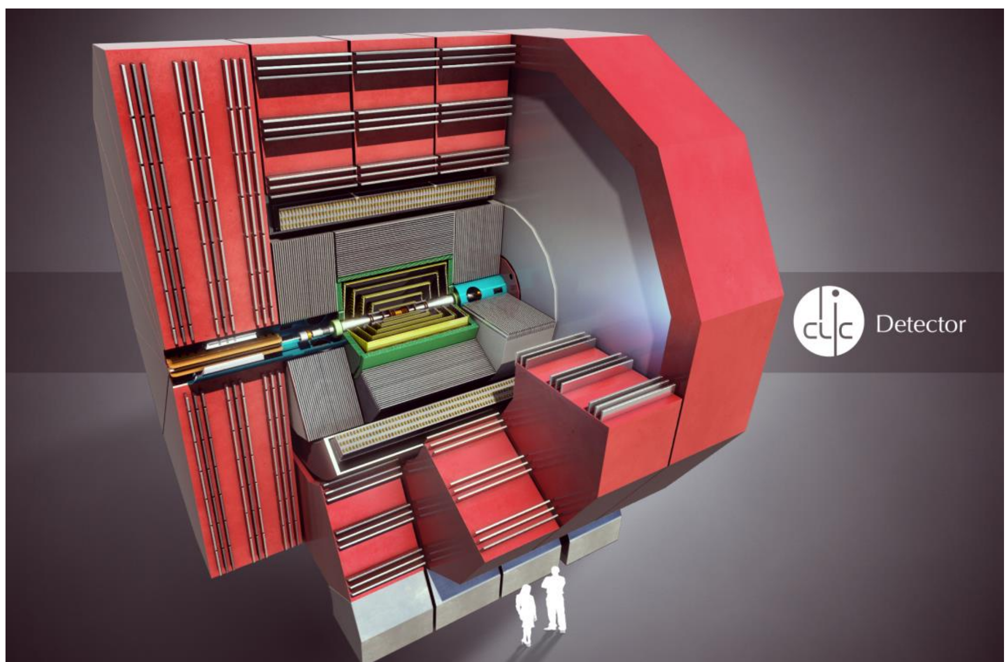
Optimisation studies and tests of low-mass support structures for the CLIC vertex detector

July 1st, 2014

François-Xavier Nuiry, on behalf of the CLICdp collaboration

francois-xavier.nuiry@cern.ch



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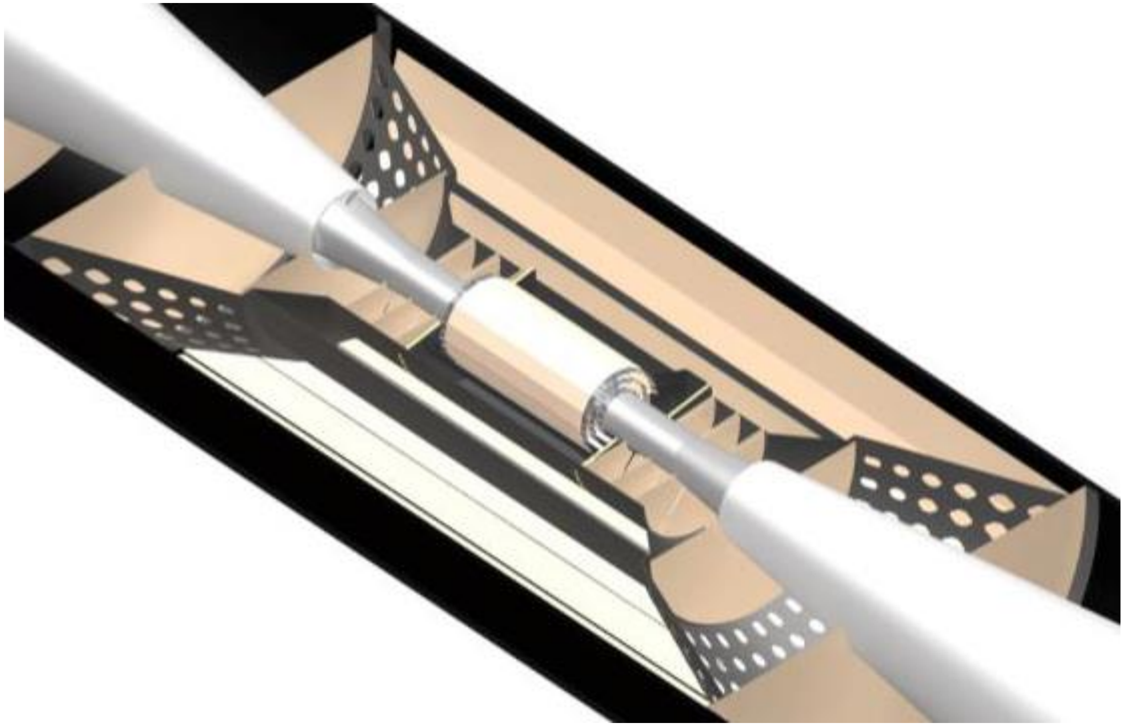
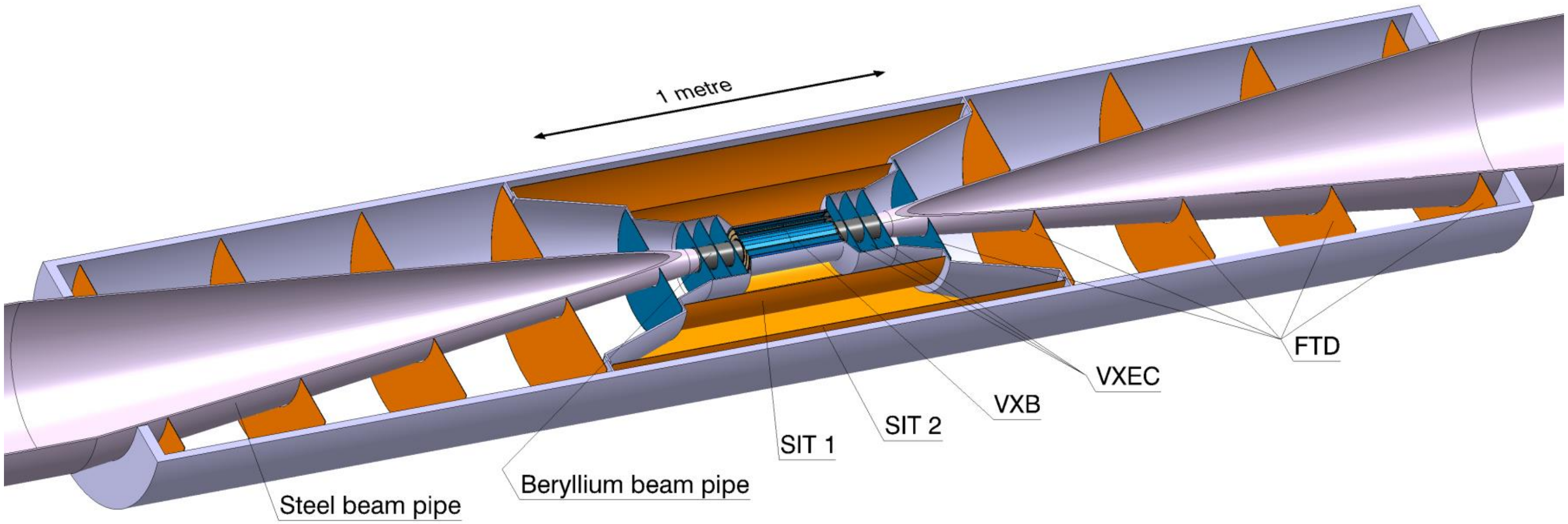


The vertex detector thermo-mechanical requirements

CLIC VERTEX CHALLENGES

→Low material budget:
(0.2% X0 per layer in VXB including 0.11% of silicon)
→Air cooling:
- Maintain detectors below 40°C;
- ~500 W Heat load to extract;

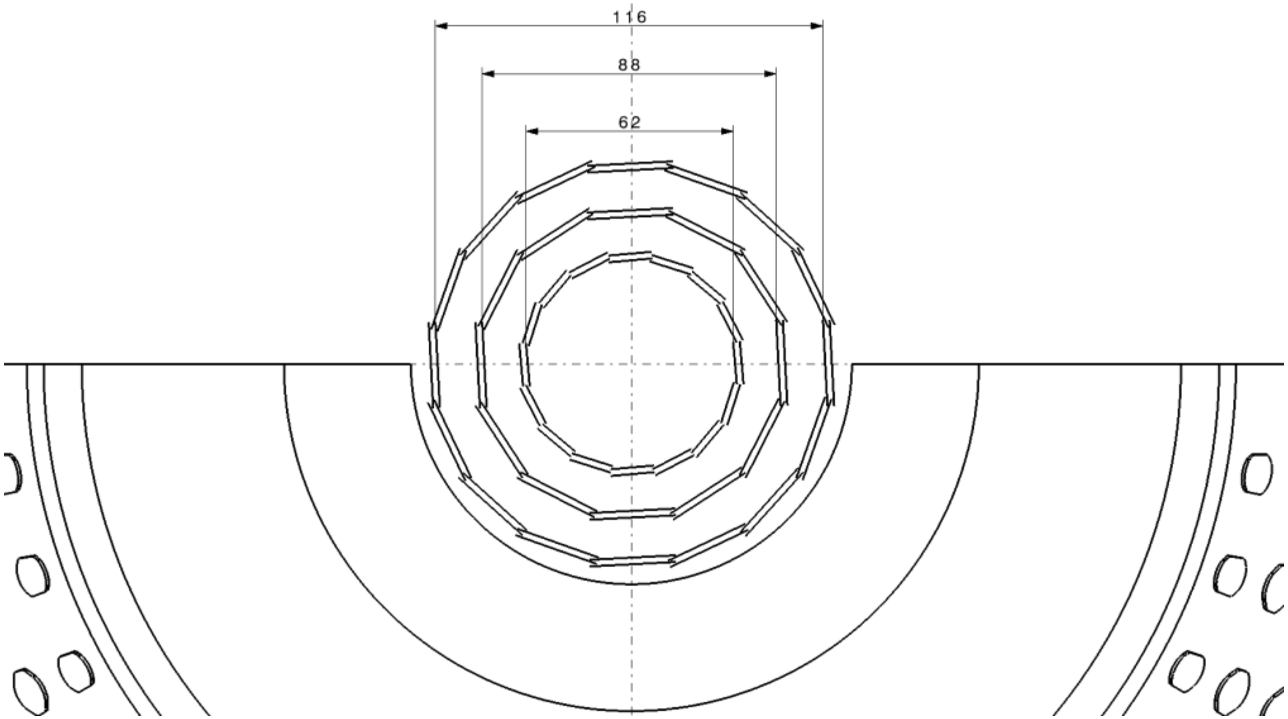
→High dimensional stability
→Radiation level <10^{11} $n_{eq}cm^{-2}year^{-1}$ (10^4 lower than LHC)

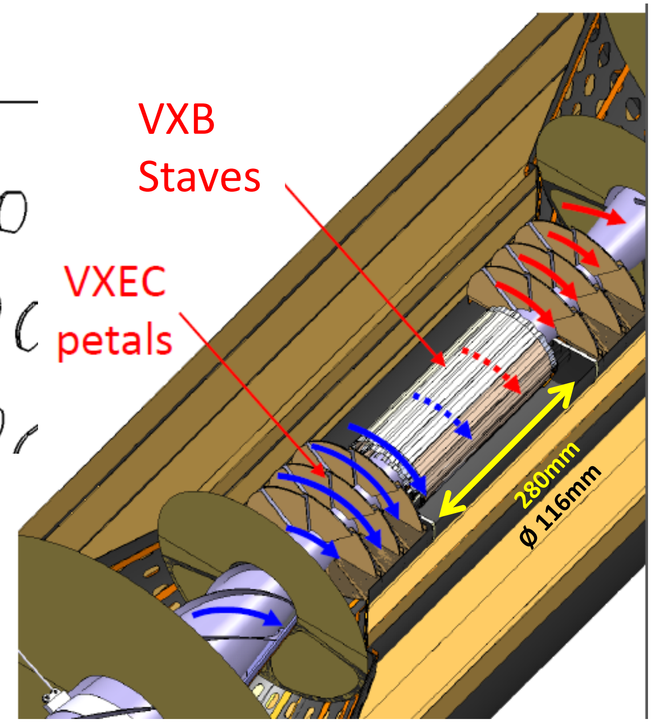


SHORT TERM OBJECTIVES:

→ Develop and characterize low-mass structures (STAVES): ~0.05% X0
→ Evaluate forced convection air cooling of the structure
Nominal heat dissipation: 50mW/cm^2, ΔT measurements
→ Measure air-flow induced vibrations on the structure
→ Validation of simulations (thermal and mechanical)

The vertex detector design



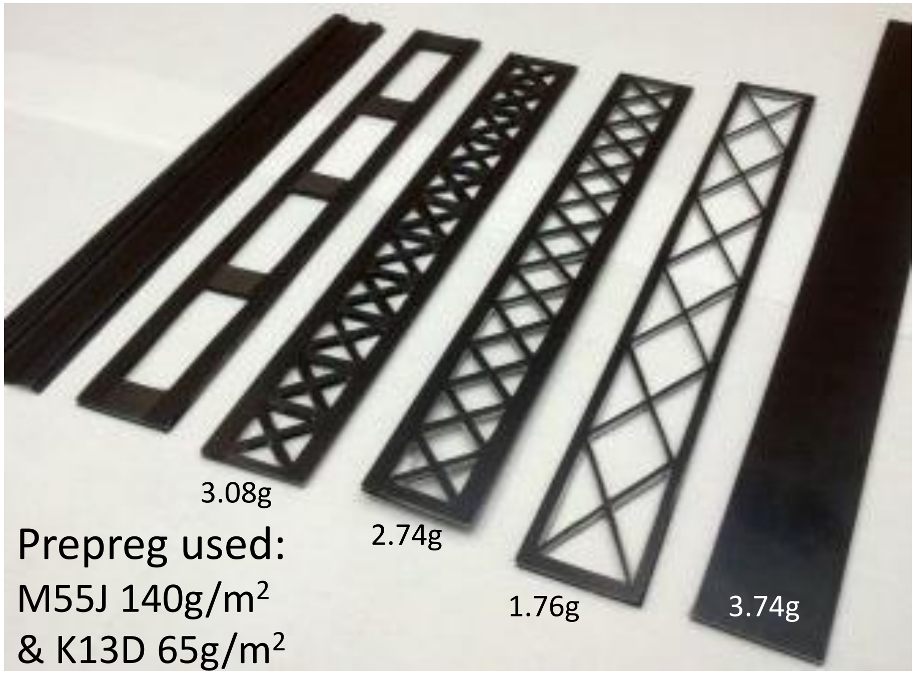


	Length	Width	Thickness	Inner Radius	Number of staves
Layer 1	280 mm	13mm	1.8mm	31mm	16
Layer 2		26mm	1.8mm	44mm	12
Layer 3		26mm	1.8mm	58mm	16

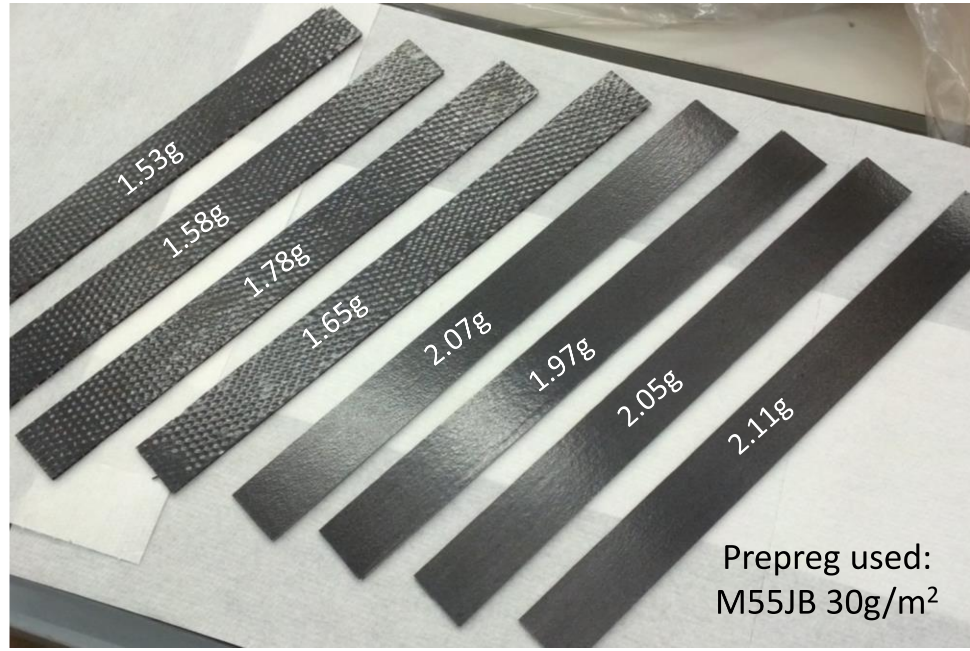
Prototyped staves

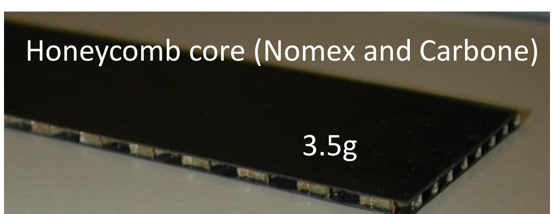
→ Several stave designs have been prototyped

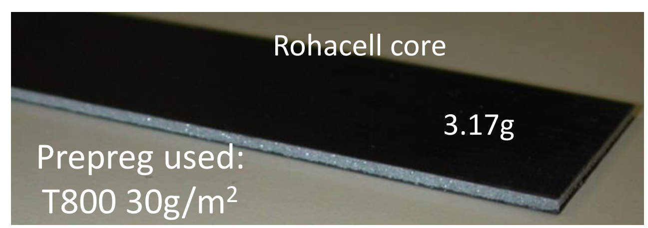
Omega stave - Cross bracing Staves – full sandwich staves prototyped under Andrea Catinaccio supervision 08/2013



New set of full sandwich staves - June 2014







Prototypes with NTPT and Composite design (Switzerland) - 9/2013

Materials used for 1st prototypes

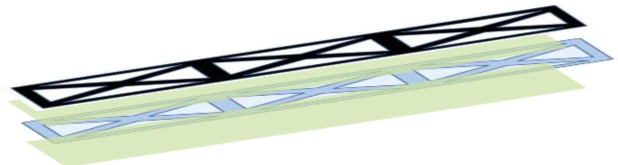
	M55J Prepreg	K13D prepreg	Rohacell
Thickness	0.140 mm	-	2 mm
Density	~140 g/m^2	65g/m^2	51 kg/m^3
Modulus	Longitudinal: 318 GPa	Longitudinal: 560 GPa	70 MPa (Isotropic)
	Transversal: 6.5 GPa	Transversal: 5.1 GPa	
Thermal conductivity	155 W/mK	800 W/mK (fibres only)	0.033 W/mK

Manufacturing process X brace staves

1. Skin manual realisation

Realisation and printing of the Pattern (CAD Model)

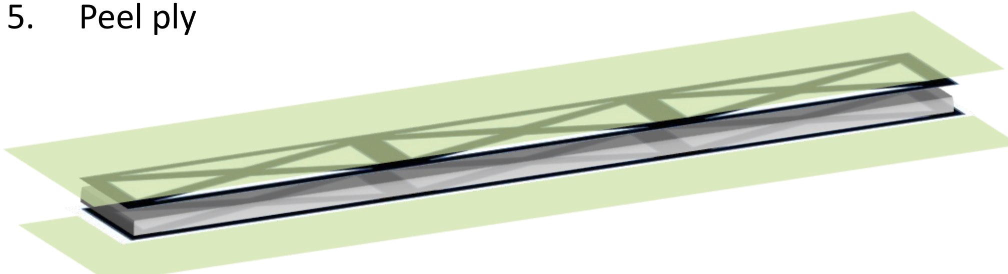
Prepreg strips are led down following the pattern

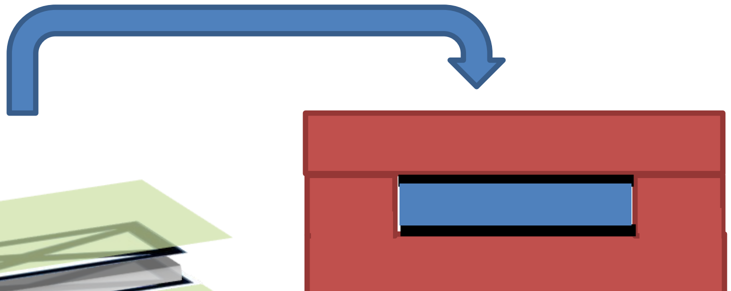


Skins are done!

2. Sandwich assembly

1. Peel ply
2. Skin
3. Rohacell
4. Skin
5. Peel ply





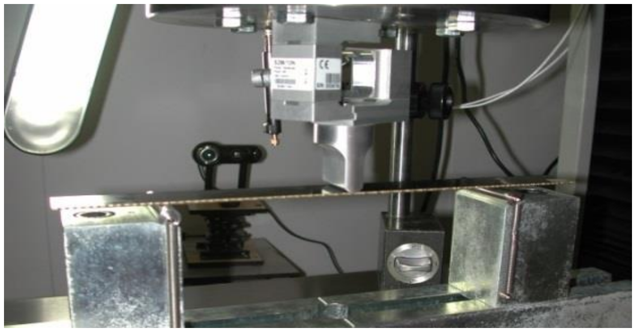
Curing 2h00 at 120°C.
Heating slop: ~6°C/min

Pressure given by the mould dimensions.

3. Rohacell cutting with a scalpel

Mechanical studies on 1st prototypes

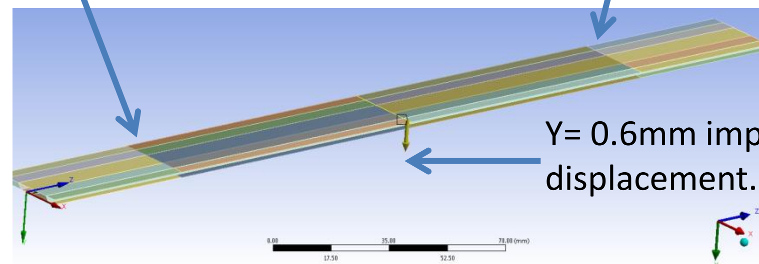
→ Stave Mechanical Characterisation. Measure of the **Flexural stiffness. Span: 180mm.**



One side with no displacements X=0, Y=0, Z=0

Other side with only vertical displacement cancelled Y=0

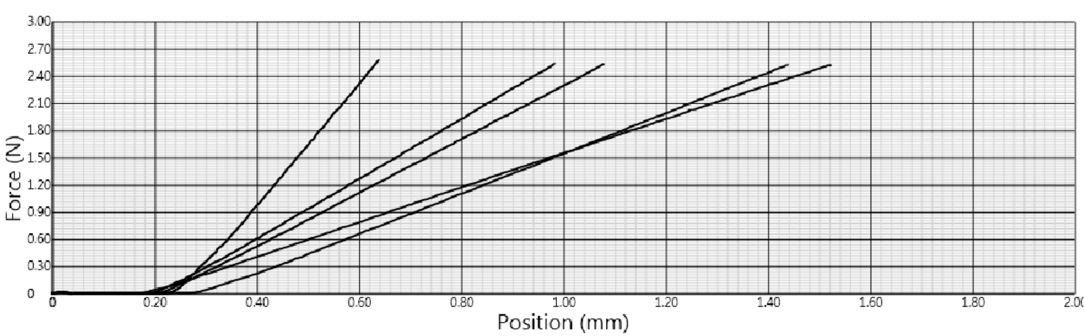
Y= 0.6mm imposed displacement.



SAMPLE ORDER : 9, 8, 7, 6, AND 4.

ASTM D790 Flexure
Strain From Position

	Width mm	Depth mm	Modulus MPa	Secant @ 1 MPa	Yield Force N	Yield Stress MPa	Yield Strain %	Ultimate N	Ultimate MPa	Ultimate %	Force @ 5% N	Stress @ 5% MPa
	25.8	1.82	20900	N/F	N/F	N/F	N/F	2.53	7.99	0.0382	N/F	N/F
	26.0	1.83	17200	N/F	N/F	N/F	N/F	2.53	7.83	0.0457	N/F	N/F
	26.1	1.82	27400	N/F	N/F	N/F	N/F	2.54	7.82	0.0288	N/F	N/F
	26.1	1.84	29800	N/F	N/F	N/F	N/F	2.54	7.78	0.0260	N/F	N/F
	25.8	1.82	63200	N/F	N/F	N/F	N/F	2.58	8.16	0.0129	N/F	N/F
Maximum	26.1											
Minimum	25.8											
Range	0.300	0.0200										
Median	26.0											
Average	26.0											
SD	0.145											
CoV	0.559											
T95	0.180											
P5/P95	1.06											
Cpk	0.354											



ASTM D790-10: Flexure - Strain From Position (rev. 13)

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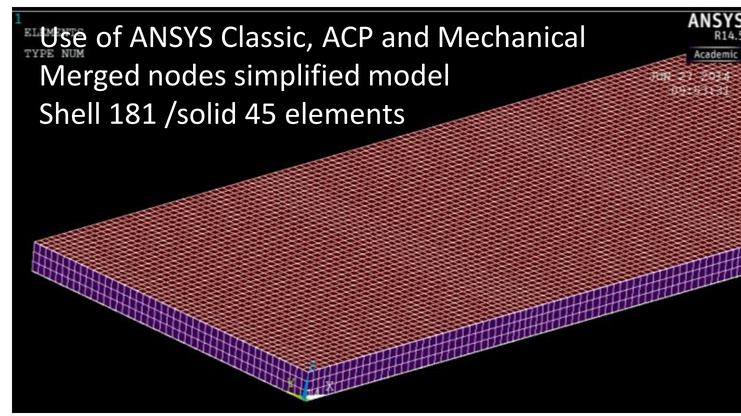
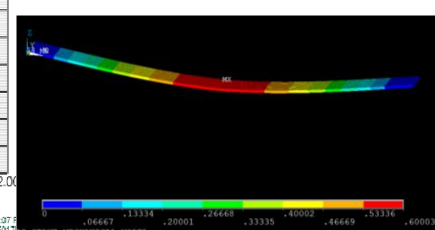
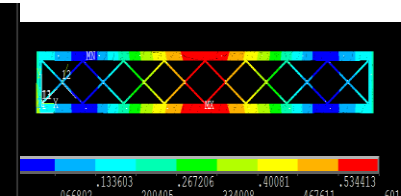


Use of ANSYS Classic, ACP and Mechanical
Merged nodes simplified model
Shell 181 /solid 45 elements





Mechanical studies on 1^{st} prototypes

→ Stave Mechanical Characterisation. Measure of the **Flexural stiffness.**
Span: 180mm.

Stave label #	#1	#2	#3	#5
Material	M55J + Rohacell 51 	M55J + Rohacell 51 	M55J + Rohacell 51 	M55J + Rohacell 51 
Flexural stiffness (N/mm) Measurements	6.95 N/mm	3.3 N/mm	2.96 N/mm	2.23 N/mm
Flexural stiffness (N/mm) FEM Model	6.95 N/mm	-	-	2.30 N/mm
Mass (g) 280mm long	3.74 g	3.08 g	2.74 g	1.76 g
X/X0 % (Calculated)	0.121 %	*(0.118 %)*	0.068 %	0.051 %

→ Full sandwich stave #1 is stiff but out of radiation length specs.
→ Cross bracing stave #5 should fulfil the radiation length goal. (0.05%).
→ Agreement between simulations and measurements, excepted for Rohacell characteristics where tunings are necessary.

Last developments: North Thin ply Technologies

FIBERS

Thin ply = up to 4 fibres diameters in the prepreg thickness (~18 microns).

→Use of PAN (Polyacrylonitrile) systems. Material use to get standard carbon fibres (starting compound/parent element).

→Use of Pitch systems. (specific molecular structures). Very high conductivity fibres.

RESIN

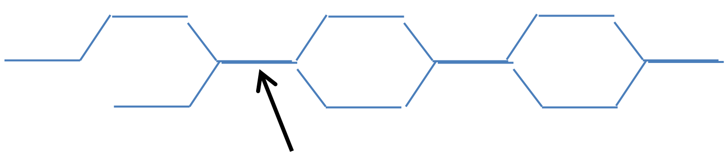
Resin quantity = About **38%** of the prepreg in mass. Up to **60%** if the resin is to be used for other purpose (e.g to fix the prepreg to the core).

→Tg from 110°C to 300°C.

→Glue layers up to 4µm are feasible.

CORE

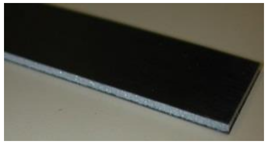
→Development of Carbon cores with an expected mass optimisation of 33%.



Only one wall instead of 2

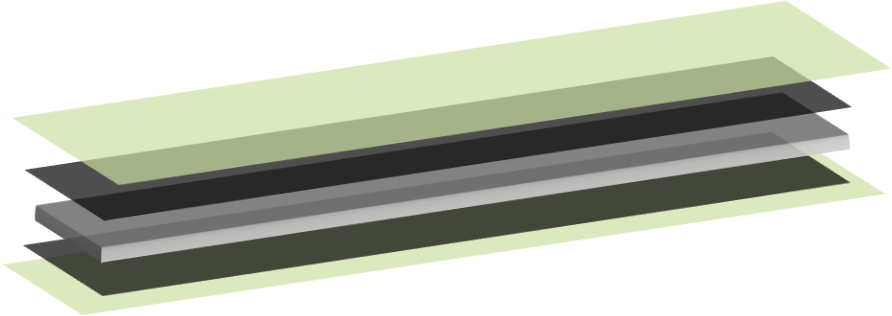
Fibre	UD ply possible thickness (microns)	Fibre modulus (GPa)
T700	30	240
T800	18 and 30	294
M40J	30	377
M46J	30	436
M55J	30	540
XN80	45	780

Manufacturing process



Full sandwich staves
2 techniques

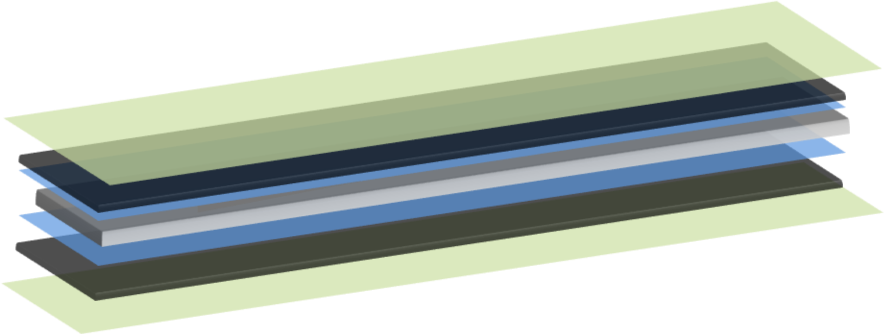
Full sandwich staves
Co-curing with prepreg matrix
Used for standard prepregs



Rohacell Stave

1. Lay down of a peel ply
2. Realisation of the sandwich: Skin / core / skin.
3. Lay down of the top peel ply
4. Curing parameters: 2h00 at 120°C. Heating slope: ~6°C/min. pressure given by the mould.
5. Un-moulding when cooled down

Full sandwich staves
Assembly done after skin curing
For thin prepregs <~50microns



Rohacell Stave

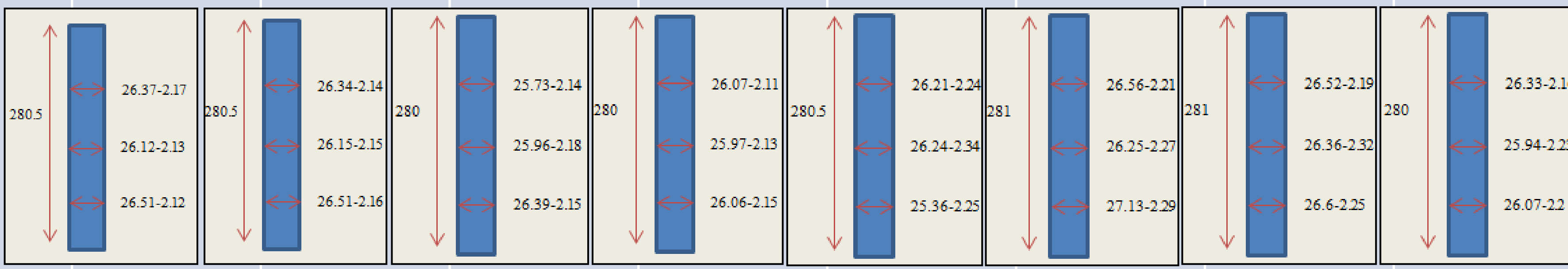
1. Liquid glue application on skins (150g/m2) DP490.
2. Realisation of the sandwich
3. Cure at room temperature under 0.2Bar

Alternative: Use of glue film

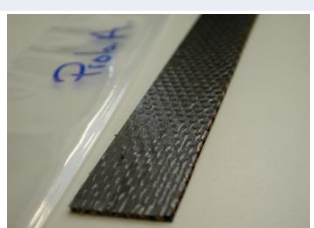
1. Glue film (30gsm) application on the 1st skin
2. Core application
3. Glue film (30gsm) application on core
4. 2nd skin lay down
5. Cure at 80°C under a vacuum bag (~1 bar pressure) during 16h

Thin prepregs used on sandwich staves
Features

Stave label	Proto 1 Nomex	Proto 2 Nomex	Proto 3 Nomex	Proto 4 Nomex	Proto 5 Rohacell	Proto 6 Rohacell	Proto 7 Rohacell	Proto 8 Rohacell
Mass (g)	1.53g	1.58g	1.78g	1.65g	2.07g	1.97g	2.05g	2.11g
Mass after drying 96h at 3%RH	1.52g	1.57g	1.75g	1.64g	-	-	-	-



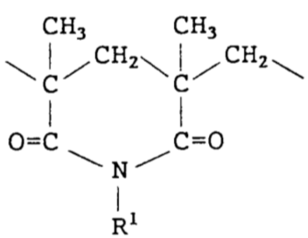
	Proto 1–4	Proto 5–8
Default observed	Local skin buckling on both skins. Stave not very flat. Extremities a bit crushed are slightly compressed. Small holes on skins.	<u>Very minor defaults:</u> Very small delimitation at extremities Small shearing on ends



X0 estimates for thin ply staves

Radiation length evaluation (based on measures and manufacturer's data)								
	PROTO 1 Nomex	PROTO 2 Nomex	PROTO 3 Nomex	PROTO 4 Nomex	PROTO 5 Rohacell	PROTO 6 Rohacell	PROTO 7 Rohacell	PROTO 8 Rohacell
Both Skins	0.0271	0.0279	0.0309	0.0313	0.0252	0.0221	0.0267	0.0233
Core	0.0145	0.0146	0.0146	0.0143	0.0268	0.0267	0.0267	0.0260
Both Glue layers	0.0155	0.0143	0.0126	0.0166	0.0120	0.0109	0.0069	0.0092
Total X0%	0.057	0.0568	0.0581	0.0622	0.0640	0.0597	0.0603	0.0584

Rohacell is PMI (*polymethacrylimide*).



$(C_8H_{10}O_2N)_x$

$X0=42.12g/cm^2$

We currently use the standard epoxy chemical formula:

C_2H_4N

$X0= 43.5g/cm^2$

We use the standard PAN *polyacrylonitrile* chemical formula for fibres:

C_3H_3N

$X0=42.86g/cm^2$

X0 measurements approximation for thin ply staves

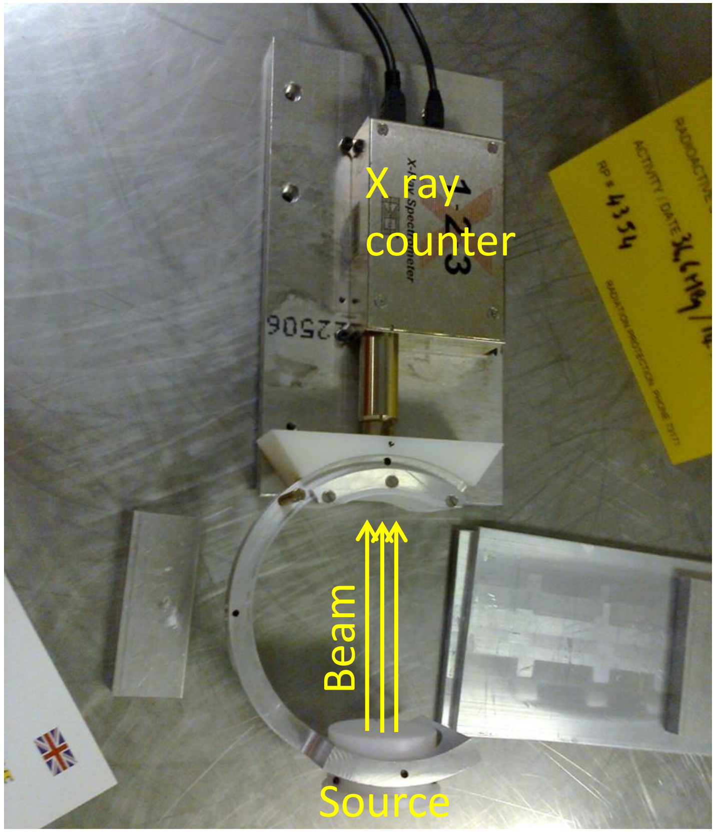
Thanks to Hideyuki Oide CERN and Mauricio Sciveres (LBL)

→Concept: measuring X-ray absorption by staves.

→We employed a fully-depleted Si-PIN X-ray counter X-123 with a 500 µm-thick, 6 mm^2 sensor produced by Amptek[4]

http://www.amptek.com/products/x-123-complete-x-ray-spectrometer-wth-si-pin-detector/

→We use a **Cd109** source with an activity of **3.1MBq** (19/06/2014)



X0 measurements approximation for thin ply staves

→Process:

- Measure of the amount of detected photons over a certain period. No Stave on the beam trajectory. → N_0
- Measure of the amount of detected photons over a similar period with the stave located on the beam trajectory. →N
- We get the X0 of the full stave sandwich thanks to the following law:

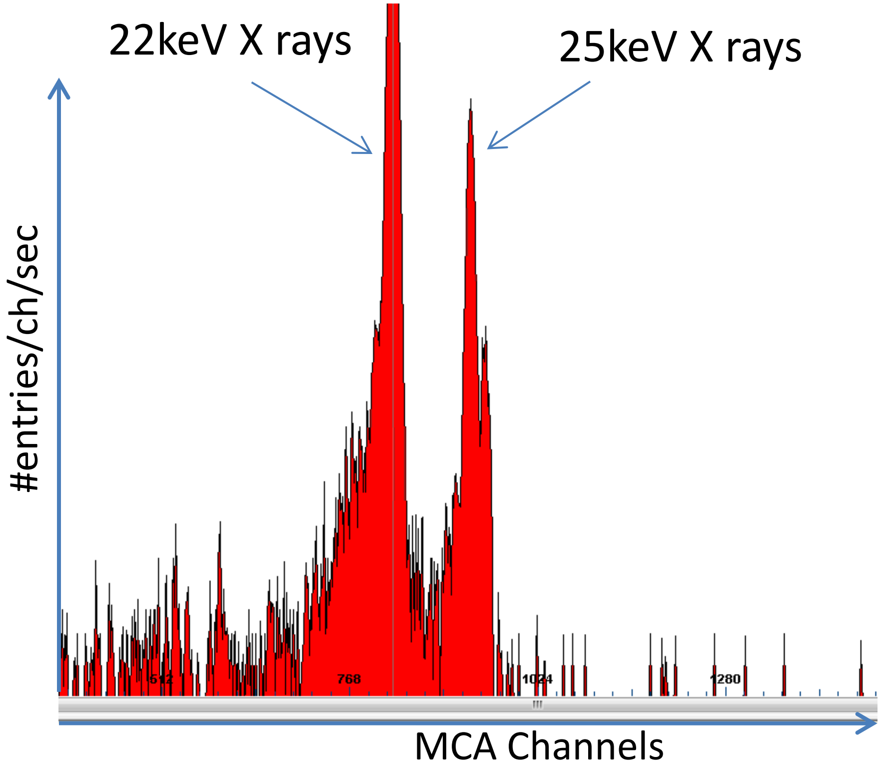
$$N/N_0 = e^{-X0}$$

Targeted X0→ $X_0 = 0.0005$

Proposed uncertainty on the X0→20% $\frac{dX_0}{X_0} = \frac{0.0001}{0.0005} = 0.2$

Photon beam counting statistical error → $\frac{\sqrt{N}}{N} \sim 1.10^{-4}$

Amount of photons to be counted **with the current set up**: $N \sim 1.10^8$



Example of the measurement of absorption of 22 keV and 25 keV X-rays from 109Cd by a sample object with X-123 detector

The effect of Compton scattering is negligibly small in this energy, and counting only the signals at the photoelectric peak is sufficient to measure the absorption.

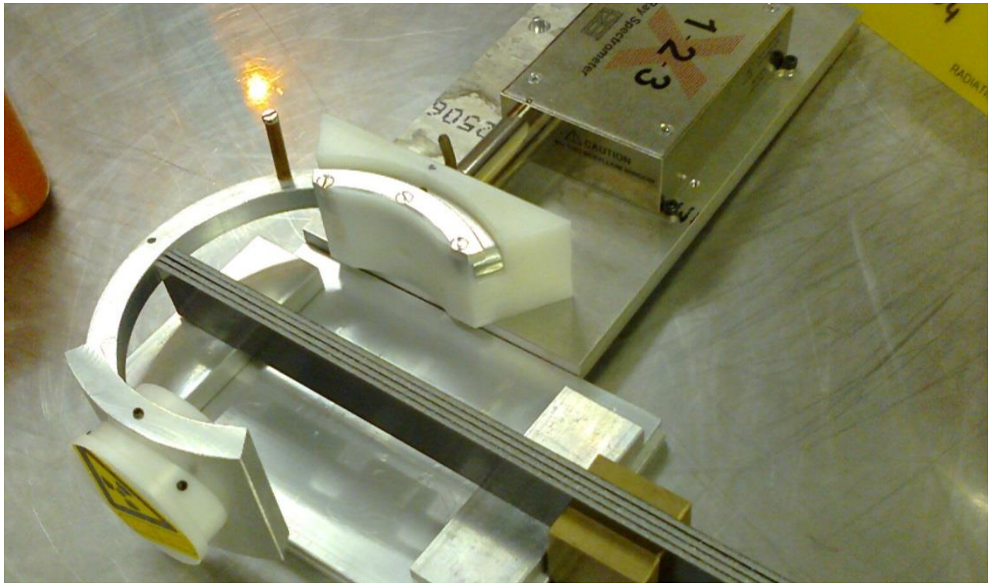
X0 measurements approximation

Current measurements and getting faster results

→ About 200 hours of measurement already taken.
→ ~3300000 photons detected.
→ To be continued…

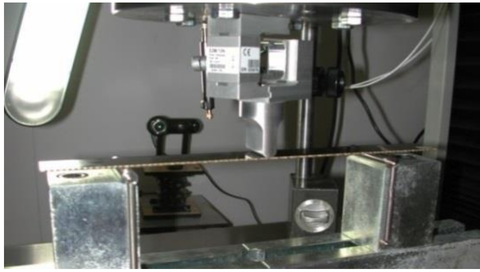
→Ongoing studies:

- Trying to measure 4 staves in one go.
  Hypothesis: staves are very similar. Problem: X_0 measurement for 1 stave not got.

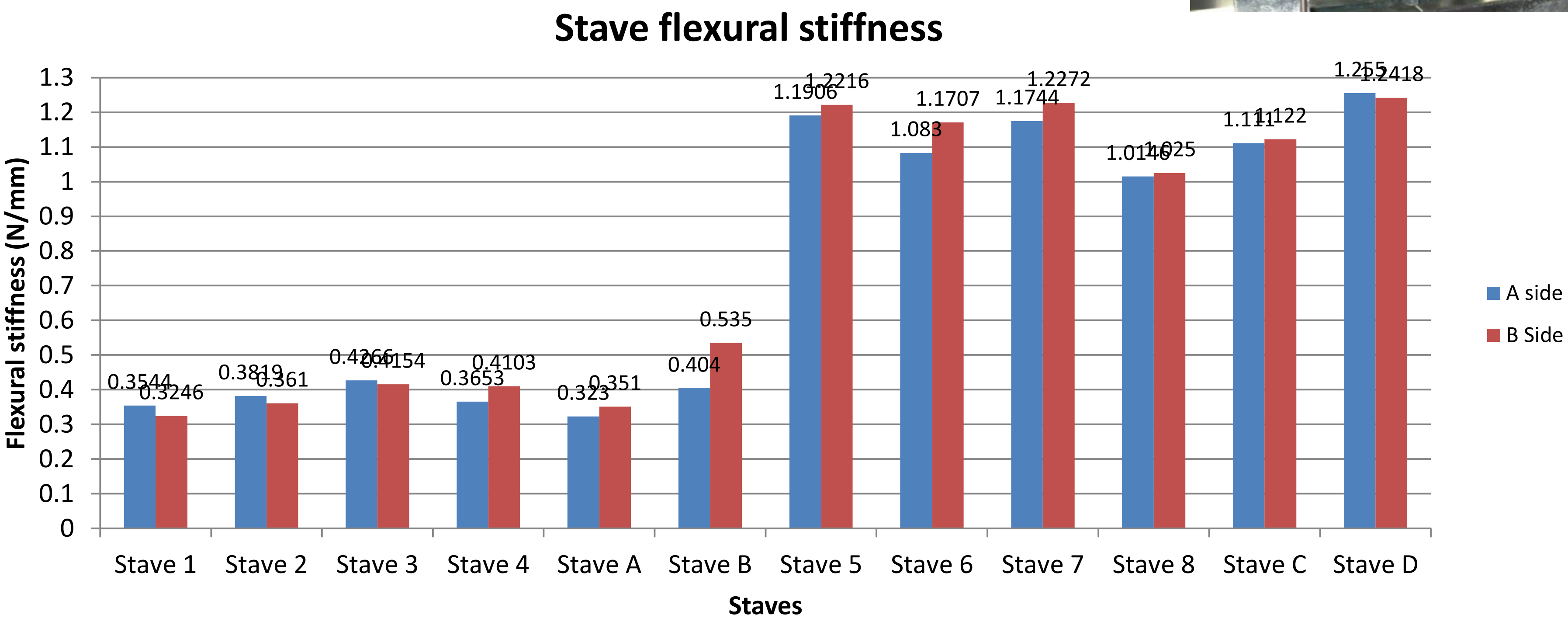


- Trying to bring the source closer to the detector.
- Trying higher activity sources.

Stave flexural stiffness measurements
Thin ply staves



→ Results for a 260mm span.



→ Honeycomb staves are more than 2 times softer than rohacell ones. (Not expected).
Possible reasons:

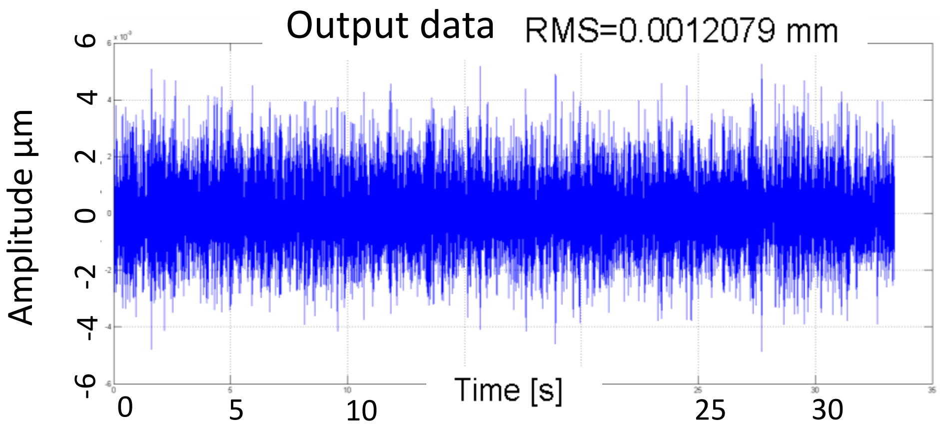
- Honeycomb staves are about 5% thinner than rohacell ones.
- Honeycomb stave skins are already locally buckling (60 microns waves, skin not flat).
- Staves are not very flat.

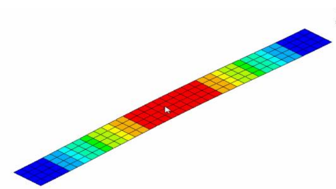
→ Rohacell staves flexural stiffness values are the one expected since the beginning. But it does not fully correspond the FEA results if stave exact dimensions are updated.

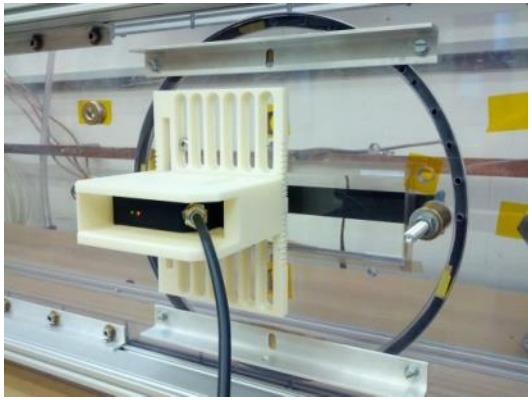
Vibration tests in the wind tunnel

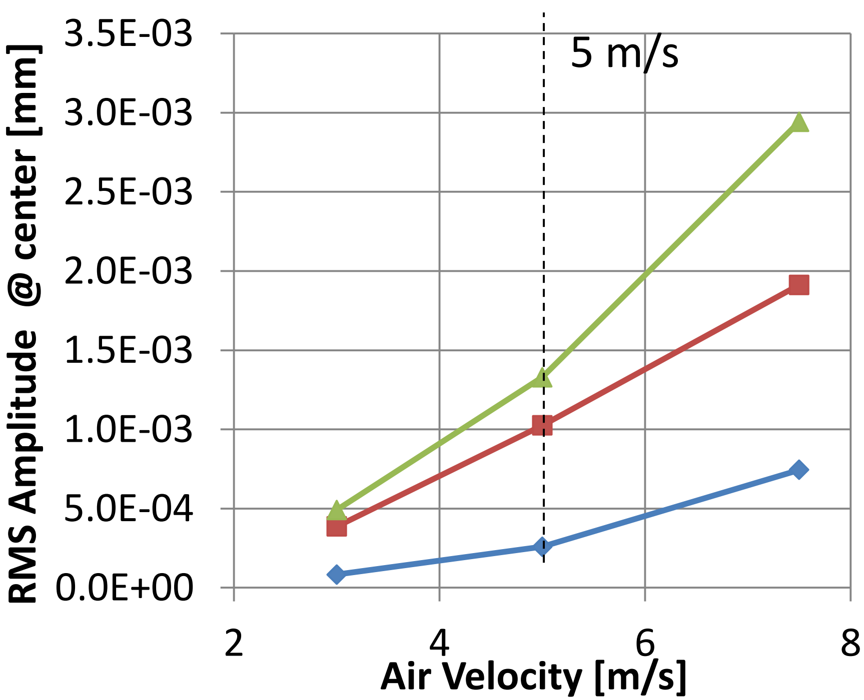
(Bare stave; Rohacell)

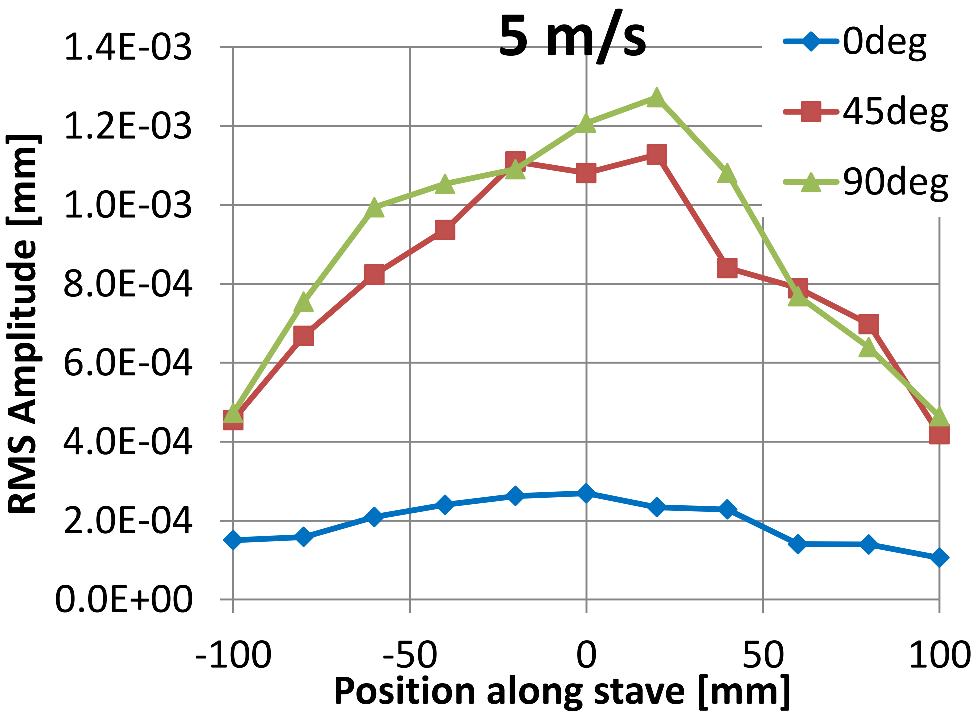
Out of plane amplitudes (17.3 mm channel)







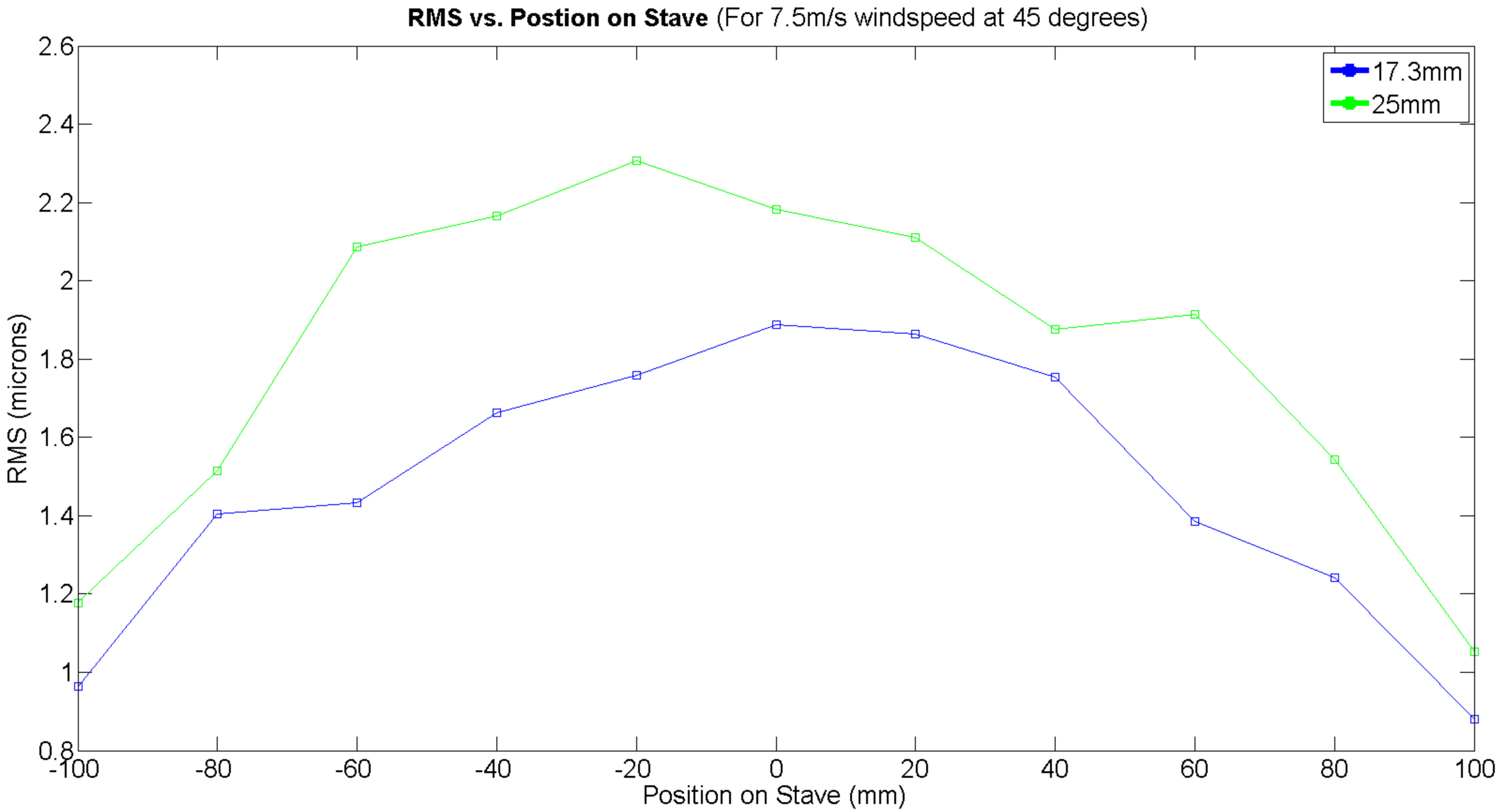




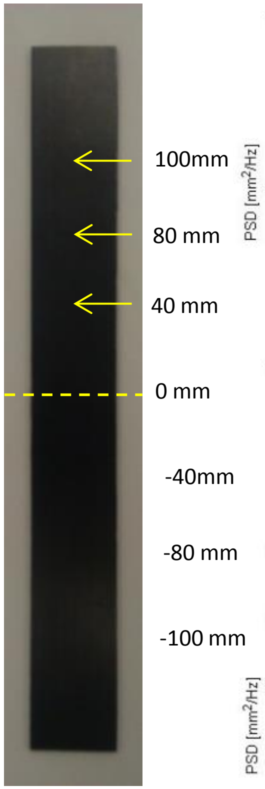
Vibration tests in the wind tunnel

(Bare stave; Rohacell)

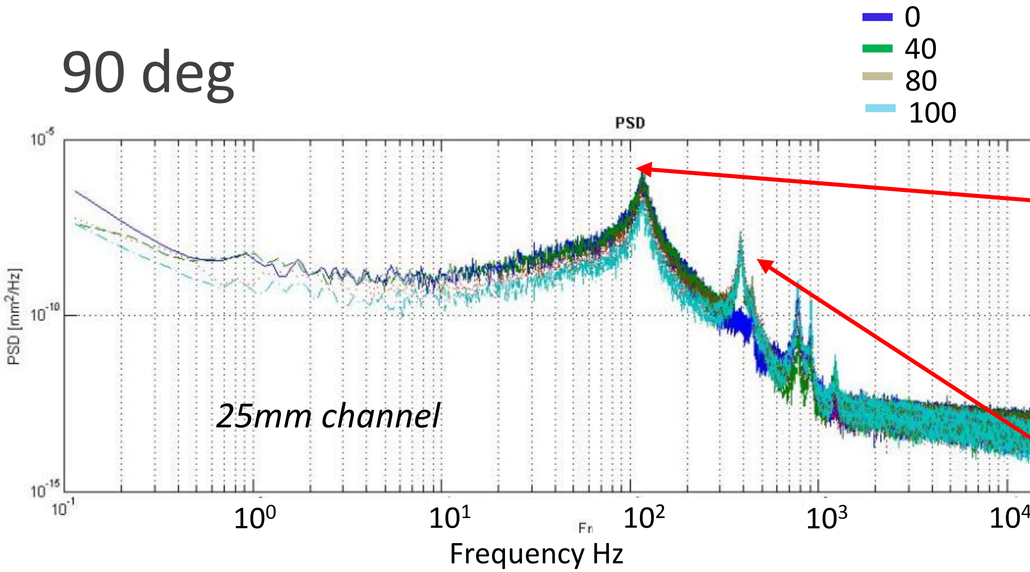
RMS graphs looking at the difference in channel height



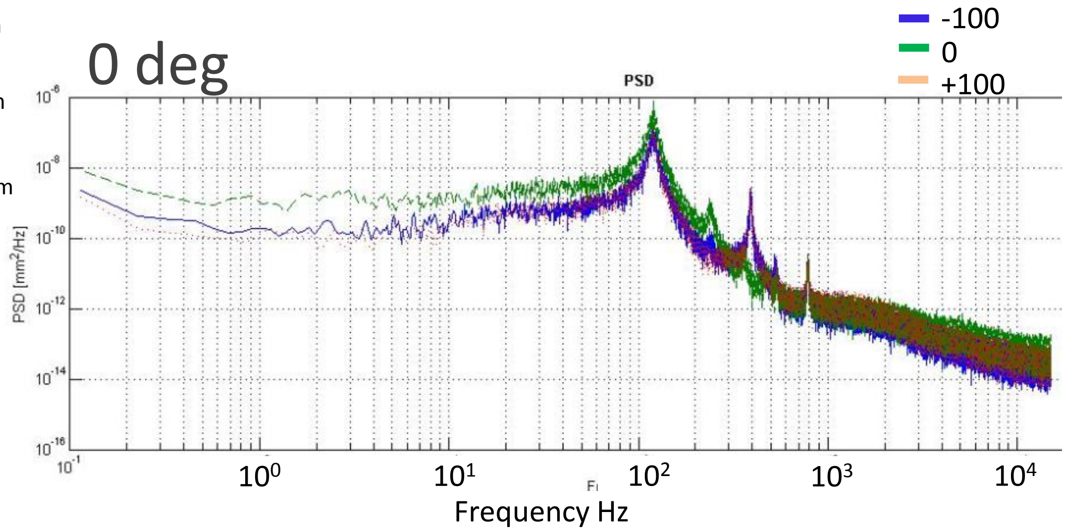
Sweep along length (Nomex HC – 7.6m/s)



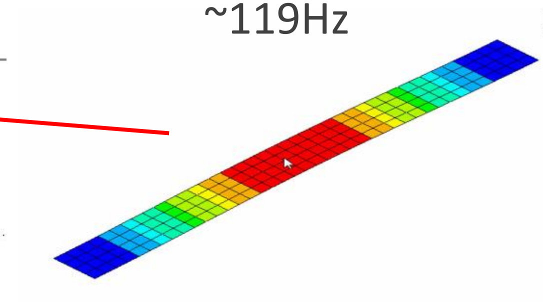
90 deg



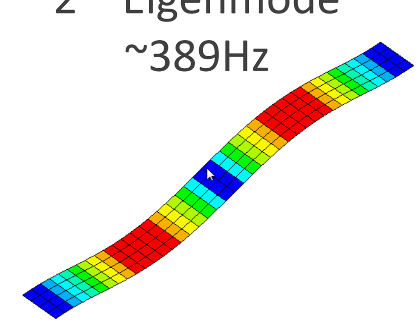
0 deg



1st Eigenmode
~119Hz

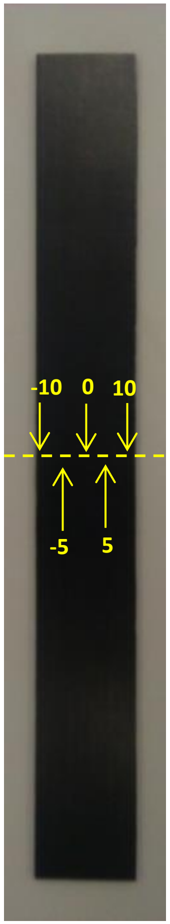


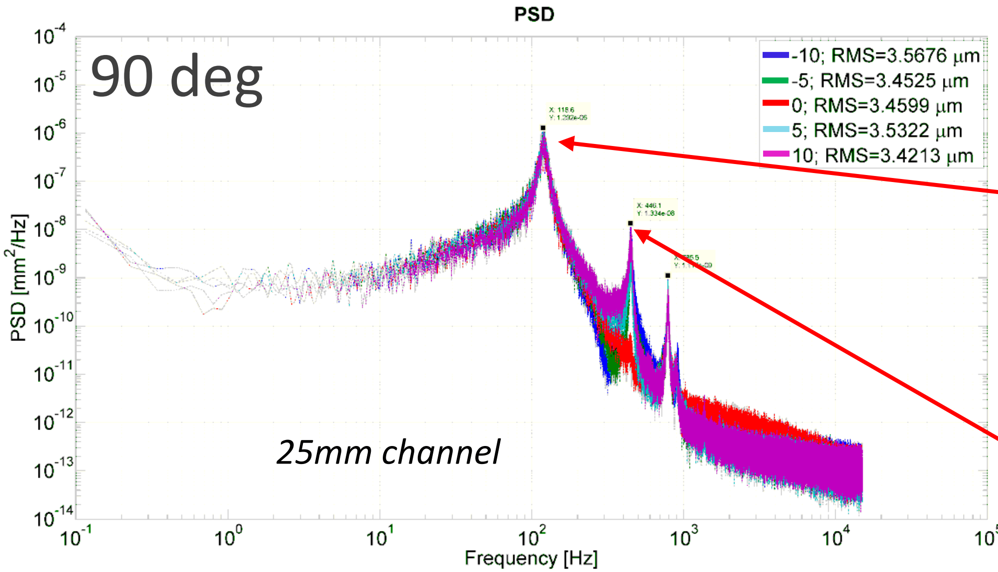
2nd Eigenmode
~389Hz

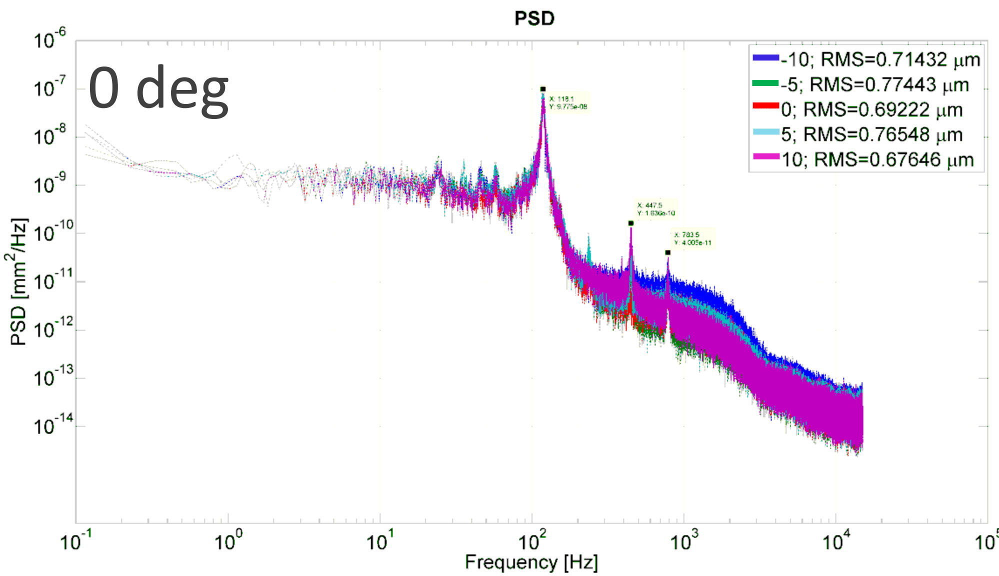


→Stave support stiffness not well known.
→At 0°, same eigenmodes are excited. Excepted one?
→Similar excited frequencies for 5m/s wind speed.

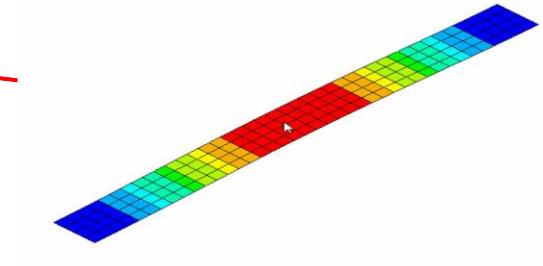
Sweep along width (Nomex HC – 7.6m/s)



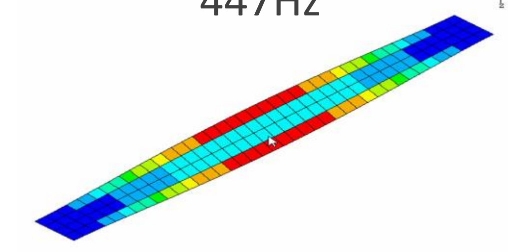




1st Eigenmode
~119Hz



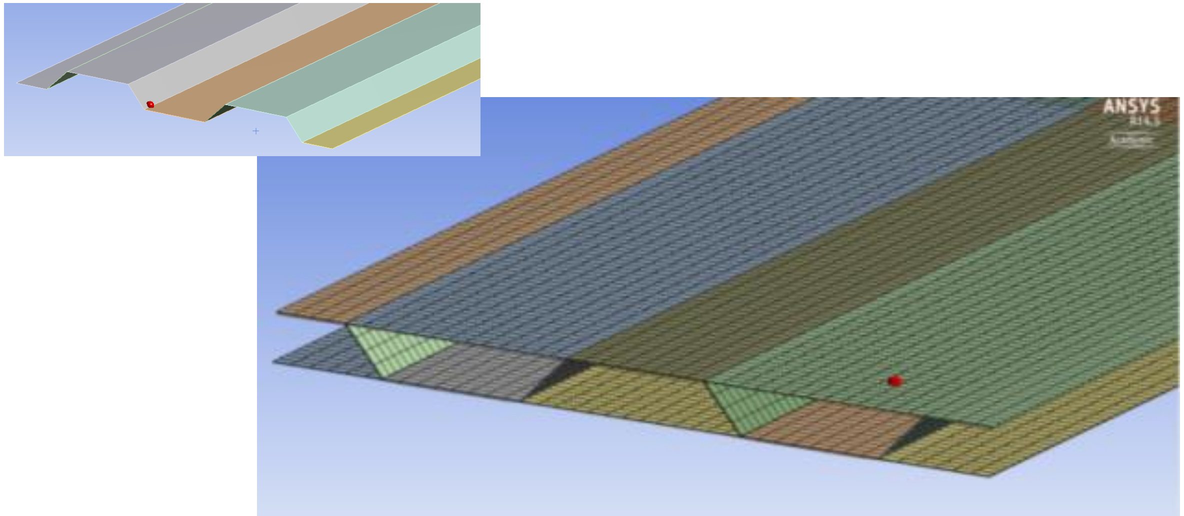
3rd Eigenmode
~447Hz

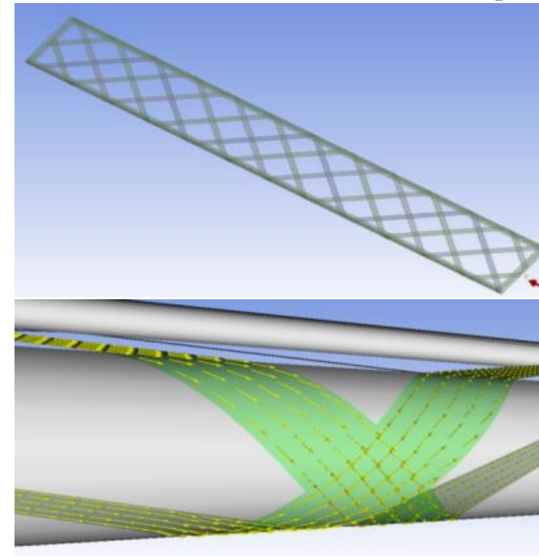


→The first three eigenmodes seem to be the most excited ones.

→The stave simulated natural frequencies are not yet agreeing with measurements.

Ongoing stave developments

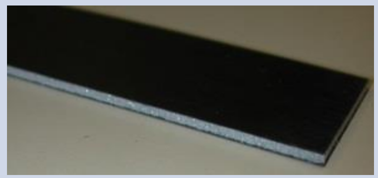
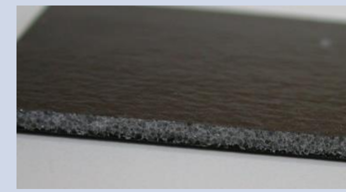




		OMEGA SHAPE (1.8mm thick)	OMEGA SHAPE (1.8mm thick)	Filament winding
Design	Skin	1 lay. M55J per skin (0°)	1 lay. XN80 per skin (0°)	High modulus carbon fibre 3K filament (M60J) wrapped around 2 foam rods
	Core	T800 3 lay. Of 20µm	M55J 1 lay. of 30µm at 90°	
Mass with glue	g	1.55g	1.69g	~1g (estimate)
Radiation length	Skin	0.022%	0.038%	0.019% (estimate)
	Core	0.024%	0.013%	0.008% (estimate)
	Glue	*(20 µm* 76%):* 0.004%	*(20 µm* 76%)* 0.004%	0.012% (estimate)
	Total	**0.05%**	**0.054%**	**0.039% (estimate)**
Flexural stiffness	N/mm	3.5N/mm	4.35N/mm	?
Approx. natural frequency	Clamped Hz	~183Hz With modules	~202Hz With modules	?

Stave flexural stiffness summary

→ Results for the **most optimised staves** with a 180mm span.

Stave label #	#1 (reference)	#5	New NTPT Staves
Material	M55J + Rohacell 51 	M55J + Rohacell 51 	M55J + Rohacell 51 
Flexural stiffness (N/mm) Measurements	6.95 N/mm	2.23 N/mm	To be measured soon.
Flexural stiffness (N/mm) FEM Model	6.95 N/mm	2.30 N/mm	3.27 N/mm
Mass (g) 280mm long	3.74 g	1.76 g	1.97 g
X/X0 % (Calculated)	0.121 %	0.051 %	0.0597 %

→ Very interesting design (#5), using standard prepreg was prototyped in order to reach the 0.5% radiation length.

→ Very simple design (NTPT) using new thin prepregs nearly reaches the X0 target and providing interesting stiffness.

Conclusion

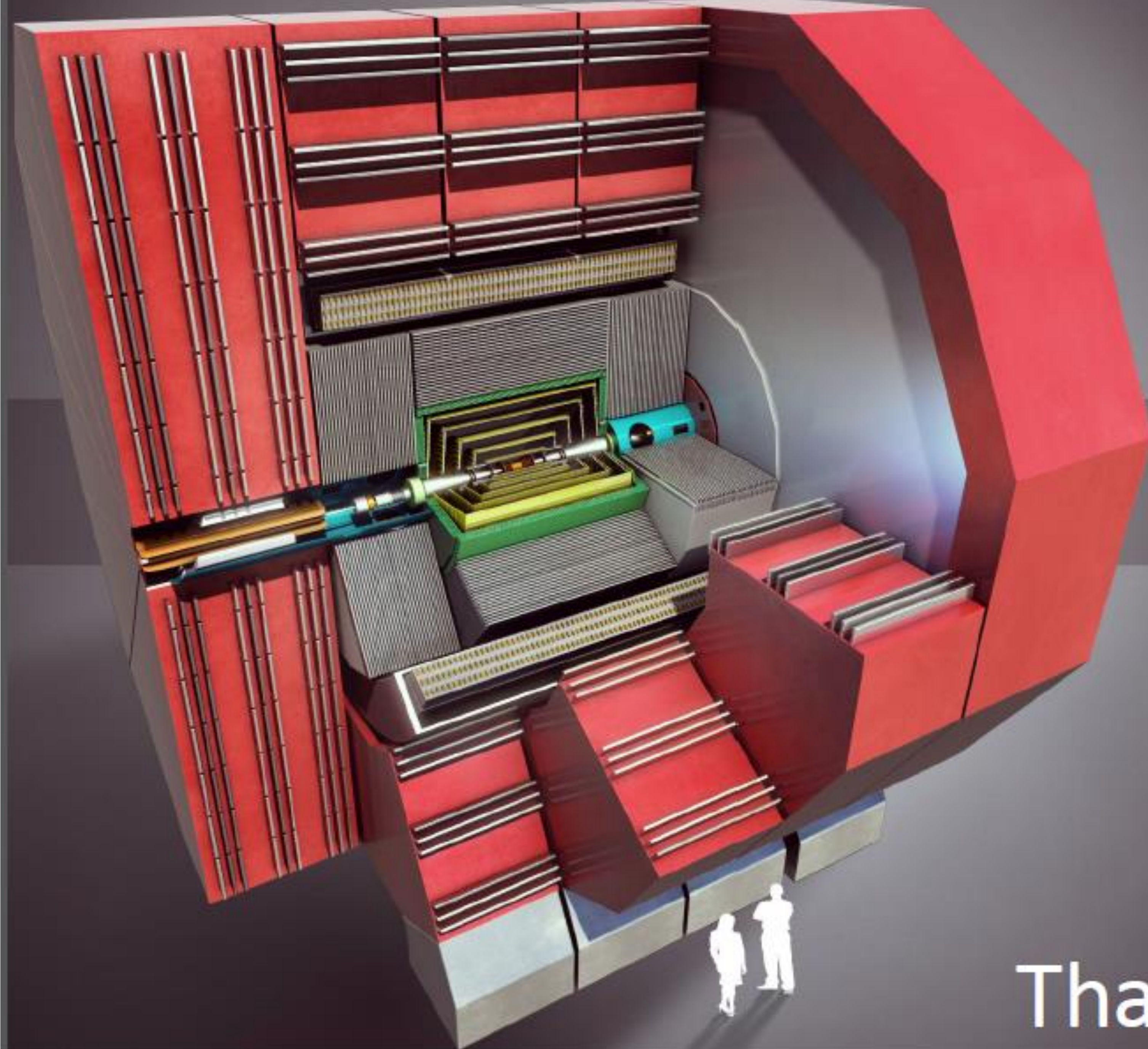
- The air cooling strategy proposed for the Vertex detector involves the design of stiff structures.
- Several designs have been prototyped including the use of new thin prepregs.
- Air flow induced vibrations are studied.

→First results shows the induced vibration amplitudes are acceptable.

- A dedicated mechanical laboratory is equipped with precise instruments. →Validations of the simulations thanks to the measurements.
- Ongoing stave developments:

→Production quality and regularity (at CERN and outside),

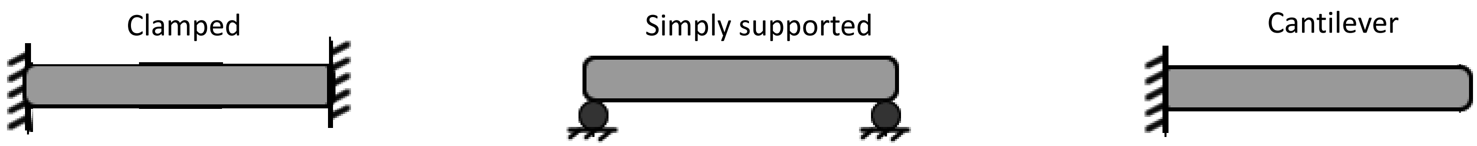
→Simulations

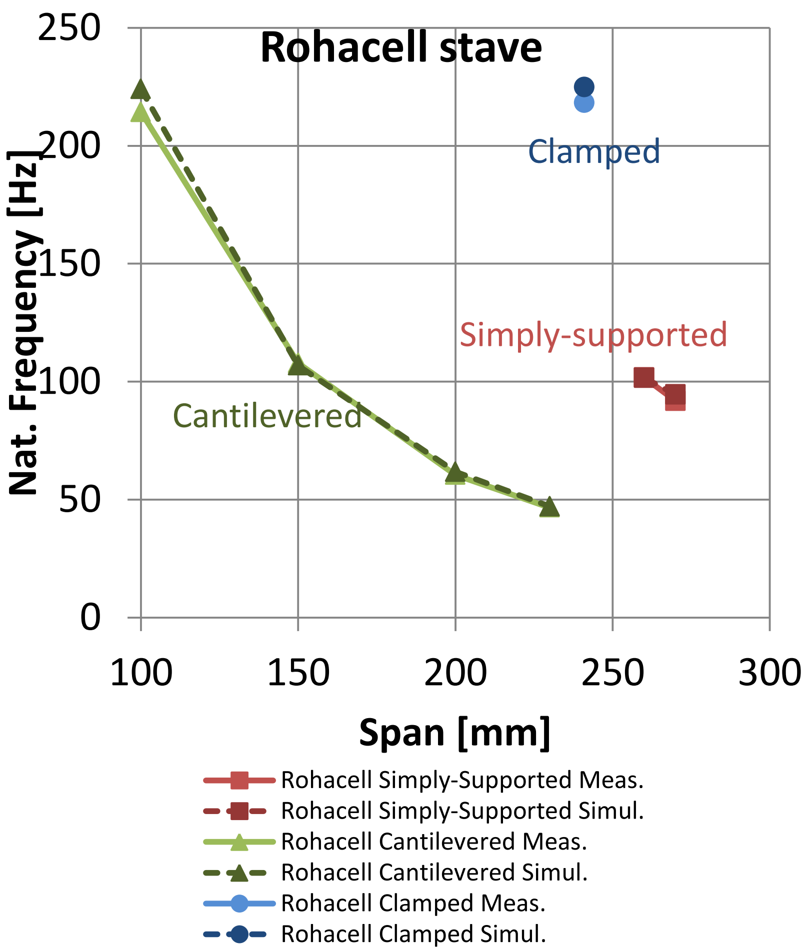


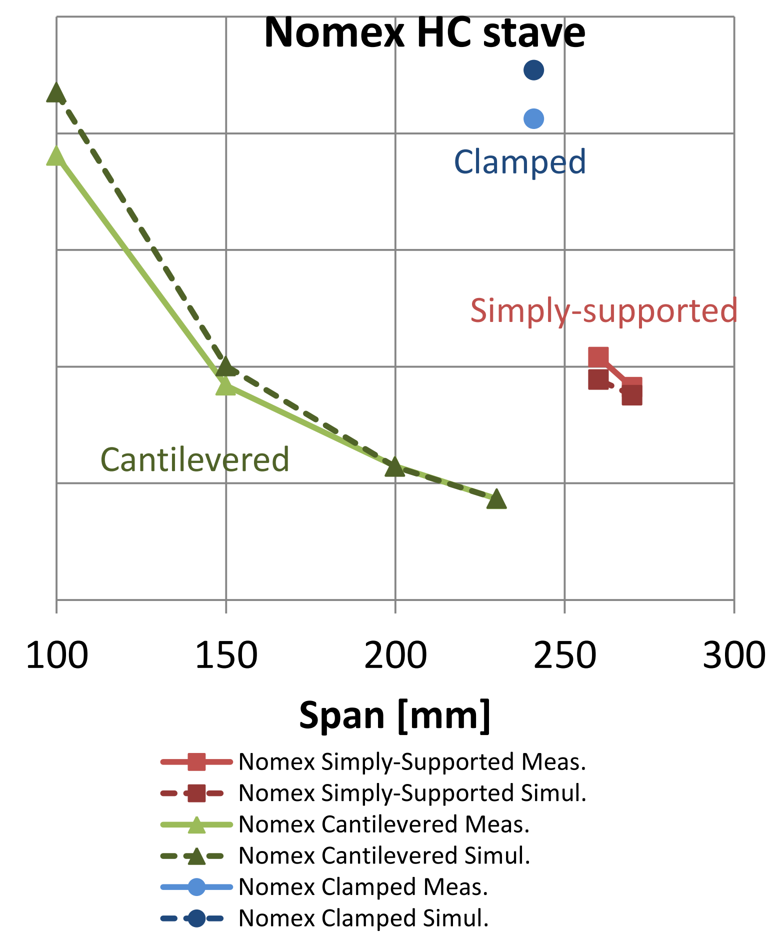
CLIC Detector

Thank you

Free vibration tests - Stave natural frequencies



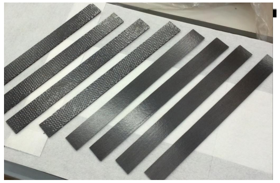




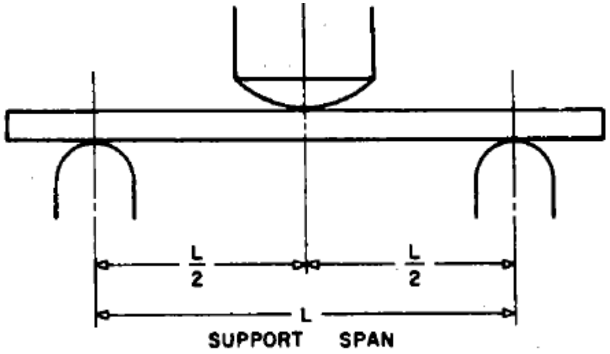
→Simulations are done with lower young modulus for staves (scaling parameter).

→Stave flatness could have an impact on vibration tests results (simply supported tests).

Stave flexural stiffness measurements
Thin ply staves



→ Objectives:
- Comparing stave stiffness versus design, geometrical imperfections, etc…
- Comparing results with FE simulations.
- Getting an idea of the stave natural frequency.



Standard used: ASTM D790-02

Configuration:
Loading nose and supports radius: 5mm
Support span : 260mm
Loading nose speed: 57.4mm/min
Test stopped when 0.3N are reached for honeycomb staves and 0.8N for rohacell staves

Polymer lab facility

Load cell:
Capacity: 100N Accuracy of 1% of applied load (~+/-0.025N)
Position measurement accuracy:
Not well known (*0.001mm ! announced by the manufacturer…)*

X0 measurements

→Process:

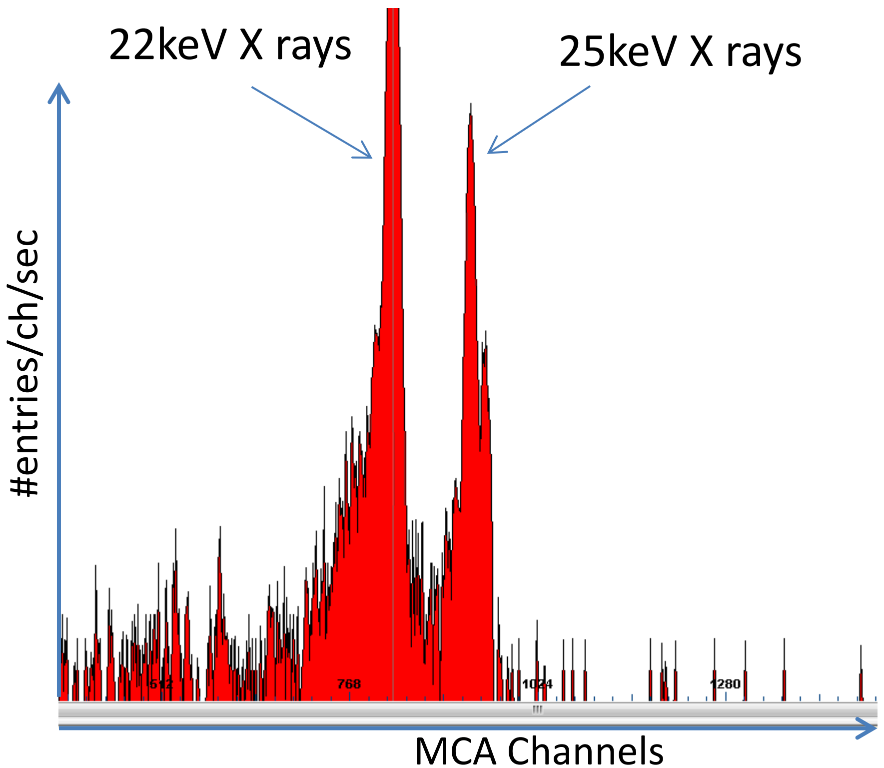
- Measure of the amount of detected photons over a certain period. No Stave on the beam trajectory. → N_0
- Measure of the amount of detected photons over a similar period with the stave located on the beam trajectory. →N
- We get the X0 of the full stave sandwich thanks to the following law:

$$N/N_0 = e^{-X0}$$

A narrow beam of monoenergetic photons with an incident intensity I_o, penetrating a layer of material with mass thickness x and density ρ, emerges with intensity I given by the exponential attenuation law :

$$I/I_o = \exp[-(\mu/\rho)x] \; .$$

x = material mass thickness
ρ = material density
μ/ρ = attenuation coefficient
I_0 = photon incident intensity
I = photon intensity after the material sample



Example of the measurement of absorption of 22 keV and 25 keV X-rays from 109Cd by a sample object with X-123 detector

The effect of Compton scattering is negligibly small in this energy, and counting only the signals at the photoelectric peak is sufficient to measure the absorption.

X0 measurements - uncertainty -

→Expectation:

- Stave is thin and made of very light materials. 0.05%X0 expected.
- The photon absorption will be small → N/N_0 close to 1.
- **Measurements could be long…**

Attenuation law → $$\frac{N}{N_0} = e^{-X_0}$$

Attenuation law → $$X_0 = -\ln\left(\frac{N}{N_0}\right) = -\ln(r)$$ given $$r = \frac{N}{N_0} \sim 1$$

$$dX_0 = \frac{dX_0}{dr}.dr = \frac{1}{r}.dr$$

$$dr = r.dX_0 = r.X_0.\frac{dX_0}{X_0} \sim X_0.\frac{dX_0}{X_0}$$

Targeted X0→ $$X_0 = 0.0005$$

Proposed uncertainty on the X0→20% $$\frac{dX_0}{X_0} = \frac{0.0001}{0.0005} = 0.2$$

$$dr \sim 1.10^{-4}$$

Photon beam counting statistical error → $$\frac{\sqrt{N}}{N} \sim 1.10^{-4}$$ →

Amount of photons to be counted:
$N \sim 1.10^{8}$

Photon rate ~ 4.72/s → 245 days of measurements…

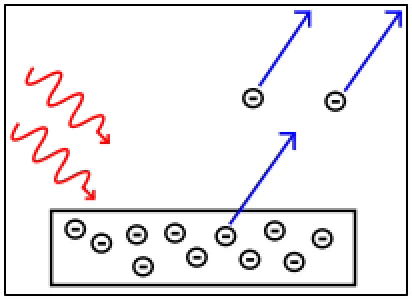
X0 measurements

→Process:

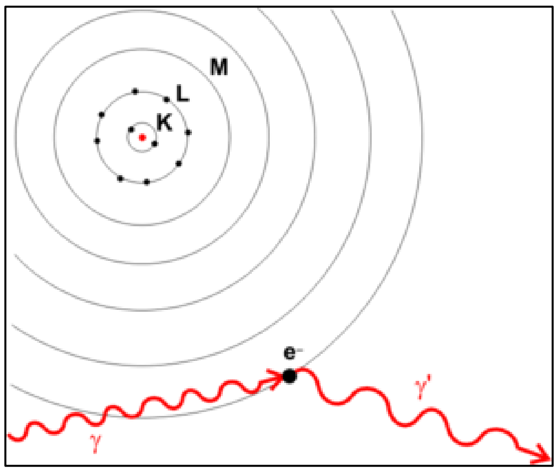
- Measure of the amount of detected photons over a certain period. No Stave on the beam trajectory. → N_0
- Measure of the amount of detected photons over a similar period with the stave located on the beam trajectory. →N
- We get the X0 of the full stave sandwich thanks to the following law:

$$N/N_0 = e^{-X0}$$

-Photo electron effect



-Compton Effect

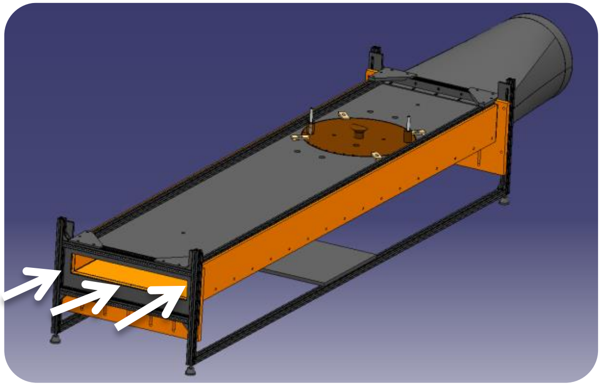


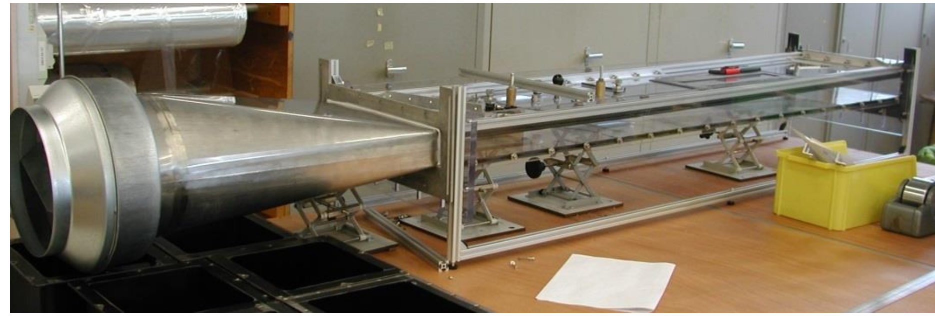
-electron pair effect (photon nucleus interaction)

$\gamma + \gamma \rightarrow e^- + e^+$

CLIC vertex laboratory at CERN

→Construction of thermo-mechanical test bench for Vertex staves

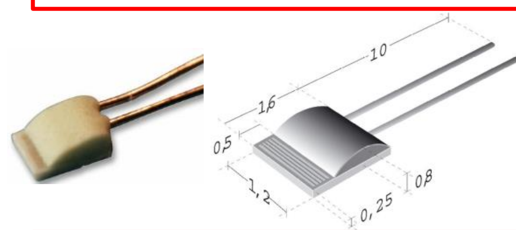




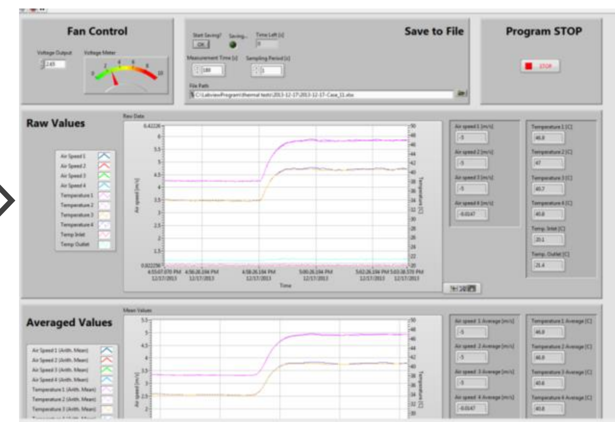
→ Read out system and equipment

Schmidt SS 20.400 anemometer

PT1000 sensor



LabVIEW interface



Laser vibration sensor Micro ε

Resolution:
→0.15µm @ 15kHz
Measuring frequency:
→up to 49 kHz

Infrared camera

Resolution:
→640*480 pixels
Images frequency:
→50Hz
Sensibility:
→< 50mK

CLIC vertex laboratory at CERN
Read out

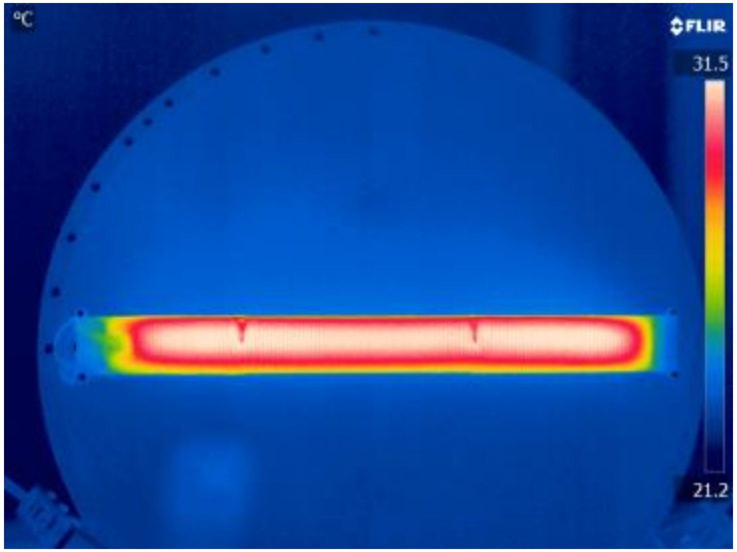
→ Read out system and equipment

PH-DT
Detector Technologies

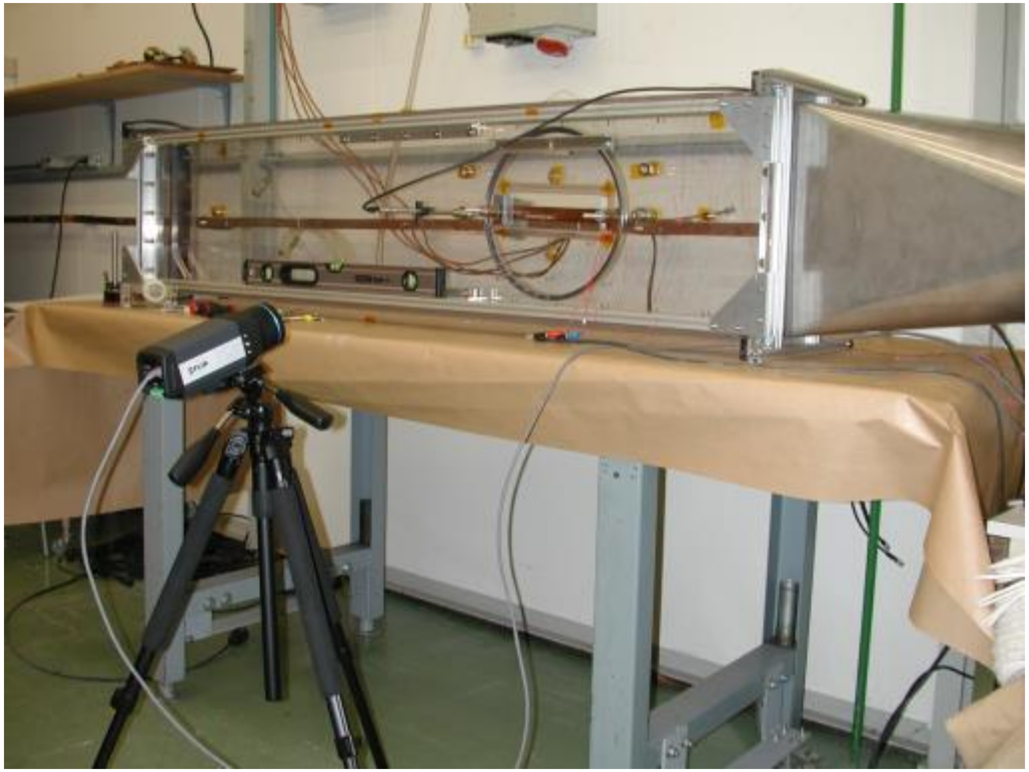
Thermal camera **FLIR A655 sc**

- -Resolution: 640*480 pixels
- -Images frequency: 50Hz
- -Sensibility: < 50mK
- -External trigger

output



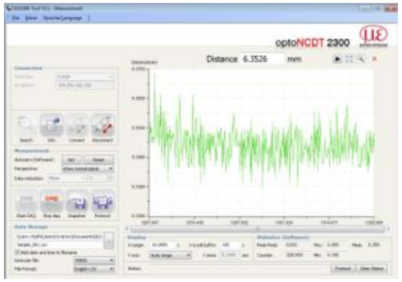
Set up



Data acquisition

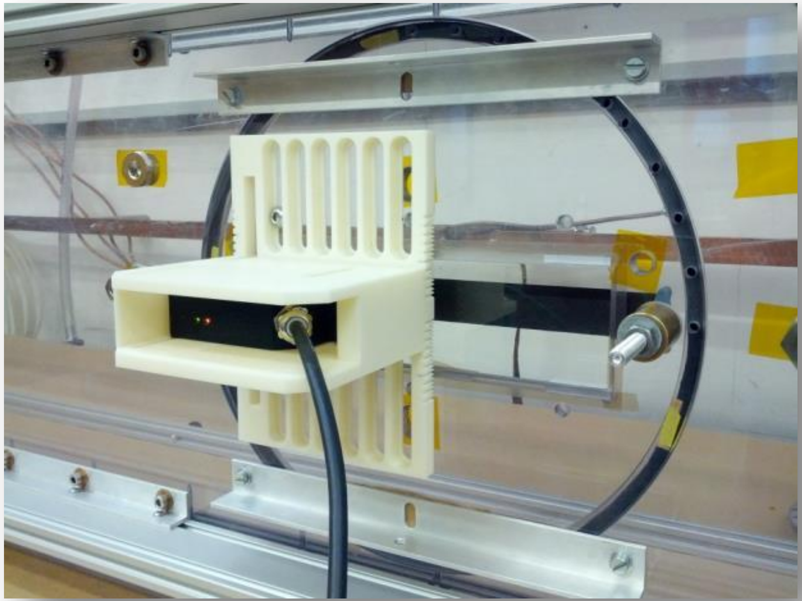
Micro-Epsilon optoNCDTLL 2300-10LL

Proprietary software



Matlab scripts

Model		ILD 2300-2LL	ILD 2300-10LL	ILD 2300-20LL
Measuring range [1]		2 (2) mm	10 (5) mm	20 (10) mm
Start of measuring range	SMR	24 (24) mm	30 (35) mm	40 (50) mm
Midrange	MMR	25 (25) mm	35 (37.5) mm	50 (55) mm
End of measuring range	EMR	26 (26) mm	40 (40) mm	60 (60) mm
Linearity		0.6µm ≤±0.03% FSO	2µm	4µm ≤±0.02% FSO
Resolution (20kHz)		0.03µm	0.15µm 0.0015% FSO	0.3µm
Measuring rate		adjustable via software 49.02 / 30 / 20 / 10 / 5 / 2.5 / 1.5kHz (49.02kHz with reduce		
Permissable ambient light		10.000…40.000lx		
Spot diameter	SMR	85 x 240µm	120 x 405µm	185 x 485µm
	MMR	24 x 280µm	35 x 585µm	55 x 700µm
	EMR	64 x 400µm	125 x 835µm	195 x 1200µm

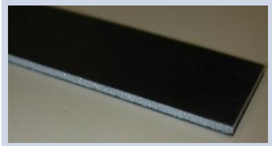
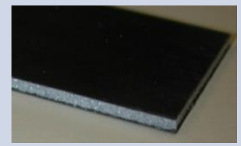


Vertex Detector Structure: Stave

→ Stave Mechanical Characterisation. Evaluation of the **Bending stiffness.**

$$f = \frac{F * l^3}{48 * E_s * I} + \frac{F * l}{4 * G * b * h} \qquad 1 = \frac{m * l^3}{48 * E * I} + \frac{m * l}{4 * G * b * h}$$

$$E * I = \frac{m * l^3}{48 * (1 - \frac{m * l}{4 * G * b * h})}$$

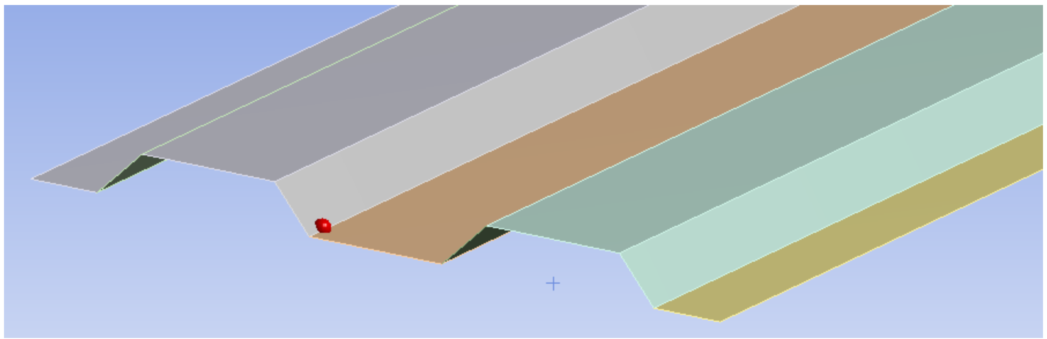
Stave label #	#5	#1	#7	#8	#9
Material	M55J + Rohacell 51 	M55J + Rohacell 51 	T800, [0°; 90°; 0°], 	T800, [0°; 90°; 0°], 	T800, [0°; 90°; 0°], 
Flexural stiffness (N/mm) Measurements	2.23 N/mm	6.95 N/mm	*2.12 N/mm*	*2.17 N/mm*	*2.24 N/mm*
Bending stiffness $N.mm^2$	$3.210*10^5$ $N.mm^2$	$1.769*10^6 N.mm^2$	$3.605*10^5 N.mm^2$	$3.132*10^5 N.mm^2$	$3.238*10^5 N.mm^2$
Natural frequency estimate (Hz) (280mm long stave clamped on both sides)	157 Hz	314 Hz	152 Hz	140 Hz	142 Hz

→ Vibration tests should tell us if such natural frequencies are close to exciting vibration of air.

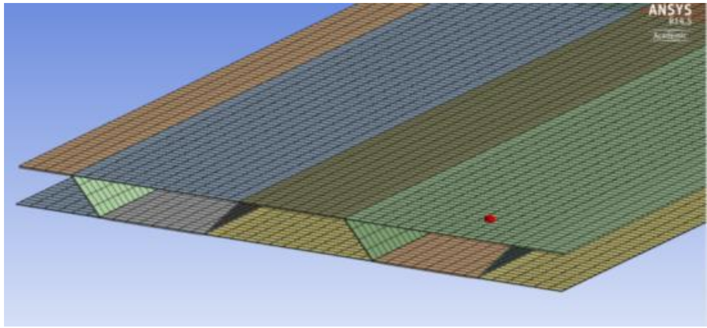
Stave ongoing simulations
Different designs studied

Omega shape

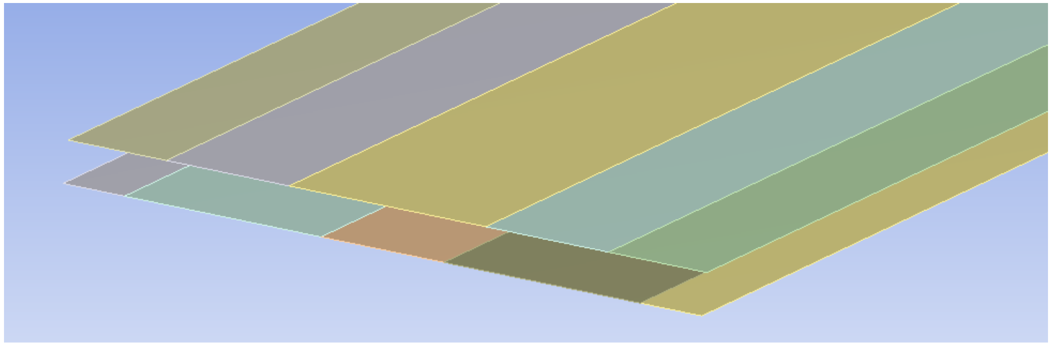
Core 3 layers [0, 90, 0] of very thin prepreg: T800, 3*0.020mm thick

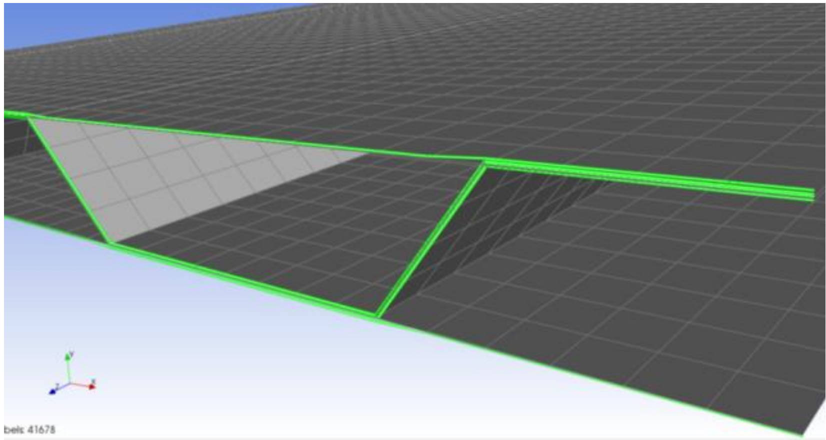


- Merged nodes simplified model
- Shell 181 elements
- Layup realised in ACP or Mechanical



Skins 1 layer per skin of high modulus prepreg: M55J : 2* 0.030mm



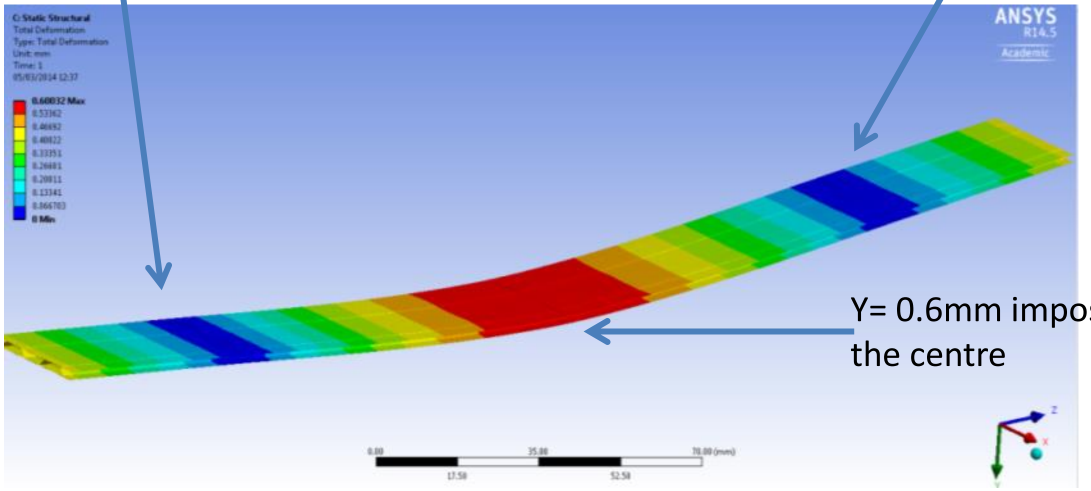


Stave ongoing simulations
Omega shape

Simulation of 180mm span:

One side with no displacements
X=0, Y=0, Z=0

Other side with only vertical displacement cancelled
Y=0



Y= 0.6mm imposed displacement in the centre

		OMEGA SHAPE (1.8mm thick)	SANDWICH SHAPE (1.8mm thick)	Former prototype
Design	Skin	1 lay. M55J per skin (0°)	1 lay. M55J per skin (0°)	3lay. T800 of 30 µm per skin
	Core	T800 3 lay. Of 20µm	Nida nomex 1.74mm thick	Rohacell
Mass with glue	g	1.55g	1.44g	3.17g
Radiation length	Skin	0.022%	0.022%	0.064%
	Core	0.024%	0.012%	0.020%
	Glue	*(20 µm* 76%):* 0.004%	*(40 µm* 200%):* 0.019%	0.042%
	Total	**0.05%**	**0.053%**	**0.126%**
Flexural stiffness	N/mm	3.5N/mm	2.69N/mm	2.12N/mm
Approx. natural frequency	Clamped Hz	~183Hz With modules	~178Hz With modules	~150Hz With modules

Stave ongoing simulations
Filament winding

Filament winding stave