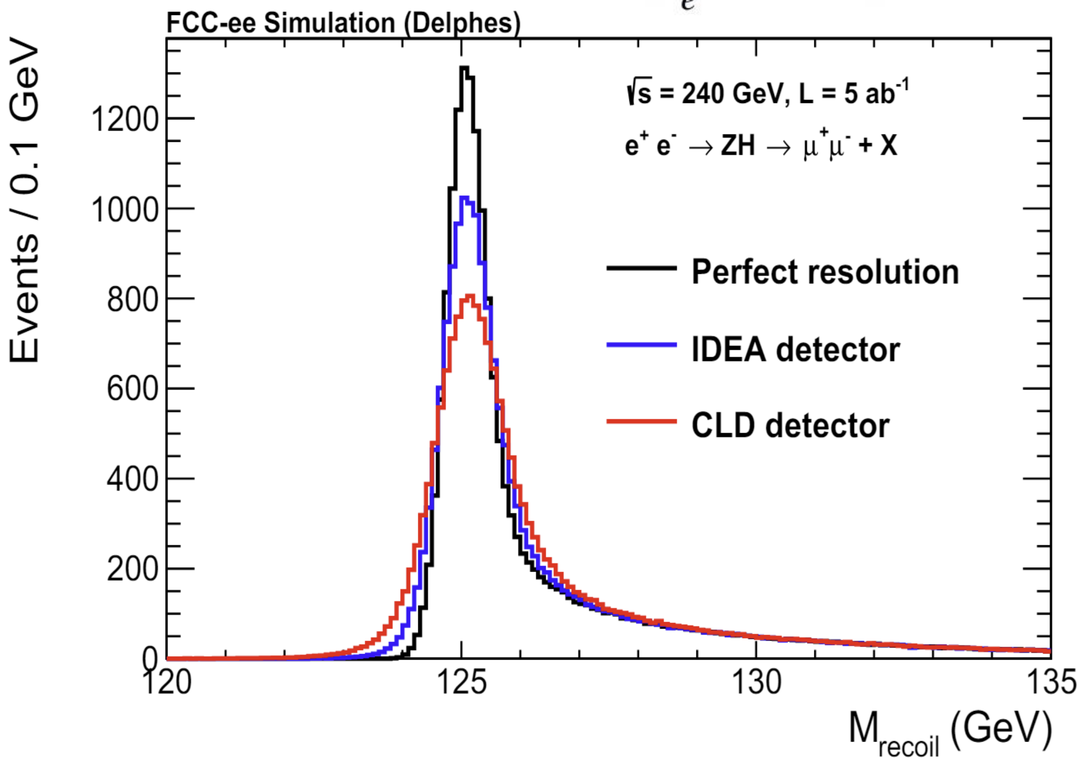
Momentum resolution requirement for the tracker



- Important to reconstruct the recoil mass distribution for the Higgs mass and ZH cross section measurements

$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

- Sensitivity dominated by the Z→μμ channel
- Require the track momentum resolution should not be worse than the beam energy spread (~0.16% at 240 GeV)
  - $\sigma(p_T)/p_T \sim 0.2\%$ at 45 GeV
  - a factor of 5~10 better than the current ATLAS and CMS inner tracker momentum resolution
- Current proposals for FCC-ee experiment inner tracker:
  - CLD: full silicon pixel+strip
  - IDEA/ALLEGRO: silicon pixel + Drift Chamber + Outer silicon wrapper

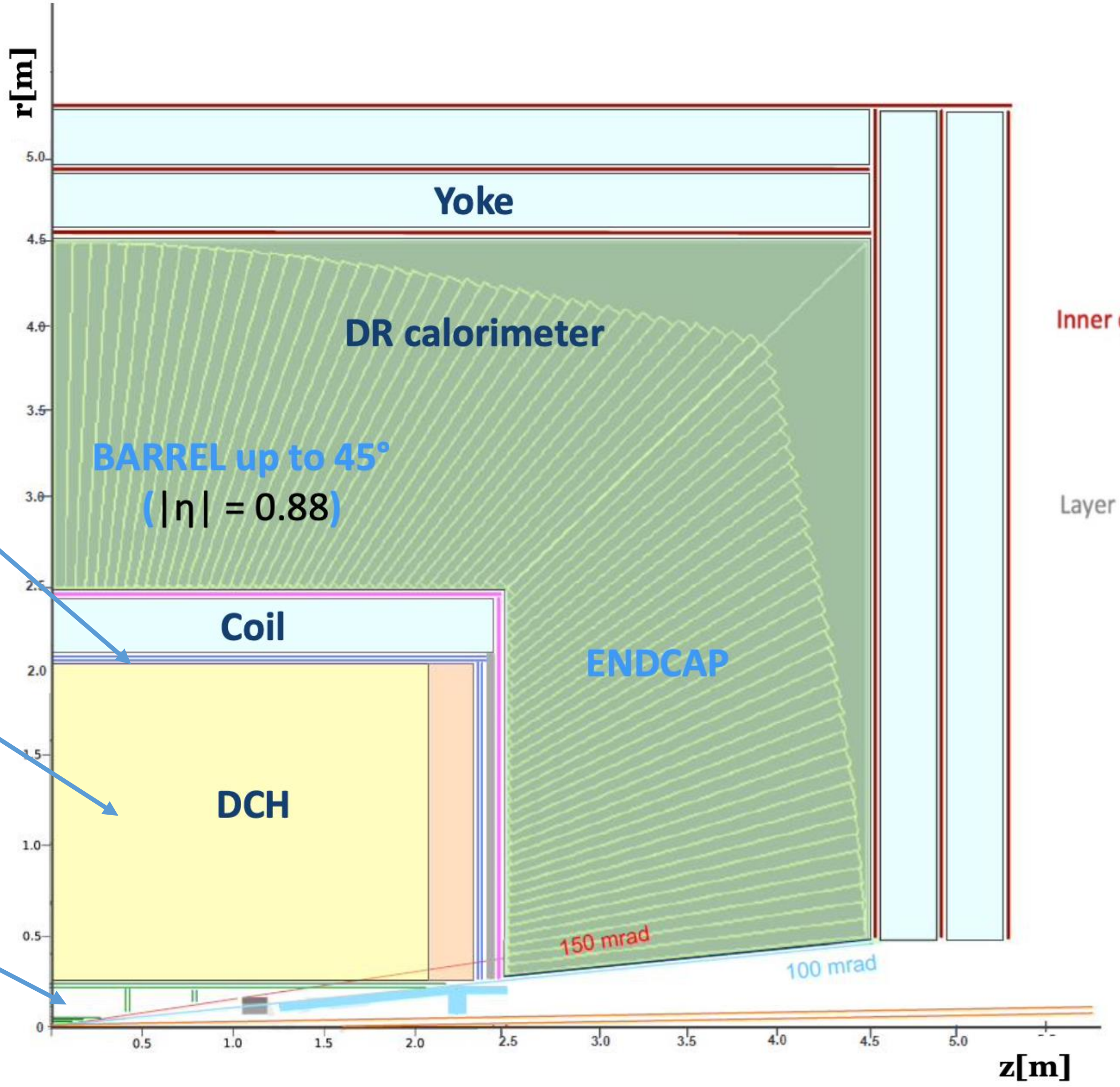


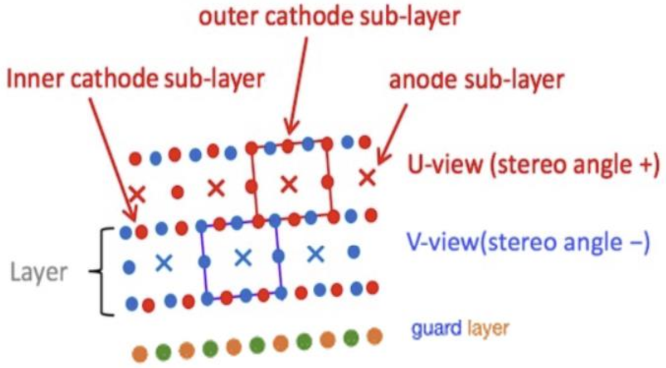
IDEA inner tracker as one example

Outer Silicon wrapper:
Si strips

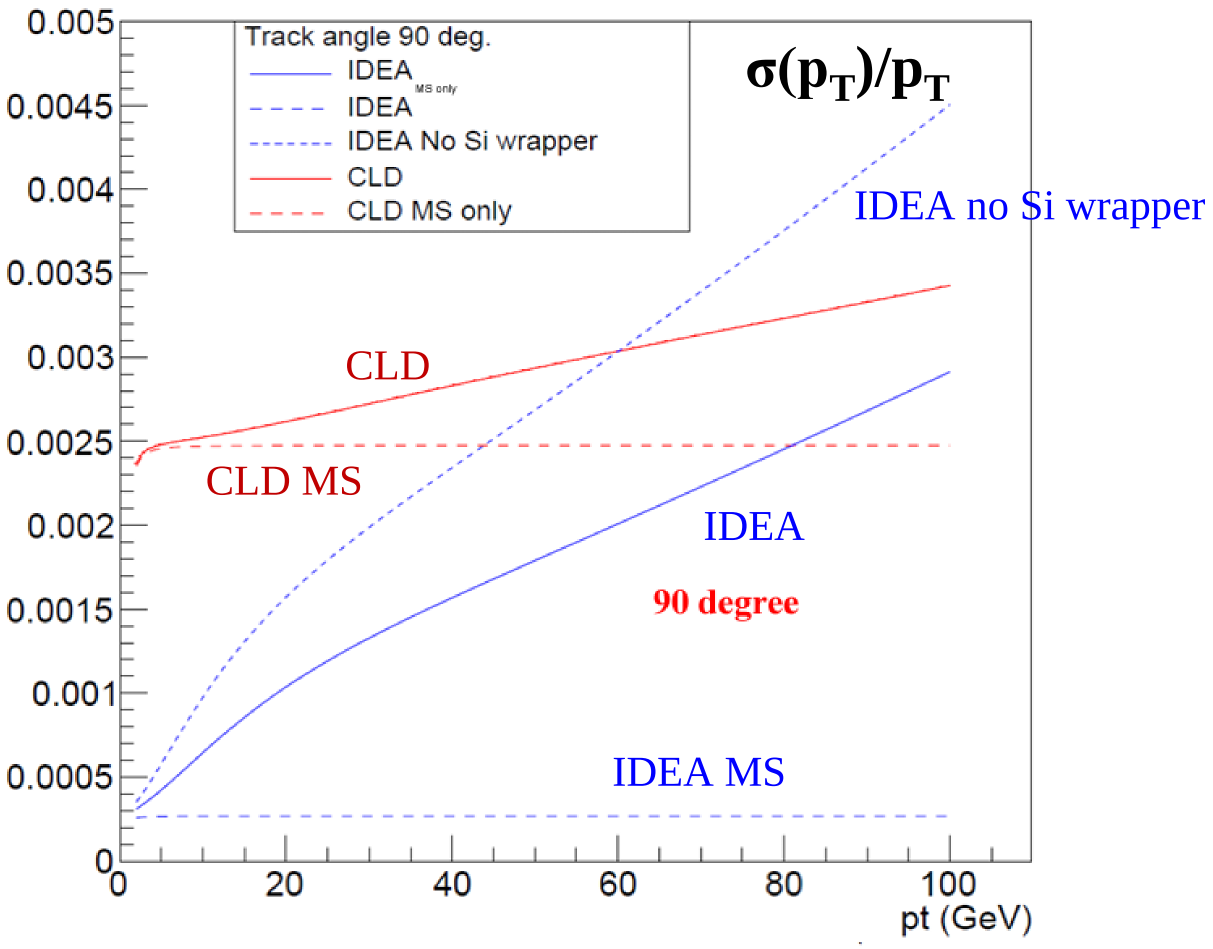
Drift Chamber: 112 layers
4 m long, R = 35-200 cm

Vertex:
5 MAPS layers
R = 1.37-31.5 cm





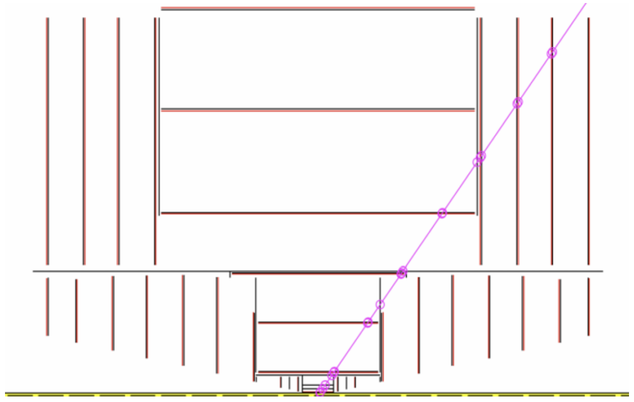
Momentum resolution

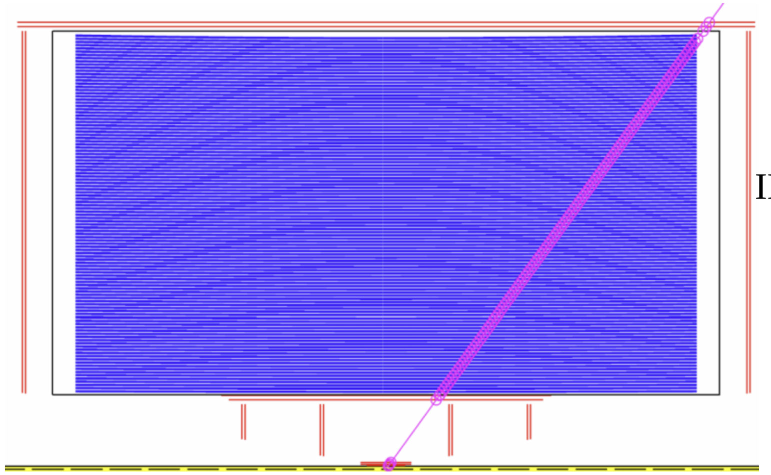


Transparent tracker is the key for the momentum resolution

Straw tracker

- We propose to have a straw tracker (combined with pixel and silicon wrapper) for an FCC-ee inner tracker:
  - Reasonable single hit resolution: 100~120 µm, similar or better momentum resolution than the pixel detector due to more hits detected and a longer lever arm
  - Low material and less multiple scattering
  - Pattern recognition
  - Particle identification (π-K, K-p identifications)
  - Long-lived particle searches
  - Capable of triggering





$$\frac{\sigma_{p_T}}{p_T}\Big|_{meas} \simeq \sqrt{\frac{720}{N+4}}\frac{\sigma_x\, p_T}{0.3BL^2}$$

p_T-resolution due to hit position resolution

Pixel: σ_x=3-5 µm
N=6
L~0.3 m

Gaseous: σ_x=100-150 µm
N~100
L~1.5 m

Straw tracker

- Straw trackers are robust and can achieve high performance for tracking and particle identification:
  - Each straw is a single unit, if a sense wire is broken, the channel can be easily electrically isolated
  - Straws with different radii can be used in different regions to optimize hit occupancy and channel counting
  - Flexible layouts for central and endcap regions
  - The electric field is radial symmetric; the resolution is independent of a particle's incident angle, no need to incorporate angular correction factors → better single hit resolution
  - Relatively low wire density: <1 wire/cm^2
  - Optimize the gas mixture to improve the PID capability
  - Different gas mixtures may be used at the same time

Straw trackers used in various experiments

Straw winding

- ATLAS
- LHCb
- PANDA
- CBM
- COMPASS
- Mu2e
- NA64
- SVD-2
- GLUEX
- COZY-TOF
- ..

Straw welding

- NA62
- COMET
- SHiP
- DUNE
- SPD NICA
- ,,

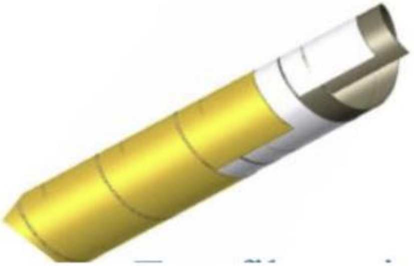
red color- straw tracker created with our participation

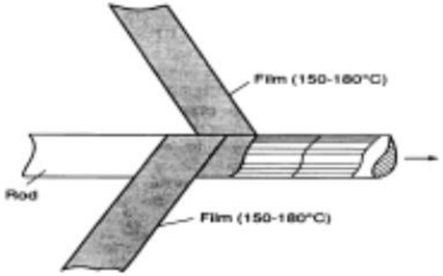
From Temur Enik
https://indico.cern.ch/event/1307673/contributions/5608746/

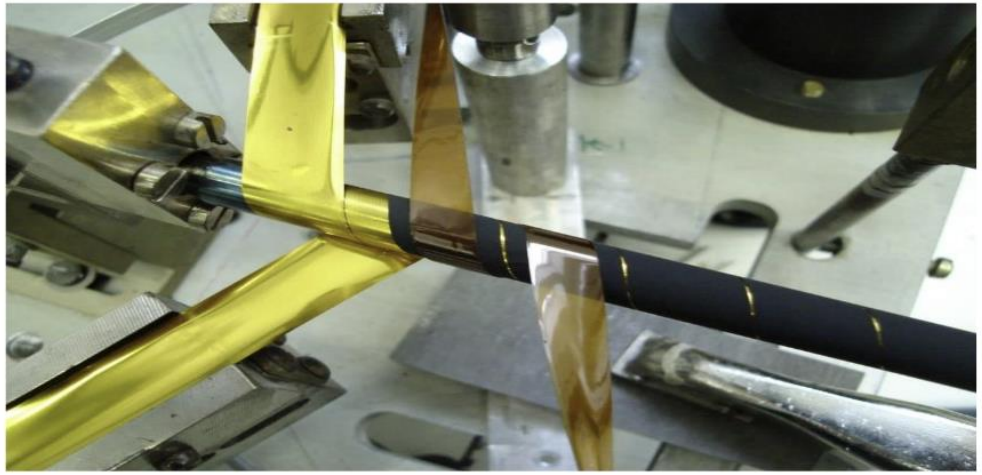
Straw production

Winding

- Production speed: 1 m/min
- Maximal length: 5.5 m
- Diameters: 2,4,6,10,20 mm
- Wall thickness: 15+ um

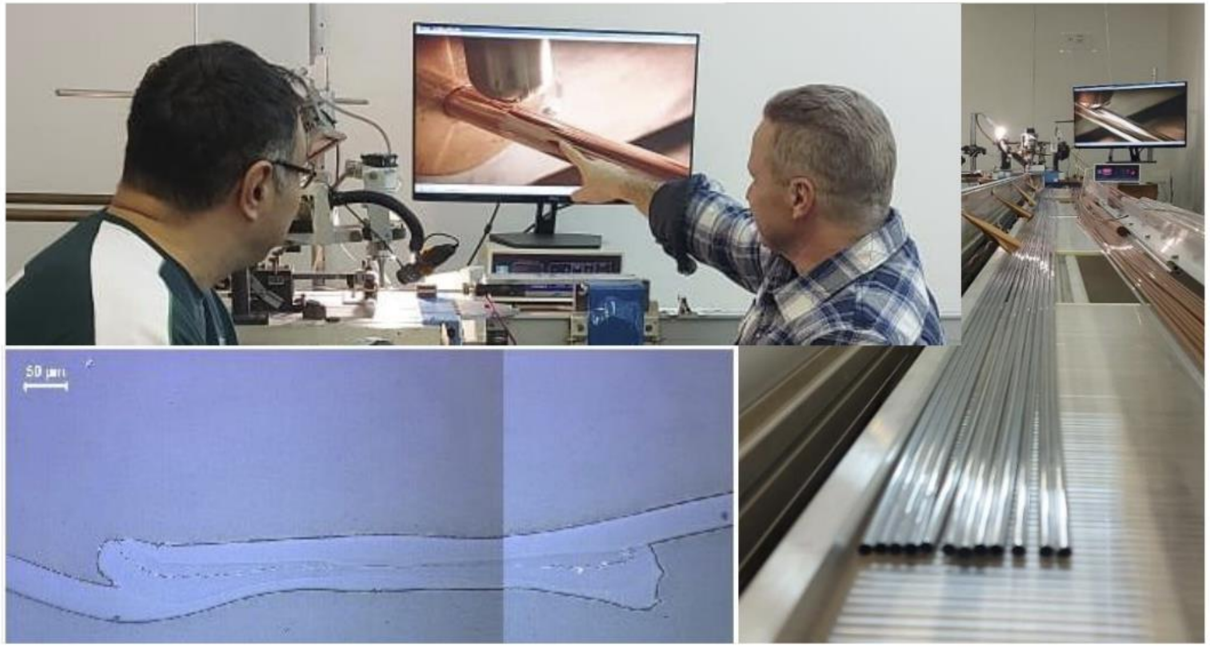






Ultrasonic welding

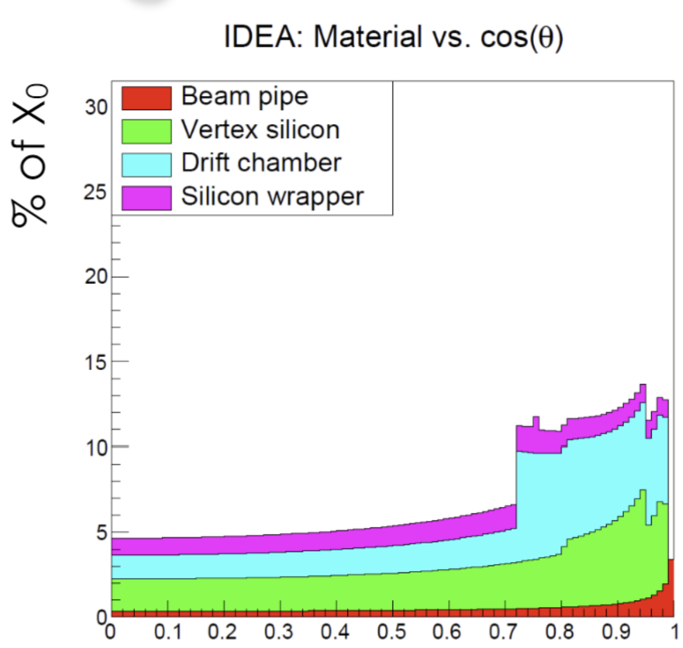
- Production speed: 1 m/min
- Maximal length: 5.5 m
- Diameters: 5,10,20 mm
- Wall thickness: 15, 20, 36, 50 um



From Temur Enik

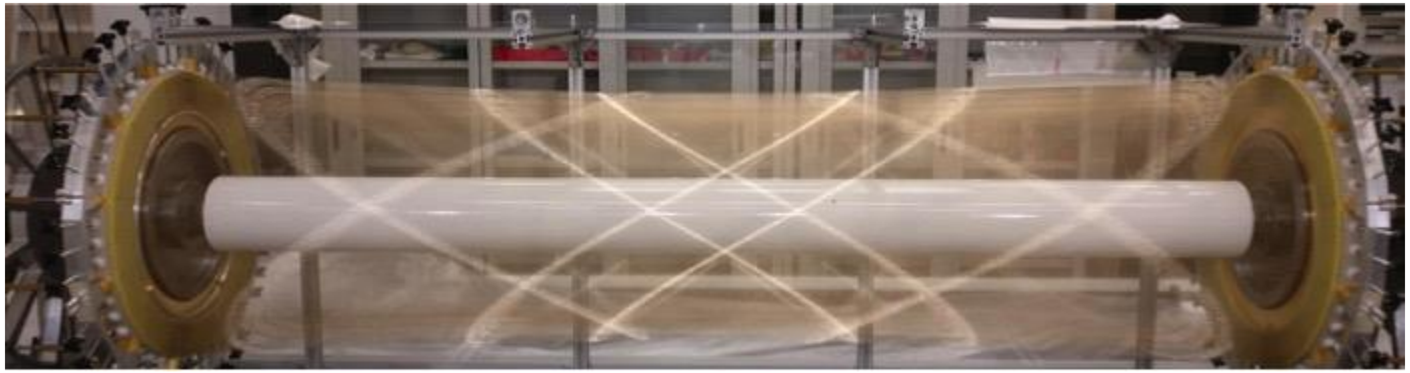
Material budget for a straw tracker

- The straw tracker for Mu2e experiment at Fermilab:
  - two layers of 6 μm mylar and 3 μm adhesive, in total the wall thickness is 15 μm (5 mm diameter, 0.44-1.14 m in length)
  - ~100 layers means in total ~3 mm mylar films ~1% X_0
  - 0.05 μm Aluminum coating on the outer wall and 0.05 μm Au coating on the inner wall, negligible contribution to the material budget
  - Endplate supporting structure could be similar to DCH
- IDEA drift chamber material estimate (slides):
  - Using similar techniques developed for the MEG-II drift chamber



current
Material budget estimates

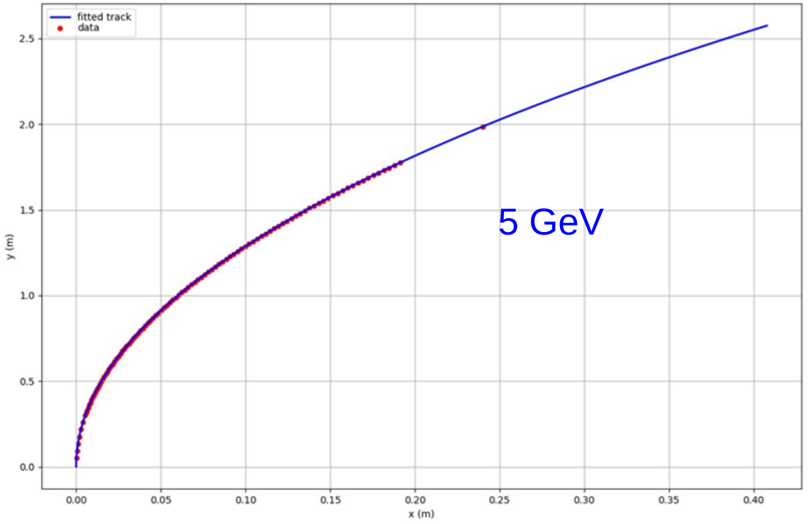
- Inner wall (from CMD3 drift chamber) — $8.4\times10^{-4}\ X_0$
  - 200 μm Carbon fiber
- Gas (from KLOE drift chamber) — $1.3\times10^{-3}\ X_0$
  - 90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) — $1.3\times10^{-3}\ X_0$
  - 20 μm W sense wires $6.8\times10^{-4}\ X_0$
  - 40 μm Al field wires $4.3\times10^{-4}\ X_0$
  - 50 μm Al guard wires $1.6\times10^{-4}\ X_0$
- Outer wall (from Mu2e I-tracker studies) — $1.2\times10^{-2}\ X_0$
  - 2 cm composite sandwich (7.7 Tons)
- End-plates (from Mu2e I-tracker studies) — $4.5\times10^{-2}\ X_0$
  - wire cage + gas envelope
  - incl. services (electronics, cables, ...)

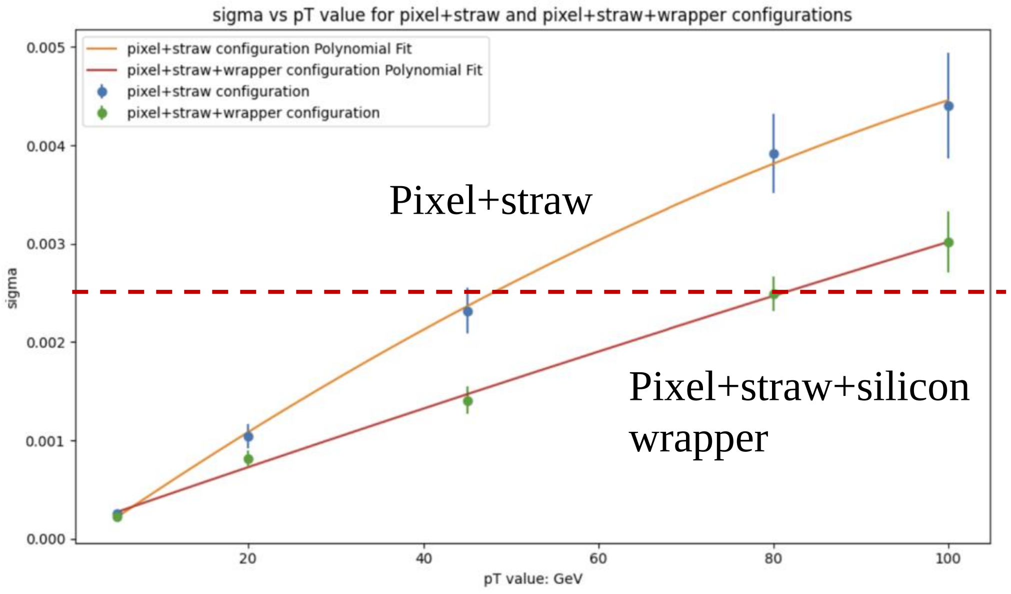


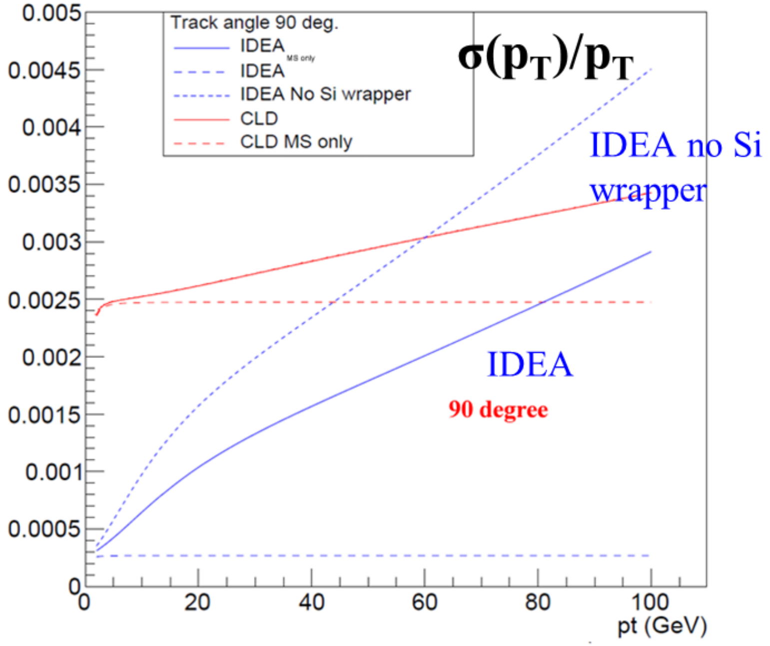
MEG-II drift chamber

Understanding the momentum resolution

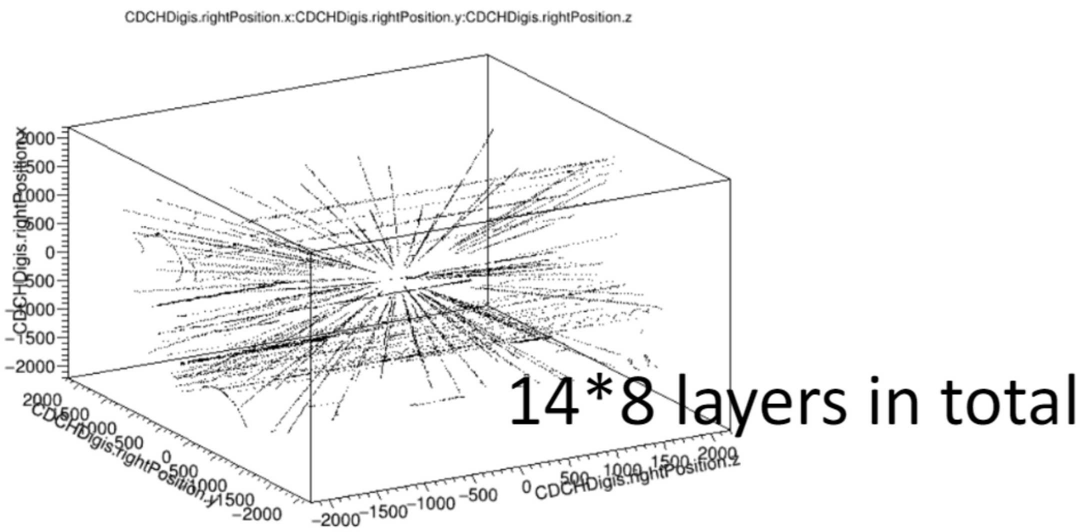
- A simple python simulation program developed to understand the effect of hit locations and resolution on the track momentum resolution
  - 2 Tesla magnetic field
  - 5 layers of pixel from 5 cm to 30 cm (σ=5 μm), 112 layers of straws from 30 cm to 180 cm (σ=120 μm), and a silicon wrapper layer at 200 cm (σ=10 μm)
  - Smear hit φ according to the resolution in the respective layer
  - A scipy minimization code developed to minimize the Chi2 to find the measured track p_T
- Can use this code to optimize tube counts, locations, resolution

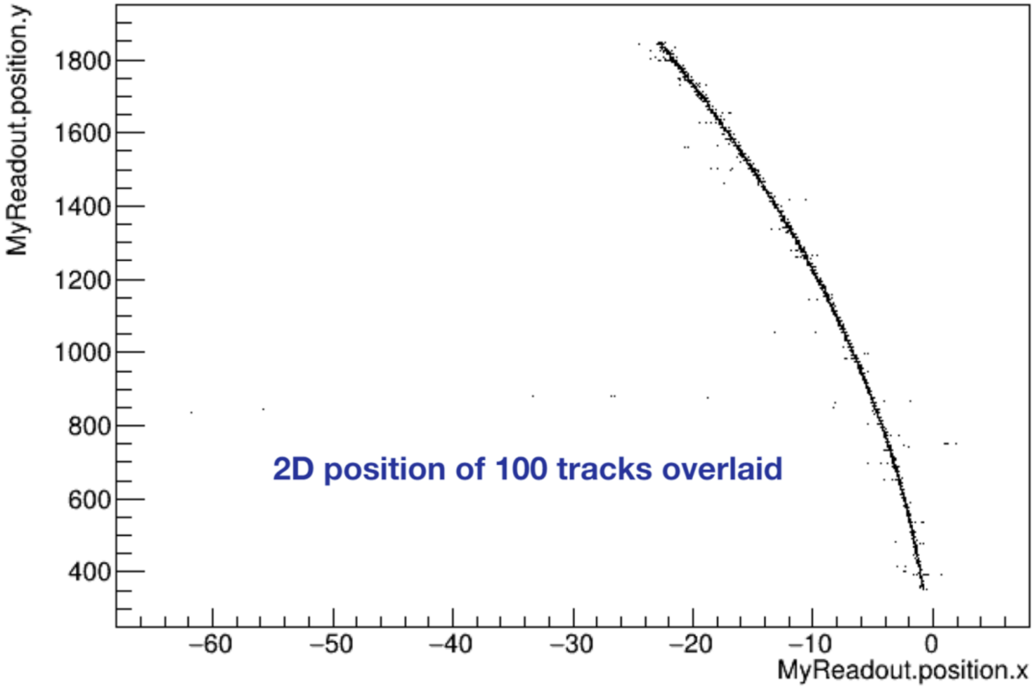






GEANT simulation





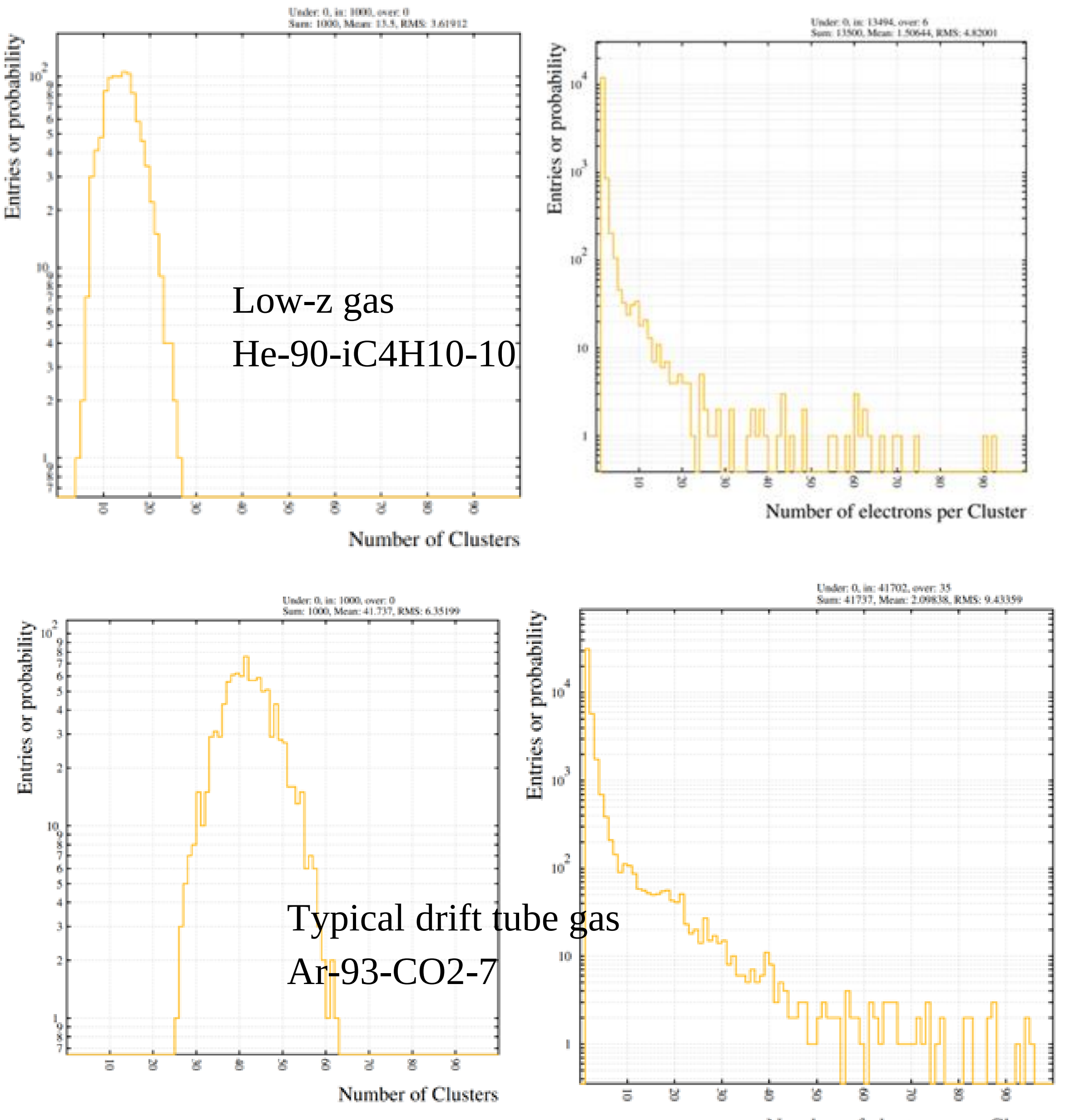
Learned to run the FCC-ee detector simulation to generate pixel and drift chamber hits (IDEA-like DCH in ALLEGRO) for 10 GeV electrons

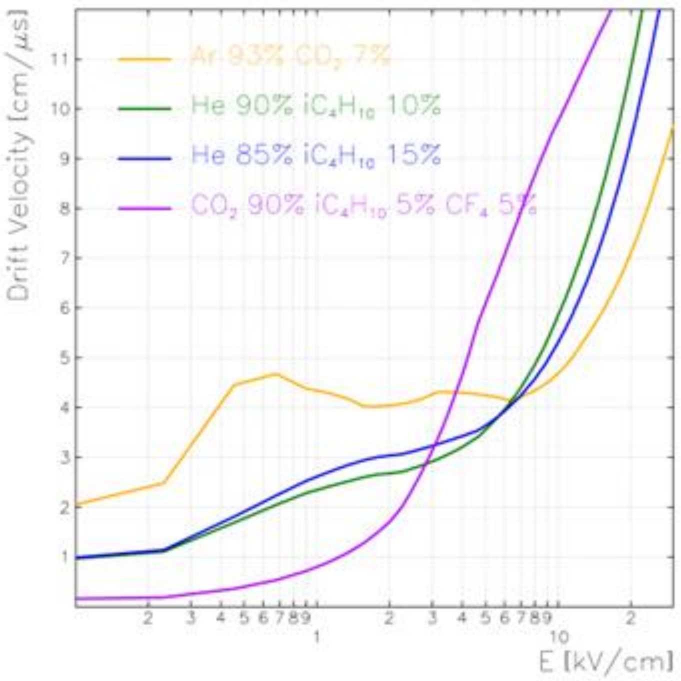
Modified the ALLEGRO simulation and replaced the drift chamber with a perfect tracker made of only air. Multiple scattering effects included.
These hits can be fitted with our simple fitting program to obtain the momentum resolution with MS effects included

Gas simulation with Garfield

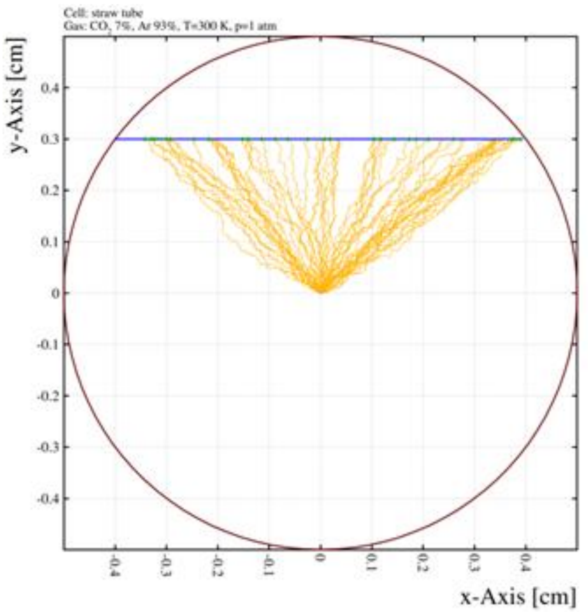
- Ongoing Garfield simulation:
  - Ionization statistics in several gas mixtures
  - Electron and ion transportation properties
  - Signal induction and timing structure
- Provide essential inputs for the gas optimization and dE/dx(dN/dx) measurement for PID

Simulated primary ionization cluster number (left) and size (right) for 4GeV muon in a 10 mm-diameter tube





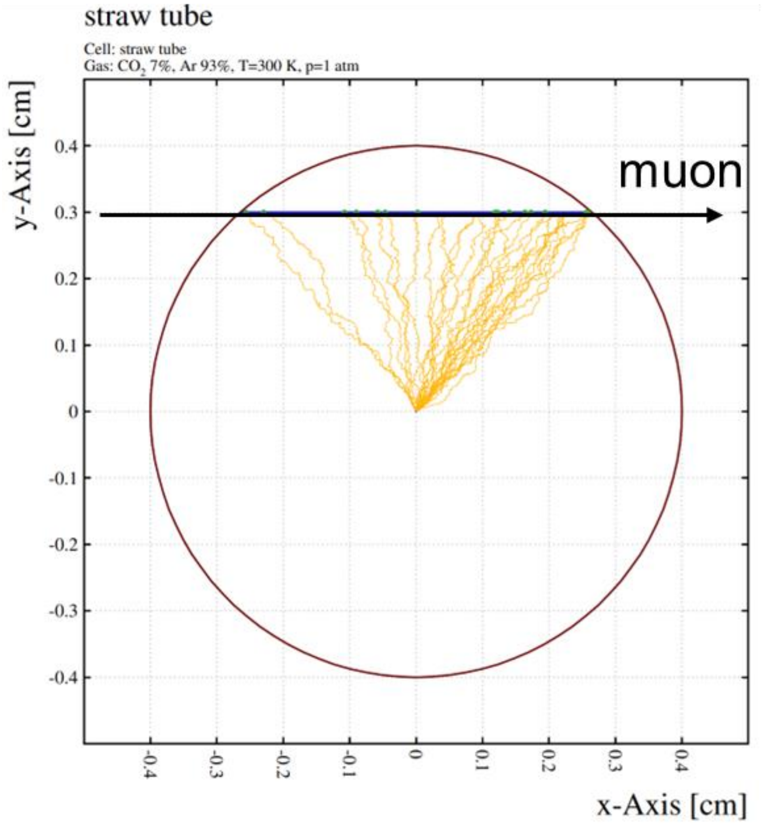
Electron drift velocity vs. e-field

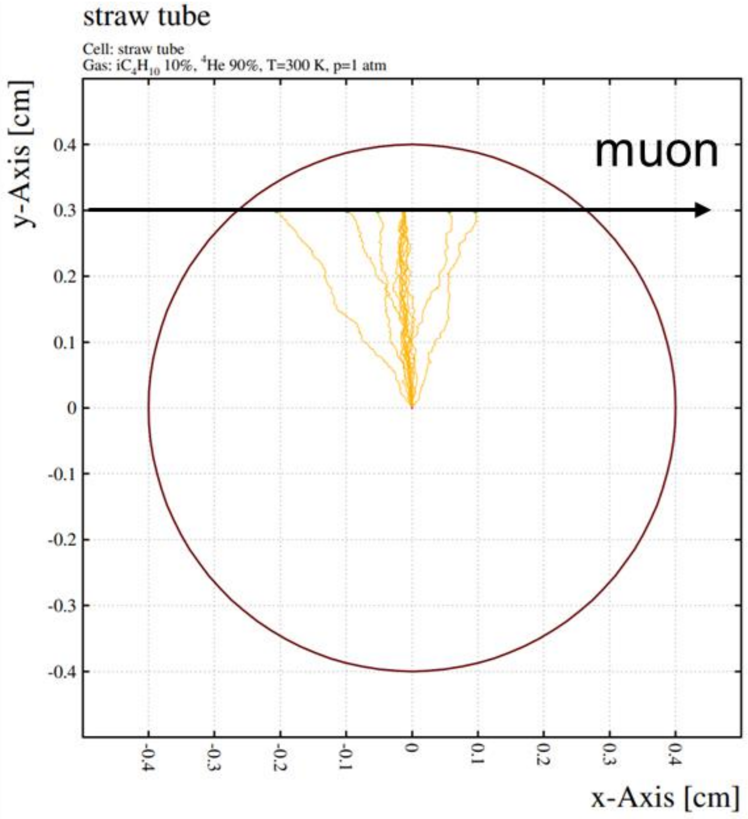


Simulated ionizations created by a muon track and primary electron drift towards wire

Gas simulation with Garfield

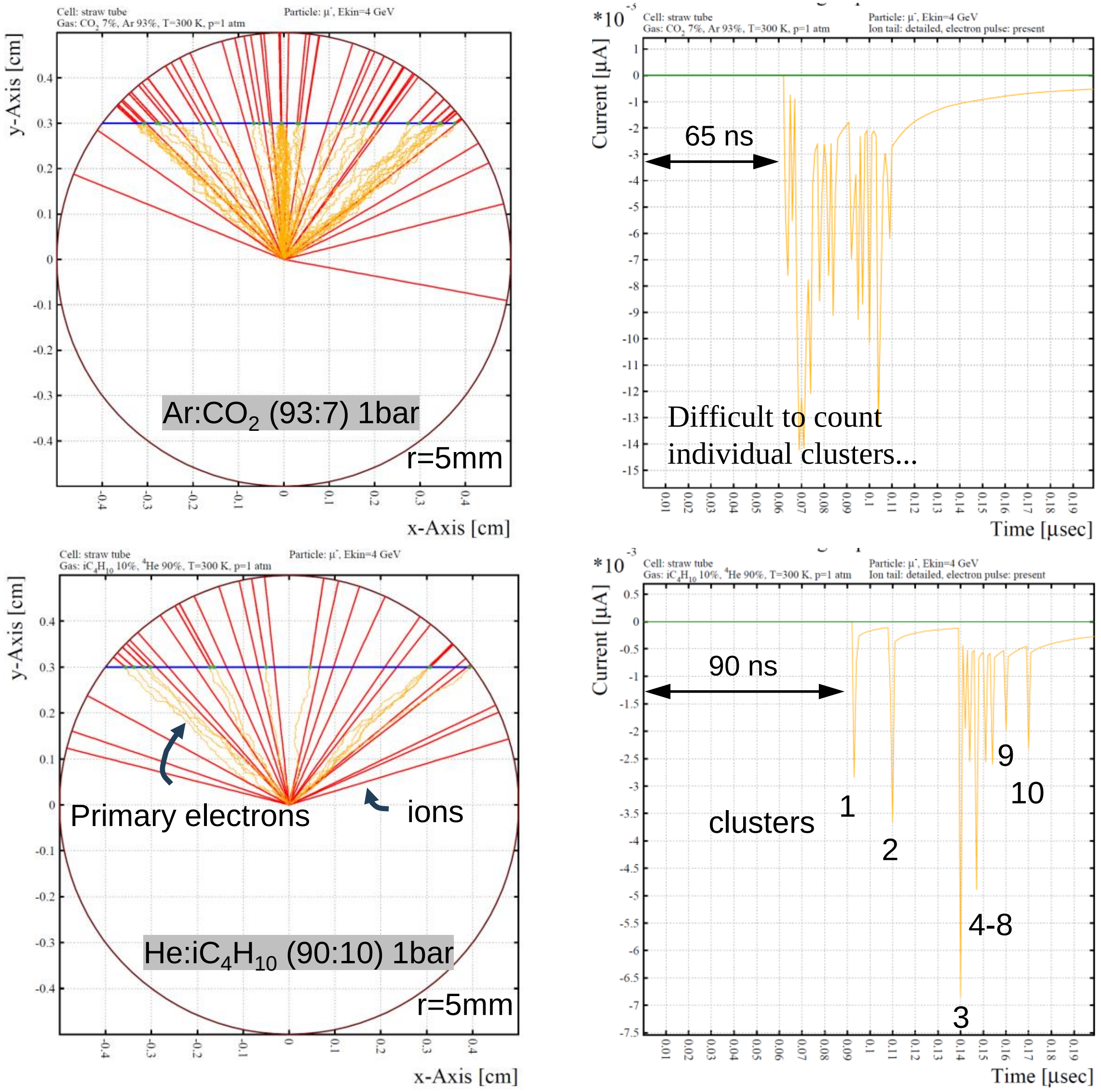
- Examples of ionized electron drift towards wire in two gas mixtures
- Much less ionization density from He-based mixtures could be observed





Simulation of signals in different gas mixtures

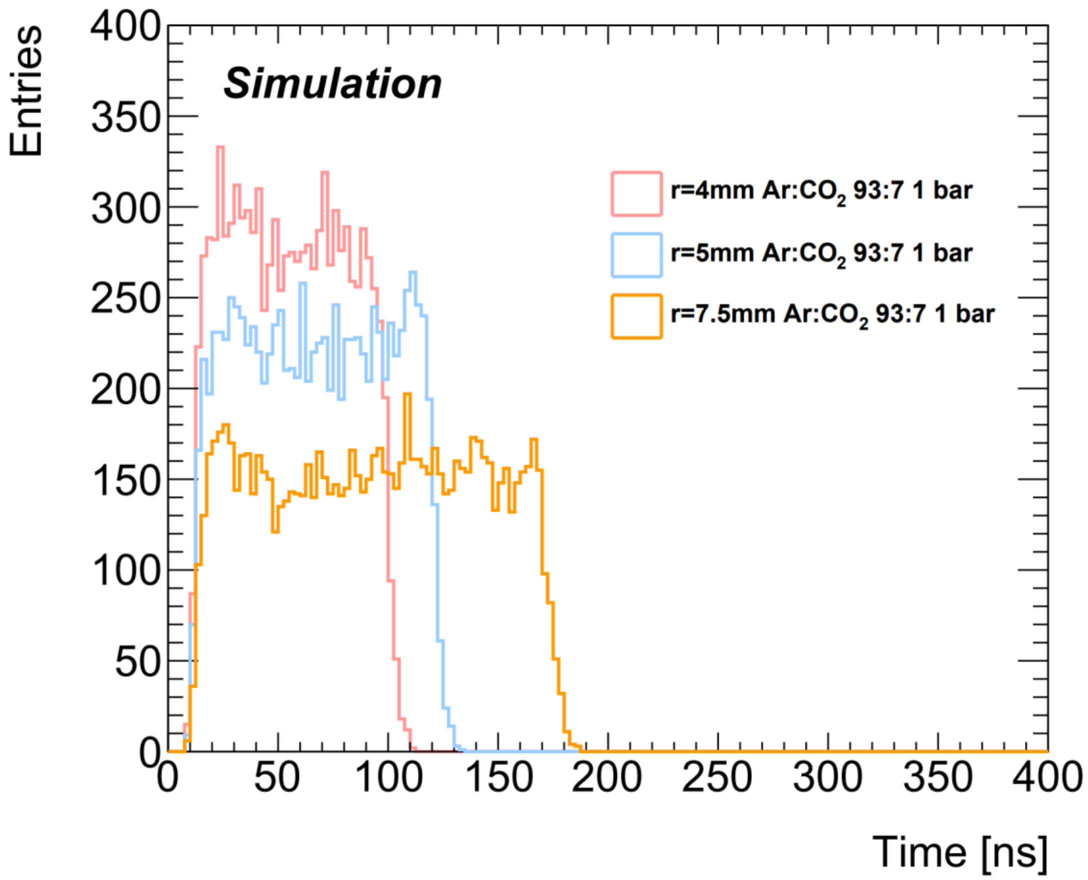
- dN/dx expected to improve dE/dx PID based on traditional charge measurements
- Ar-based gas: high ionization density (~40/cm) and moderate electron drift velocity 50 mm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~5ns
- He-based gas: lower ionization density (~20/cm) and 30 mm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~15ns

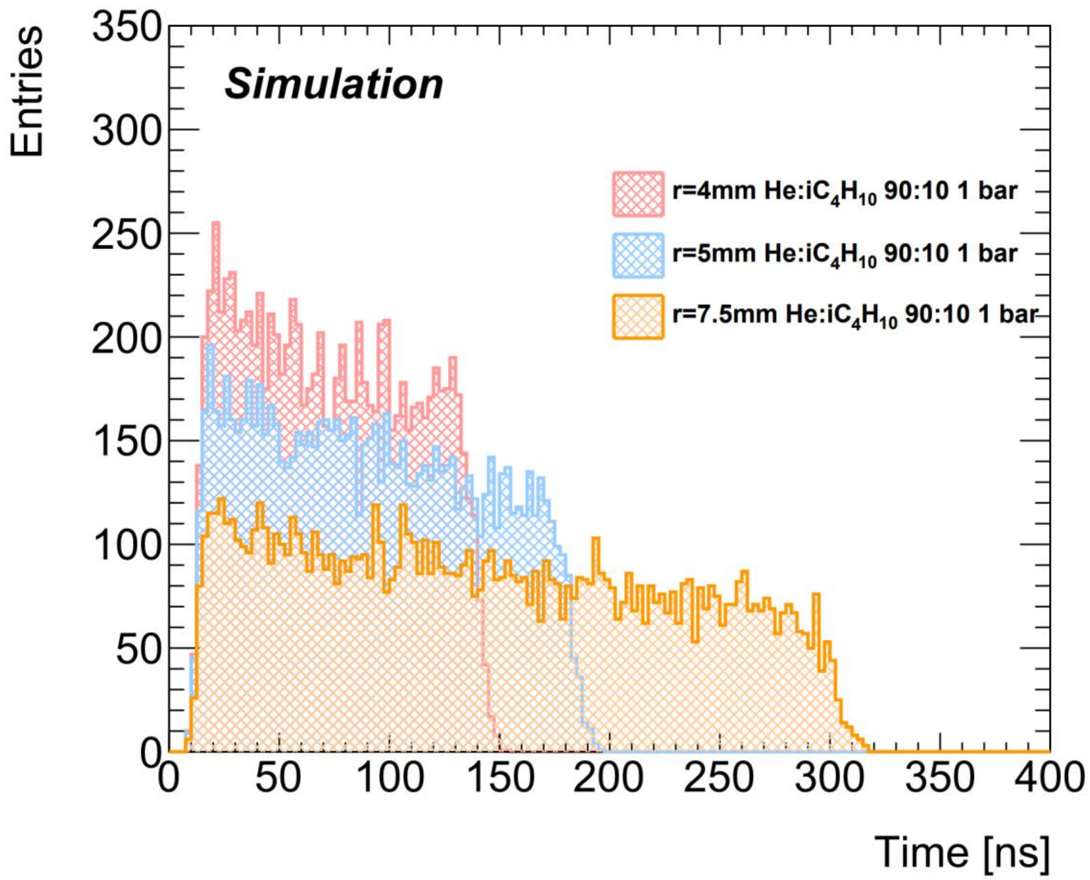


5mm radius tube with 1 bar and 1kV simulated here

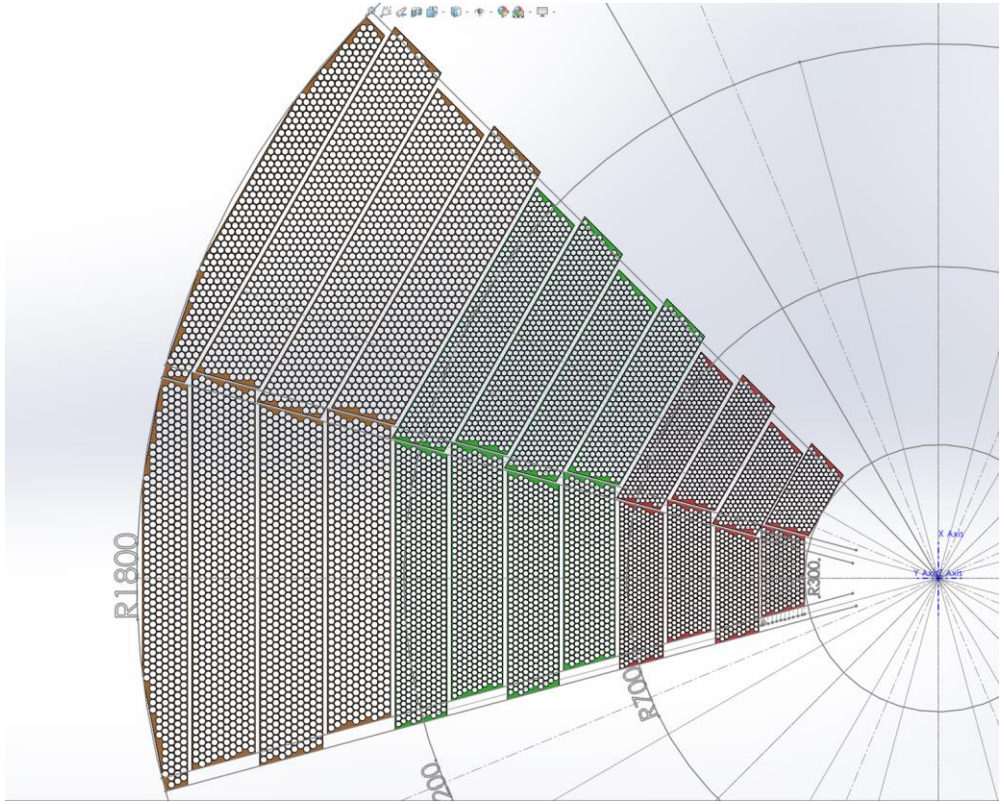
Simulation of the drift time spectrum

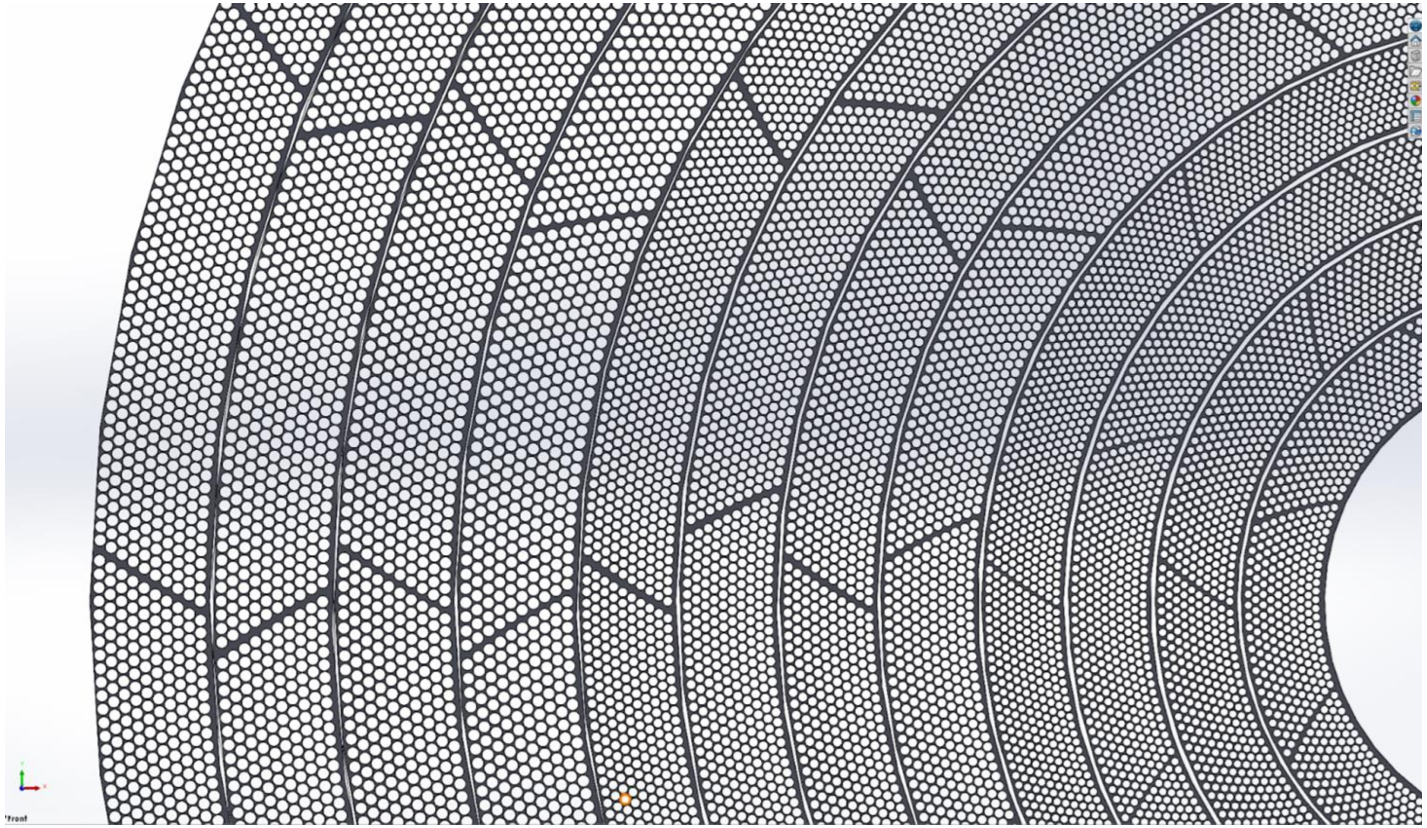
- simulation of the straw tube drift time spectrum (convolution of earliest cluster arrival time and the amplifier response):
  - drift time spans 10-300 ns, comparable to ATLAS drift tubes.
  - ~50% longer drift time in He-based gas compared with Ar-based gas (1bar)





Possible detector layouts

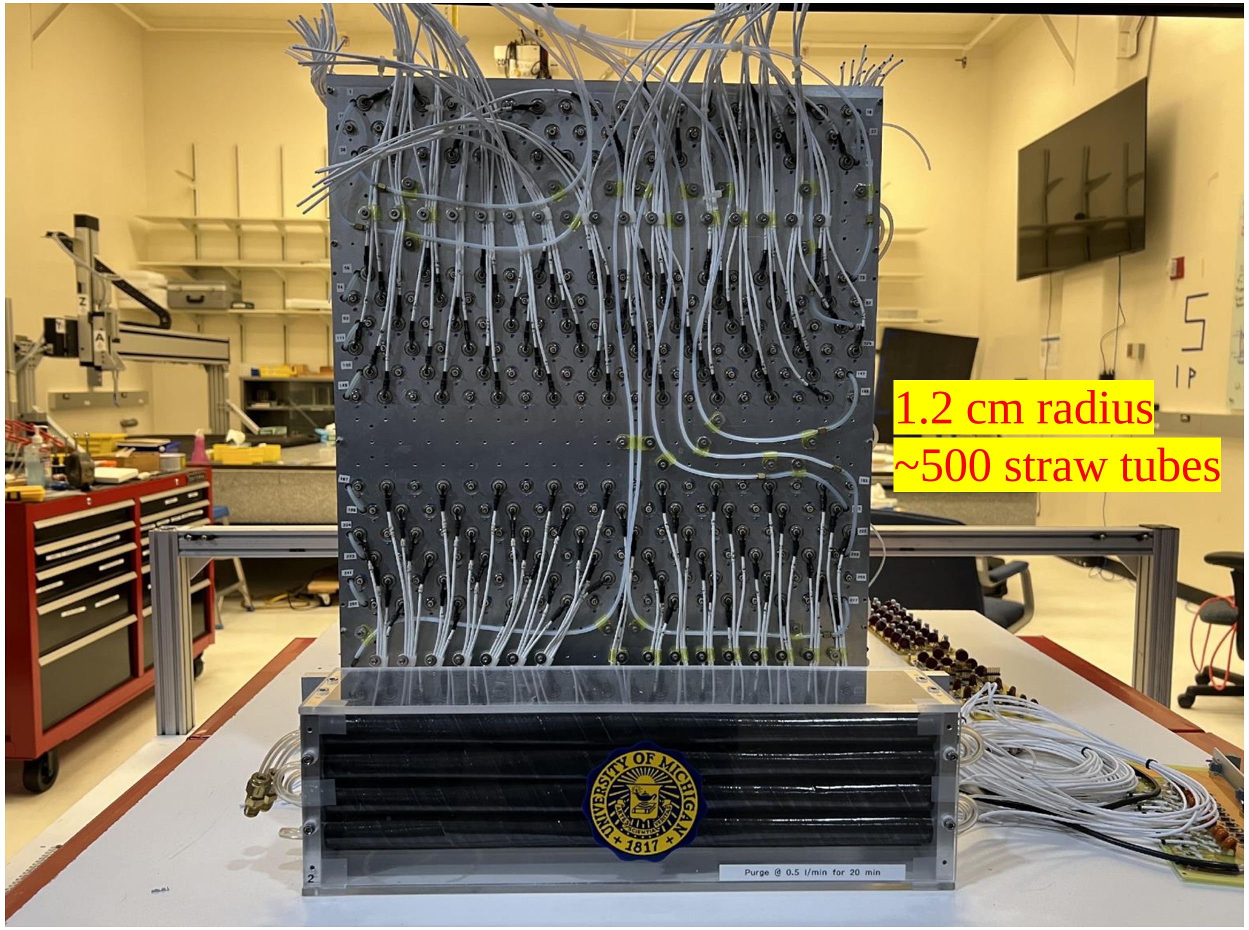




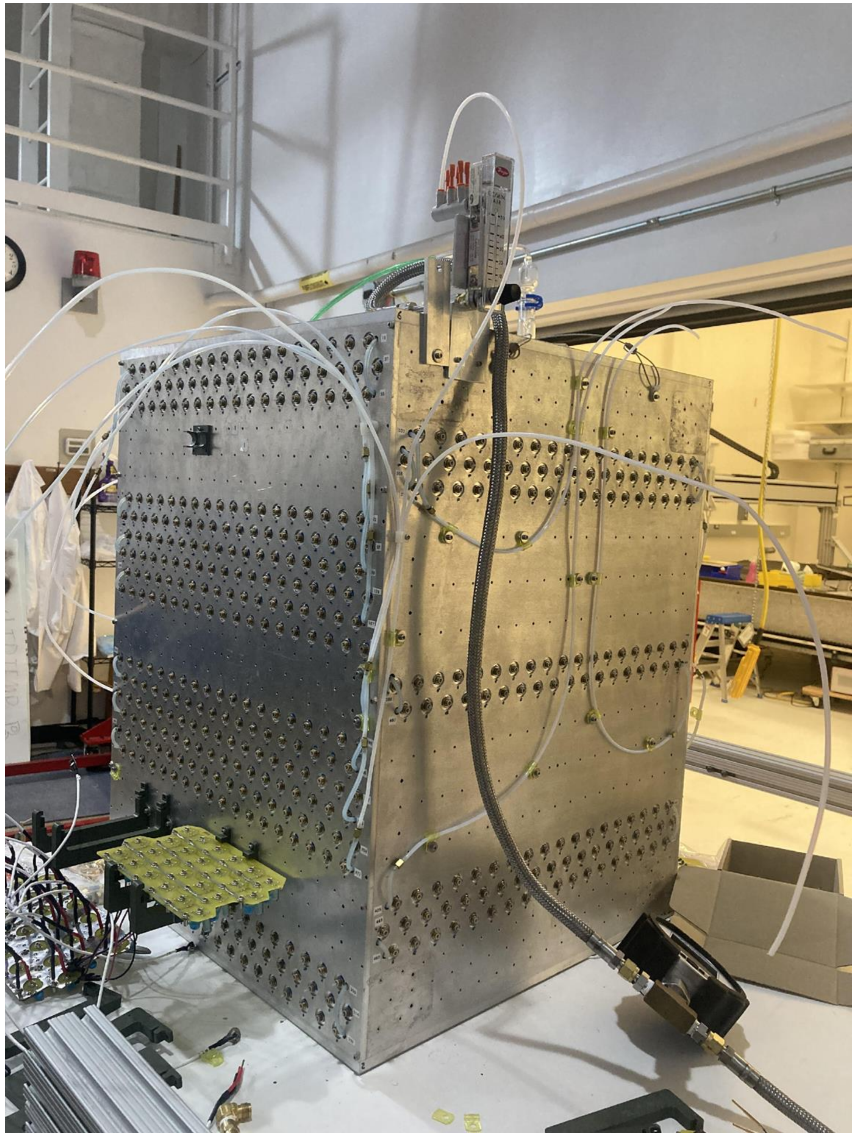
Straws with different diameters (1-1.5 cm) considered for different regions, the actual diameters needed to be determined from the simulation and physics studies

~60k straws (it will depend on the straw radius used for the final detector)

Straw tracker at Michigan

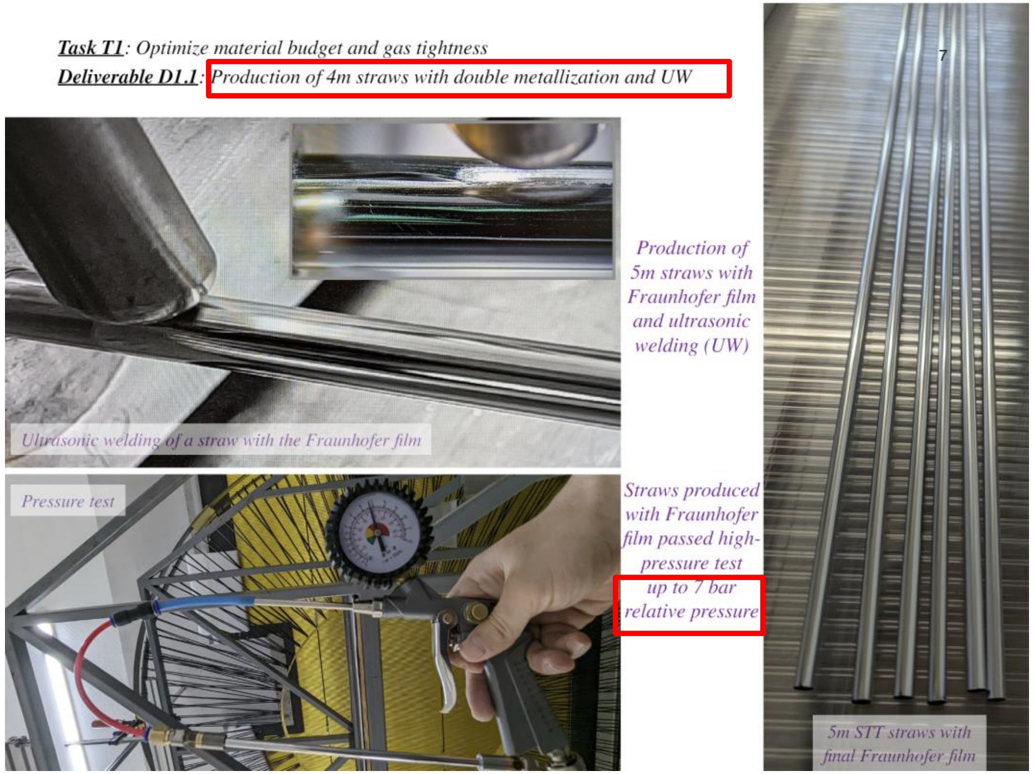


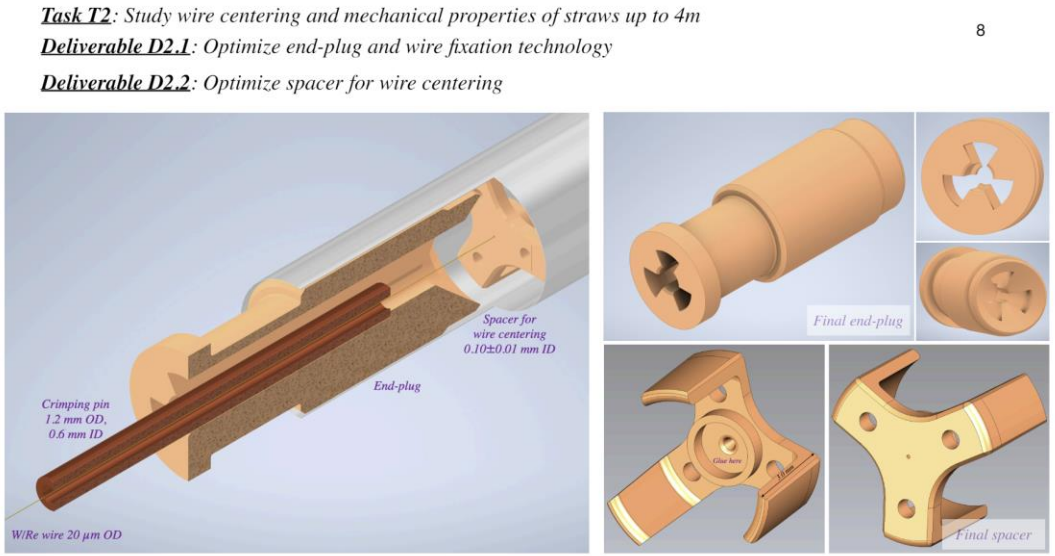
A straw tracker at the UM ATLAS muon detector construction lab

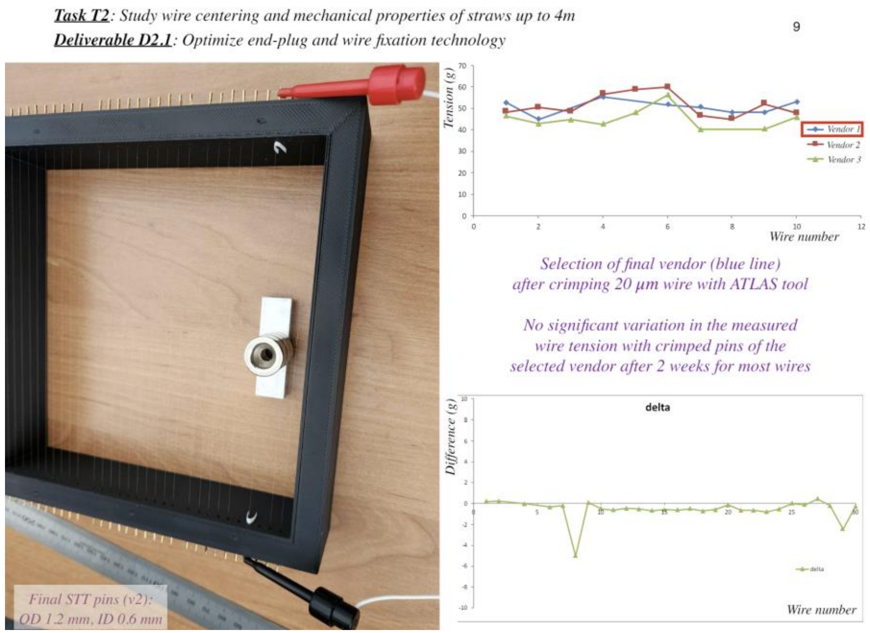


- Only three shorten wires found
- Gas flow tested for all straws
- Cables remade so that they can be inserted into the ATLAS MDT hedgehog cards
- MDT mezz, CSM and miniDAQ system ready

Recent developments from DUNE





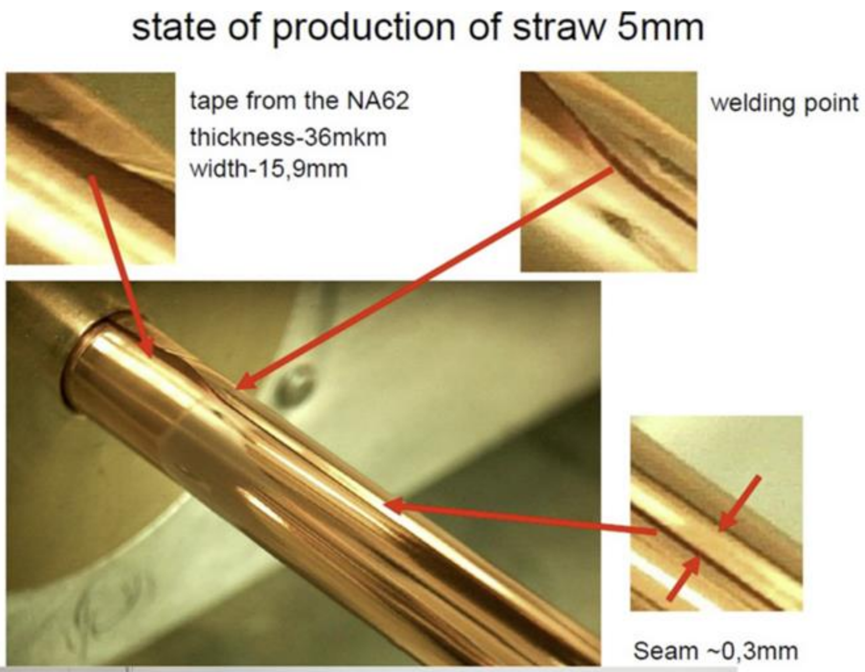


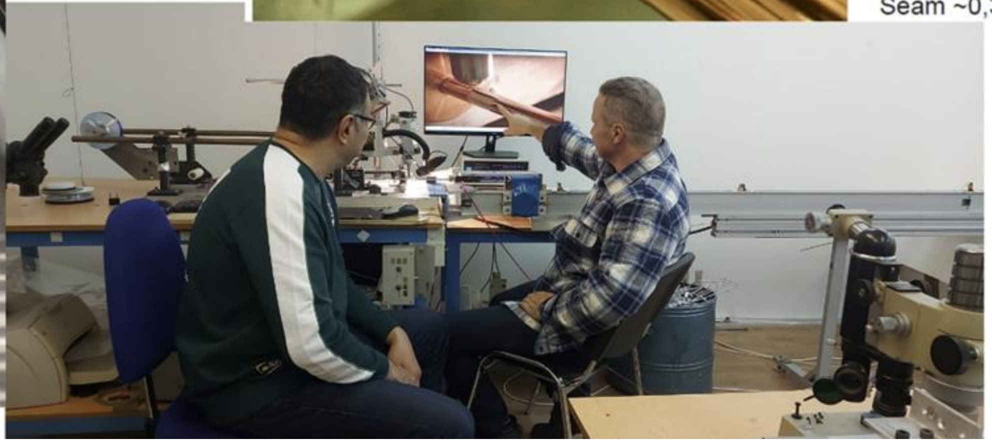
12+ μm thick long mylar film available

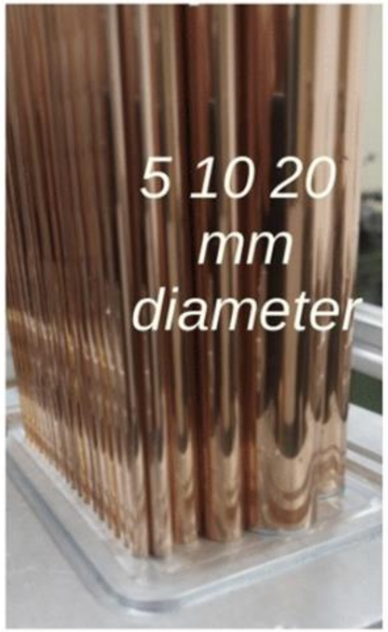
From Roberto Petti (USC)

https://indico.cern.ch/event/1423760/contributions/5988046/attachments/2876206/5037062/DRD1-ProjectD-12Jun24.pdf

Straws from Temur





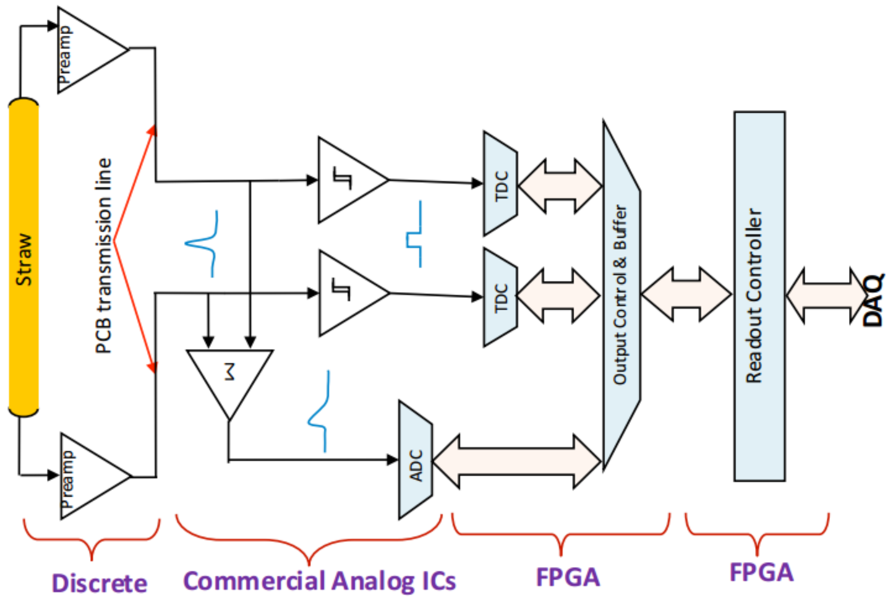


From Temur Enik

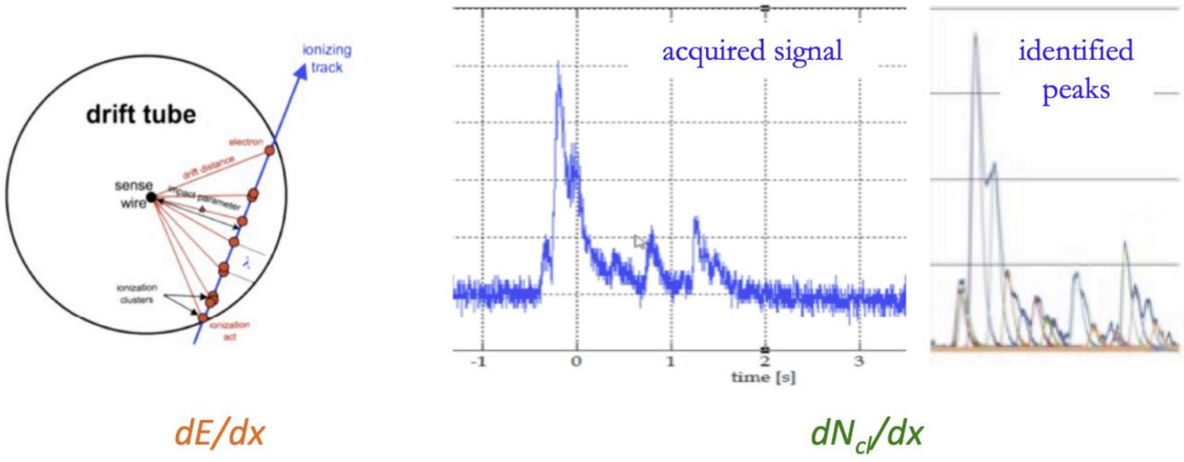
Temur Enik from Germany/Kazakhstan (ultra-sonic welding of thin straws) will send us a few straw samples to perform studies this month

Studies to be performed

- Straw materials, centering and mechanical support (work closely with straw production companies)
- Implement a straw tracker in the FCC-ee GEANT simulation framework and perform optimization studies for straw layout and design optimization
- Detailed Garfield simulation of the gas mixture and raw detector signal
- Algorithms and electronics to perform dE/dx (dN/dx) for PID and readout from both ends to determine the hit position along the tube (signal propagation speed ~15 cm/ns)
- Readout the existing chamber and perform cosmic ray studies and compare simulation with data
- Build a small prototype with 20-50 long thin-film straws and perform various studies
- …



Mu2e straw tracker electronics



dE/dx and dN/dx

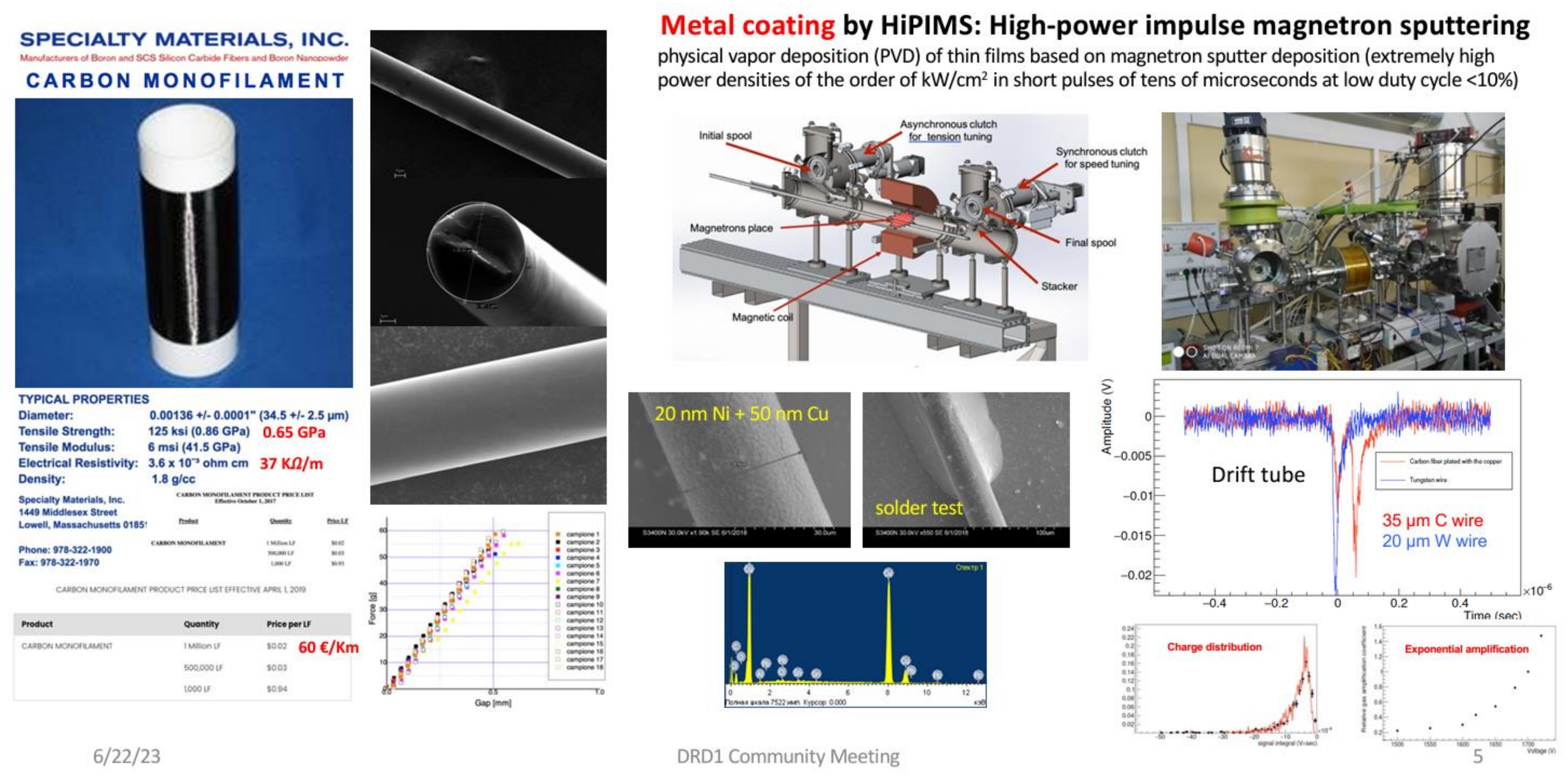
Conclusions

- A straw tracker could be a good option for FCC-ee experiments
  - Reasonable material budget (~1% X_0 for ~100 layers)
    - straws with 12 μm-thick wall (ultrasonic welding) and 3.5 (×2) μm-thick wall (winding) are available
    - will have another 10+ years for industry to develop even thinner films
    - could use >4 m straws to extend the tracker volume
  - material budget is not the only parameter that determine the performance of a tracker
    - larger radius straws mean less material and better resolution, even though less number of hits along the path
- Mature technology, robust and can achieve high performance for tracking and particle identification
- DRD1 WP3 Project A "Straw and Drift tube development for future collider experiments", Oliver Kortner (MPI) and Junjie Zhu (Michigan) are coordinators
- Participating institutions include MPI, Michigan, UMass-Amherst, Tufts, Harvard, MSU, UCI (Let us know if you want to participate in this design and relevant studies)
- Close collaboration with people working on the drift chamber idea, straw production companies, and other experiments using straws
- Synergies with almost all drift chamber studies: gas, frontend electronics, dE/dx(dN/dx) etc

A mini-workshop to discuss the straw tracker option on Oct 14-15 at the University of Michigan

https://sites.google.com/umich.edu/strawtracker2024/home

Backup

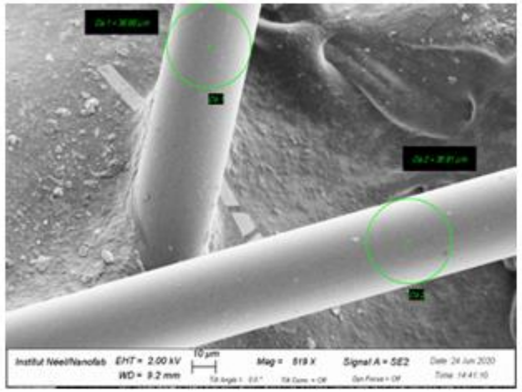


From F. Grancagnolo
https://indico.cern.ch/event/1273991/contributions/5456858/attachments/2671647/4631392/DRD1_Jun23_compressed.pdf

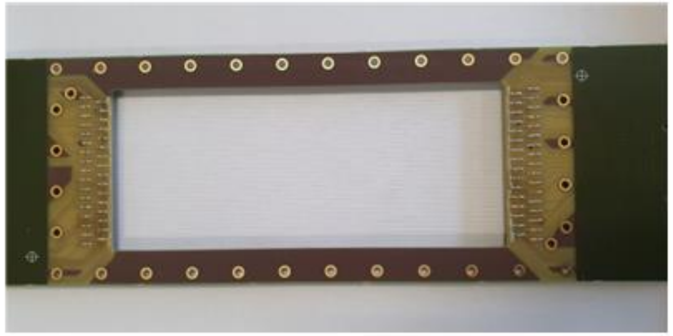
Blue Sky R&D at in2p3 to find new wire material

3 groups implied
2 with wiring machines

Design a simple detector (active area 17x7 cm^2) to test different types of wires



Carbone wires seen from SEM



Carbon wire chamber soldered then glued

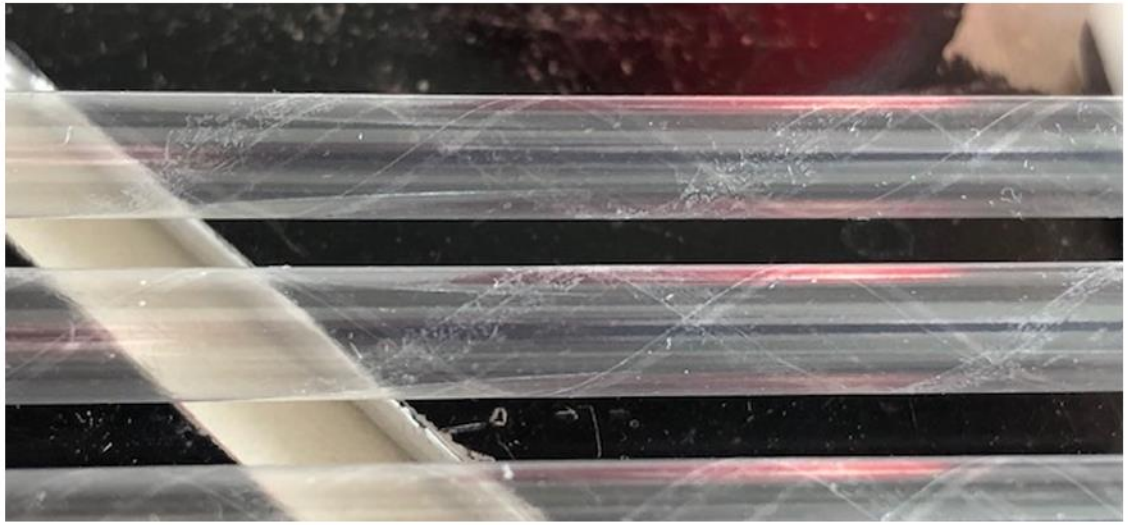
First results in 2017 *Carbon wire chamber at sub-atmospheric pressure, G. Charles et al., NIM A*

Tests with radioactive sources at 1 atm are on going for carbon wires and soldered AlMg5 wires.

Next step will be beam tests and **internationalize the collaboration**.

From F. Grancagnolo
https://indico.cern.ch/event/1273991/contributions/5456858/attachments/2671647/4631392/DRD1_Jun23_compressed.pdf

How thin can you make straws?



Pressurized 8 μm Mylar Straws

8 μm Mylar Straw

Test structure: 3.5 µm Mylar + 1 µm adhesive + 3.5 µm Mylar double helical wrap straws

Made by same drinking straw company that made Mu2e straws

These straws held 15 PSI for multiple days and 400 g Tension without visible distortion.
Looking into what the needed initial tension to limit sag an acceptable distance (< .3 mm).

From Dan Ambrose:
https://indico.fnal.gov/event/46746/contributions/210371/attachments/141297/177867/CPAD_Mu2e_Tracker.pdf