An ultra-low mass Tracking Chamber with Particle Identification capabilities for SCTF at BINP

Istituto Nazionale di Fisica Nucleare

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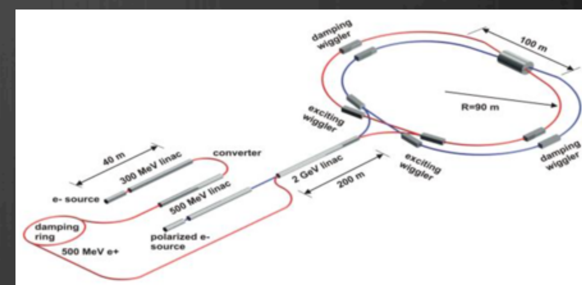


Joint Workshop on
future tau-charm factory

December 4-7, 2018
Laboratoire de l'Accélérateur Linéaire, **Orsay, France**

Bruno Mazoyer LAL 2018

Road to proposal

I. **KLOE** ancestor chamber at INFN LNF Daϕne φ factory (commissioned in 1998 and operating for the last 20 years)

II. **CluCou** Chamber proposed for the **4th-Concept** at ILC (2009)

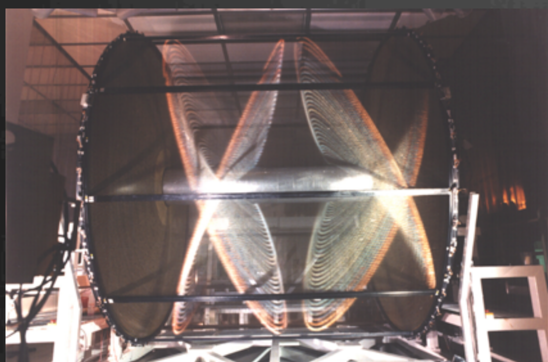
III. **I-tracker** chamber proposed for the **Mu2e experiment** at Fermilab (2012)

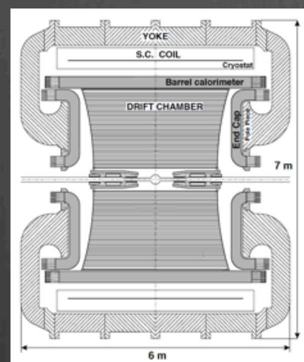
IV. **DCH** for the **MEG upgrade** at PSI (designed in 2014, just completed at INFN and under commissioning)

V. **IDEA** drift chamber proposal for FCC-ee and CEPC (2016)

Road to proposal

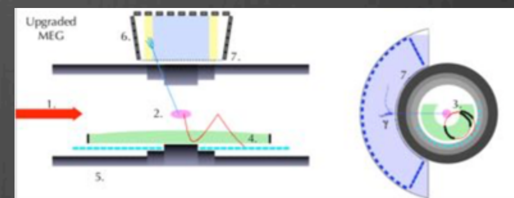
The KLOE Drift Chamber (1998)

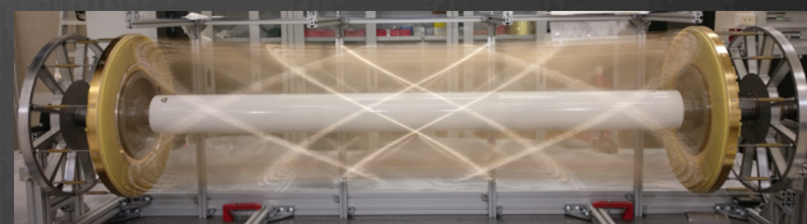




A unique volume, all stereo, cylindrical drift chamber, co-axial to B (0.6 T).
Rin = 25 cm, Rout = 200 cm, L = 2.8÷3.3 m,
12+46 co-axial layers,
at alternating sign stereo angles from 60 mrad to 150 mrad.
Square cell size $2\times2/3\pi$ (inner 12) and $3\times\pi$ (outer 46) cm^2.
Total number of drift cells 12582. Total number of wires 52140

The MEG2 Drift Chamber (2018)





A unique volume, high granularity, all stereo, low mass cylindrical drift chamber, co-axial to B (1.27÷0.49 T).
Rin = 18 cm, Rout = 30 cm, L = 2 m,
10 co-axial layers,
at alternating sign stereo angles from 100 mrad to 150 mrad,
Square cell size ≈7×7 mm^2.
Total number of drift cells 1920. Total number of wires 12,678

The evolution

from KLOE ...

I. Wire configuration **fully stereo** (no axial layers)

II. new **light Aluminum** wires

III. Very light gas mixture **90% He – 10% iC_4H_{10}**

IV. Mechanical structure entirely in **Carbon Fiber**

V. Largest volume **drift chamber** ever built (45 m^3)

... to SCTF

I. **Cluster timing** for improved spatial resolution

II. **Cluster counting** for particle identification

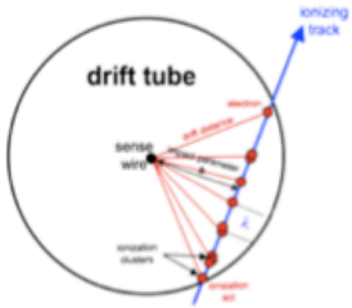
III. No **feed-through** wiring

IV. **larger number** of **thinner** (and **lighter** wires)

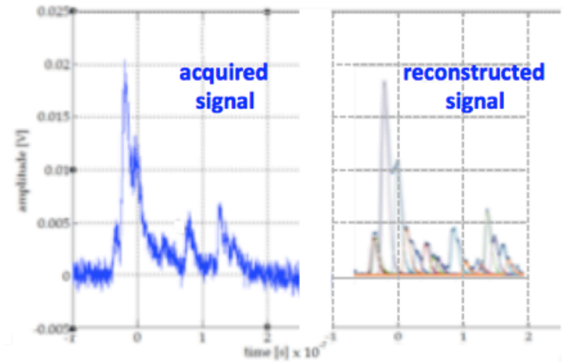
V. **Gas containment** from **wire support** functions separation

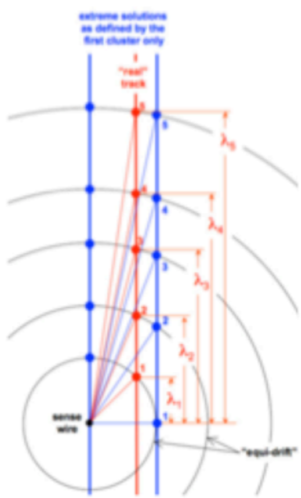
VI. New concepts for **wire tension compensation**

Cluster Timing

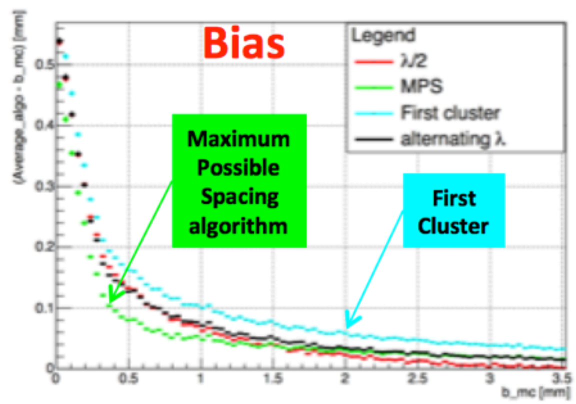


From the **ordered sequence of the electrons arrival times,** considering the average time separation between clusters and their time spread due to diffusion, **reconstruct the most probable sequence of clusters drift times:** $\{t_i^{cl}\}\quad i=1,N_{cl}$





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

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

from *Walenta parameterization (1980)*

versus

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2}$$

from *Poisson distribution*

dE/dx

truncated mean cut (70-80%) reduces the amount of collected information

n **=** 64 and .6 **m track** at **1 atm** give

σ ≈ 8.1%

Increasing ***P*** to 2 atm improves resolution by 20% (σ ≈6.5% but at a **considerable** cost of multiple scattering contribution to momentum and angular resolutions.

dN_{cl}/dx

δ_{cl} = 12.5/cm for He/iC_4H_{10}=90/10 and .6 m **track** give

σ ≈ 3.6%

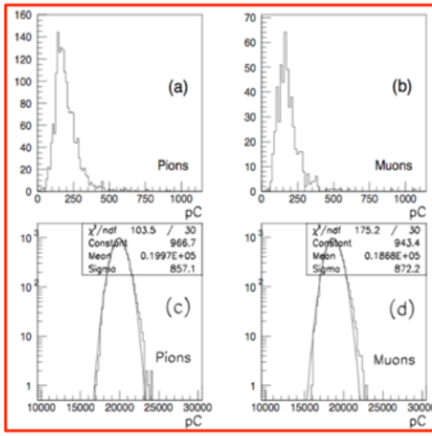
A small increment of iC_4H_{10} from 10% to 20% (δ_{cl} = 20/cm) improves resolution by 20% (σ ≈2.8% at only a **reasonable** cost of multiple scattering contribution to momentum and angular resolutions.

Cluster Counting

The data shown refer to a beam of **μ and π at 200 MeV/c**, taken with a gas mixture **He/iC_4H_{10}=95/5, δ_{cl} = 9/cm, 100 samples, 2.6 cm** each **at 45°** (for a **total track length of 3.7 m**, corresponding to **N_{cl} = 3340, $1/\sqrt{N_{cl}}$ = 1.7%**).

Setup:
25 μm sense wire
(**gas gain 2x10^5**),
through a high BW preamplifier
(**1.7 GHz, gain 10**),
digitized at
2 GSa/s, 1.1 GHz, 8 bits

(*NIM A386 (1997) 458-469* and references therein)

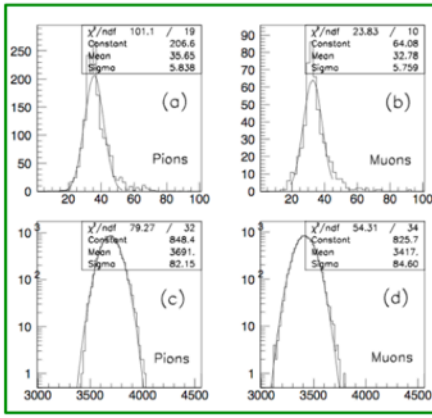


dE/dx

100 samples 3.7 cm

theory:
($\sigma = 0.41\, n^{-0.43} (L[m]P[atm])^{-0.32}$)
σ = 3.7%
≈ 2.0σ separation

experiment
20% truncated mean
σ = 4.5%
≈ 1.4σ separation

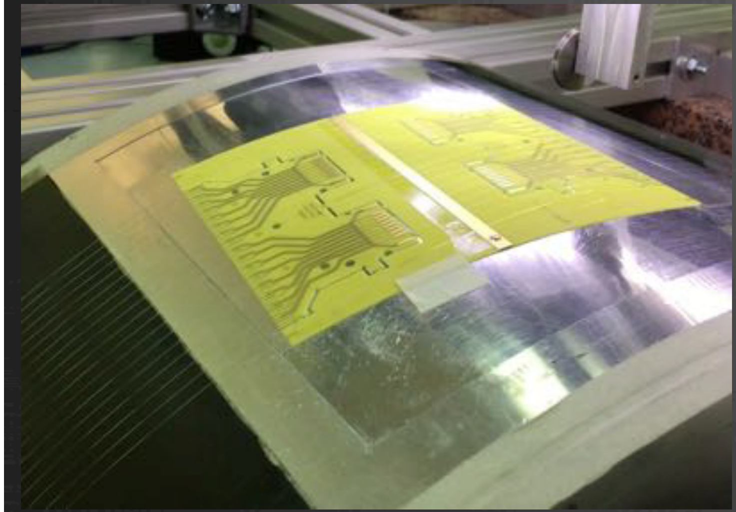


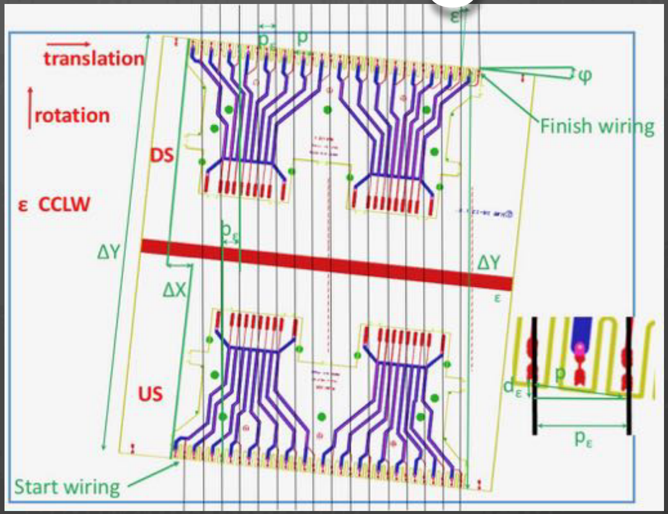
dN_{cl}/dx

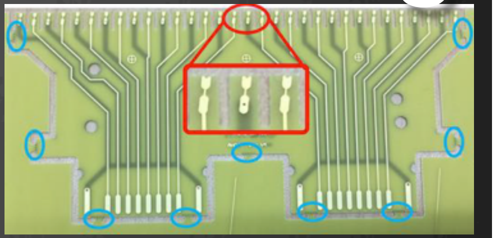
theory
Poisson distribution
σ = 1.7%
≈ 5σ separation

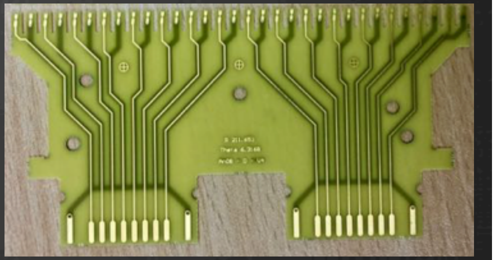
experiment
σ = 2.5%
≈ 3.2σ separation

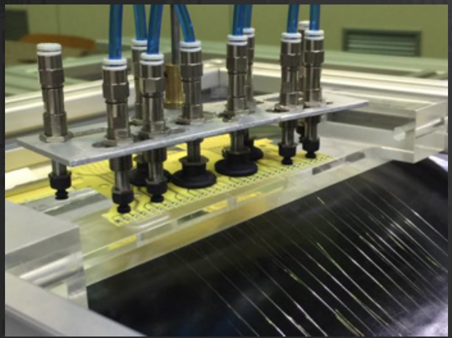
The MEG2 feed-through-less wiring

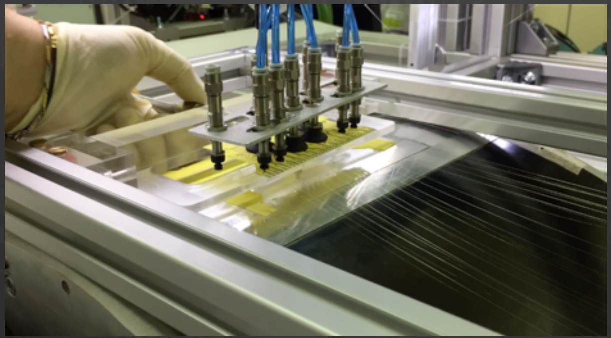


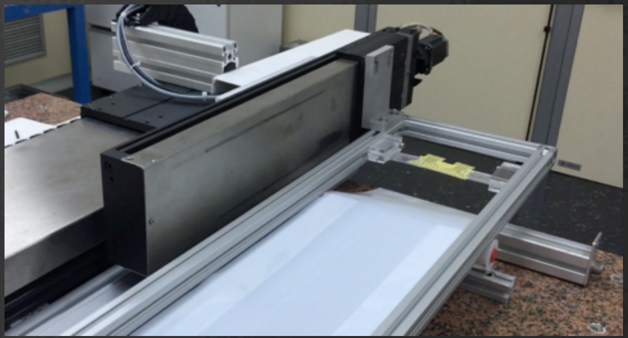




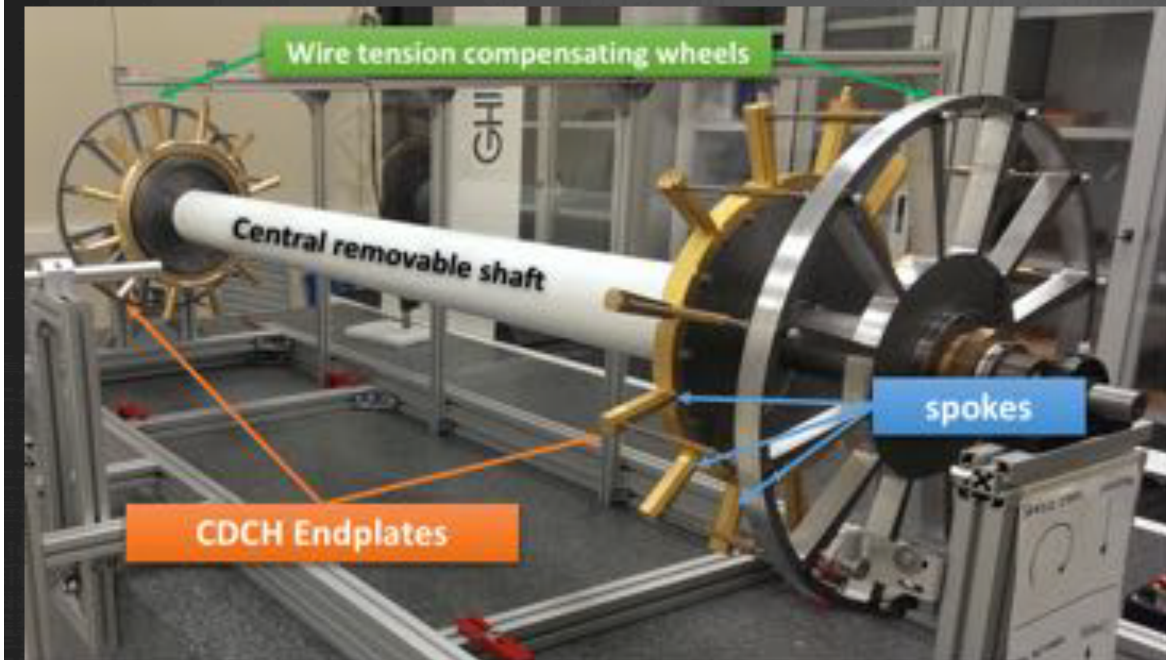


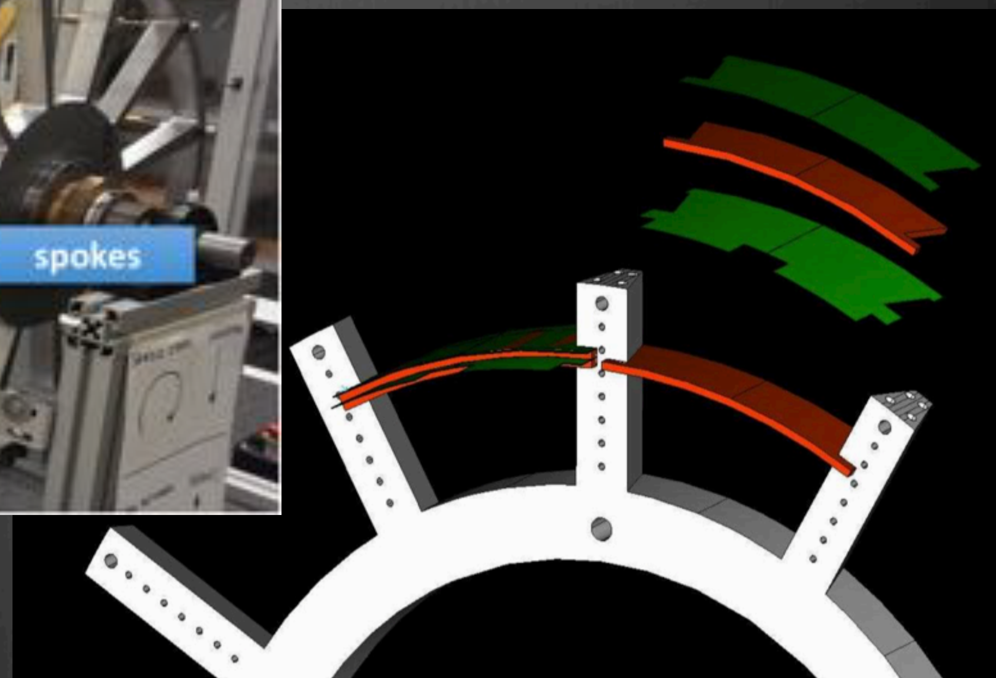




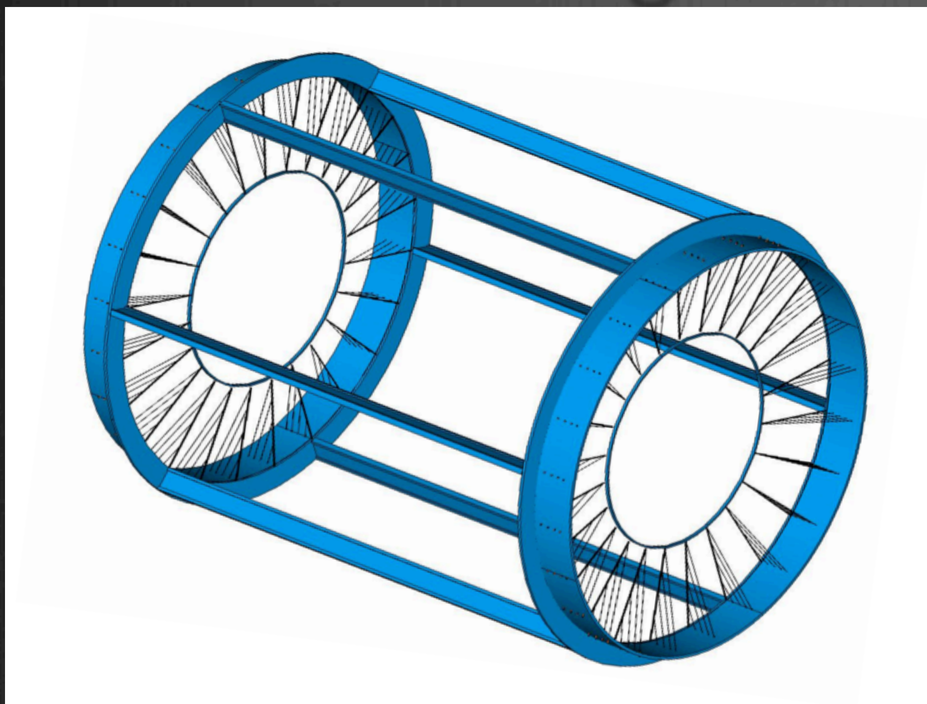


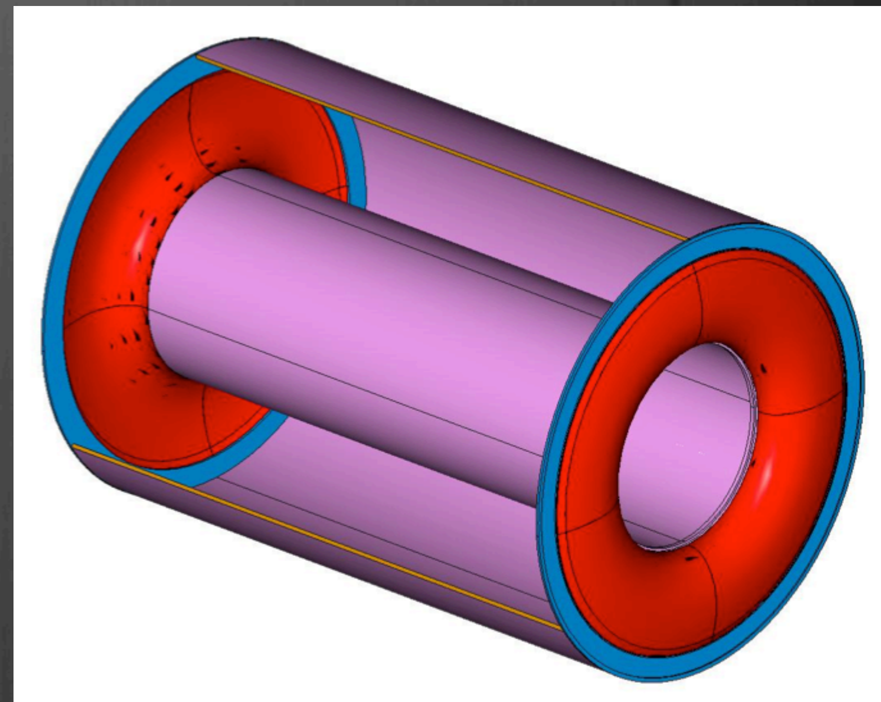
The MEG2 feed-through-less wiring





"Wire Cage" and "Gas Envelope"





Wire support:

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

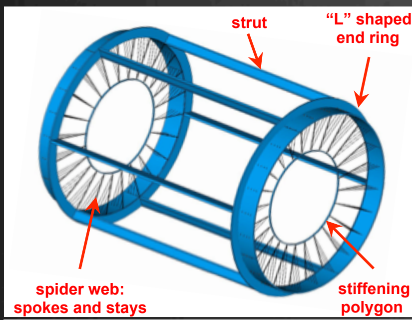
Gas containment:

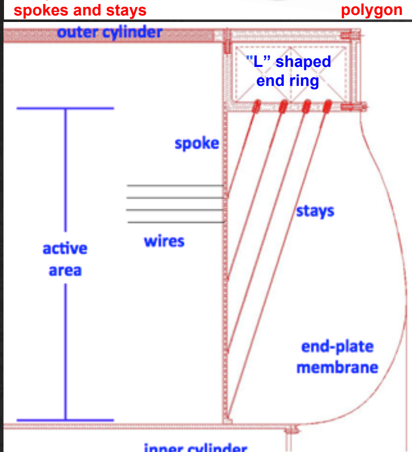
Gas envelope can freely deform without affecting the internal wire position and tension.

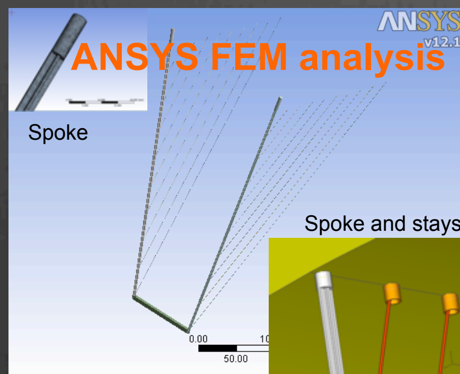
The Mu2e I-Tracker proposal

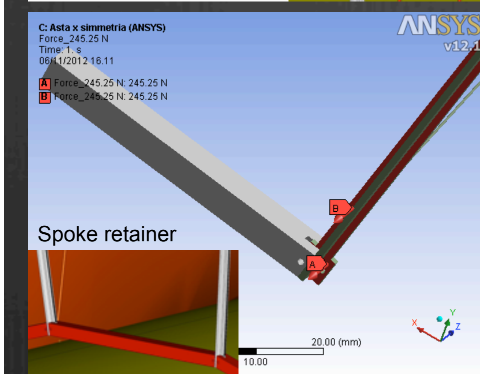
Wire cage

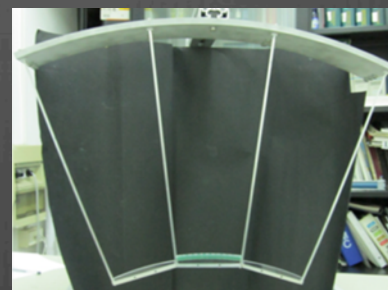
turn all bending moments into traction or compression!

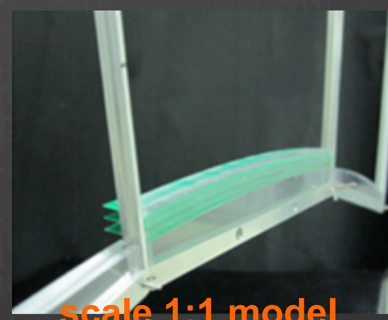












- **feed-through-less chamber** allows for reducing wire spacing, thus increasing cell granularity:
  - **smaller cells**
  - **larger ratios of field to sense wires**
- **larger ratios of field to sense wires** allows for thinner field wires, thus reducing
  - **wire contribution to multiple scattering**
  - **total wire tension**

Instrumented end-plate:

wire PCB, spacers, HV distrib. and cables, limiting R, decoupling C and signal cables

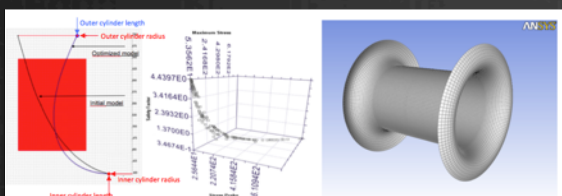
0.28 g/cm²

$1\times10^{-2}\ X_0$

The Mu2e I-Tracker proposal

Gas envelope

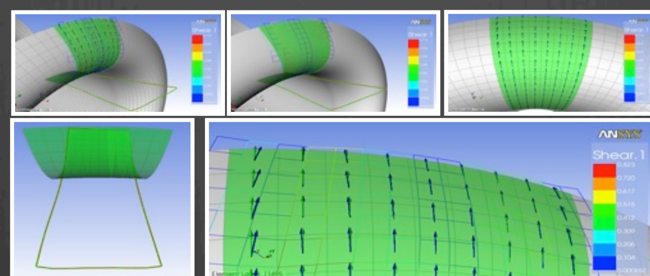
- A structural multivariate analysis to find **the optimal shape for the end plates profile** by **minimizing the total maximum stress and the stress on the inner cylinder**



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

use the 3-steps recipe to minimize materials

- A proper **unidirectional pre-preg** to form **ply draping** of the laminates and **flat-wrap** of the optimized model



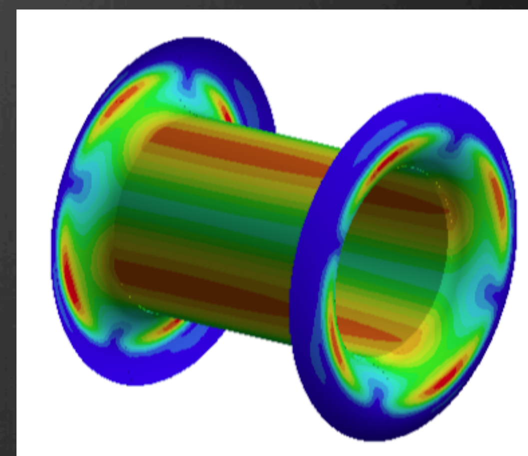
End plate:

4-ply × 38μm/ply
orthotropic (0/90/90/0)
0.021 g/cm²
$6\times10^{-4}\ X_0$

Inner cylinder:

2 C-fiber skins, 2-ply,
+ 5 mm C-foam core
0.036 g/cm²
$8\times10^{-4}\ X_0$

- reduce **inner cylinder buckling** by increasing the **moment of inertia** with proper **light core composite sandwich**

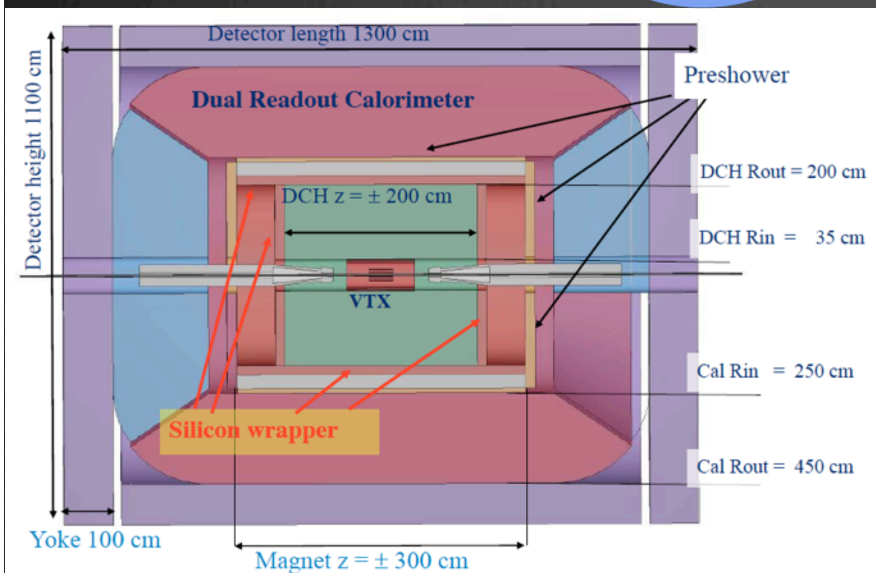


The IDEA Drift Chamber at CEPC and FCC-ee

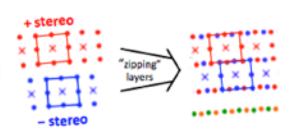
The **IDEA** Detector at

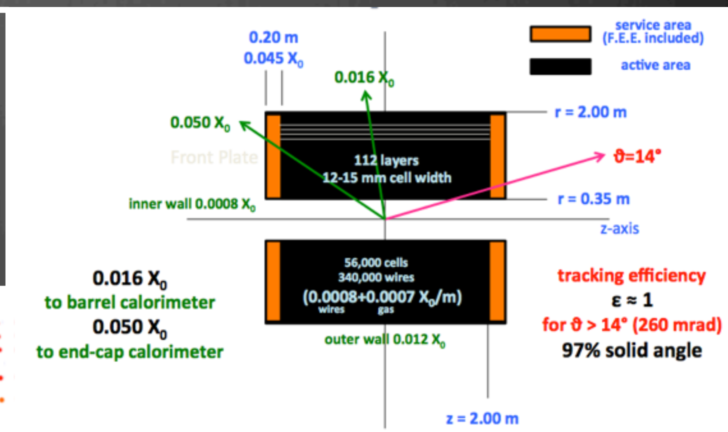
FCC-ee at CERN

CEPC at IHEP-China



The IDEA Drift Chamber





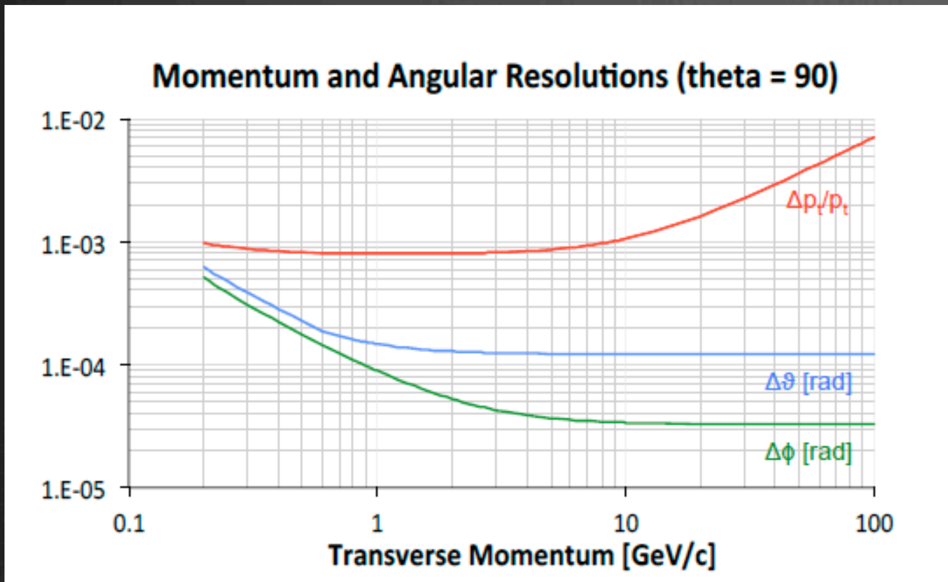
	R_{in} [mm]	R_{out} [mm]	z [mm]
drift chamber	350	2000	±2000
service area	350	2000	±(2000÷2250)

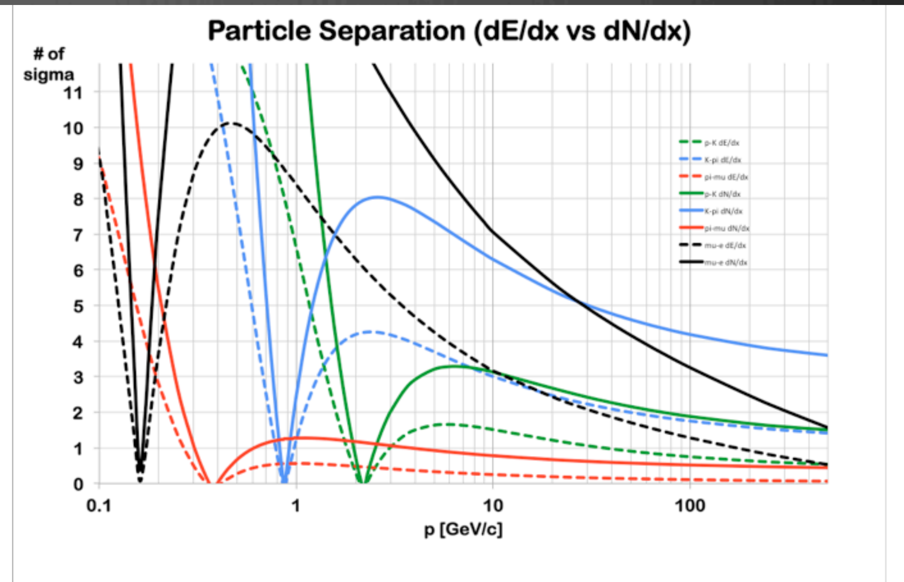
	inner wall	gas	wires	outer wall	service area
thickness [mm]	0.2	1000	1000	20	250
X_0 [%]	0.08	0.07	0.13	1.2	4.5

# of layers	112	min 11.8 mm – max 14.9 mm
# of cells	56448	192 at first layer – 816 at last layer
average cell size	13.9 mm	min 11.8 mm – max 14.9 mm
average stereo angle	134 mrad	min 43 mrad – max 223 mrad
transverse resolution	100 μm	80 μm with cluster timing
longitudinal resolution	750 μm	600 μm with cluster timing

active volume	50 m^3	0.9 He-0.1 iC_4H_{10}
readout channel	112,896	r.o. from both ends
max drift time	400 ns	800 × 8 bit at 2 GHz

The IDEA Drift Chamber Performance





$\Delta p_t/p_t = (0.7 p_t \oplus 8.3) \times 10^{-4}$

$\Delta\vartheta = (1.1 \oplus 9.4/p) \times 10^{-4}$ rad

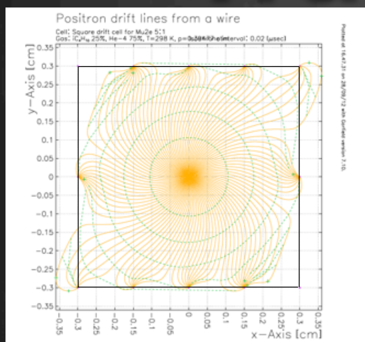
$\Delta\varphi = (0.33 \oplus 9.4/p) \times 10^{-4}$ rad

dE/dx = 4.3 %

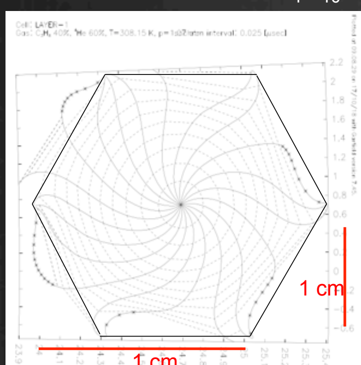
dN/dx = 2.2 % (at ε_N = 80 %)

TraPId: A proposal for SCTF

square cell vs. hex cell



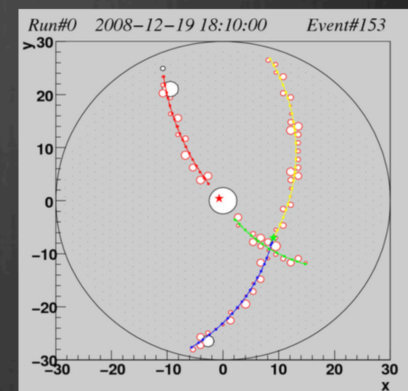
from: Mu2e I-tracker
B = 1 T - 75%He-25%iC_4H_{10}

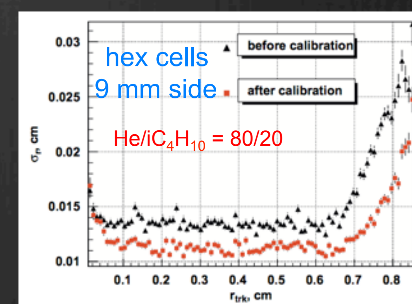


from: https://ctd.inp.nsk.su/wiki/mages/e/e7/DCvariant.pdf
B = 1.5 T - 60%He-40%C_3H_8

- small deviation from perfect polygonal shape: 3.3% vs. 3.1% at innermost layer
- field to sense wire ratio: 5 to 1 vs. 2 to 1
  - more field wires implies better E-field isotropy and smaller E×B asymmetries
  - thinner field wires: 40 μm vs. 100-125 μm
    - less multiple scattering
    - less tension on end plates
- smaller gaps in B-field
- larger time-to-distance distortions
  - longer tails (> 500 ns for 1 cm cell) in signal pulse (hit pattern, dE/dx, pile up)
- easy implementation of a full stereo configuration

CMD-3 at VEPP2000



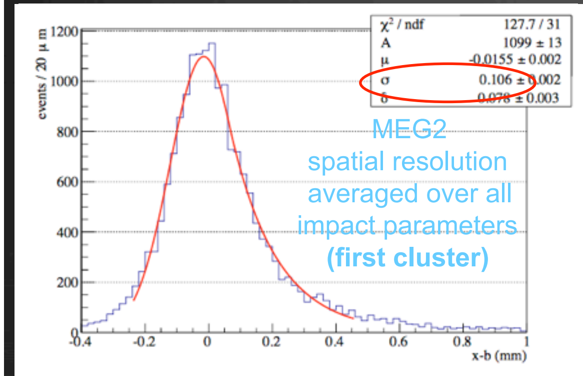


TraPId: A proposal for SCTF

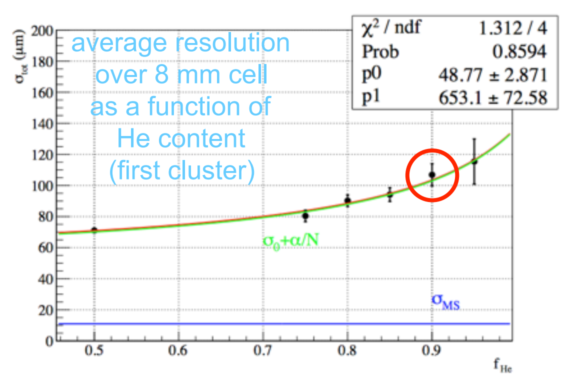
$R_{in} – R_{out}$ [mm]		200 – 800
active L – service area [mm]		1800 – 200
inner cylindrical wall		
C-fiber/C-foam sandwich	2×80 µm / 5 mm	0.036 g/cm² – 8×10^{-4} X/X_0
outer cylindrical wall		
C-fiber/C-foam sandwich	2×5 mm / 10 mm	0.512 g/cm² – 1.2×10^{-2} X/X_0
end plate		
gas envelope	160 µm C-fiber	0.021 g/cm² – 6×10^{-4} X/X_0
instrumented wire cage	wire PCB, spacers, HV distr. and cables, limiting R, decoupling C and signal cables	0.833 g/cm² – 3.0×10^{-2} X/X_0

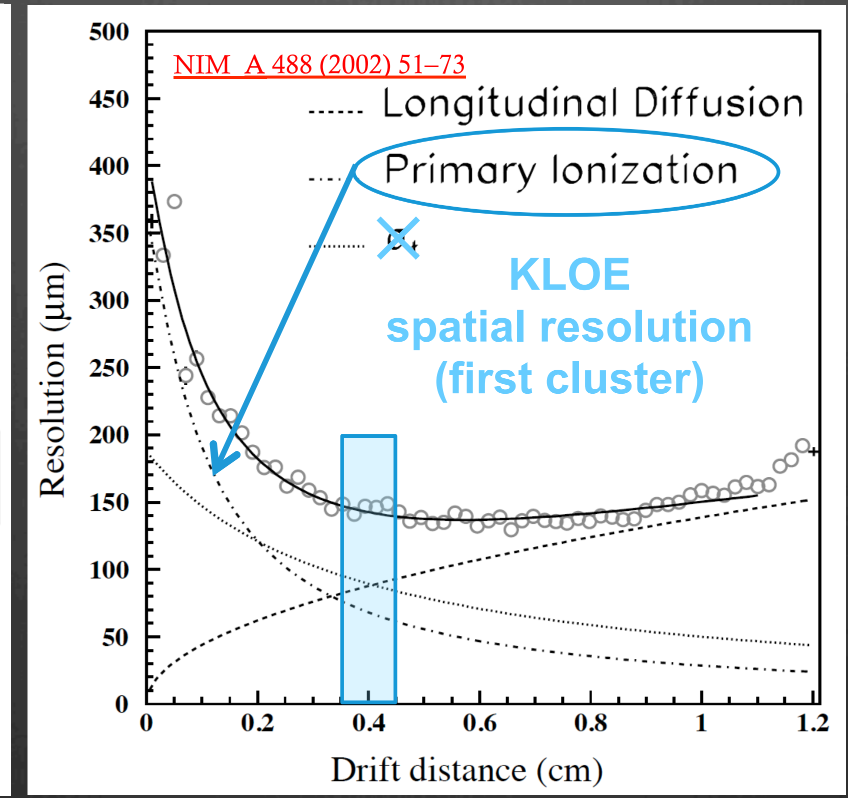
cell	
shape	square
size [mm]	7.265 – 9.135
layer	
8 super-layers	8 layer each
64 layer total	
stereo angles	66 – 220 mrad
n. sense wires [20µm W]	23,040
n. field wires [40/50µm Al]	116,640
n. total (incl. guard)	141,120
gas + wires [600 mm]	
90%He – 10%iC_4H_{10}	4.6×10^{-4}
wires (W=53%, Al=47%)	13.1×10^{-4}

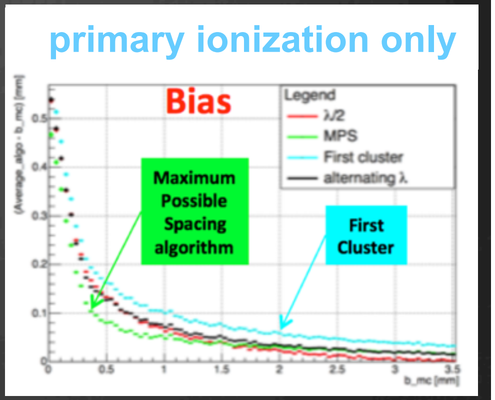
TraPId: spatial resolution



Baldini, A.M. *et al.* JINST 11 (2016) P07011







cluster timing allows to reduce average spatial resolution from 100 μm down to ≤ 85 μm in a 8 mm cell

TraPId: Tracking Performance

Expected Performance: Track parameters resolutions

n = 64, B = 1.5 T, R_{out} = 0.8 m, L = 2.0 m, (0.8+1.8)x10^{-3} X/X_0, σ_{xy} = 100 μm, σ_z = 0.8 mm

measurement

$$\frac{\Delta p_\perp}{p_\perp} = \frac{8\sqrt{5}\sigma}{.3BR_{out}^2\sqrt{n}} p_\perp = 7.8\times10^{-4} p_\perp [GeV/c]$$

$$\Delta\phi_0 = \frac{4\sqrt{3}\sigma}{R_{out}\sqrt{n}} = 1.1\times10^{-4}$$

$$\Delta\theta = \frac{\sqrt{12}\sigma_z}{R_{out}\sqrt{n}} \frac{1+\tan^2\theta}{\tan^2\theta} = 3.8\times10^{-4} \text{ at } \theta=90^o$$

multiple scattering (gas + wires + inner wall)

$$\frac{\Delta p_\perp}{p_\perp} = \frac{0.0523[GeV/c]}{\beta BL}\sqrt{\frac{L}{X_0}} = \frac{1.8\times10^{-3}[GeV/c]}{\beta}$$

$$\Delta\phi_0 = \frac{13.6\times10^{-3}[GeV/c]}{\beta p}\sqrt{\frac{L}{X_0}} = \frac{6.9\times10^{-4}[GeV/c]}{\beta p}$$

$$\Delta\theta = \frac{13.6\times10^{-3}[GeV/c]}{\beta p}\sqrt{\frac{L}{X_0}} = \frac{6.9\times10^{-4}[GeV/c]}{\beta p}$$

$$\frac{\Delta p_\perp}{p_\perp} = 7.8\times10^{-4} p_\perp \oplus 1.8\times10^{-3}$$

$(7.8 \rightarrow 6.6 \text{ with cluster timing})$

$$\Delta\phi = 1.1\times10^{-4} \oplus \frac{6.9\times10^{-4}}{p}$$

$$\Delta\theta = 3.8\times10^{-4} \oplus \frac{6.9\times10^{-4}}{p}$$

TraPId: Tracking Performance

Expected Performance: Track parameters resolutions

n = 64, B = 1.5 T, R_{out} = 0.8 m, L = 2.0 m, (0.8+1.8)x10^{-3} X/X_0, σ_{xy} = 100 μm, σ_z = 0.8 mm

measurement	multiple scattering (gas + wires + inner wall)

$$\frac{\Delta p_\perp}{p_\perp} = 2.0\times10^{-3},\ \Delta\phi = 0.70\ mrad, \Delta\theta = 0.78\ mrad$$

$$\text{at } p = 1\ GeV/c$$

$$\frac{\Delta p_\perp}{p_\perp} = 7.8\times10^{-4}\, p_\perp \oplus 1.8\times10^{-3}$$

(7.8 → 6.6 with cluster timing)

$$\Delta\phi = 1.1\times10^{-4} \oplus \frac{6.9\times10^{-4}}{p}$$

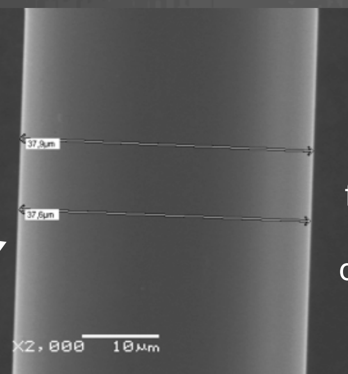
$$\Delta\theta = 3.8\times10^{-4} \oplus \frac{6.9\times10^{-4}}{p}$$

TraPId: A proposal for SCTF

$R_{in} – R_{out}$ [mm]		200 – 800
active L – service area [mm]		1800 – 200
inner cylindrical wall		
C-fiber/C-foam sandwich	2×80 µm / 5 mm	0.036 g/cm² – 8×10⁻⁴ X/X_0
outer cylindrical wall		
C-fiber/C-foam sandwich	2×5 mm / 10 mm	0.512 g/cm² – 1.2×10⁻² X/X_0
end plate		
gas envelope	160 µm C-fiber	0.021 g/cm² – 6×10⁻⁴ X/X_0
instrumented wire cage	wire PCB, spacers, HV distr. and cables, limiting R, decoupling C and signal cables	0.833 g/cm² – 3.0×10⁻² X/X_0

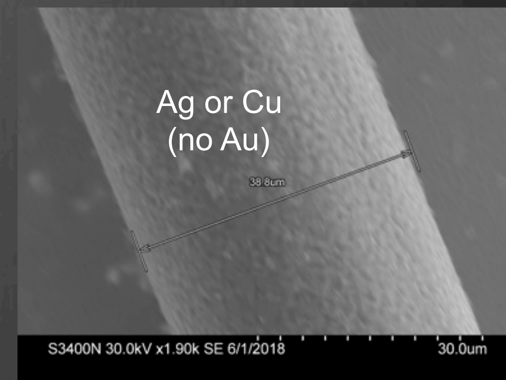
cell	
shape	square
size [mm]	7.265 – 9.135
layer	
8 super-layers	8 layer each
64 layer total	
stereo angles	66 – 220 mrad
n. sense wires [20µm W]	23,040
n. field wires [40/50µm Al]	116,640
n. total (incl. guard)	141,120
gas + wires [600 mm]	
90%He – 10%iC_4H_{10}	4.6×10⁻⁴
wires (W=53%, Al=47%)	**13.1×10⁻⁴**

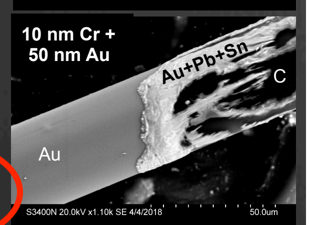
TraPId: Metal coated C wires?



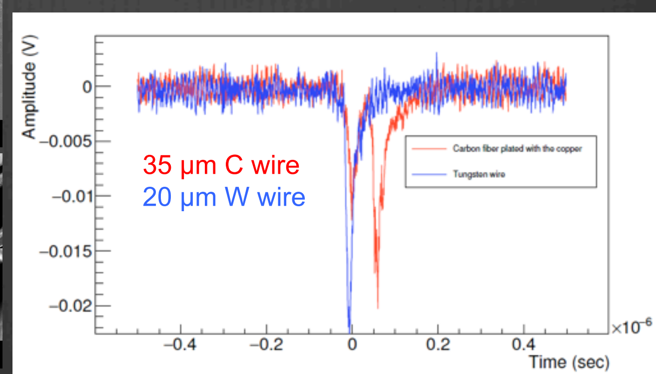
High-power impulse magnetron sputtering (HiPIMS)

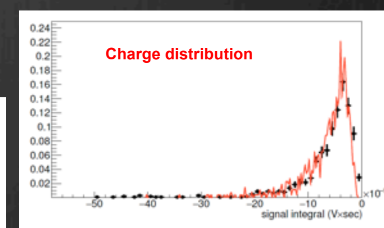
physical vapor deposition of thin films based on magnetron sputter deposition (extremely high power densities of the order of kW/cm^2 in short pulses of tens of µs at low duty cycle <10%)

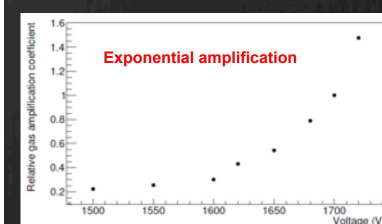




thanks to A. Popov - V. Logashenko, BINP







TraPId: A proposal for SCTF

$R_{in} - R_{out}$ [mm]		200 – 800
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gas envelope	160 µm C-fiber	0.021 g/cm^2 – 6×10^{-4} X/X_0
instrumented wire cage	wire PCB, spacers, HV distr. and cables, limiting R, decoupling C and signal cables	0.833 g/cm^2 – 3.0×10^{-2} X/X_0

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shape	square
size [mm]	7.265 – 9.135
layer	
8 super-layers	8 layer each
64 layer total	
stereo angles	66 – 220 mrad
n. sense wires [20µm W]	23,040
n. field wires [40/50µm Al]	116,640
n. total (incl. guard)	141,120
gas + wires [600 mm]	
90%He – 10%iC_4H_{10}	4.6×10^{-4}
W + 5 Al → Ti + 5 C	**(13.1 → 2.5)×10^{-4}**

TraPId: Tracking Performance

Expected Performance: Track parameters resolutions

n = 64, B = 1.5 T, R_{out} = 0.8 m, L = 2.0 m, (0.8+0.7)x10^{-3} X/X_0, σ_{xy} = 100 µm, σ_z = 0.8 mm

measurement	multiple scattering (gas + wires + inner wall)

$$\frac{\Delta p_\perp}{p_\perp} = 1.6\times10^{-3},\ \Delta\phi = 0.54\ mrad,\ \Delta\theta = 0.65\ mrad$$

at $p = 1\ GeV/c$

$$\frac{\Delta p_\perp}{p_\perp} = 7.8\times10^{-4}\, p_\perp \oplus 1.4\times10^{-3}$$

(7.8 → 6.6 with cluster timing)

$$\Delta\phi = 1.1\times10^{-4} \oplus \frac{5.3\times10^{-4}}{p}$$

$$\Delta\theta = 3.8\times10^{-4} \oplus \frac{5.3\times10^{-4}}{p}$$

TraPId: PId Performance

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

from *Walenta parameterization (1980)*

$L_{track} = 0.6\ m$
$P = 1\ atm$
$n = 64$

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 8.1\%$$

6.9% for $L_{track} = 1\ m$

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2}$$

from *Poisson distribution*

$L_{track} = 0.6\ m$
$\delta_{cl} = 12.5/cm$

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = 3.6\%$$

2.8% for $L_{track} = 1\ m$

Summary of performance

	$\frac{\Delta p_t}{p_t} \times 10^3$	at $p_t = 1 GeV$	$\frac{dE}{dx} \Big/ \frac{dN}{dx}$	
KLOE	$0.5 p_t \oplus 2.6$	2.6×10^{-3}	5%	
BaBar	$1.3 p_t \oplus 4.5$	4.7×10^{-3}	7.5%	
Belle	$2.8 p_t \oplus 3.5$	4.5×10^{-3}	6.9%	
BelleII	$1.9 p_t \oplus 2.9$	3.5×10^{-3}	6.4%	
BESIII	$2.7 p_t \oplus 4.7$	5.1×10^{-3}	$6-7\%$	
Cleo3	$1.0 p_t \oplus 9.0$	9.1×10^{-3}	5%	
SCTF (Todyshev)	$2.6 p_t \oplus 5.1$	5.7×10^{-3}	7%	
TraPId (this proposal)	$0.78 p_t \oplus 1.8$	2.0×10^{-3}	3.6%	with cluster counting (dE/dx = 8.1%)
TraPId (this proposal)	$0.66 p_t \oplus 1.4$	1.6×10^{-3}	2.8%	with cluster timing and Ti + C wires 1 m track length - (dE/dx = 6.9%)

CONCLUSIONS

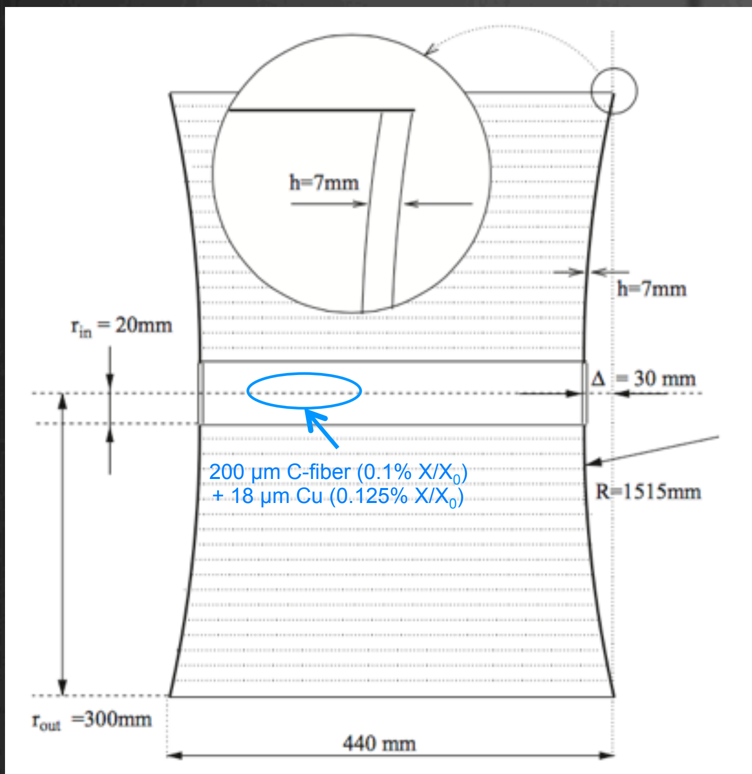
I. **An ultra-low mass drift chamber for SCTF** with a material budget **$<1.5\times10^{-2}$ X/X_0** in the radial direction and **$<5\times10^{-2}$ X/X_0** in the forward and backward directions (including HV and FEE services) **can be built today** with the novel technique adopted for the successful construction of the MEG2 drift chamber

II. **$\Delta p_t/p_t = 2.0\times10^{-3}$, $\Delta\theta = 0.70$ mrad, $\Delta\phi = 0.78$ mrad at $p = 1$ GeV/c.**

III. Particle identification at the level of **3.6%** with **cluster counting** allowing for **π/K separation $\geq 3\sigma$** over a wide range of momenta.

IV. Further gain (**>25%**) in momentum and angular resolutions can be obtained by
- applying **cluster timing** techniques,
- exploiting the possibilities of large scale production of **metal coated C wires,**
- **operating the chamber at lower pressures**, with moderate degradation of PId performance

Support slides



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Drift chamber for the CMD-3 detector

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CMD-3	$(4.3p_t \oplus 1.2)\times10^{-2}$	45×10^{-3}	10-13%
CMD-3 TraPId proposal	$(0.9p_t \oplus 0.33)\times10^{-2}$	9.6×10^{-3}	5.8%