DRIFT CHAMBER - DEVELOPMENTS AND PLANS

International Workshop on the Circular Electron-Positron Collider (CEPC)

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On behalf of the IDEA-DC and CEPC Collaboration

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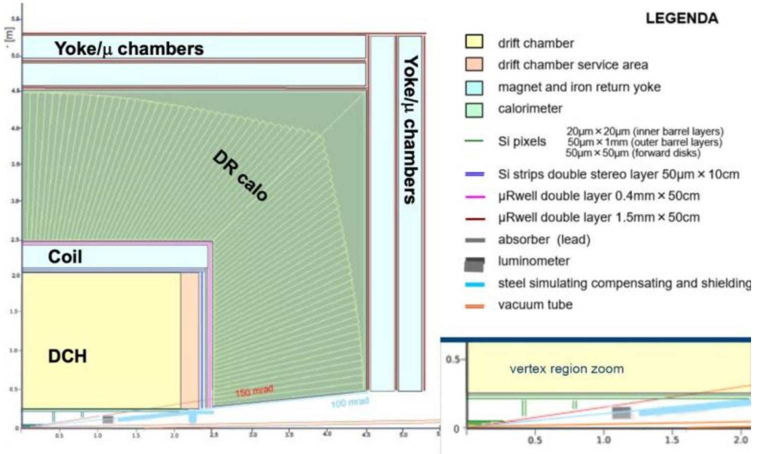
Outline

1. Overview of IDEA DCH
2. Full mechanical and prototype design
3. Spoke mechanical simulation studies and production process
4. New studies on wires
5. Future plans
6. Overview of CEPC DCH

IDEA Drift Chamber: evolution and new concepts

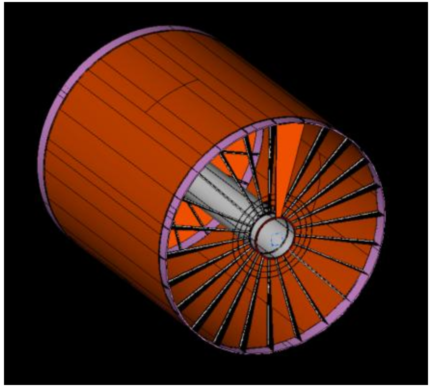
KLOE (1998) → CMD-2 (2006) → MEG2 (2014) → IDEA (2017)

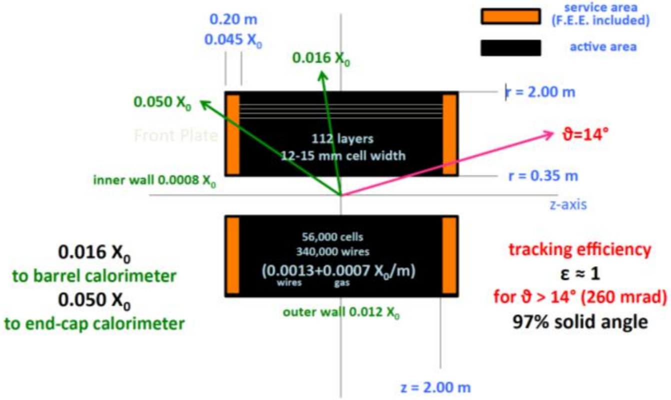
- New mechanical assembly procedure by separating the **gas containment** from the **wire support** functions
- New concepts for **wire tension compensation** resulting in end caps with a 5% X_0 (including front end electronics and cables) and 1.6% X_0 in the radial direction
- A larger number of thinner 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



Tracking → 150 mrad → No material in front of luminometer
Calorimetry → 100 mrad

IDEA Drift Chamber: some details





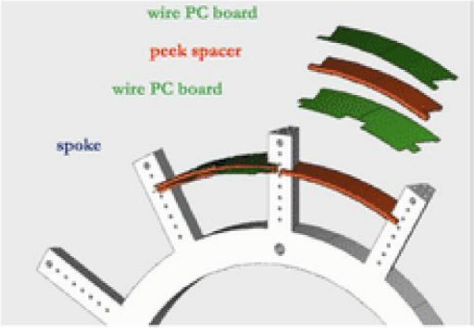
- Low mass cylindrical with **2T** solenoid field and a light gas mixture **He 90% - iC_4H_{10} 10%**
- Inner radius **R_{in} = 35 cm**, outer radius **R_{out} = 200 cm**
- Length **L = 400 cm**

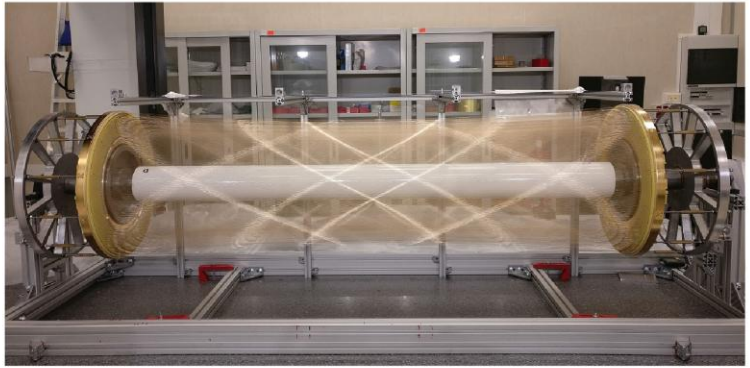
- **343968 wires** in total:
  - 56448 sense wires – 20 μm diameter W(Au)
  - 229056 field wires – 40 μm diameter Al(Ag)
  - 58464 field and guard wires – 50 μm diameter Al(Ag)

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

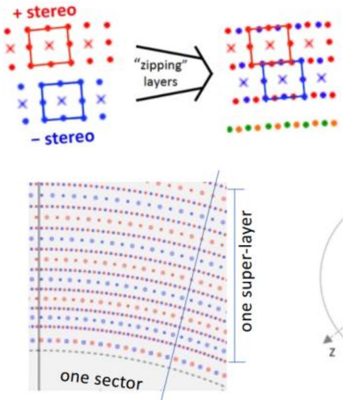
IDEA Drift Chamber: wire cage

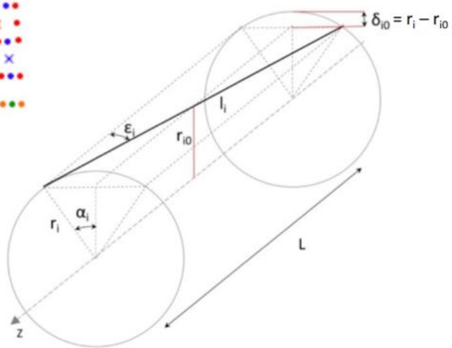
- The **Wires** are soldered to the PCB and inserted between the spokes.
- **112 co-axial layers** (grouped in 14 superlayers of 8 layers each) **of para-axial wires**, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors.
- **Stereo configuration:** one sector is connected with the second corresponding sector in the opposite endcap (hyperbolic profile).





MEG2 experiment





IDEA Drift Chamber: cell size

Electrostatic stability condition

$$T_c \geq \frac{C^2 V_0^2}{4\pi\epsilon w^2} L^2$$

T_c wire tension
w cell width
L wire length

C capacitance per unit length
V_0 voltage anode-cathode

For w = 1 cm, L = 4 m:

T_c **> 26 g** for 40 µm Al field wires (δ_{grav} = 260 μm)
T_c **> 21 g** for 20 µm W sense wires (δ_{grav} = 580 μm)

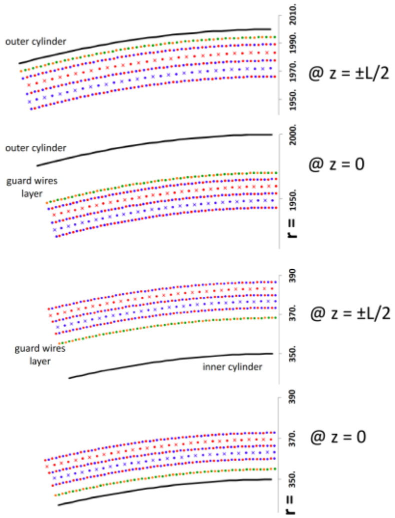
Elastic limit condition

$T_c < YTS \times \pi \cdot r_w^2$ *YTS = 750 Mpa* for W, *290 Mpa for Al*

T_c **< 36 g** for 40 µm Al field wires (δ_{grav} = 190 μm)
T_c **< 24 g** for 20 µm W sense wires (δ_{grav} = 510 μm)

The drift chamber length (**L = 4 m**) imposes strong constraints on the drift cell size (**w = 1 cm**)
Very little margin left ⇒ increase wires radii or cell size
⇒ use different types of wires

- Drift length ~ 1 cm, drift time ~150 ns, $\boldsymbol{\sigma_{xy}}$ **< 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 wires < **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.

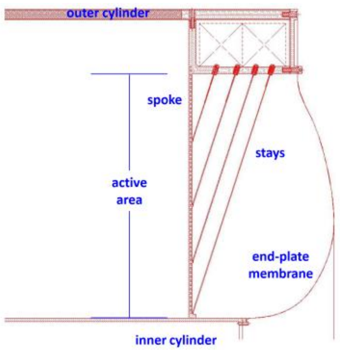
30 gr tension for each wire → **10 tonnes** of total load on the **endcap**

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

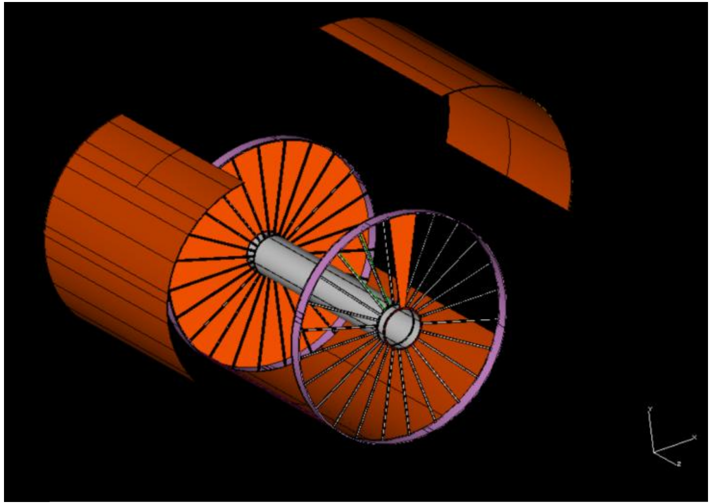
Load on stays (14 stays/spoke) → **100 kg/stay** average (<Φ> = 8.6°)

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

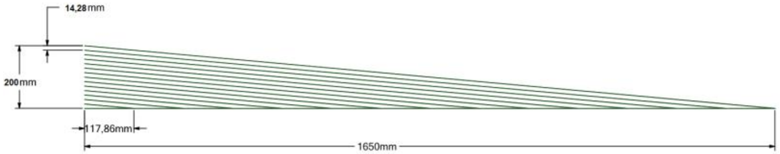
Stays (s = 3 mm^2)



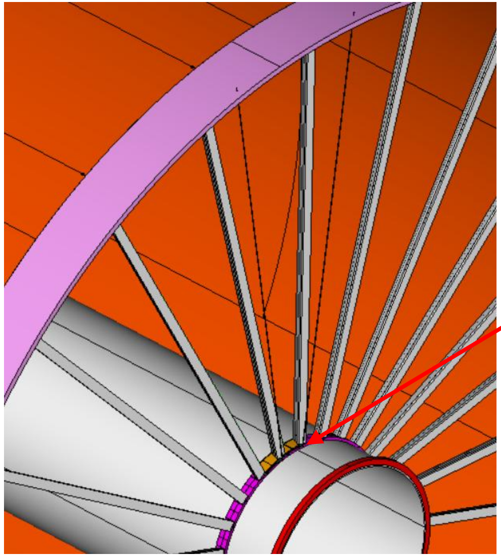
IDEA Drift Chamber: mechanical design overview

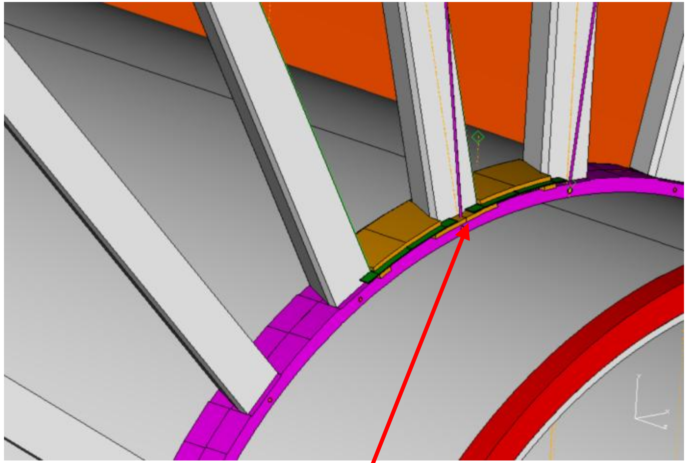


- **Outer cylinder** made of 3 big panels **2cm** thick made of 3 layers (2 monolithic CF with aluminum honeycomb structure in the middle)
- **External and internal ring** made of monolithic CF
- **Endplates** made of 48 **Spokes** (24 per endcap) forming 24 azimuthal sectors.
- Each spoke is supported by 15 **Stays.**
- Spoke length **l = 165cm**
- Inner cylinder wall thickness **200 µm** CF (from CMD3 dch) – not structural



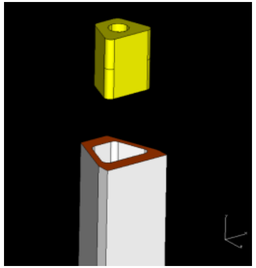
Mechanical design: details





- Spacers (yellow) and PCBs (green) are inserted between the spokes. The spacers have holes for the distribution of the gas
- The edge of the PCB acts as a stop on the spoke, providing a reference.

The supporting cables are anchored to some spacers appropriately shaped



Carbon foam core **6x** lighter than aluminum – FOAM ROHACELL® 35 HTC

Full-length prototype: Motivations

- **Check the limits of the wires' electrostatic stability at full length and at nominal stereo angles**

- **Test different wires**: uncoated Al, C monofilaments, Mo sense wires, …, of different diameters
  - Test different wire anchoring procedures (soldering, welding, gluing, crimping, …) to the wire PCBs
  - Test different materials and production procedures for spokes, stays, support structures and spacers
  - Test compatibility of proposed materials with drift chamber operation (outgassing, aging, creeping, …)

- Validate the **concept of the wire tension recovery scheme** with respect to the tolerances on the wire positions
  - Optimize the layout of the wires' PCBs (sense, field and guard), according to the wire anchoring procedures, with aim at minimizing the end-plate total material budget

- Starting from the new concepts implemented in the MEG2 DCH robot, **optimize the wiring strategy**, by taking into account the 4m long wires arranged in multi-wire layers

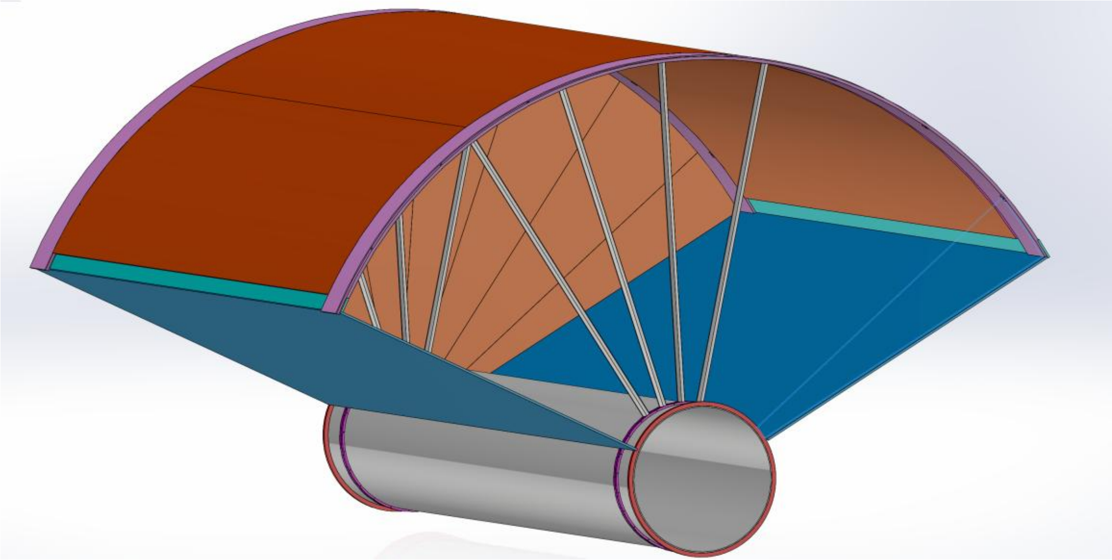
- Define and validate **the assembly scheme** (with respect to mechanical tolerances) of the multi-wire layers on the end plates
  - Define the front-end cards channel multiplicity and their location (cooling system necessary?)

- **Optimize the High Voltage and signal distribution** (cables and connectors)

- Test performance of **different versions of front-end, digitization and acquisition chain**

Full-length prototype: full overview

Target: construction a full length DCH prototype with 3 sectors per endcap

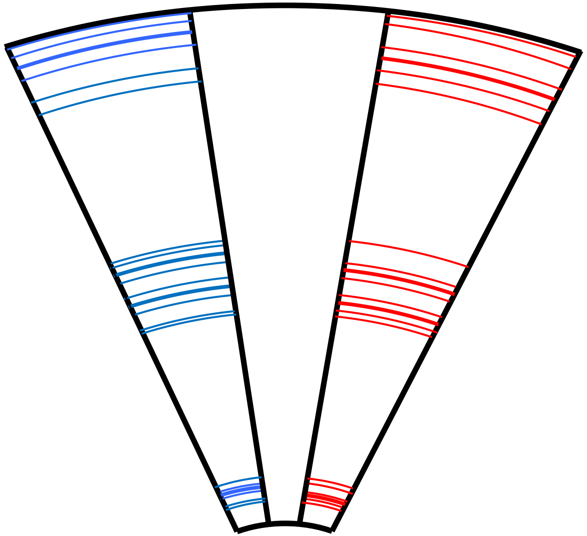


- 8 spokes (4 per endcap)
- Internal ring
- 1/3 outer ring
- 1/3 cylindrical panel

Collaboration with **CETMA composites**

- **New technique for wiring and installing PCBs on the structure**

Prototype wiring proposal



First two layers of superlayer #1
V and U guard layers (2 x 9 guard wires)
V and U field layers (2 x 18 field wires)
U layer (8 sense + 9 guard)
U and V field layers (2 x 18 field wires)
V layer (8 sense + 9 guard)
V and U field layers (2 x 18 field wires)
V and U guard layer (2 x 9 guard wires)

Last two layers of superlayer #7
V and U guard layers (2 x 21 guard wires)
V and U field layers (2 x 42 field wires)
U layer (20 sense + 21 guard)
U and V field layers (2 x 42 field wires)
V layer (20 sense + 21 guard)
V field layer (42 field wires)

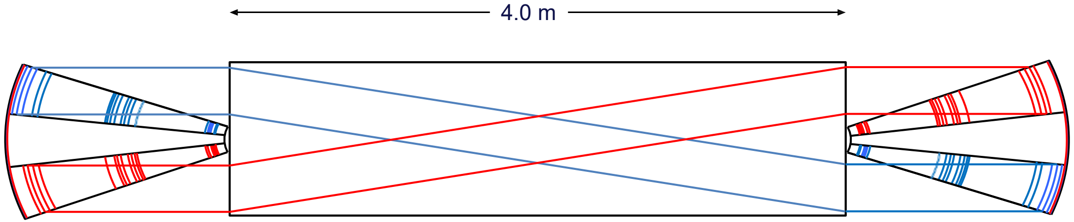
First two layers of superlayer #8
U field layer (46 field wires)
U layer (22 sense + 23 guard)
U and V field layers (2 x 46 field wires)
V layer (22 sense + 23 guard)
V and U field layers (2 x 46 field wires)
V and U guard layer (2 x 23 guard wires)

Last two layers of superlayer #14
V and U guard layers (2 x 35 guard wires)
V and U field layers (2 x 70 field wires)
U layer (34 sense + 35 guard)
U and V field layers (2 x 70 field wires)
V layer (34 sense + 35 guard)
V and U field layers (2 x 70 field wires)
V and U guard layer (2 x 35 guard wires)

TOTAL LAYERS: 8
Sense wires: 168
Field wires: 965
Guard wires: 264

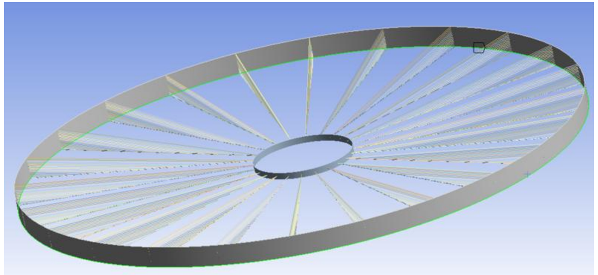
PCBoards wire layers: 42
Sense wire boards: 8
Field wire boards: 22
Guard wire boards: 12
HV values: 14

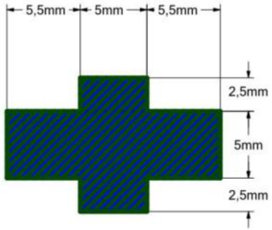
Readout channels: 8+8 + 16+16+16+16 + 16+16 = 112

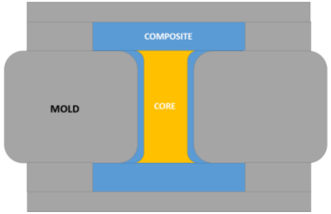


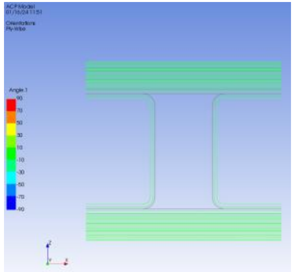
Spoke Cross Section – Tuning

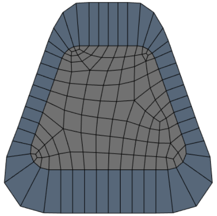
- The structural parts of the drift chamber mechanics will be built in carbon fibre.
- A key element of the wire cage structure is the “spoke”.
- Spoke manufacturing technique influences the individuation of more performant cross sections
- Optimization of spoke cross section: we investigate 3 different shapes

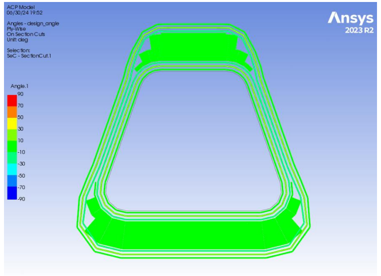












Pros:

- Well defined mating surfaces (pultruded rod) for PCB insertion
- Resistant to torsional loads

Cons:

- Deflection on the wings

Finite Element Analysis (FEA) of the spoke

Materials:

- Epoxy-Carbon UD (395 GPa) Prepreg ➔ skins of the spoke
- Epoxy Carbon UD (230 GPa) Prepreg ➔ core of the spoke
- Aluminum Alloy ➔ inner and outer cylindrical walls

Loads & Boundary Conditions:

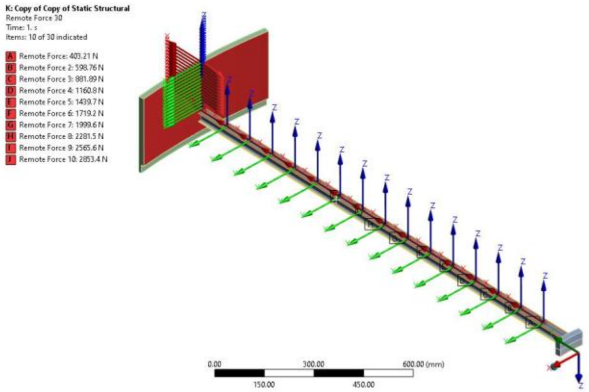
The effect of the PCBs' wire tension was defined as a pressure radially varying a from 0 to 0.159 MPa corresponding to a total load acting on the spoke of 444 kgf. Constraint fixed on top and bottom of spoke

Reaction forces:

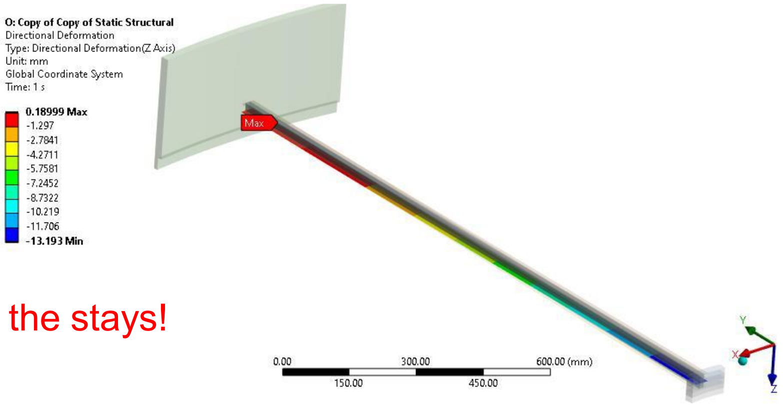
The number of stays has been estimated in 15.
The reaction forces on these constraints are the vertical components of the tensile force each stay should apply to the spoke.

Result:

Such forces were applied to the system obtaining a directional **deformation of 0.19 mm** in its maximum value.



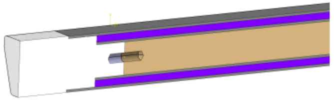
Vforce [N]	Hforce [N]
47.7	400.4
70.8	594.6
104.2	875.7
137.1	1152.7
169.9	1429.6
202.7	1707.2
235.4	1985.6
268.2	2265.7
301.1	2547.9
334.0	2833.8
367.1	3125.6
400.7	3430.7
440.6	3805.1
468.4	4116.5
499.9	4621.2

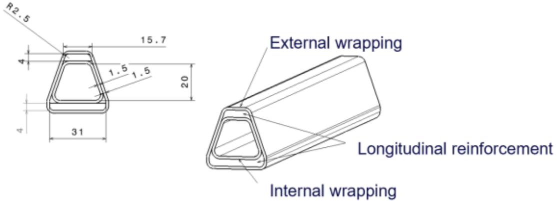


A possible improvement with pretension of the stays!

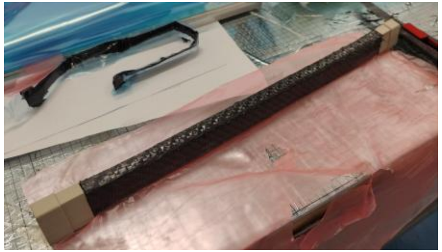
Production of the spoke

- The core was milled with a numerically controlled machine.
- The winding foils were manually cut into strips of the sizes above.
- The PEEK side inserts were glued with acrylic adhesive.





Item	Material	CPT (mm)	Layup	T (mm)
Internal wrapping	Prepreg Tissue 430g/m2	0.5	(0)3	1.5
Longitudinal reinforcement	Prepreg Tissue 800g/m2	0.86	(0)4	4
External wrapping	Prepreg Tissue 430g/m2	0.5	(0)3	1.5



Wire tests with standard protocol

Tests started in a small clean room at INFN Bari:

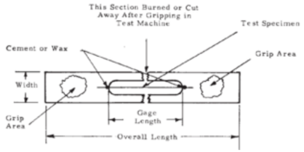
- Tungsten coated with gold
- Molibden coated with gold
- Carbon monofilament

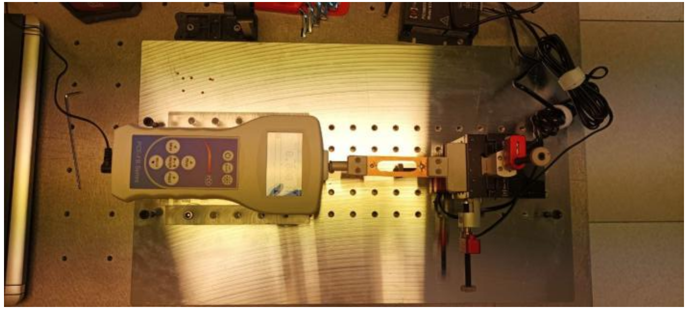
Setup:

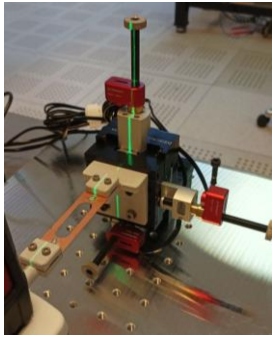
- 3 axis picometer motor (30nm step)
- Digital dynamometer (acc. 0.001N)

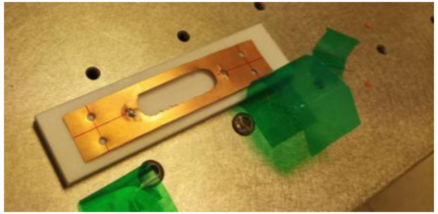
Standard ASTM D 3379 – 75

- **Scope**: Tensile Strength and Young's modulus for High-Modulus (>21 GPa) Single-Filament Materials (gage length > 2000*wire diameter)
- **Summary**: The filaments are center-line mounted on special slotted tabs. The tabs are gripped so that the test specimen is aligned axially in the jaws of a constant-speed movable-crosshead test machine. The filaments are then stressed to failure at a constant strain rate.





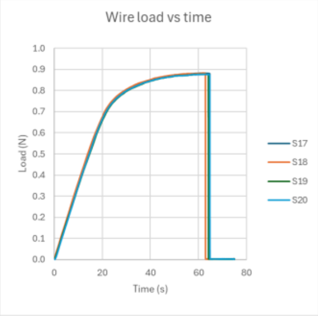


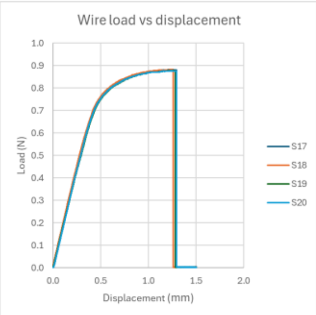


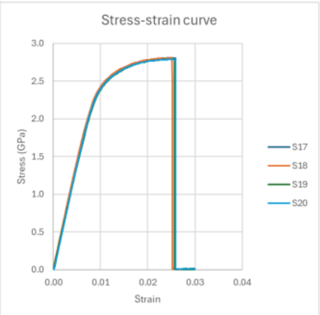
W+Au wire test

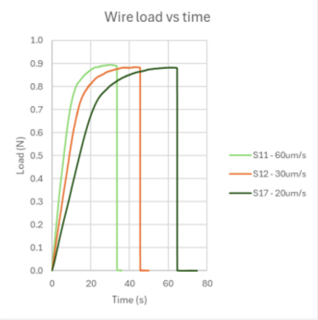
Wire diameter: 20µm

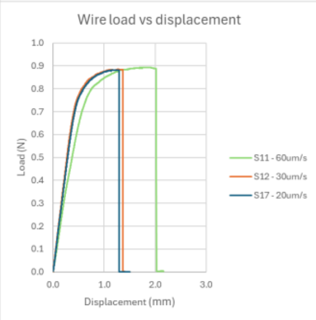
Specimen number	Tensile Strength - UTS (GPa)	Young module (Gpa)	R^2	Effective test time (s)	Total wire elongation (mm)	Elongation (%)	
1	2.811	186.561	0.9990	34.15	2.049	4.098	
2	2.820	172.631	0.9980	35.23	2.114	4.227	v=60 µm/s l=60mm
3	2.814	178.624	0.9995	38.90	2.334	4.668	
4	2.718	172.790	0.9998	40.00	2.400	4.800	
5	2.833	185.590	0.9993	34.88	2.093	4.185	
Av. Set	2.799	179.239	0.9991	36.63	2.198	4.396	
11	2.843	211.047	0.9972	33.70	2.022	4.044	
33	2.827	220.920	0.9991	29.30	1.758	3.516	v=60 µm/s l=50mm
34	2.839	246.097	0.9962	26.48	1.589	3.177	
35	2.820	246.673	0.9974	25.13	1.508	3.015	
36	2.820	209.416	0.9998	29.13	1.748	3.495	
Av. Set	2.830	226.831	0.9980	28.75	1.725	3.449	
12	2.817	295.044	0.9998	45.58	1.367	2.735	
13	2.811	289.015	0.9992	40.53	1.216	2.432	v=30 µm/s l=50mm
15	2.820	278.925	0.9997	47.95	1.439	2.877	
16	2.814	303.444	0.9997	43.55	1.307	2.613	
37	2.843	308.218	0.9998	41.90	1.257	2.514	
Av. Set	2.821	294.929	0.9996	43.90	1.317	2.634	
17	2.807	281.131	0.9998	64.75	1.295	2.590	
18	2.811	283.814	0.9997	62.95	1.259	2.518	v=20 µm/s l=50mm
19	2.792	274.393	0.9997	64.15	1.283	2.566	
20	2.792	282.702	0.9996	64.75	1.295	2.590	
38	2.792	291.537	0.9997	60.63	1.213	2.425	
Av. Set	2.799	282.715	0.9997	63.45	1.269	2.538	

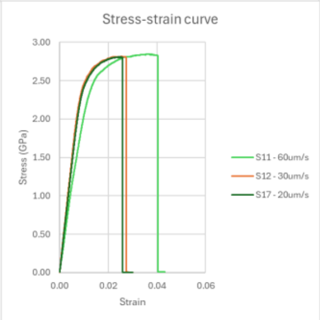


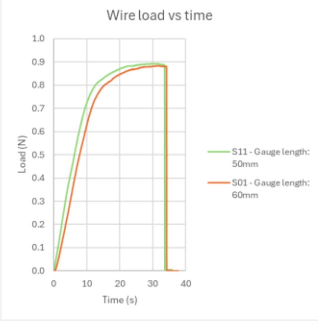


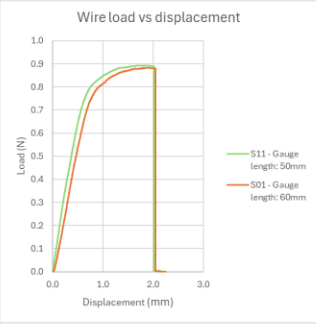


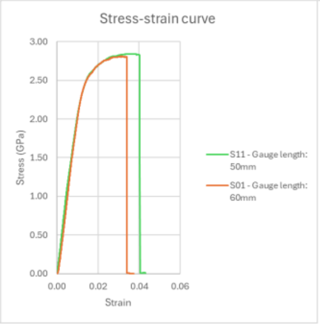










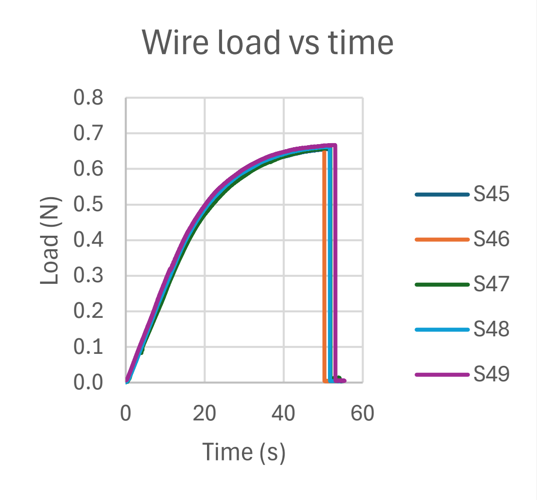


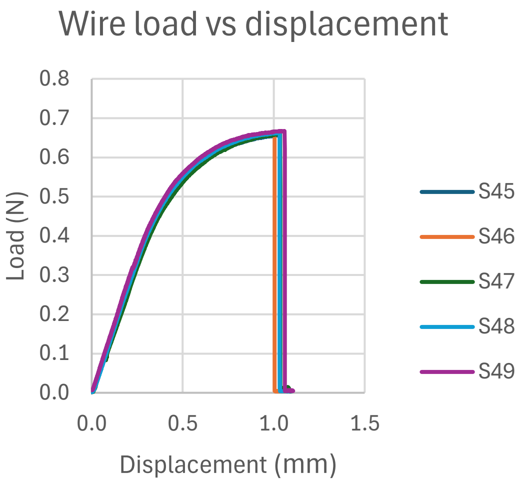
Mo+Au wire test

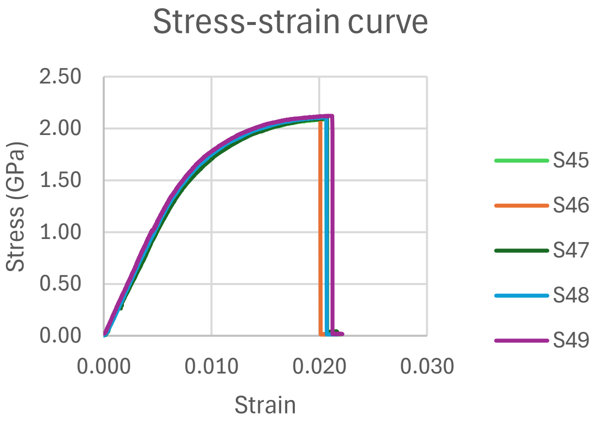
Specimen number	Tensile Strength - UTS (GPa)	Young module (Gpa)	R^2	Effective test time (s)	Total wire elongation (mm)	Elongation (%)
45	2.091	220.031	0.9992	51.675	1.034	2.067
46	2.107	226.061	0.9995	50.275	1.006	2.011
47	2.101	206.040	0.9979	54.175	1.084	2.167
48	2.110	222.461	0.9997	51.700	1.034	2.068
49	2.123	224.851	0.9993	53.075	1.062	2.123
Average Set	2.107	219.889	0.999	52.180	1.044	2.087

Wire diameter: 20µm

v=20 µm/s
l=50mm





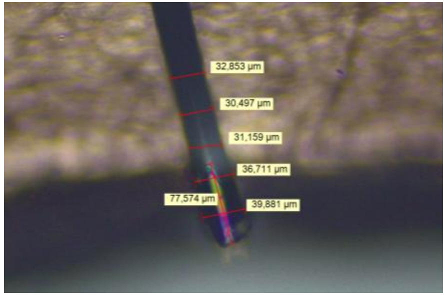


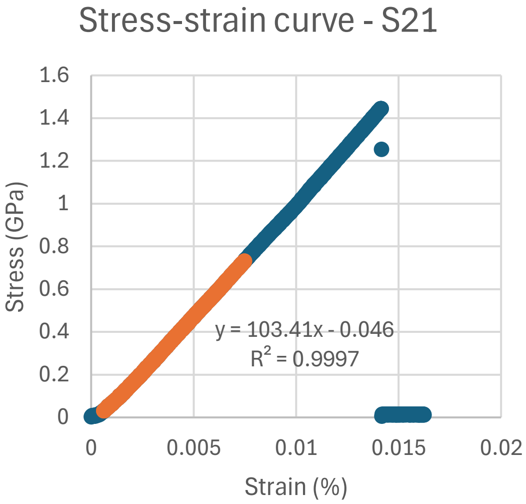
Monofilament C wire test

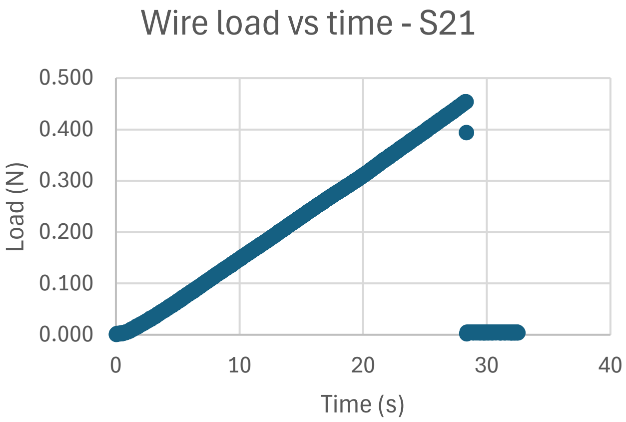
Specimen number	Tensile Strength - UTS (GPa)	Young module (Gpa)	R^2	Effective test time (s)	Total wire elongation (mm)	Elongation (%)
21	1.445	103.413	0.9997	28.350	0.567	1.418
22	1.732	102.886	0.9996	33.725	0.675	1.686
23	2.120	103.973	0.9999	41.375	0.828	2.069
24	2.247	98.236	0.9986	45.650	0.913	2.283
25	2.247	107.915	0.9996	41.425	0.829	2.071
Average Set	1.958	103.284	0.999	38.105	0.762	1.905

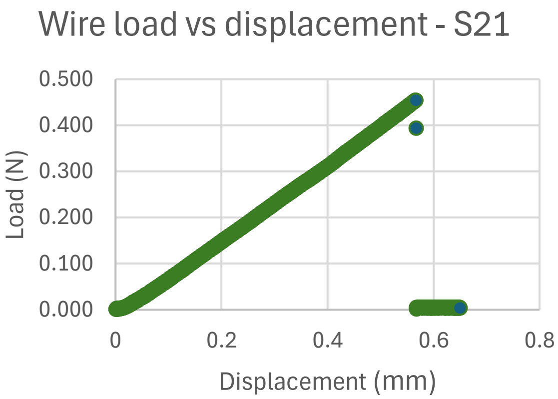
Wire diameter: 33.5µm

v=20 µm/s
l=40mm









What happens now?

Simulations:

- Study the stability of the outer and inner rings with all the connections
- Study the best solution for **connect the stays at the spokes**
- **Buckling** analysis on outer cylinder

Production:

- More spokes prototype
- Mechanical test with torsion, compression, bending
- Internal and external ring with the connection

Test to do in parallel:

- Characterize Al wires we have (micrometer positioning stages) – next month

Summary and plans

Good progress reported on:

- mechanical structure design
- on going effort to build a full-length prototype next year
- testbeam data analysis → results ongoing

Plenty of areas for collaboration (also in the context of DRD1 WP2):

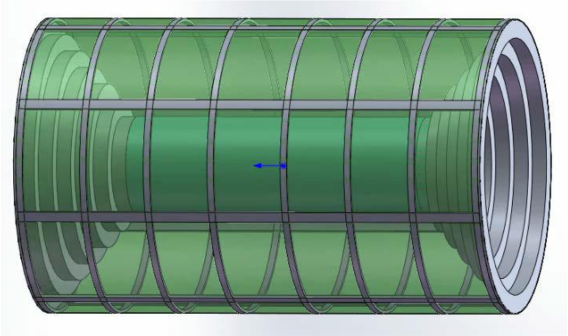
- detector design, construction, beam test, performance
- local and global reconstruction, full simulation
- physics performance and impact
- etc.

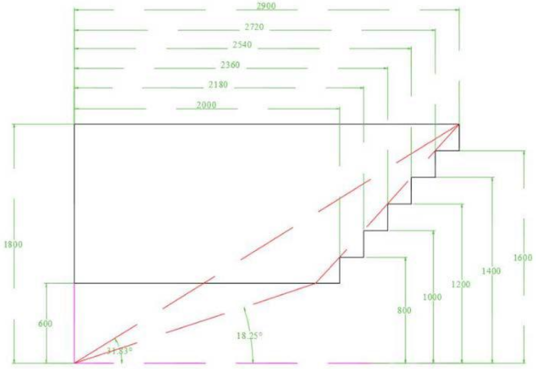
Effort to build a international collaboration enforced

- well established collaboration with IHEP for NN-based cluster counting algorithms
- started to collaborate with US people from BNL

- First phase of conceptual design of full chamber completed as of today by a collaboration of EnginSoft and INFN-LE mechanical service: final draft of technical report ready
- Full design of full-scale prototype completed by summer 2024 by EnginSoft (purchase order issued) with INFN-LE mechanical service
- Preparation of samples of prototype components (molds and machining) ready by fall 2024 by CETMA consortium
- All mechanical parts (wires, wire PCBs, spacers, end plates) ready by autumn of 2025
- MEG2 CDCH2 Wiring robot transported from INFN-PI (being used for MEG2 CDCH2 until May 2024) to INFN-LE/BA, refurbished and re-adapted, to be operational by autumn 2025
- Wiring and assembling clean rooms:
  - INFN-LE clean room currently occupied by ATLAS ITK assembly (until 2026 ?)
  - Investigating the possibility of renovate a clean room at INFN-BA or at CNR-LE (subject to agreement between INFN and CNR)
- Prototype built by end of 2025/beginning 2026 and ready to be tested during 2026

CEPC Drift Chamber: overview





CF Frame structure: 8 longitudinal hollow beams + 8 annular hollow beams

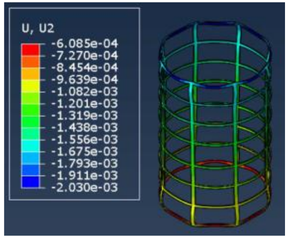
Length: 5800mm

Outer diameter: 3600mm

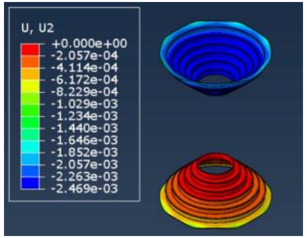
Inner Diameter: 1200mm；

Thickness of each end plate: 25mm

Weight: 1100kg



CF frame deformation: 2mm



Endplate deformation 2.5mm

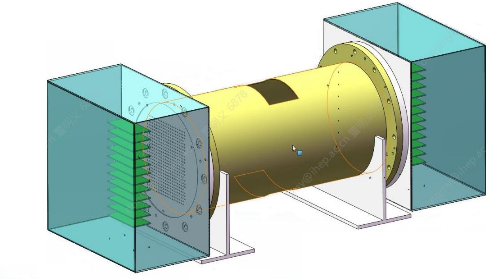
Optimization →

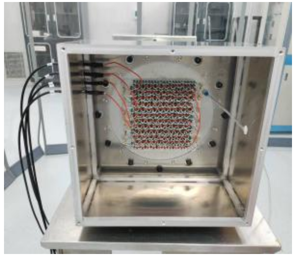
Thickness (mm)	Max Equivalent Elastic Strain (mm)	Max Equivalent (von-Mises) Stress (MPa)
15	2.08e-4	14.75
17.5	7.28e-5	5.17
20	3.63e-5	2.55
22.5	3.09e-5	2.19
25	2.91e-5	2.07

CEPC Drift Chamber: design of a multi-layer drift chamber prototype

A Prototype was designed for the study of dN/dx

- A cylinder + two end plates
- 12 layers, 10 cells/ layer
- **120 cells in total**
- **Length: 60cm**
- Cell size : 18 mm × 18 mm
- Ratio of field wires to sense wires : 3:1
- Sense wire: 20 μm Au-plated tungsten
- Field wire: 70 μm Aluminum



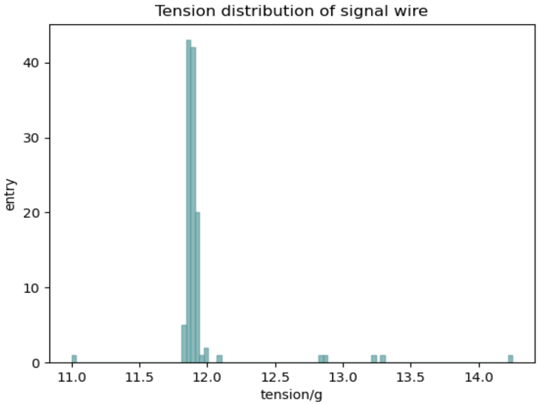


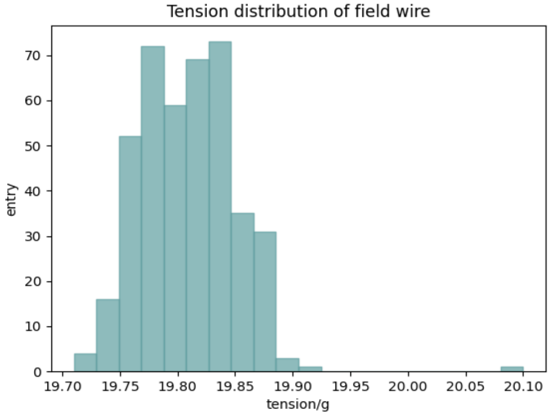
Sense wire tension: 11g , Sag : 50μm

field wire tension: 19g, Sag : 50μm

Leak current: < 1nA

- **Finished the prototype construction, cabling and HV training**
- Gas mixture: He/iC_4H_{10} =90/10
- **Commissioning and preliminary testing with cosmic-ray are ongoing**





Thanks for your attention

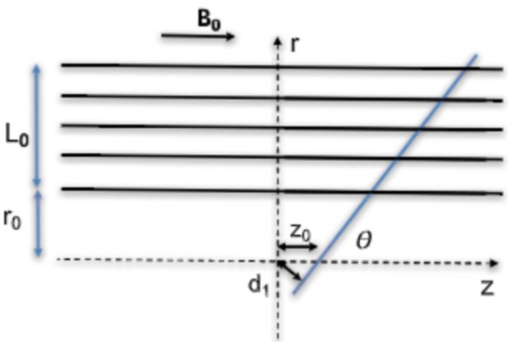
Backup

IDEA Drift Chamber: Momentum and Angular Resolutions

$$\frac{\Delta p_T}{p_T}\Big|_{res.} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}}$$
$$\approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{N}{\sqrt{(N+1)(N-1)}}\,\frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0} \times \sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}\left(1+0.038\ln\frac{d}{X_0\,\sin\theta}\right)$$
$$\approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

$$\Delta\theta|_{res.} = \frac{\sigma_z\,\sin^2\theta}{L_0}\sqrt{\frac{12N}{(N+1)(N+2)}}$$
$$\approx \frac{2\,\sigma_z\,\sin^2\theta}{L_0}\sqrt{\frac{3}{N+3}}$$
$$\Delta\theta|_{m.s.} = \frac{\sin\theta}{\beta\, p_T}\, f\left(\frac{d}{X_0\,\sin\theta}\right)$$
$$\approx \frac{0.0136\,\mathrm{GeV/c}\,\sin\theta}{\beta\, p_T}\sqrt{\frac{d}{X_0\,\sin\theta}}$$

$$\Delta\phi|_{res.} \approx \frac{\sigma_{r\phi}}{L_0}\frac{8\sqrt{3}}{\sqrt{N+5}}\sqrt{1+\frac{15}{4}\frac{r_0}{L_0}+\frac{15}{4}\frac{r_0^2}{L_0^2}}$$
$$\Delta\phi|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T}\sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+2\left(\frac{r_0}{L_0}\right)+4\left(\frac{r_0}{L_0}\right)^2}$$



Acceptance constraints:

$\Delta\Omega \approx 98.5\% \implies \vartheta_{min} = 10°$

$r_0 = L_z/2 \tan\vartheta_{min} = 0.35$ m

(also considerations about **occupancy** due to **beam bkgnds**)

given $\mathbf{B_0 = 2}$ **Tesla**, $\mathbf{L_0 = 1.65}$ **m**, at high momenta:

$\Delta(^1/_{p_T}) \sim 2\times10^{-5} \implies N > 100,\ \sigma_{r\phi} \lesssim 100\ \mu m$ (*for a drift chamber, DC*)

$\implies N > 5,\ \sigma_{r\phi} \lesssim 30\ \mu m$ (*for a solid state detector, SSD*)

at low (multiple scattering dominated) momenta:

$\Delta(^1/_{p_T}) \sim 1\times10^{-3}/(p_T \cdot \sin\vartheta) \implies d_{tot} \lesssim 5\times10^{-3} X_0$ ($\sim$ *satisfied for a DC, gas + wires*)

($\cong$ *one single plane of a SSD*)

with $\mathbf{r_0 = 0.35}$ **m**, $\boldsymbol{\vartheta} \mathbf{= 45°}$, **p = 45 GeV/c** ($p_T$ = 32 GeV/c):

$$\Delta\vartheta|_{m.s.} \text{ and } \Delta\phi|_{m.s.} \approx 40\ \mu rad$$

Material budget

Material budget estimates

- Inner wall (from CMD3 drift chamber) $8.4\times10^{-4}\ X_0$
  200 μm Carbon fiber
- Gas (from KLOE drift chamber) $1.3\times10^{-3}\ X_0$
  90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) $1.3\times10^{-3}\ X_0$
  20 μm W sense wires $6.8\times10^{-4}\ X_0$
  40 μm Al field wires $4.3\times10^{-4}\ X_0$
  50 μm Al guard wires $1.6\times10^{-4}\ X_0$
- Outer wall (from Mu2e I-tracker studies) $1.2\times10^{-2}\ X_0$
  2 cm composite sandwich (7.7 Tons)
- End-plates (from Mu2e I-tracker studies) $4.5\times10^{-2}\ X_0$
  wire cage + gas envelope
  incl. services (electronics, cables, ...)

Increase cell size to *w > 1.5 cm (+10%)*

(56,448 → 45,700 cells, 112 → 100 layers, 340,000 → 500,000 wires, 9 → 18 Ton)
and **replace 20 μm W and 40-50 μm Al** (5:1) with
(2 (0.5) μm Ag coated) **35 μm C wires** (10:1). Stability condition:
30 g < T_c < 87 g corresponding to ***270 (158) μm > δ_{grav} > 93 (54) μm***
(safety factor within ample margin!)

Contribution to m. scatt. from wires: $1.3\times10^{-3}\ X_0 \rightarrow 0.9\times10^{-3}\ X_0$

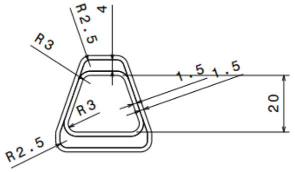
Why 200 μm deformation as main goal?

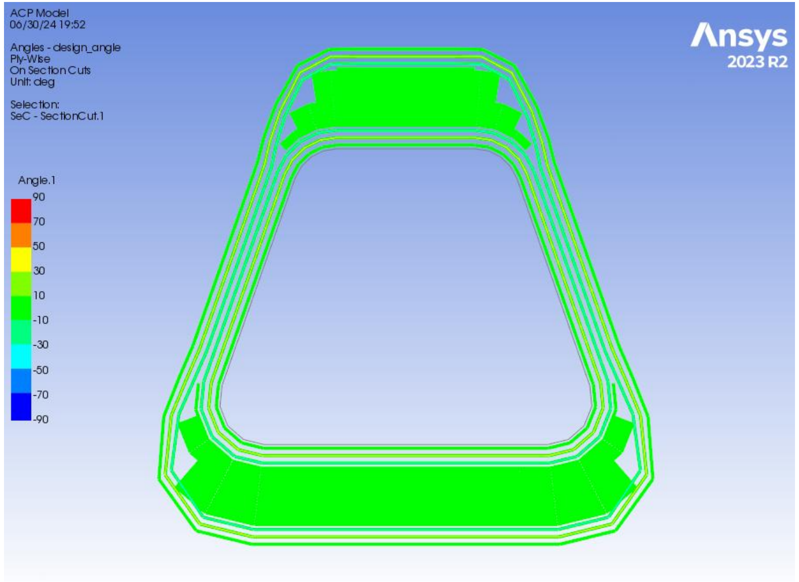
- A wire tensioned at 30g stretches by 3mm/m, on 4m we have **12mm** of tension length on the wire.

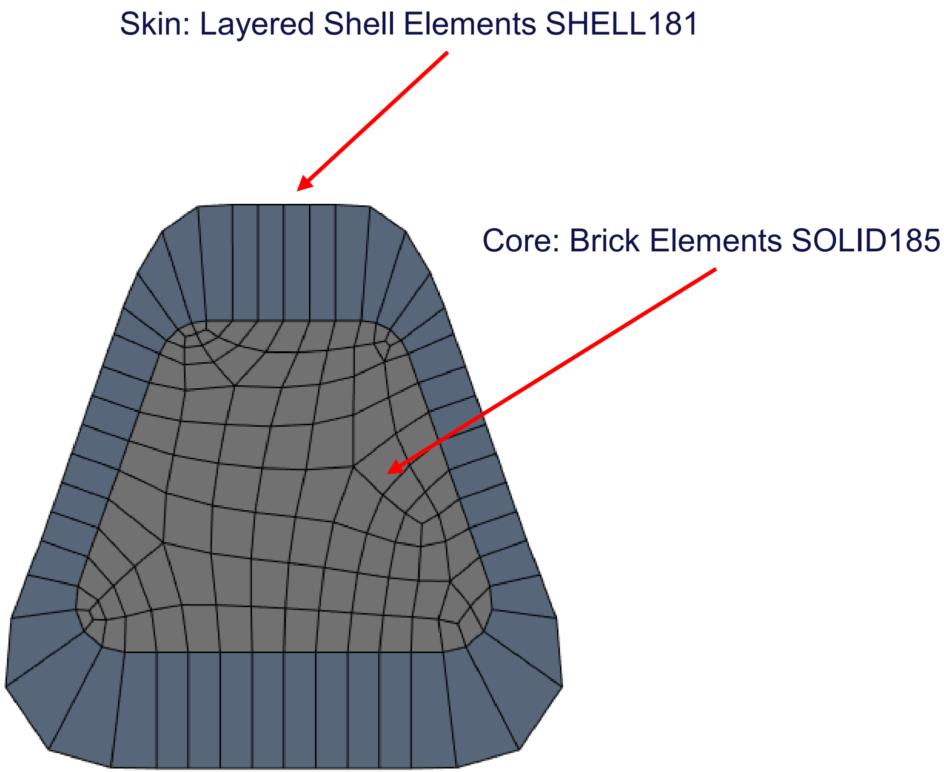
- If we assume 2% error -> 240 μm
- If the spokes deform by 240 μm it means that the tension of the wire changes by 2% (0.6gr) and we are wrong by 2% on the sagitta therefore by **8μm**. This added in quadrature to the 50 μm gives us an acceptable value.

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

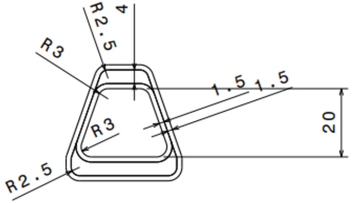
Spoke Cross Section – Tuning

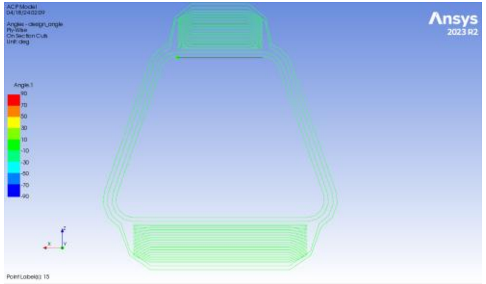


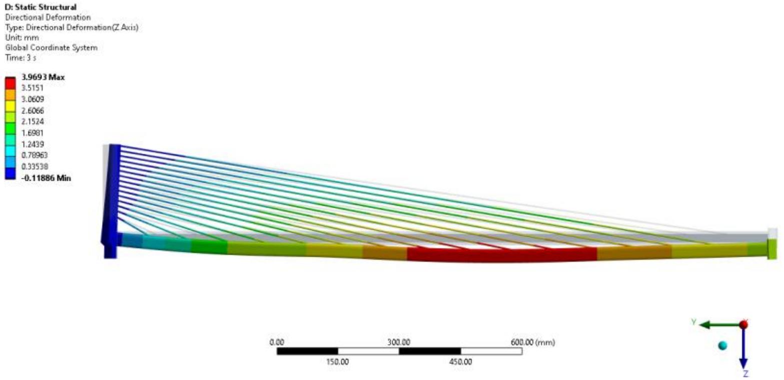




Simulation studies: progress about the final design of the cross section of the spoke



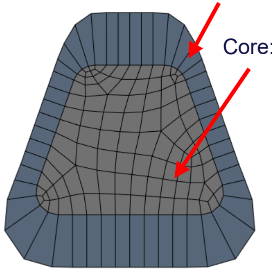




Statical structural simulation: deformation along z

Skin: Layered Shell Elements SHELL181

Core: Brick Elements SOLID185

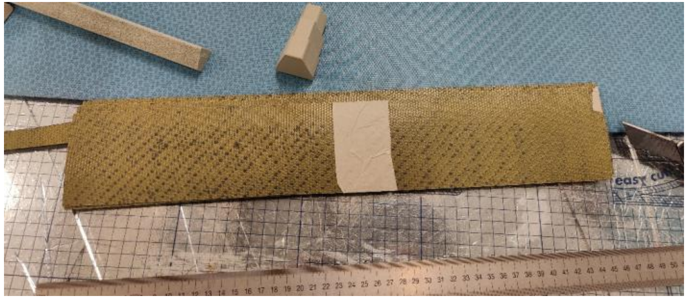
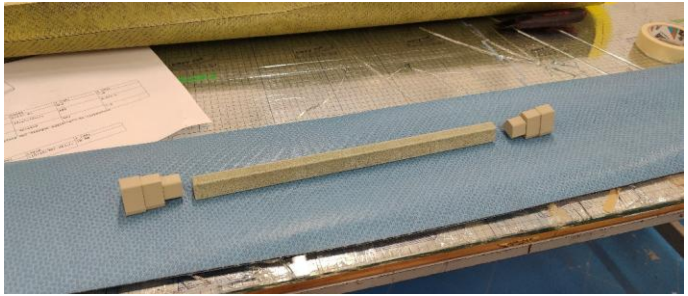
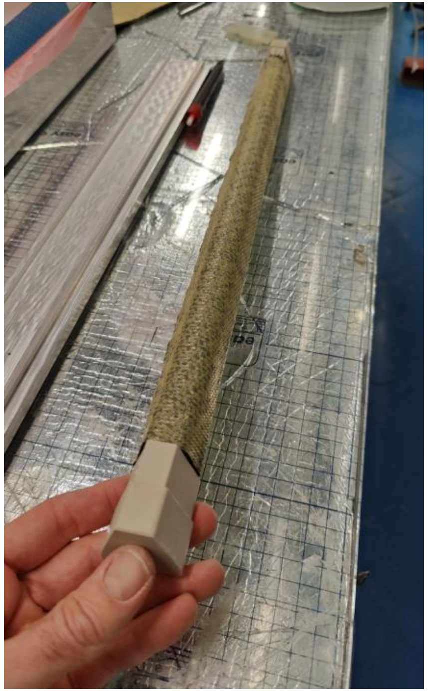


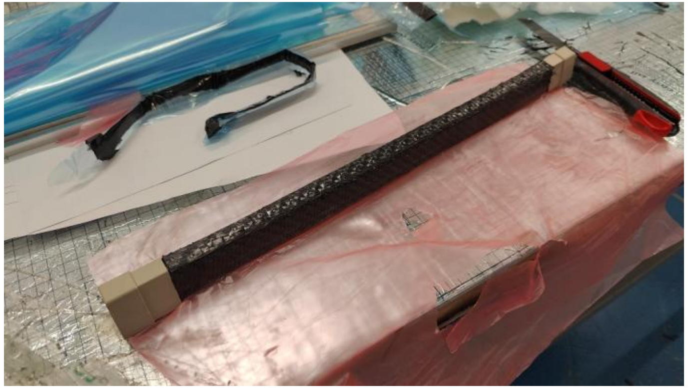
Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	1.	-0.11291859	10.385392	5.6093398
2	2.	-0.12170477	6.1265187	3.3920221
3	3.	-0.11885951	3.9693396	2.5614909

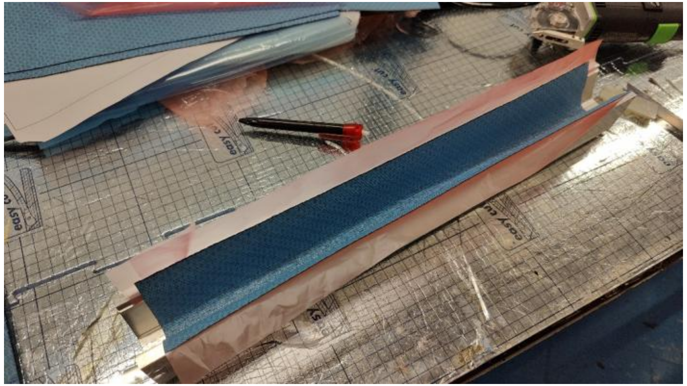
Our **main goal** was to limit the deformation of the spokes to **200 µm** while ensuring the structural integrity.

Internal wrapping

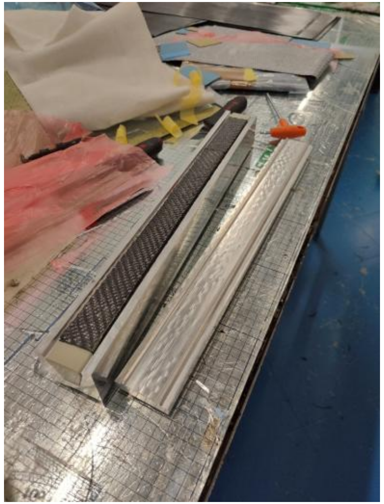
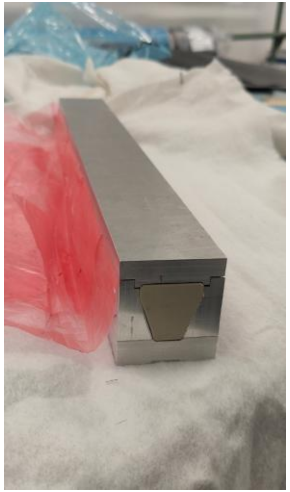


External wrapping



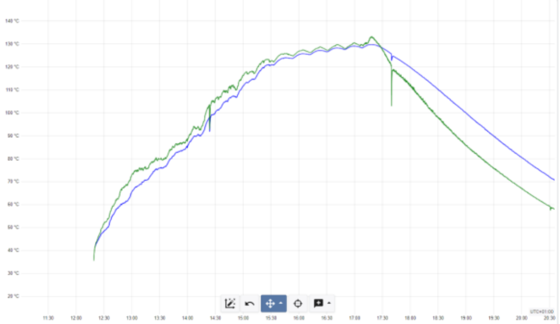
The external winding sheets were placed directly on the surface of the mold, taking care to leave some release agent near the areas to be overlapped to close the section.

External reinforcement lamination

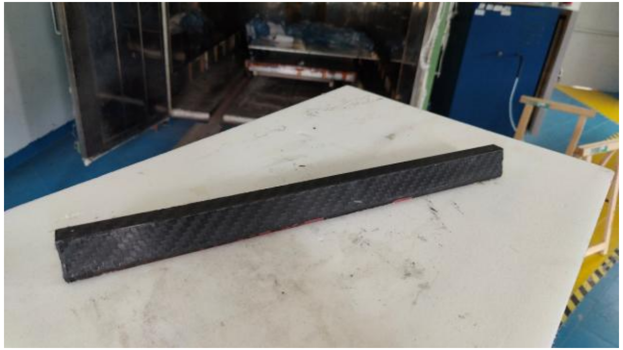

The vacuum mold is placed in the oven for curing with the following thermal cycle. The temperature is controlled by thermocouples on the mold.

- From 25 °C to 80 °C with a 2 °C/min
- From 80 °C to 135 ° with a 0.5 °C/min
- Stasis at 130 °C for two hours
- Natural cooling with the oven off



Spoke extraction

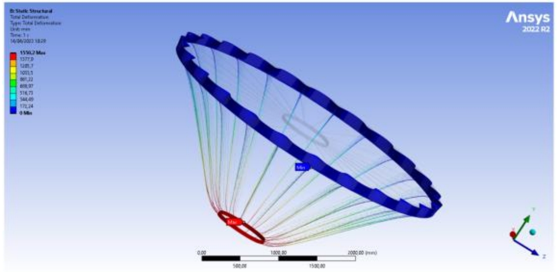
- The component is easily removed from the mold and cleaned manually from excess resin.
- The PEEK inserts show poor adhesion to the prepreg. The acrylic adhesive that joined the three pieces weakens due to the temperature and the parts detach from each other.
- Now we're investigating a solutions with carbon-based inserts.




Preliminary design: FEM analysis

Linear analysis

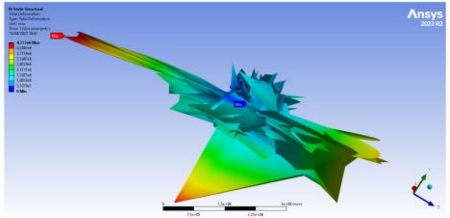
HP: small deformations in a **single time step**
Goal: find errors in the model with small computational time



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

Non-Linear analysis

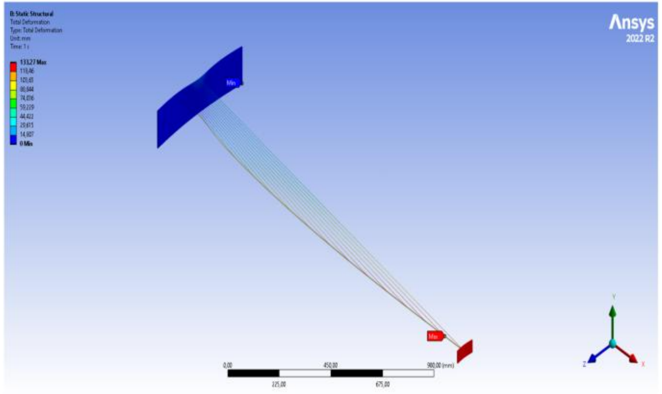
HP: Large strain, rotation, stress stiffening
The load is applied in a **single time step** ⟶ discrepancy between applied and internal element forces



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

↓

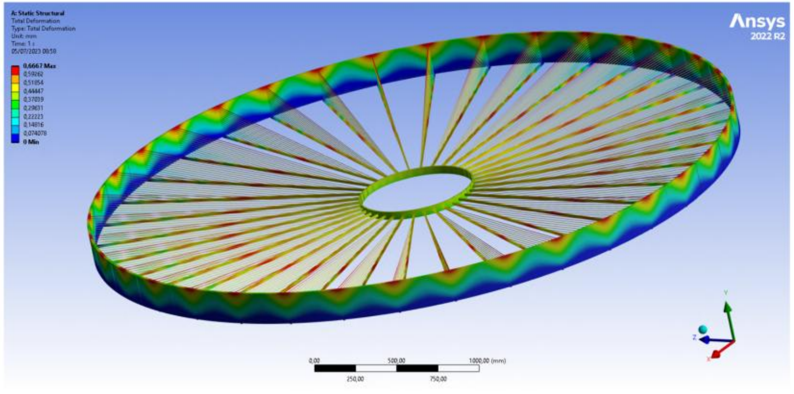
Linearly increasing line pressure

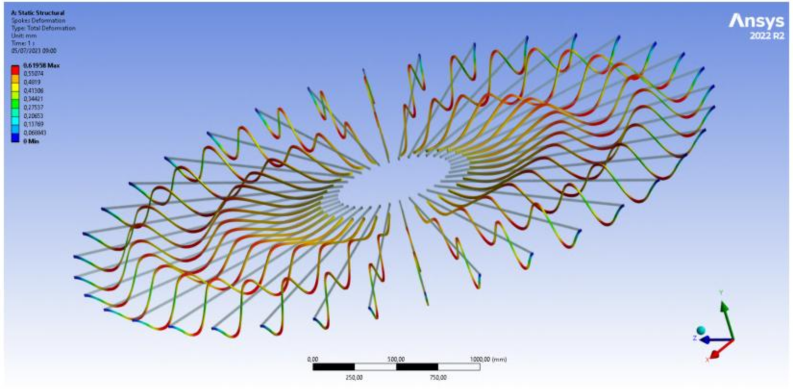
Goal: minimizing the deformation of the spokes using prestressing force in the cables

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

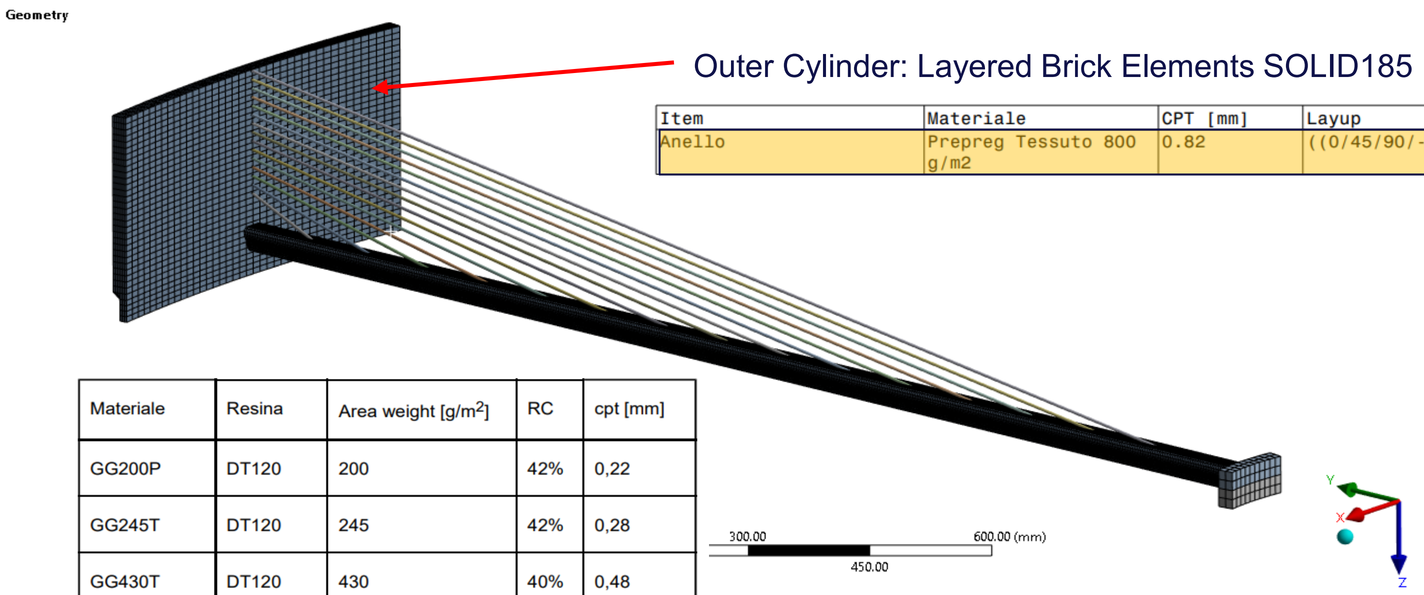
Total deformation (mm) of the drift chamber with the edge of the outer cylinders fixed

No prestress		Prestress in the cables	
Spokes	Outer cylinder	Spokes	Outer cylinder
14.099	0.63	0.62	0.67





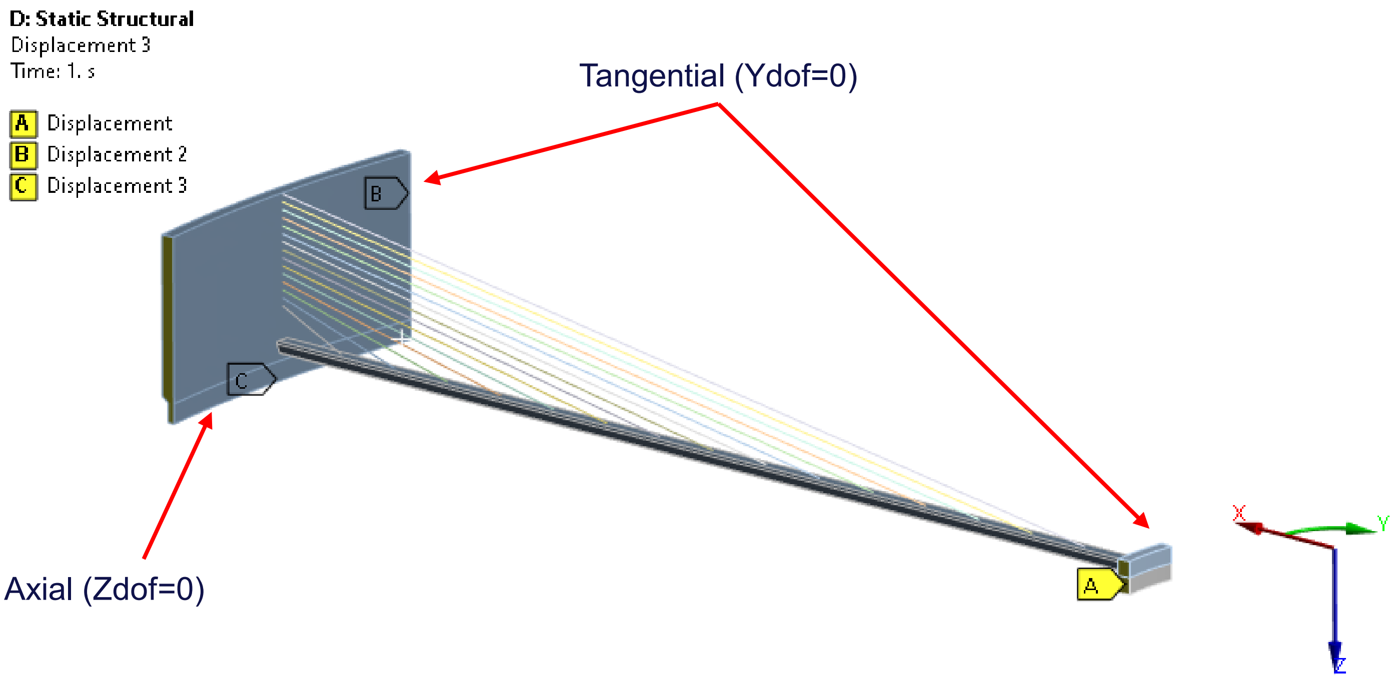
Outer Cylinder – Lamination by Manufacturer



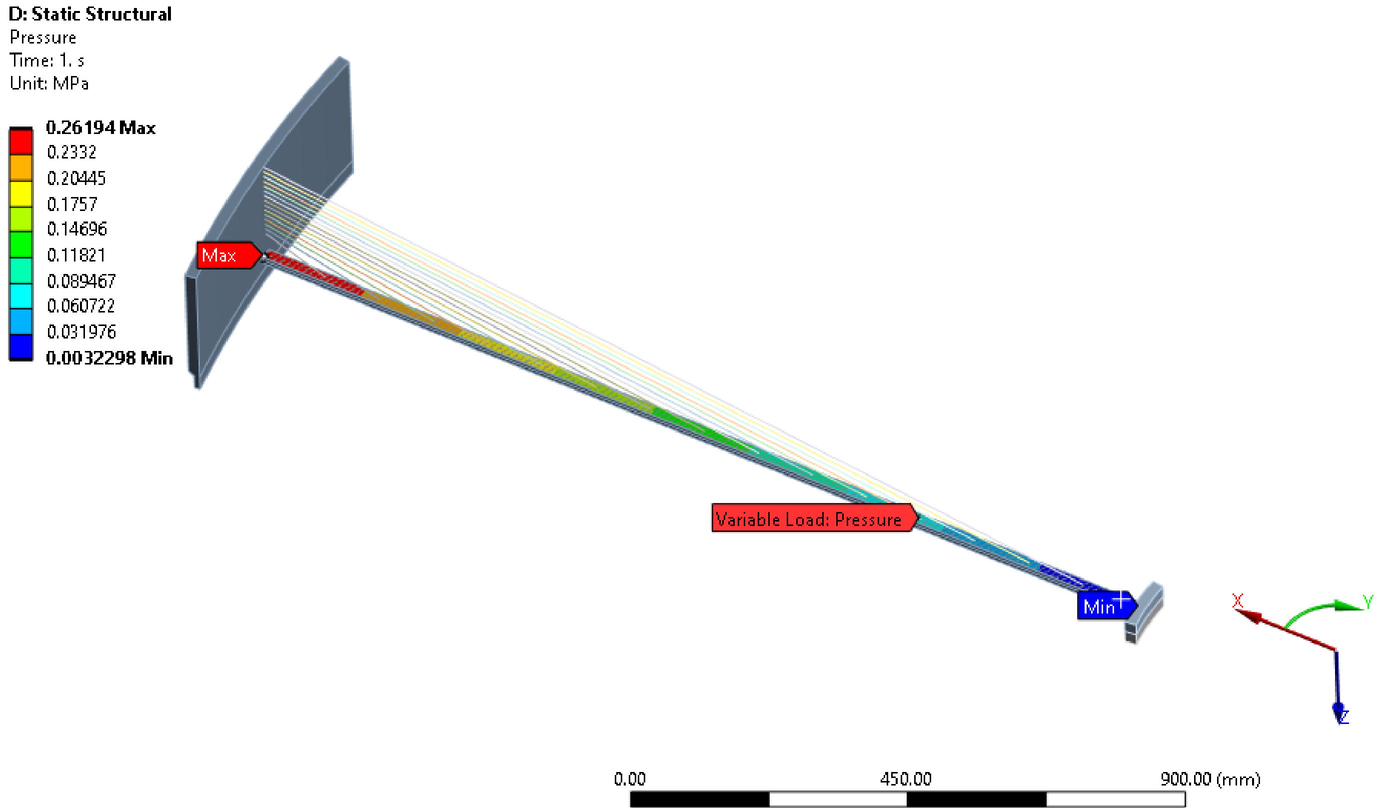
Item	Materiale	CPT [mm]	Layup	t [mm]
Anello	Prepreg Tessuto 800 g/m2	0.82	$((0/45/90/-45)_3)_s$	19.68

Materiale	Resina	Area weight [g/m^2]	RC	cpt [mm]
GG200P	DT120	200	42%	0,22
GG245T	DT120	245	42%	0,28
GG430T	DT120	430	40%	0,48
GG630T	DT120	630	37%	0,66
GG800T	DT120	800	36%	0,82
UD200	DT120	200	36%	0,2

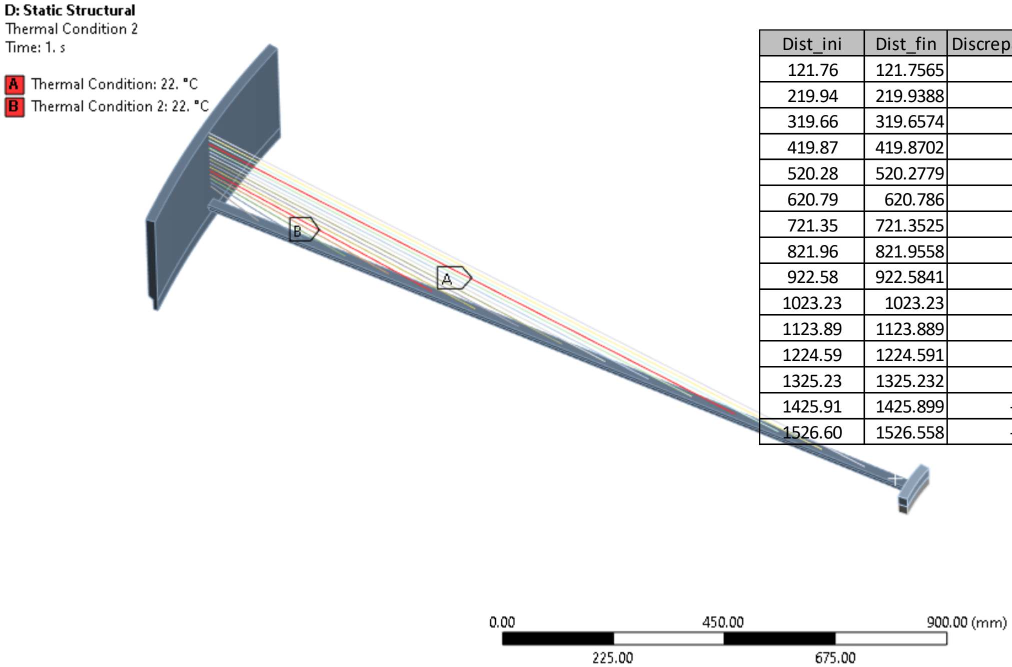
Loads & Boundary Conditions



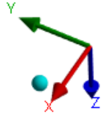
Loads & Boundary Conditions



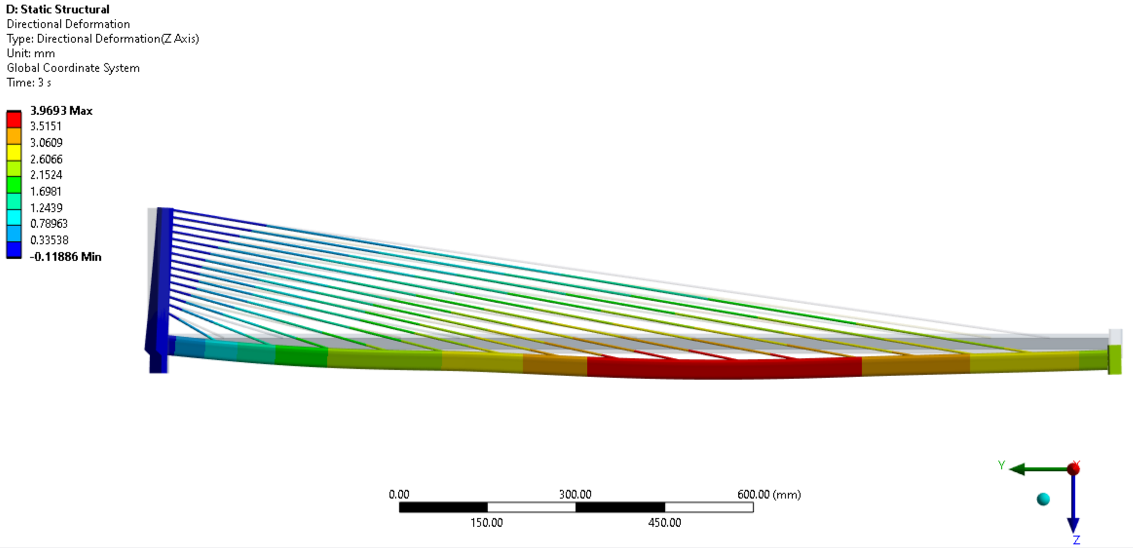
Loads & Boundary Conditions

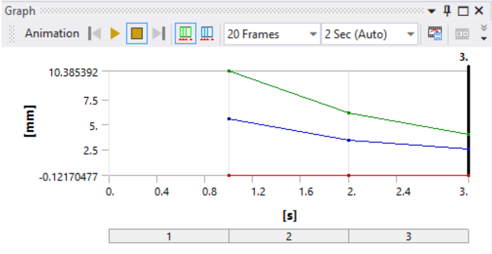


Dist_ini	Dist_fin	Discrepancy	Nuova_dist	Delta	Alpha [1/°C]	Delta T [°C]	T1 [°C]	T2 [°C]	
121.76	121.7565	0.00	121.5806661	0.18	1.20E-05	120.32	22	-98.32	
219.94	219.9388	0.00	219.6749201	0.26		99.91		-77.91	
319.66	319.6574	0.00	319.308515	0.35		90.87		-68.87	
419.87	419.8702	0.00	419.4359116	0.43		86.12		-64.12	
520.28	520.2779	0.00	519.7576378	0.52		83.26		-61.26	B
620.79	620.786	0.00	620.1804246	0.61		81.23		-59.23	
721.35	721.3525	0.00	720.6642402	0.69		79.45		-57.45	
821.96	821.9558	0.00	821.185227	0.77		78.08		-56.08	
922.58	922.5841	0.00	921.732505	0.85		76.88		-54.88	
1023.23	1023.23	0.00	1022.299678	0.93		75.73		-53.73	
1123.89	1123.889	0.00	1122.879125	1.01		74.82		-52.82	
1224.59	1224.591	0.00	1223.502694	1.09		74.00		-52.00	A
1325.23	1325.232	0.00	1324.067583	1.16		73.24		-51.24	
1425.91	1425.899	-0.02	1424.674271	1.24		72.45		-50.45	
1526.60	1526.558	-0.04	1525.288659	1.31		71.60		-49.60	



Results





Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	1.	-0.11291859	10.385392	5.6093398
2	2.	-0.12170477	6.1265187	3.3920221
3	3.	-0.11885951	3.9693396	2.5614909

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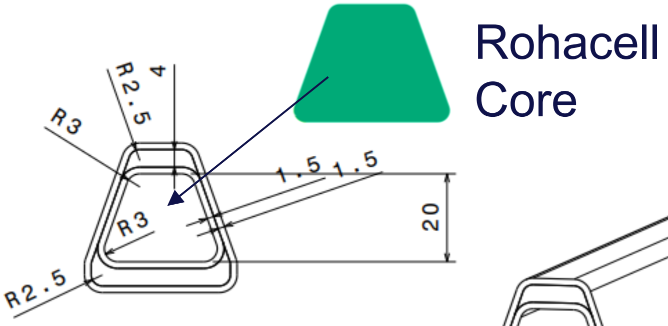
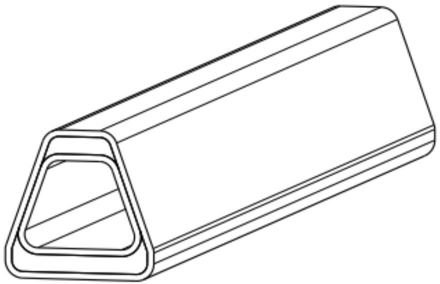
Spoke Cross Section – Lamination by Manufacturer





Materiale	Resina	Area weight [g/m^2]	RC	cpt [mm]
GG200P	DT120	200	42%	0,22
GG245T	DT120	245	42%	0,28
GG430T	DT120	430	40%	0,48
GG630T	DT120	630	37%	0,66
GG800T	DT120	800	36%	0,82
UD200	DT120	200	36%	0,2

Item	Materiale	CPT [mm]	Layup	t [mm]
Avvolgimento interno	Prepreg Tessuto 430 g/m2	0.5*	0/45/-45	1.5
Riforzo Longitudinale	Prepreg UD 200 g/m2	0.2	$(0)_{20}$	4
Avvolgimento esterno	Prepreg Tessuto 430 g/m2	0.5*	-45/45/0	1.5

Spoke Cross Section – Lamination by Manufacturer

Table 1

GG200T(Toray FT300B)-DT120-42 Fabric Laminate

GG430T(Tenax HTS40)-DT120-38 Fabric Laminate

Mechanical Tests	Test Method	RT GG200T	RT GG430T
Tensile Strength (0°) (MPa)	ASTM D 3039	693	1070
Tensile Modulus (0°) (GPa)	ASTM D 3039	55.8	62.3
Tensile Strength (90°) (MPa)	ASTM D 3039	610	976
Tensile Modulus (90°) (GPa)	ASTM D 3039	53.7	61.5
Compression Strength (0°) (MPa)	ASTM D 6641	552	715
Compression Modulus (0°) (GPa)	ASTM D 6641	50.7	59.3
Compression Strength (90°) (MPa)	ASTM D 6641	558	694
Compression Modulus (90°) (GPa)	ASTM D 6641	51.3	59.8
In-Plane Shear Strength (MPa)	EN 6031	109.1	107.6
In-Plane Shear Modulus (GPa)	EN 6031	3.12	3.33
ILSS (MPa)	EN 2563	67.7	72.4

Table 2

Toray M30SC-DT120-200-36 UD Laminate

Mechanical Tests	Test Method	RT
Tensile Strength (0°) (MPa)	ASTM D 3039	3010
Tensile Modulus (0°) (GPa)	ASTM D 3039	145.0
Tensile Strength (90°) (MPa)	ASTM D 3039	39
Tensile Modulus (90°) (GPa)	ASTM D 3039	6.4
Compression Strength (0°) (MPa)	ASTM D 6641	1020
Compression Modulus (0°) (GPa)	ASTM D 6641	133.0
Compression Strength (90°) (MPa)	ASTM D 6641	138.0
Compression Modulus (90°) (GPa)	ASTM D 6641	8.1
In-Plane Shear Strength (MPa)	EN 6031	95.6
In-Plane Shear Modulus (GPa)	EN 6031	3.38
ILSS (MPa)	EN 2563	77.2

Property	Test Method*	Unit	ROHACELL® 51 RIMA	ROHACELL® 71 RIMA	ROHACELL® 110 RIMA
Density	ISO 845 ASTM D 1622	kg/m³ lbs/ft³	52 3.25	75 4.68	110 6.87
Compressive Strength	ISO 844 ASTM D 1621	MPa psi	0.8 116	1.7 246	3.6 522
Tensile Strength	ISO 527-2 ASTM D 638	MPa psi	1.6 232	2.2 319	3.7 536
Tensile Modulus	ISO 527-2 ASTM D 638	MPa psi	75 10,875	105 15,225	180 26,100
Elongation at Break	ISO 527-2 ASTM D 638	%	7	7	7
Shear Strength	DIN 53294 ASTM C 273	MPa psi	0.8 116	1.3 188	2.4 348
Shear Modulus	DIN 53294 ASTM C 273	MPa psi	24 3,480	42 6,090	70 10,170
Coefficient of Thermal Expansion		1/K*10E-5	4.06	3.40	3.64

Technical data values presented above are typical for nominal density, subject to normal manufacturing variations. *Data values are based on ISO & DIN standard test methods, however ASTM values can be confirmed upon request. All ROHACELL® products are closed-cell rigid foams based on polymethacrylimide (PMI) chemistry and contain no CFC's.

Full-length prototype for the IDEA DCH @ FCC-ee

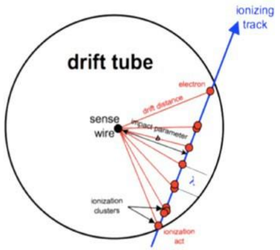
Goals:

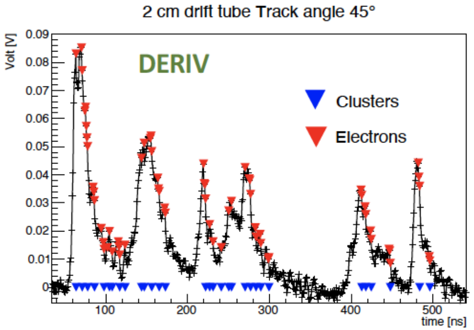
- ▶ **Check the limits of the wires electrostatic stability at full length and at nominal stereo angles**
- ▶ Test different wires: uncoated Al, C monofilaments, Mo sense wires of different diameters
- ○ **Test different wire anchoring procedures (soldering, welding, gluing, crimping, …) to the wire PCBs**
- ○ **Test different materials and production procedures for spokes, stays, support structures and spacers**
- ○ Test compatibility of proposed materials with drift chamber operation (outgassing, aging, creeping, …)
- ▶ Validate the concept of the wire tension recovery scheme with respect to the tolerances on the wire positions
- ○ Optimize the layout of the wires' PCBs (sense, field and guard), according to the wire anchoring procedures, with aim at minimizing the end-plate total material budget
- ▶ **Starting from the new concepts implemented in the MEG2 CDCH robot, optimize the wiring strategy, by taking into account the 4m long wires arranged in multi-wire layers**
- ▶ **Define and validate the assembly scheme** (with respect to mechanical tolerances) **of the multi-wire layers on the end plates**
- ○ Define the front-end cards channel multiplicity and their location (cooling system necessary?)
- ▶ Optimize the High Voltage and signal distribution (cables and connectors)
- ▶ **Test performance of different versions of front-end, digitization and acquisition chain**

IDEA Drift Chamber: Cluster Counting/Timing and PID

Principle: In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.





- collect signal and identify peaks
- record the time of arrival of electrons generated in every ionisation cluster
- reconstruct the trajectory at the most likely position

Requirements
fast front-end electronics
(**bandwidth ~ 1 GHz**)
high sampling rate digitization
(**~ 2 GSa/s, 12 bits, >3 KB**)

- Landau distribution of dE/dx originated by the mixing of primary and secondary ionizations, has large fluctuations and limits separation power of PID → primary ionization is a Poisson process, has small fluctuations

- The cluster counting is based on replacing the measurement of an ANALOG information (the [truncated] mean dE/dX) with a DIGITAL one, the number of ionisation clusters per unit length:

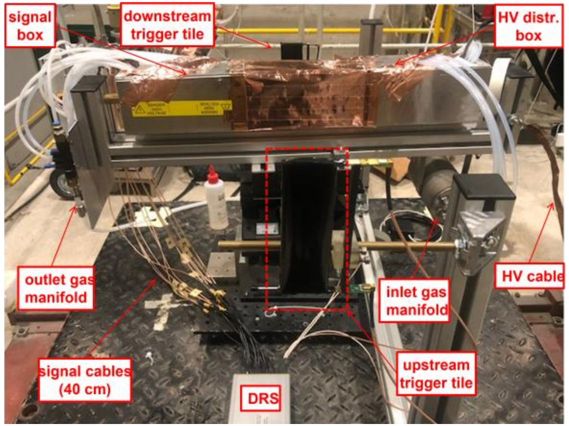
dE/dx: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx 4.3\%$

dN_{cl}/dx: for He/iC_4H_{10}=90/10 and a 2m track gives $\sigma_{dNcl/dx}/(dN_{cl}/dx) < 2.0\%$

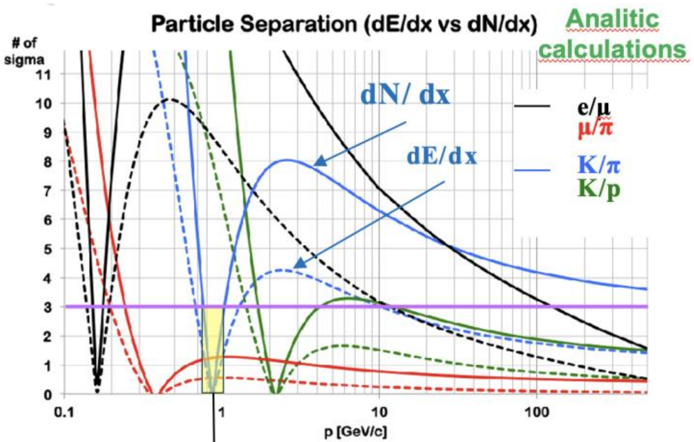
IDEA Drift Chamber: Cluster Counting/Timing and PID

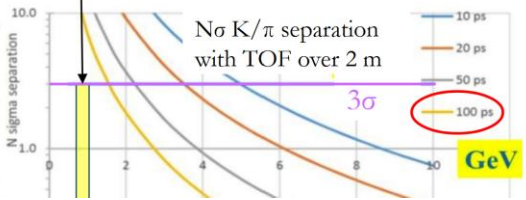
- Analitic calculations: Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)

- Simulation with Garfield++ and with the Garfield model ported in GEANT4:
  - the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 found considerably worse than in Garfield
  - the dN_{cl}/dx Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope
  - finding answers by using real data from beam tests



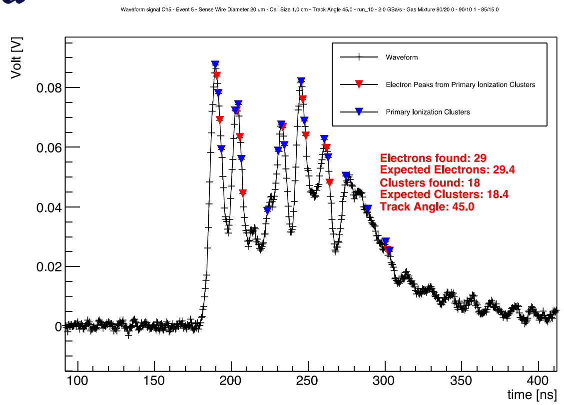
90%He-10%iC_4H_{10}
nominal HV+20, 45°,
Gas gain ~ $2 \cdot 10^5$,
165 GeV/c



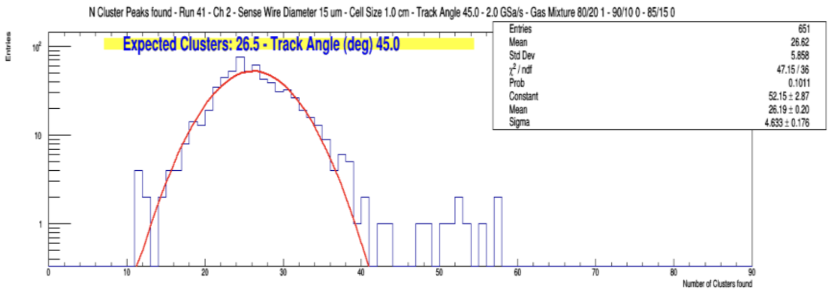


Testbeam analysis: 2021-2022 data

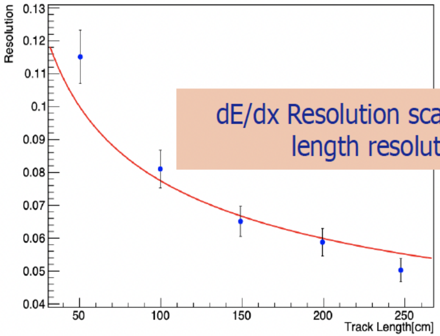
- Several algorithms developed for electron peak finding:
  - ✓ Derivative Algorithm (DERIV)
  - ✓ and Running Template Algorithm (RTA)
  - ✓ NN-based approach (developed by IHEP)
- Clusterization algorithm to merge electron peaks in consecutive bins
- Poissonian distribution for the number of clusters as expected
- Different scans have been done to check the performance: (HV, Angle, gas gain, template scan)



Sense Wire Diameter 15 μm;
Cell Size 1.0 cm
Track Angle 45; Sampling rate 2 GSa/s
Gas Mixture He:IsoB 80/20

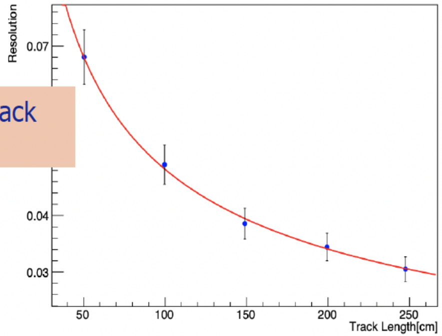


dE/dx Resolution



dE/dx Resolution scan vs track length resolution

dN/dx Resolution



dE/dx resolution dependence on the track length $L^{-0.37}$

dN/dx resolution dependence on the track length $L^{-0.5}$

~ **2 times** improvement in the resolution using dN/dx method

Loads

	cell number/step	length	Sense wire tension(g) /cell	Field wire tension(g) /cell	Sense wire tension (kg)	Field wire tension (kg)	total tension(kg) /step
	2684	4000	43.29	66.52	116.19	535.59	651.78
	3452	4360	51.43	79.03	177.55	818.41	995.95
	4220	4720	60.28	92.62	254.37	1172.51	1426.88
	4988	5080	69.82	107.29	348.27	1605.36	1953.63
	5756	5440	80.07	123.03	460.87	2124.39	2585.27
	6524	5800	91.02	139.85	593.79	2737.07	3330.85
total	27623				1951	8993	10944

Yield strength of 7075 Aluminum: 505MPa

Young's modulus (E) = 71.7 GPa

Poisson's ration = 0.33

Composite material : HIGH MODULUS Carbon fiber M55J

COMPOSITE PROPERTIES

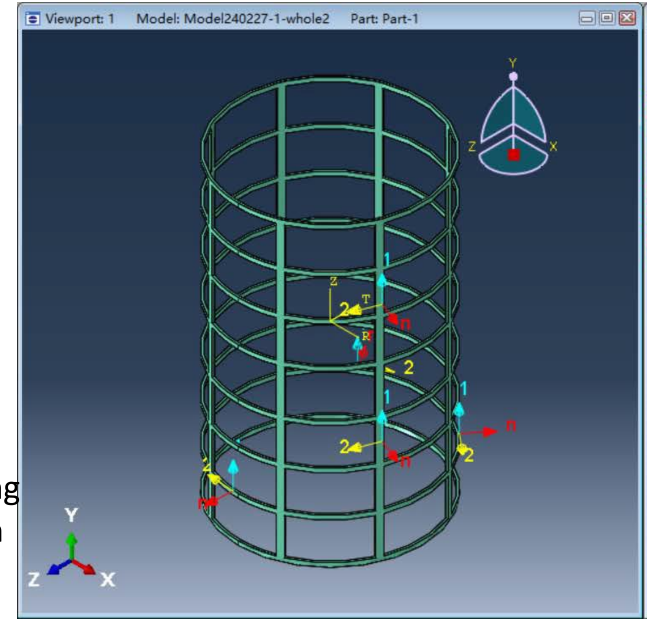
PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength*	293 ksi	2,020 MPa	ASTM D-3039
Tensile Modulus*	49 Msi	338 GPa	ASTM D-3039
Tensile Strain		0.61%	ASTM D-3039
Compressive Strength*	129 ksi	890 MPa	SACMA SRM 1R-94
Flexural Strength*	171 ksi	1,180 MPa	ASTM D-790
Flexural Modulus*	40 Msi	274 GPa	ASTM D-790
ILSS	11 ksi	73.2 MPa	SACMA SRM 8R-94
In Plain Shear Strength	10 ksi	68 MPa	ASTM D-3518
90° Tensile Strength	5 ksi	37 MPa	ASTM D-3039

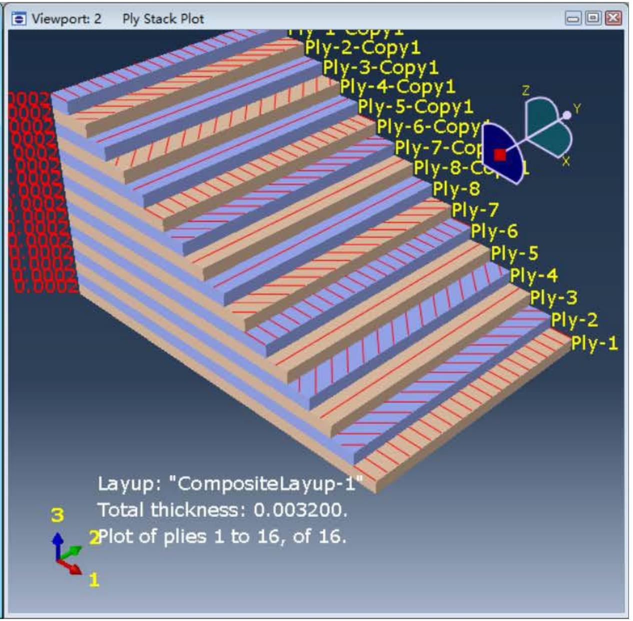
Finite element analysis - barrel

Cross section of longitudinal HB：
125mm*40mm， thickness: 3.2mm
weight： 78kg

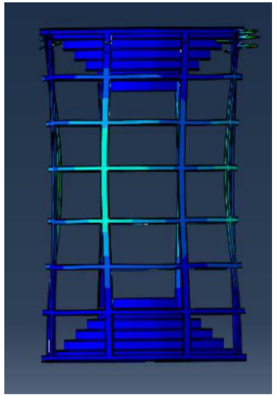
Cross section of annular HB ：
80*40mm
Thickness: 3.2mm
weight： 111kg

Thickness of CF wall: 3.2mm， including 16 composite layers, Thickness of each composite layer: 200μm

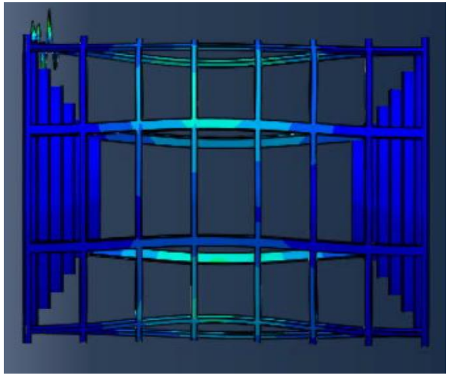




Buckling studies

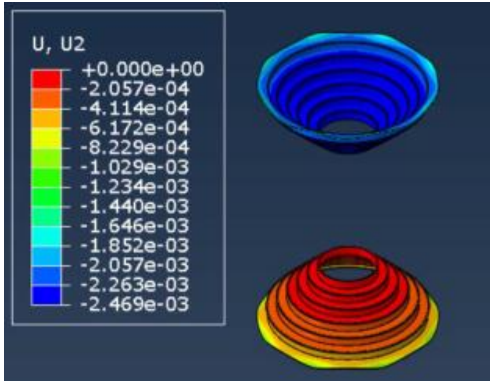


Vertical self weight
Buckling coefficient :~12

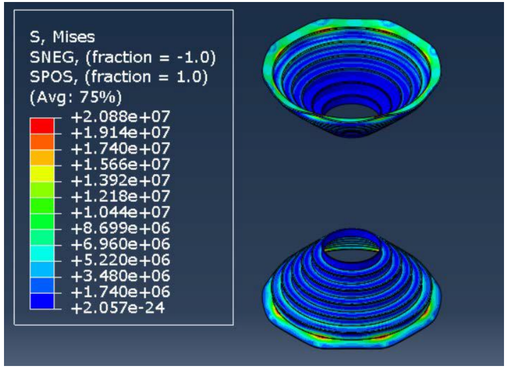


Horizontal self weight
Buckling coefficient : ~14

FEA Aluminum endcap

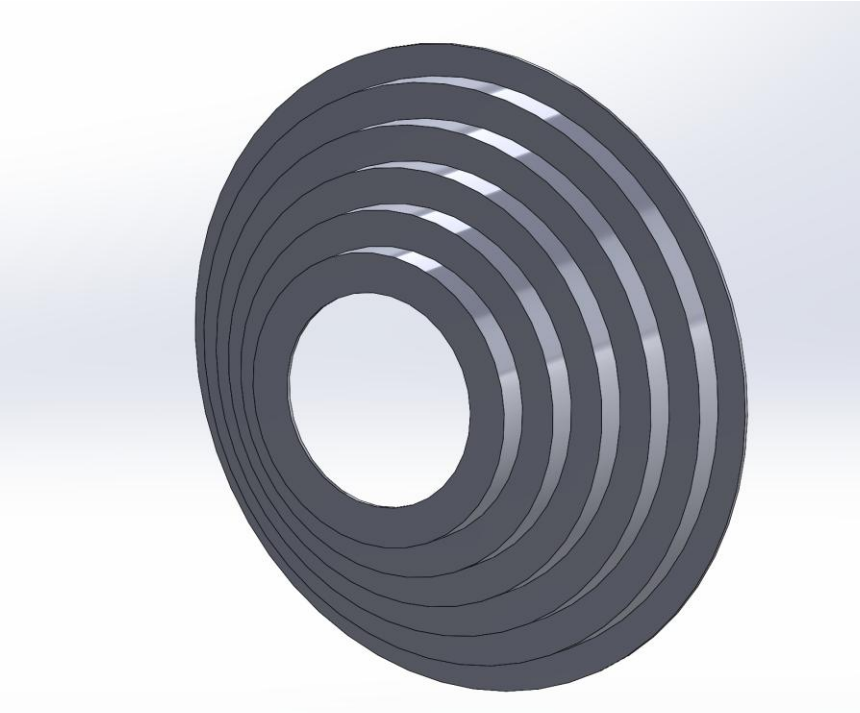


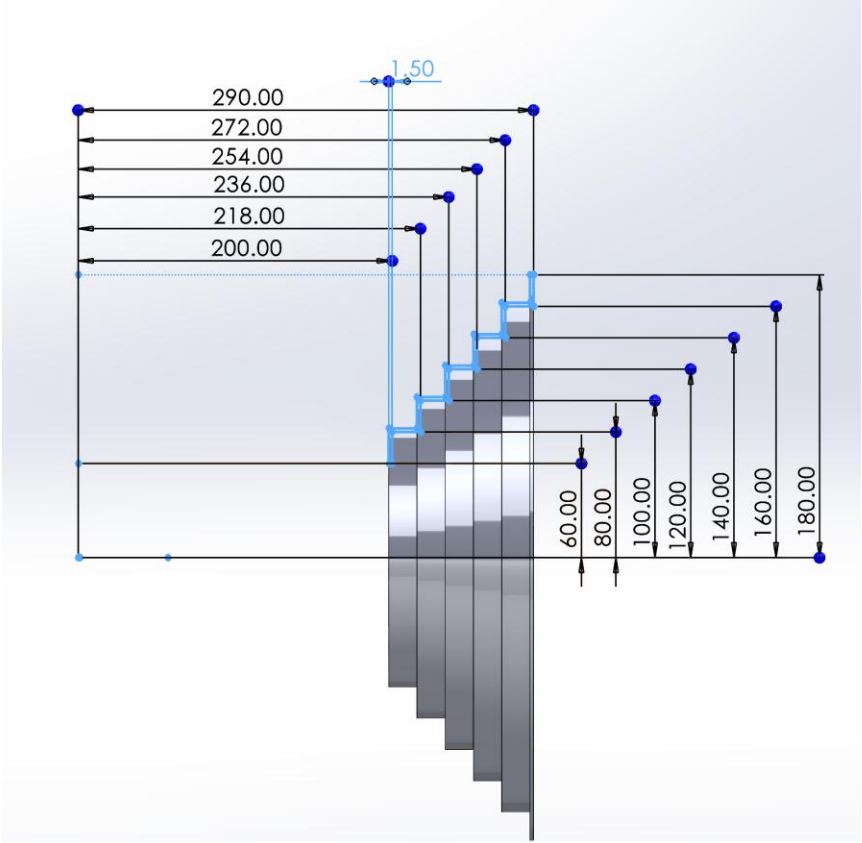
Endplate deformation 2.5mm



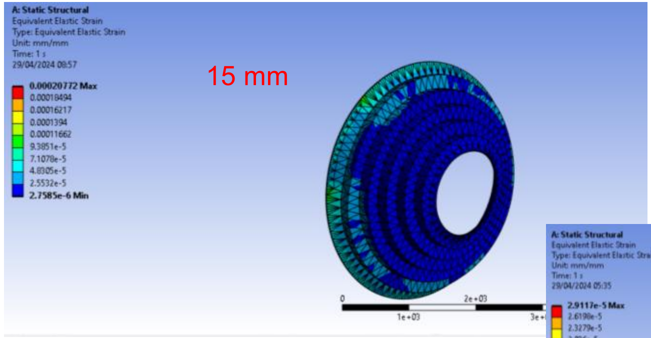
Stress 20.9MPa

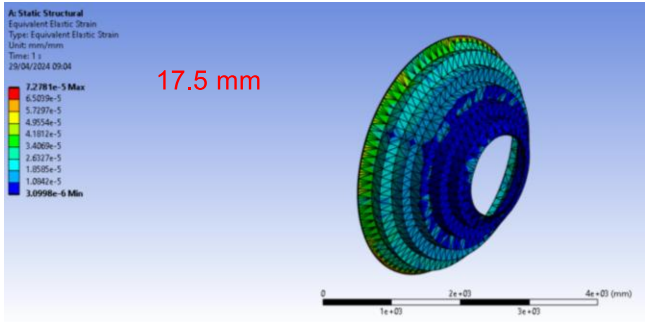
Proposal endplate optimization: version I

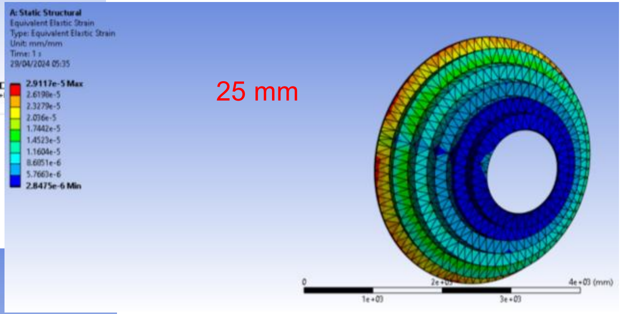


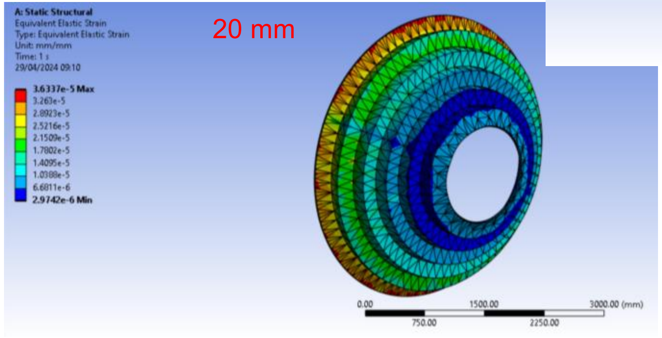


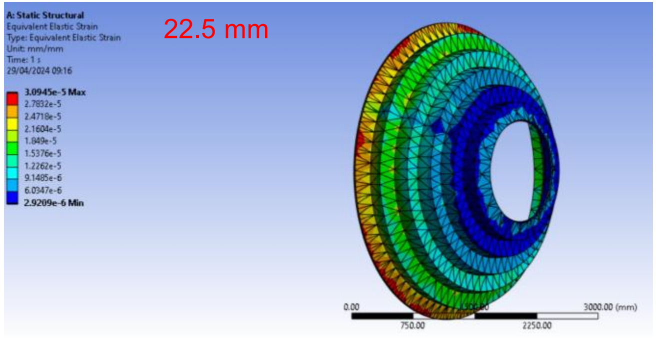
Thickness scan: Equivalent Elastic Strain



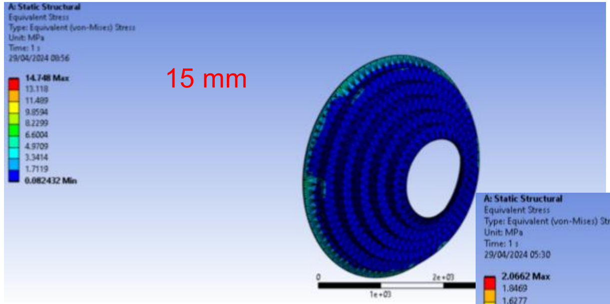


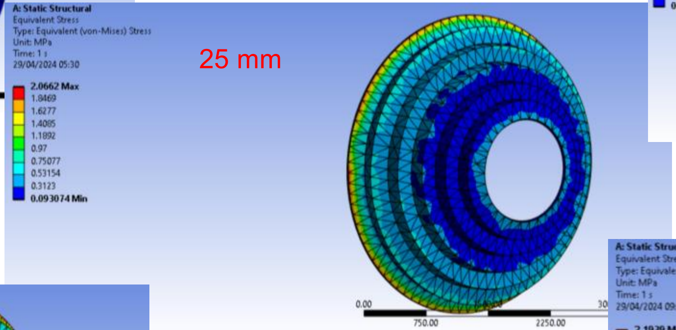


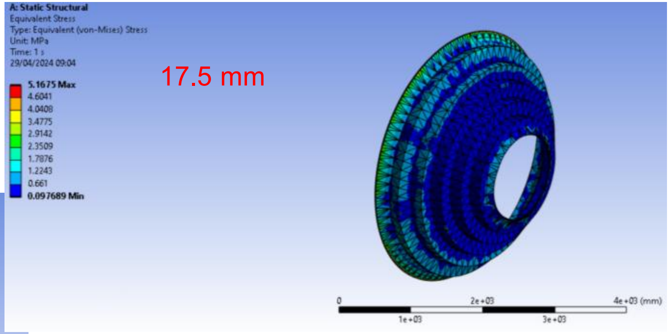


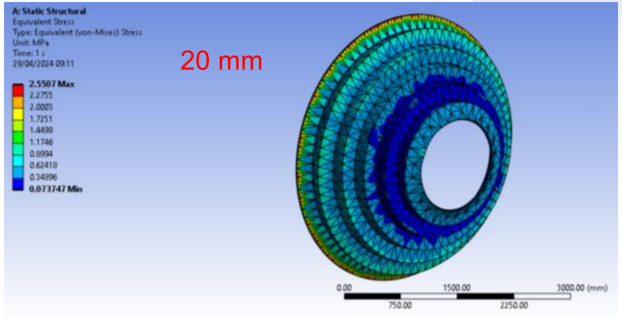


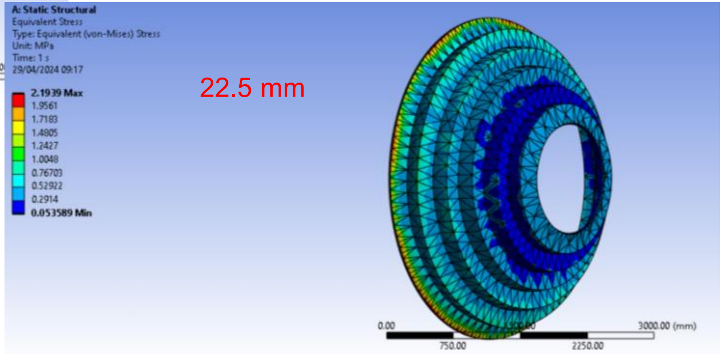
Thickness scan: Equivalent (von-Mises) Stress







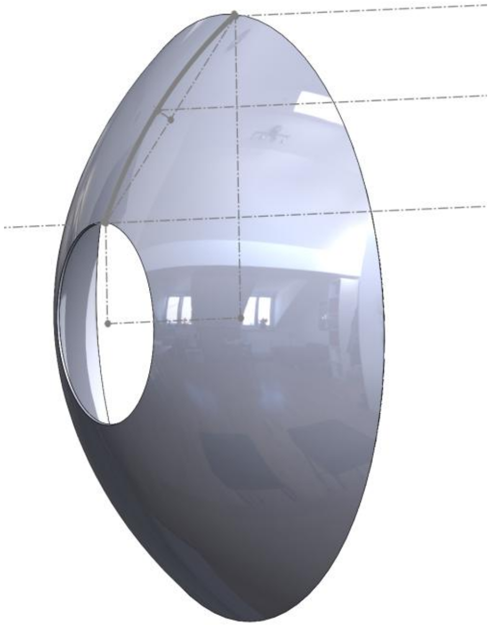


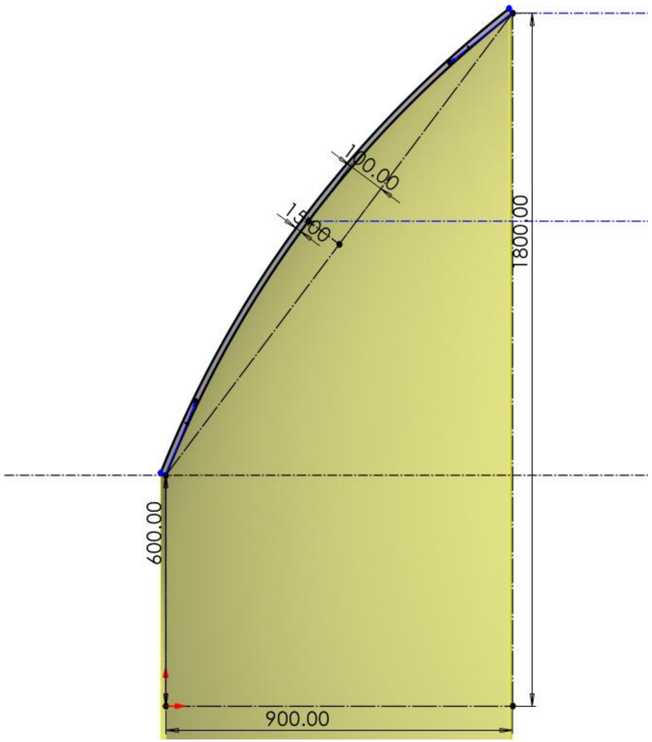


Thickness scan: summary

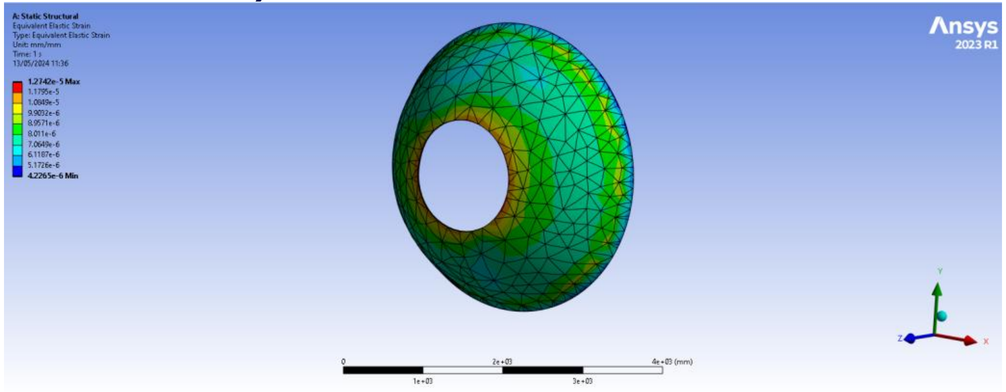
Thickness (mm)	Max Equivalent Elastic Strain (mm)	Max Equivalent (von-Mises) Stress (MPa)
15	2.08e-4	14.75
17.5	7.28e-5	5.17
20	3.63e-5	2.55
22.5	3.09e-5	2.19
25	2.91e-5	2.07

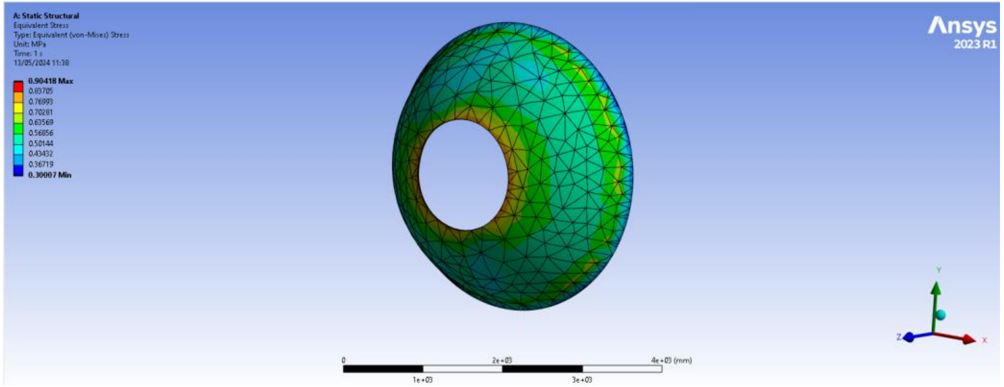
Proposal endplate: version II





Equivalent Elastic strain and Equivalent (von-Mises) Stress: 15mm thickness case





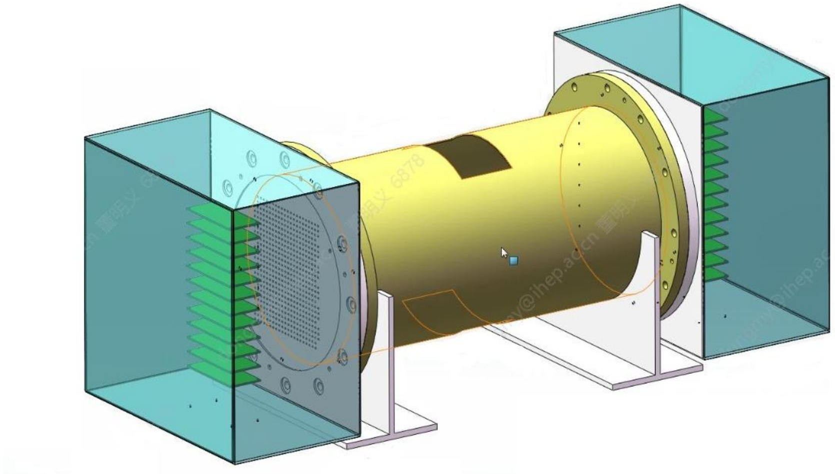
	Version I	Version II
Strain	2.08e-4	1.27e-5
Stress	14.75	0.90

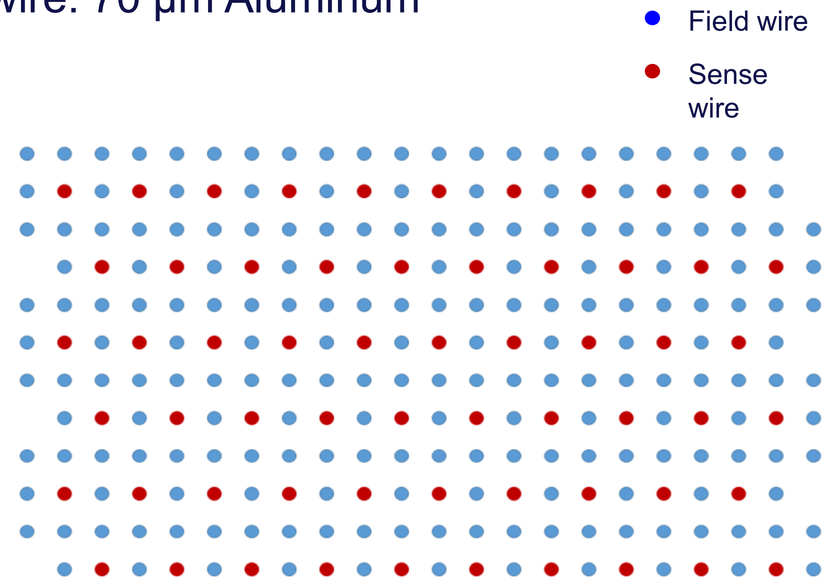
Design of a multi-layer drift chamber prototype

A Prototype was designed for the study of dN/dx

- A cylinder + two end plates
- 12 layers, 10 cells/ layer
- 120 cells in total
- Length: 60cm

- Cell size : 18 mm × 18 mm
- Ratio of field wires to sense wires : 3:1
- Sense wire: 20 μm Au-plated tungsten
- Field wire: 70 μm Aluminum

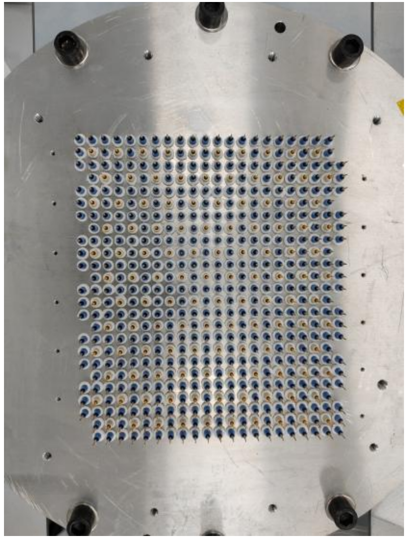




Construction of the prototype

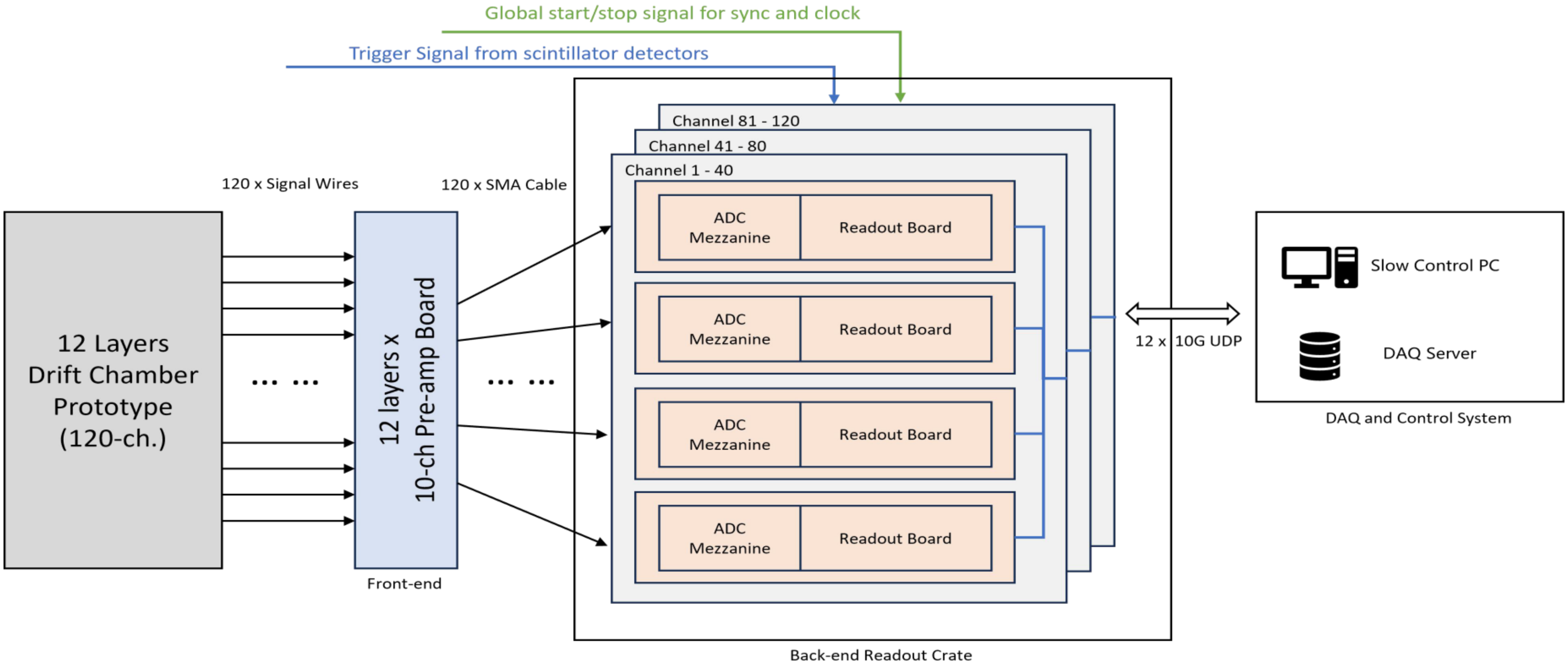
Feedthroughs are employed for positioning and fixing wires
Vertical wiring technology is adopted


wiring



Feedthroughs

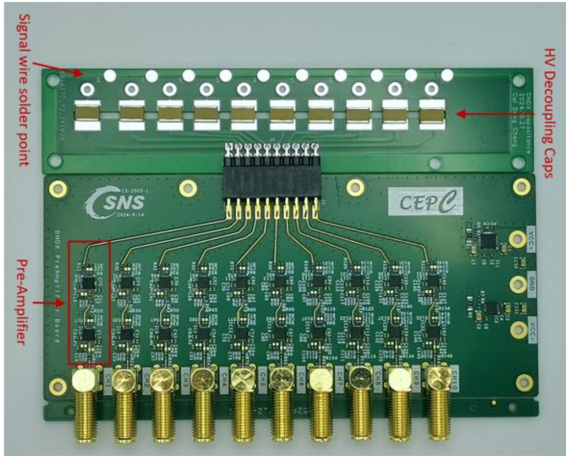
Design of readout electronics

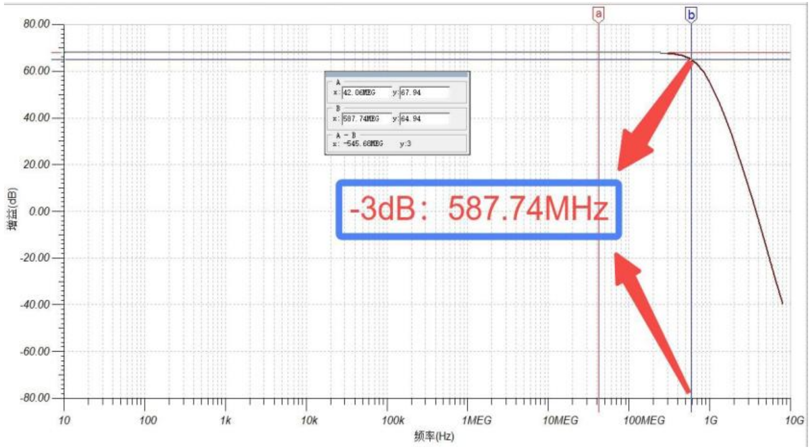


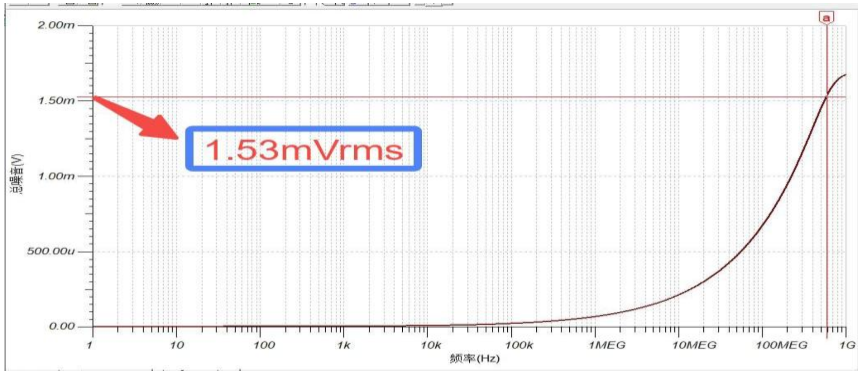
Front–end: Low noise and high bandwidth preamplifier

Front–end: High speed ADC module + digital signal acquisition module

Preamplifier board

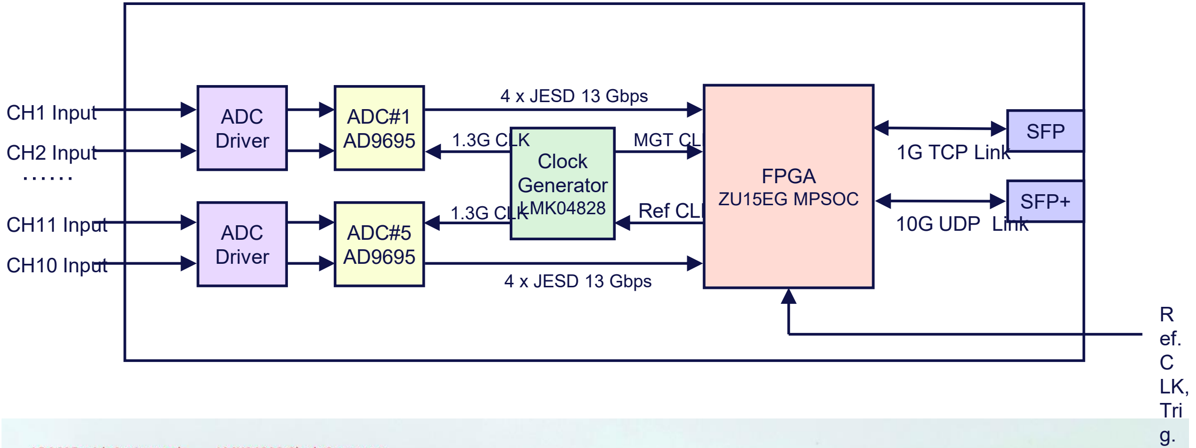




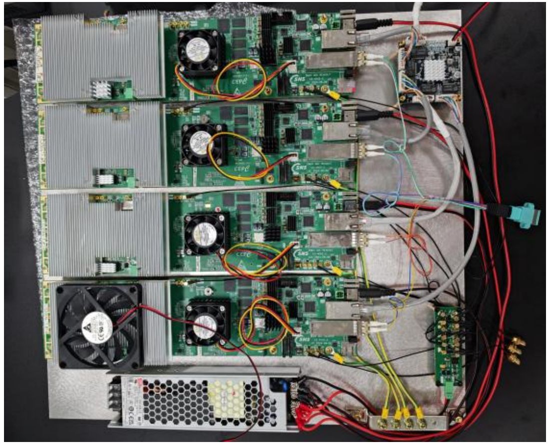


- Cascade amplification design
- in-phase operational amplifier circuit based on LMH6629 chips
- Bandwidth: 587.74MHz @-3dB
- Baseline noise(simulation and test) : 1.53 mVrms

ADC and Readout board



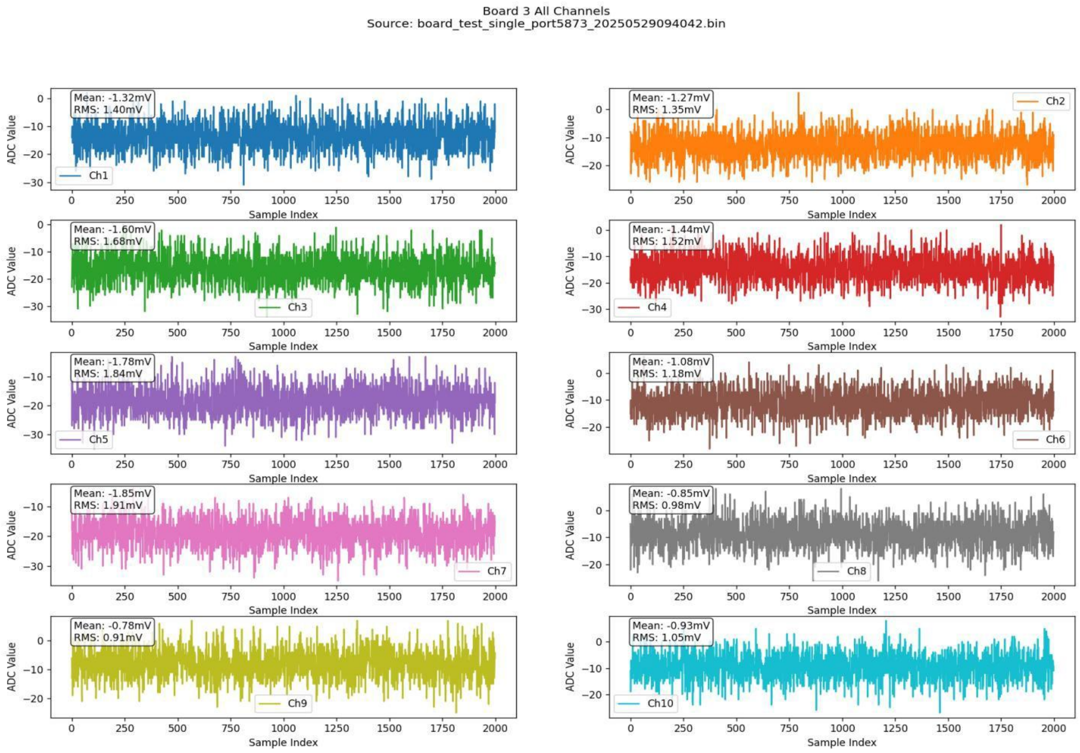
- 10ch ADC board (AD9695)
- Sampling rate: 1.3 Gsps@ 14 bit
- Xilinx Ultrascale+ ZU15EG Readout Board



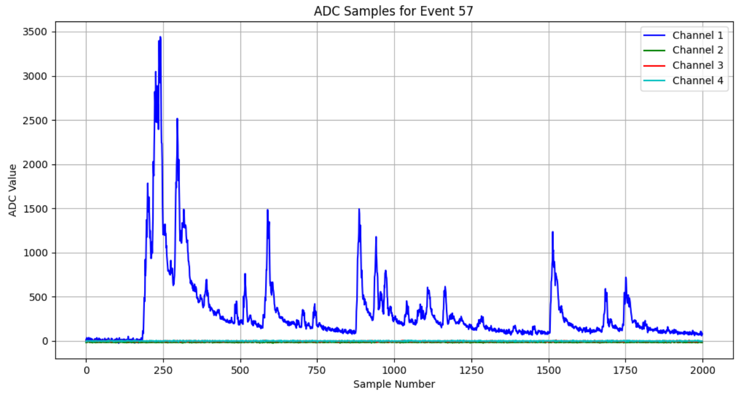
10-Ch AD9695

Xilinx Ultrascale+ ZU15EG Readout Board

Preliminary tests of the readout electronics



Baseline tests （10 channels）



Signal tests