An ultra-light drift chamber with particle identification capabilities

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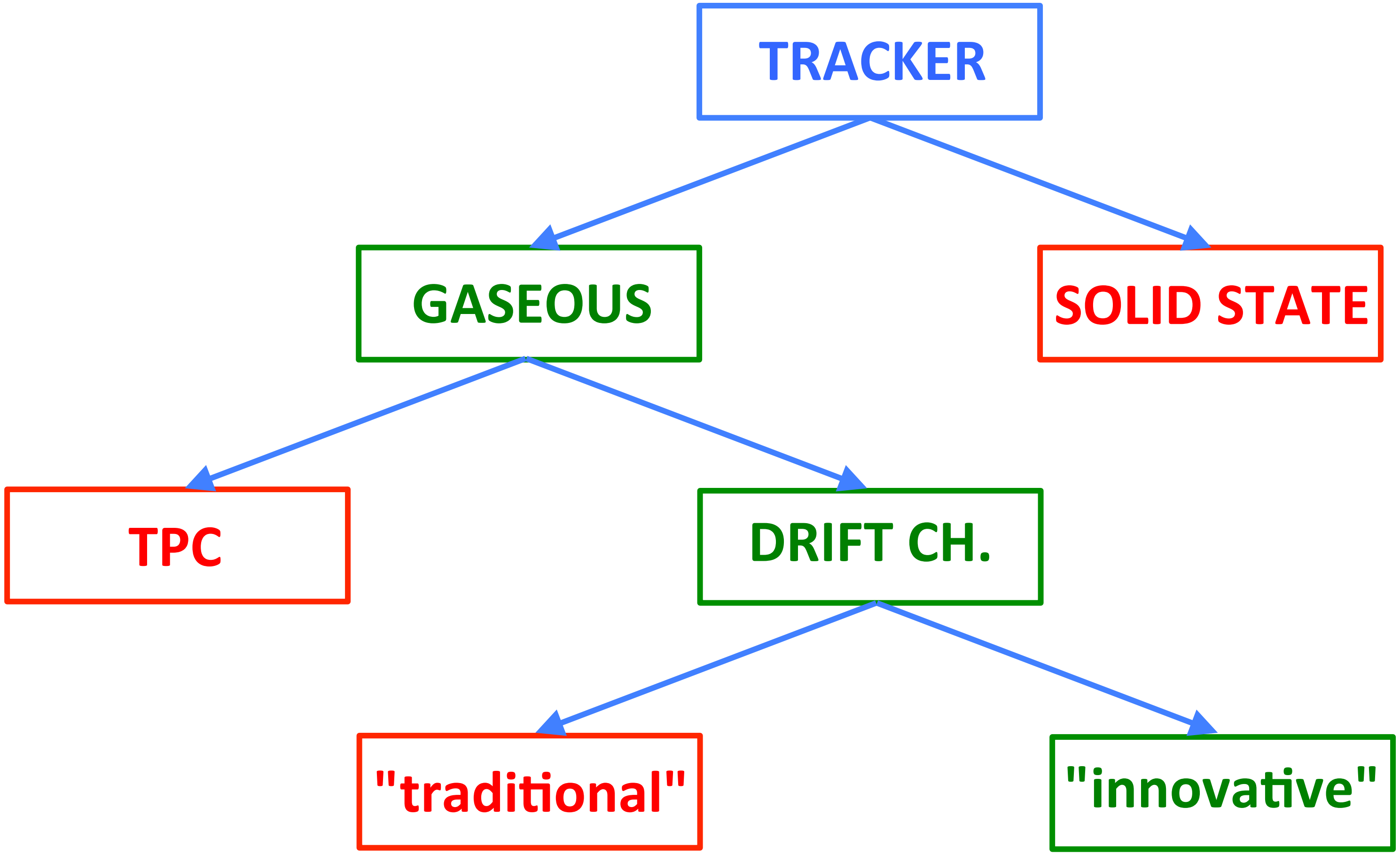
Tracker alternatives



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 (2013)
- **DCH** for the **MEG2 upgrade** at PSI (under construction at INFN and to be commissioned during spring 2017)

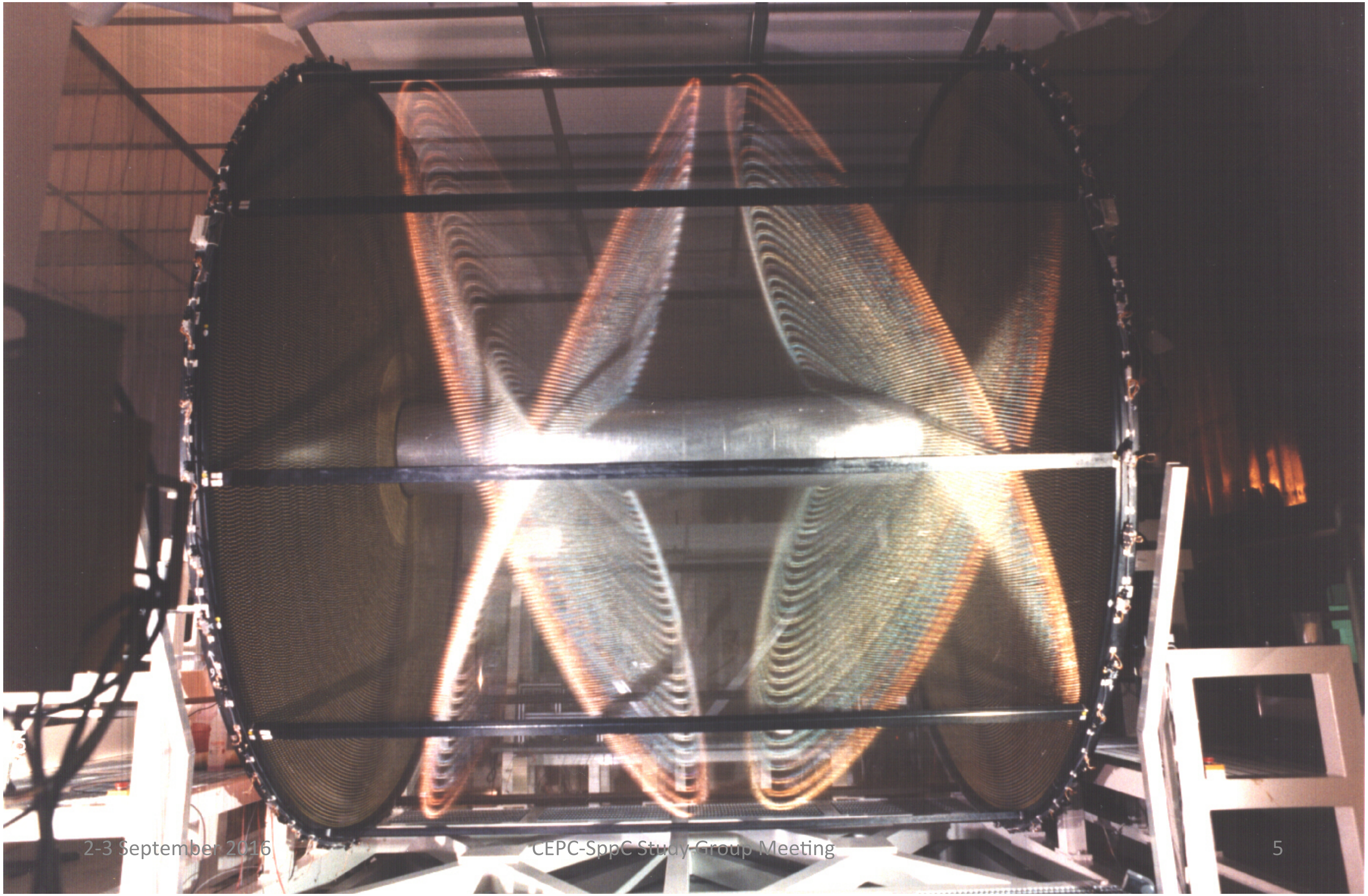
"Traditional" Drift Chamber

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:

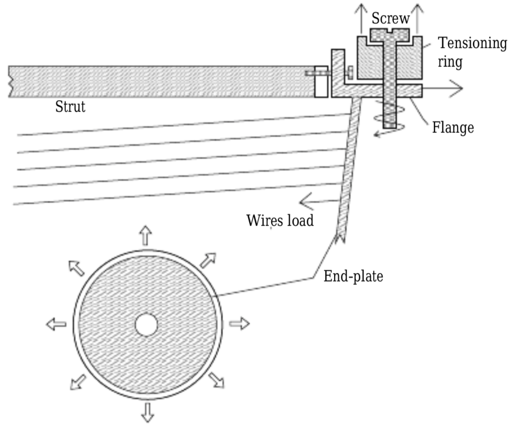
- The **end walls**, holding the feed-through (which limit the chamber granularity), the FE electronics and the relative cabling, must be rigid enough to transfer the load due to the wire tension (of the order of several Tons) to the **outer cylindrical wall**, without deforming.
- The **inner cylindrical 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.

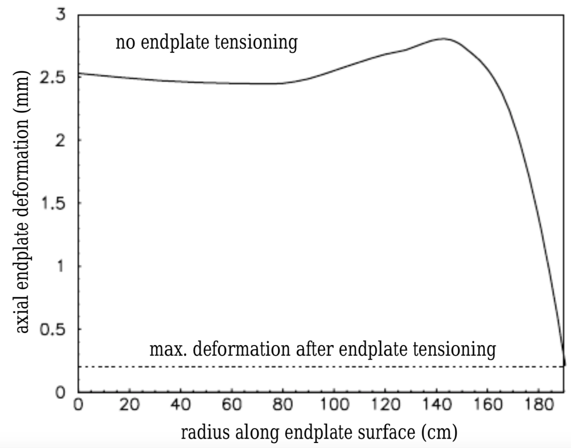
The KLOE Drift Chamber



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 ($0.03X_0$)
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

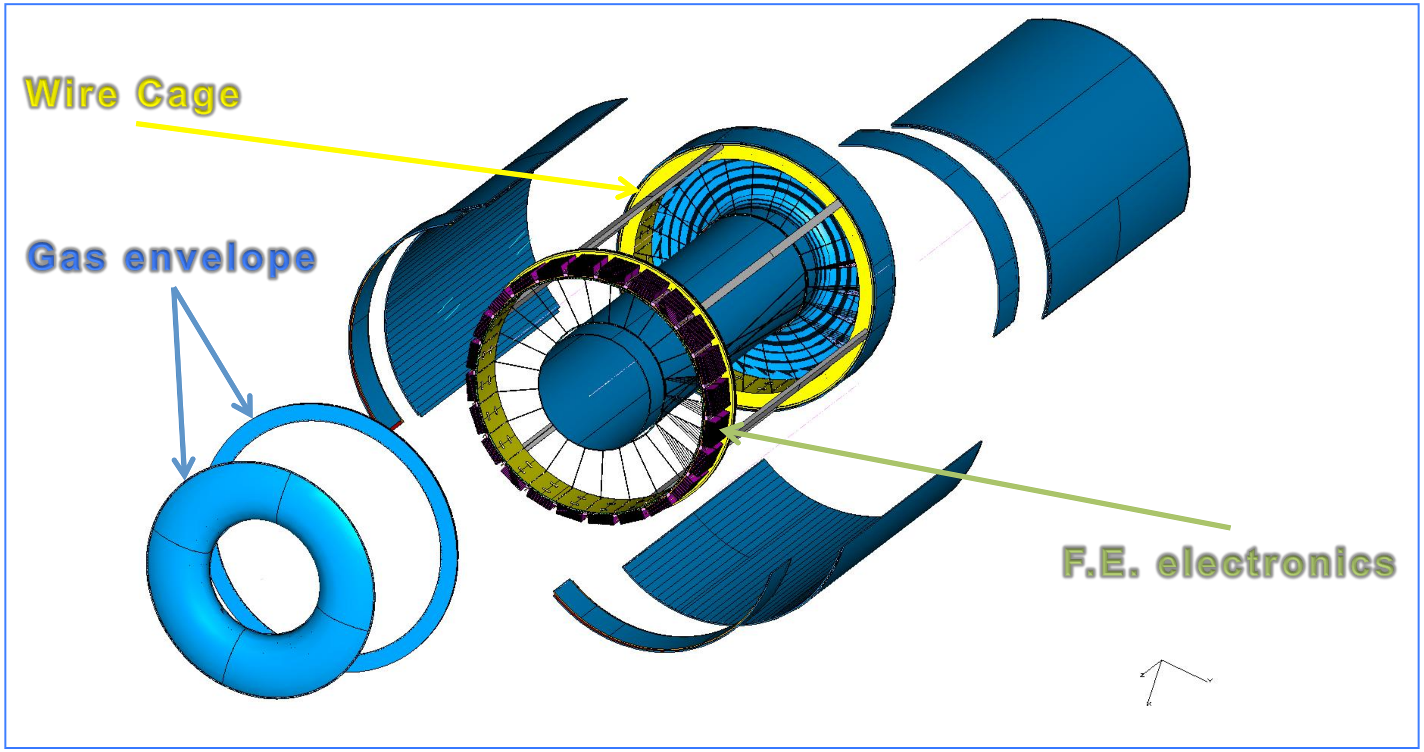




Drift Chamber "Innovations"

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



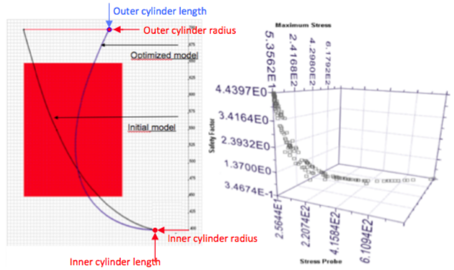
Gas containment — **Gas envelope** can freely deform without affecting the internal wire position and tension.

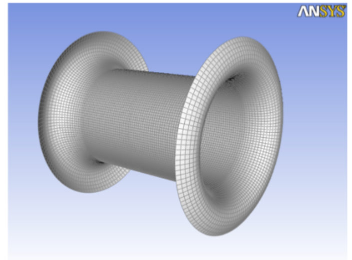
Wire support — **Wire cage** structure not subject to differential pressure can be light and feed-through-less.

Example: The Mu2e I-Tracker proposal

Gas Envelope

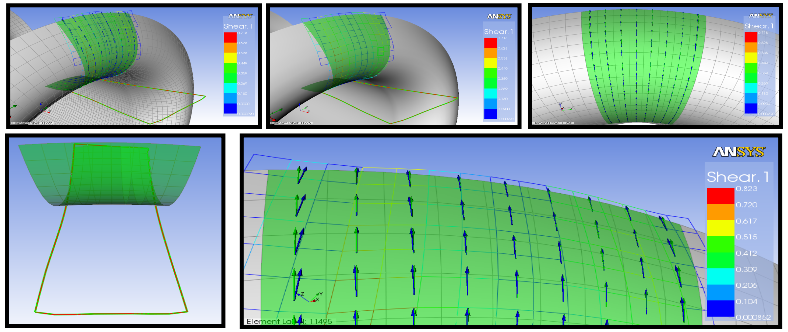
A structural multivariate analysis software (**ModeFrontier®**) has enabled to find the optimal shape for the **profile of the end plates** by minimizing maximum stress and stress on inner cylinder



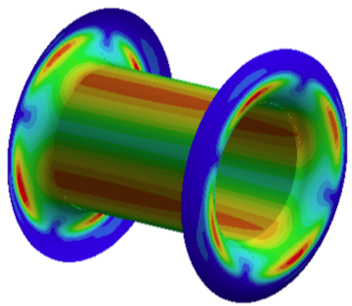


parameters	Initial model	Optimized model
Maximum stress	357.5 MPa	58.7 MPa
Stress at inner boundary	267.4 MPa	26.6 MPa
Safety factor	0.783	4.44

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:

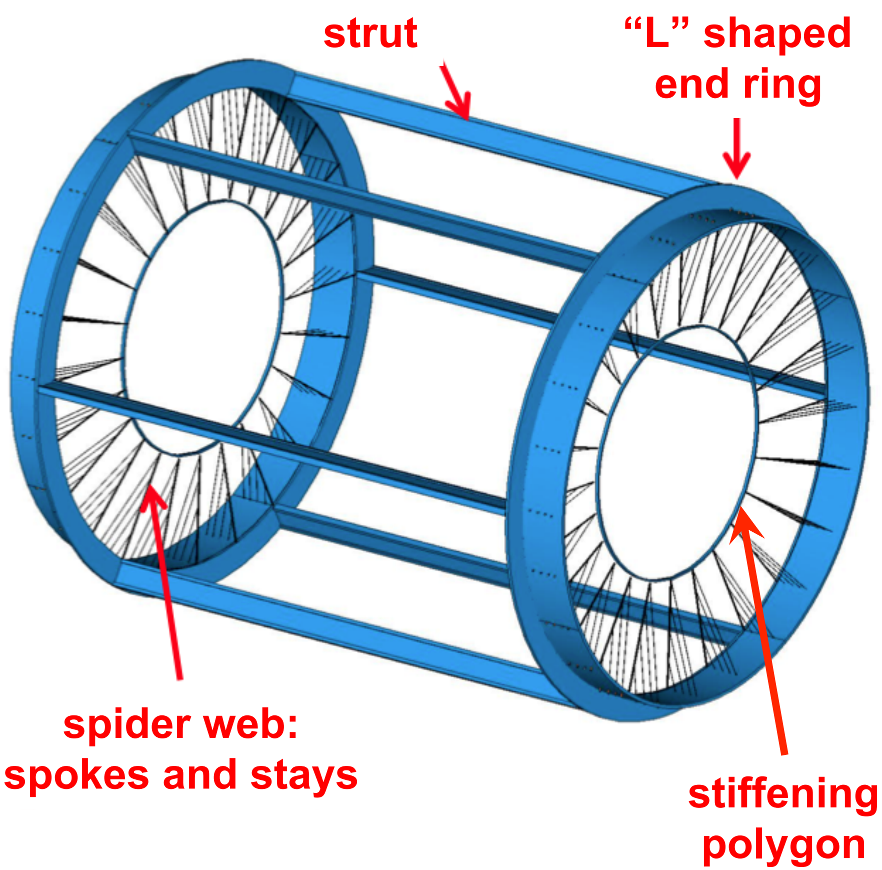
4-ply 38µm/ply
orthotropic (0/90/90/0)
0.021 g/cm²
5×10⁻⁴ X₀

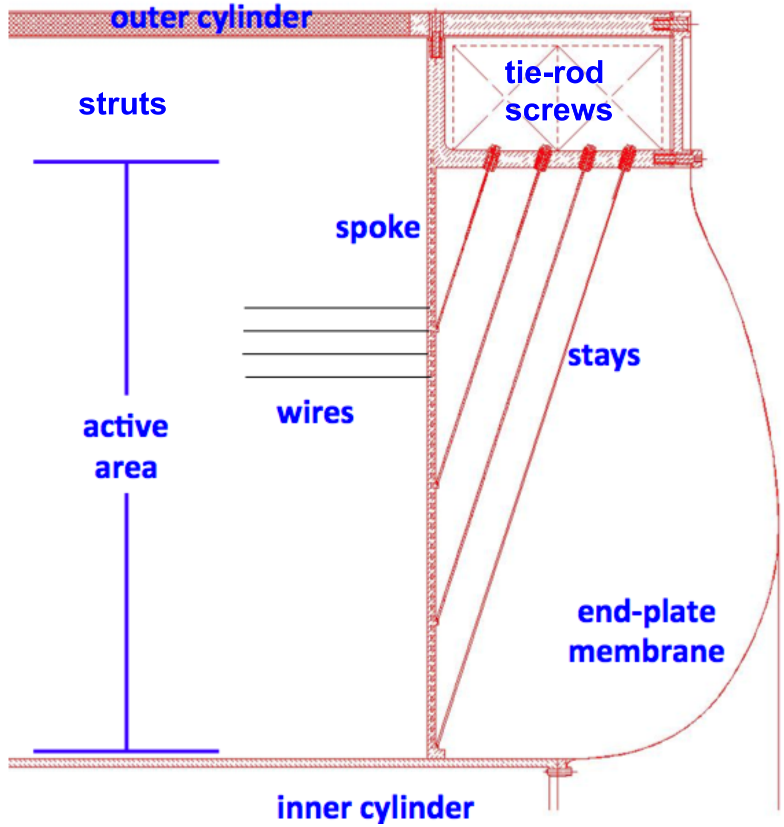
Inner cylinder:

2 C-fiber skins, 2-ply,
C-foam core, 5 mm
0.036 g/cm²
9×10⁻⁴ X₀

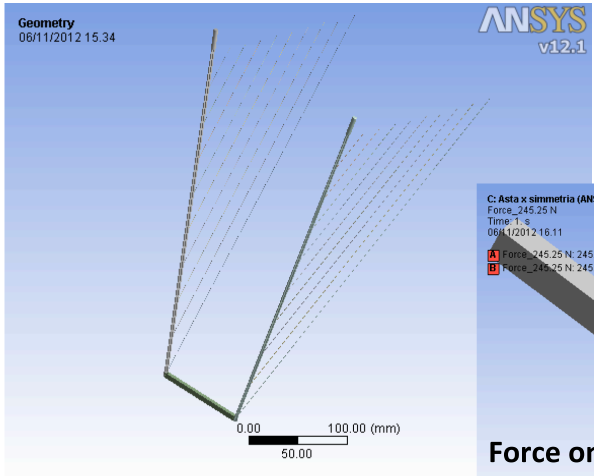
Example: The Mu2e I-Tracker proposal

Wire cage (conceptual)

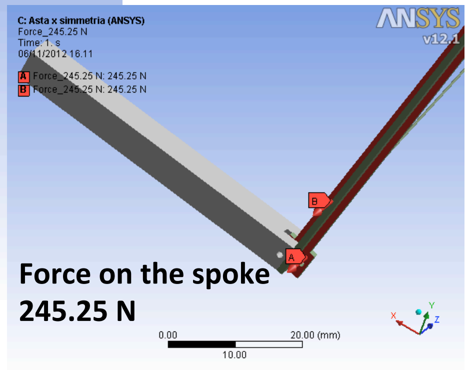


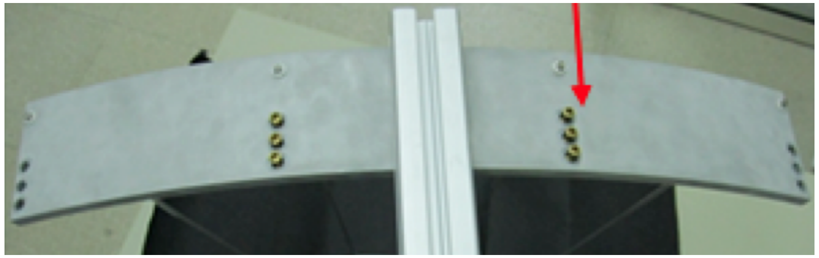


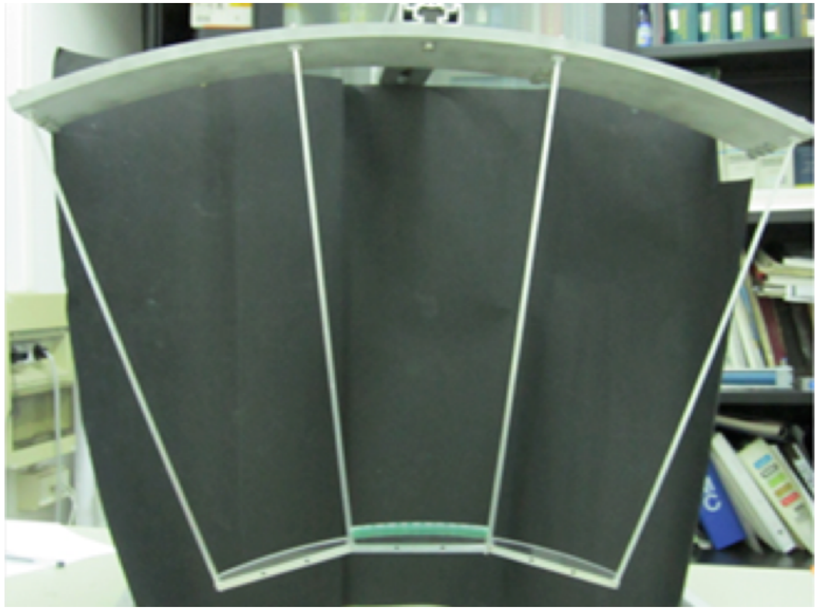
Verification of validity of principle



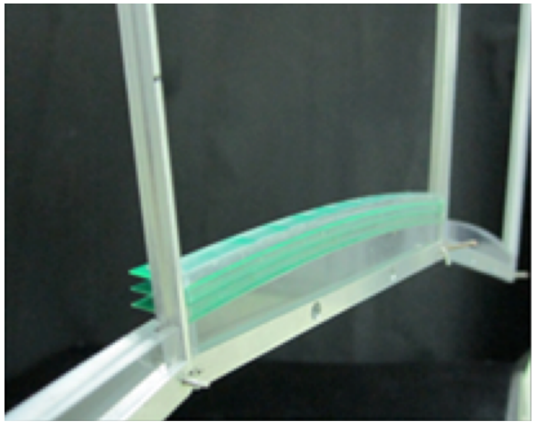
ANSYS
FEM
analysis







scale 1:1
model
to verify
validity
of principle



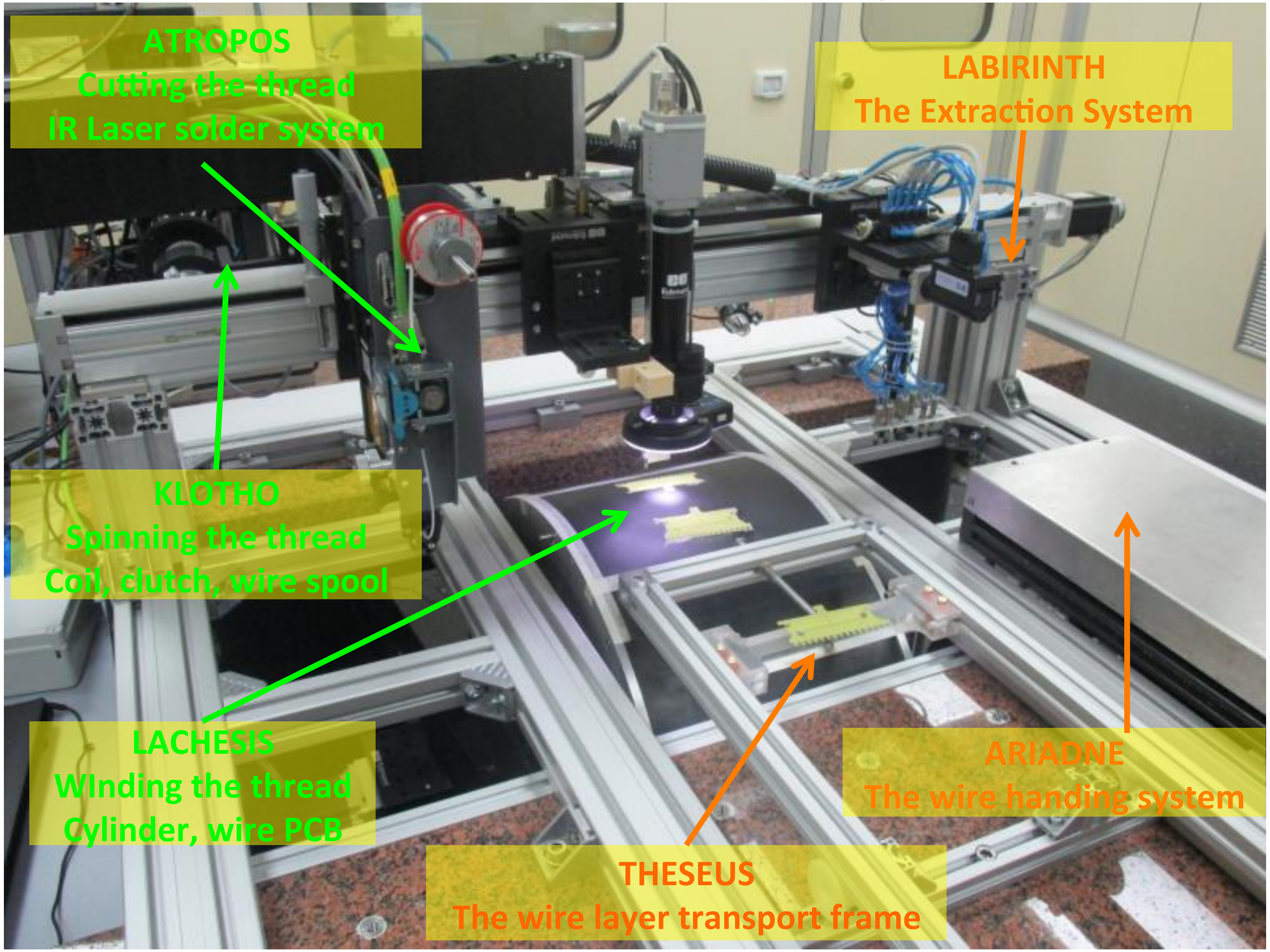
Wire Cage

- 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**.

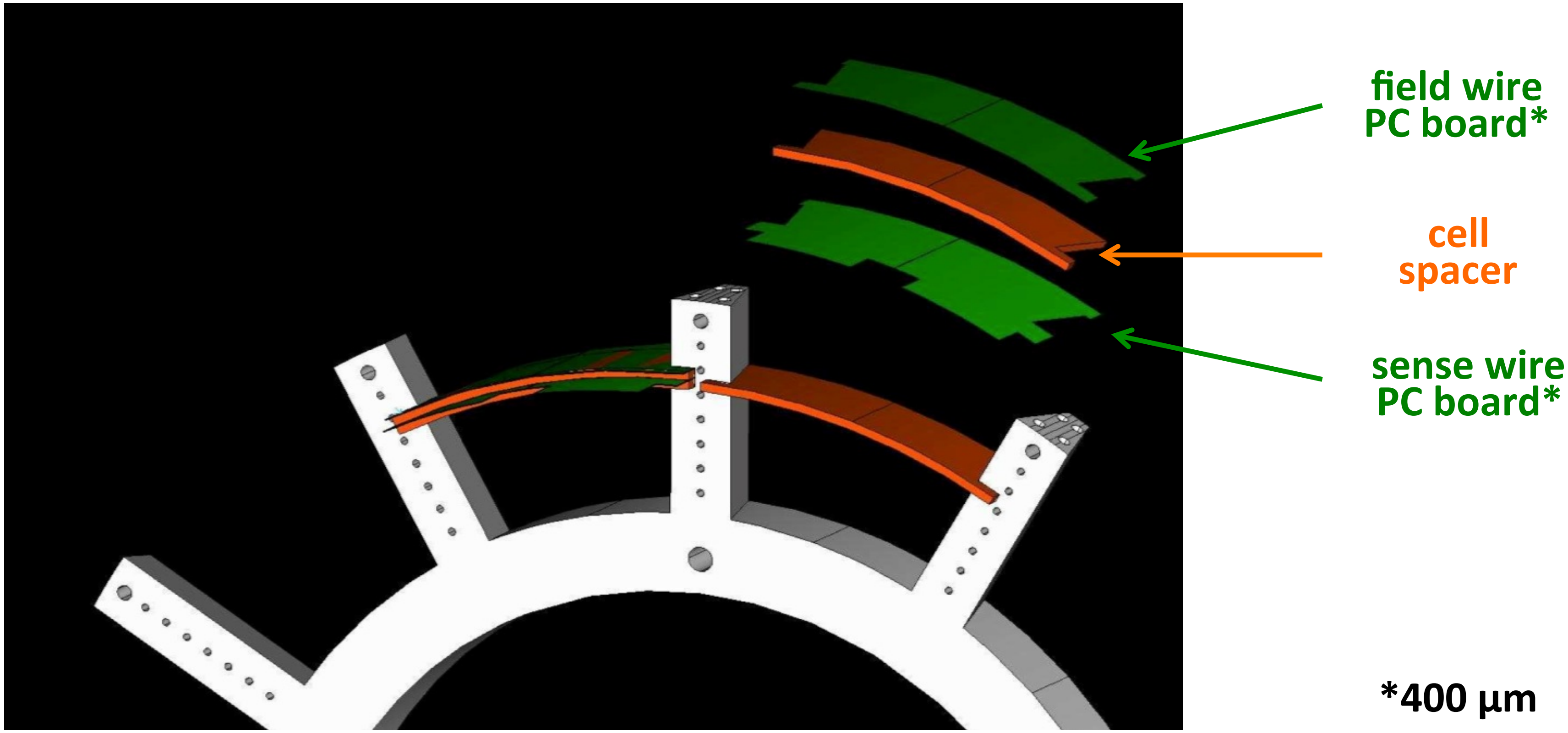
- **Larger field to sense wires ratio** and, therefore, **thinner field wires**, help reducing **multiple scattering contribution** and **total wire tension** on support structure.

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

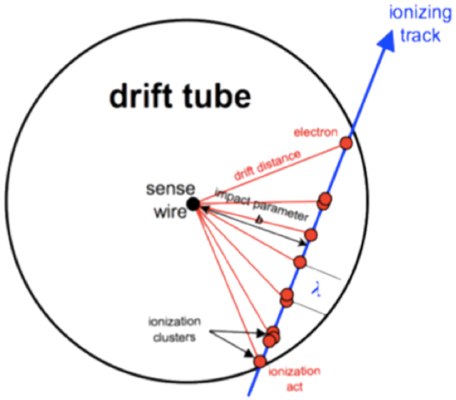
The MEG2 DC approach:
OLIMPUS: the wiring robot



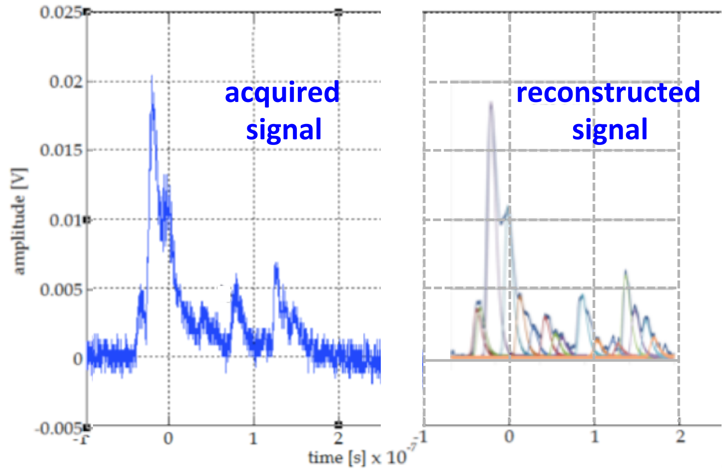
MEG2 DC (under construction) wire support structure

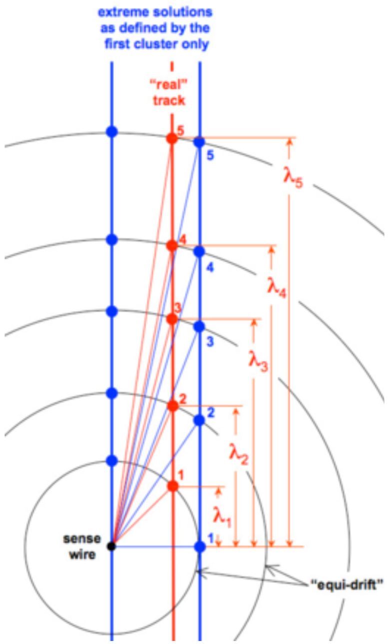


Cluster Timing

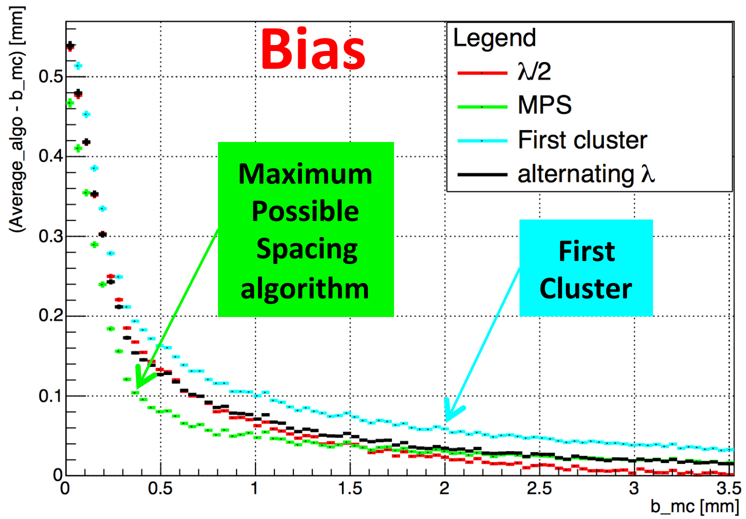


From the **ordered sequence of the electrons arrival times**, considering the average time separation between clusters and their time spread due to diffusion, **reconstruct the most probable sequence of clusters drift times:** $\{t_i^{cl}\} \quad i = 1, N_{cl}$



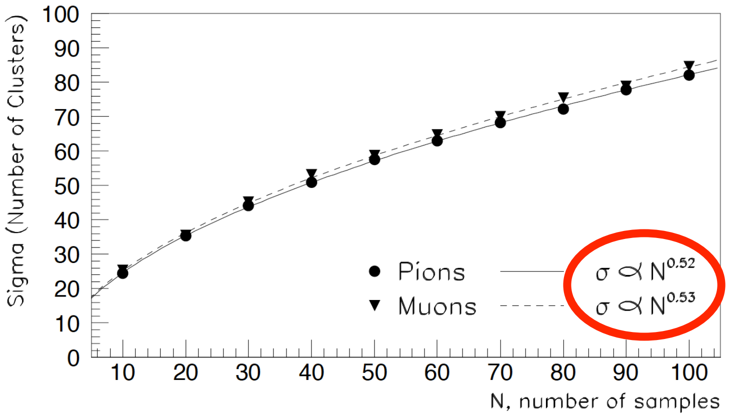


For any given first cluster (**FC**) drift time, the **cluster timing technique** exploits the drift time distribution of all successive clusters $\{t_i^{cl}\}$ to determine the most probable impact parameter, thus reducing the **bias** and the average **drift distance resolution** with respect to those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

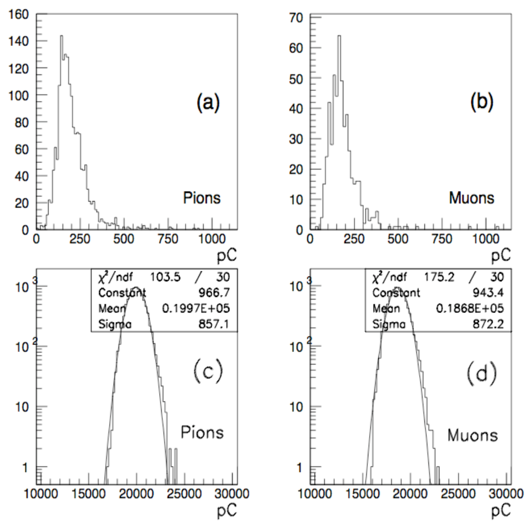


Cluster Counting

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

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

σ = 3.7%

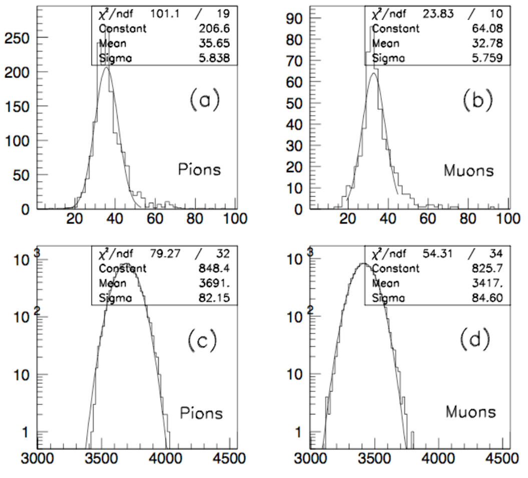
≈ 2.0σ separation

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 (1.5×10^{-3} X_0 and 8×10^{-3} X_0, respectively, for the Mu2e proposal).
- **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)

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

FEE: 1 GHz BW, x20 gain (S/N ratio ≈ 10) - digitizer: 2 GSa/s sampling rate, >8 bits

A proposal for CepC (1)

- **24 super-layers**, each one made of **8 para-axial layers** (**192 total**) at alternating sign stereo angles, arranged in **16 equal azimuthal sectors**;
- **18 square, single sense wire, drift cells** per sector (288 total) on first super-layer with 3 cells increment per sector on each successive super-layer to keep cell size constant as a function of super-layer radius;
- **Cell sizes** ranging from **7.2 mm to 8.7 mm** along r and z;
- **Alternating sign stereo angles** in consecutive layers ranging from **32 to 187 mrad (**constant azimuthal angular displacement)
- **Length: 4000 mm**; fully efficient up to **cosϑ=0.975** (>16 hit)
- **Inner Wall:** made of 25 µm of Kapton plus 0.1µm of Au (**1.2×10^{-4} X_0**) at **Radius = 320 mm**;
- **Outer Wall:** Sandwich of 4-ply C-fiber (0° and 90°, total of 250 µm) - 2.5 mm Rohacell30 - 4-ply C-fiber (**4.2×10^{-3} X_0**) at **Radius = 1950 mm** (must support **15 Tons** - check for buckling over 4 m);
- **End plates:**
  - **Wire cage (**in analogy to Mu2e I-Tracker): 0.6 g/cm^2 - **2×10^{-2} X_0** (incl. power distr., decoupling C's, term. resistors and signal and HV cables).
  - **Gas envelope** made of 6 ply (quasi-isotropic, 6×38 µm = 228 µm) C-fiber plus 0.3 µm Au, for a total of 0.060 g/cm^2 – **2.1×10^{-3} X_0**;
- **Gas: 90% He - 10% iC4H10** ($\delta = 4\times10^{-4}$ g/cm^3, X_0 = 1410 m), - 12.5 p.i./cm, gas gain: 4×10^5 at V ≈ 1400 V on 20 µm wire, v_{drift} ~ 2.5 cm/µs - **4.7×10^{-4} X_0/1m track**
- **Wires**: - **161,280 sense** (20µm Sn coated Ti); **648,480 field** (40µm Sn coated C); **164,640 guard** (50µm Sn coated Al) for a total equivalent thickness of **9.8×10^{-4} X_0/1m track**

Expected spatial resolution

Expected Performance: Track parameters resolutions

n = 192, B = 3.5 T, R_{out} = 1.95 m, L = 2.0 m or 2.8×10^{-3} X_0, σ_{xy} = 100 μm, σ_z = 1.0 mm

measurement

$$\frac{\Delta p_\perp}{p_\perp} = \frac{8\sqrt{5}\sigma}{.3BL^2\sqrt{n}} p_\perp = 3.1\times10^{-5} p_\perp [GeV/c]$$

$$\Delta\phi_0 = \frac{4\sqrt{3}\sigma}{R_{out}\sqrt{n}} = 3.2\times10^{-5}$$

$$\Delta\theta = \frac{\sqrt{12}\sigma_z}{R_{out}\sqrt{n}} \frac{1+\tan^2\theta}{\tan^2\theta} = 1.6\times10^{-4} \frac{1+\tan^2\theta}{\tan^2\theta}$$

multiple scattering (gas + wires)

$$\frac{\Delta p_\perp}{p_\perp} = \frac{0.0523[GeV/c]}{\beta p B L \sin\theta} \sqrt{\frac{L}{X_0}} = \frac{3.4\times10^{-4}[GeV/c]}{\beta p \sin\theta}$$

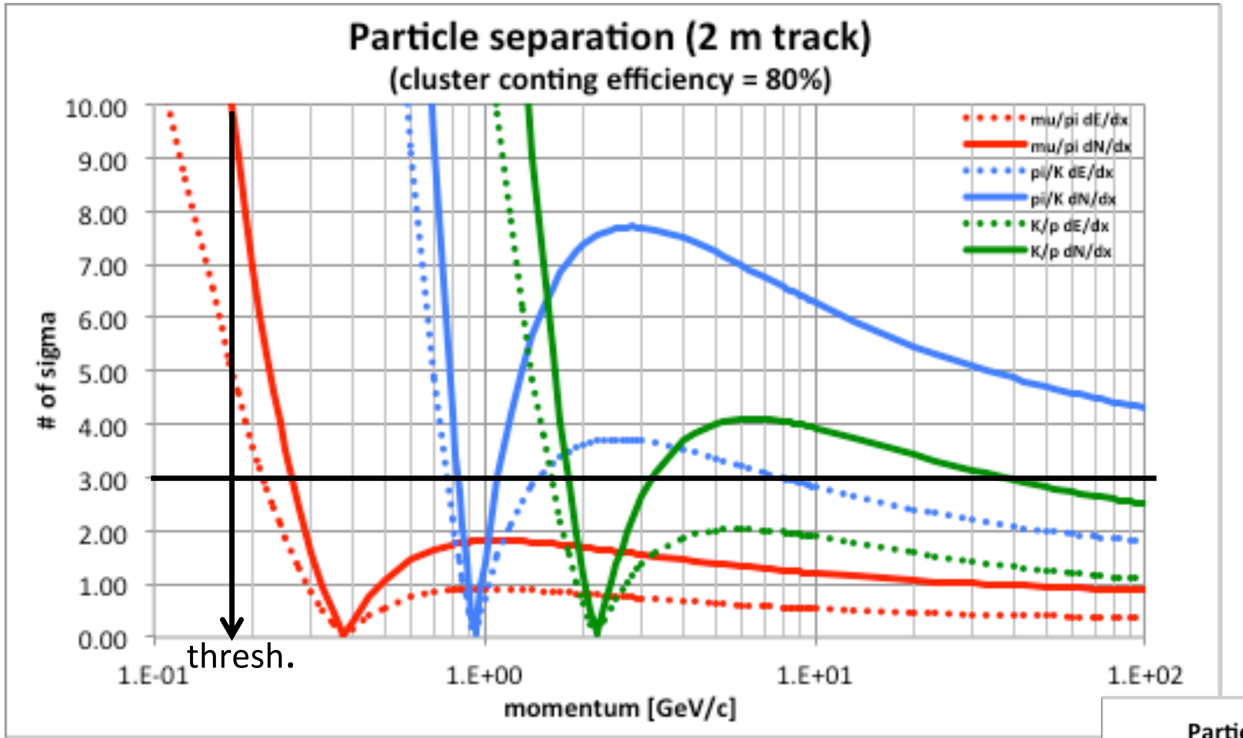
$$\Delta\phi_0 = \frac{13.6\times10^{-3}[GeV/c]}{\beta p} \sqrt{\frac{L}{X_0}} = \frac{7.2\times10^{-4}[GeV/c]}{\beta p}$$

$$\Delta\theta = \frac{13.6\times10^{-3}[GeV/c]}{\beta p} \sqrt{\frac{L}{X_0}} = \frac{7.2\times10^{-4}[GeV/c]}{\beta p}$$

$$\frac{\Delta p_\perp}{p_\perp} = 2.2\times10^{-4}; \quad \frac{\Delta p}{p} = \frac{\Delta p_\perp}{p_\perp} \oplus \frac{\Delta\theta}{\tan\theta} = 4.0\times10^{-4}$$

for $p = 10$ GeV/c and $\theta = 45°$

Expected p. id. capabilities

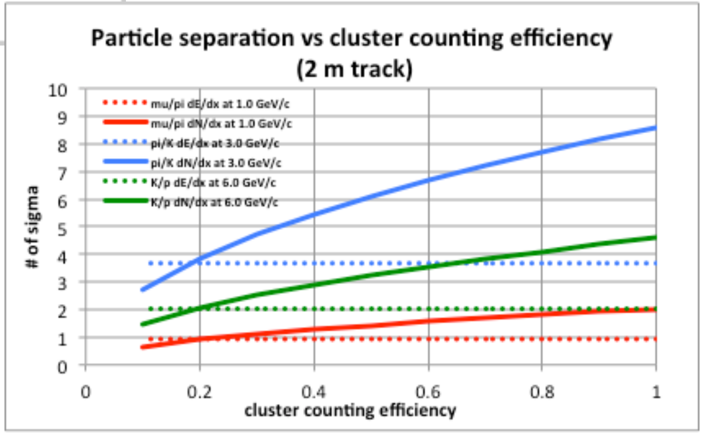


$\sigma_{dE/dx}/dE/dx =$
$= 5.4\ L[m]^{-0.37}\ \%$
(Lehraus parametrization)
4.2% for L=2m

cluster counting efficiency
$\varepsilon = 80\%$

$\sigma_{dN_{cl}/dx}/dN_{cl}/dx =$
$= \varepsilon \times L \times 12.5/cm =$
2.2% for L=2m

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 CepC 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, small size square cells:
  - **R_{in} = 32 cm**; **R_{out} = 195 cm**; **L = 400 cm**; **192 layers × 8.2 mm**; **160,000 cells**; >16 hits (90% efficiency) down to **cosϑ = 0.975**; stereo angles ranging from **32 mrad to 187 mrad**;
  - Inner cylindrical wall: **$1.2\times10^{-4}\ X_0$**
  - Outer cylindrical wall: **$4.2\times10^{-3}\ X_0$**
  - End plates (fully instrumented): **$2.2\times10^{-2}\ X_0$**
  - Gas + wires: **$4.7\times10^{-4}\ X_0$/1m track + $9.8\times10^{-4}\ X_0$/1m track**
- Expected spatial resolutions: **$\sigma_{r\varphi}$ < 100 μm, σ_z < 1 mm**
- Expected momentum resolution: **$\Delta p_t/p_t = 2.2\times10^{-4}$**, **$\Delta p/p = 4.0\times10^{-4}$** for p=10GeV/c and ϑ=45°
- Expected p. id.: π/κ separation **> 3σ for p < 820 MeV/c and p > 1100 MeV/c**

At current status of art: it doesn't need any major R&D

Back up slides

solid state drawbacks (1)

- **multiple scattering**
  - Si detector + electronics + cooling + mechanical supports amounts to > 5% X_0 per layer, for a total of **> 25% X_0 in the barrel region** and **> 30% X_0 in the end-cap region**, in front of the electromagnetic calorimeters (from SiD at ILC)
- **redundancy**
  - despite the excellent space resolution (**$\sigma \approx$ 10 µm**) per layer, only a limited number (**N ≈ 5**) of layers can be implemented, for a momentum resolution $\propto \sigma/\sqrt{N}$, equivalent to a gas tracker (**$\sigma \approx$ 100 µm and N ≈ 200**).
  - However, because of the small N, it suffers from **lack of redundancy**, against inefficiencies and background hits, and **high combinatory for pattern recognition**

solid state drawbacks (2)

- **number of channels and cost**
  - necessary of the order of 30 million channels (SiD at ILC) for only 5 space points with a leverage compatible with the momenta to be measured
  - implications on system complexity, cost, power consumption, ...
- **alignment**
  - relative alignment at the level of < 5 μm among the many staves, the barrel layers and the forward planes constituting the tracker
  - absolute alignment with inner vertex detector and beam axis at same level
  - stability of alignment parameters w.r.t. temperature, CO_2 cooling flow, mechanical vibrations, ...
- **particle identification**
  - no particle identification possible

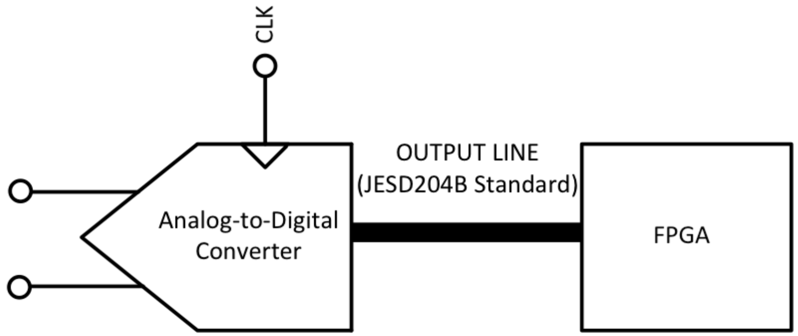
TPC drawbacks (1)

- **gas mixture**
  - at v_{drift} = 5 cm/μs, total drift time ≈ 50 μs, integrating ≈ 15 bunch crossings (occupancy at low p_t: curling for 170 < p_t < 950 MeV/c).
  - $\Delta v_{drift}/v_{drift} \approx$ 1%/10 ppm (H_2O)!
  - attachment (O_2, electronegative impurities < a few ppm!)?
- **positive ions backflow**
  - no sufficiently efficient gating strategy envisioned yet for a continuous beam, leading to large track distortions.
  - ion space charge density affects ion backflow even in triple GEM configuration, particularly at smaller radii.
- **alignment**
  - relative alignments must be below 50 μm (<< distortion corrections).

TPC drawbacks (2)

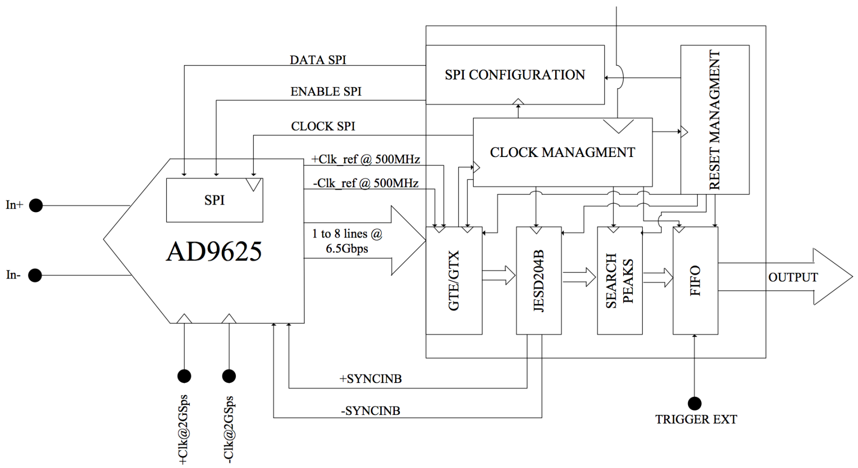
- **number of readout channels**
  - expected point resolution requires readout pad sizes of a few mm^2 for a total of millions of channels per endplate (≈ 10 m^2).
- **power consumption**
  - even at 10 mW/ch (ALICE TPC: 40 mW/ch), tens of kW per end plate necessary (no power pulsing like ILC) requiring sophisticated cooling systems (more material in front of the end-cap calorimeter).
- **multiple scattering**
  - end plates must support field cage, MPGD readout system, cooling system, power and FEE cables: hard to keep equivalent end plates thickness in front of the electromagnetic calorimeter below 30% X_0.

BLOCK DIAGRAM



CLUSTER TIMING/COUNTING PROTOTYPE READOUT SCHEME

- **Analog to Digital Converter**: Analog Devices AD9625
  - Sampling frequency: 2.0 GSPS
  - Resolution: 12 bits
  - Supply voltage: 1.3V, 2.5
- **FPGA**: Virtex 6 xc6vlx240t-1ff1156



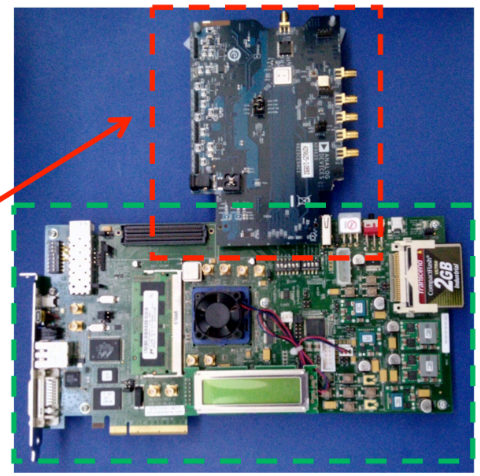
EVALUATION BOARDS USED

AD9625 evaluation board:
AD9625-2.0EBZ [4]

xc6vlx240t-1ff1156 evaluation board:
UG534 ML605 [5]

AD9625-2.0EBZ

UG534 ML605



(4) http://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/eval-ad9625.html#eb-overview
(5) http://www.xilinx.com/support/documentation/boards_and_kits/ug534.pdf