An ultra-light drift chamber with particle identification capabilities

F. Grancagnolo
INFN – Lecce, ITALY

WG11 Detector Design Meeting

CERN

17 October 2016

Road to proposal

- Ancestor chamber: **KLOE** at INFN LNF Daφne ϕ factory (commissioned in 1998 and currently operating)
- **CluCou** Chamber proposed for the **4th-Concept** at ILC (2009)
- **I-tracker** chamber proposed for the **Mu2e experiment** at Fermilab (2012)
- **DCH** for the **MEG2 upgrade** at PSI (under construction at INFN and to be commissioned during spring 2017)

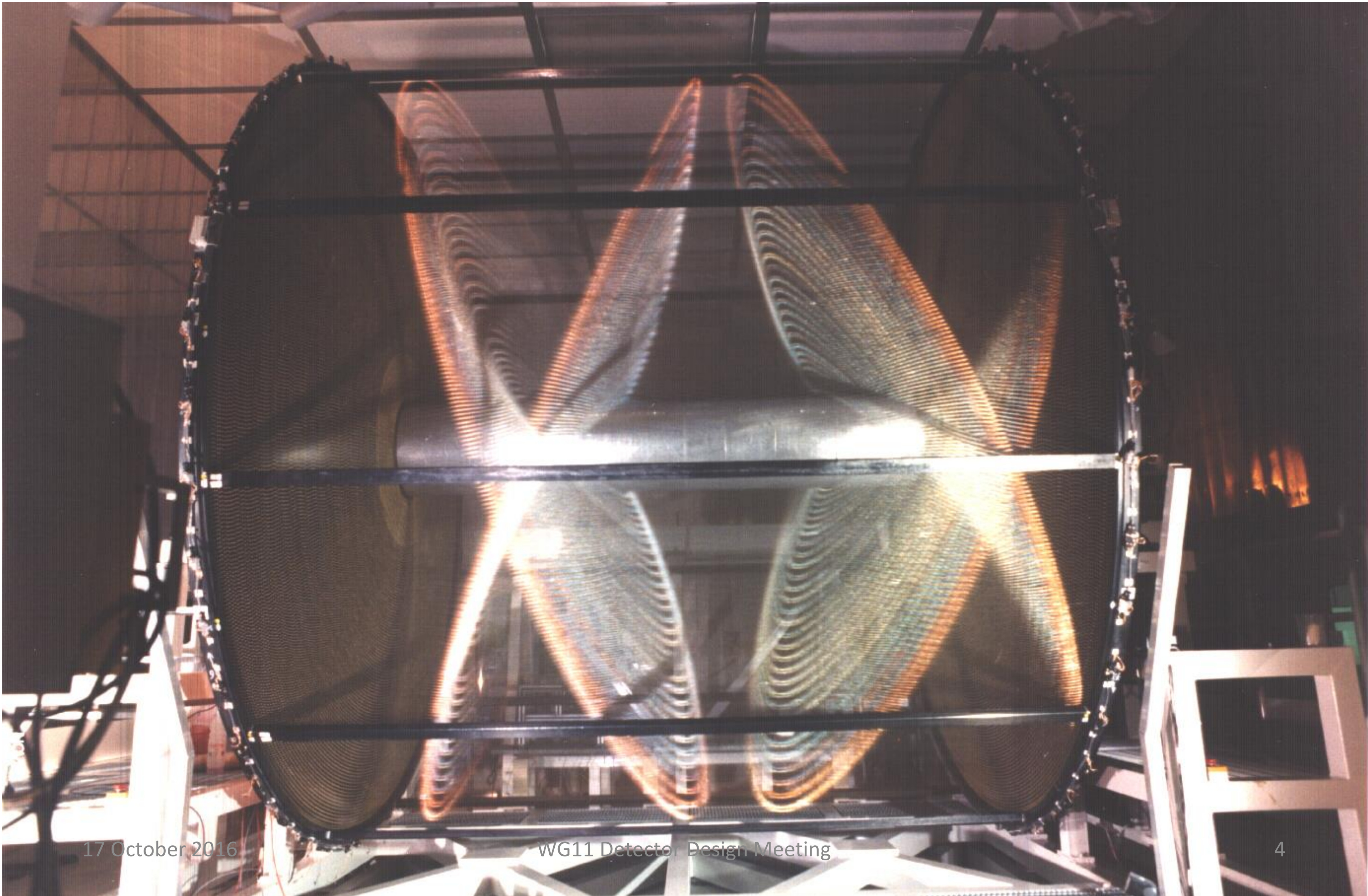
"Traditional" Drift Chamber

A cylindrically symmetric gas volume with (para-)axial wires defining a strong electric field, strung under mechanical tension for electrostatic stability and fixed at their extremities to the end walls by means of feed-through.

CONSTRAINTS:

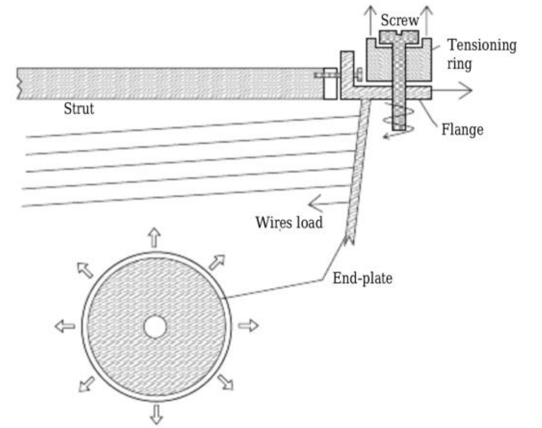
- The **end walls**, holding the feed-through (which limit the chamber granularity), the FE electronics and the relative cabling, must be rigid enough to transfer the load due to the wire tension (of the order of several Tons) to the **outer cylindrical wall**, without deforming.
- The **inner cylindrical wall**, usually, does not bear any load, to minimize the multiple scattering of incoming particles.
- The **gas tightness** relies on the hermetic properties of all surfaces and of all their relative joints.

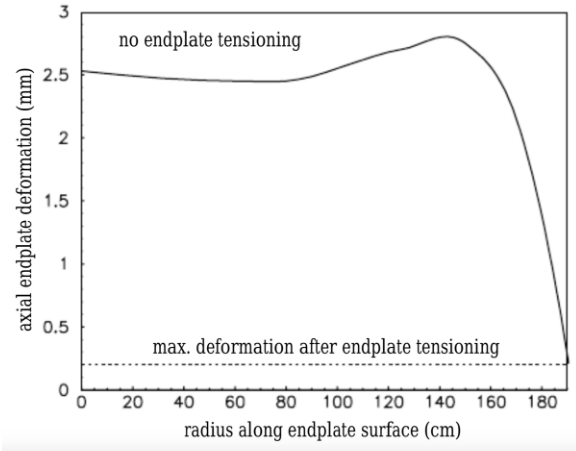
The KLOE Drift Chamber



The KLOE Drift Chamber

Mechanical and construction characteristics	
Outer radius	1980 mm
Outer panels thickness	39.0 mm
Inner cylinder radius	250 mm
Inner cylinder thickness	1.1 mm
End-plate radius of curvature	9760 mm
End-plate thickness	9 mm ($0.03 X_0$)
C-fiber X_0	26.7 cm
Maximum length	3320 mm
Minimum length	2800 mm
Number of drift cells	12,582
Number of wires	52,140
End-plate wire load	3500 kg

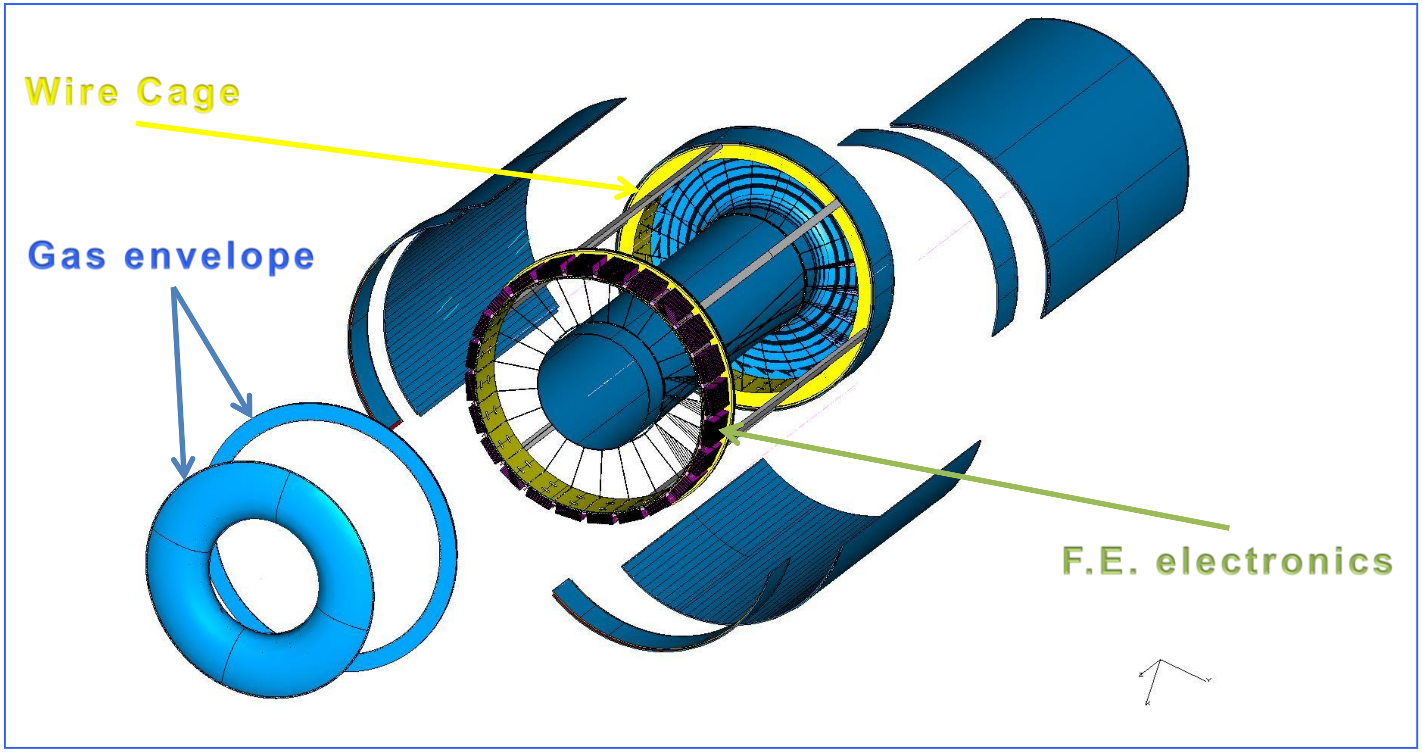




Drift Chamber "Innovations"

1. Separating **gas containment** from **wire support** functions
2. Using **a larger number** of **thinner** (and **lighter** wires)
3. No **feed-through** wiring
4. Using **cluster timing** for improved spatial resolution
5. Using **cluster counting** for particle identification

Gas containment and Wire support



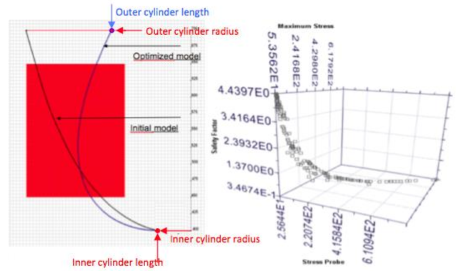
Gas containment — **Gas envelope** can freely deform without affecting the internal wire position and tension.

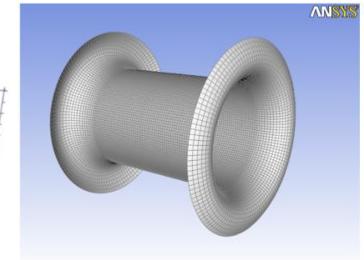
Wire support — **Wire cage** structure not subject to differential pressure can be light and feed-through-less.

Example: The Mu2e I-Tracker proposal

Gas Envelope

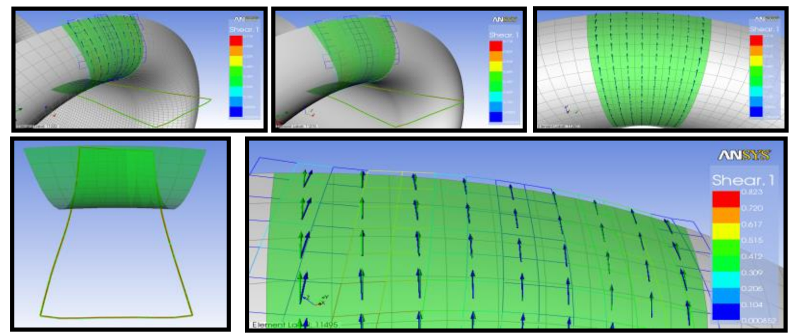
A structural multivariate analysis software (**ModeFrontier®**) has enabled to find the optimal shape for the **profile of the end plates** by minimizing maximum stress and stress on inner cylinder



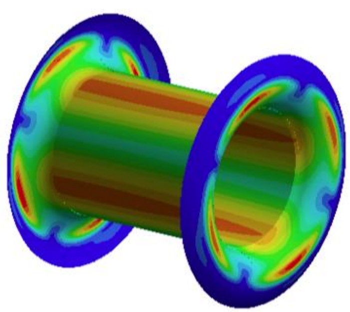


parameters	Initial model	Optimized model
Maximum stress	357.5 MPa	58.7 MPa
Stress at inner boundary	267.4 MPa	26.6 MPa
Safety factor	0.783	4.44

ANSYS ACP® has chosen the proper unidirectional prepreg to form **ply**, **draping** of the laminates and **flat-wrap** of the optimized model



Solve buckling problems of inner cylinder by increasing the **moment of inertia** with use of proper light core composite sandwich



End plates:

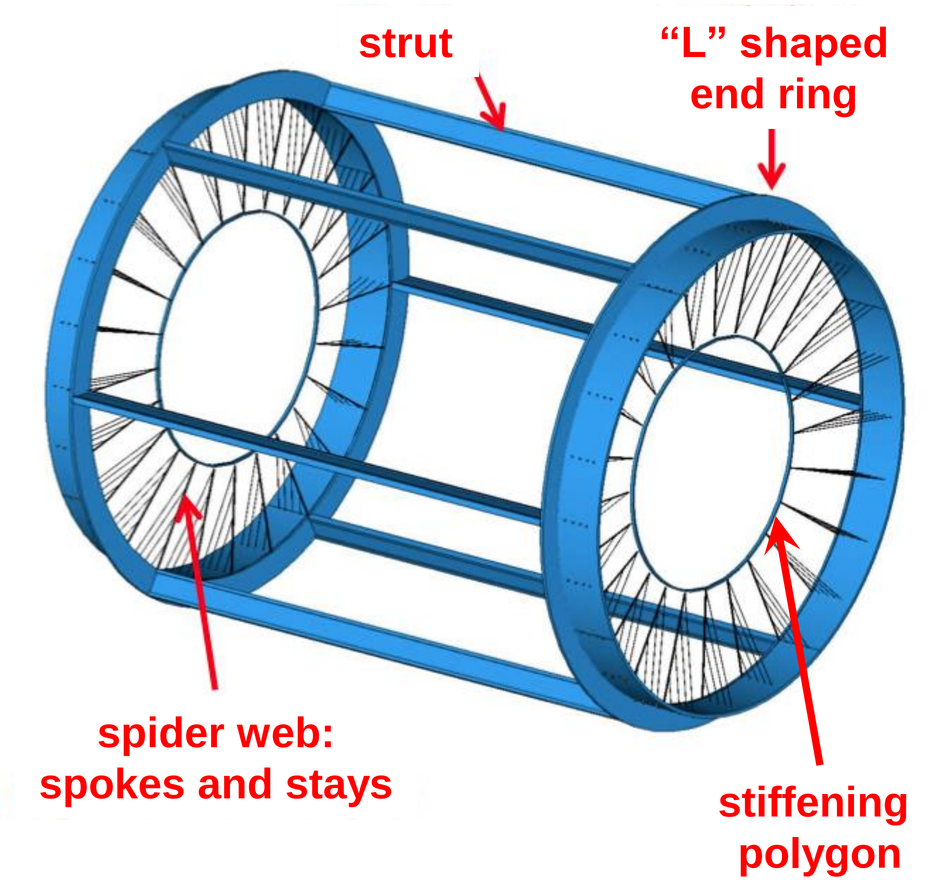
4-ply 38μm/ply
orthotropic (0/90/90/0)
0.021 g/cm²
5×10^{-4} X_0

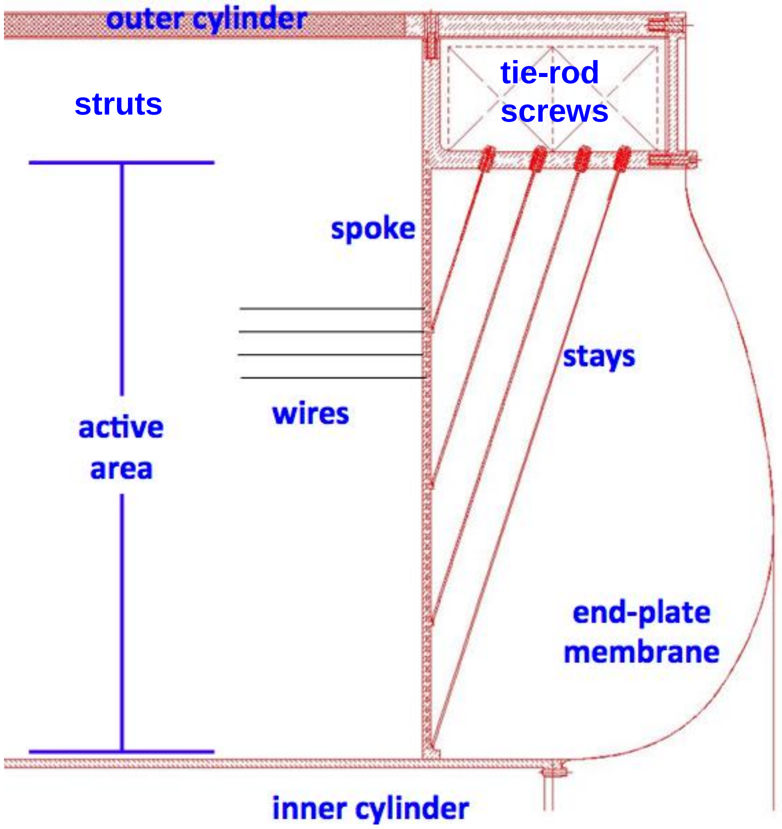
Inner cylinder:

2 C-fiber skins, 2-ply,
C-foam core, 5 mm
0.036 g/cm²
9×10^{-4} X_0

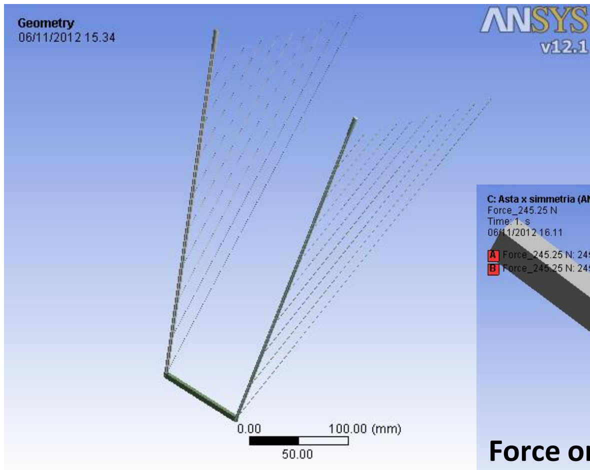
Example: The Mu2e I-Tracker proposal

Wire cage (conceptual)

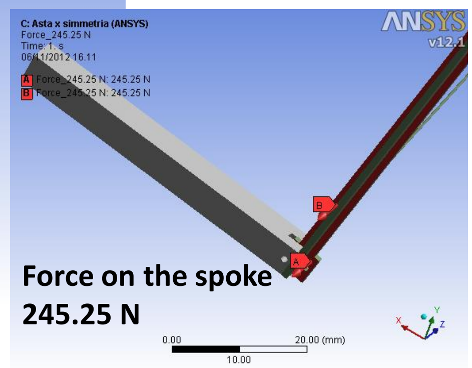


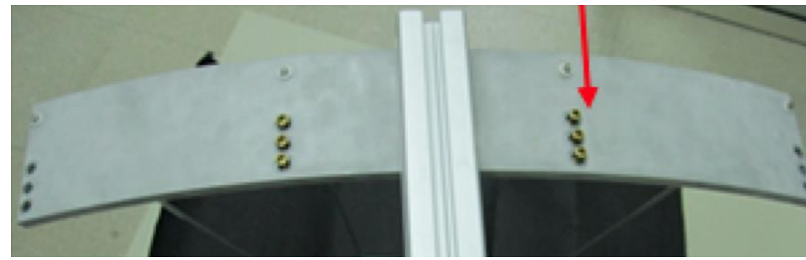


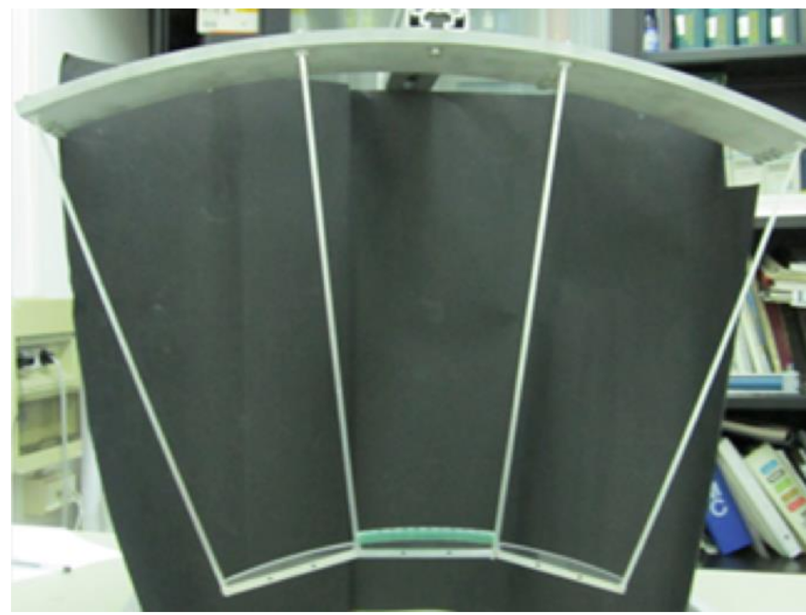
Verification of validity of principle



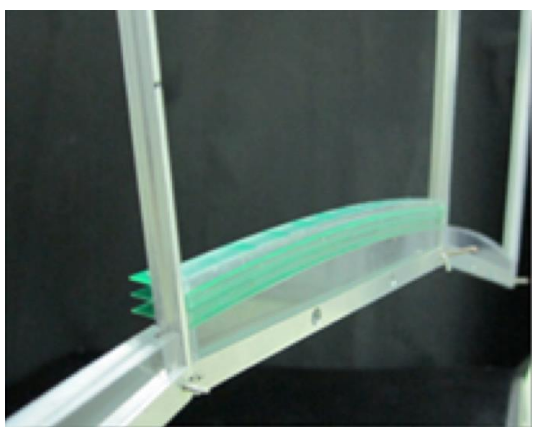
ANSYS FEM analysis







scale 1:1 model to verify validity of principle



Wire Cage

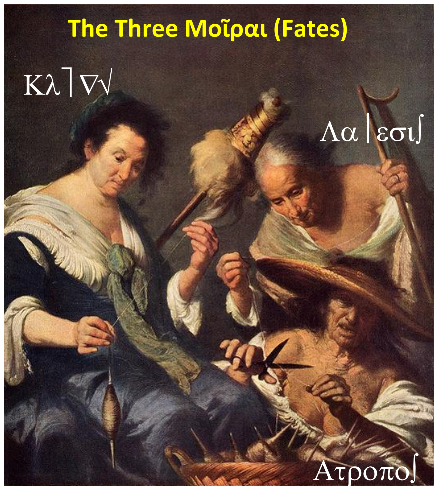
- This scheme does not require **wire feed-through** thus allowing for denser wire spacing, i.e. **smaller cells** (finer chamber granularity) and for **larger field to sense wires ratios**.

- **Larger field to sense wires ratio** and, therefore, **thinner field wires**, help reducing **multiple scattering contribution** and **total wire tension** on support structure.

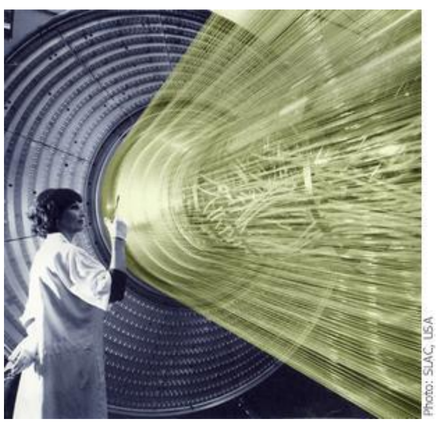
- Large number of wires and small cells, however, require complex and cumbersome **assembly procedures**, which call for a **novel approach** to the wiring problem.

DC stringing: the old way

The Old Way

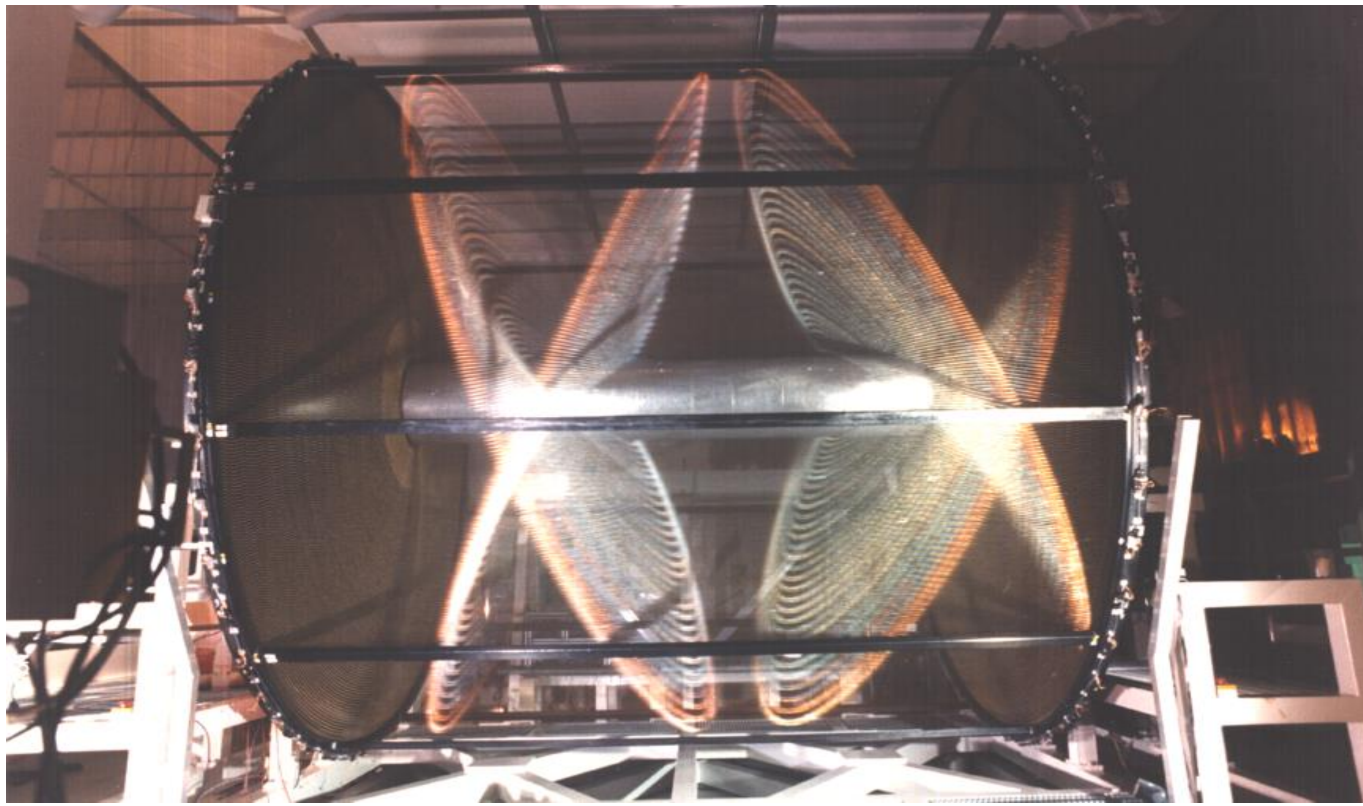


Bernardo Strozzi – Le tre Parche – Venezia, circa 1620

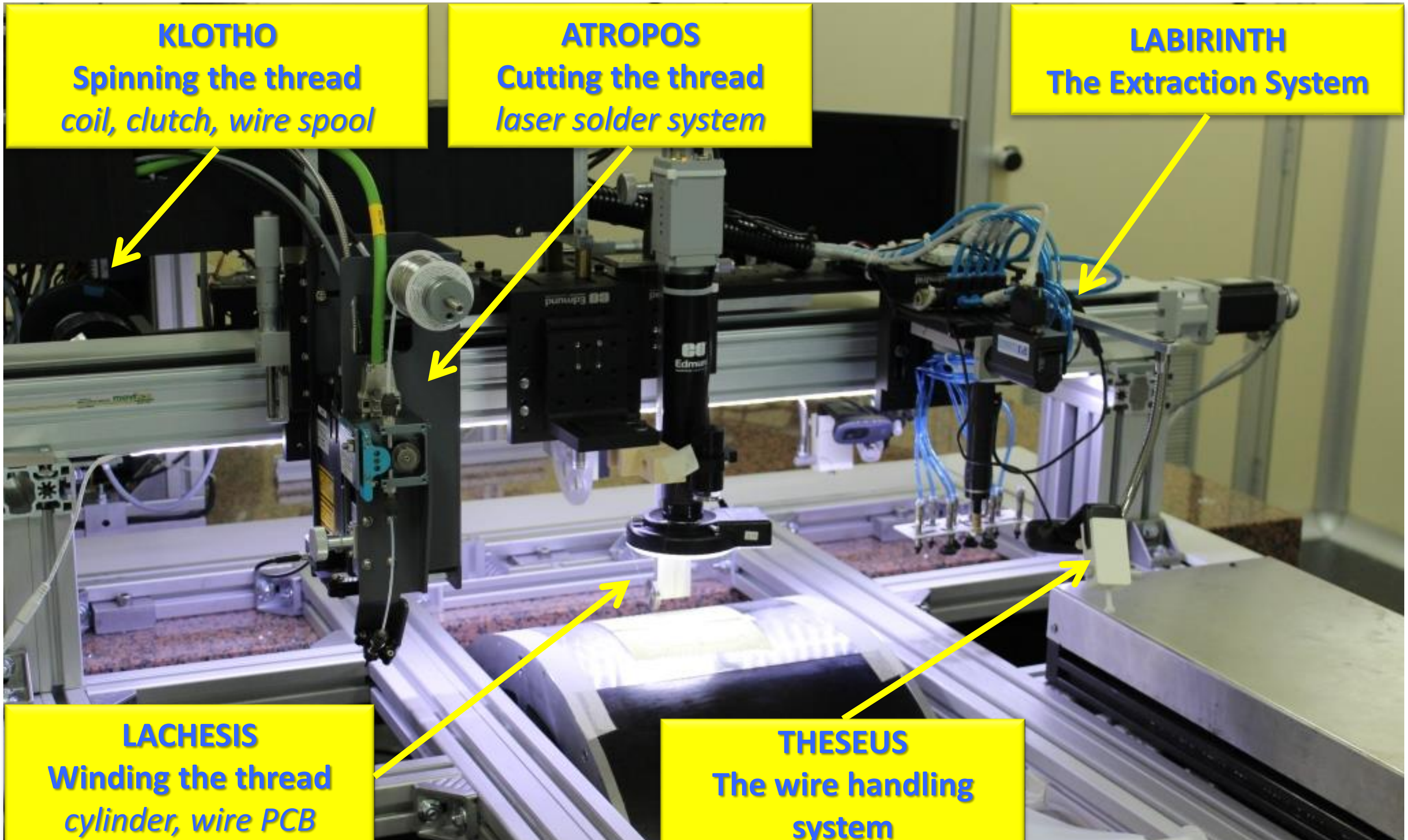


The KLOE Drift Chamber

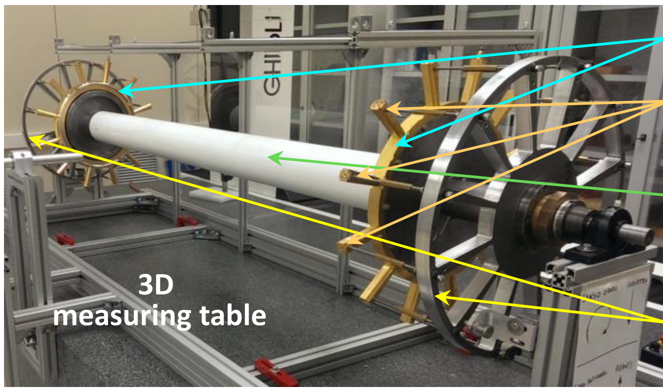
45 m^3 > 52,000 wires He/iC_4H_{10}



DC stringing: the novel way



MEG2 DC EndPlates

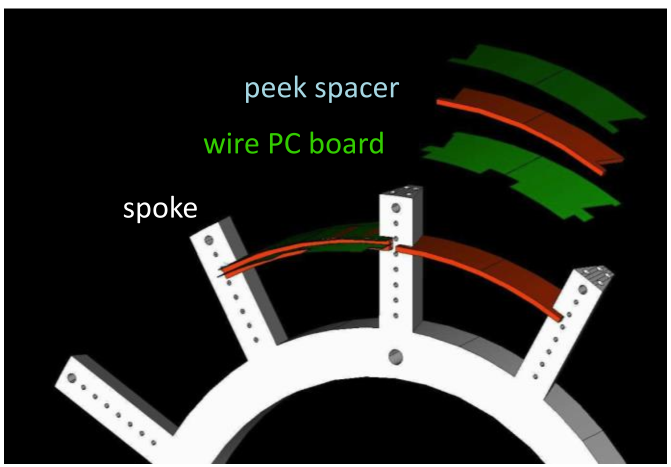


end-plates

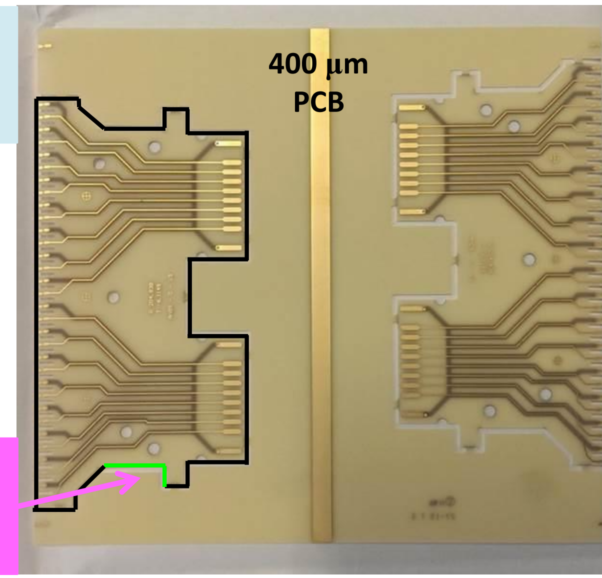
spokes

structural removable shaft

wire tension compensating wheels



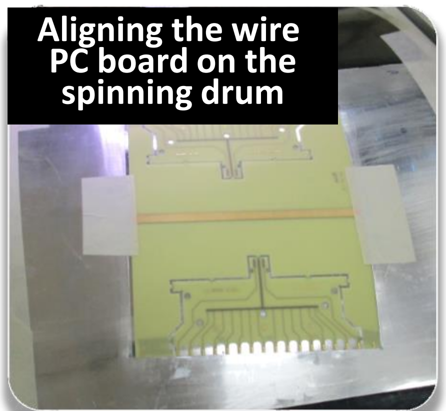
sense wires PC boards (16 cells)

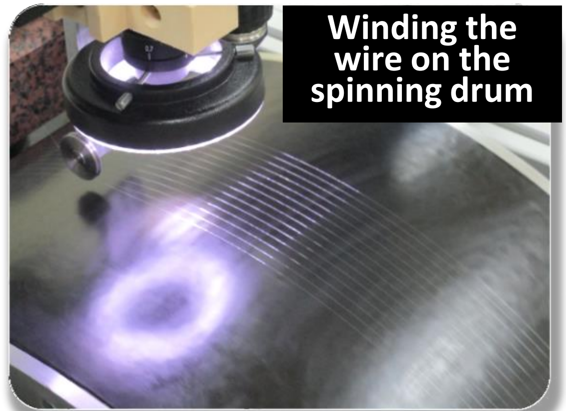


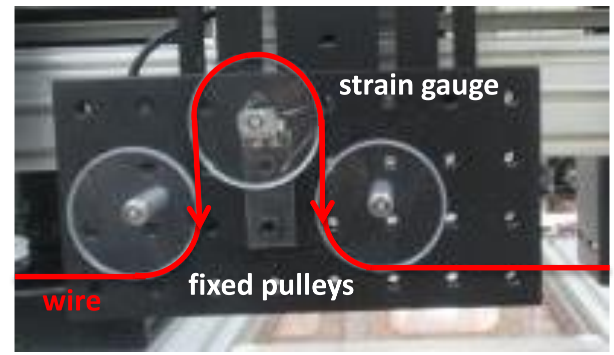
fiducial reference edge

NC machined peek spacer (½ cell thick 1 sector wide)

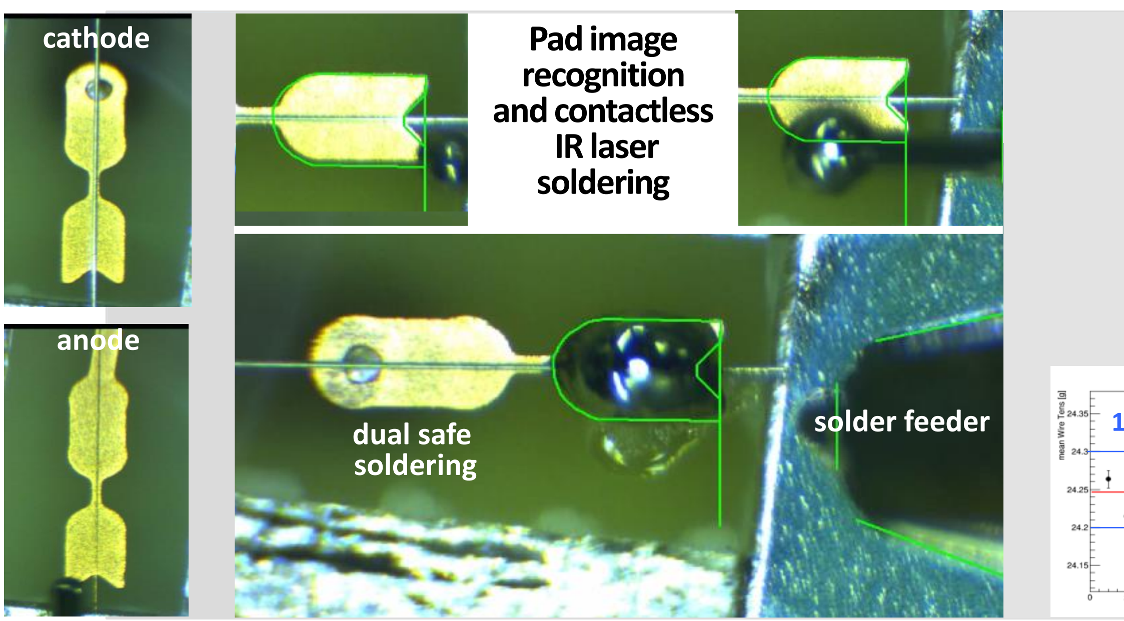
MEG2 DC Wiring

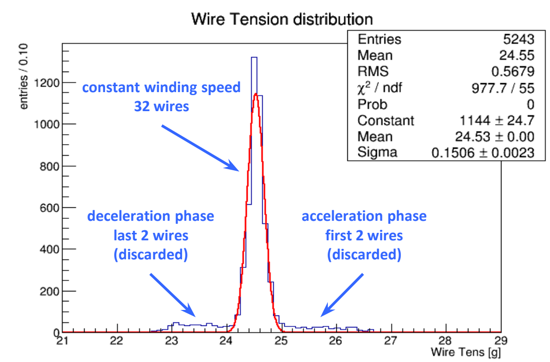


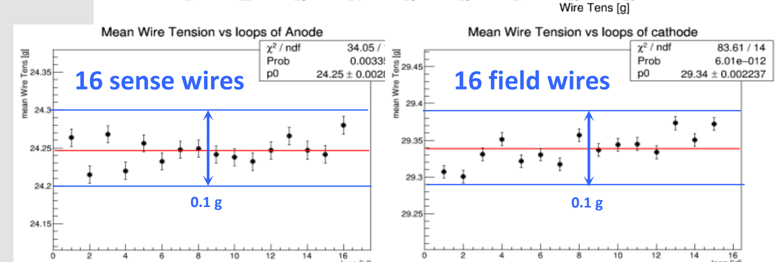




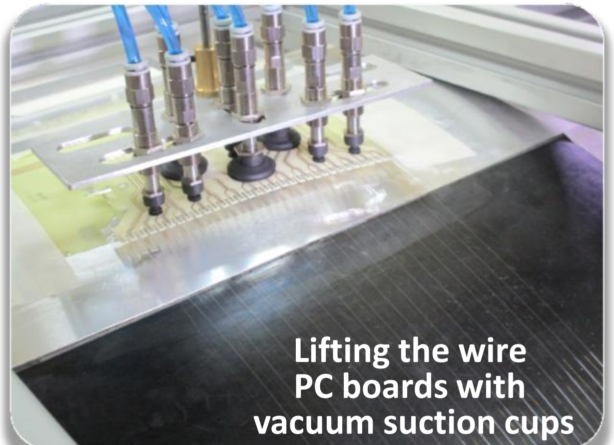
Wire tension set up with a real time strain gauge feedback system on the spooling el. mag. clutch

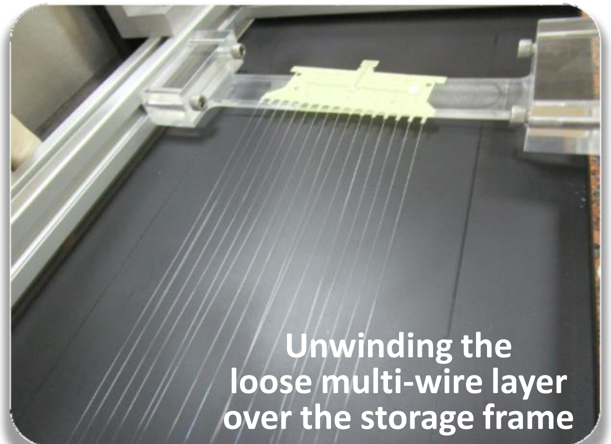


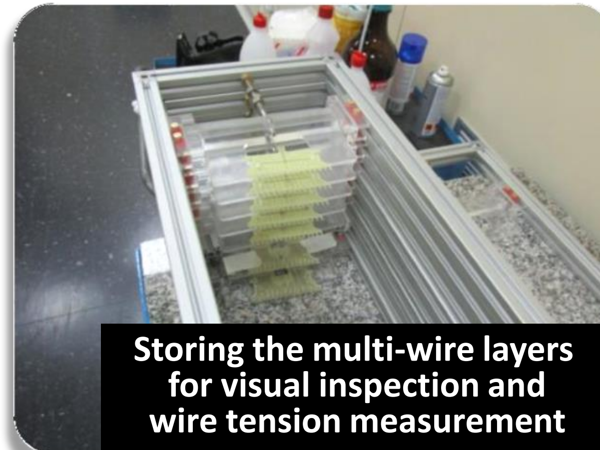


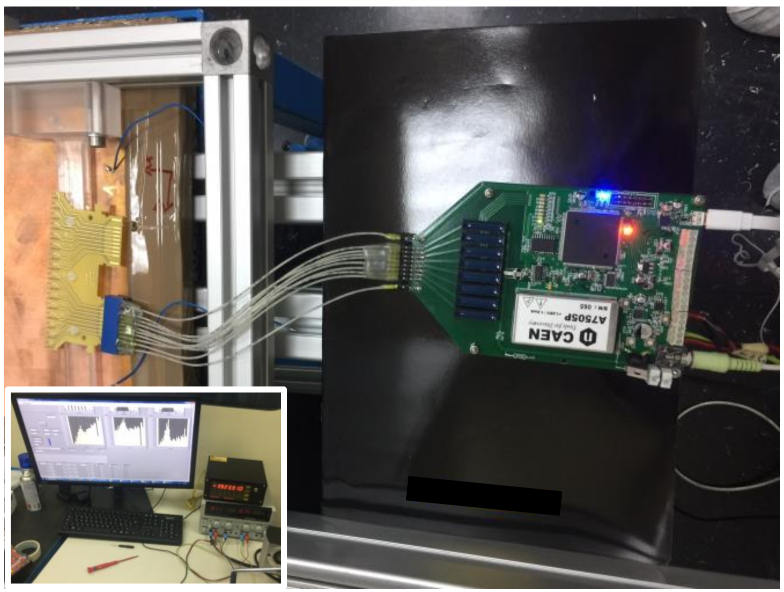


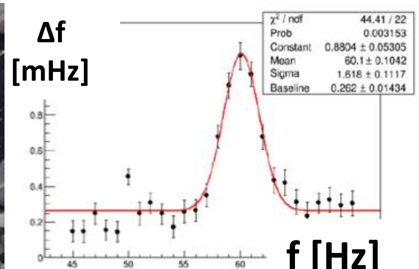
MEG2 DC Wiring

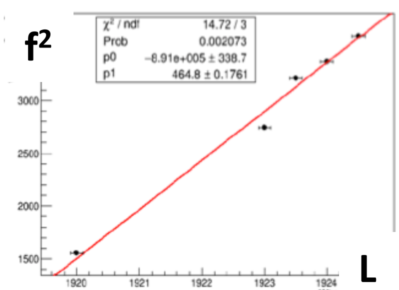

Lifting the wire PC boards with vacuum suction cups


Unwinding the loose multi-wire layer over the storage frame


Storing the multi-wire layers for visual inspection and wire tension measurement



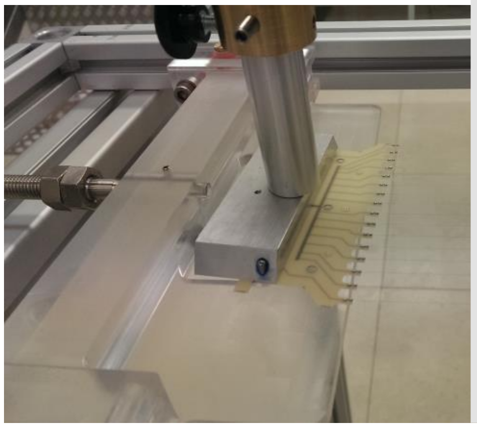


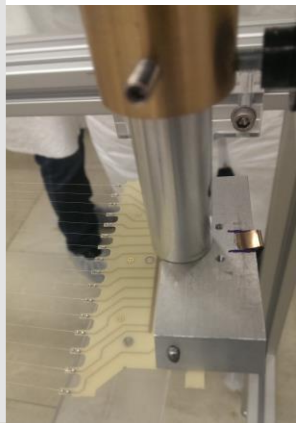


Chamber accuracy

stereo angle	< 35 μrad
wire position on PCB pad	< 25 μm
cell width (wire pitch)	< 1 μm
cell height (spacer)	< 50 μm
wire tension	< 0.1 g
PCB offset vs spoke	< 50 μm
chamber length	< 200 μm

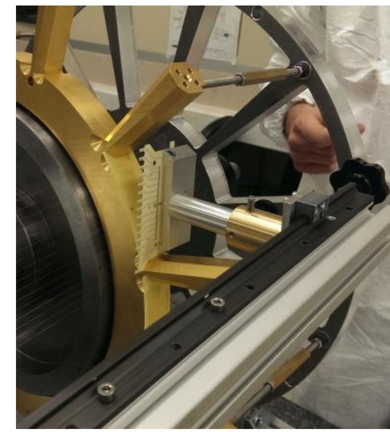
MEG2 DC Assembly

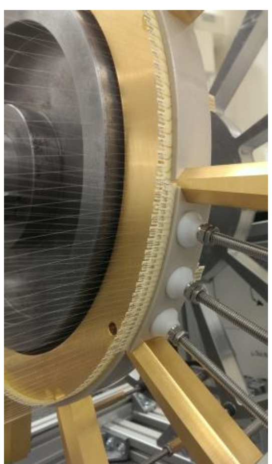




wire PC Boards are lifted up by adjustable arm ...

... and presented to the end plates moved closer by a few mm





A pressure sensitive tape holds them in the correct position above the peek spacer.

At completion of each layer (12 sectors), the end plates are moved away to the nominal length. The layer radial coordinates and the tension of all wires are then measured.

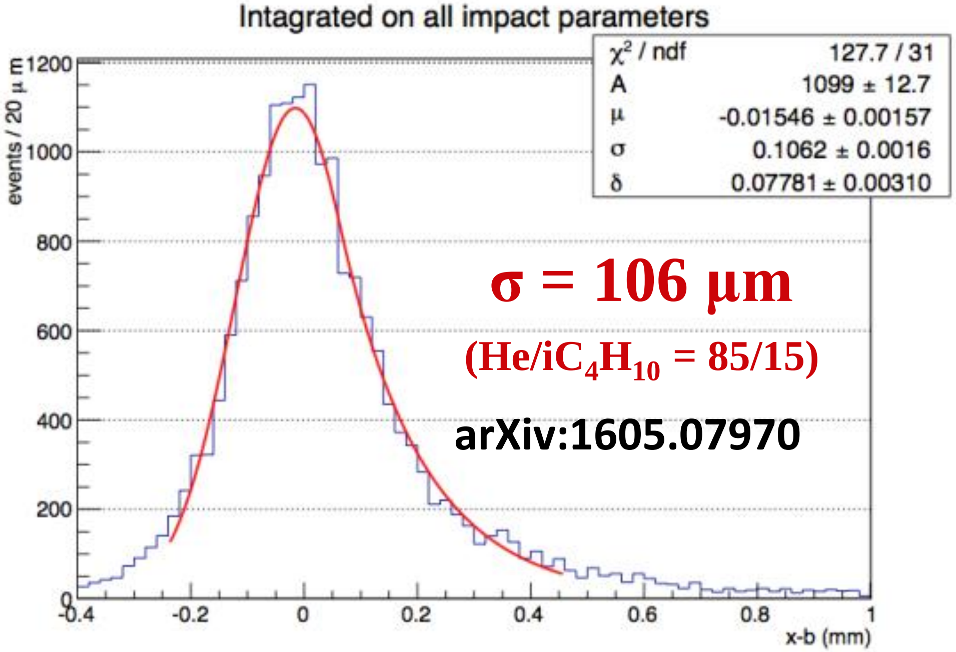
After last layer has been mounted, the outer structural carbon fiber cylindrical shell is placed and the inner shaft is removed. The end plates are sealed, the inner mylar cylinder is mounted, together with the extensions for the FEE

MEG2 DC Spatial resolution

Single-hit resolution **measured** with three different prototypes.

Results are all in agreement, yielding a resolution of about 110 μm averaged throughout the cell.

Further improvements expected thanks to the implementation of a wide bandwidth front end electronics allowing for the exploitation of the **cluster timing** technique.

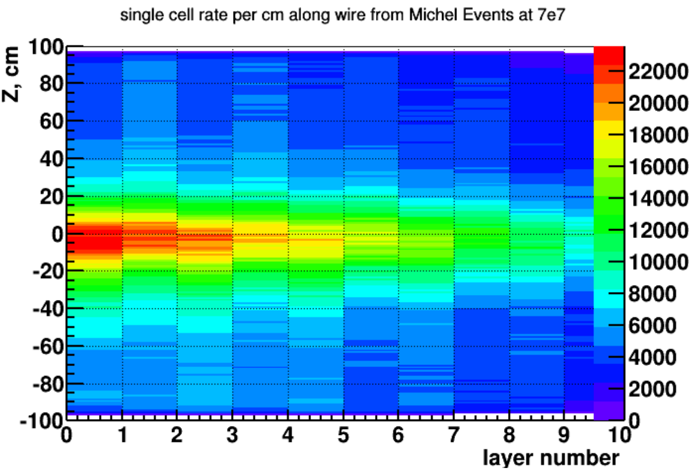


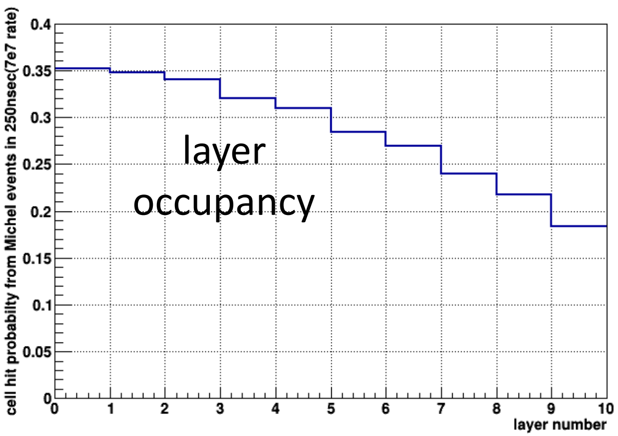
σ = 106 μm

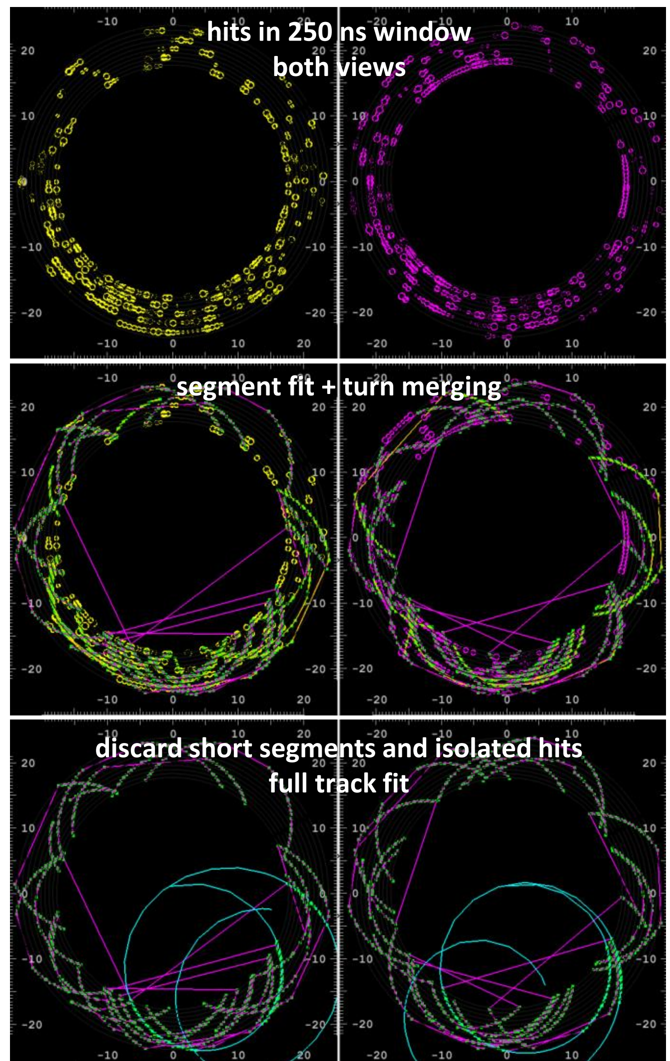
(He/iC_4H_{10} = 85/15)

arXiv:1605.07970

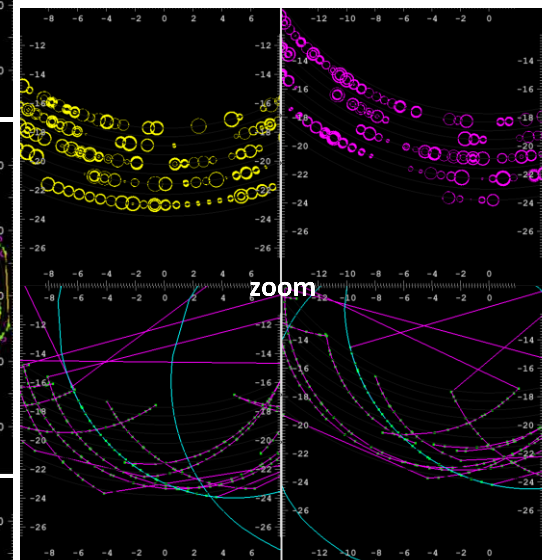
MEG2 DC Expected Perf.





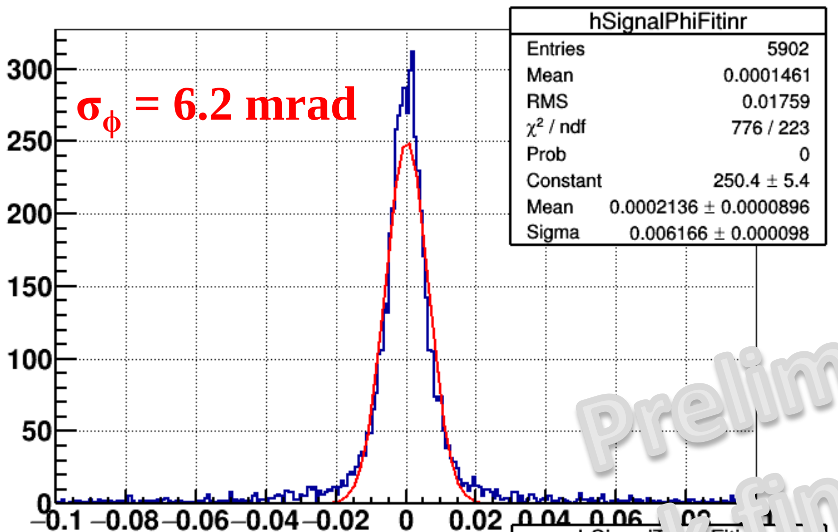


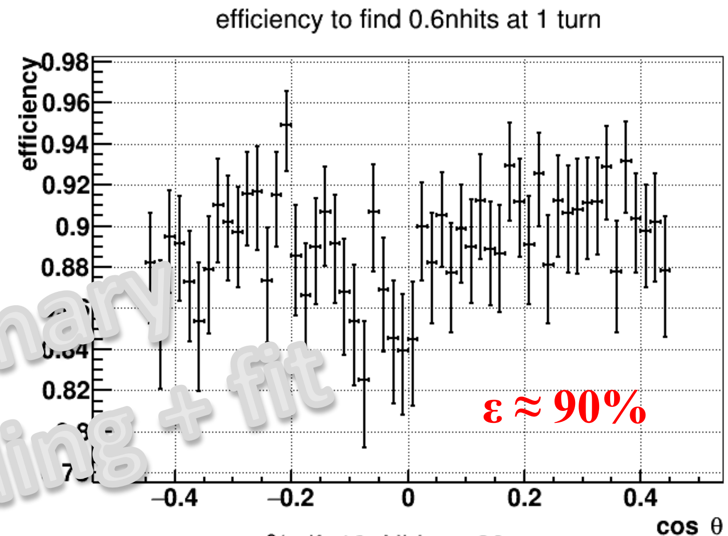
3D
track finding
and fit

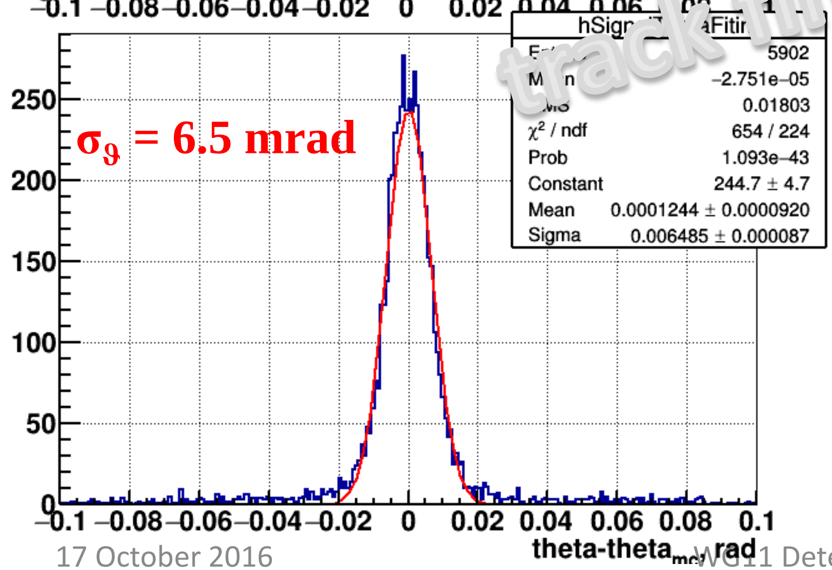


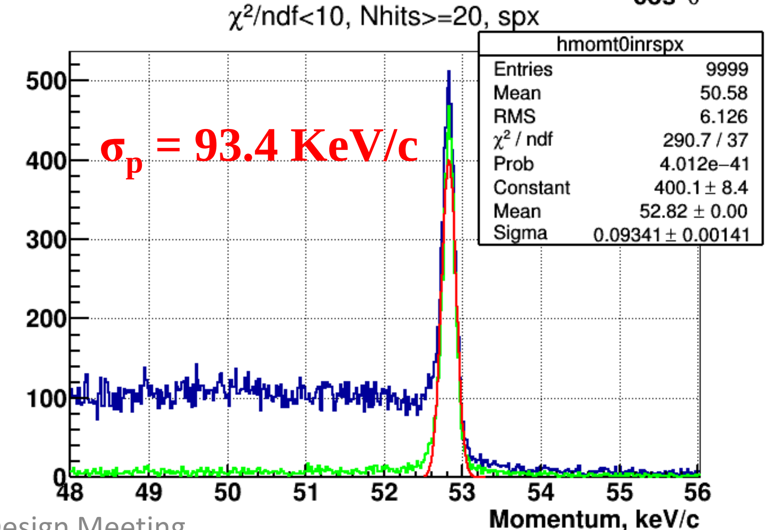
michel tracks
signal track

MEG2 DC Expected Perf.

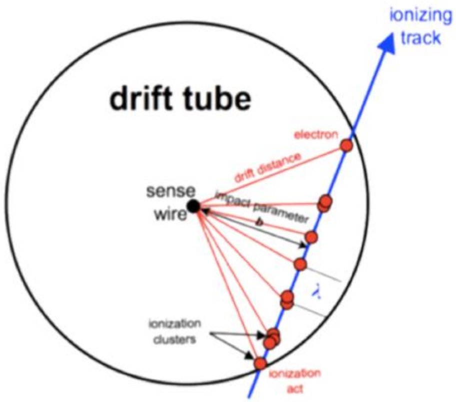




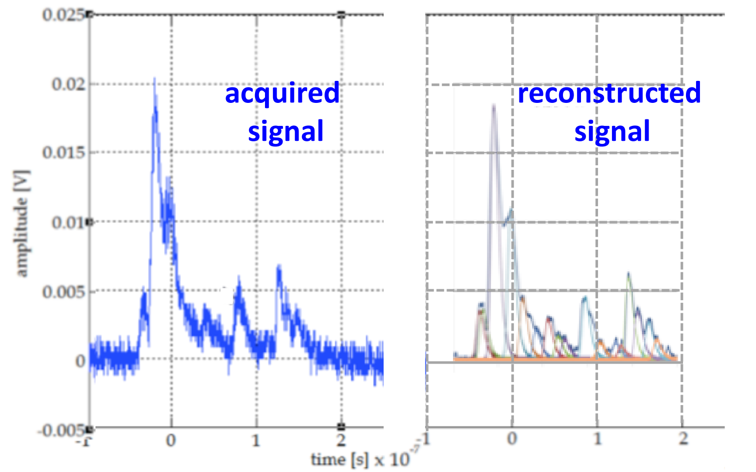


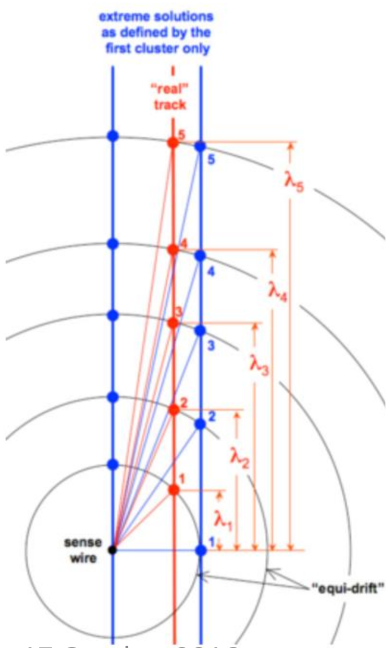


Cluster Timing

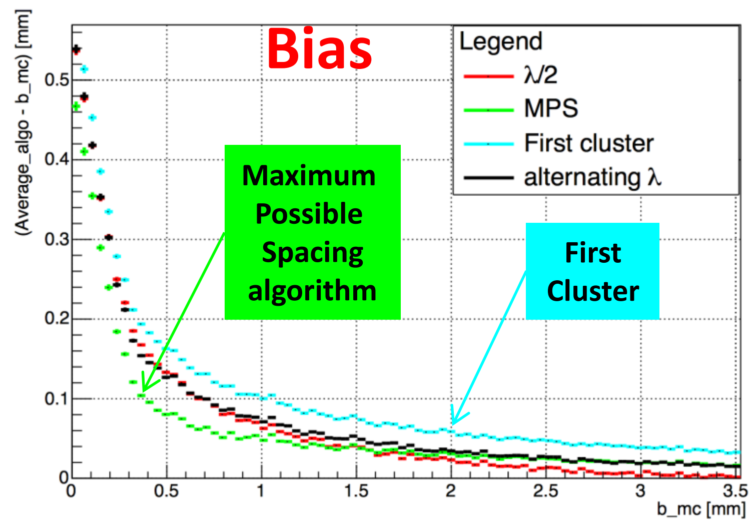


From the **ordered sequence of the electrons arrival times**, considering the average time separation between clusters and their time spread due to diffusion, **reconstruct the most probable sequence of clusters drift times:** $\{t_i^{cl}\} \quad i = 1, N_{cl}$



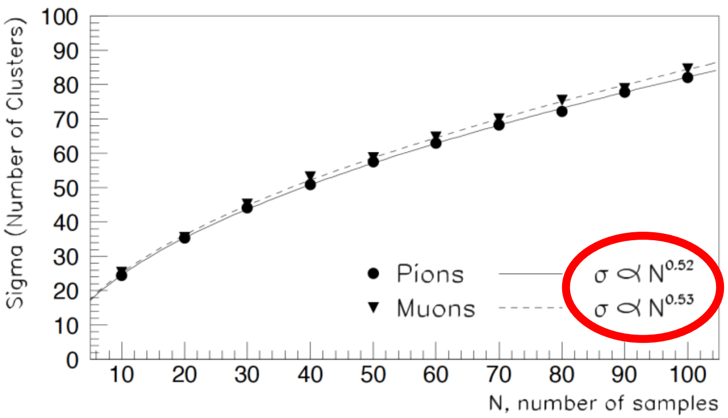


For any given first cluster (**FC**) drift time, the **cluster timing technique** exploits the drift time distribution of all successive clusters $\{t_i^{cl}\}$ to determine the most probable impact parameter, thus reducing the **bias** and the average **drift distance resolution** with respect to those obtained from with the FC method alone.

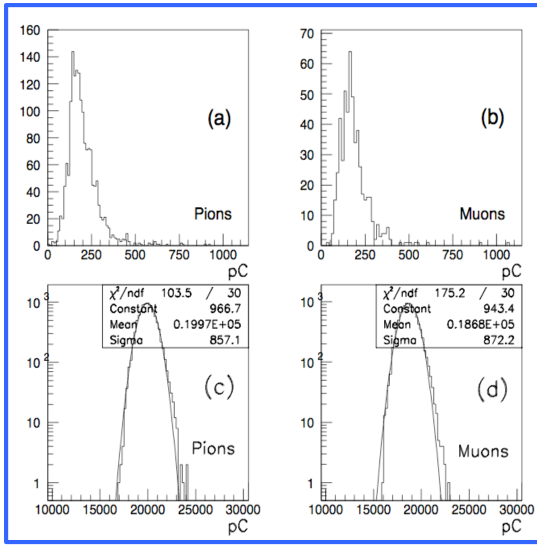


Cluster Counting

Thanks to the **Poisson nature of the ionization process**, by counting the total number of ionization clusters N_{cl} along the trajectory of a charged track, for all the hit cells, one can reach a relative resolution of $N_{cl}^{-1/2}$.



The data taken with a beam of **μ and π at 200 MeV/c** momentum at PSI, refer to a gas mixture **He/iC_4H_{10}=95/5**, **N_{cl} = 9/cm**, **100 samples**, **2.6cm** each **at 45°** (to avoid space charge effects), for a **total track length of 3.7 m**. A **25 μm sense wire** (**gas gain 2x10^5**), readout through a high bandwidth (**1.7 GHz**, **gain 10**) preamplifier, is digitized with a **2 GSa/s 1.1 GHz**, **8 bits** digital scope. (***NIM*** *A386 (1997) 458-469* and references therein)



dE/dx

100 samples 3.7 cm

($\sigma[\%]=40.7\ n^{-0.43}\ L[m]^{-0.32}$)

σ = 3.7%

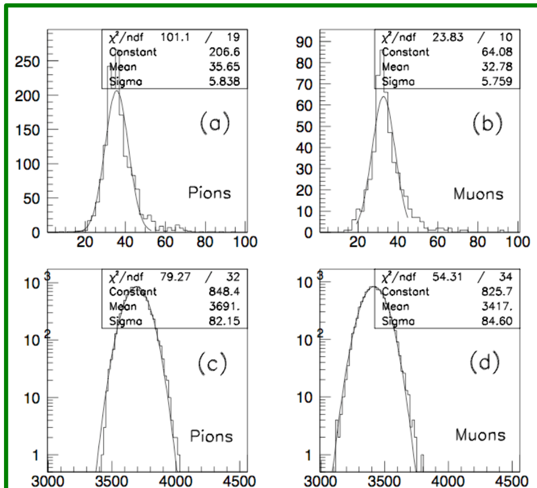
≈ 2.0σ separation

20% truncated mean

σ = 4.5%

≈ 1.4σ separation

μ−π 200 MeV/c



dN_{cl}/dx

Poisson distribution

σ = 1.7%

≈ 5σ separation

Experimental distribution

σ = 2.5%

≈ 3.2σ separation

μ−π 200 MeV/c

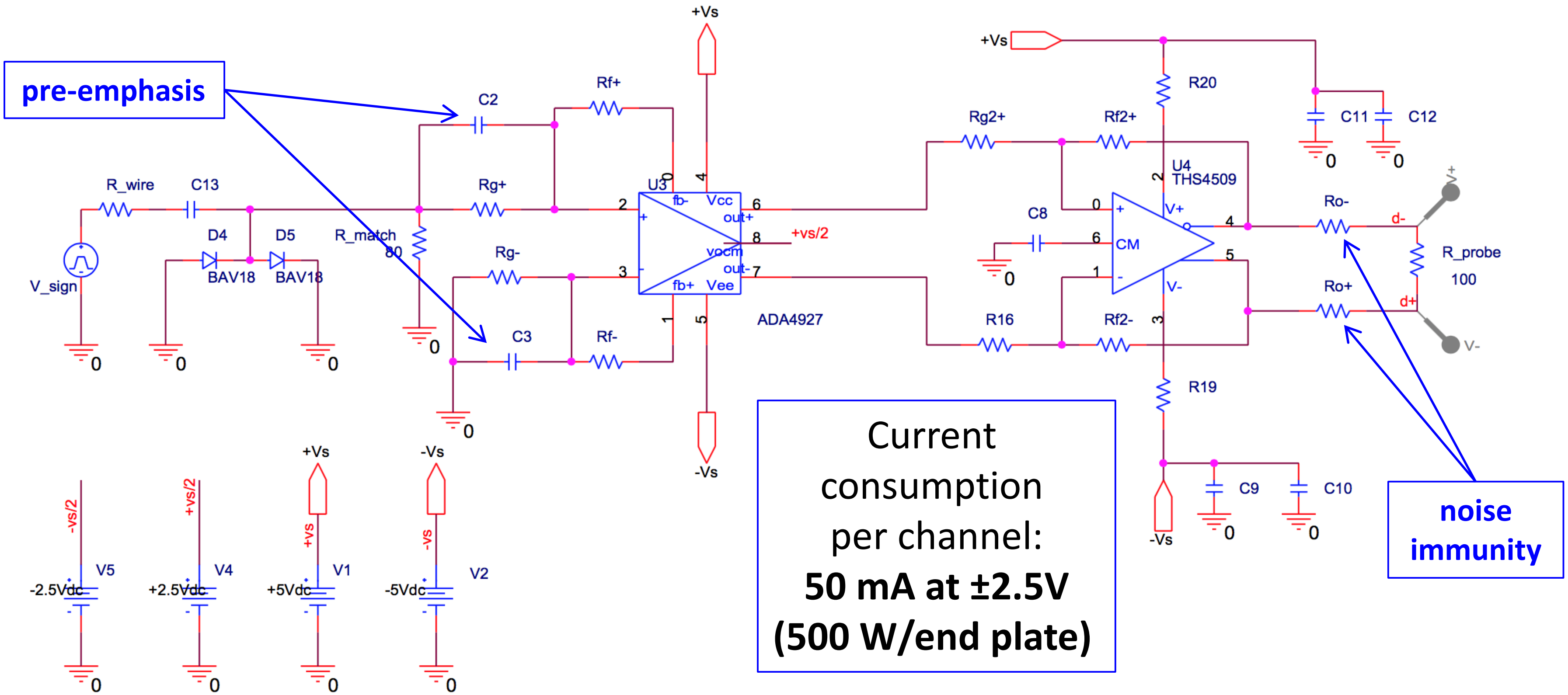
"Innovative DC" advantages

- **Gas containment** – **wire support** separation and **feed-through-less wiring**
  - allow to reduce material to **≈ 10^{-3} X_0 for the inner cylinder** and to **a few x 10^{-2} X_0 for the end-plates**, including FEE, HV supply and signal cables (Mu2e proposal design: 1.5×10^{-3} X_0 and 8×10^{-3} X_0, respectively).
- **Feed-through-less wiring**
  - allows to increase **chamber granularity** and field/sense wire ratio to reduce **multiple scattering** and **total tension on end plates** due to wires
- **Cluster timing**
  - allows to reach **spatial resolution < 100 μm** for 8 mm drift cells in He based gas mixtures (such a technique is going to be implemented in the MEG2 drift chamber under construction)
- **Cluster counting**
  - allows to reach **dN_{cl}/dx resolution < 3%** for particle identification (a factor 2 better than dE/dx as measured in a beam test)

Recipe for cluster timing/counting in He based gas mixtures:

FEE: 1 GHz BW, x10 gain (S/N ratio ≈ 8) - digitizer: 2 GSa/s sampling rate, >8 bits

MEG2 DC Front End El.

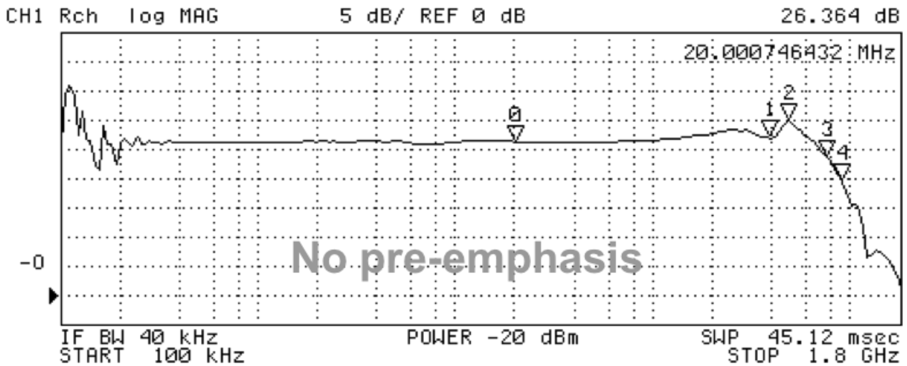


Current consumption per channel:
50 mA at ±2.5V
(500 W/end plate)

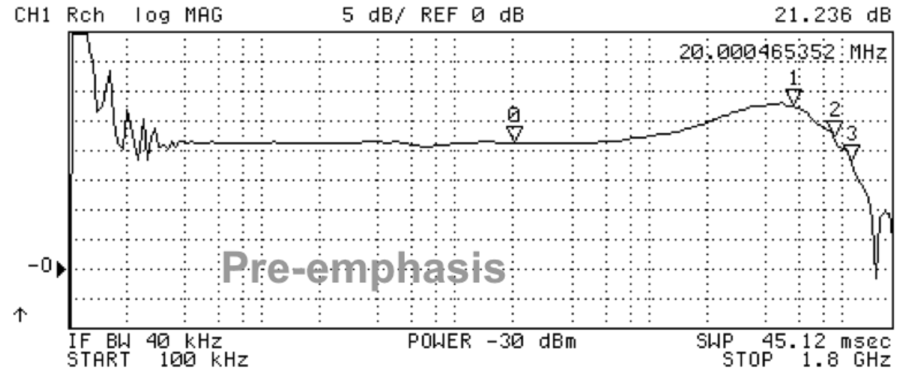
Op-amp **ADA4927** first gain stage: low noise, ultralow distortion, high speed, current feedback differential amplifier achieving wide bandwidth, low distortion, and low noise (1.3 nV/√Hz) and low power consumption.

THS4509 second gain stage and output driver: wideband, fully differential op-amp, very low noise (1.9 nV/√Hz), extremely low distortion, ideal for pulsed applications.

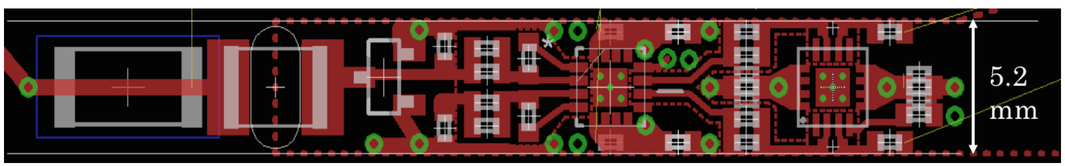
MEG2 DC Front End El.

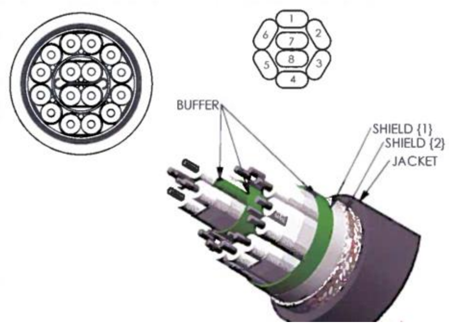


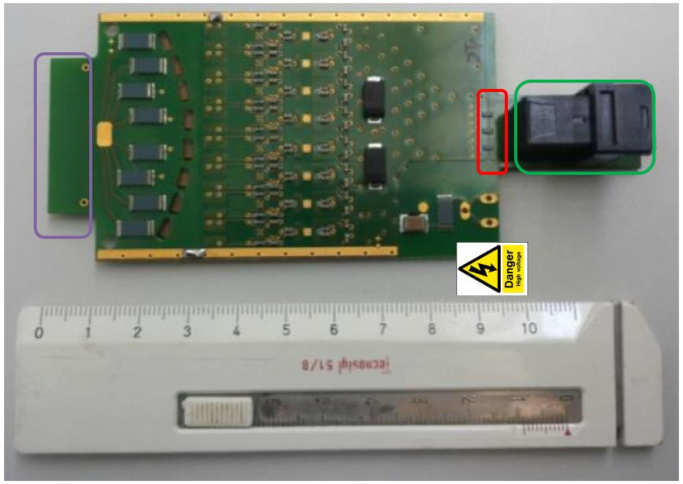
	N	SWP PARAM	VAL
	0	20.000746432 MHz	26.364 dB
	1	387.431573185 MHz	27.042 dB
Peak	2	484.430980668 MHz	29.955 dB
BW	3	756.290673874 MHz	23.666 dB
	4	899.763007493 MHz	19.788 dB



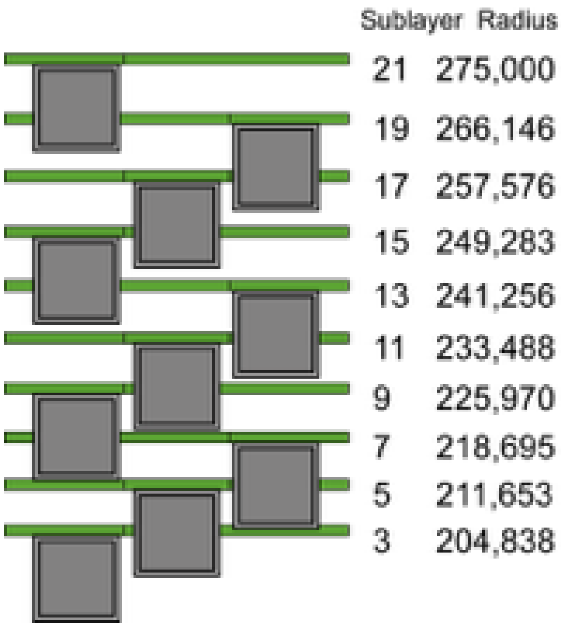
	N	SWP PARAM	VAL
	0	20.000465352 MHz	21.236 dB
	1	554.109452707 MHz	27.458 dB
Peak	2	899.74895028 MHz	22.206 dB
BW	3	1.099455926016 GHz	18.203 dB

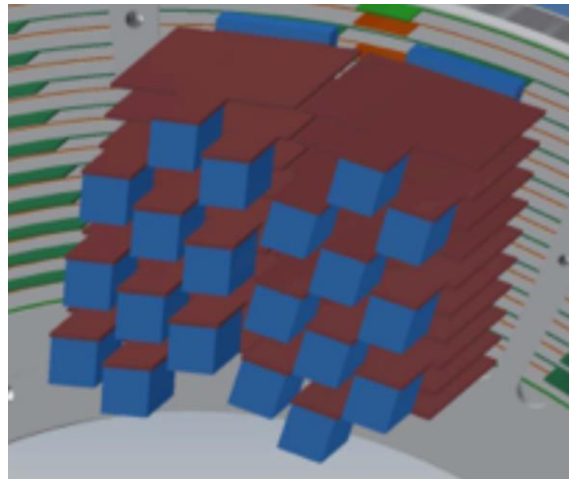


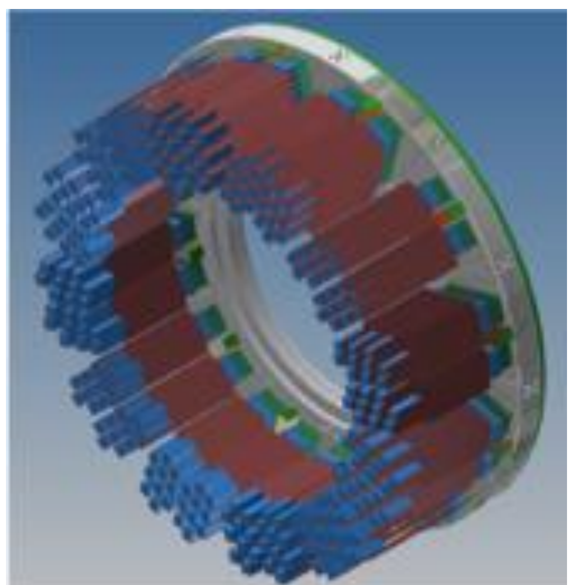


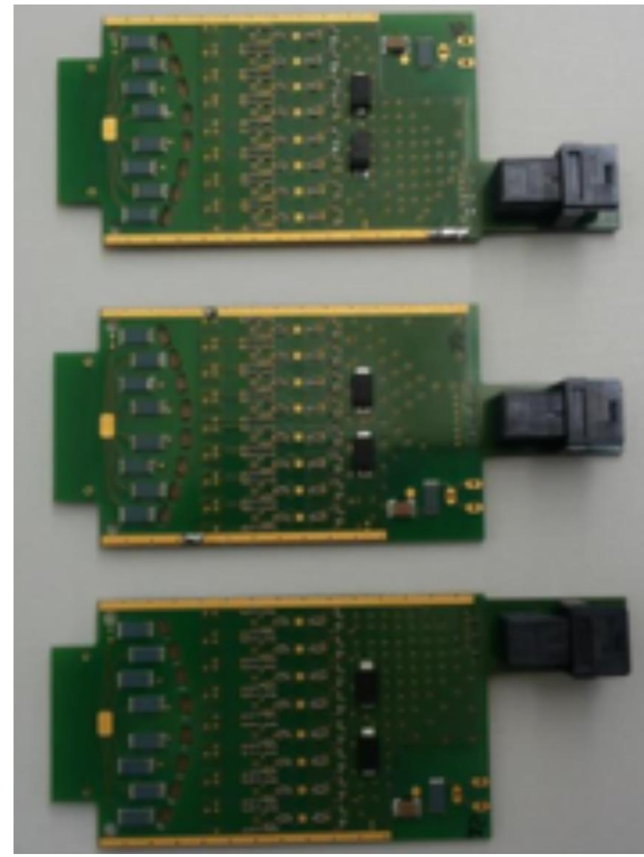


MEG2 DC Front End El.

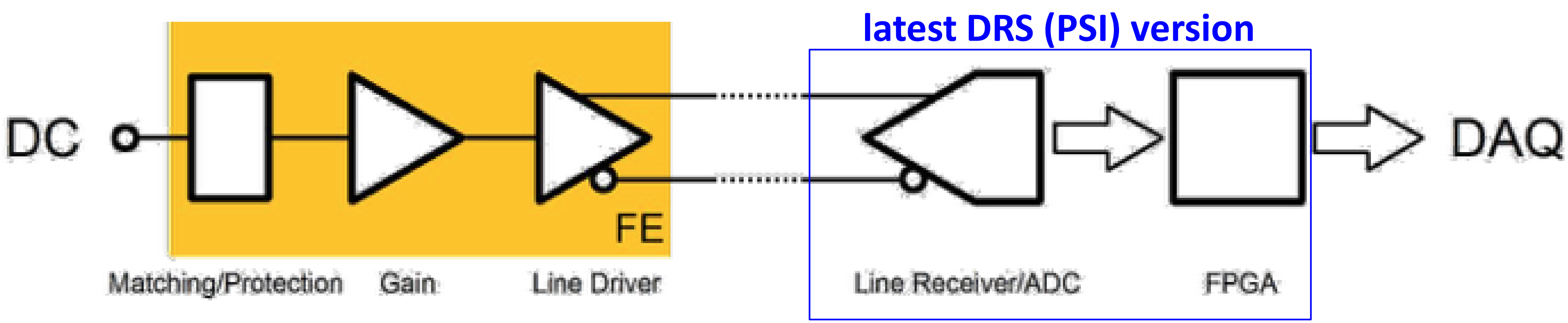






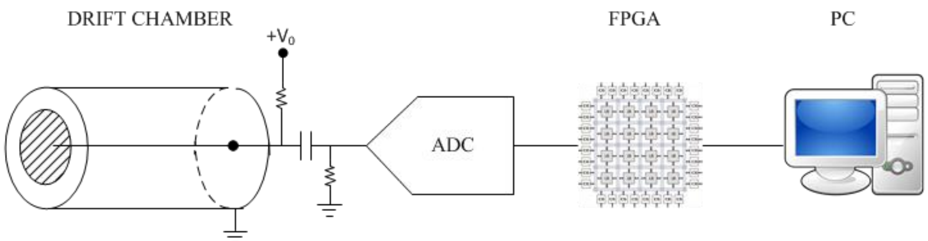


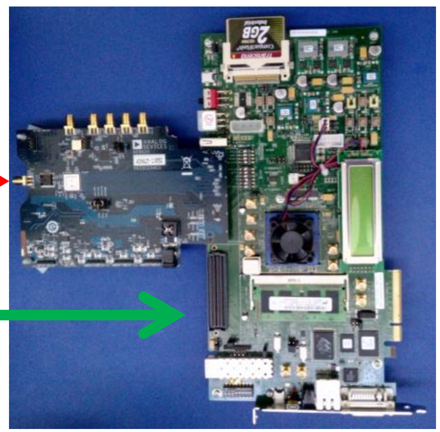
MEG2 DC Read Out



More generally, in a large DCH (60,000 channels, 30% occupancy, 1 μs drift time, 2 GSa/s - 12 bits digitization), at a 5 kHz trigger rate, expect: > 100 GB/s!

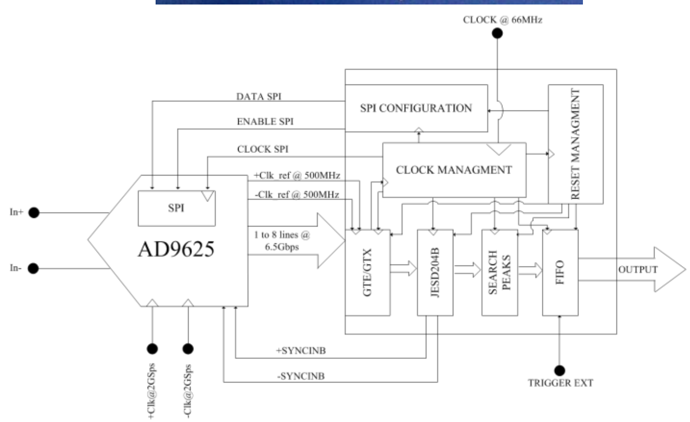
Clu-Tim/Cou Read Out

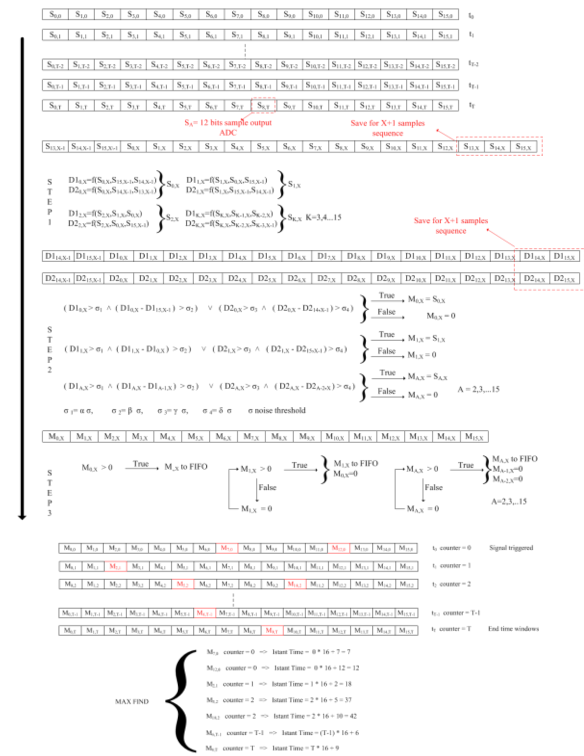


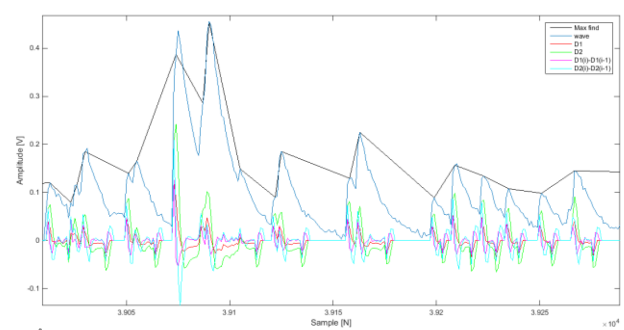


AD9625-2.0EBZ

UG534 ML605







How long a drift chamber can be?

Gravitational sag

wire L along x-axis, f force per unit length along y, T tension of wire $f \cdot dx = T \frac{d^2 y}{dx^2} dx$

f independent of x, parabolic solution $y = ax^2 \Rightarrow y = \frac{T}{2f} x^2$ sag $\delta = \frac{f}{8T} L^2$

wire radius r, volume density ρ, gravitational sag $f = \pi r^2 g \rho \Rightarrow \delta = \frac{\pi r^2 \rho}{8} \left(\frac{g}{T} \right) L^2$

Example:

L=2m; sense: 20μm W(Au), T=27g; field: 40μm Al(Ag), T=17g; guard: 50μm Al(Ag), T=26.5g

$\delta_{sense} = 110\,\mu m$ $\delta_{field} = 110\,\mu m$ $\delta_{guard} = 110\,\mu m$

How long a drift chamber can be?

Electrostatic stability

Simplified model of a wire of radius R at voltage V_0, placed between two parallel grounded planes at distance W/2 from the wire

linear charge density $$\lambda = \frac{2\pi\varepsilon V_0}{\ln\left(\frac{\{2\}W}{2R}\right)}$$

cap. per unit length $$C = \frac{2\pi\varepsilon}{\ln\left(\frac{\{2\}W}{2R}\right)}$$

perfectly symmetric geometry $f = 0$

assume a wire displacement Δ towards one plane

$$f = \frac{2C^2V_0^2}{\pi\varepsilon W^2}\Delta$$

$$\delta = \frac{f}{8T}L^2 = \frac{C^2V_0^2L^2}{4\pi\varepsilon T W^2}\Delta$$

$$\frac{\delta}{\Delta} < 1 \Rightarrow T > \frac{C^2V_0^2L^2}{4\pi\varepsilon W^2}$$

stability condition

How long a drift chamber can be?

Electrostatic stability: a numerical example MEG2

20μm W sense wire, V_0= 1500V, W = 7mm, L = 2m, T = 0.25N

linear charge density $\lambda = 1.3 \times 10^{-8} Coul/m$

assume a wire displacement Δ = 50 μm

cap. per unit length $C = 8.5 pF/m$

$f = 1.2 \times 10^{-5} N$ $\quad \delta = 24 \mu m$

stability condition $T > 0.12N$ or $L < 2.8m$

increase sense wire diameter to **50μm**, T = 1.56N, for the same gain (same λ) need **V_0=1750V**

$C = 9.9 pF/m \quad f = 2.2 \times 10^{-5} N \quad \delta = 7.0 \mu m$ $\quad T > 0.22N$ or $L < 5.3m$

drawback:

multiple scattering and **force on end plates** increase by a factor **2.5^2**

(Ti(Sn) instead of W(Au)? to regain a factor 4 in mass and 10 in X_0)

A proposal for FCCee

- **112 para-axial layers** at alternating sign stereo angles, arranged in **16 equal azimuthal sectors**;
- **32 square, single sense wire, drift cells** per sector (512 total per layer) increasing linearly as a function of layer radius;
- **Cell sizes** ranging from **6.3 mm to 25 mm** from inner to outer radius;
- **Alternating sign stereo angles** in consecutive layers ranging from **40 to 160 mrad** (constant azimuthal angular displacement)
- **Length: 5000 mm**; fully efficient up to **cosϑ = 0.97** (≥16 hit)
- **Inner Wall:** made of 25 µm of Kapton plus 0.1µm of Au (**1.2×10^{-4} X_0**) at **Radius = 500 mm**;
- **Outer Wall:** Sandwich of 8-ply C-fiber (0° and 90°, total of 250 µm) - 2.5 mm Rohacell30 - 8-ply C-fiber (**8.0×10^{-3} X_0**) at **Radius = 2060 mm** (must support **20 Tons** - check for buckling over 5 m);
- **End plates:**
  - **Wire cage (**in analogy to Mu2e I-Tracker):
    0.9 g/cm^2 - **3×10^{-2} X_0** (incl. power distr., decoupling C's, term. resistors and signal and HV cables).
  - **Gas envelope** made of 8 ply (quasi-isotropic, 10×38 µm = 380 µm) C-fiber plus 0.3 µm Au, for a total of 0.090 g/cm^2 – **3.0×10^{-3} X_0**;
- **Gas: 90% He - 10% iC4H10** (δ = 4×10^{-4} g/cm^3, X_0 = 1410 m), - 12.5 p.i./cm, gas gain: 4×10^5 at V ≈ 1700 V on 50 µm wire, v_{drift} ~ 2.5 cm/µs – **0.47×10^{-3} X_0/1m track**
- **Wires**: - **57,344 sense** (50µm Sn coated Ti); **290,816 field and guard** (100µm Sn coated C); for a total equivalent thickness of **1.34×10^{-3} X_0/1m track**

Expected spatial resolution

Expected Performance: Track parameters resolutions

n = 112, B = 2.0 T, R_{out} = 2.05 m, L = 3.0 m or 5.43×10^{-3} X_0, σ_{xy} = 100 µm, σ_z = 1.0 mm

measurement

$$\frac{\Delta p_\perp}{p_\perp} = \frac{8\sqrt{5}\sigma}{.3BL^2\sqrt{n}} p_\perp = 7.1 \times 10^{-5} p_\perp \left[GeV/c\right]$$

$$\Delta \phi_0 = \frac{4\sqrt{3}\sigma}{R_{out}\sqrt{n}} = 4.0 \times 10^{-5}$$

$$\Delta \theta = \frac{\sqrt{12}\sigma_z}{R_{out}\sqrt{n}} \frac{1+\tan^2\theta}{\tan^2\theta} = 2.1 \times 10^{-4} \frac{1+\tan^2\theta}{\tan^2\theta}$$

multiple scattering (gas + wires)

$$\frac{\Delta p_\perp}{p_\perp} = \frac{0.0523\left[GeV/c\right]}{\beta p BL \sin\theta} \sqrt{\frac{L}{X_0}} = \frac{5.5 \times 10^{-4}\left[GeV/c\right]}{\beta p \sin\theta}$$

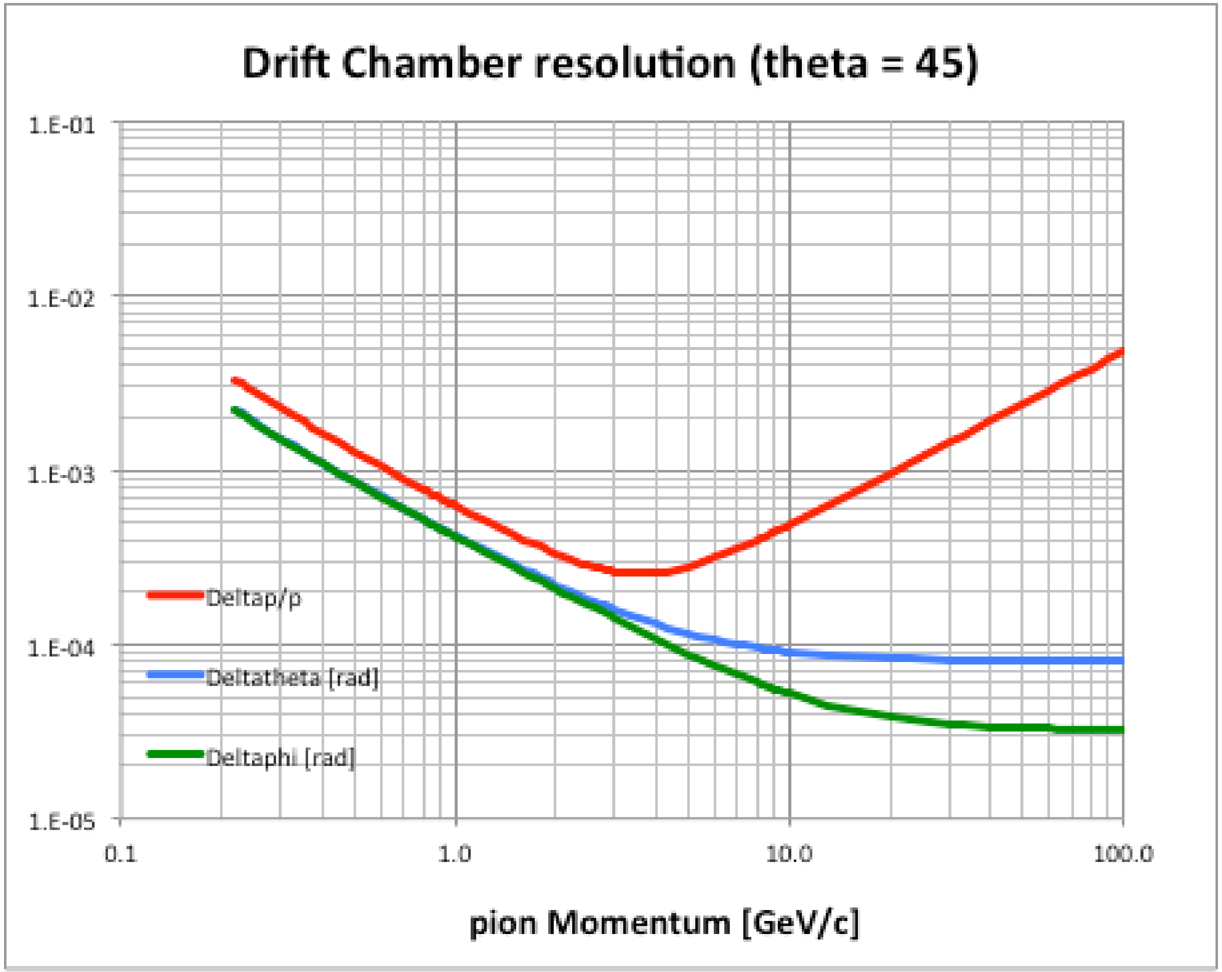
$$\Delta \phi_0 = \frac{13.6 \times 10^{-3}\left[GeV/c\right]}{\beta p} \sqrt{\frac{L}{X_0}} = \frac{1.0 \times 10^{-3}\left[GeV/c\right]}{\beta p}$$

$$\Delta \theta = \frac{13.6 \times 10^{-3}\left[GeV/c\right]}{\beta p} \sqrt{\frac{L}{X_0}} = \frac{1.0 \times 10^{-3}\left[GeV/c\right]}{\beta p}$$

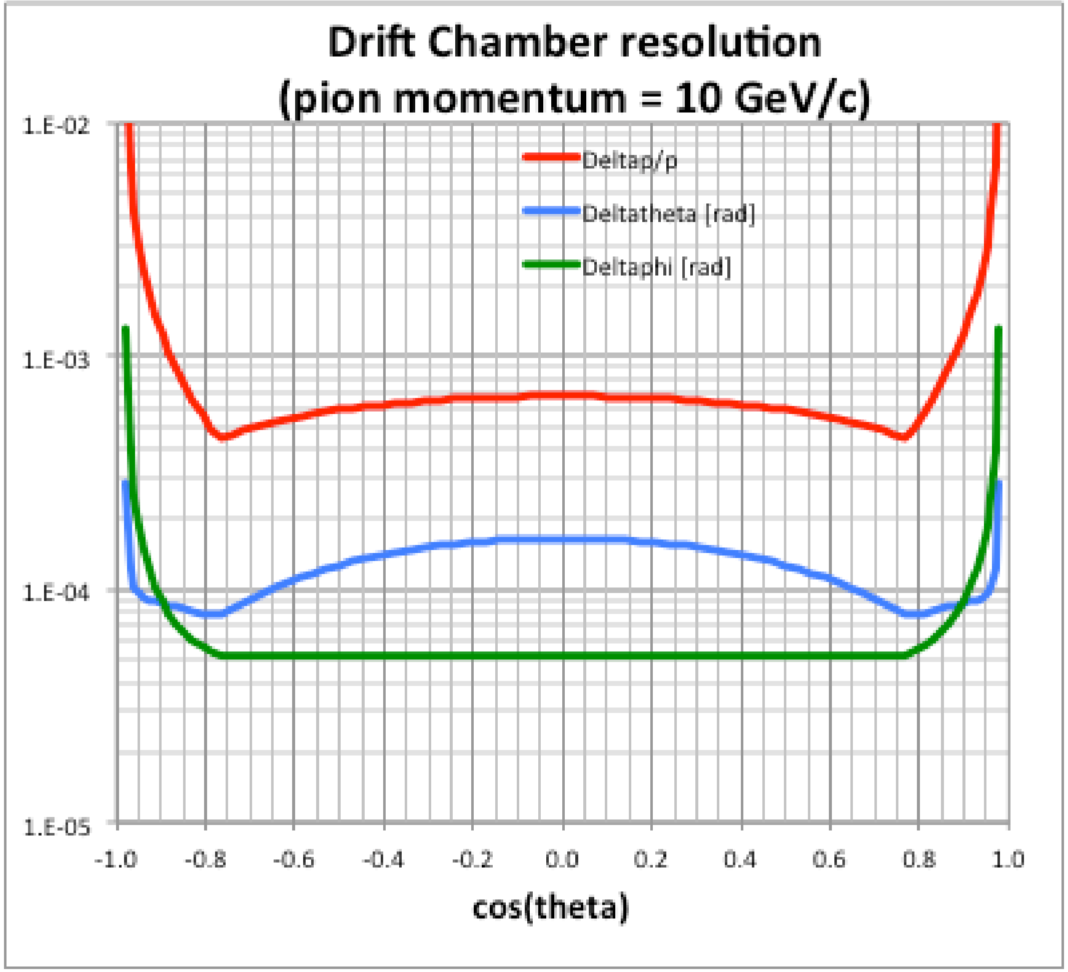
$$\frac{\Delta p_\perp}{p_\perp} = 5.8 \times 10^{-4}; \quad \frac{\Delta p}{p} = \frac{\Delta p_\perp}{p_\perp} \oplus \frac{\Delta \theta}{\tan\theta} = 6.1 \times 10^{-4}$$

$$\text{for } p = 10 \text{ GeV/c and } \theta = 45°$$

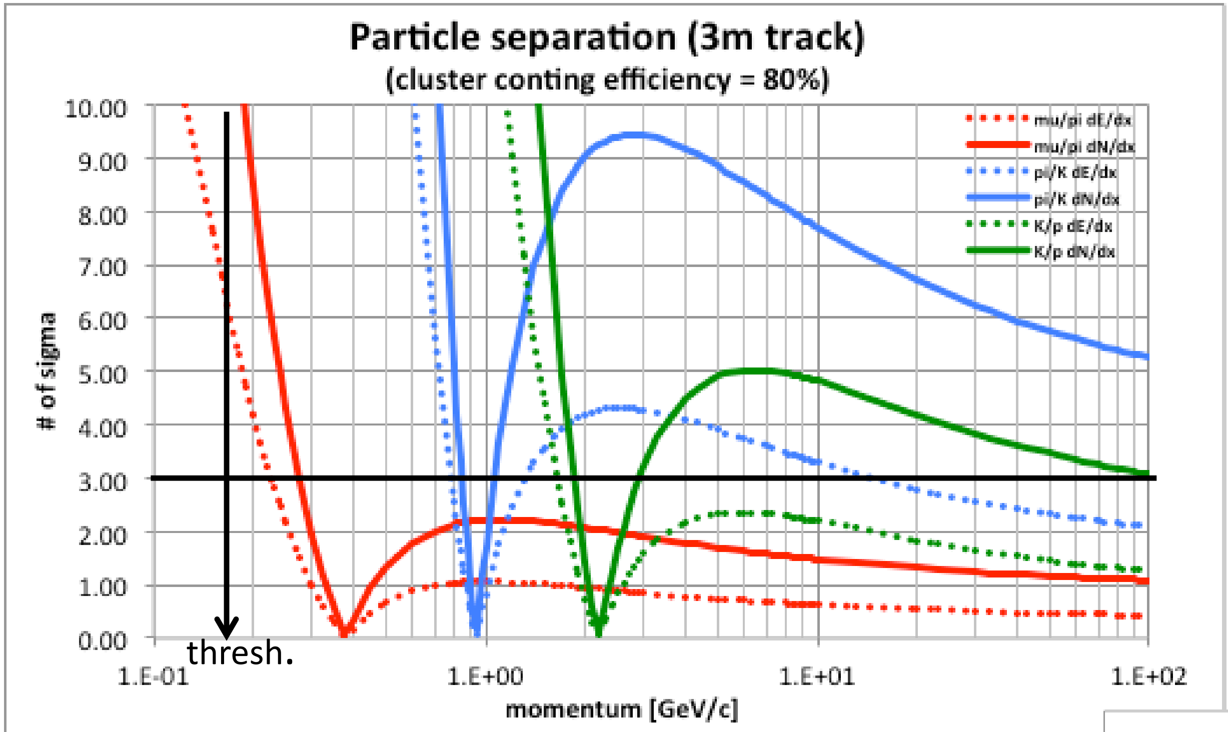
Expected spatial resolution



Expected spatial resolution



Expected p. id. capabilities

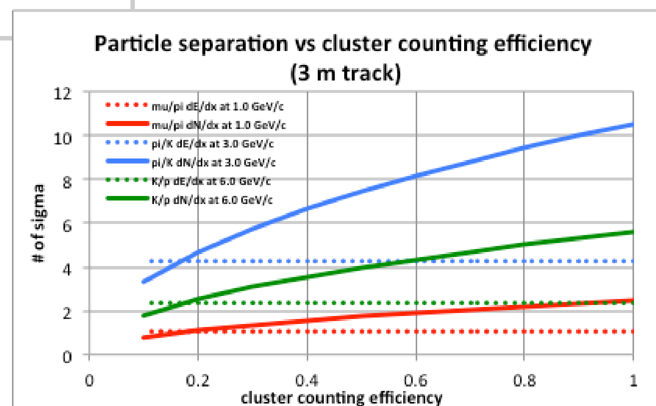


$\sigma_{dE/dx}/dE/dx =$
$= 5.4\ L[m]^{-0.37}\ \%$
(Lehraus parametrization)
3.6% for L=3m

cluster counting efficiency
$\varepsilon = 80\%$

$\sigma_{dN_{cl}/dx}/dN_{cl}/dx =$
$= \varepsilon \times L \times 12.5/cm =$
1.8% for L=3m

Particle separation power as a function of cluster counting efficiency for 2m tracks.
Cluster counting outperforms dE/dx for counting efficiencies as low as 20%.



Conclusions

- We propose for FCCee an innovative tracking system based on a

  "**ultra-light drift chamber with peculiar particle identification capabilities**"
  using cluster timing/counting techniques.
- It consists of a full stereo, single sense wire, square cells:
  - **R_{in} = 50 cm**; **R_{out} = 205 cm**; **L = 500 cm**; **112 layers × (6.3 to 25.0 mm)**; **57,344 cells**; >16 hits down to **cosϑ = 0.97**; stereo angles ranging from **40 mrad to 160 mrad**;
  - Inner cylindrical wall: **$1.2\times10^{-4}\ X_0$**
  - Outer cylindrical wall: **$8.0\times10^{-3}\ X_0$**
  - End plates (fully instrumented): **$3.3\times10^{-2}\ X_0$**
  - Gas + wires: **$.47\times10^{-3}\ X_0$/1m track + $1.34\times10^{-3}\ X_0$/1m track**
- Expected spatial resolutions: **$\sigma_{r\varphi} < 100\ \mu m$, $\sigma_z < 1$ mm**
- Expected momentum resolution: **$\Delta p/p = 4.9\times10^{-4}$, $\Delta\vartheta = 0.9\times10^{-4}$, $\Delta\varphi = 0.5\times10^{-4}$** for p = 10 GeV/c and ϑ = 45°
- Expected p. id.: π/κ separation **> 3σ for p < 850 MeV/c and p > 1070 MeV/c**

At current status of the art no need for major R&D