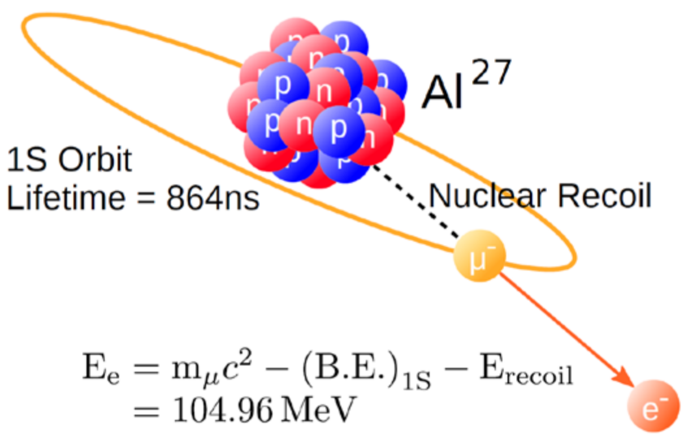
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

The mu2e straw tracker

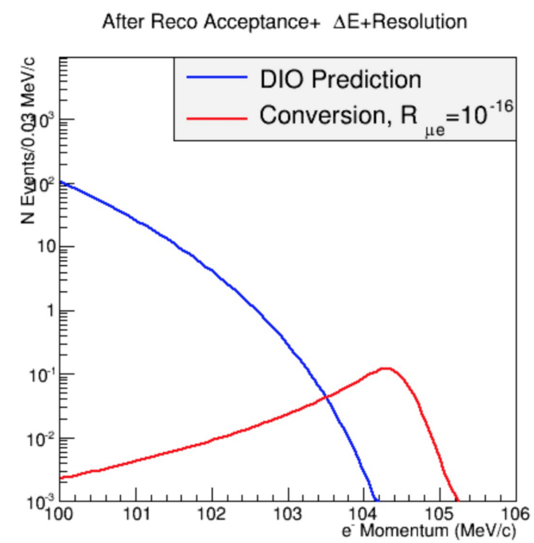
Vadim Rusu

IDTM Lisboa 2023

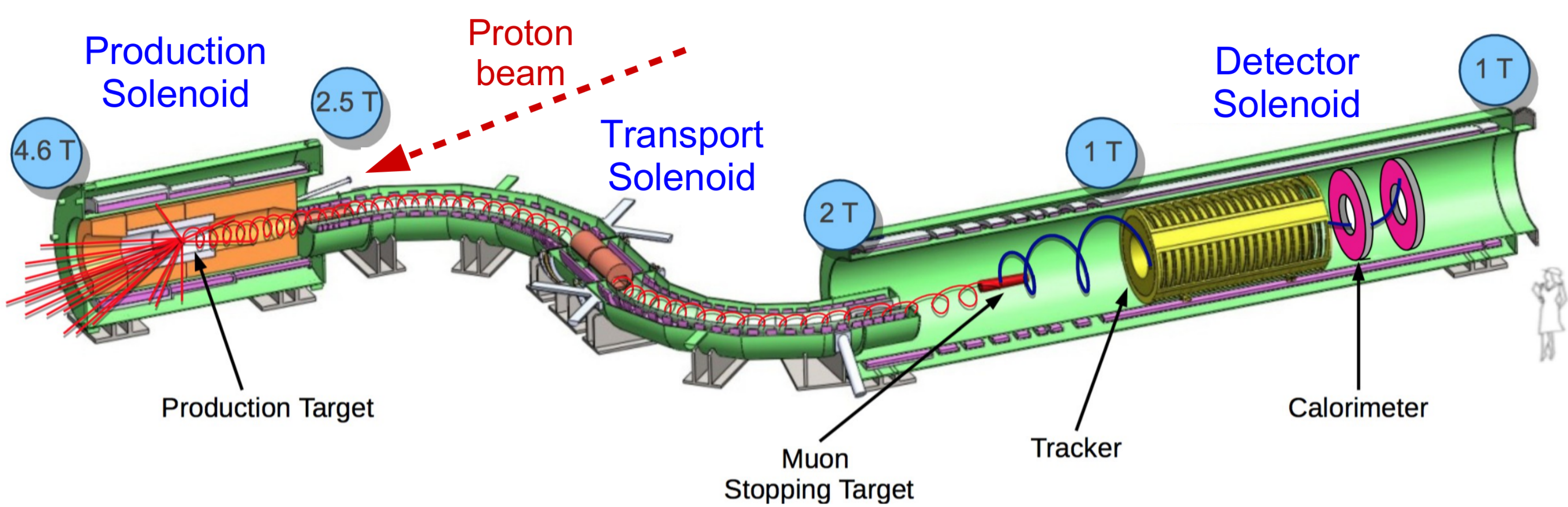
Search for lepton flavor violation though μ→e conversion



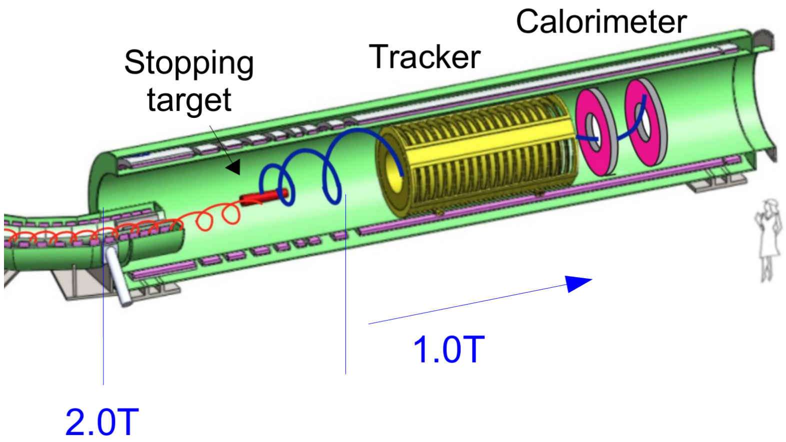
$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil}$$
$$= 104.96\,MeV$$

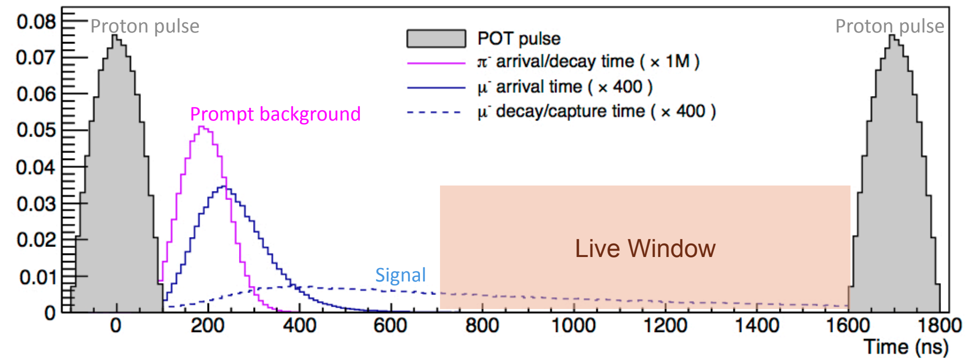


• Tracker makes the key momentum measurement



Challenges for detector construction

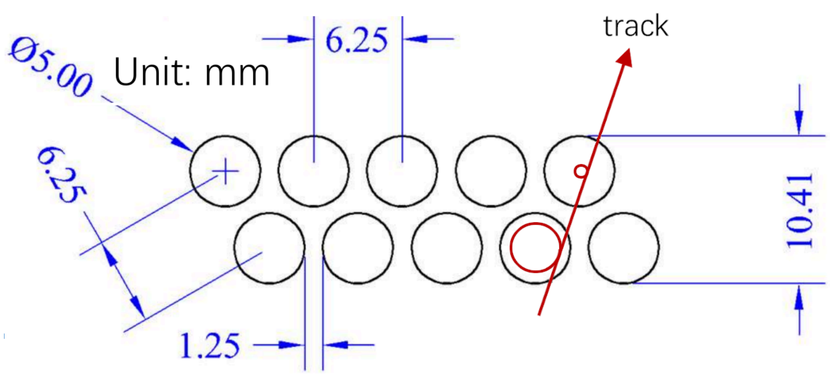


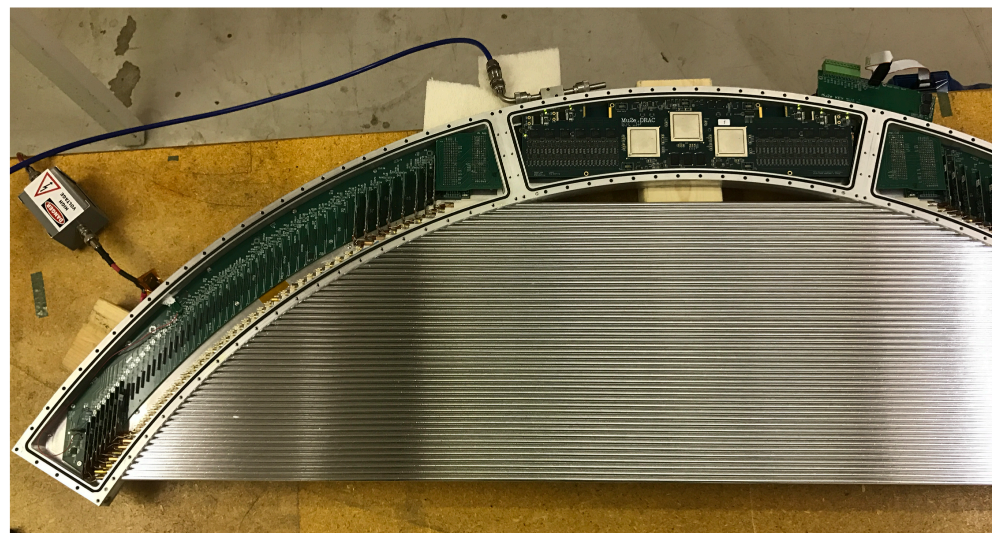


- To reach target sensitivity, need momentum resolution <200keV/c
  - Detector needs to be low mass + in vacuum
- Minimal external constraints
  - Don't know t_0 (1μs event window)
  - Don't know starting vertex
  - Signal is single track
- Radiation damage on electronics (150kRad requirement)
  - All COTS based
- 1T B field

Low mass straw tracker design

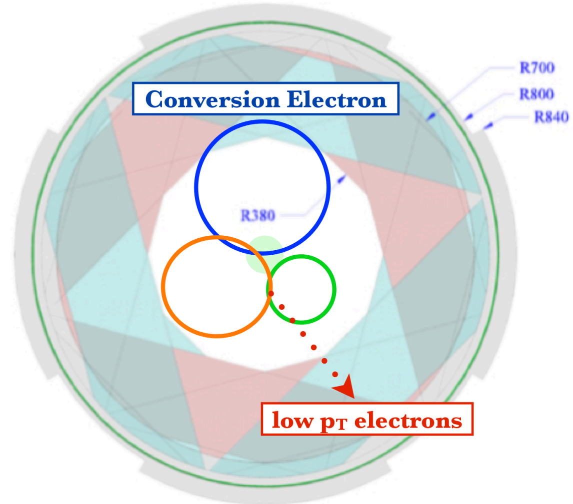
- ~21000 low mass straw tubes in vacuum
- Modular assembly in harp shaped ‘panels’ of 96 straws in two staggered lengths
- 5mm diameter, 0.5-1.2m long, held at tension
- 15 µm thick mylar walls, 25µm tungsten wire @~1500V
- 1atm 80/20 Ar:CO_2 drift gas

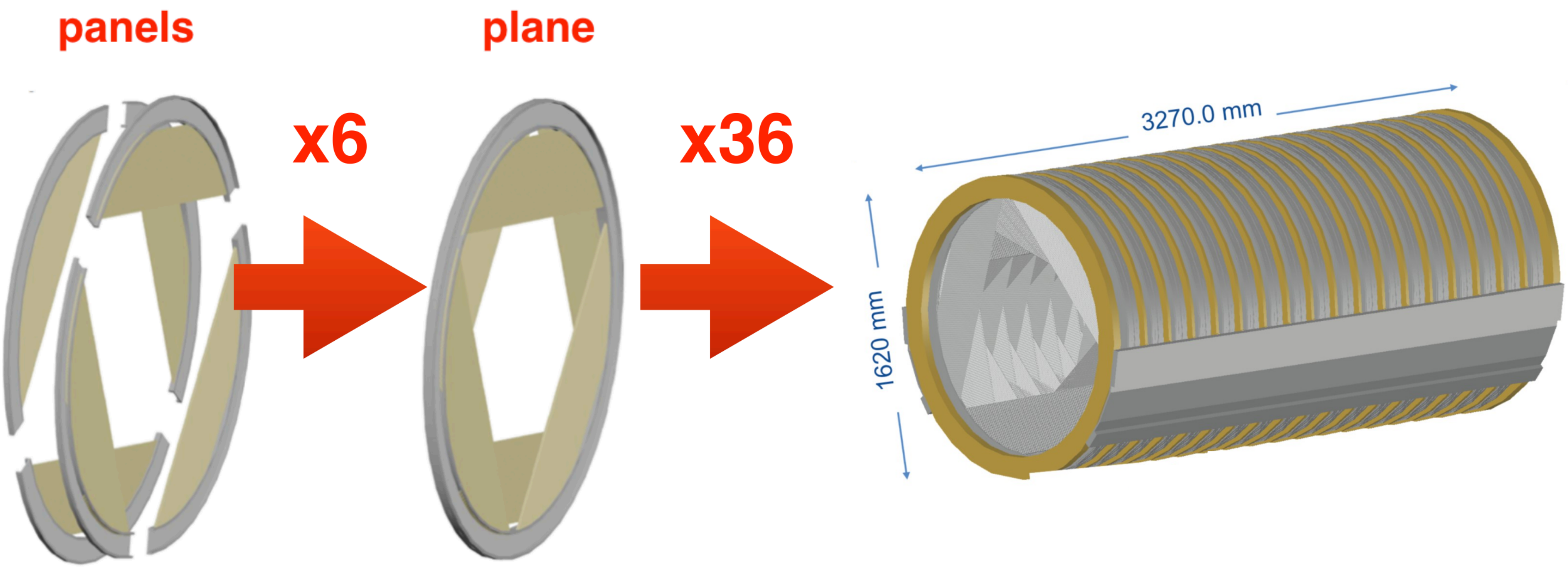




Modular design

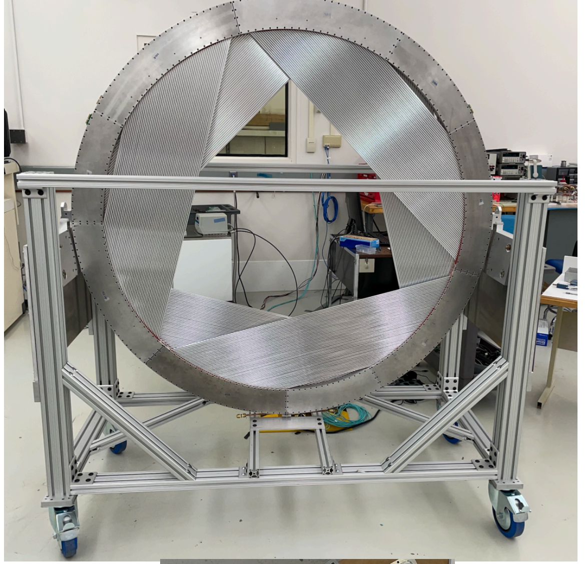
- 36 planes each containing 6x 120 deg panels for stereo
- Blind to low momentum particles (e.g. Decay in orbit)
  - Reduced hit rate and radiation load (aging)

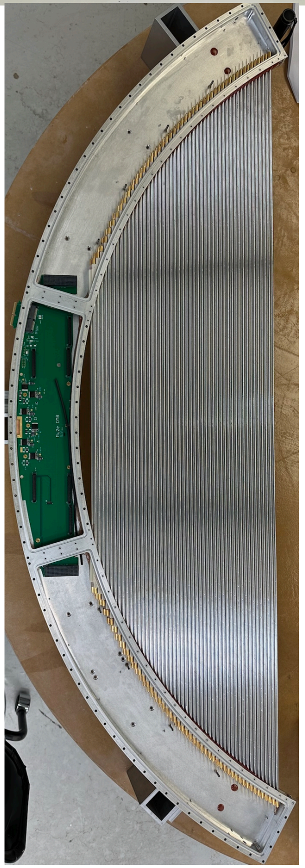


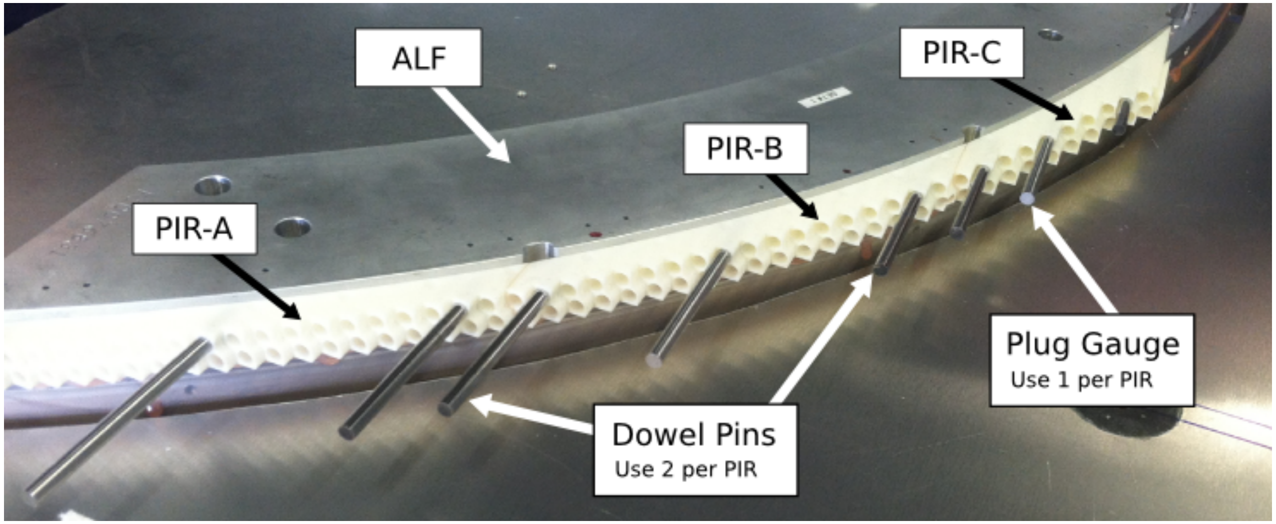


Panel construction

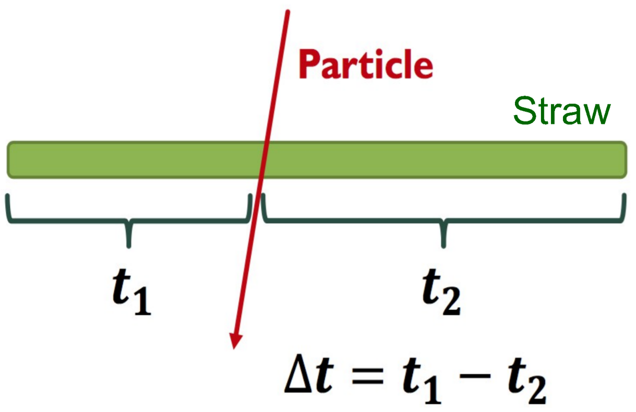
- Circular vacuum manifold for gas and electronics
  - All electronics on the detector
- Minimize joints to vacuum exposure
- 3D printed insert to house straw terminations
- Only vacuum penetrations inside the panel are power and high speed signal to drive the optical interface

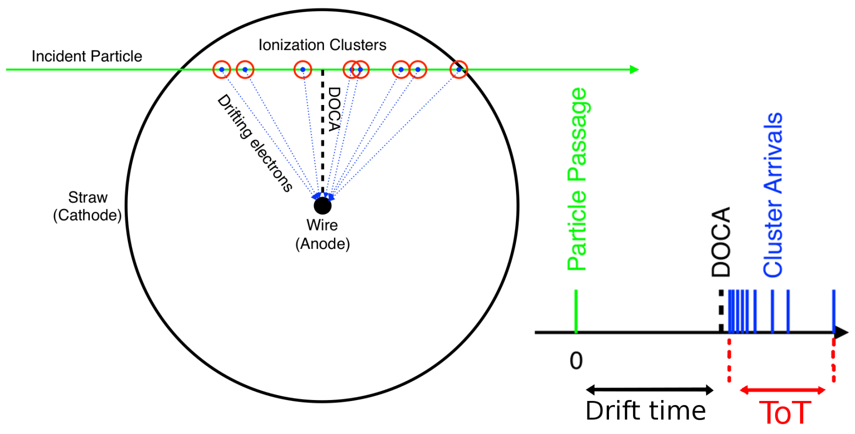






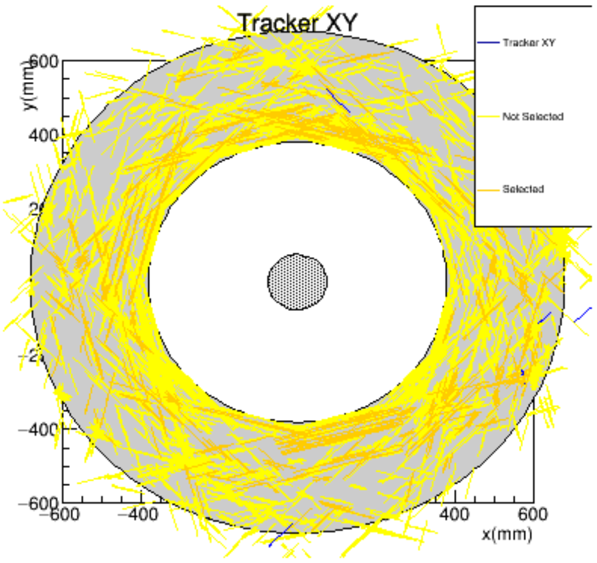
Basic straw measurements

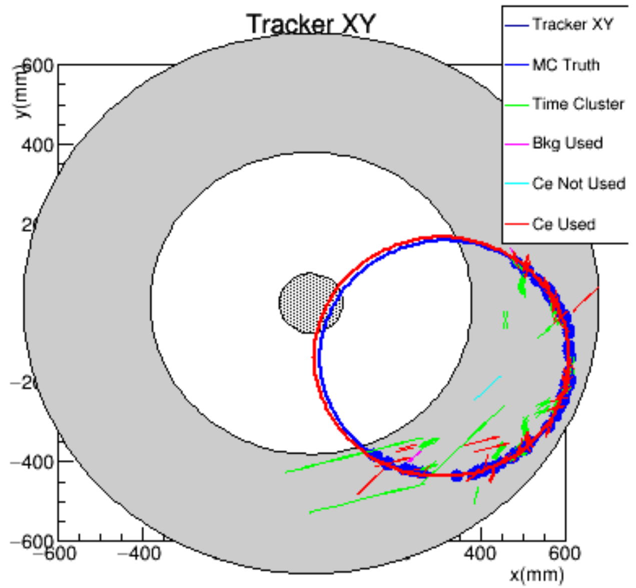


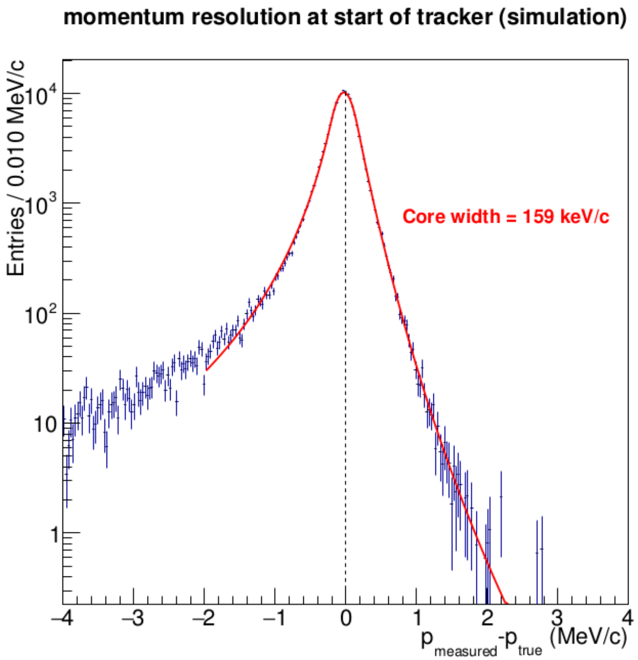


- Drift time → radial resolution ~250 µm
- Time division → longitudinal resolution ~4 cm (~200ps)
- Time-over-threshold → Measure of path length / radius independent of t_0
- Digitize waveform to reject highly ionizing backgrounds

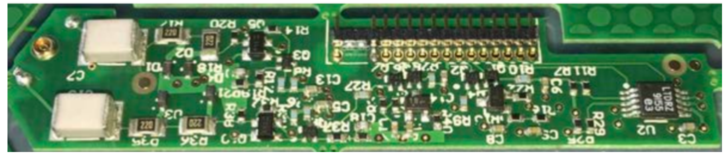
Helix reconstruction and momentum resolution



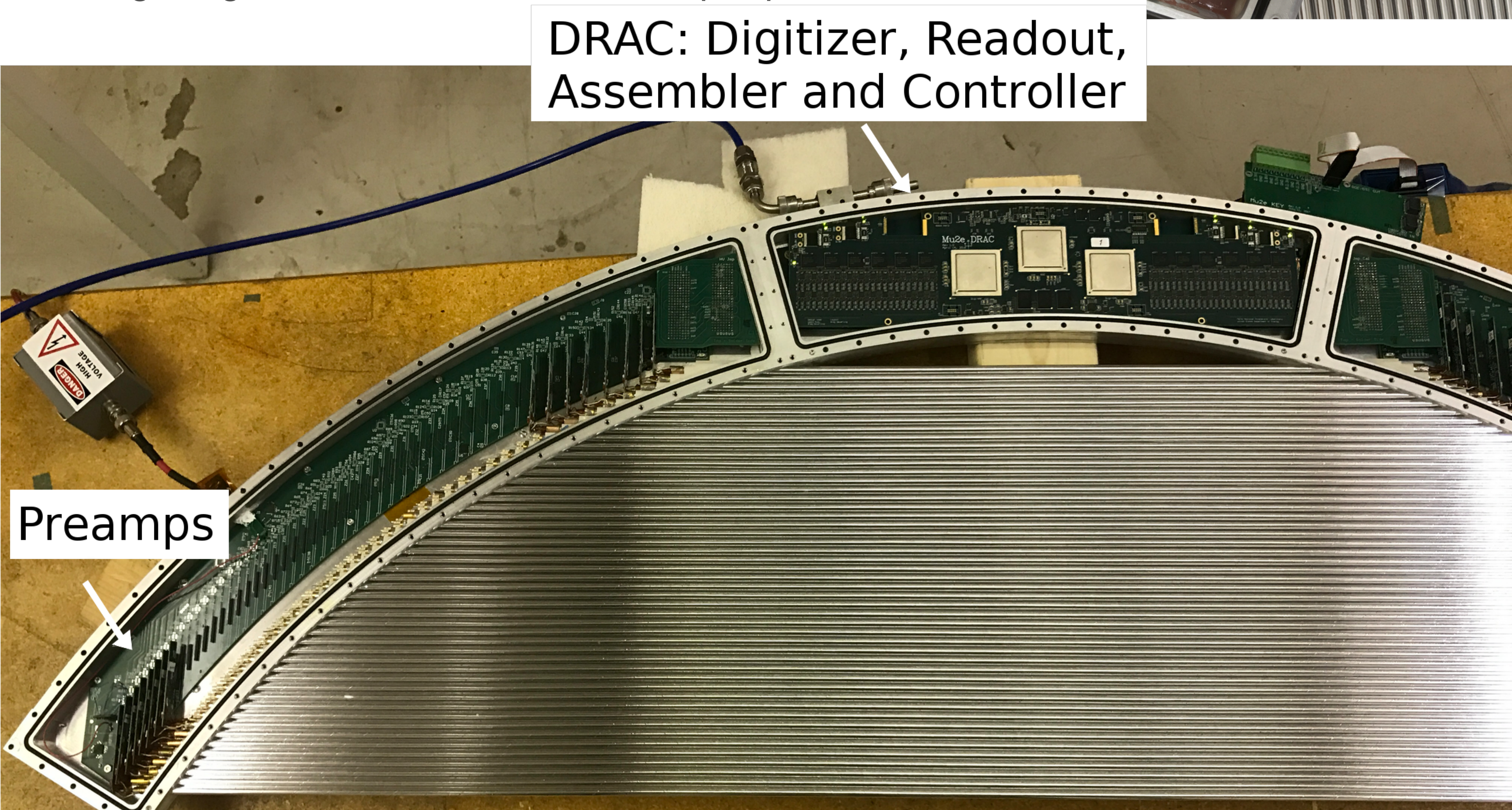




Time division



- Instrument both sides with preamps (SiGe BJT front-end)
- >100MHz BW design → noise considerations
- Single digitization and readout board per panel



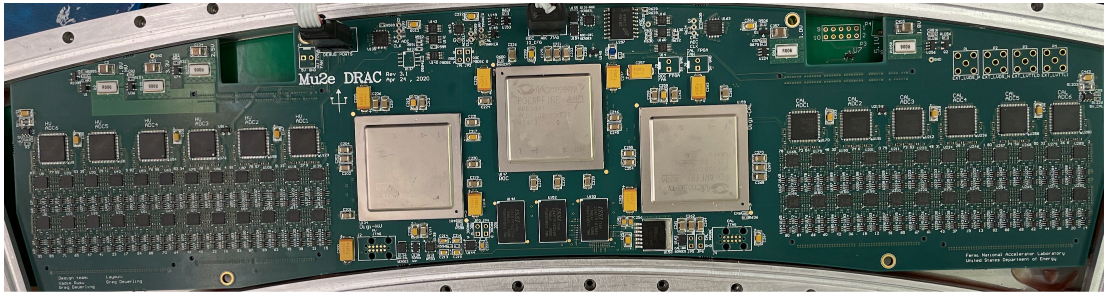
Front end electronics: DRAC

- 3x Microsemi PolarFire FPGAs
  • Two digitizers and one readout controller
  • 196 TDCs with <70 ps resolution per channel firmware based on delay chain dithering

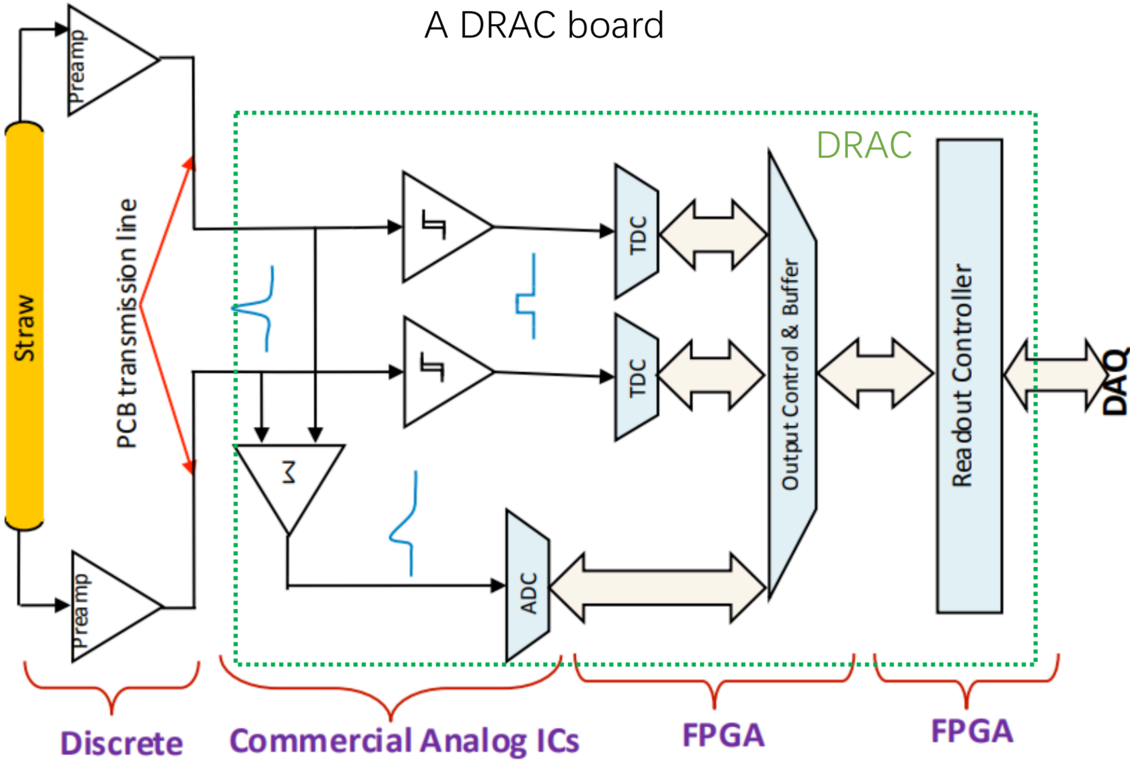
- 50 MHz commercial ADCs to digitize waveform

- DDR4 memory for buffering • Takes advantage of ~30% beam dutyfactor

- VTRx optical transceivers to TDAQ
  • 200 MHz detector clock and time synchronization from TDAQ over fiber

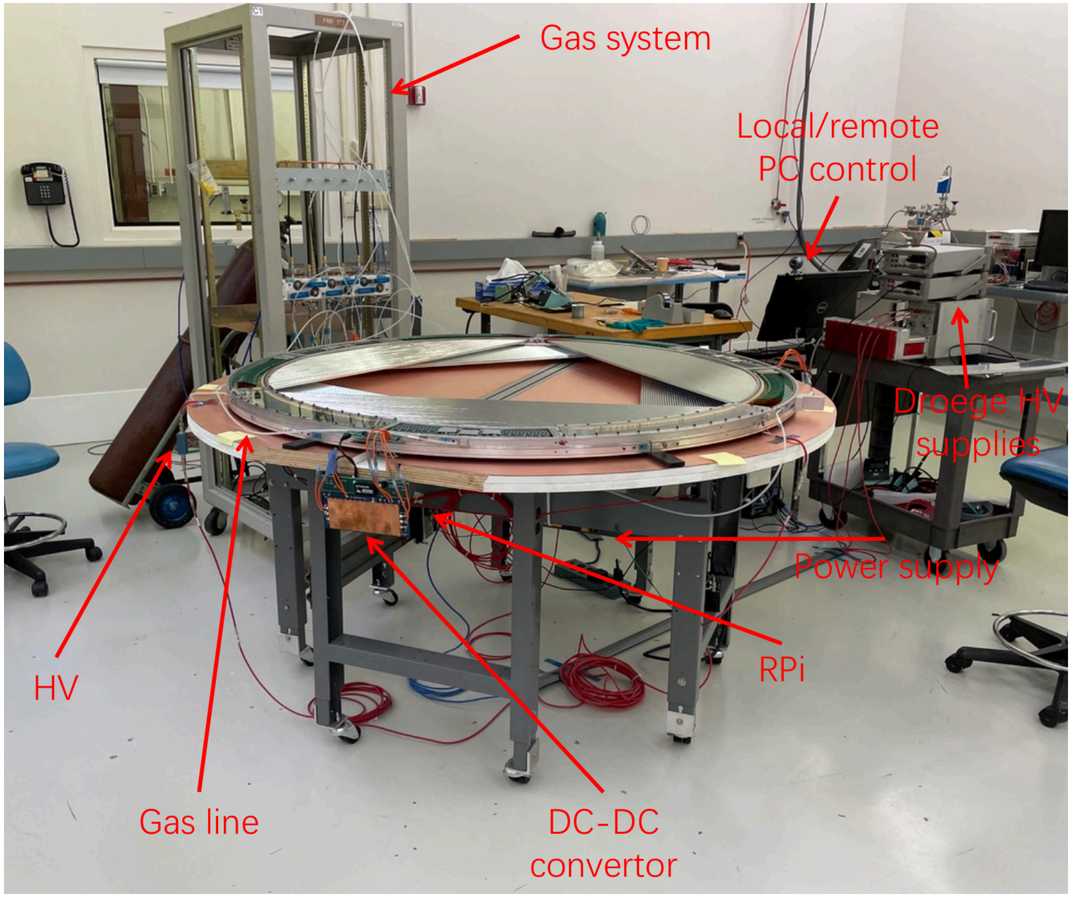


A DRAC board



Signal flow chart

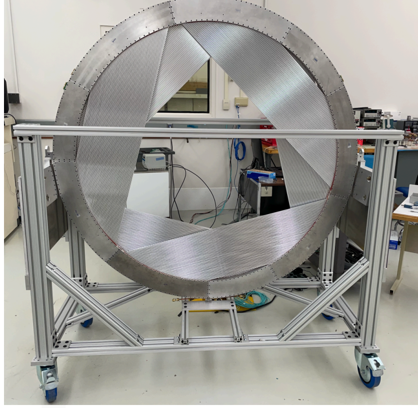
Completed VST program for physics level quantities

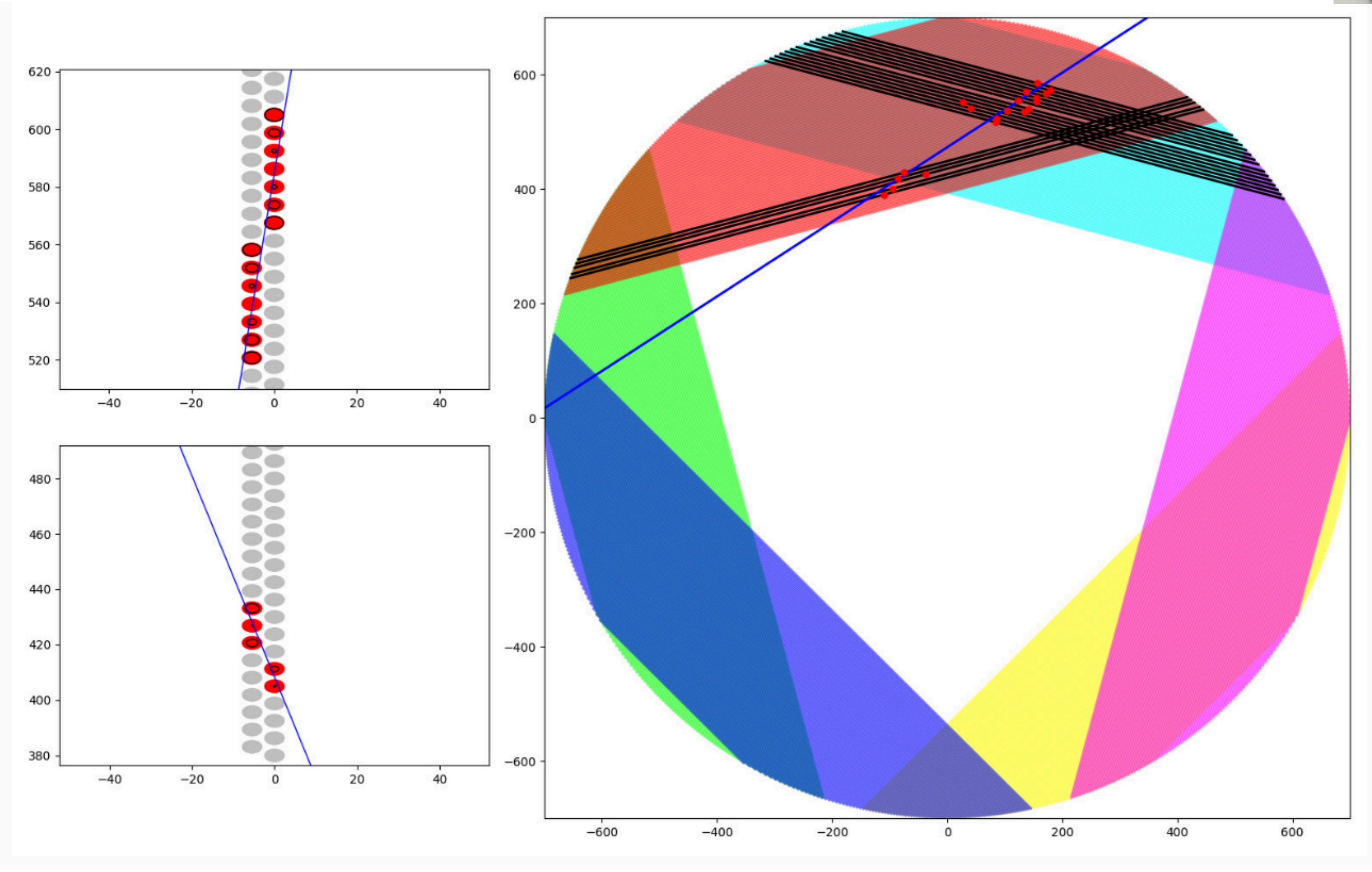


- 'Vertical slice': Testing full chain from straws to readout to processed data on disk
- Six fully instrumented pre-production panels in plane configuration with associated HV/ gas/cooling infrastructure
- Read out by TDAQ over optical fiber
- Source and cosmic ray data taken in several configurations
- Demonstrates performance under realistic conditions

Cosmic data with VST

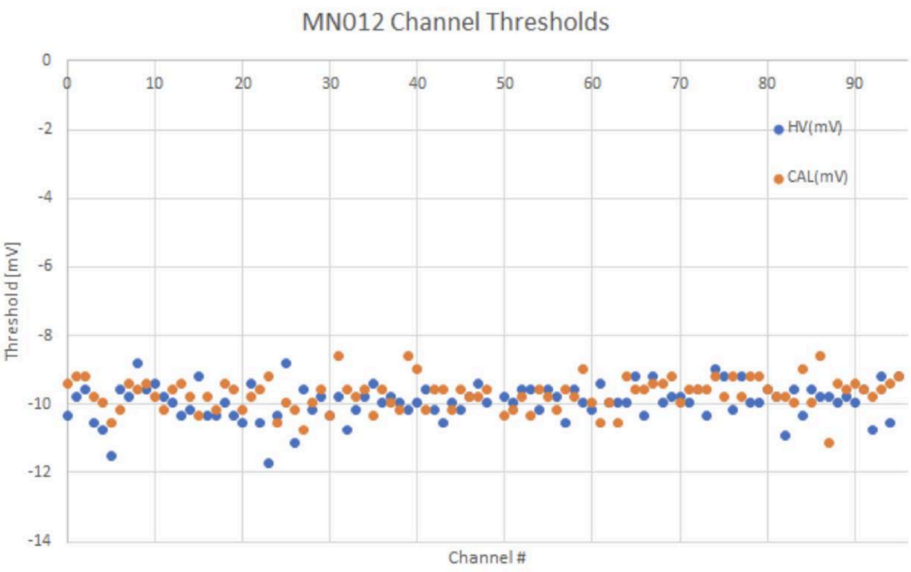
- Simplified straight track reconstruction

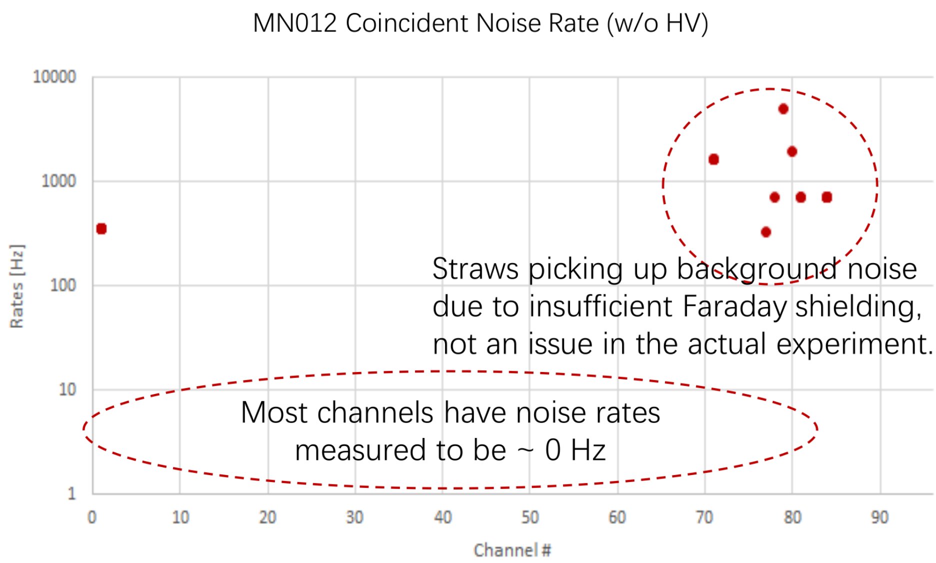




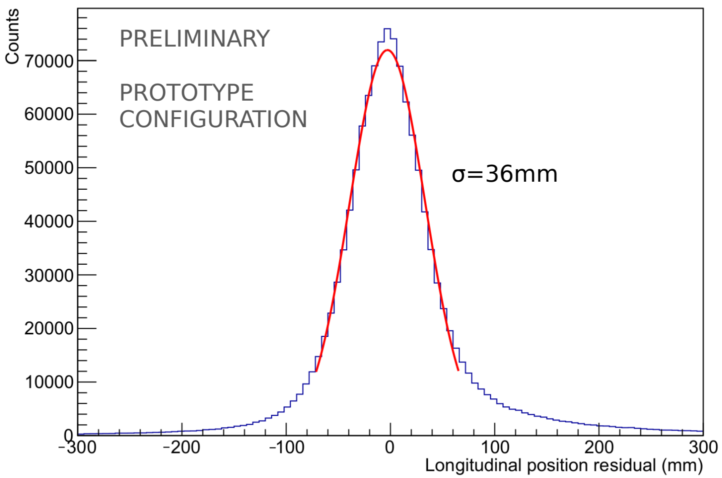
Noise performance

- Physics simulations and analysis assumes 12-mV threshold
- At thresholds of ~10 mV, demonstrated close-to-zero noise level in all channels (requirement is < 5 kHz at 90% efficiency threshold)



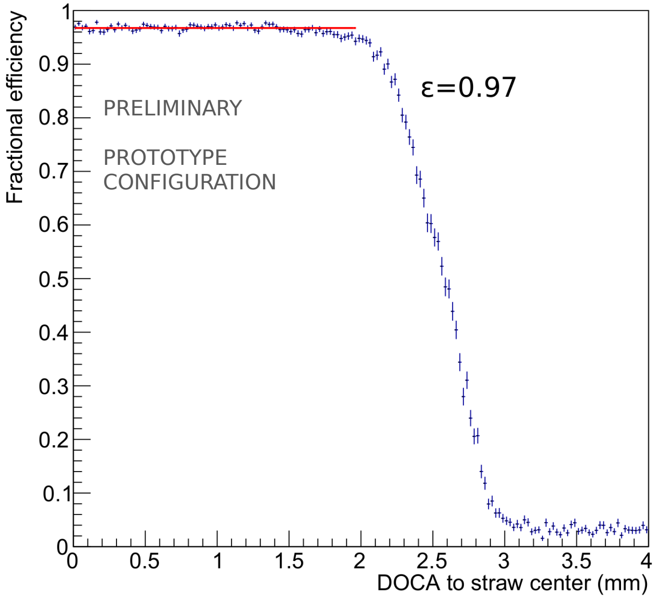


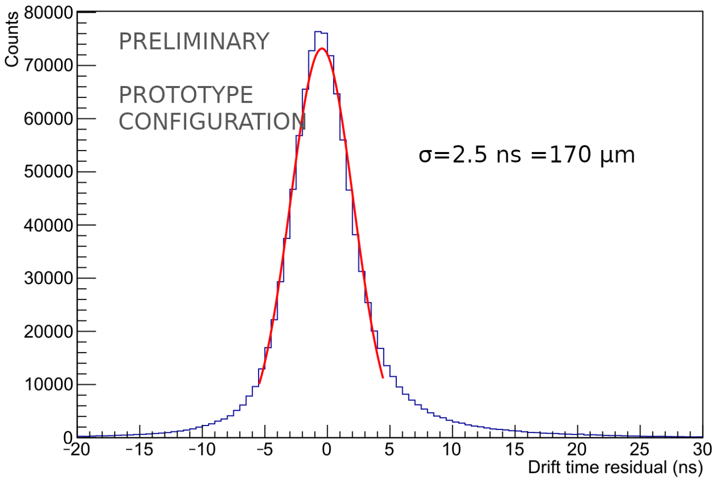
High level performance with VST



Longitudinal resolution, middle 80% of straw length (VST data), requirement <40 mm (~200ps equivalent)

Efficiency vs distance to wire (VST data), requirement >90%

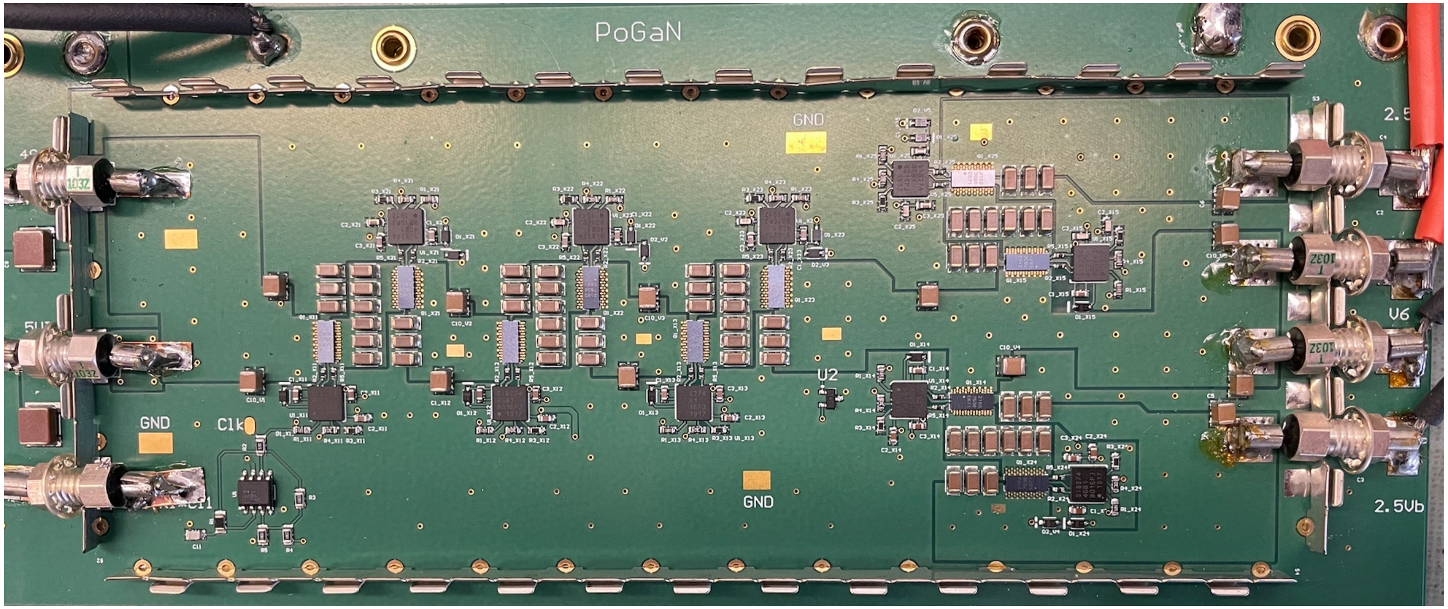




Drift resolution, excluding inner 0.5mm (VST data), requirement <250 μm

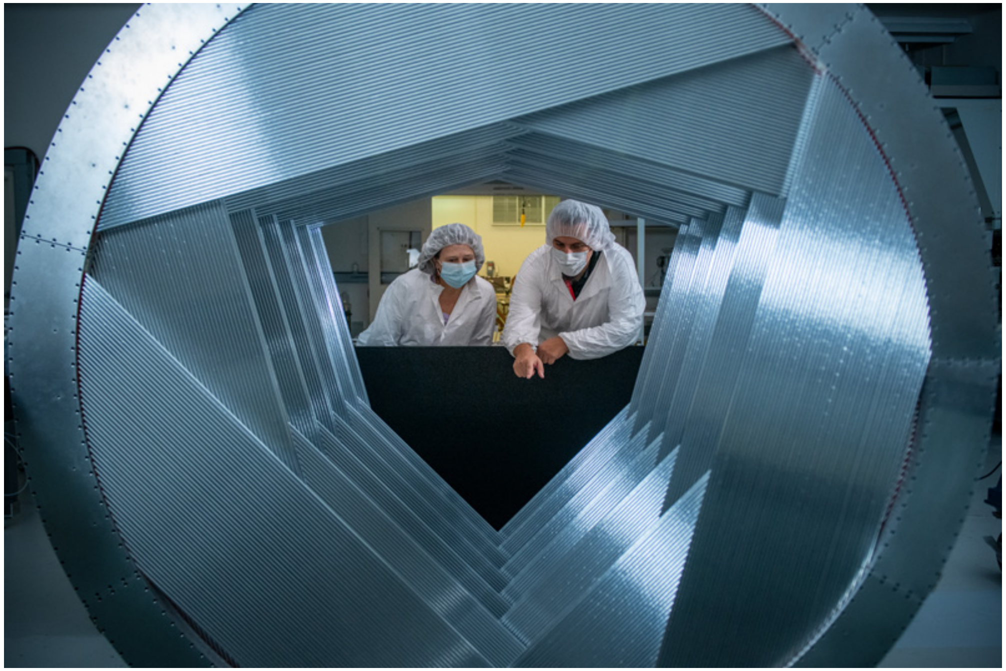
Power distribution

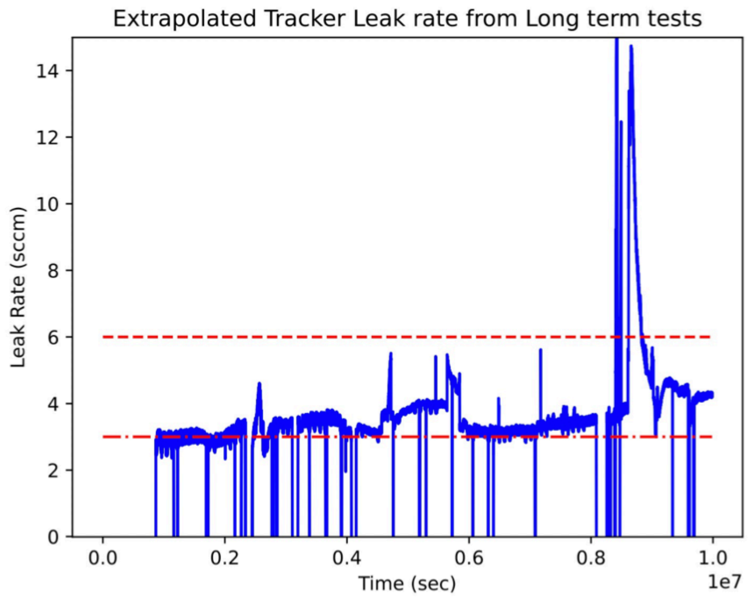
- ~50W consumed by each panel
  - 2 main rails (2.5V and 5V) to reduce vacuum penetrations
  - ~10A on one rail - unrealistic to bring power from outside cryostat while maintaining uniformity in B-field
- DC/DC converter requirements
  - Work in 1T field
  - Maintain performance to 150kRad
- GaN FET based charge pump (in reverse) - bring in power from outside @48V
  - GaN - higher electron mobility and higher critical electric field (vs Si)



Tracker construction

- Panel construction complete
- 26 out of 36 planes complete
- Electronics procurement underway
- Planes kept under pressure after construction to measure leak tightness behavior over time
  - Separate electronics chain to continuously measure pressure





Summary

- Tracker construction for mu2e underway
- Design had to overcome several challenging aspects
- Performance demonstrated with integrated prototypes
- Data taking in FY26