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INFN
Istituto Nazionale di Fisica Nucleare

The ultralight drift chamber for the Super Charm Tau Factory

F. Cuna on behalf of Cremlin+ INFN Bari and Lecce groups

Workshop on future Super c-tau factories
15-17 November 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

Outline

1. Design of SCTF drift chamber
2. R&D within Cremlin+:
   - CMD3 drift chamber as prototype for SCTF drift chamber
   - Development of a new type of field and sense wires
3. Cluster counting
   - Simulation of cluster counting technique
   - Test beam

TraPId

TraPId (Tracking and Particle Identification), the Central Tracker proposed by the Bari and Lecce INFN groups for the detector at SCTF, is an **ultra-light** drift chamber equipped **with cluster counting/timing readout techniques.**

Main peculiarities are the:

- **high transparency** in terms of multiple scattering contribution to the momentum measurement of charged particles
- **very precise particle identification capabilities**

Steps towards the development:

- Construction and operation of the KLOE ancestor chamber at INFN LNF Dafne φ factory
- Design studies of the CluCou Chamber proposed for the 4th-Concept at ILC (2009)
- Design studies of the I-tracker chamber proposed for the Mu2e experiment at Fermilab
- Design and construction of the DCH for the MEG upgrade at PSI
- Design studies of the IDEA drift chamber proposal for FCC-ee and CEPC
- Design of the drift chamber of the CMD3

Tip and tricks

From KLOE

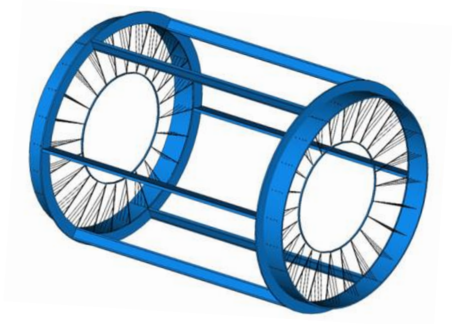
- Wire configuration fully stereo (no axial layers)
- Light Aluminum wires
- Very light gas mixture 90% He -10% iC_4H_{10}
- Mechanical structure entirely in Carbon Fiber
- Largest volume drift chamber ever built (45 m^3)

To SCTF

- New concept for wire tension compensation
- Larger number of thinner and lighter wires
- No feed-through
- Gas containment from wire support functions separation
- Cluster timing for improved spatial resolution
- Cluster counting for particle identification

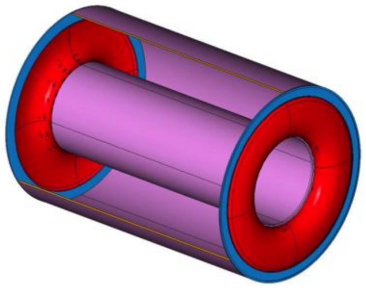
The MEG2 drift chamber

- Separation of the wire anchoring function from the mechanical and wire containment



Wire support

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



Gas containment

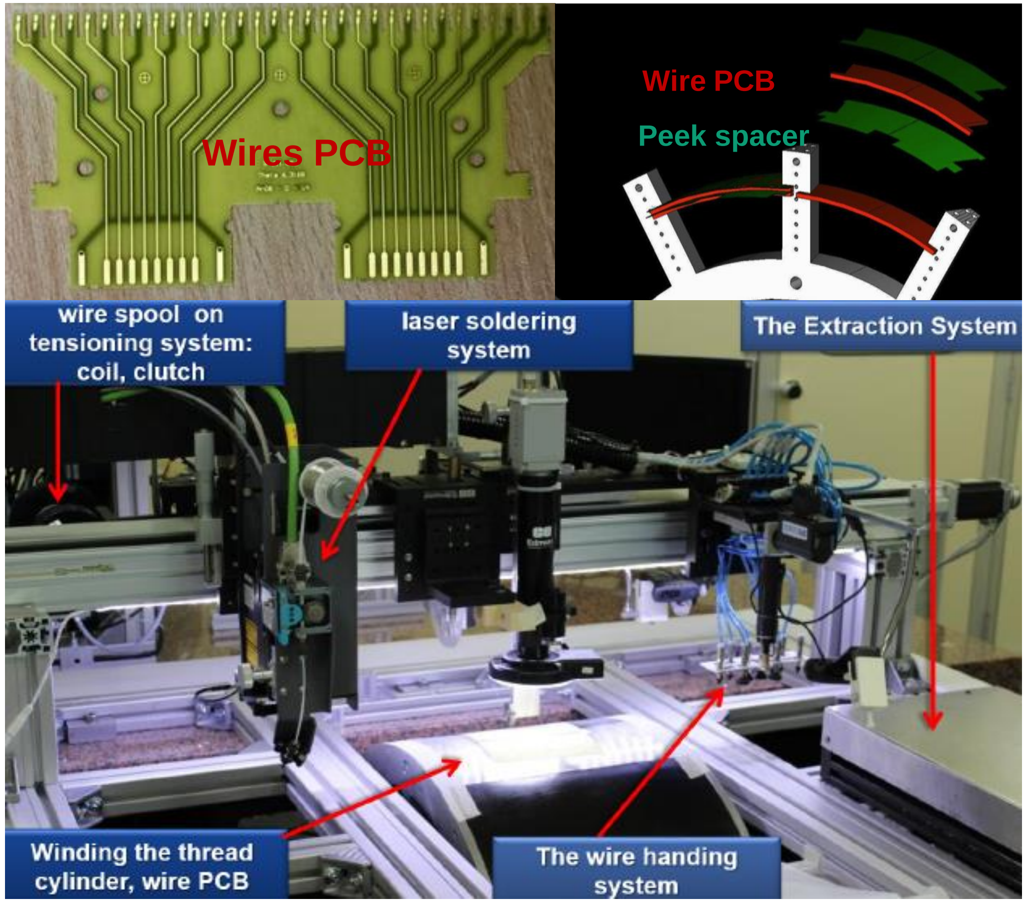
Gas envelope can freely deform without affecting the internal wire position and tension.

- Wire PCB

The high wires density (12 wires/cm^2) imposes the use of ***wires PCBs*** where the wires are accurately positioned and strung at the correct mechanical tension.

- Wiring robot

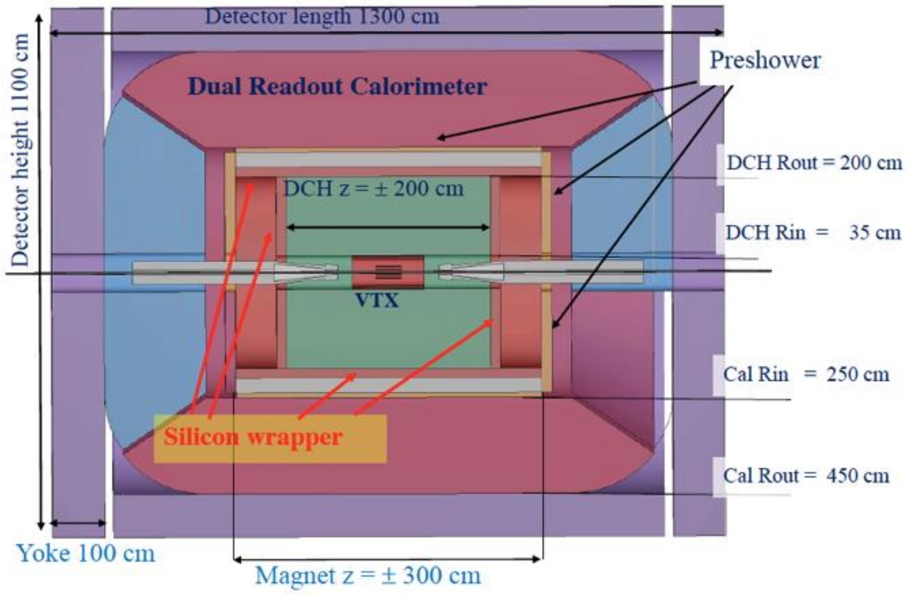
Stringent requirements on the precision of wire position and on the uniformity of the wire mechanical tension impose the use of an automatic system (Wiring Robot), to operate the wiring procedures.

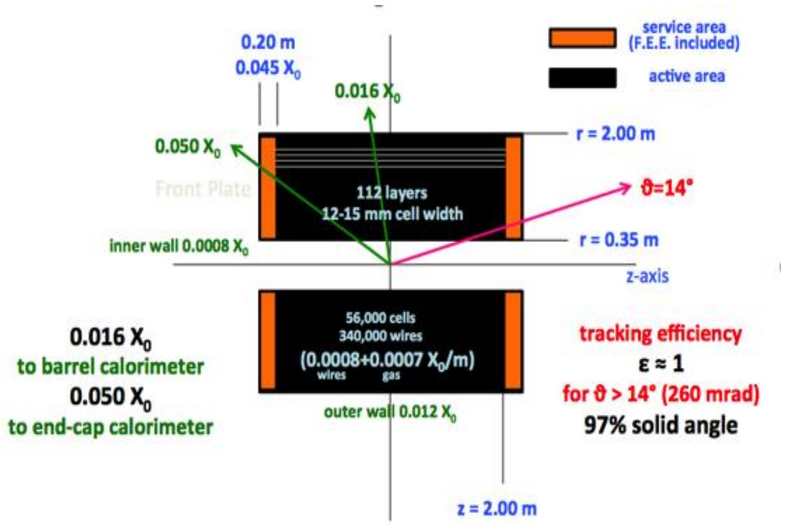


The IDEA drift chamber for FCC-ee and CEPC

The IDEA Central Drift Chamber (DCH) is a unique-volume, high granularity, fully stereo, low-mass cylindrical drift chamber, co-axial with the 2 T solenoid field, operating with a helium based gas mixture.

It extends from an inner radius R_{in} = 0.35 m to an outer radius R_{out} = 2 m, for a length L = 4 m and consists of 112 co-axial layers, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors, a layout similar to the one used in MEG II drift chamber.





# 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

	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

An ultra-low mass Tracking Chamber with Particle Identification capabilities for SCTF at BINP. F.Grancagnolo at Workshon on future tau-charm factory, December, 4-7 ,2018

The proposal for SCTF drift chamber

Ultra low mass DC with rectangular cell, 64 stereo layers, total number of very thin wires is about 100000 and gas mixture He and iC_4H_{10} (90/10).
Basic idea: decrease as much as possible the impact to momentum resolution from Coulomb multiple scattering of particles in materials of the chamber.

$R_{in} – R_{out}$ [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/cm^2 – **8×10^{-4} X/X$_0$**
outer cylindrical wall		
C-fiber/C-foam sandwich	2×5 mm / 10 mm	0.512 g/cm^2 – **1.2×10^{-2} X/X$_0$**
end plate		
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$_0$**

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} X/X$_0$**
wires (W=53%, Al=47%)	**13.1×10^{-4}X/X$_0$**

- Field to sense ratio 5:1
  - more field wires implies better E-field isotropy and smaller E×B asymmetries
- Thinner field wires:
  - less multiple scattering
  - less tension on end plates

Spatial resolution

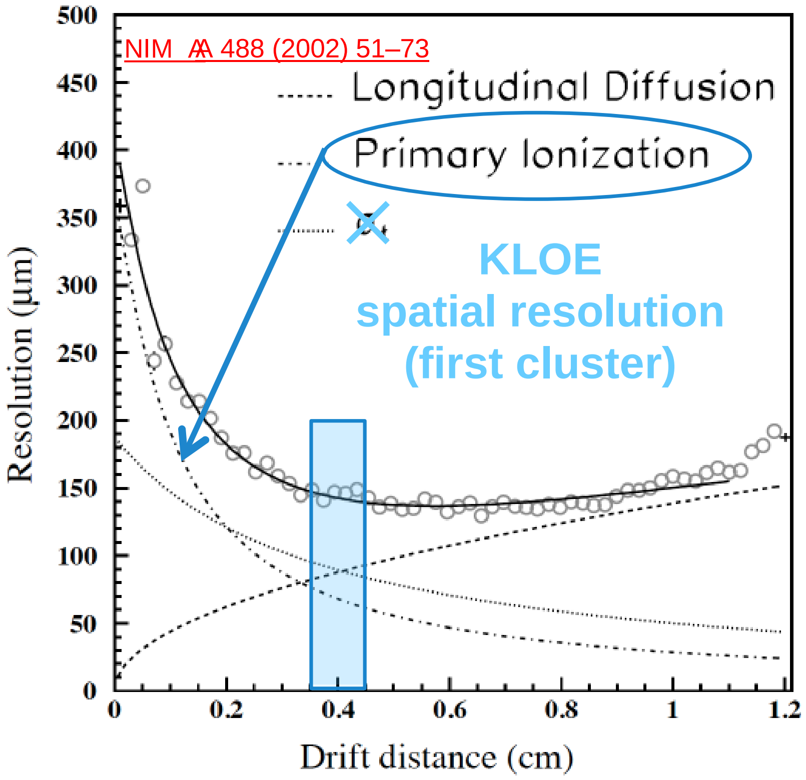
Spatial resolution depends on the longitudinal diffusion, primary ionization and electronics.
The primary ionization contribution can be modelled as

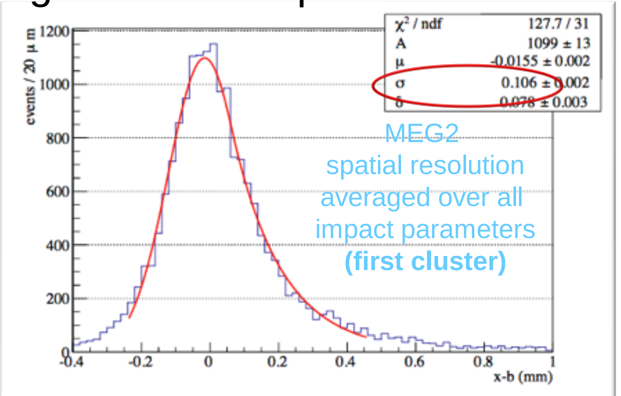
$$\sigma_d = \sigma_0 + \alpha / N$$

→ Number of clusters

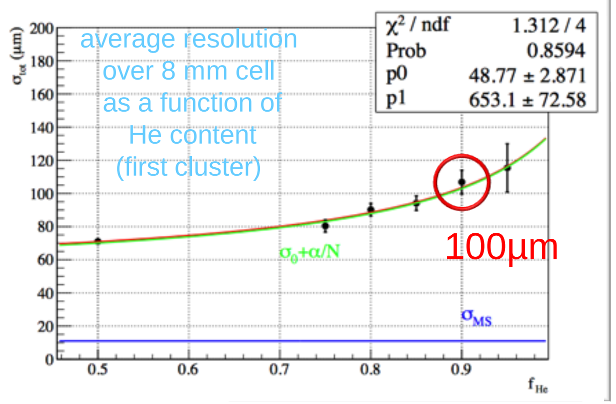
Free parameters

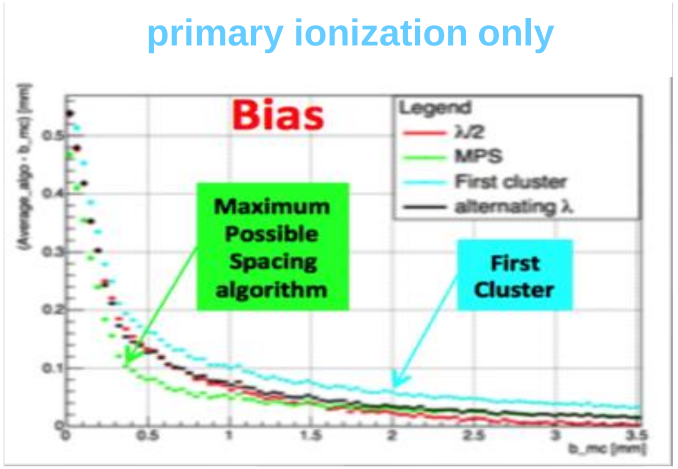
The contribution from multiple scattering is added in quadrature





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

Tracking performance

Track parameters resolutions

Number of layers = 64, B = 1.5 T, R_{out} = 0.8 m, L = 2.0 m, σ_{xy} = 100 µm, σ_z = 0.8 mm

measurement

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

$$\Delta\varphi_0 = \frac{4\sqrt{3}\sigma}{R_{out}\sqrt{N}} = 1.1\times10^{-4}$$

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

multiple scattering (gas + wires + inner wall)

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

$$\Delta\varphi_0 = \frac{13.6\times10^{-3}[GeV/c]}{\beta p}\sqrt{\frac{L}{X_0}} = \frac{6.9\times10^{-4}[GeV/c]}{\beta p}$$

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

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

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

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

With cluster timing 7.8 → 6.6

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

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

Using wires of Titanium+ Carbonium

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

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

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

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

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

Particle identification 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*

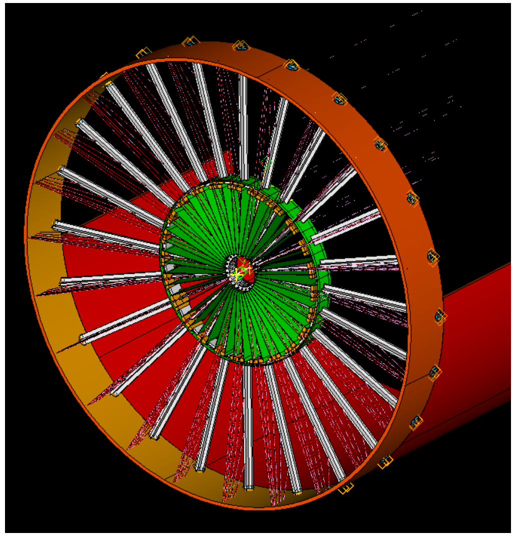
L_{track} = 0.6 m
δ_{cl} = 12.5/cm

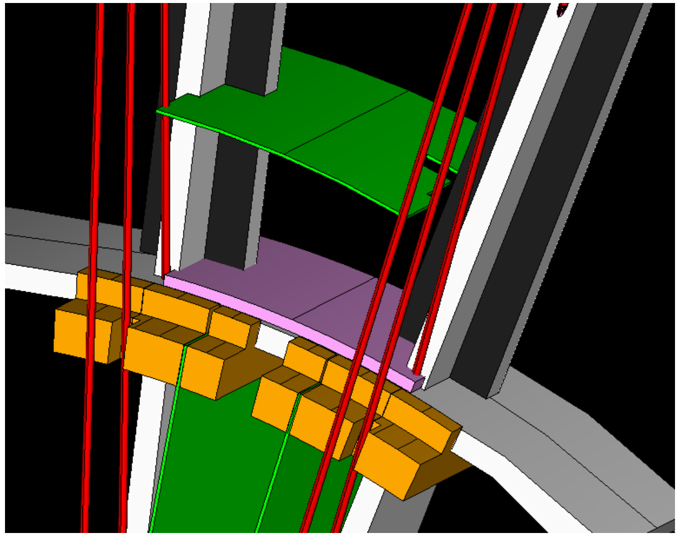
$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = 3.6\%$$

2.8% for L_{track} = 1 m

	$\frac{\Delta p_t}{p_t} \times 10^3$	at $p_t = 1GeV$	$\frac{dE}{dx} / \frac{dN}{dx}$	
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%)

R&D within Cremlin+ : CMD3, the SCTF drift chamber prototype





The mechanical design for CMD3 drift chamber has been developed traying to combine two main goals:

- the high transparency
- the mechanical stability of the whole structure

Simulations of mechanical tension recovery

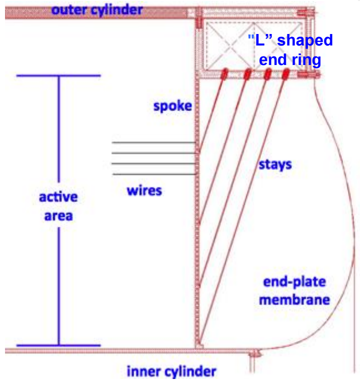
Three stays loaded with:

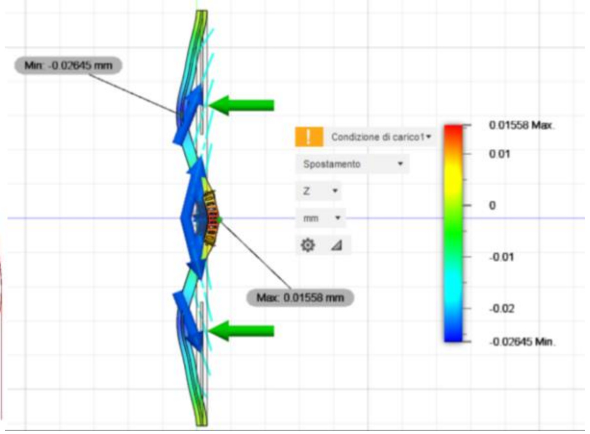
- 145 N at ≈10°
- 240 N at ≈14°
- 200 N at ≈21°

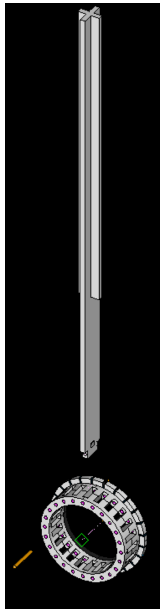
max deflection obtained < ±25 μm

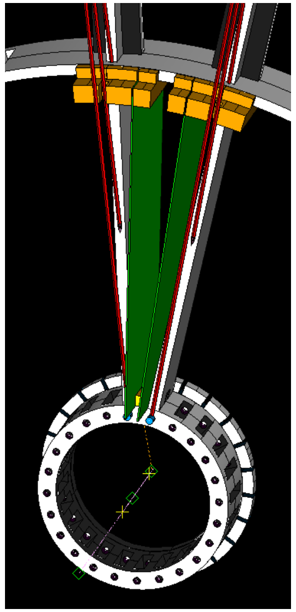
The simulations prove the feasibility of the project.

Optimization in progress .





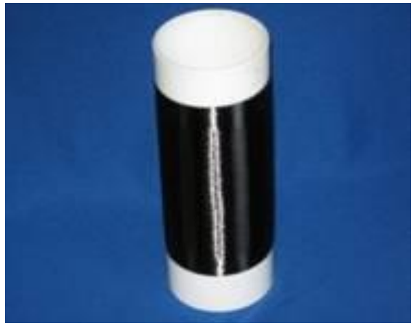




Talk at CREMLINplus WP5 General Meeting:
Task 5.5-Drift Chamber Prototyping, 28-29 September 2020

Talk at CREMLINplus WP5 General Meeting:
Task 5.5-Drift Chamber Prototyping, 17-18 February 2021

Development of a new type of field and sense wires



SPECIALTY MATERIALS, INC.
Manufacturers of Boron and SCS Silicon Carbide Fibers and Boron Nanopowder
CARBON MONOFILAMENT

TYPICAL PROPERTIES

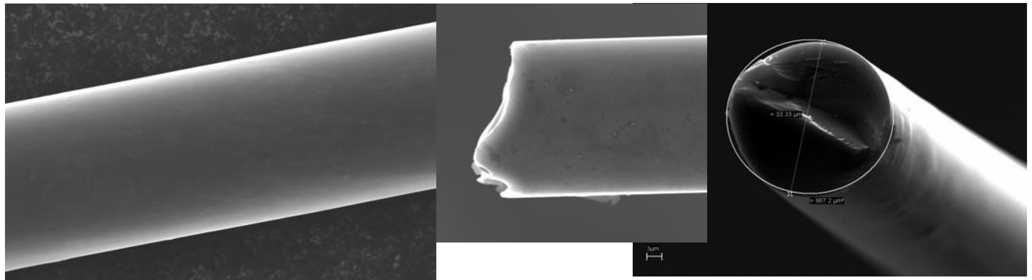
Diameter:	0.00136 +/- 0.0001" (34.5 +/- 2.5 µm)
Tensile Strength:	125 ksi (0.86 GPa)
Tensile Modulus:	6 msi (41.5 GPa)
Electrical Resistivity:	3.6 x 10^{-3} ohm cm
Density:	1.8 g/cc

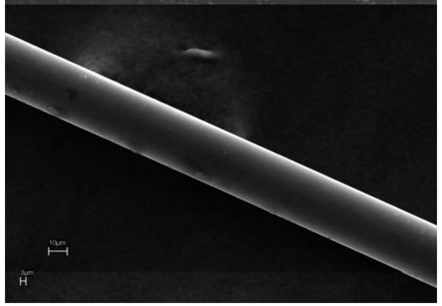
Specialty Materials, Inc.
1449 Middlesex Street
Lowell, Massachusetts 01851

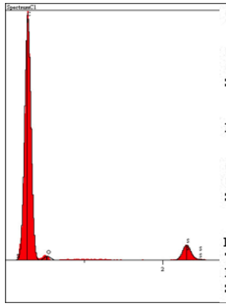
Phone: 978-322-1900
Fax: 978-322-1970

CARBON MONOFILAMENT PRODUCT PRICE LIST
Effective October 1, 2017

Product	Quantity	Price LF
CARBON MONOFILAMENT	1 Million LF	$0.02
	500,000 LF	$0.03
	1,000 LF	$0.93



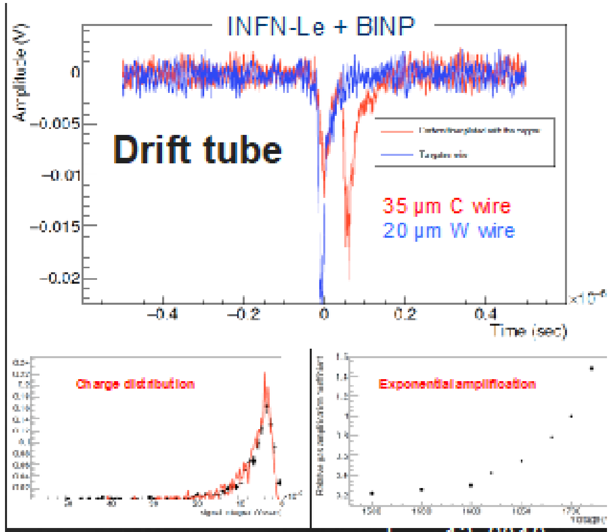




Component	Type	Mole Conc.	Conc.		
O	Calc	5.592	7.248	wt.%	
C	Calc	93.865	91.340	wt.%	
S	Calc	0.543	1.412	wt.%	
		100.000	100.000	wt.%	Total

Elt.	Line	Atomic %	Conc		
C	Ka	93.865	91.340	wt.%	
O	Ka	5.592	7.248	wt.%	
S	Ka	0.543	1.412	wt.%	
		100.000	100.000	wt.%	Total

kV	20.0
Takeoff Angle	35.0°
Esc	On
Sum Peak	On



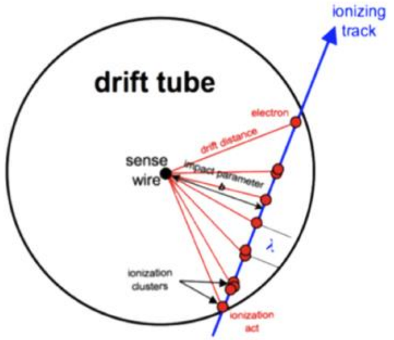
- 40 µm and 50 µm "bare" (uncoated) Al5056 as new solution for field wires, to be coated by BINP magnetron.
- 35 µm Carbon monofilament, to be coated by BINP magnetron, to be used either as field.
- small single cell drift chamber prototypes are being designed to test operatively new wire proposals.
- 10 µm and 15 µm Molybdenum wires as sense wires (instead of Tungsten) to be used in conjunction with 35 µm Carbon as field.

Cluster counting for particle identification

Using the information about energy deposit by a track in a gaseous detector, particle identification can be performed.
The large and inherent uncertainties in total energy deposition represent a limit to the particle separation capabilities.

Cluster counting technique can improve the particle separation capabilities.

The method consists in singling out, in ever recorded detector signal, the isolated structures related to the arrival on the anode wire of the electrons belonging to a single ionization act (dN/dx).



dE/dx

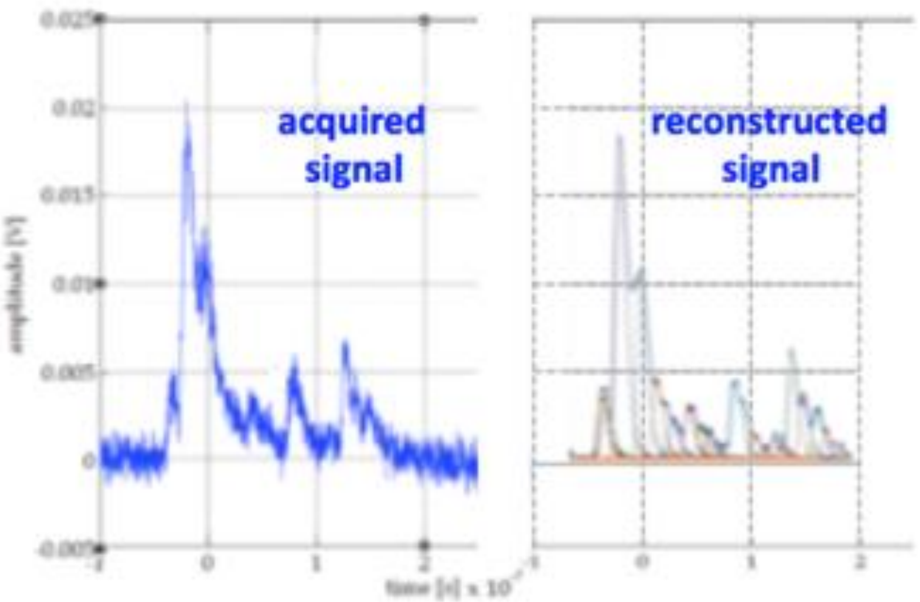
Truncated mean cut (70-80%) reduces the amount of collected information
n ≈ 100 and a 2m track at 1 atm give

σ ≈ 4.3%

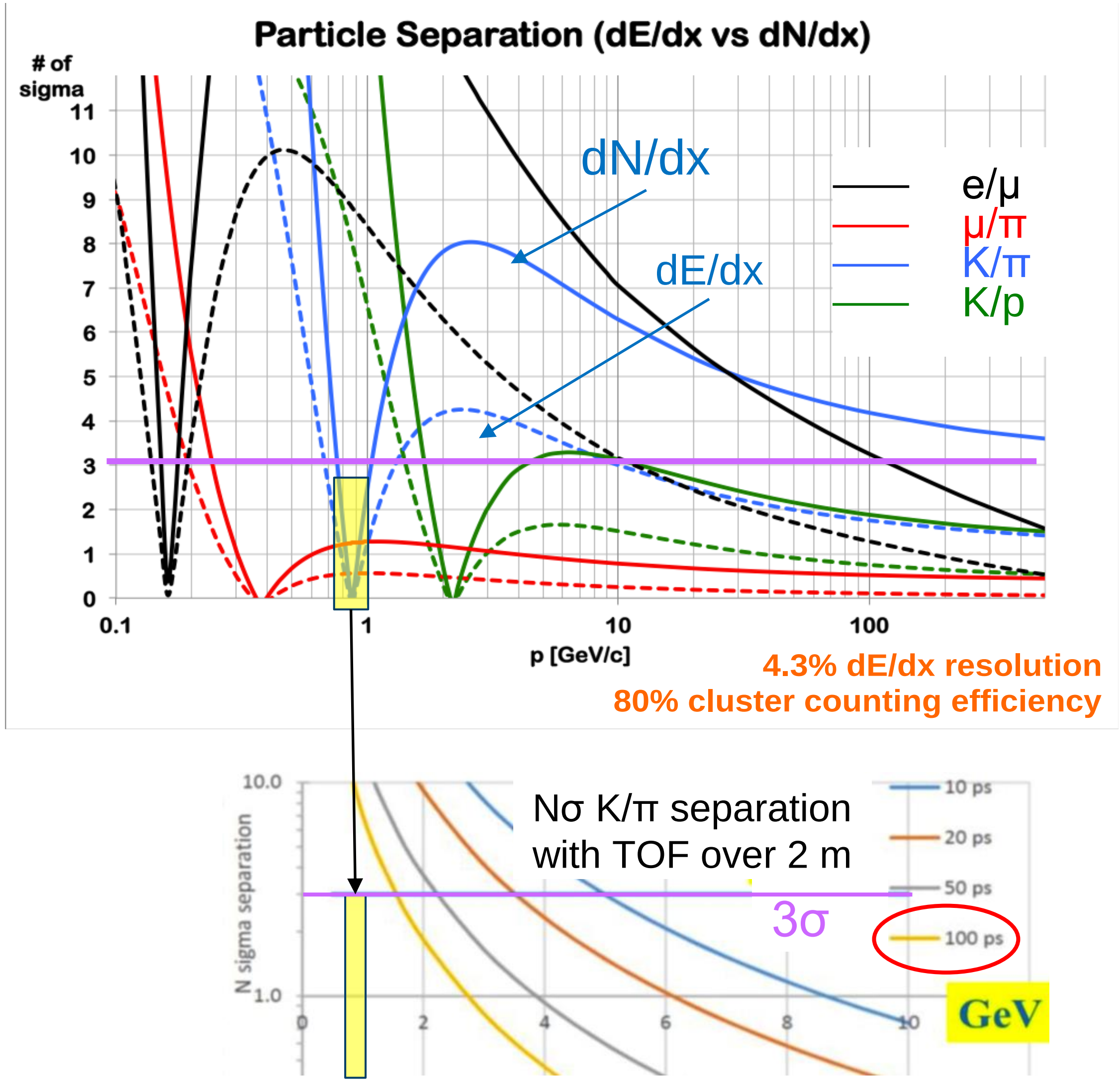
dN_{cl}/dx

δ_{cl} = 12.5/cm for He/iC_4H_{10}=90/10 and a 2m track give

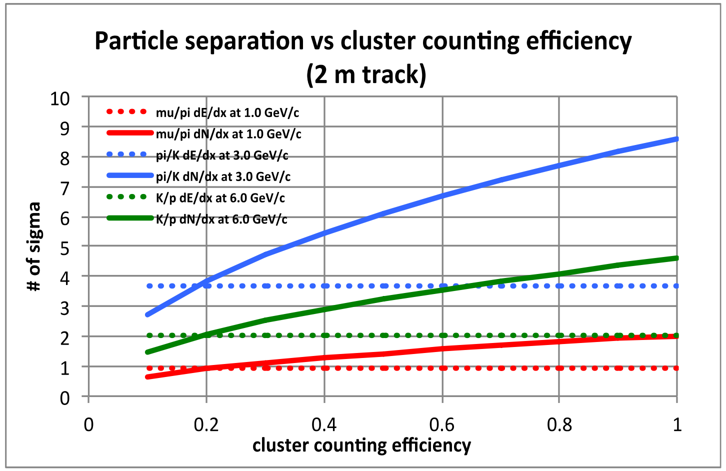
σ ≈ 2.0%



Cluster counting for particle identification: expected performance



- 80% cluster counting efficiency.
- Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)
- Could recover with timing layer



Analytic evaluation, prof F.Grancagnolo
To be checked with test beam and simulations

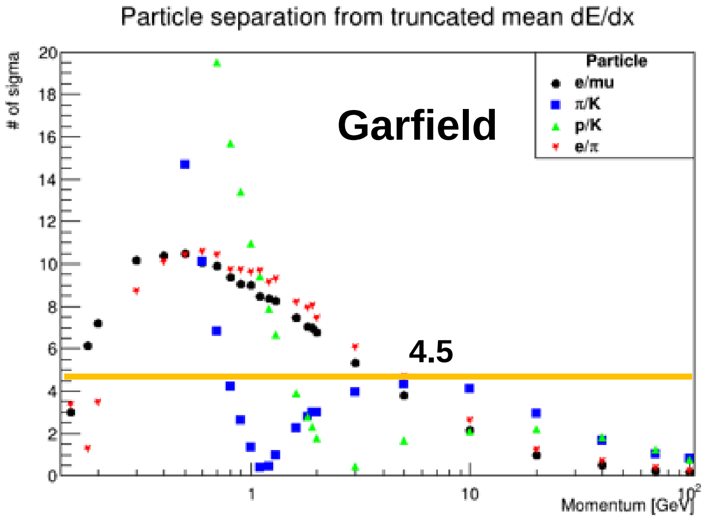
Cluster counting for particle identification: simulation results

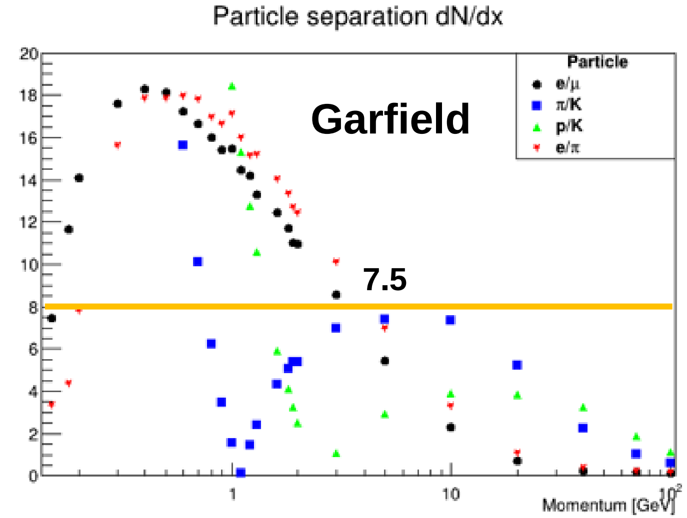
A simulation of the ionization process in 1 cm long side cell of 90% He and 10% iC_4H_{10} has been performed in **Garfield++** and **Geant4**.

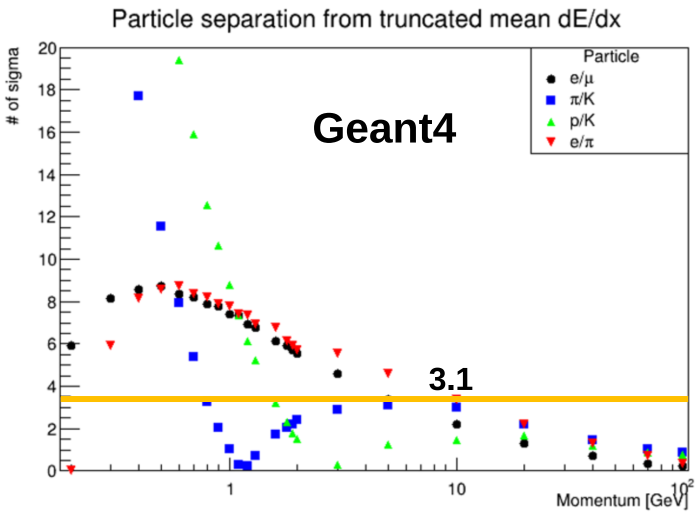
Geant4 software can simulate in details a full-scale detector, but the fundamental properties and the performances of the sensible elements have to be parameterized or an “ad hoc” physics model has to be implemented.

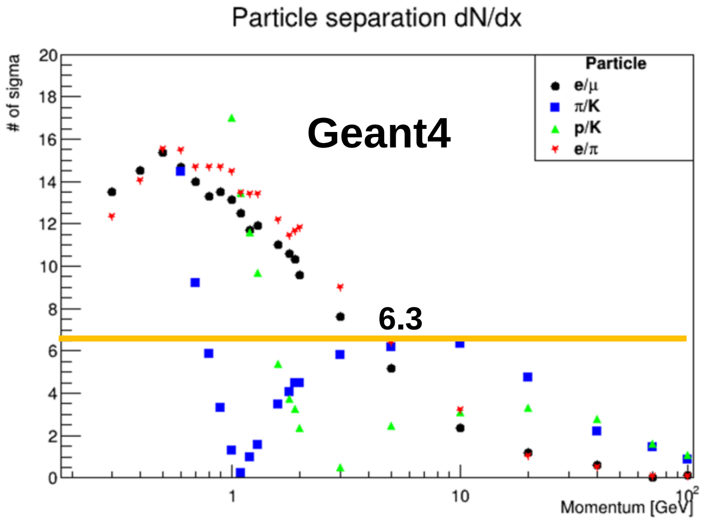
Three different algorithms have been implemented to simulate in Geant4*, in a fast and convenient way*, the number of clusters and clusters size distributions, using the energy deposit provided by Geant4.

The simulations confirm the prediction!
But…





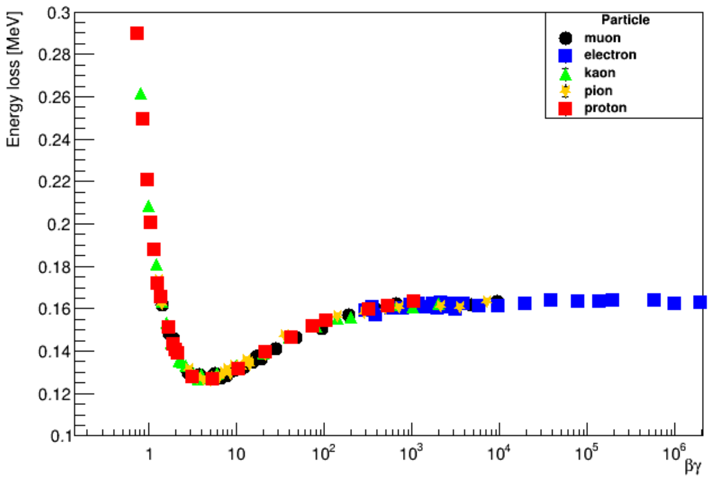


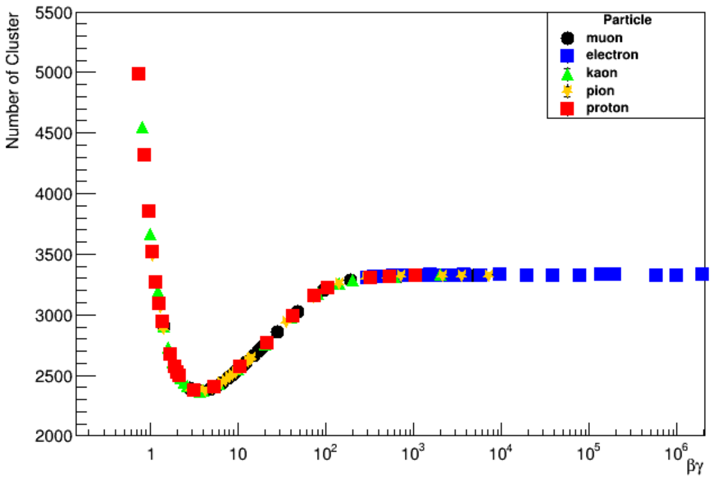


We are assuming a cluster counting efficiency of 100%.

Cluster counting for particle identification: TEST BEAM

- Lack of experimental data on cluster density and cluster population for He based gas, particularly in the relativistic rise region to compare predictions.
- Despite the fact that the Heed model in GEANT4 reproduces reasonably well the Heed predictions, why particle separation, both with dE/dx and with dNcl/dx, in GEANT4 is considerably worse than in Heed?
- Despite a higher value of the dNcl/dx Fermi plateau with respect to dE/dx, why this is reached at lower values of βγ with a steeper slope?





These questions are crucial for establishing the particle identification performance at FCCee, CEPC and **SCTF**

The only way to ascertain these issues is an experimental measurement!

Cluster counting for particle identification: TEST BEAM

Goals

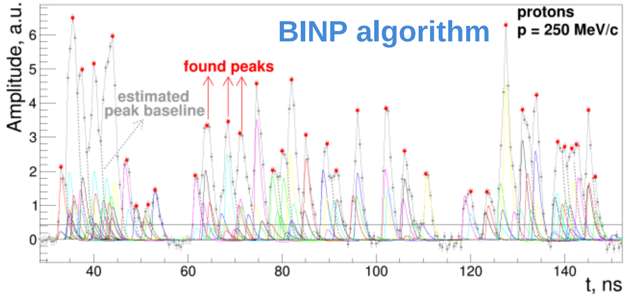
- **Demonstrate the ability to count clusters:**

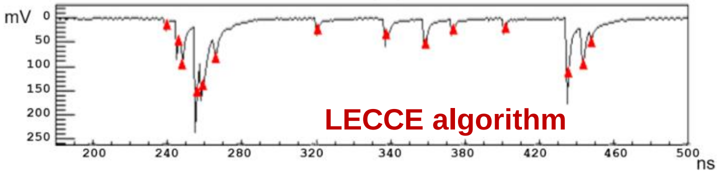
  at a fixed βγ (e.g. muons at a fixed momentum) count the clusters by changing

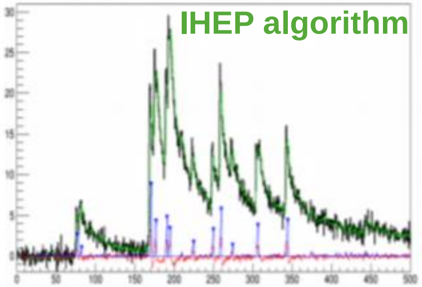
  - **the cell size (1 – 3 cm)**
  - **the track angle (1- 6 cm)**
  - **the gas mixture (90/10: 12 cl/cm, 80/20: 20 cl/cm)**

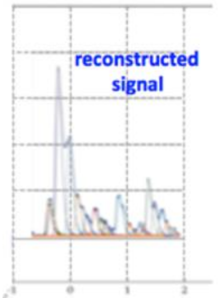
- **Establish the limiting parameters for an efficient cluster counting:**

  - **cluster density as a function of impact parameter**
  - **space charge (by changing gas gain, sense wire diameter, track angle)**
  - **gas gain stability**



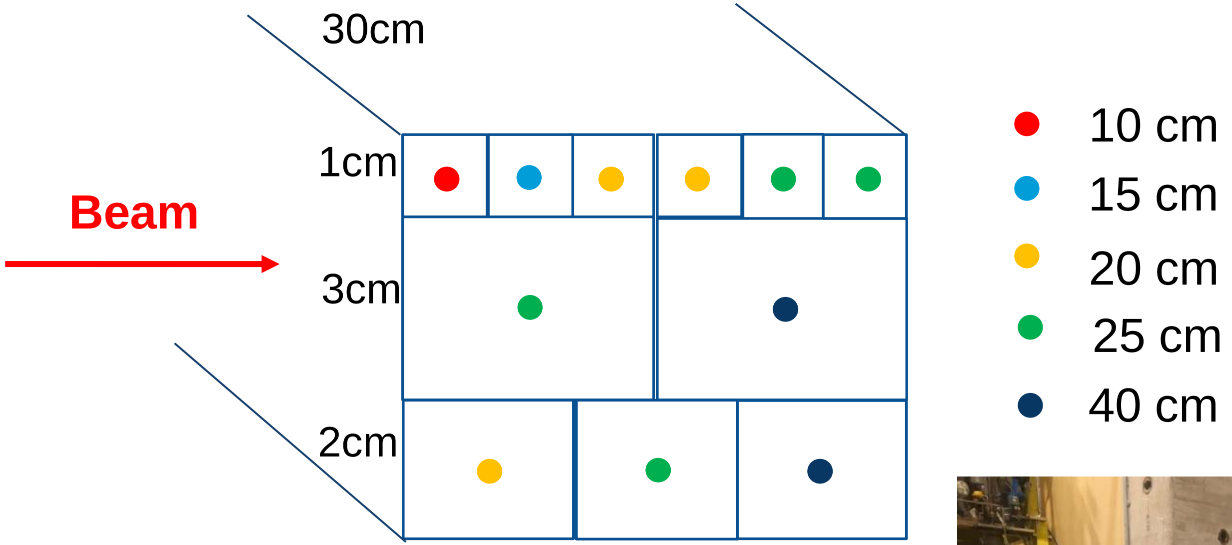






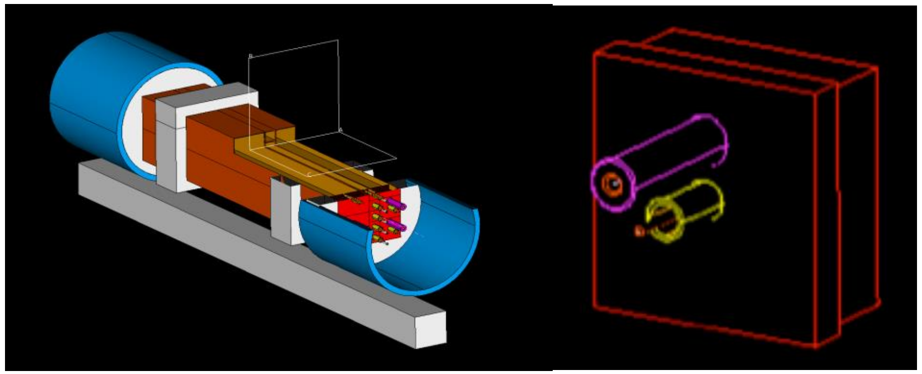
- In optimal configuration, measure the relativistic rise as a function of βγ, both in dE/dx and in dNcl/dx, by scanning the muon momentum from the lowest to the highest value (from a few GeV/c to about 250 GeV/c at CERN/H8).
- Use the experimental results to fine tune the predictions on performance of cluster counting for flavor physics and for jet flavor tagging both in fast and in full simulation.

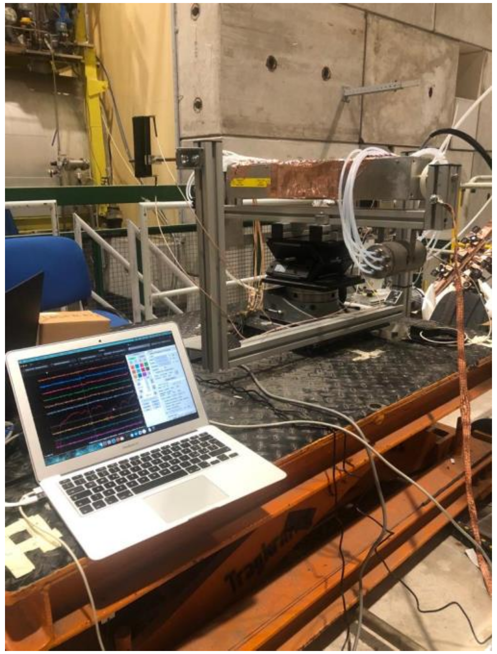
Cluster counting for particle identification: TEST BEAM
Set up

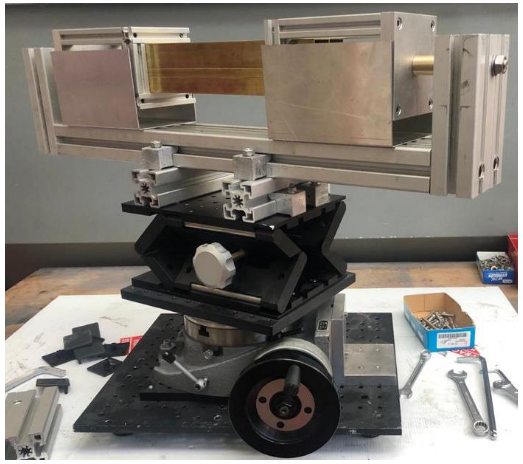


The set up consists of:

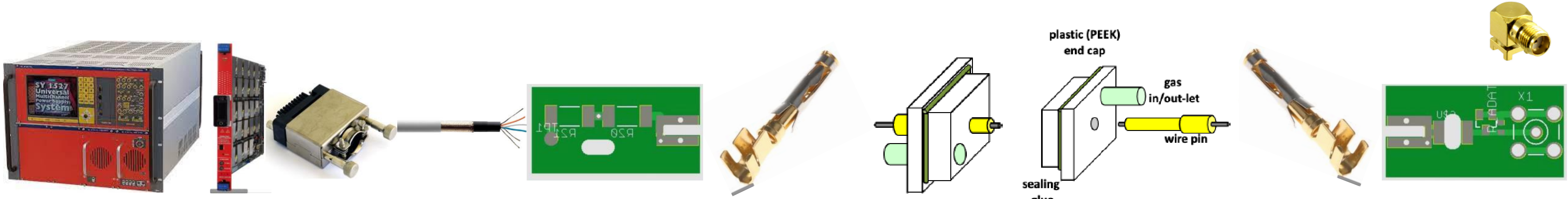
- **6 drift tubes 1 cm × 1 cm × 30 cm**
  - **1 with 10 μm sense wire, 1 with 15, 2 with 20 μm, 2 with 25 μm**
- **3 drift tubes 2 cm × 2 cm × 30 cm**
  - **1 with 20 μm sense wire, 1 with 25 μm, 1 with 30 μm**
- **2 drift tubes 3 cm × 3 cm × 30 cm**
  - **1 with 20 μm sense wire, 1 with 30 μm**
- DRS for data acquisition
- Gas mixing, control and distribution (only He and iC_4H_{10})
- 2 trigger scintillators







Connecting scheme



SY 1527 Mainframe — 1535P 24ch — CAEN A996 Radiall 691803004 — 24 leads HV cable — HV distribution board — connecting pin — drift tube end cap — connecting pin — HV decoupling board

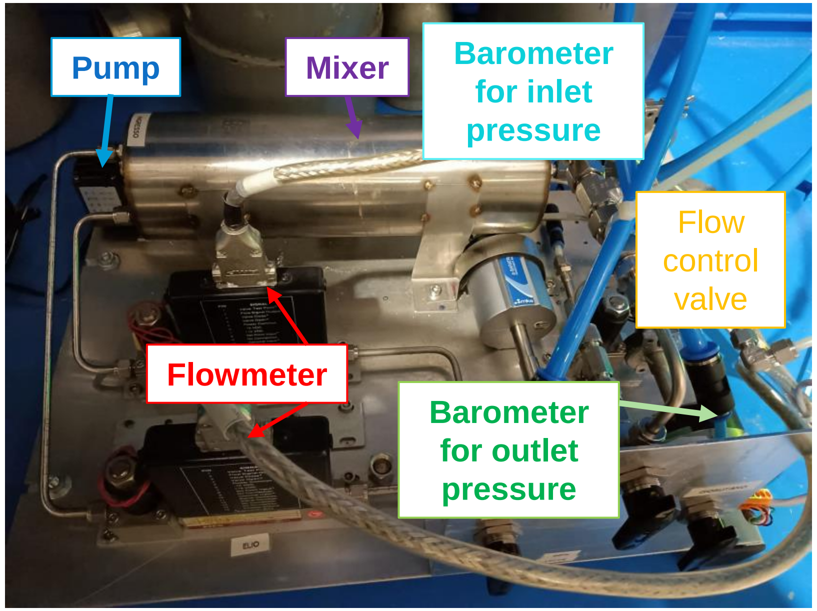
Trigger scintillator

Two scintillator tiles (12 cm x 4 cm), placed upstream and downstream of the drift tubes pack, instrumented with SiPM.

Portable gas system

The gas system :

- sets the needed gas mixture
- checks the gas pressure at the entrance and at the exit of the tubes
- maintains constant the gas pressure inside the tubes, by using a proportional valve and a pump.



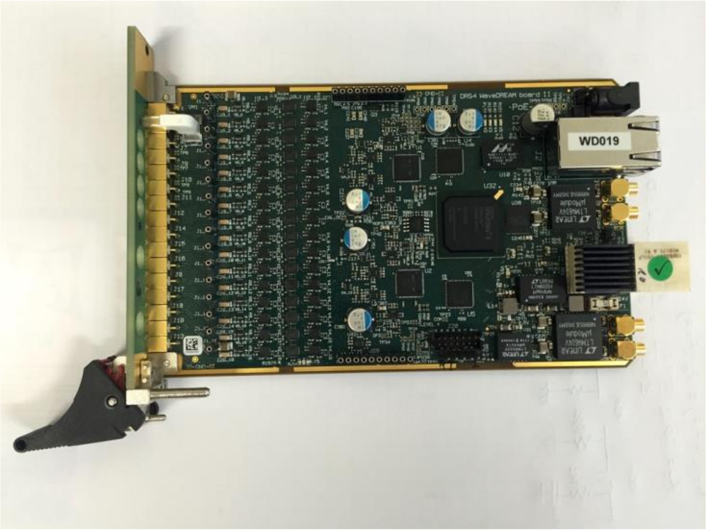
Data acquisition system: DRS

Data acquisition has been driven by the **DRS**.

Analog switched capacitor array: analog memory with a depth of 1024 sampling cells developed at PSI, perform a “**sliding window**” sampling.

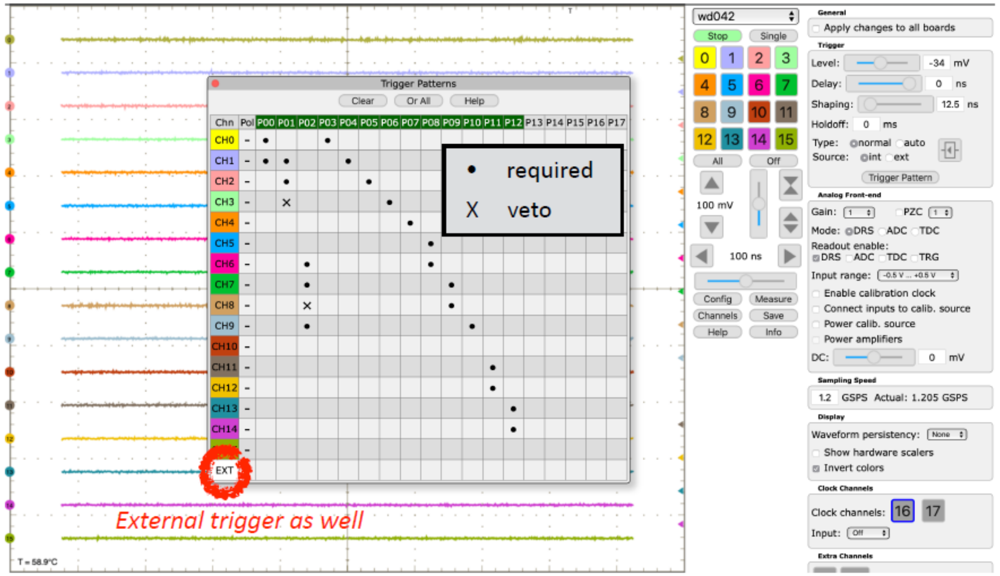
500MSPS ↔ 5GSPS sampling speed with 11.5 bit signal-noise ratio
8 analog channels + 1 clock-dedicated channel for sub 50ps time alignment

Selectable frontend **gain**



Server software using Mongoose C/C++ Framework
Easy low level calls for fast DAQ operations
Single executable with no need of dedicated http server

DRS interface is similar to the interface of an oscilloscope with 16 channels



DRS: Examples event screen

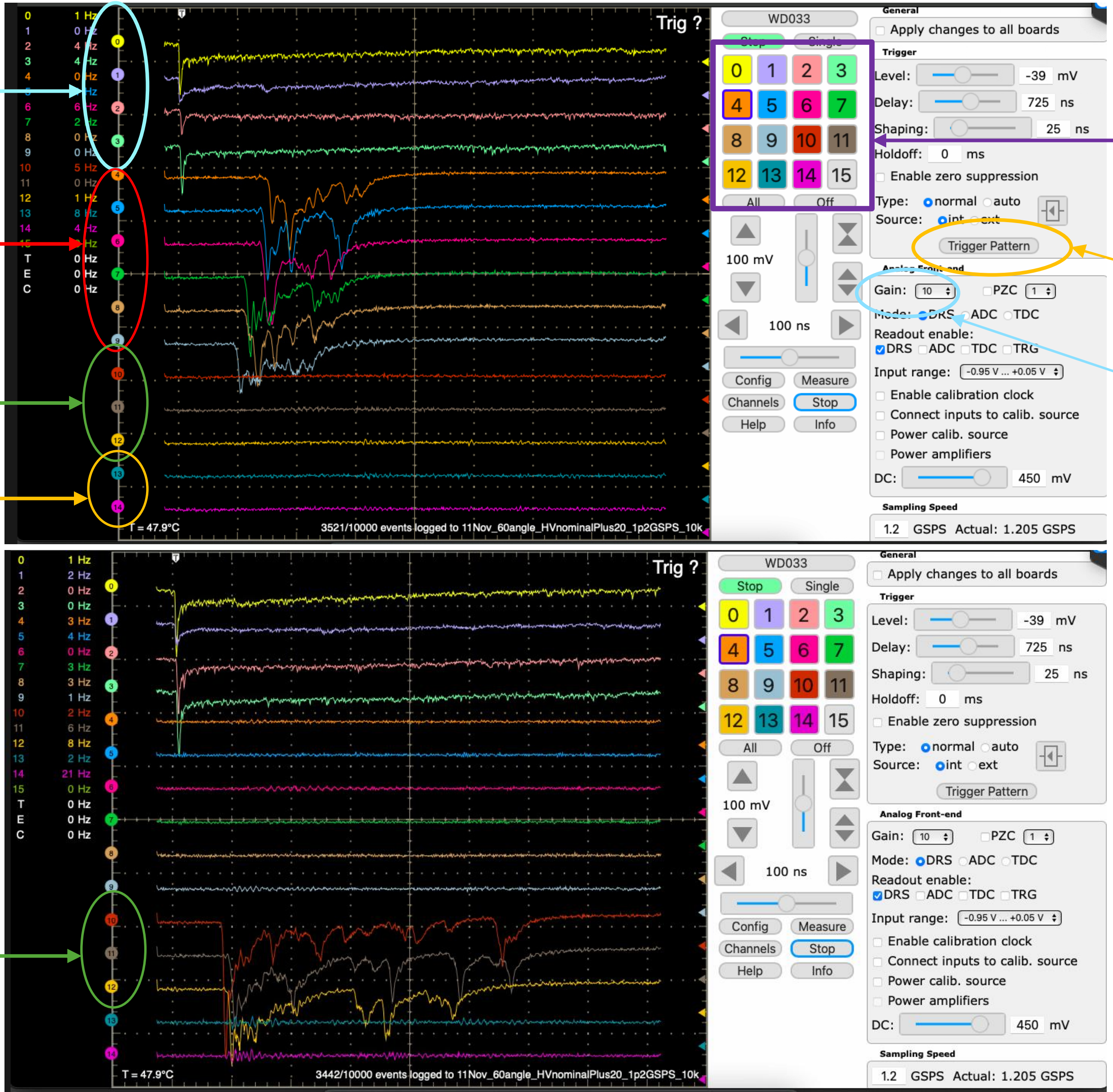
4 trigger channels

6 tubes 1 cm cell size with typical event

3 tubes 2 cm cell size

2 tubes 3 cm cell size

typical event



Channel selection panel

Trigger selection pattern

Gain selection

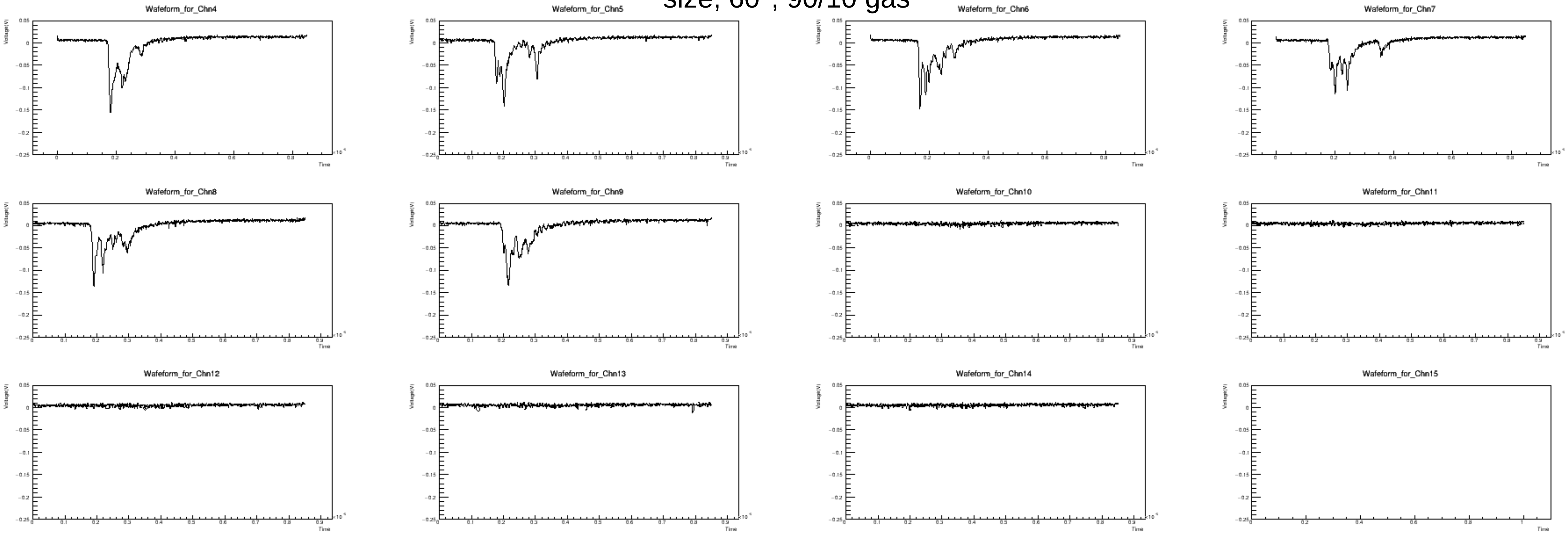
Each data file has been saved in binary format and then converted in root files

Cluster counting for particle identification: TEST BEAM
Some preliminary results

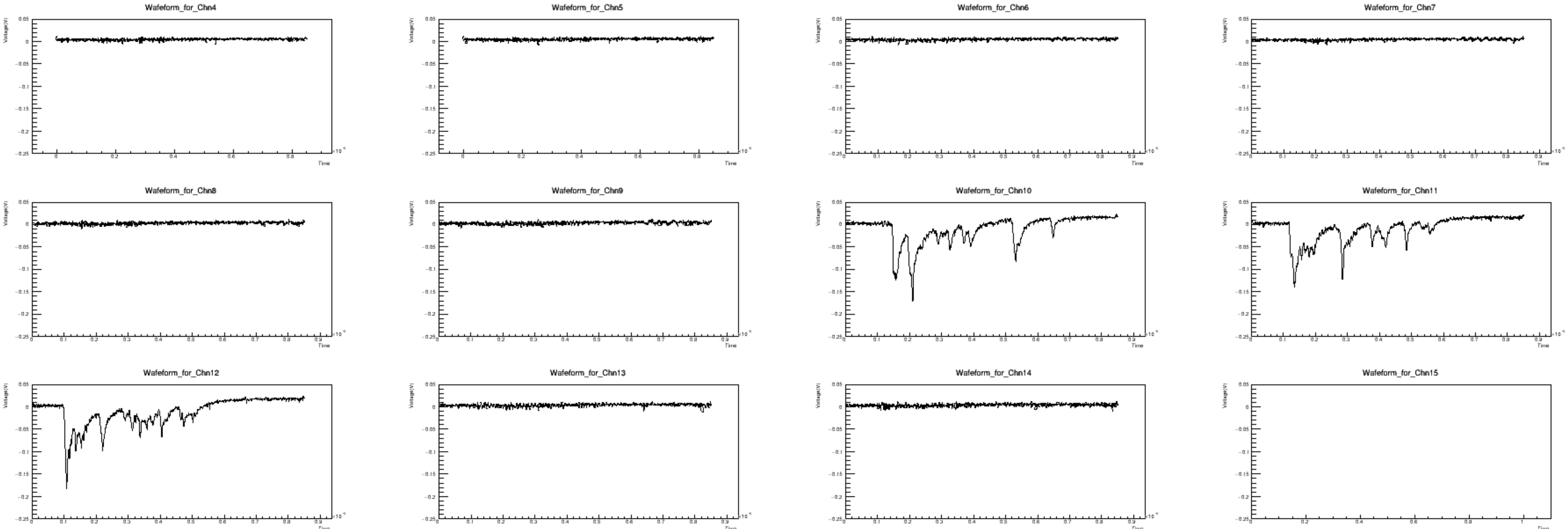
Data have been taken performing scan

- in angle: 0°, 15°, 30°, 45°, 60°
- in HV

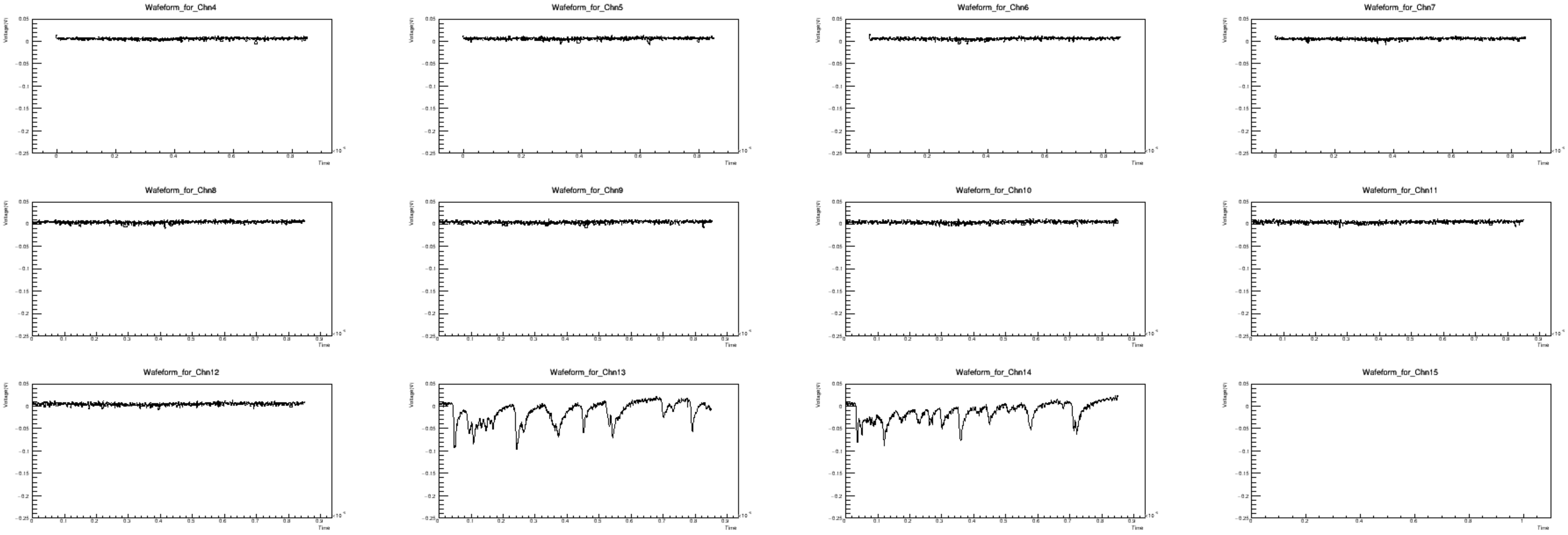
Signal on the 6 tubes 1 cm cell size, 60°, 90/10 gas



Signal on the 3 tubes 2 cm cell size, 60°, 90/10 gas



Signal on the 2 tubes 3 cm cell size, 60°, 90/10 gas



The slow drift velocity of the 90/10 gas mixture gives a maximum drift time larger than the DRS scale.

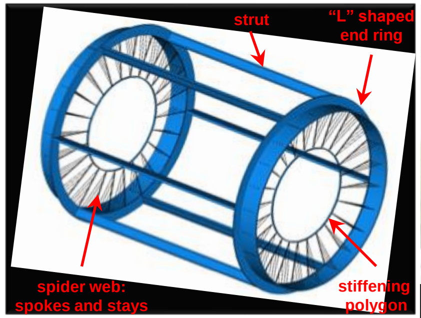
Conclusion

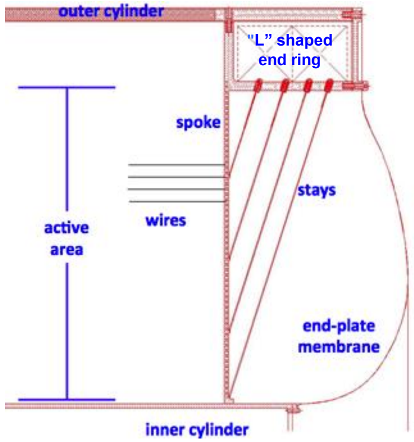
- **An ultra-low mass drift chamber for SCTF** with a material budget **<1.5x10^{-2} X/X$_0$** in the radial direction and **<5x10^{-2} X/X$_0$** in the forward and backward directions (including HV and FEE services) **can be built today** with the novel technique adopted for the successful construction of the MEG2 drift chamber
- **$\Delta p_t/p_t$ = 2.0×10^{-3}, $\Delta\theta$ = 0.70 mrad, $\Delta\phi$ = 0.78 mrad at p = 1 GeV/c**.
- Particle identification at the level of **3.6%** with **cluster counting** allowing for **π/K separation ≥ 3σ** over a wide range of momenta.
- 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
- The test beam provides us the possibility to study the:
  - counting efficiency as a function of gas mixture, gain, geometrical configuration (cell size, sense wires size), arrival time of the first cluster
  - cluster density as a function of ionization length and angle
  - cluster dimension as a function of gain and cell size
  - definition of the optimal condition for the next test whose goal will be the measurement of the relativistic rise of dN/dx and dE/dx

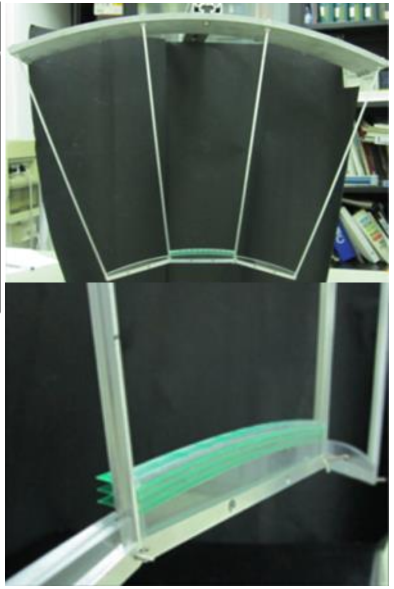
BACKUP

The CMD3 tracker mechanical design (inspired by the Mu2e I-tracker)

Wire support





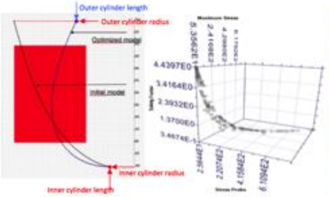


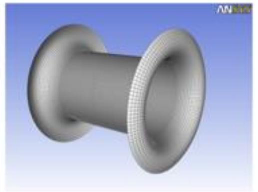
Turn all bending moments into traction or compression!

Feed-through-less chamber allows for reducing wire spacing, thus increasing cell granularity:

- **smaller cells**
- **larger ratios of field to sense wires,** which allows for thinner field wires, thus reducing :
  - **wire contribution to multiple scattering**
  - **total wire tension**

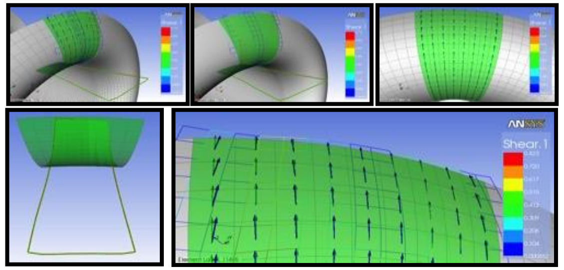
Gas containment



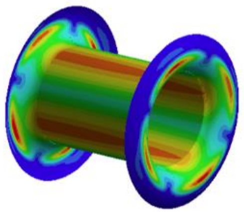


parameters	Initial model	Optimized model
Maximum stress	357.5 MPa	58.7 MPa
Stress at inner boundary	267.4 MPa	26.6 MPa
Safety factor	0.783	4.44

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.



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



Reduce inner cylinder buckling by increasing the moment of inertia with proper light core composite sandwich.

Instrumented end-plate: (wire PCB, spacers, HV distrib. and cables):
1×10^{-2} X0

End plate: 4-ply × 38μm/ply orthotropic (0/90/90/0) :
6×10^{-4} X0

Inner cylinder: 2 C-fiber skins, 2-ply, + 5 mm C-foam core
8×10^{-4} X0