CERN | FUTURE CIRCULAR COLLIDER

THE IDEA DRIFT CHAMBER FOR A LEPTON COLLIDER

II ECFA Workshop on e^+e^- Higgs/EW/Top Factories

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F. M. Procacci[1], N. De Filippis[1], A. Miccoli[2]
On behalf of the IDEA Collaboration

[1]INFN – Sezione di Bari & Politecnico di Bari
[2]INFN – Sezione di Lecce

INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

Politecnico di Bari

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eurizon
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for developing new horizons for RIs

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Outline

- Overview on drift chamber details
- Mechanical simulation studies
- Prototyping
- Next developments

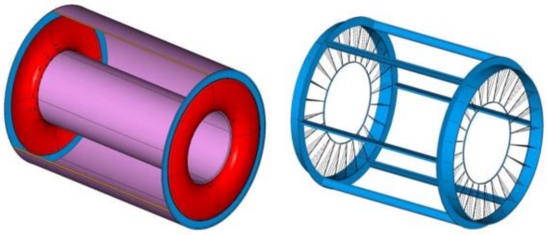
IDEA Drift Chamber: evolution and new concepts

KLOE → CMD-2 → MEG2 → IDEA

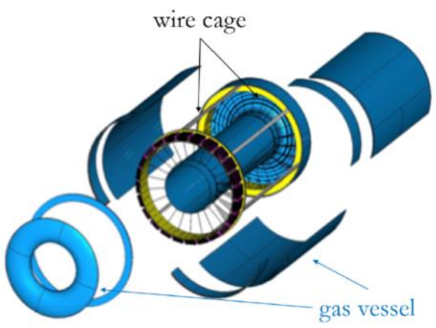
(1998) (2006) (2014) (2017)

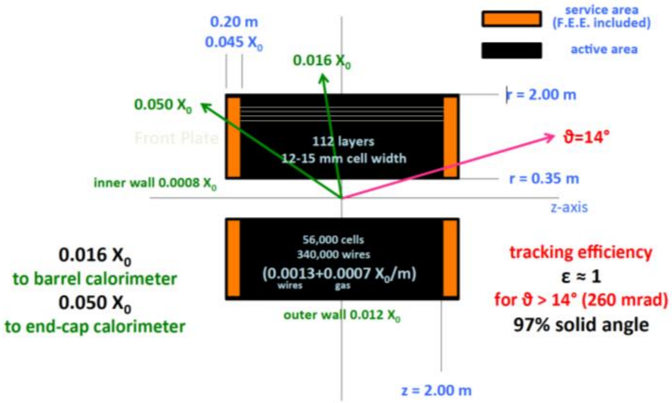
- New mechanical assembly procedure by separating the **gas containment** from the **wire support** functions
- New concepts for **wire tension compensation** resulting in end caps with a 5% X_0 (including front end electronics and cables) and 1.6% X_0 in the radial direction
- A larger number of thinner (and lighter wires) resulting in **less total stress** on end plates
- No use of massive feed-through → **Feed-through-less** wiring
- Use of **cluster counting** for particle identification
- Use of **cluster timing** for improving spatial resolution

See W. Elmetenawee contribution



IDEA Drift Chamber: some details

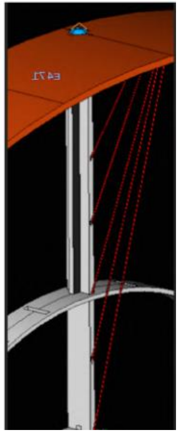




- Low mass cylindrical with **2T** solenoid field and a light gas mixture **He 90% - iC_4H_{10} 10%**
- Inner radius **R_{in} = 35 cm**, outer radius **R_{out} = 200 cm**
- Length **L = 400 cm**
- Inner wall thickness **200 µm** Carbon fiber (from CMD3 dch)
- Outer wall thickness **2cm** composite material sandwich (from Mu2e)
- **343968 wires** in total:
  - 56448 sense wires – 20 µm diameter W(Au)
  - 229056 field wires – 40 µm diameter Al(Ag)
  - 58464 field and guard wires – 50 µm diameter Al(Ag)

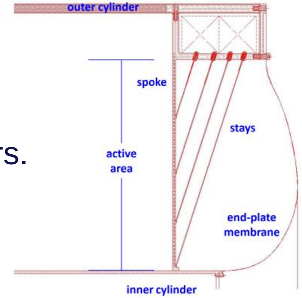
Thin wires → **increase the chamber granularity** → reducing both multiple scattering and the overall tension on the end plates

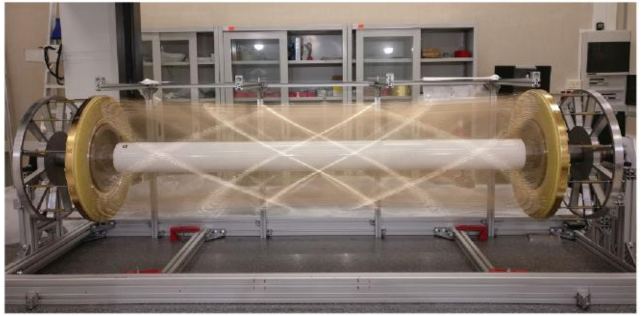
IDEA Drift Chamber: a closer eye on wire cage



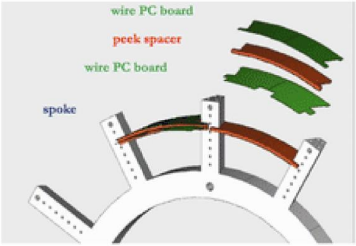
Simple and clean structure

- **Inner cylinder** and **Outer cylinder** are connected with 48 **Spokes** (24 per endcap) forming 24 azimuthal sectors.
- Each spoke is supported by 14 **Cables/Stays.**
- The **Wires** are soldered to the PCB and inserted between the spokes.
- **112 co-axial layers** (grouped in 14 superlayers of 8 layers each) **of para-axial wires**, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors.
- **Stereo configuration:** one sector is connected with the second corresponding sector in the opposite endcap (hyperbolic profile).

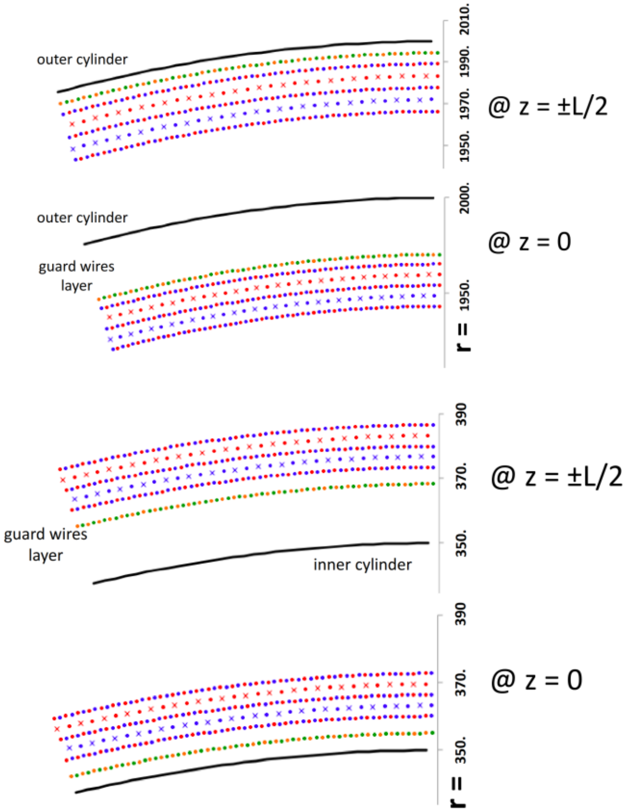




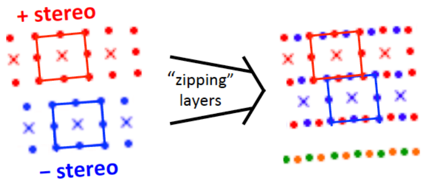
MEG2 experiment



IDEA Drift Chamber: wires layout



- Drift length ~ 1 cm, drift time ~150 ns, **σ_{xy} < 100** µm σ_z < 1 mm
- Ratio of field wires to sense wires = **5 : 1**
- 192 (at inner layer), 816 (at outer layer) **square drift cells** (16 per sector)
- **Cell size** ranging from 11.8 mm at the innermost layer, to 14.9 mm at the outermost one



Radii (at z = 0)			Radii (at end plate)		
Inner Cylinder	350	mm	Inner Cylinder	350	mm
Guard wires layer	354	mm	Guard wires layer	366	mm
First active layer	356	mm	First active layer	369	mm
Last (112th) active layer	1915	mm	Last (112th) active layer	1982	mm
Guard wires layer	1927	mm	Guard wires layer	1995	mm
Outer Cylinder	2000	mm	Outer Cylinder	2000	mm

Active length	2000	mm
Number of super-layers (8 layers) Number of sectors	(14x8) = 112 24	
Number of cells per layer / per sector	192÷816 / 16	
Cell size (at z=0)	11.8 ÷ 14.9	mm
2α angle	30°	
Stereo angle	43 ÷ 223	mrad
Stereo drop	12.5 ÷ 68.0	mm

sense wires	56 448
field wires	284 256
guard wires	2 016
Total wires	342 720

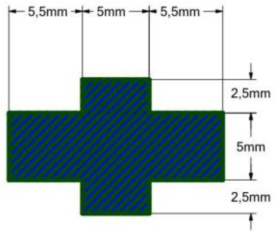
Big Problems to manage!

- σ_{xy} < **100 μm** → accuracy on the position of the anodic **< 50 μm**.
- The anodic and cathodic wires should be parallel in space to preserve the constant electric field.
- A 20 μm tungsten wire, 4 m long, will bow about 400 μm at its middle point, if tensioned with a load of approximately 30 grams.

30 gr tension for each wire → **10 tonnes** of total load on the **endcap**

Load on spokes (24 sectors): 208 kg/spoke (165cm) → **1.26 kg/cm average**

Load on stays (14 stays/spoke) → **100 kg/stay** average (<Φ> = 8.6°)



Spokes like cantilever beam (L = 1650mm, s = 16x10 mm^2 , t = 1mm)

Cables (s = 3 mm^2)

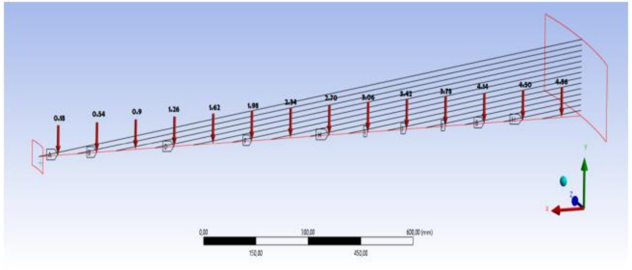
Mechanical Simulation roadmap

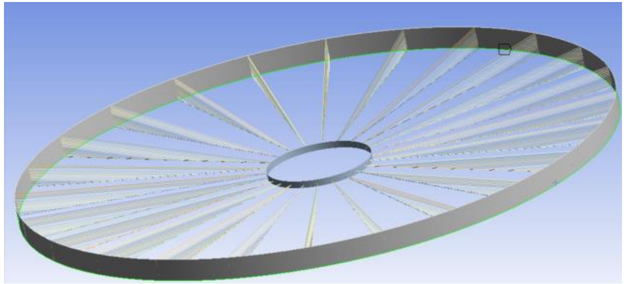
1. **Single endcap simulation (almost done):**
   - Spokes and cables behaviour under wires pressure. 10 tonnes load as uniformly distributed over the surface of the end plates (80000 cm^2) in 1.5 cm^2 units of 180 grams each.
2. Complete 3 sectors simulation (undergoing):
   - 3 sectors per endcap with stereo wire configuration, drift cells and physical connection criteria
3. Complete chamber simulation (next future):
   - overall stability of the mechanical structure

Preliminary design: development of Base FEM model

- Materials: **Epoxy Carbon Unidirectional Prepeg** for **cylinders** and **spokes**, **Structural steel** are used for the **cables.**

- **Element to test:** The outer and the inner cylinders are modelled with **Shell element**, spokes with **Beam element,** cables with **Truss element** (no bending, no pressure supported)**.**
- **Loading:** loads are **uniformly varying** with maximum value (5.050 N/mm) at the outer cylinder to a minimum value (0 N/mm) at the inner cylinder.
- **Boundary conditions**: fixing the face of the outer cylinder (non-deformable surface) or fixing the edge of the outer cylinder (study deformability)
- Parametric study on mesh size of outer cylinder : large domain to manage: **1mm** mesh size is numerically accurate.

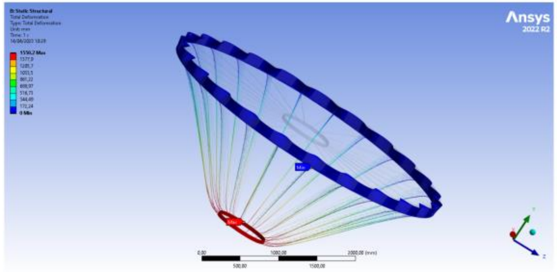




Preliminary design: FEM analysis

Linear analysis

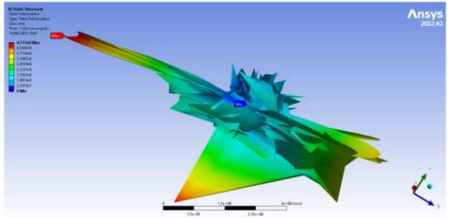
HP: small deformations in a **single time step**
Goal: find errors in the model with small computational time



The maximum deformation occurs on inner cylinder **1550,2 mm**

Non-Linear analysis

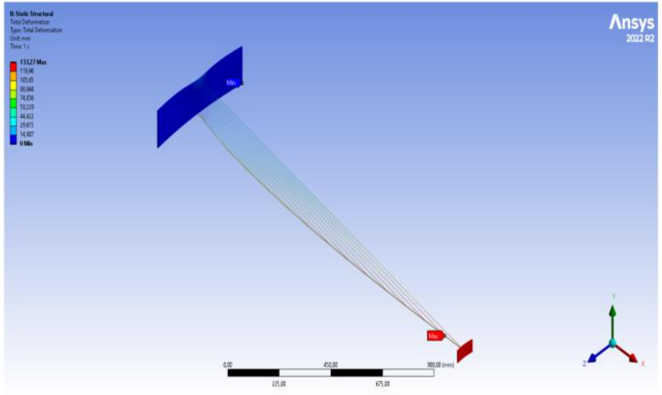
HP: Large strain, rotation, stress stiffening
The load is applied in a **single time step** ⟶ discrepancy between applied and internal element forces



Non-convergent solution

Time stepping algorithm

- the time step size and loads are automatically determined in response to the current state of the analysis.
- estimate the next time step size Δt_{n+1}, based on current t_n and past analysis Δt_n conditions, and make proper load adjustments



The maximum deformation occurs on inner cylinder **135,03 mm**

Preliminary design: FEM analysis validation

Development of the **Finite Element Method** with **Ansys**
Model validation with 3 different configurations.

1. **Materials**: composite carbon fiber and steel
   Boundary conditions: fixing the lower edge of the outer cylinder.
   Realistic model.
2. **Materials**: composite carbon fiber and steel
   Boundary conditions: fixing the face of the outer cylinder.
   Comparison model.
3. **Materials**: Structural steel
   Boundary conditions: fixing the lower edge of the outer cylinder.
   Results simple to interpret.

	Edge fixed	Face fixed	Edge fixed
Material type	Composite and steel	Composite and steel	structural steel
Max. Total deformation in model (mm)	135.03	96.83	108.37
Max. Total deformation in outer cylinder (mm)	14.73	-	7.84
Min. Axial force in Spokes (N)	-365.87	-1957.80	-1312.40
Max. Axial force in Spokes (N)	12294.00	13497.00	13103.00
Max. Equivalent stress in Cables (MPa)	3245.70	3350.90	3330.50
Avg. Equivalent stress in Cables (MPa)	71.49	89.95	82.88
Max. Equivalent stress in Inner cylinder (MPa)	1646.70	1885.20	1952.90
Avg. Equivalent stress in Inner cylinder (MPa)	280.11	317.02	335.90
Max. Equivalent stress in Outer cylinder (MPa)	1976.00	-	1618.30
Avg. Equivalent stress in Outer cylinder (MPa)	139.77	-	224.33
Mass (kg) per sector	0.69587	0.69587	2.7773
Volume (mm^3) per sector	3.54E+05	3.54E+05	3.54E+05

Preliminary design: conclusion

- Improvement of the stresses and strain of the outer cylinder as the model evolves.
- Good behaviour of the system

FEM analysis: Parametric Design Exploration

Design exploration: varying input parameters in some possible ranges in order to see how the system responds

The input parametric variables are:

1. Height and thickness of the outer cylinder;
2. Dimensions (breadth and depth) of the spokes;
3. Dimensions (radius) of the cables;
4. Thickness of the inner cylinder.

Parameters:	
Height:	200 mm
Innerthickness:	10 mm
Outerthickness:	14.4 mm
Rectangle_B:	9.6 mm
Rectangle_H:	16.6 mm
Circle_R:	1.5 mm
Responses:	
Maximum_Deformation:	22.995 mm (Linear Analysis)
Maximum_Deformation:	21.643 mm (Non-Linear Analysis)

Parametric Design Exploration: Conclusion

- Select the optimal dimensions of the drift chamber
- Total deformation of the model from **135,03 mm** to **21,64 mm.**

It is still **too high!**

FEM analysis: Prestressing

Uniformly distributed line pressure

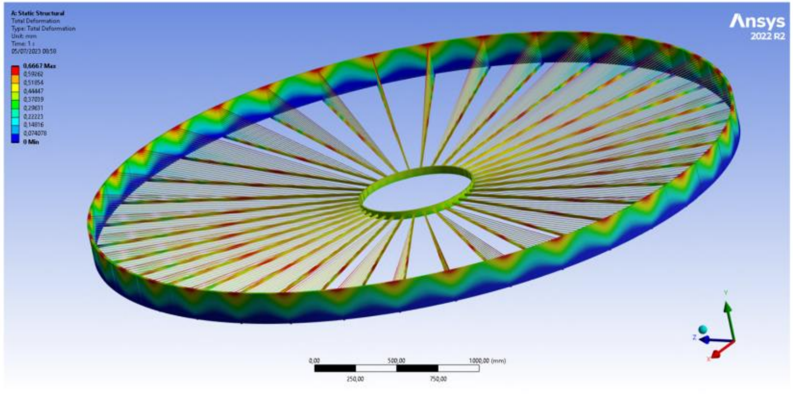
↓

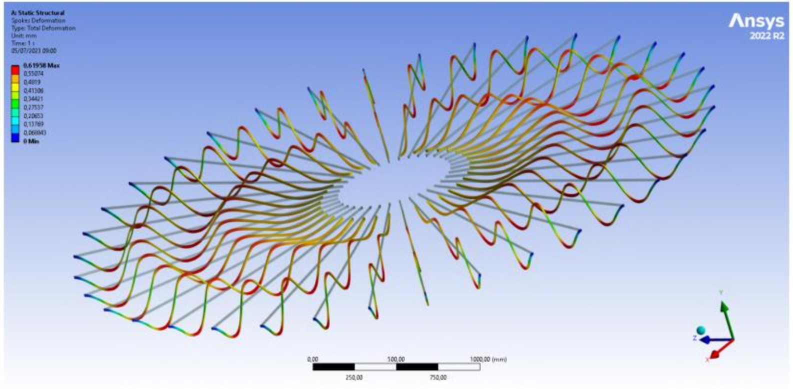
Linearly increasing line pressure

Goal: minimizing the deformation of the spokes using prestressing force in the cables

Finding the correct prestressing force in 14 cables → solving 15 dimensional optimization problem

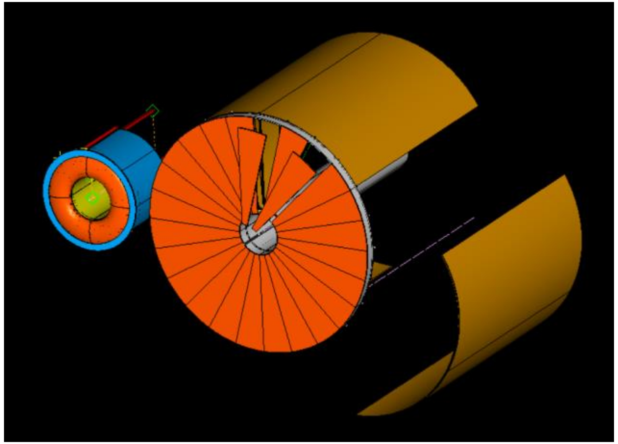
Total deformation (mm) of the drift chamber with the edge of the outer cylinders fixed			
No prestress		Prestress in the cables	
Spokes	Outer cylinder	Spokes	Outer cylinder
14.099	0.63	0.62	0.67



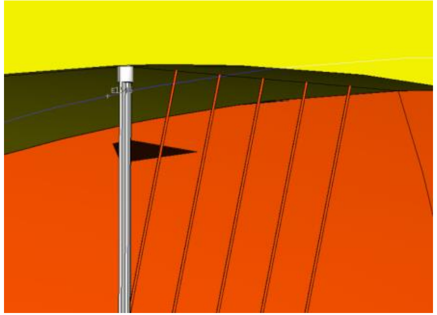


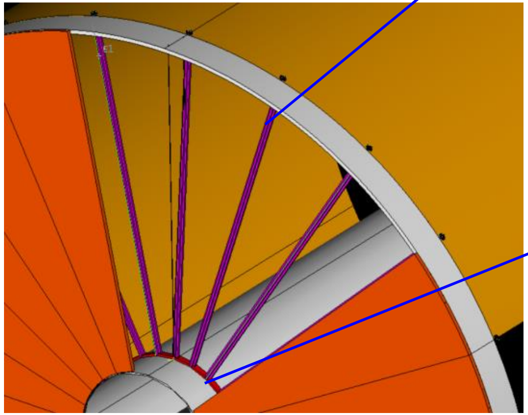
Realistic model: from concept to CAD prototyping

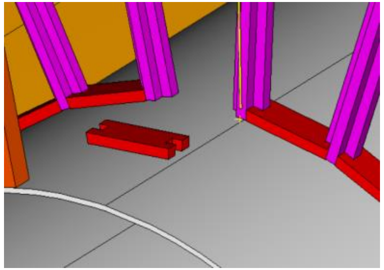
1. Mechanically accurate
2. Precise definition of the connections of the cables on the structure
3. Connections of the wires on the PCB
4. Location of the necessary spacers
5. Connection between wire cage and gas containment structure



Upper junction: cross profile spoke and supporting cables







Lower junction: joint design

What happens now?

Our **main goal** was to limit the deformation of the spokes to **200 µm** while ensuring the structural integrity.
The structure exhibited a deformation of **600 µm.**

Next developments

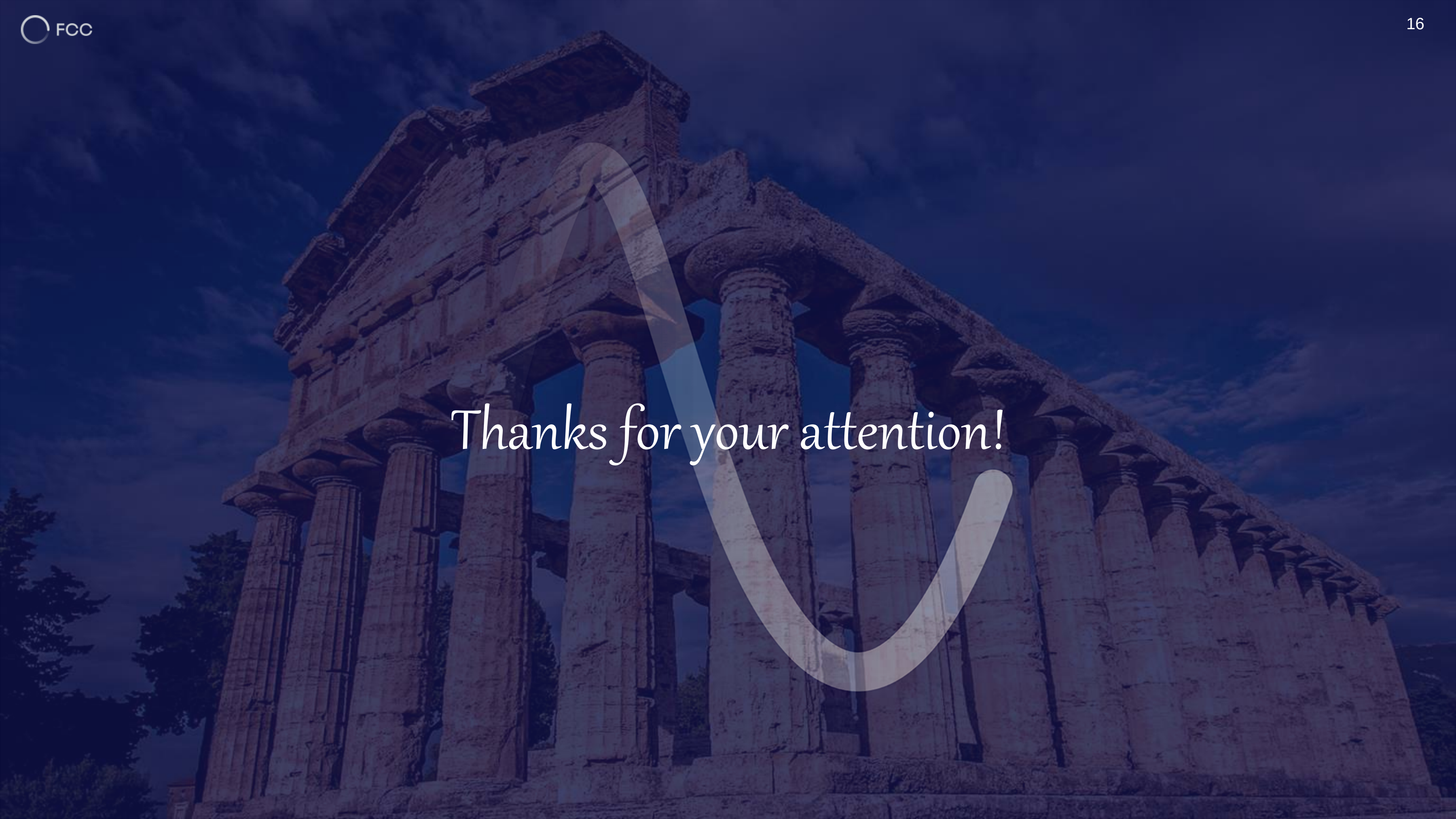
- Including **prestressing of spokes**
- Investigate various spoke section shapes
- **Buckling** analysis on outer cylinder
- Investigate more **composite structures** (different layer orientation)
- Develop a refined simulation of 3 sectors

} Complete endcap simulations } **Goal**: the mechanical simulation project will be ready by the end of 2023

- **Real model design in order to start prototyping** → **Target**: construction of a full length DCH prototype (3 sectors)

Start a collaboration with **EnginSoft**: one of the leading technology transfer companies in the field of Simulation Based Engineering Science

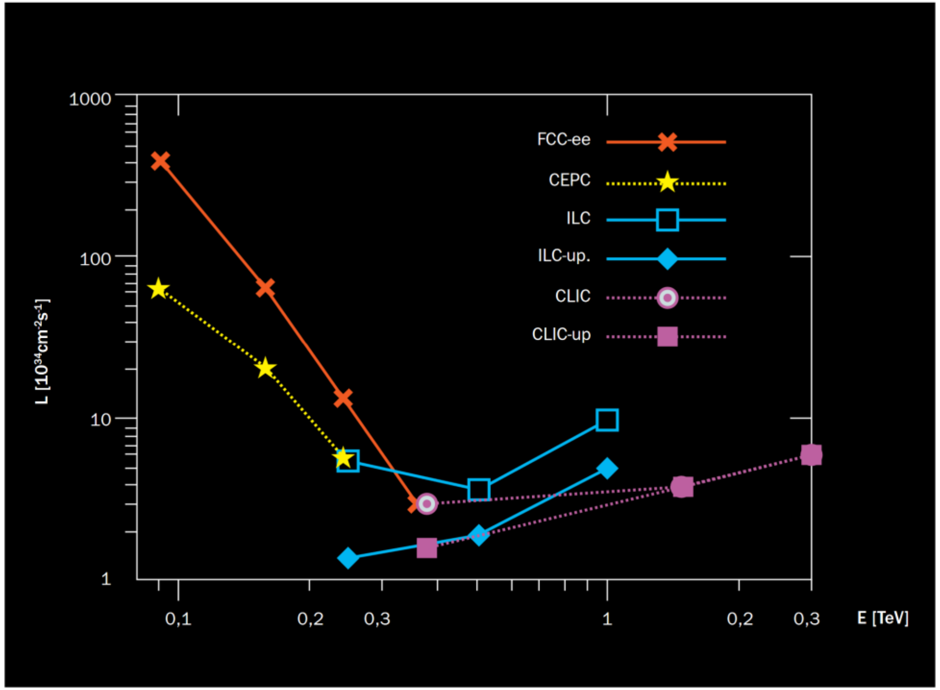
ENGINSOFT

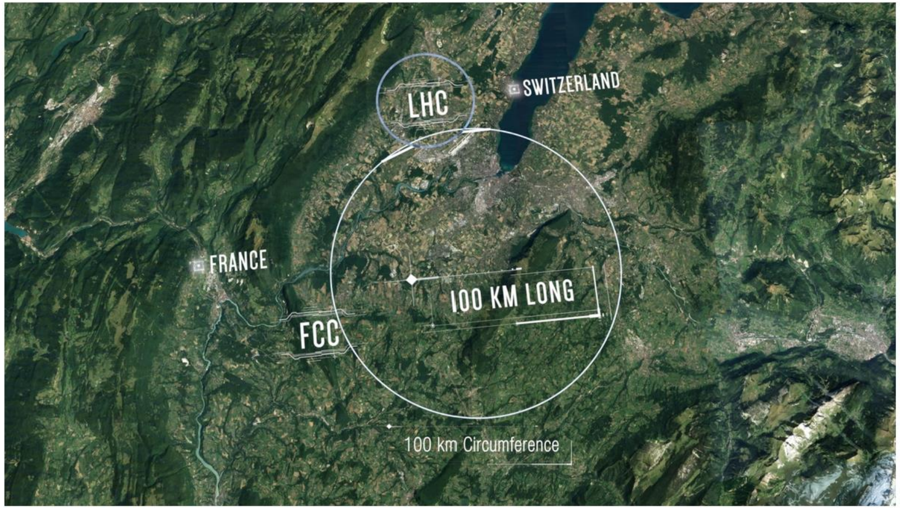


Thanks for your attention!

Backup

Future Circular Collider - ee

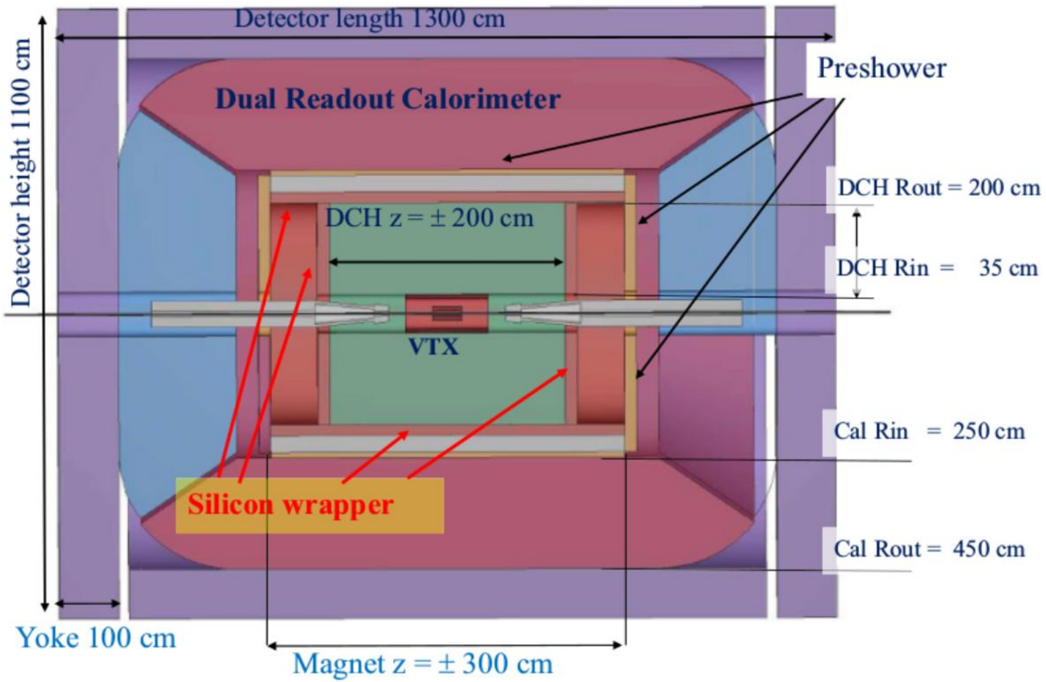




- Precision studies at low energy (EW factory)
- 250 GeV (Higgs factory)
- 350 GeV (Higgs-top)

IDEA experiment

- Silicon pixel vertex detector – VTX
- Central tracking Light Drift Chamber – DCH
- Silicon microstrip wrapper
- Ultra-thin superconducting solenoid coil
- Dual Readout Calorimeter supplemented by a Preshower detector
- Muon chambers in the solenoid return yoke



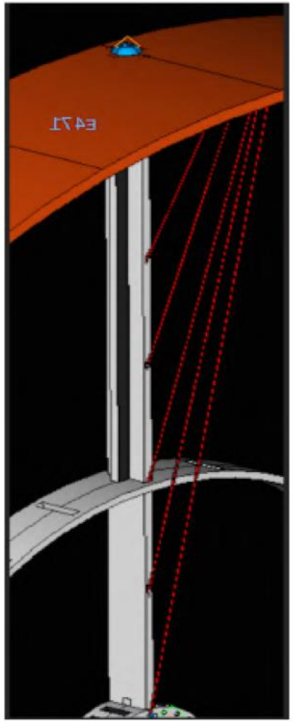
IDEA Design Guidelines

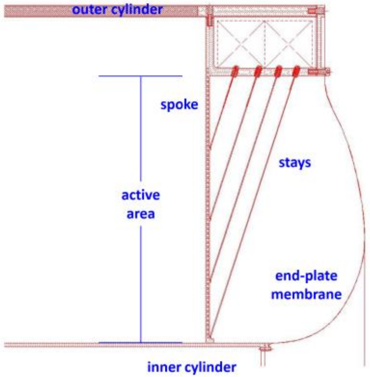
- Large **angular coverage**
- High **angular resolution** ($\Delta\vartheta \leq 0.1$ mrad for monitoring beam spread ($Z \rightarrow \mu\mu$))
- High **granularity** (to cope with occupancy at inner radii)
- High **tracking efficiency**
- High **momentum resolution**

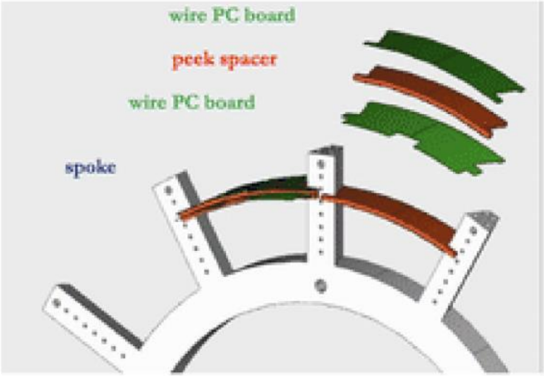
  $\delta p/p^2 \leq$ few x 10^{-5}, small wrt 0.12% beam spread for
  - Higgs mass recoil
  - cLFV processes like $Z \rightarrow e\mu, e\tau, \mu\tau$ (BR $\approx 10^{-54} - 10^{-60}$)

  current exp. limits ($\leq 10^{-6}$) can be improved by > 5 orders of magnitude
- High capabilities for **Particle Identification** (dE/dx resolutions $\lesssim$ 3%)
  - Flavor Physics
  - CPV ($B_s \rightarrow D_s K$)
  - A_{FB}(b), exclusive b-hadron decays reconstruction
  - Hadron spectroscopy
- High **V^0 and kink** capability for CPV (CP eigenstates usually long-lived particles)

IDEA Drift Chamber: a closer eye on wire cage





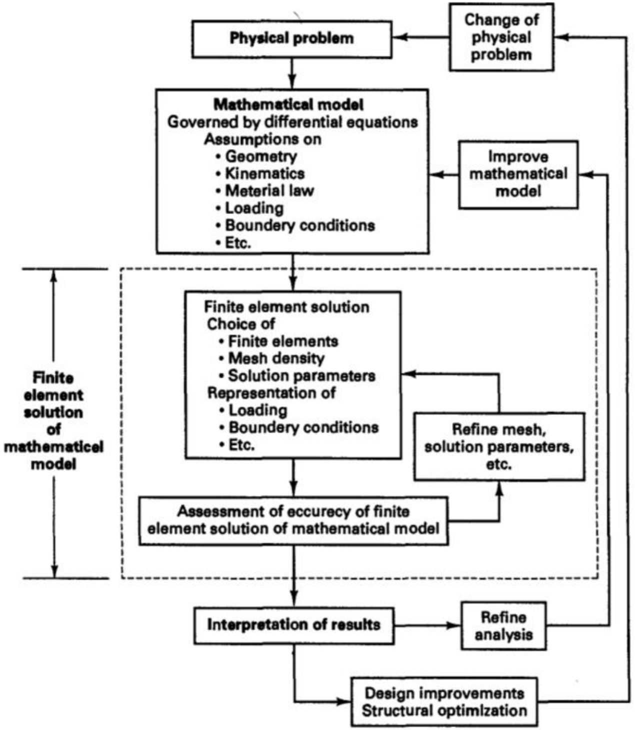


Conservative estimates:

- Inner wall (from CMD3 drift chamber) **8.4×10^{-4} X_0**
  200 µm Carbon fiber
- Gas (from KLOE drift chamber) **7.1×10^{-4} X_0/m**
  90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) **1.3×10^{-3} X_0/m**
  20 µm W sense wires 4.2×10^{-4} X_0/m
  40 µm Al field wires 6.1×10^{-4} X_0/m
  50 µm Al guard wires 2.4×10^{-4} X_0/m
- Outer wall (from Mu2e I-tracker studies) **1.2×10^{-2} X_0**
  2 cm composite sandwich (7.7 Tons)
- End-plates (from Mu2e I-tracker studies) **4.5×10^{-2} X_0**
  wire cage + gas envelope
  incl. services (electronics, cables, ...)

Finite Element Method

- Complex Domain → Simple independent Subdomain (Finite Element)
- Approximate the governing equations by means variational method: differential equations → discrete algebraic equations
- Connect subdomains in a way functions and derivatives are continuous at connecting points
- Define accuracy criteria: consistency, stability, convergence



FEM analysis: Composite material

We develop, validate and calibrate a **Layered Composite Material** made from Epoxy carbon prepeg with the fibres oriented at 0°

Component Type	Orientation of Ply	No. of Ply	Total thickness (mm)
Outer Cylinder	0°	72	14.40
Inner Cylinder	0°	50	10.00
Spokes	0°	83	16.60

		Spokes			Outer Cylinder		
	Total Load (N)	Min (mm)	Max (mm)	Average (mm)	Min (mm)	Max (mm)	Average (mm)
Composite design	100000	0	24.339	14.757	0	1.2846	0.4742
Monolithic design		0	25.385	15.375	0	1.2649	0.33894
Composite design	70000	1.23E-03	17.913	10.681	0	0.9274	0.340
Monolithic design		0	18.309	10.922		0.8913	0.24046
Composite design	60000	1.53E-03	15.63	9.2621	0	0.8034	0.29447
Monolithic design		0	17.206	10.256		0.84069	0.22506
Composite design	50000	1.28E-03	13.26	7.8075	0	0.67658	0.24747
Monolithic design		0	13.356	7.8823	0	0.64765	0.1733
Composite design	30000	7.73E-04	8.271	4.801	0	0.41502	0.15116
Monolithic design		0	8.1818	4.7763	0	0.39178	0.10481
Composite design	10000	2.59E-04	2.8733	1.6412	0	0.14145	5.13E-02
Monolithic design		0	2.7856	1.6081	0	0.13163	3.52E-02

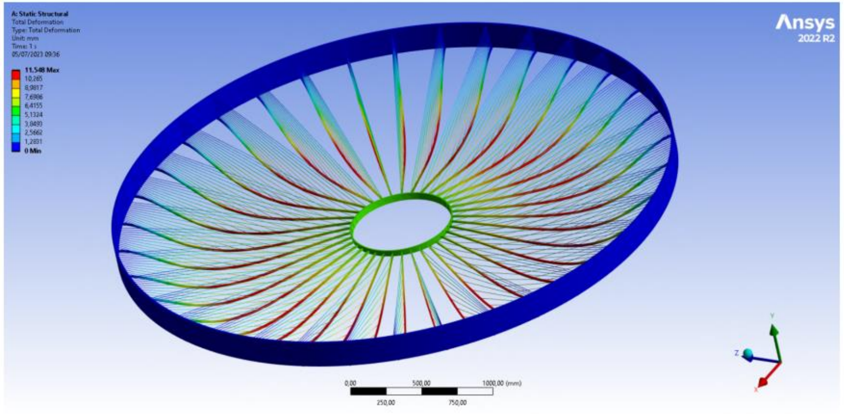
FEM analysis: Prestressing

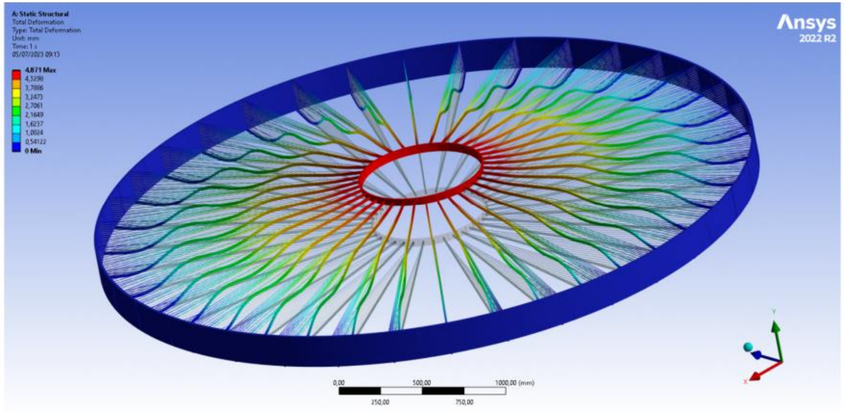
Constraint: **face of the outer cylinders fixed**

- drift chamber pulled upwards
- very high total deformation

Total deformation (mm) of the drift chamber with the face of the outer cylinders fixed	
No prestress	Prestress in the cables
Drift chamber	Drift chamber
11.54	4.871

Accurate definition of **boundary conditions** on the overall deformation of the spoke



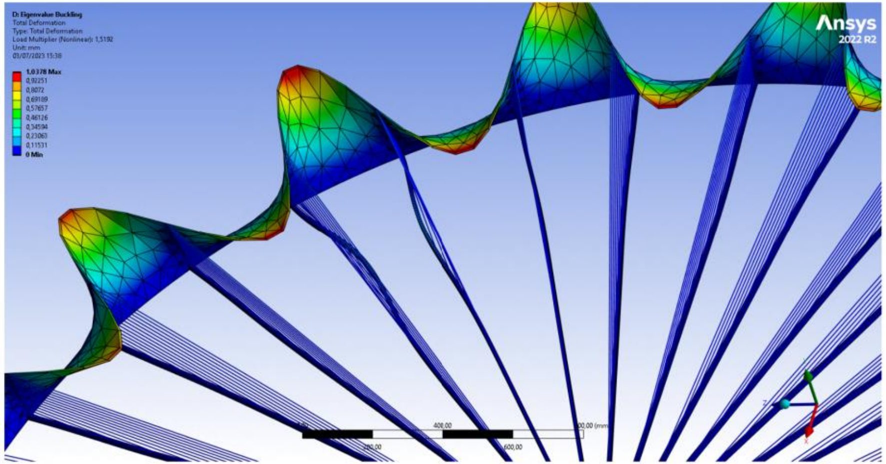


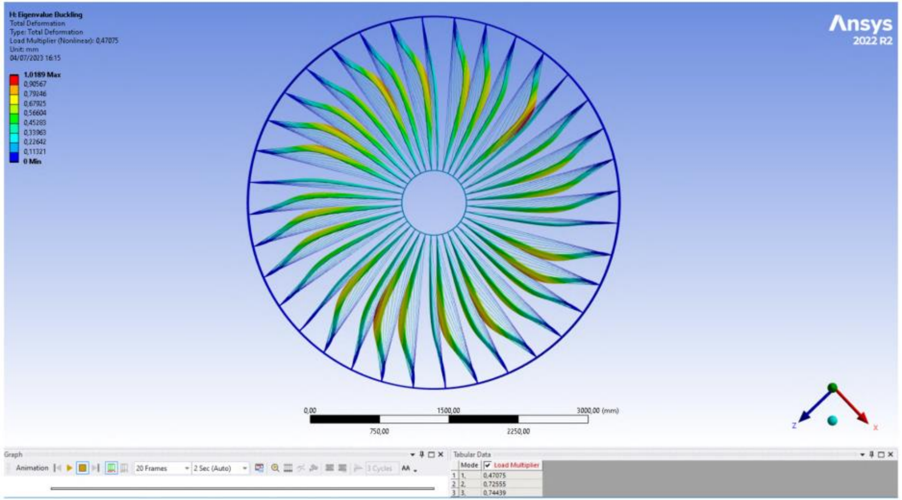
FEM analysis: Buckling analysis

Buckling behaviour is essential for us to ensure the **safety** and **reliability** of this drift chamber.

Linear buckling analysis assumes small deflections and linear material behaviour.

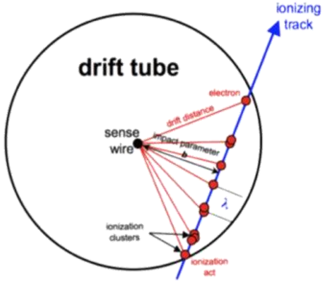
Failure primarily occurs in the spokes while the outer cylinder remains undamaged (right).





- Spokes interact with the cylinder
- Deformation near the outer cylinder (left)

Cluster Timing

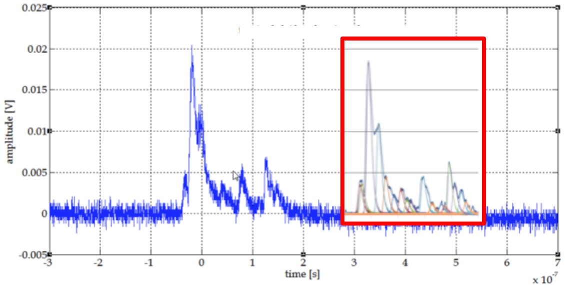


Determine, in the signal, the **ordered sequence of the electrons arrival times**:

$$\{t_j^{el}\} \qquad j=1,n_{el}$$

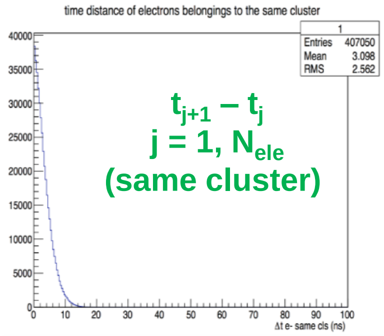
Based on the dependence of **the average time separation between consecutive clusters** and on the **time spread due to diffusion**, as a function of the drift time, **define the probability function**, that the ***j***

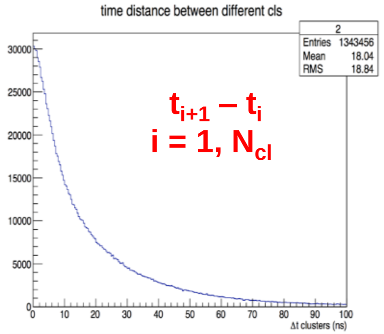
$$P(j,i) \qquad j=1,n_{el}, \quad i=1,n_{cl}$$



from this **derive** the most probable **time ordered sequence of the original ionization clusters:**

$$\{t_i^{cl}\} \qquad i=1,n_{cl}$$





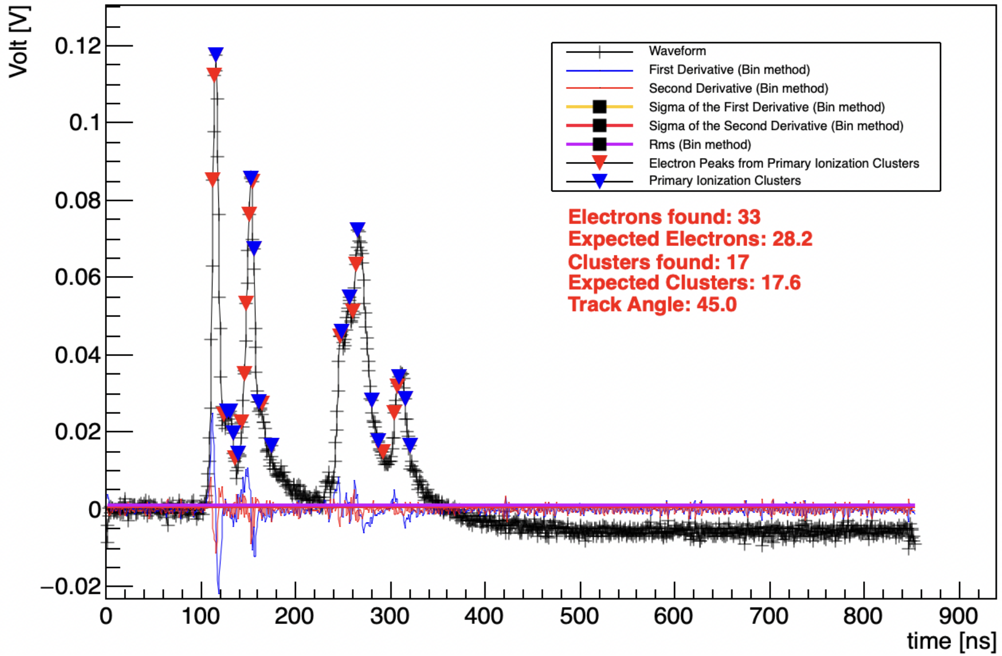
For any given first cluster (**FC**) drift time **t_1**, the **cluster timing technique** exploits the drift time distribution of all successive clusters to statistically (**MPS**) or using **ML techniques**, determine, hit by hit, the most probable **impact parameter**, thus reducing the **bias** and improving the average **spatial resolution** with respect to that obtainable with the FC method alone:

over a 1 cm drift cell, **spatial resolution** may improve by ≳ 20% **down to ≲ 80 μm**.

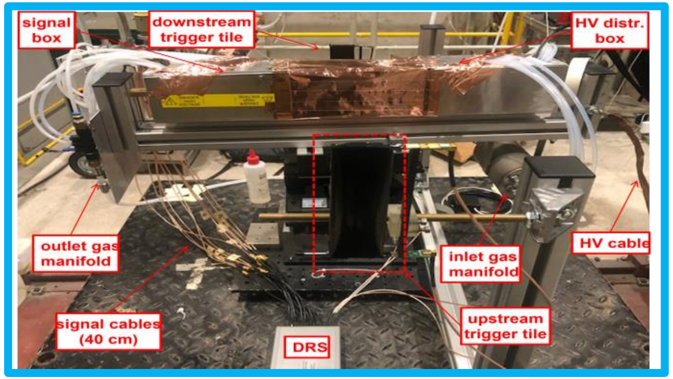
Fringe benefits of the cluster timing technique are:

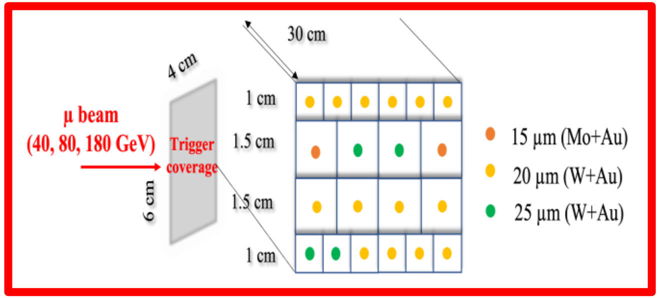
- **event time stamping (at the level of ≈ 1 ns);**
- **improvements on charge division;**
- **Improvements on left-right time difference.**

IDEA Drift Chamber: Beam Tests



Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV





Why 200 μm deformation as main goal?

- A wire tensioned at 30g stretches by 3mm/m, on 4m we have **12mm** of tension length on the wire.

- If we assume 2% error -> 240 μm
- If the spokes deform by 240 μm it means that the tension of the wire changes by 2% (0.6gr) and we are wrong by 2% on the sagitta therefore by **8um**. This added in quadrature to the 50 μm gives us an acceptable value.

- For **600 μm** as we currently have, there are **25 μm** of error on the sagitta which becomes comparable with the precision error of the wire.