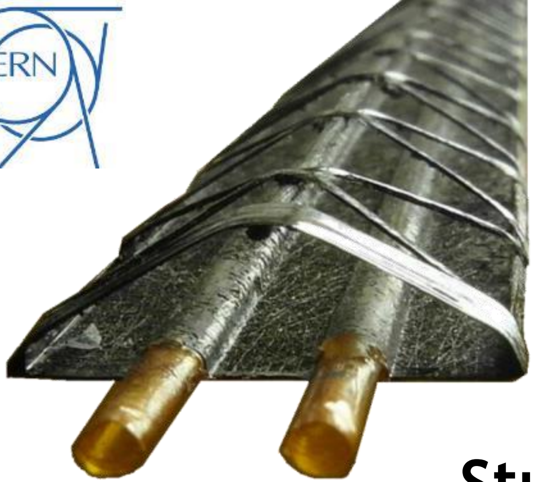
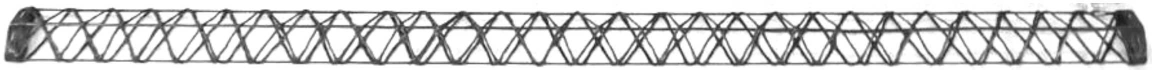


Studies
on the mechanics and cooling of the ALICE ITS upgrade based on carbon fibre structures



Forum on Tracking Detector Mechanics
DESY, Hamburg, 30June-2July 2014

Corrado Gargiulo
on behalf of
Alice Collaboration

Outline

ALICE NEW INNER TRACKER SYSTEM

STAVE LAYOUT
- MATERIALS
- PRODUCTION PROCESSES
- CHARACTERIZATION
    - MATERIAL BUDGET
    - MECHANICAL
    - THERMOELASTIC
    - POLYIMIDE PIPES
    - THERMAL (Manuel talk)

LAYERS, BARRELS

INTEGRATION IN ALICE

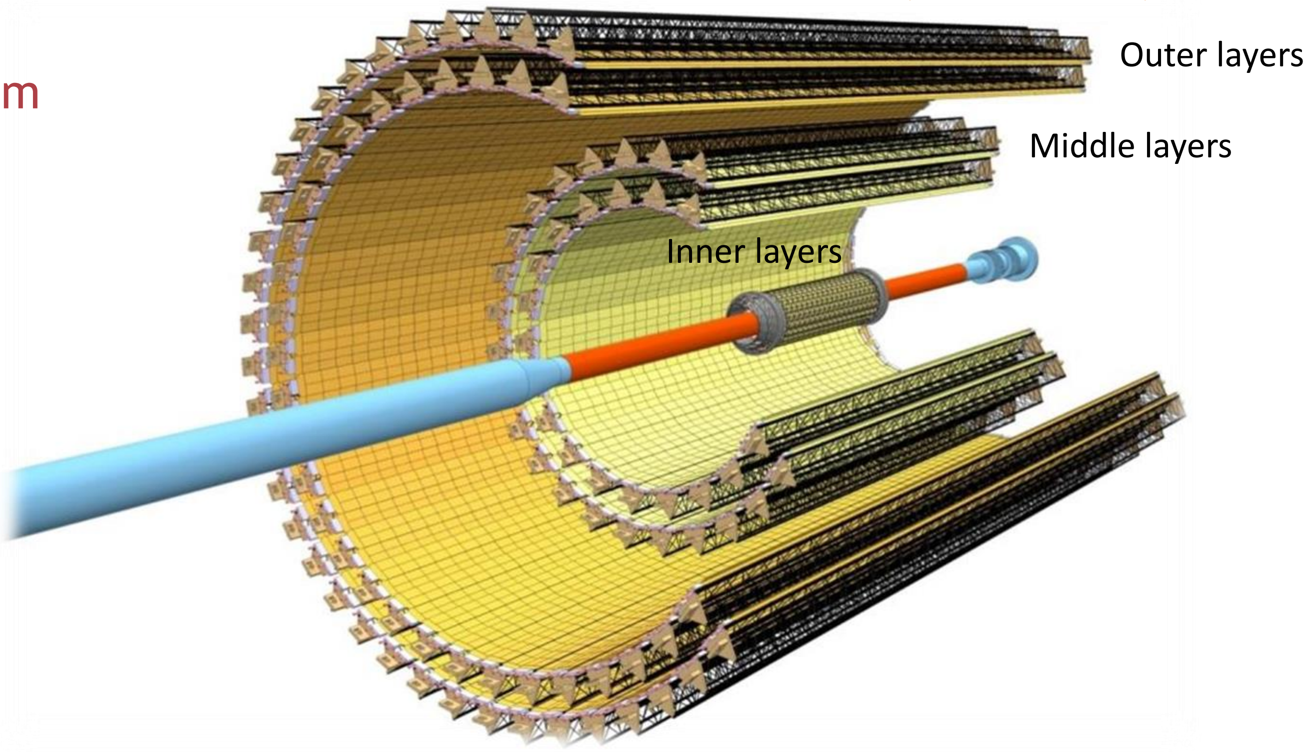
New Inner Tracker System

7 layers of Monolithic Active Pixel Sensors

12.5 G-pixel camera (~10m^2)

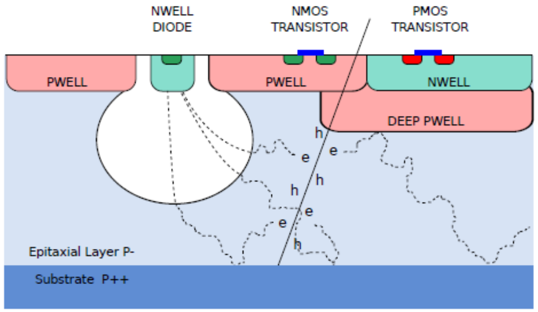
r coverage: 22 – 400 mm

η coverage: $|\eta| \leq 1.22$
for tracks from 90%
most luminous region

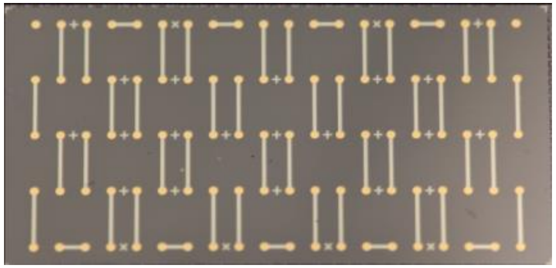


- Beam pipe 19mm OR, ITS beam pipe minimum gap 2.8mm
- Fast installation and extraction
- Radiation length X/X0 (%)~0.3 inner layers ; X/X0 (%)< 1.0 middle-outer layers
- Power Dissipated <100 mW/cm^2
- Detector Operative T=30°C; acceptable ΔT=5°C along stave
- Radiation environment 700 krad/ 1x10^{13} 1 MeV n$_{eq}$ includes safety factor 10

Pixel chip



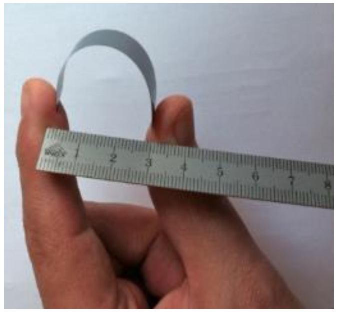
Schematic cross section of a Monholitic Active Pixel Sensor

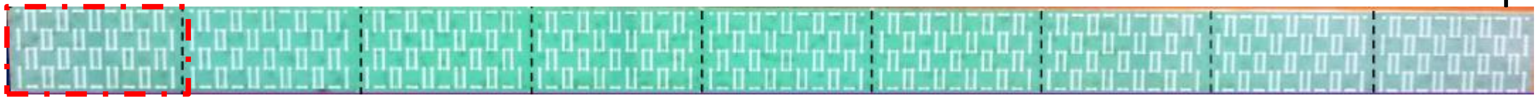


(30mmx15mmx0.05mm)

Pixel Chip: CMOS TowerJazz 0.18 μm

- Chip size: 15 mm x 30 mm
- Pixel pitch ~ 30 μm
- Si thickness: 50 μm
- Spatial resolution ~ 5 μm
- Power density < 100 mW/cm^2
- Integration time < 30 μs
- Supply pads over the pixel matrix

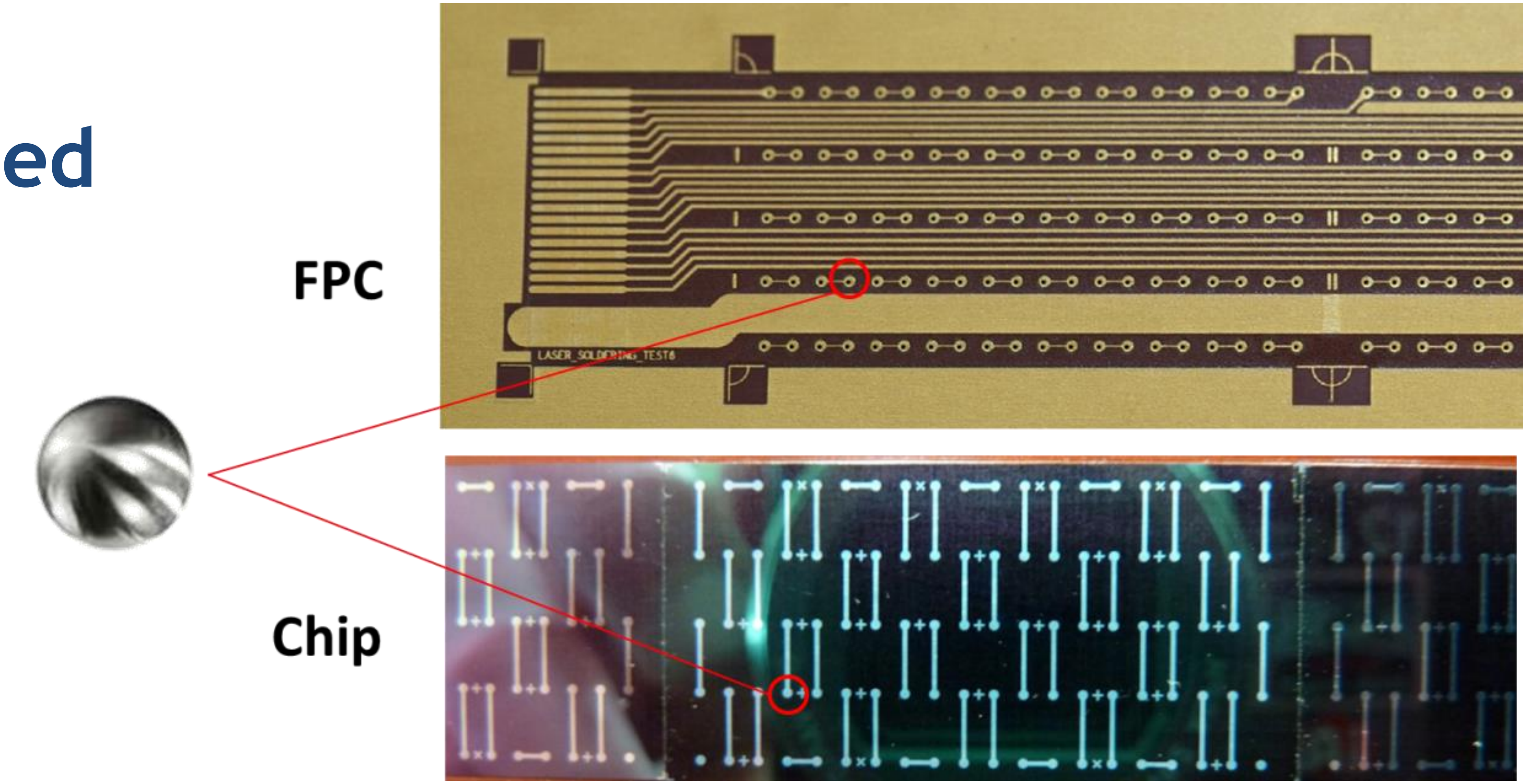




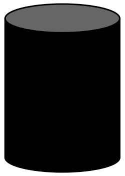
Flex Printed Circuit FPC

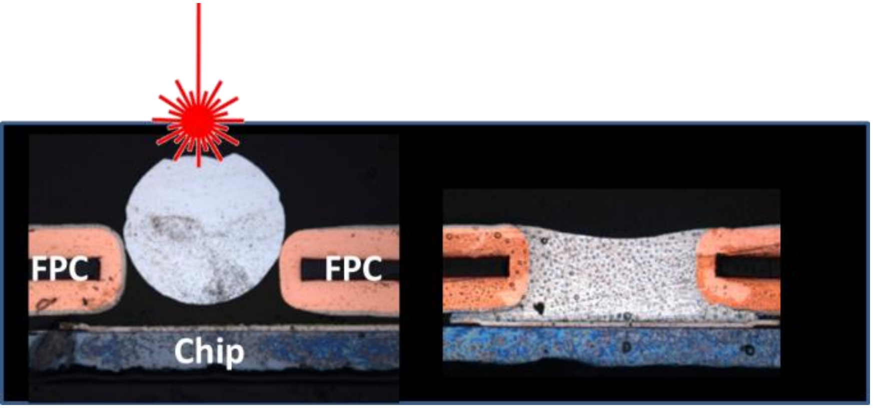
Layout for Inner Barrel

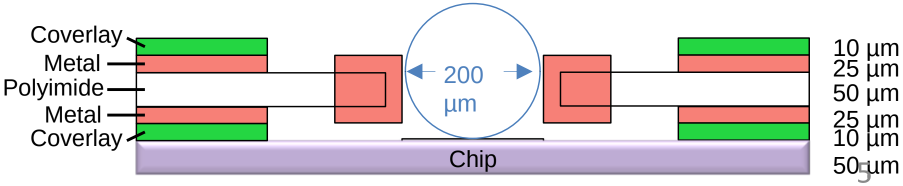
Hybrid Integrated Circuit



Interconnection of Pixel chip on FPC by selective laser soldering



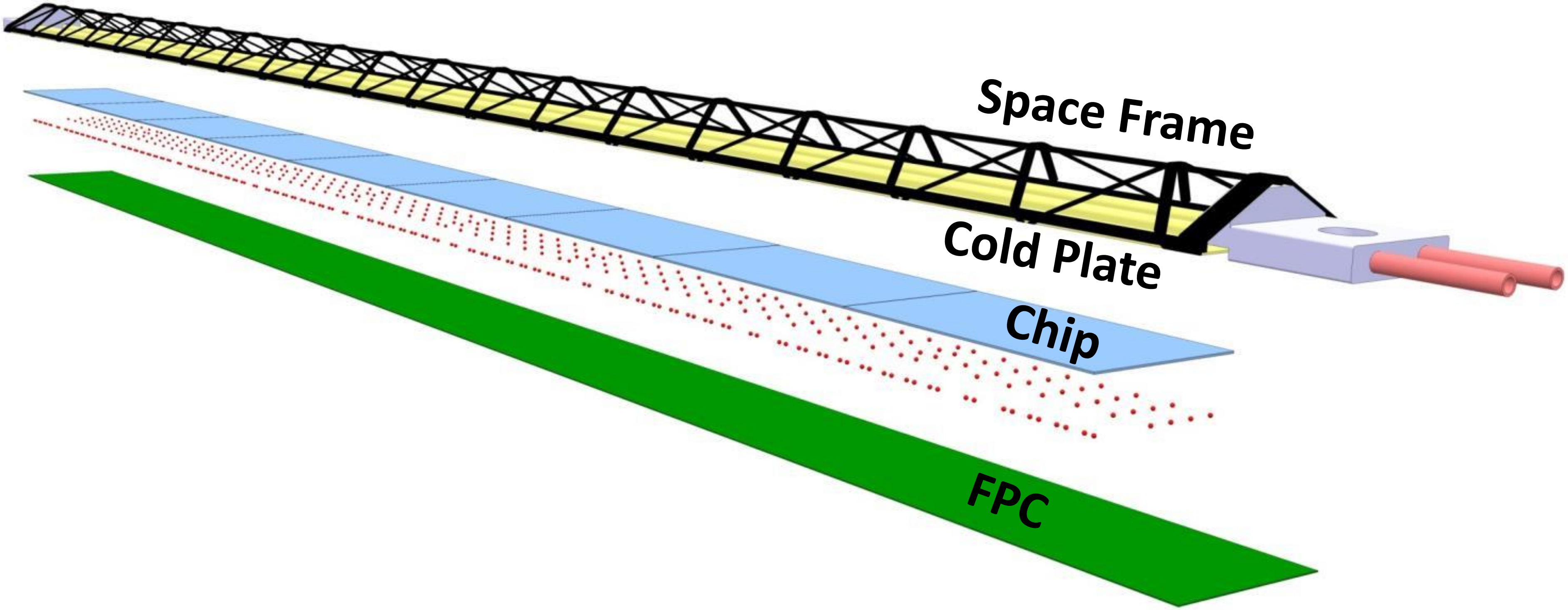




Inner Barrel Stave

Space Frame: truss-like lightweight mechanical support structure based on composite material (carbon fibre).;

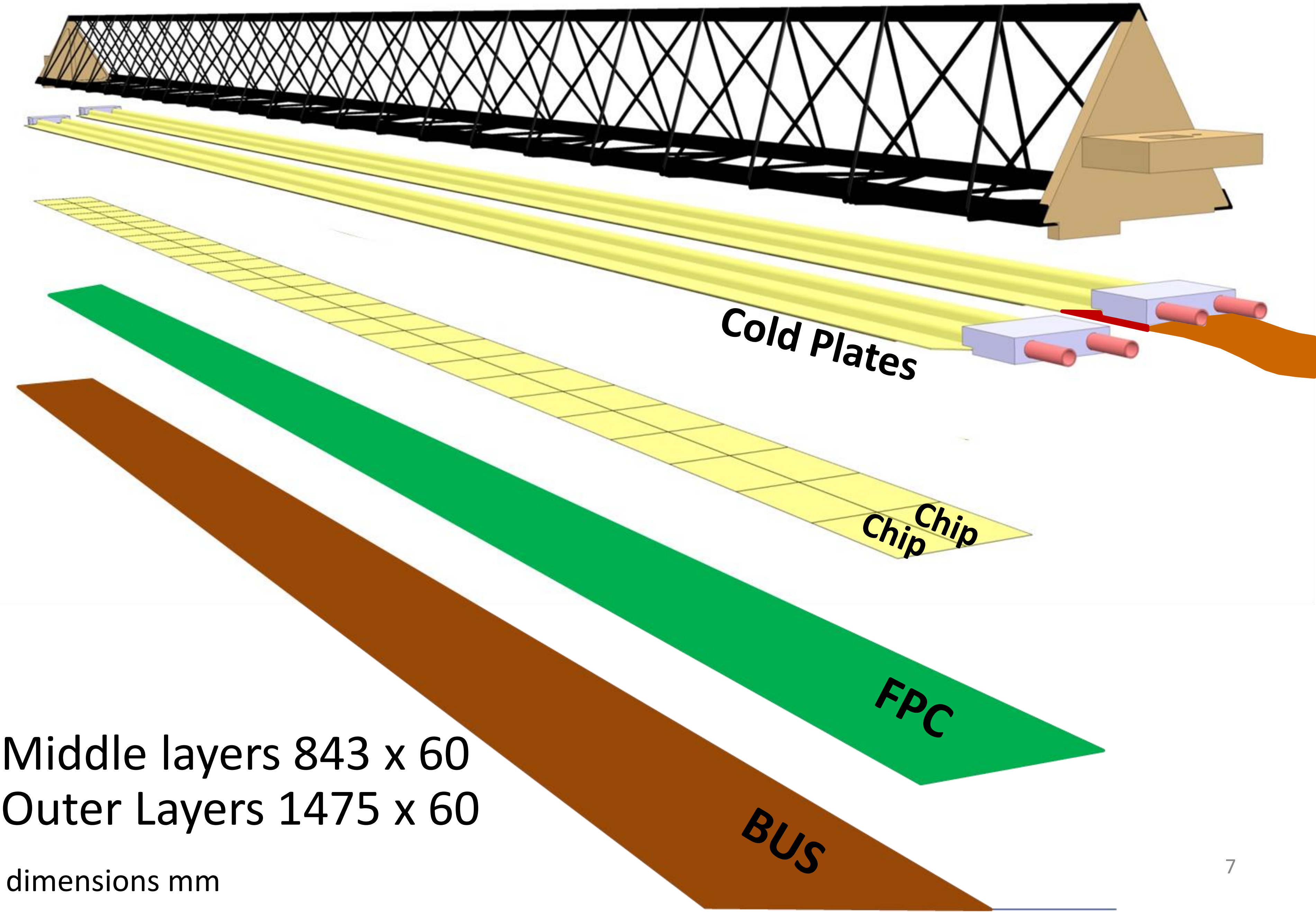
Cold Plate: a sheet of high-thermal conductivity carbon fibre with embedded polyimide cooling pipes, which is integrated with the Space Frame



270x15

dimensions mm

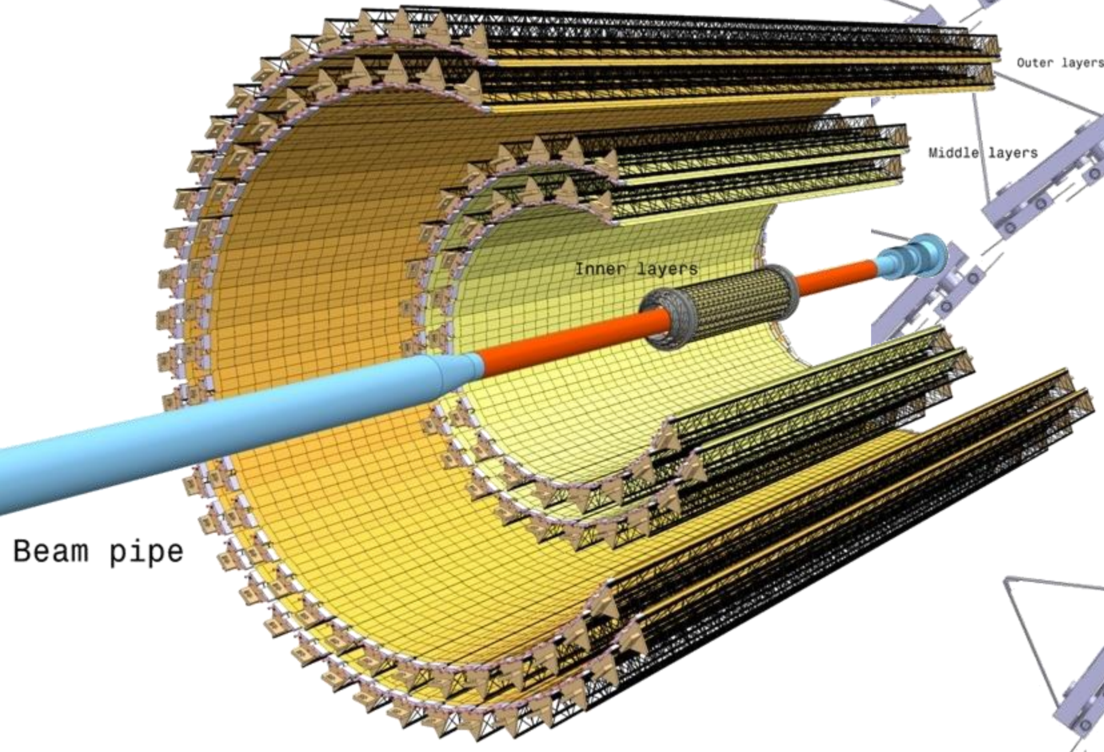
Outer Barrel Stave

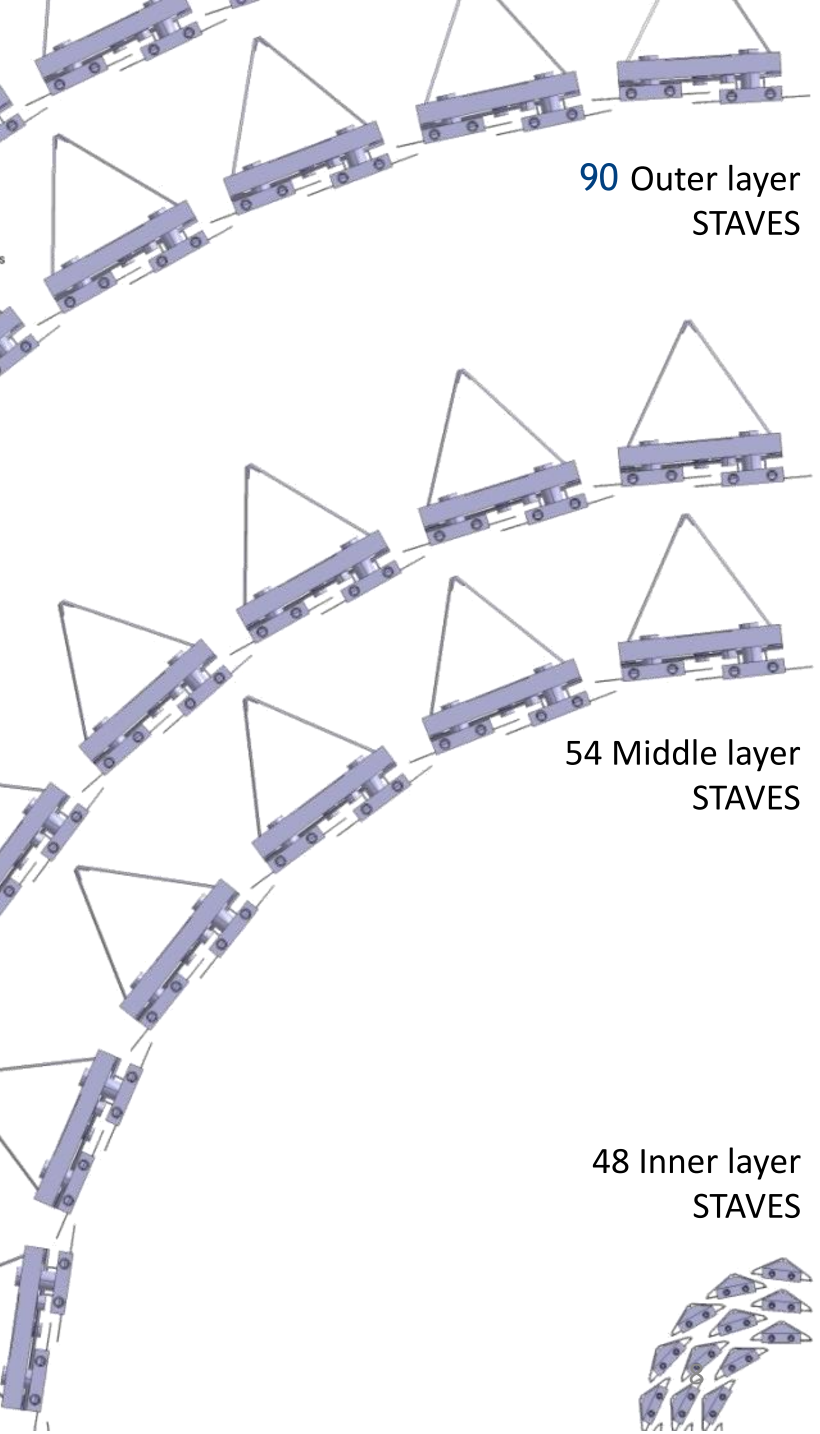


Middle layers 843 x 60
Outer Layers 1475 x 60

dimensions mm

Layers layout

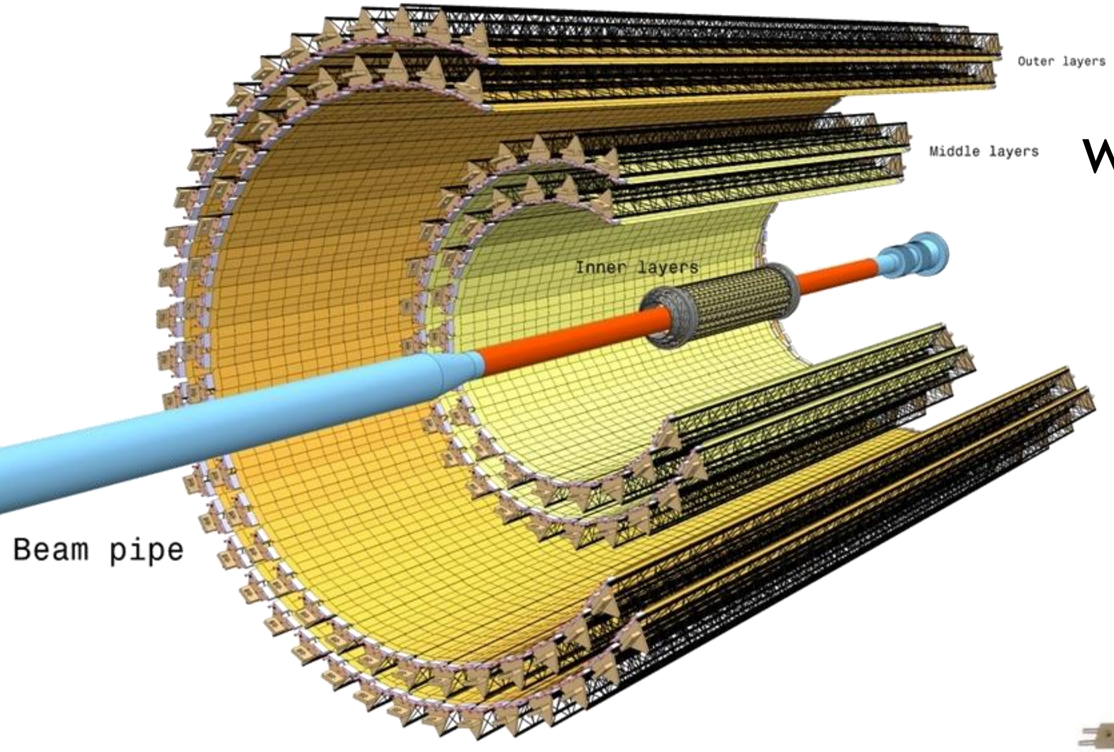




The ITS layers are azimuthally segmented in Staves, which are mechanically independent.

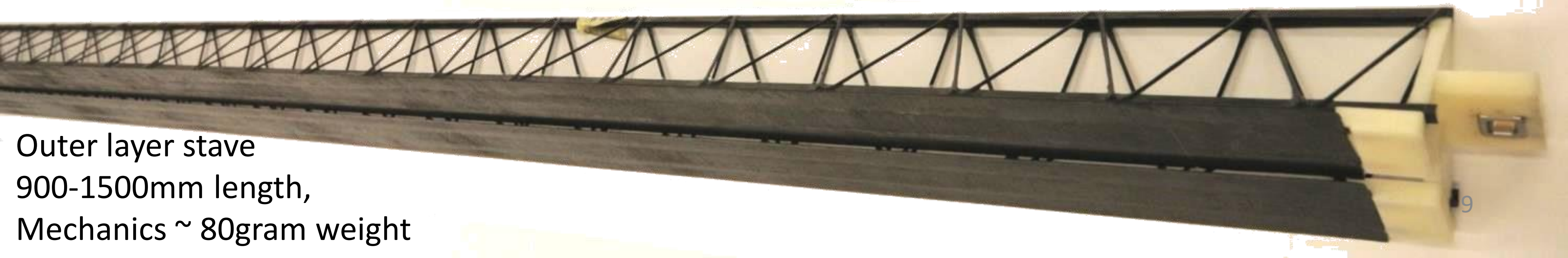
Radial coverage
22-406mm

Stave mechanics and cooling



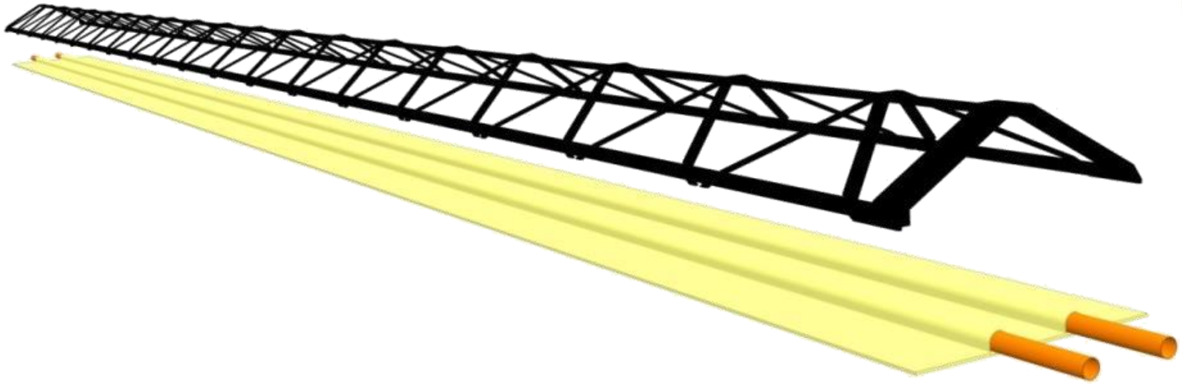
Carbon Fibre reinforced structure
with embedded polyimide cooling pipes

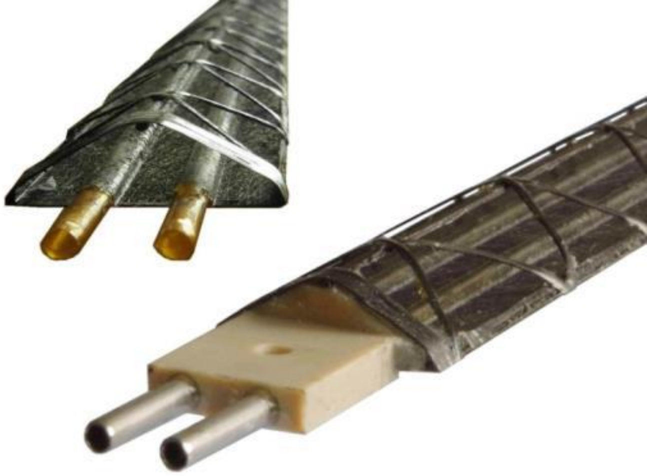
Inner layer stave
290mm length,
mechanics~1.4gram weight



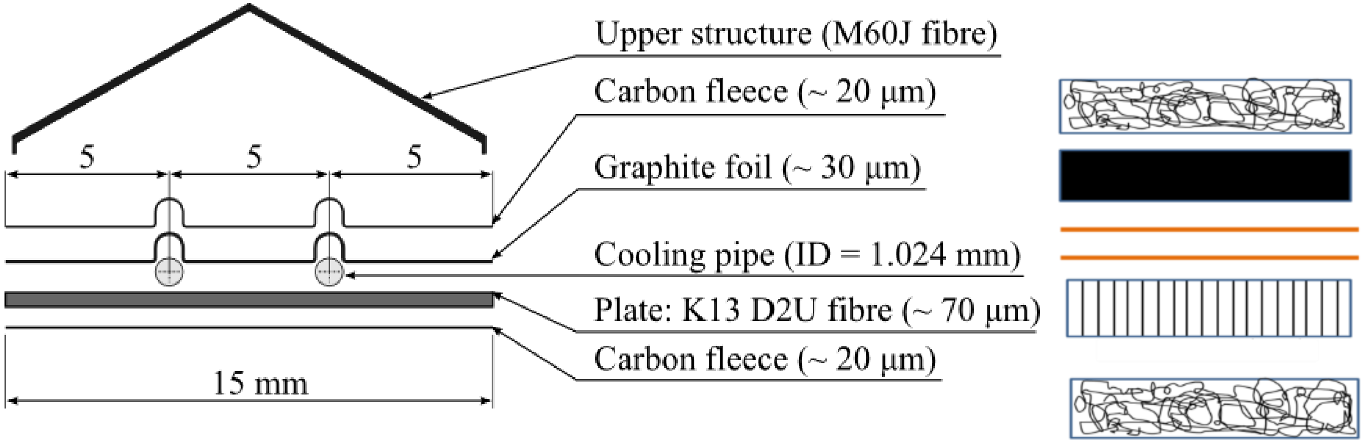
Outer layer stave
900-1500mm length,
Mechanics ~ 80gram weight

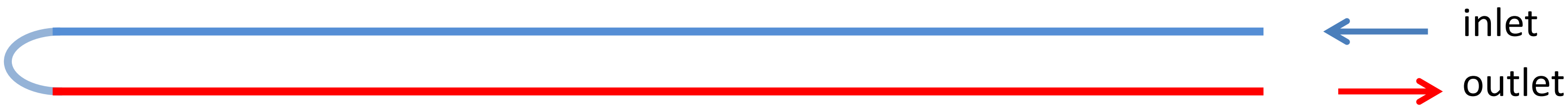
Inner Barrel Stave



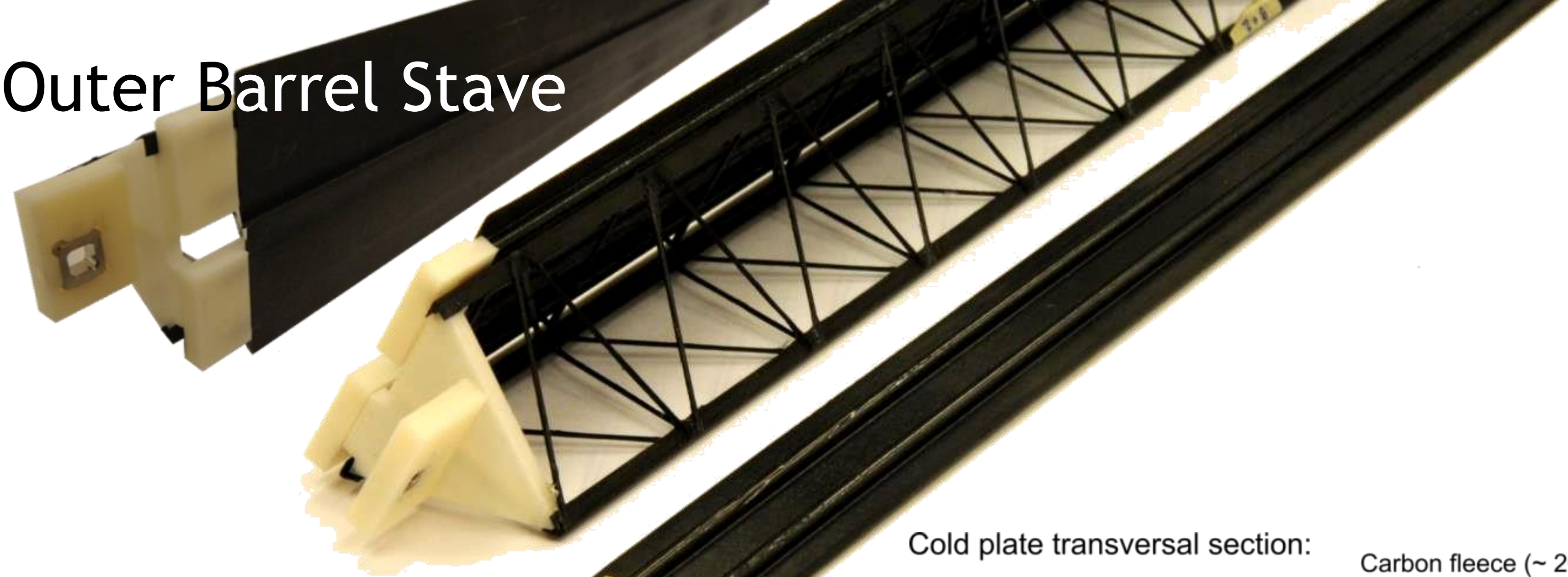


Transversal section:

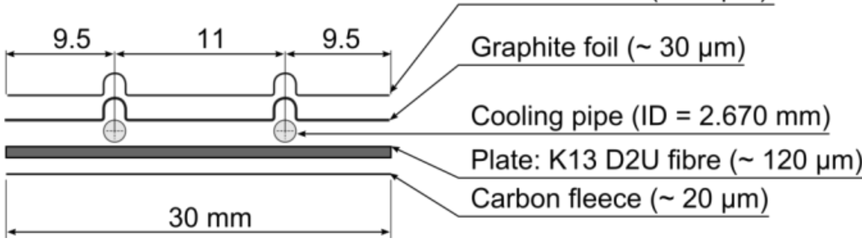


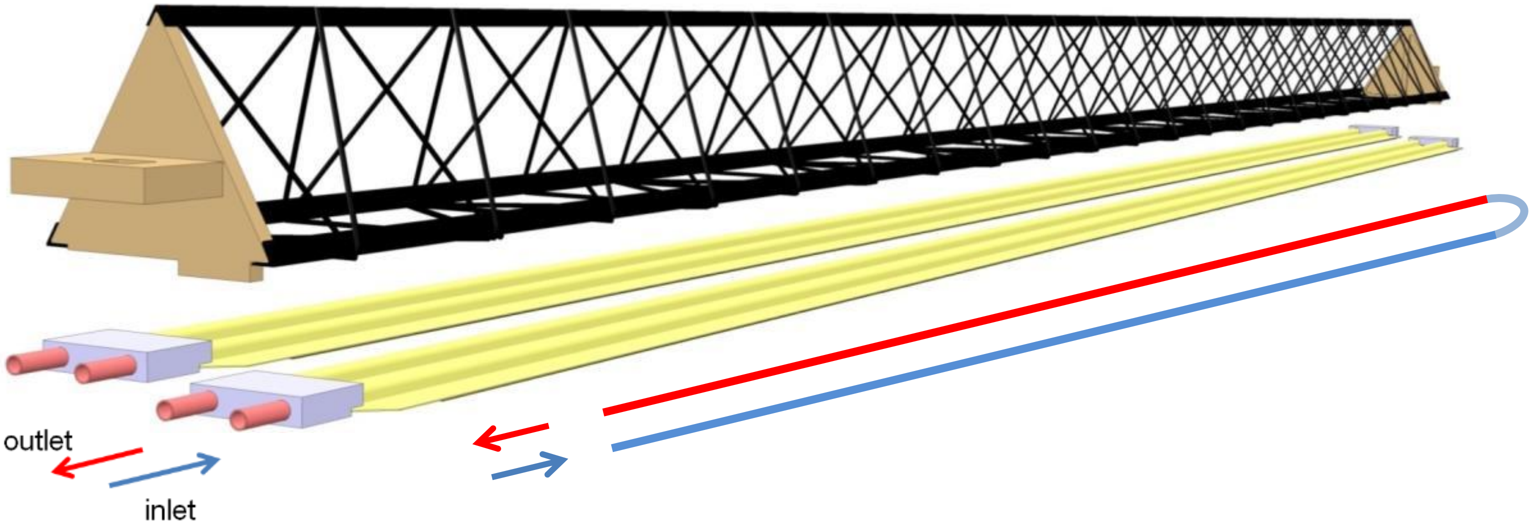


Outer Barrel Stave



Cold plate transversal section:





Materials

Carbon Structural

E [GPa]	X_t [GPa]	
240	4,4	**HT fiber**

Carbon Fleece

continuous-strand mat finished with a chemical binder to hold fibers in place

filament diameter= 5μm

t=20 μm, 8g/m2

	Filaments [K=1000]	Tex [g/km]	E [GPa]	X_t [GPa]	K [W/mK]	CTE [K^{-1}]
M60j	3K	110	588	3,9	140	$-1{,}1x\ 10^{-6}$
M55j	6K	220	540	4,2	150	$-1{,}1x\ 10^{-6}$

Carbon Roving

Bunches of filament parallel to each other

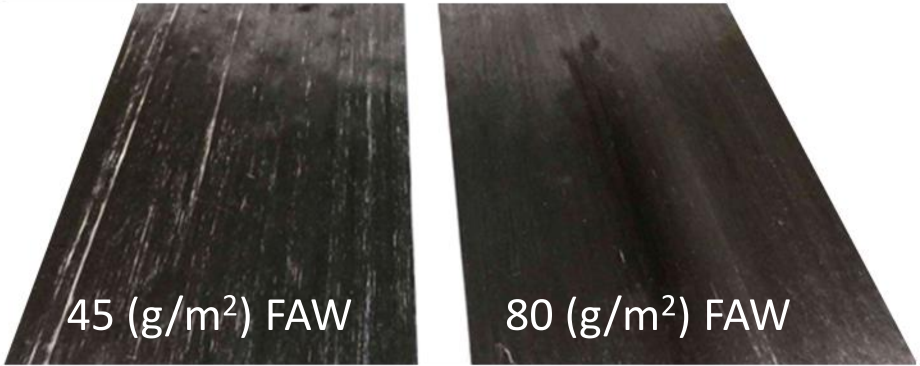
filament diameter= 5μm

Carbon Thermal

Carbon Unidirectional Prepreg

Ready to mold or cure material in sheet form which contains fiber all aligned in one direction

filament diameter= 11μm



	Filaments [K=1000]	E1 [GPa]	X_t /X_c [MPa]	E2 [GPa]	Y_t [MPa]	K [W/mK]	CTE [$10^{-6}K^{-1}$]
K13D2U [0] fibre	2K	935	3600			800	-1,2
K13D2U [0] prepreg	2K	560	1800/340	5,1	25	~450	-1 / 61

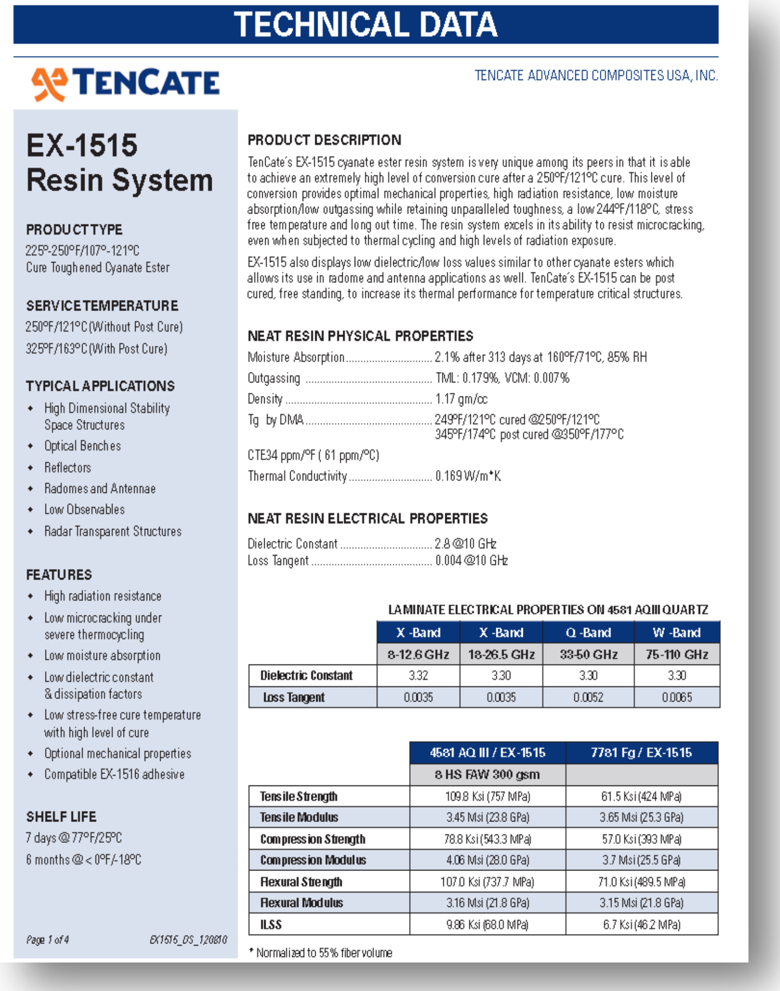
Carbon Paper

Thermal management material with very high thermal conductivity and flexibility

Thick. [μm]	Density [g/cm3]	K pl [W/mK]	K th [W/mK]
30	1.6	1500	15

Resin system: TenCate EX-1515

Optimal mechanical properties, high radiation resistance, low moisture absorption



TECHNICAL DATA

TENCATE

TENCATE ADVANCED COMPOSITES USA, INC.

EX-1515 Resin System

PRODUCT TYPE

225°-250°F/107°-121°C
Cure Toughened Cyanate Ester

SERVICE TEMPERATURE

250°F/121°C (Without Post Cure)

325°F/163°C (With Post Cure)

TYPICAL APPLICATIONS

- High Dimensional Stability Space Structures
- Optical Benches
- Reflectors
- Radomes and Antennae
- Low Observables
- Radar Transparent Structures

FEATURES

- High radiation resistance
- Low microcracking under severe thermocycling
- Low moisture absorption
- Low dielectric constant & dissipation factors
- Low stress-free cure temperature with high level of cure
- Optional mechanical properties
- Compatible EX-1516 adhesive

SHELF LIFE

7 days @ 77°F/25°C

6 months @ < 0°F/-18°C

PRODUCT DESCRIPTION

TenCate's EX-1515 cyanate ester resin system is very unique among its peers in that it is able to achieve an extremely high level of conversion cure after a 250°F/121°C cure. This level of conversion provides optimal mechanical properties, high radiation resistance, low moisture absorption/low outgassing while retaining unparalleled toughness, a low 244°F/118°C, stress free temperature and long out time. The resin system excels in its ability to resist microcracking, even when subjected to thermal cycling and high levels of radiation exposure.

EX-1515 also displays low dielectric/low loss values similar to other cyanate esters which allows its use in radome and antenna applications as well. TenCate's EX-1515 can be post cured, free standing, to increase its thermal performance for temperature critical structures.

NEAT RESIN PHYSICAL PROPERTIES

Moisture Absorption	2.1% after 313 days at 160°F/71°C, 85% RH
Outgassing	TML: 0.179%, VCM: 0.007%
Density	1.17 gm/cc
Tg by DMA	249°F/121°C cured @250°F/121°C 345°F/174°C post cured @350°F/177°C

CTE34 ppm/°F (61 ppm/°C)

Thermal Conductivity	0.169 W/m*K

NEAT RESIN ELECTRICAL PROPERTIES

Dielectric Constant	2.8 @10 GHz
Loss Tangent	0.004 @10 GHz

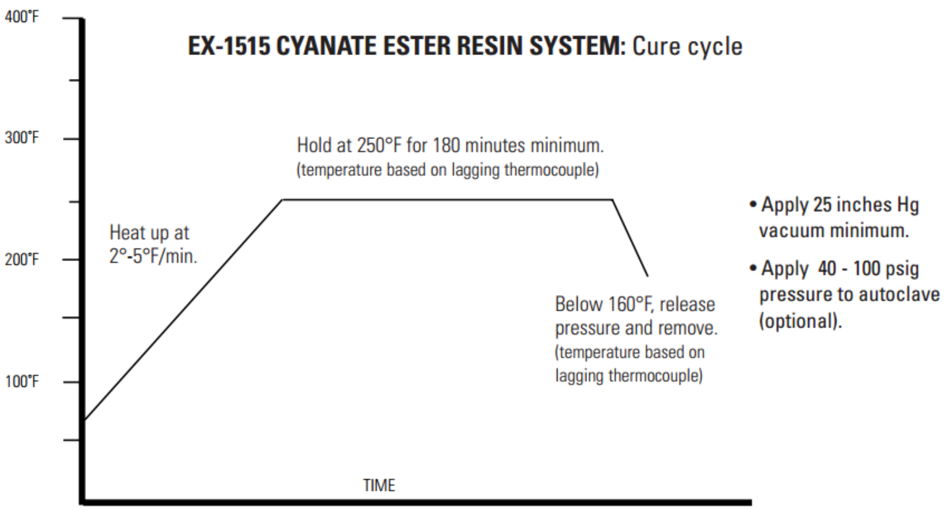
LAMINATE ELECTRICAL PROPERTIES ON 4581 AQIII QUARTZ

	X -Band	X -Band	Q -Band	W -Band
	8-12.6 GHz	18-26.5 GHz	33-50 GHz	75-110 GHz
Dielectric Constant	3.32	3.30	3.30	3.30
Loss Tangent	0.0035	0.0035	0.0052	0.0065

	4581 AQ III / EX-1515	7781 Fg / EX-1515
	8 HS FAW 300 gsm	
Tensile Strength	109.8 Ksi (757 MPa)	61.5 Ksi (424 MPa)
Tensile Modulus	3.45 Msi (23.8 GPa)	3.65 Msi (25.3 GPa)
Compression Strength	78.8 Ksi (543.3 MPa)	57.0 Ksi (393 MPa)
Compression Modulus	4.06 Msi (28.0 GPa)	3.7 Msi (25.5 GPa)
Flexural Strength	107.0 Ksi (737.7 MPa)	71.0 Ksi (489.5 MPa)
Flexural Modulus	3.16 Msi (21.8 GPa)	3.15 Msi (21.8 GPa)
ILSS	9.86 Ksi (68.0 MPa)	6.7 Ksi (46.2 MPa)

* Normalized to 55% fiber volume

Page 1 of 4 *EX1515_DS_120810*



EX-1515 CYANATE ESTER RESIN SYSTEM: Cure cycle

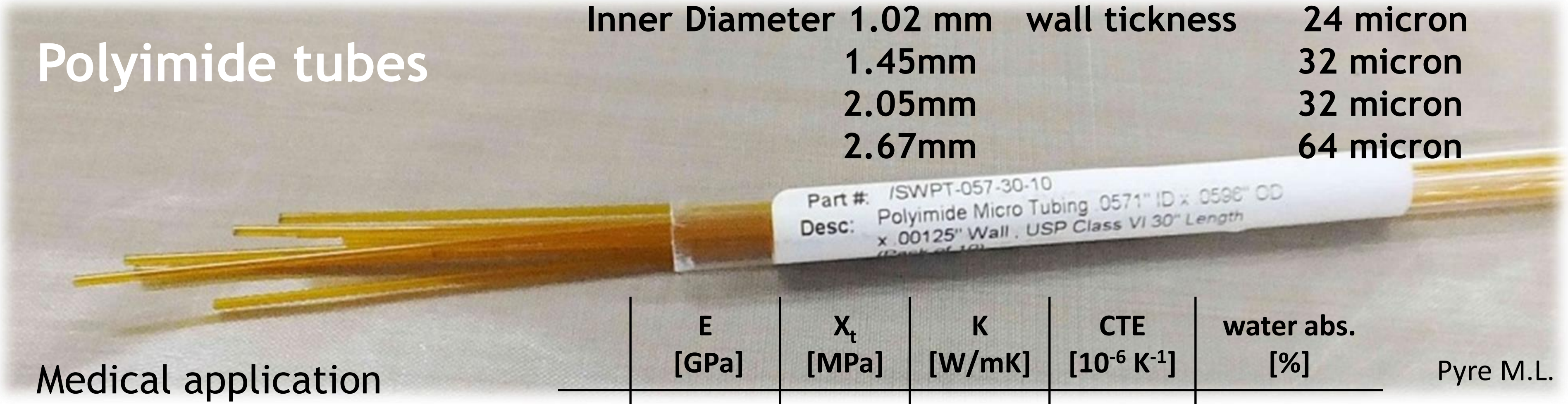
- Apply 25 inches Hg vacuum minimum.
- Apply 40 - 100 psig pressure to autoclave (optional).

EX-1515 TENCATE (127°C)
-radiation resistance
-extensive use at CERN
- Low curing temperature, 127°C

RS-3 TENCATE (177°C)
-the other predominant Cyanate Ester (CE) resin used at CERN.

Hexcel 954 (177°C)
-moderate use at CERN

Polyimide tubes



Inner Diameter	wall tickness
1.02 mm	24 micron
1.45mm	32 micron
2.05mm	32 micron
2.67mm	64 micron

Medical application

	E [GPa]	X_t [MPa]	K [W/mK]	CTE [10^{-6} K^{-1}]	water abs. [%]
PI	2,5	305	0,205	40	0,841

Pyre M.L.

High radiation hardness: according to **CERN-98-01** report, **polyimide**:

No problem below 10^7 Gy, Mild damage between 10^7 to 5 10^7 Gy

1st layer of ITS Inner Barrel will be exposed to 700 krad/yr.=7000 Gy/yr.

Ageing: physical and chemical stability over time.

Plastic Pipe Institute states corrosion is not an issue in plastic pipes.

Fire Safety: Comply to LHC Fire Safety Instruction (IS-41)

Polyimide is allowed.

High radiation length material

Polyimide: X_0 = 29 cm, minimum wall thickness is 0.025 mm.

PEEK: X_0 = 31.45 cm, minimum wall thickness is 0.25 mm.

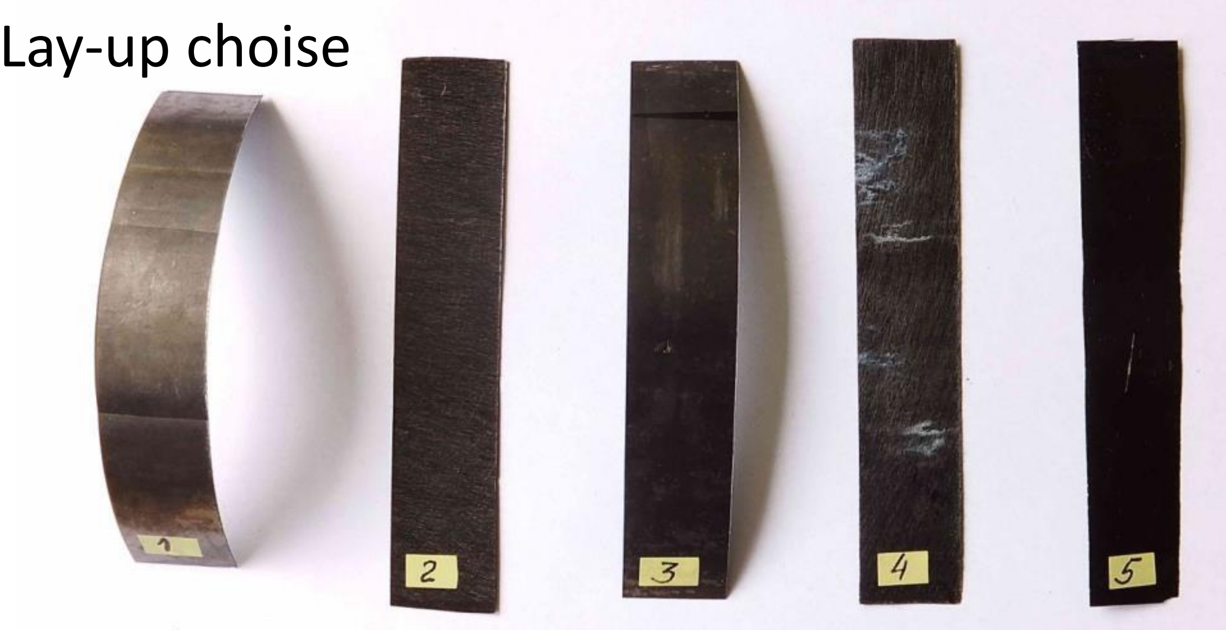
CERN Standards Reference Document

CERN Doc. Nr	Iss.	Year	Title	Category	Link
IS-23	3	2005	Criteria and Standard Test Methods for the Selection of Electric Cables and Wires with Respect to Fire Safety and Radiation Resistance	safety/ radiation	https://edms.cern.ch/file/335745/4/E_IS23.pdf
IS-41	1	2005	The Use of Plastics and other Non-Metallic Materials at CERN with respect to Fire Safety and Radiation Resistance	safety/ radiaton	https://edms.cern.ch/file/335806/1.02/IS41_E.pdf
CERN 79–04	1	1979	Compilation of radiation damage test data, Part I: Cable-insulating materials	radiation	http://cds.cern.ch/record/133188/files/CERN-79-04.pdf
CERN 89–12	2	1989	Compilation of radiation damage test data, Part I, 2nd edition: Halogen-free cable-insulating materials	radiation	http://cds.cern.ch/record/205520/files/CERN-89-12.pdf
CERN 79–08	1	1979	Compilation of radiation damage test data, Part II: Thermosetting and thermoplastic resins	radiation	http://cds.cern.ch/record/120566/files/CERN-79-08.pdf
CERN-98-01	2	1998	Compilation of radiation damage test data, Part II: 2nd Thermosetting and thermoplastic resins	radiation	http://cds.cern.ch/record/357576/files/CERN-98-01.pdf
CERN 82–10	2	1982	Compilation of radiation damage test data, Part III: Materials used around high-energy accelerators	radiation	http://cds.cern.ch/record/141784/files/CERN-82-10.pdf?version=2
CERN 2001–006	1	2001	Compilation of radiation damage test data, Part IV: Adhesive for use in radiation areas	radiation	http://cds.cern.ch/record/531818/files/CERN-2001-006.pdf?version=2
CERN-TIS-94-13	1	1994	Radiation resistance and other safety aspects of high-performance plastic by ERTA (p.157)	safety/ radiaton	http://cds.cern.ch/record/268908/files/p157.pdf?version=1
CERN 85–02	1	1985	Radiation Test on selected electrical insulation materials for High Power and High voltage application	radiation	http://cds.cern.ch/record/158707/files/CERN-85-02.pdf

Production process
Inner Barrel Stave

Production Process: Manual Lay-Up

Lay-up choise

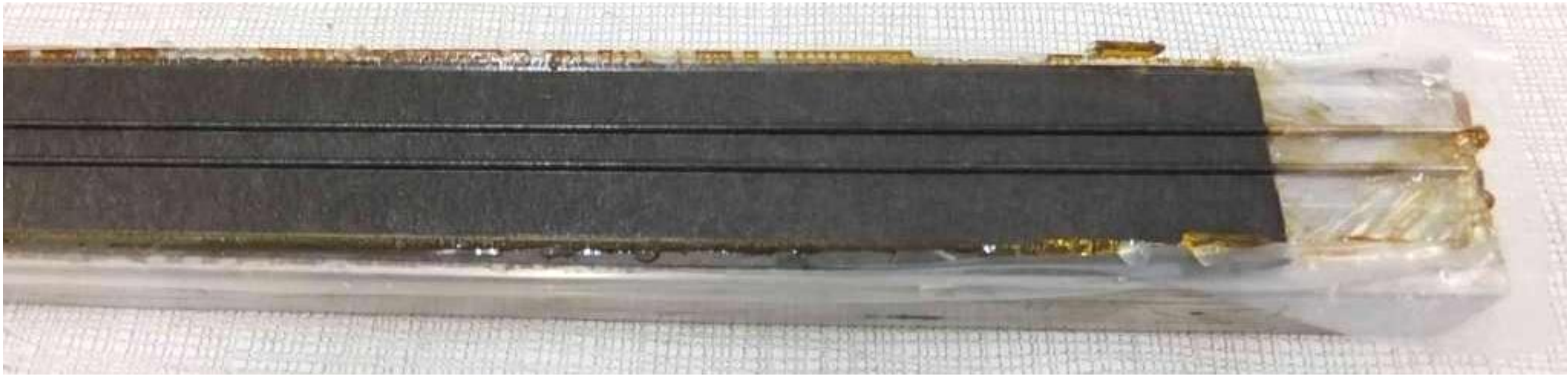


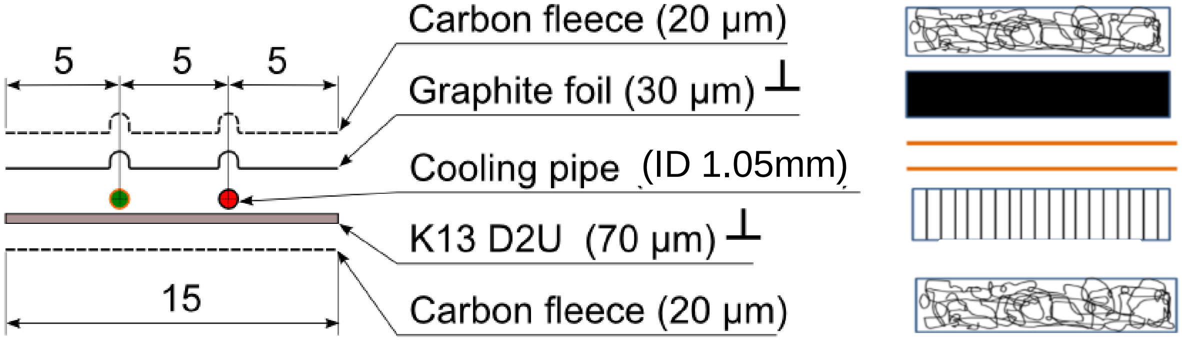
19x100mm

Lay up samples	1	2	3	4	5
	Prepreg	C Fleece	Mylar	Glass Fleece	Prepreg
	CF Paper	Prepreg	Prepreg	Prepreg	
		CF Paper	CF Paper	Glass Fleece	
		C Fleece	Mylar		
thick (mm)	0.09	0.14	0.11	0.12	0.07
Weight (gram)	0.33	0.40	0.37	0.31	0.20

Production Process: Manual Lay-up

New innovative design developed fo ALICE ITS Upgrade

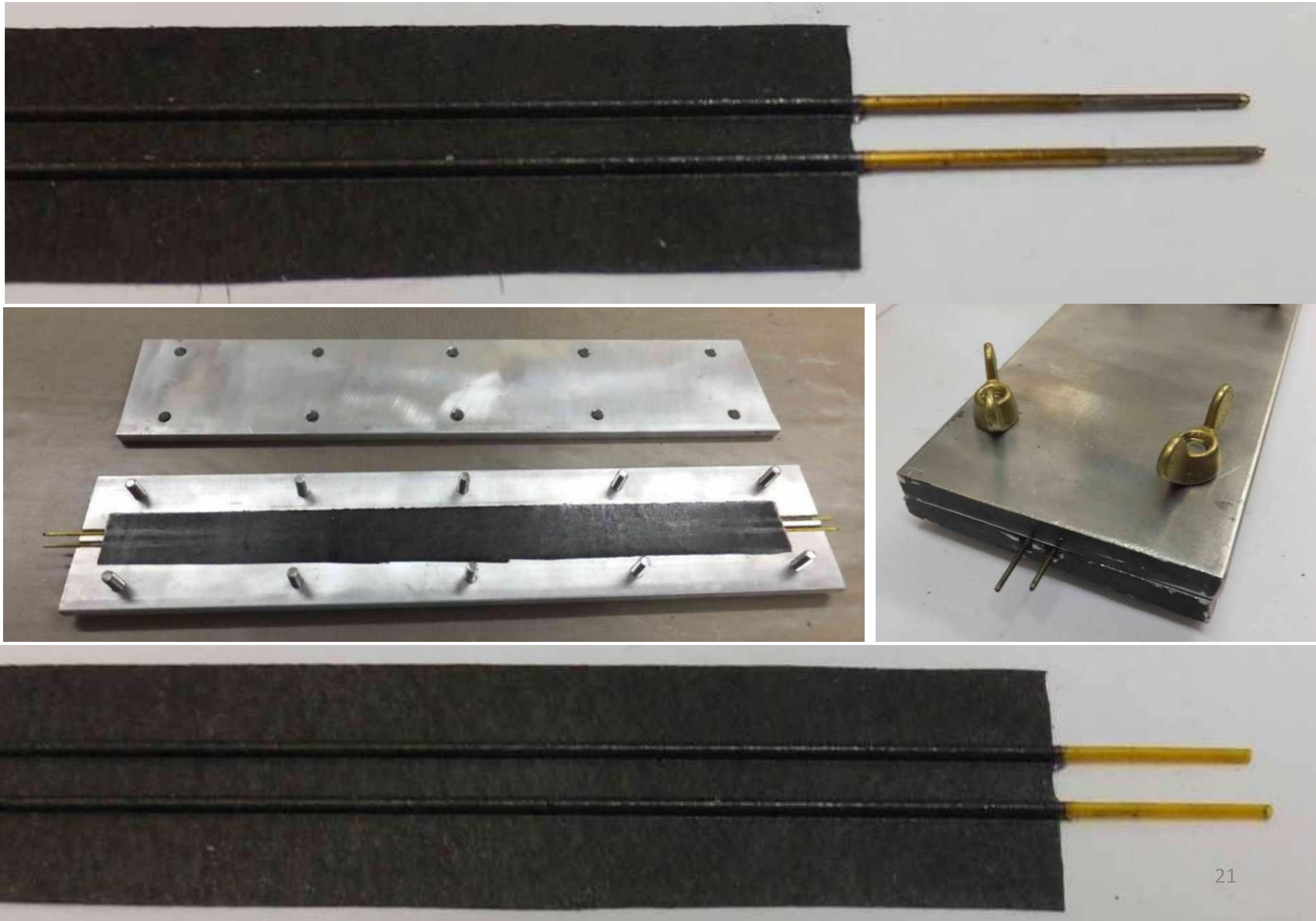




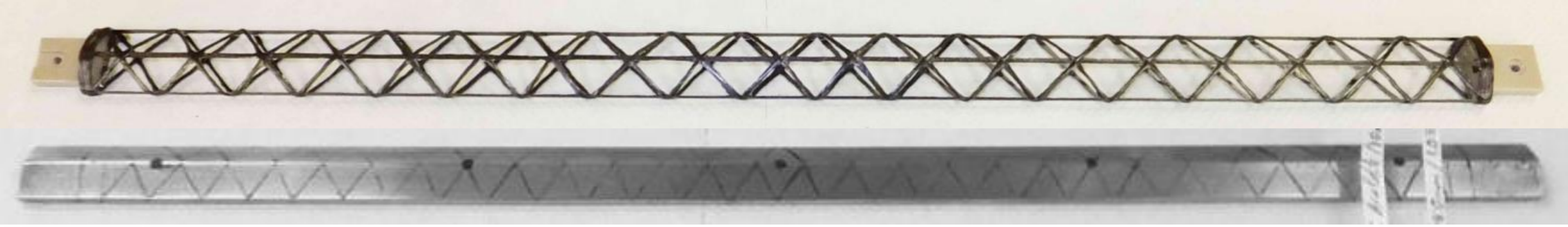
mandrels

(steel piano wires)

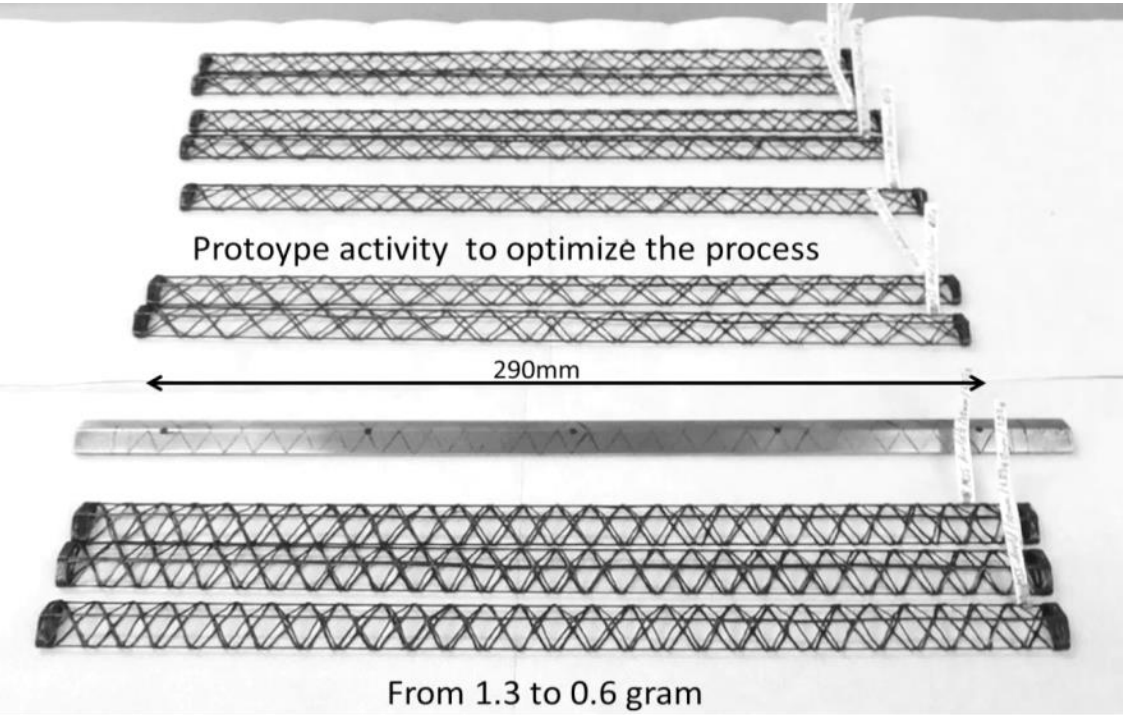
Production Process: Mandrels extraction



Production Process: Filament winding

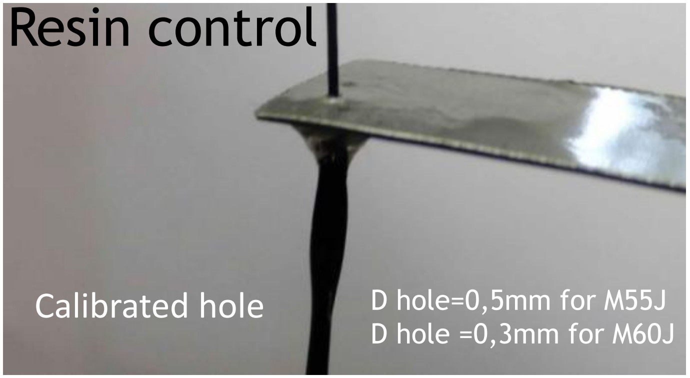


M55j & M60j


Protoype activity to optimize the process

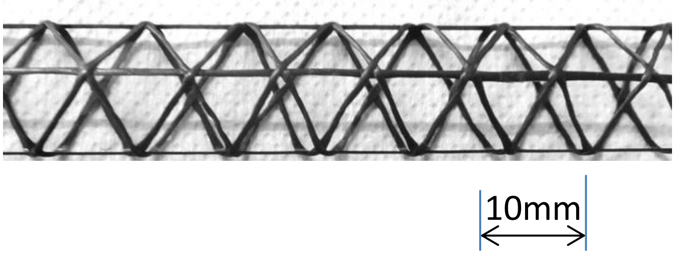
From 1.3 to 0.6 gram

Resin control

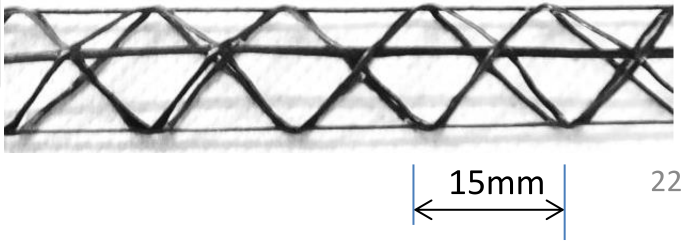


D hole=0,5mm for M55J
D hole =0,3mm for M60J

Roving Twisting

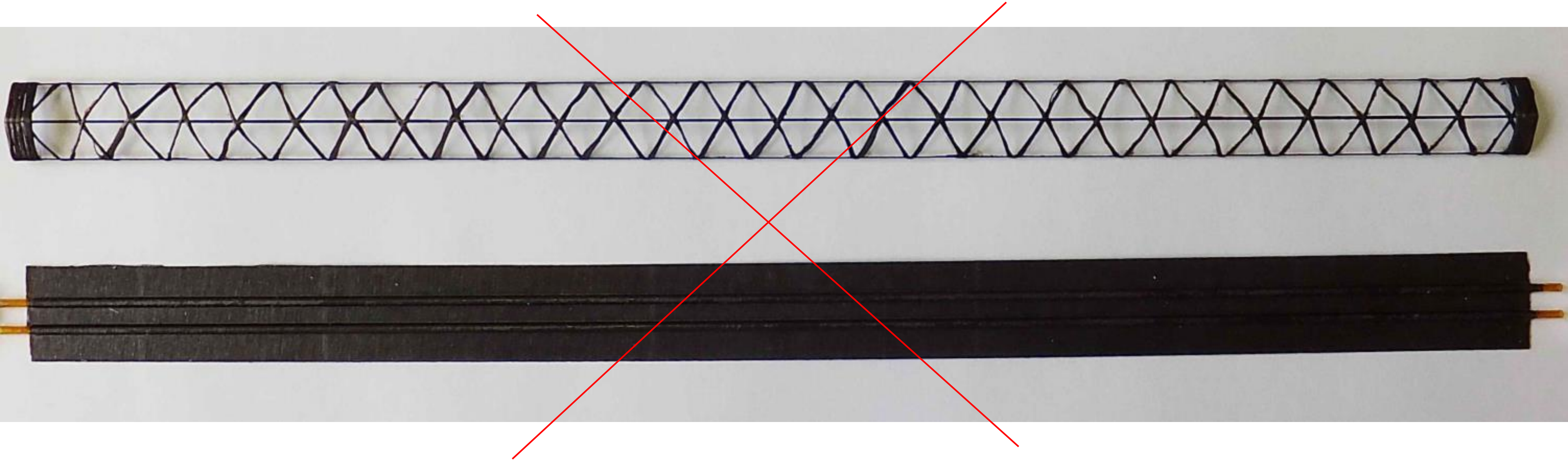


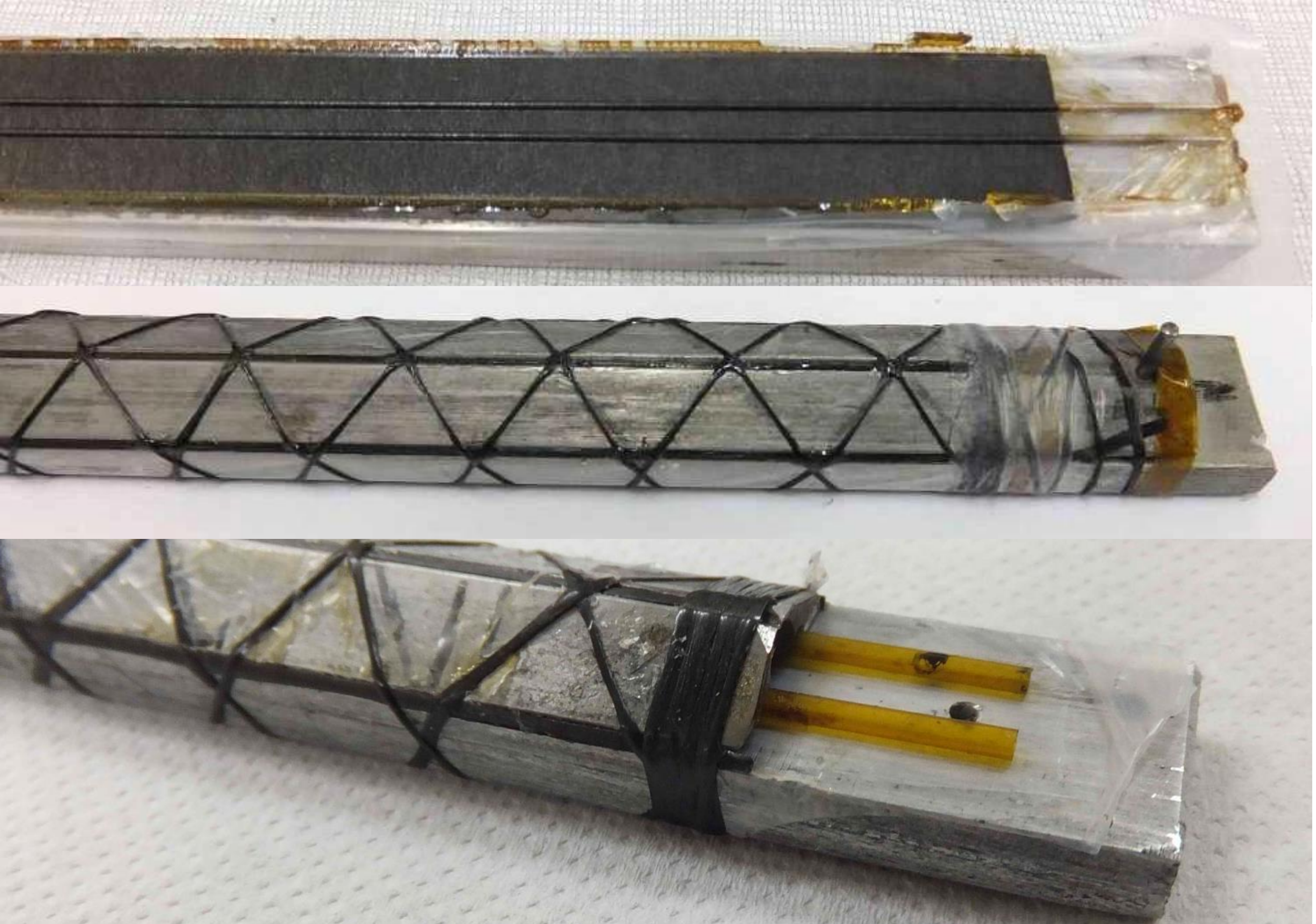
Winding Angle



Production Process: Gluing parts

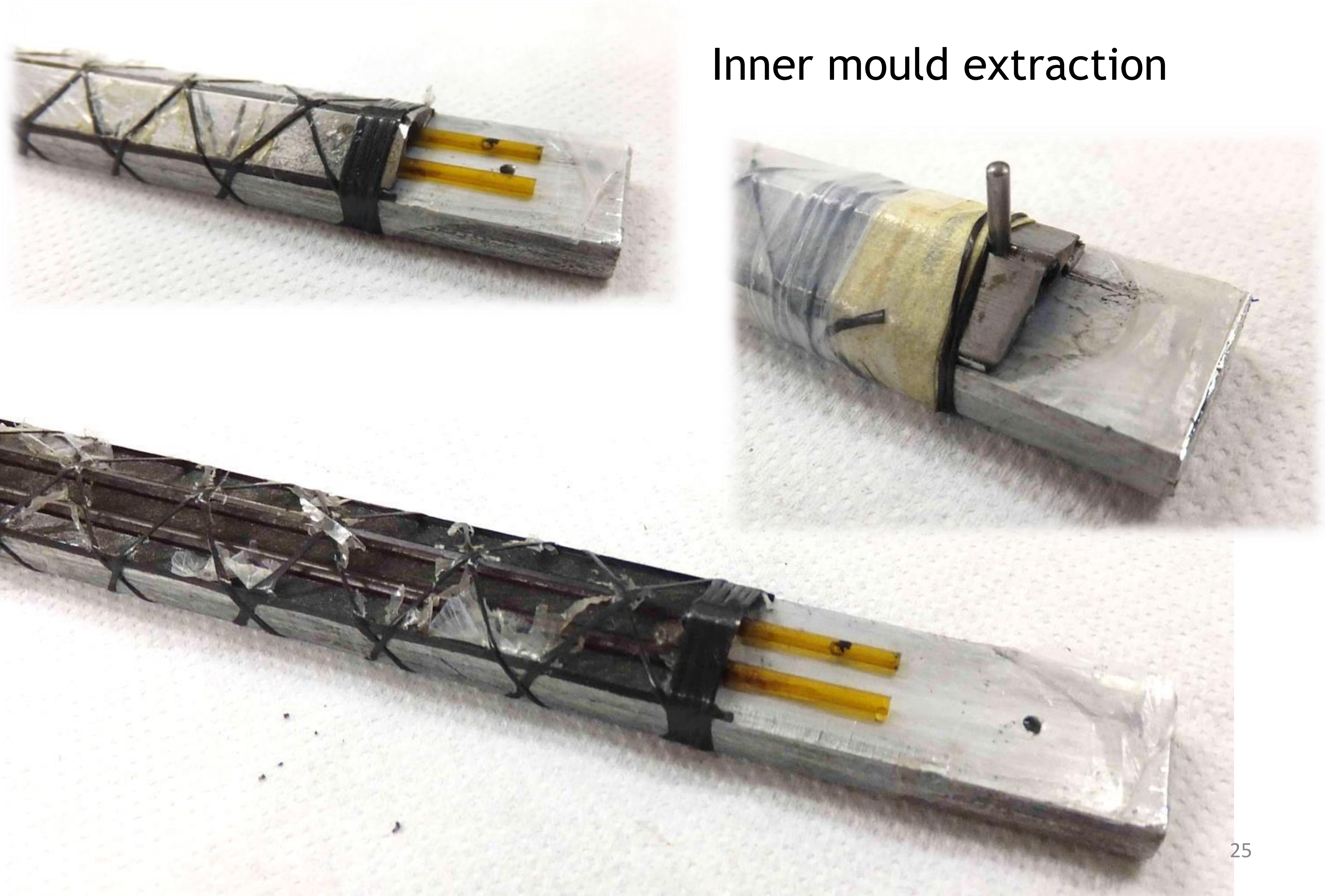
Minimize gluing steps, it is diffucult to take under control the weight of glue





Production Process: Co-curing process

Production Process: Co-curing process



Inner mould extraction

Production Process: parts separation

Cut and mould separation

~1.4 gram @290mm length

Production process

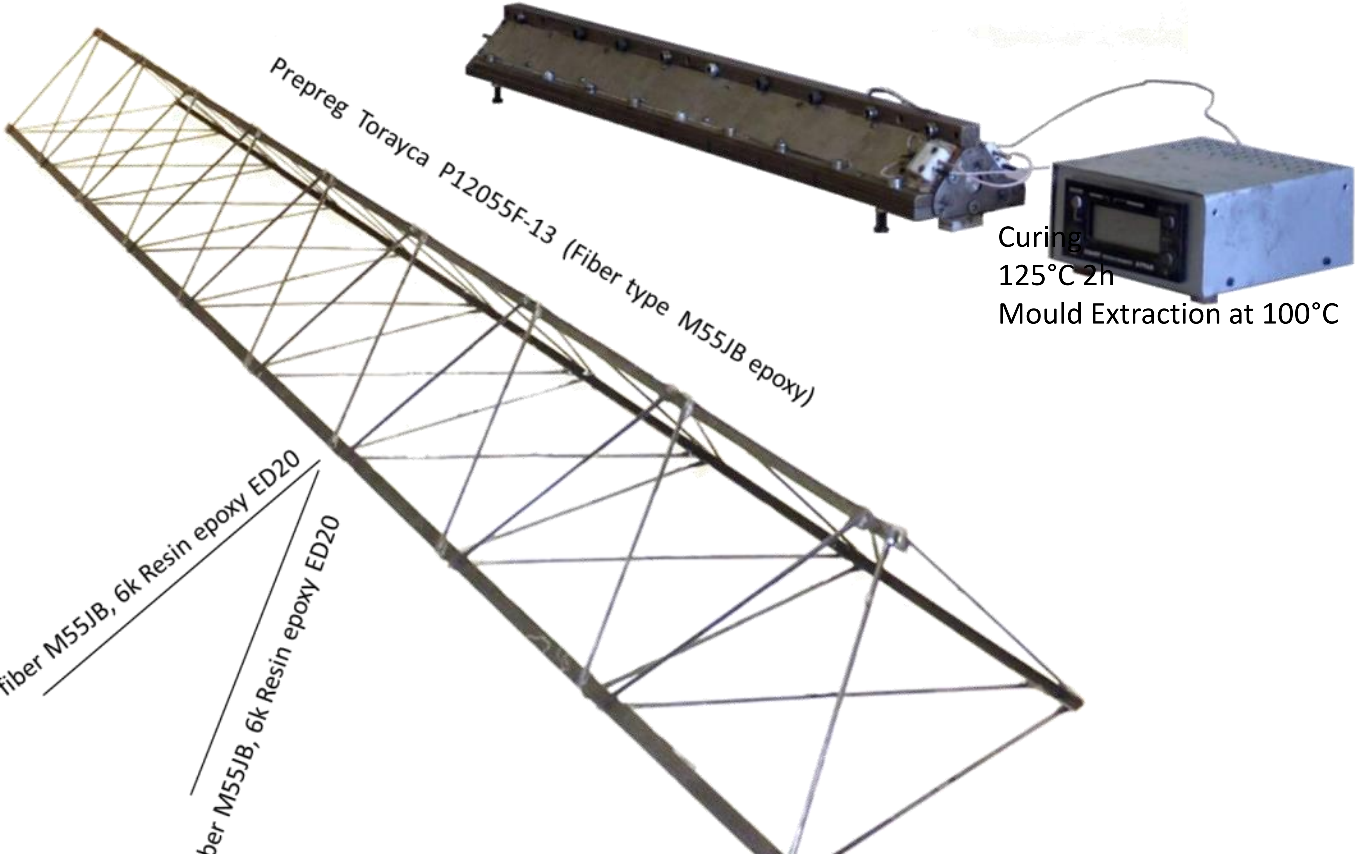
Outer Barrel Stave

Outer barrel stave

Production Process: Spaceframe

Bassed on original design developed by St Petersburg University, Utrecth Univeristy and INFN Torino for the ALICE tracker now in operation.

Spaceframe <1m

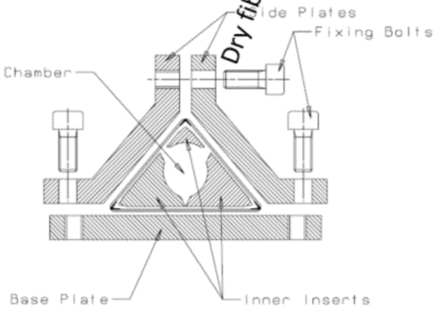


Prepreg Torayca P12055F-13 (Fiber type M55JB epoxy)

Curing
125°C 2h
Mould Extraction at 100°C

Dry fiber M55JB, 6k Resin epoxy ED20

Dry fiber M55JB, 6k Resin epoxy ED20

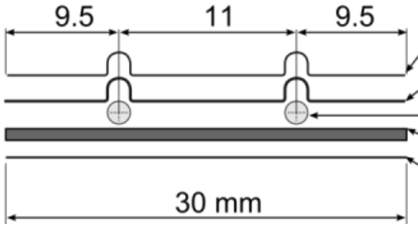


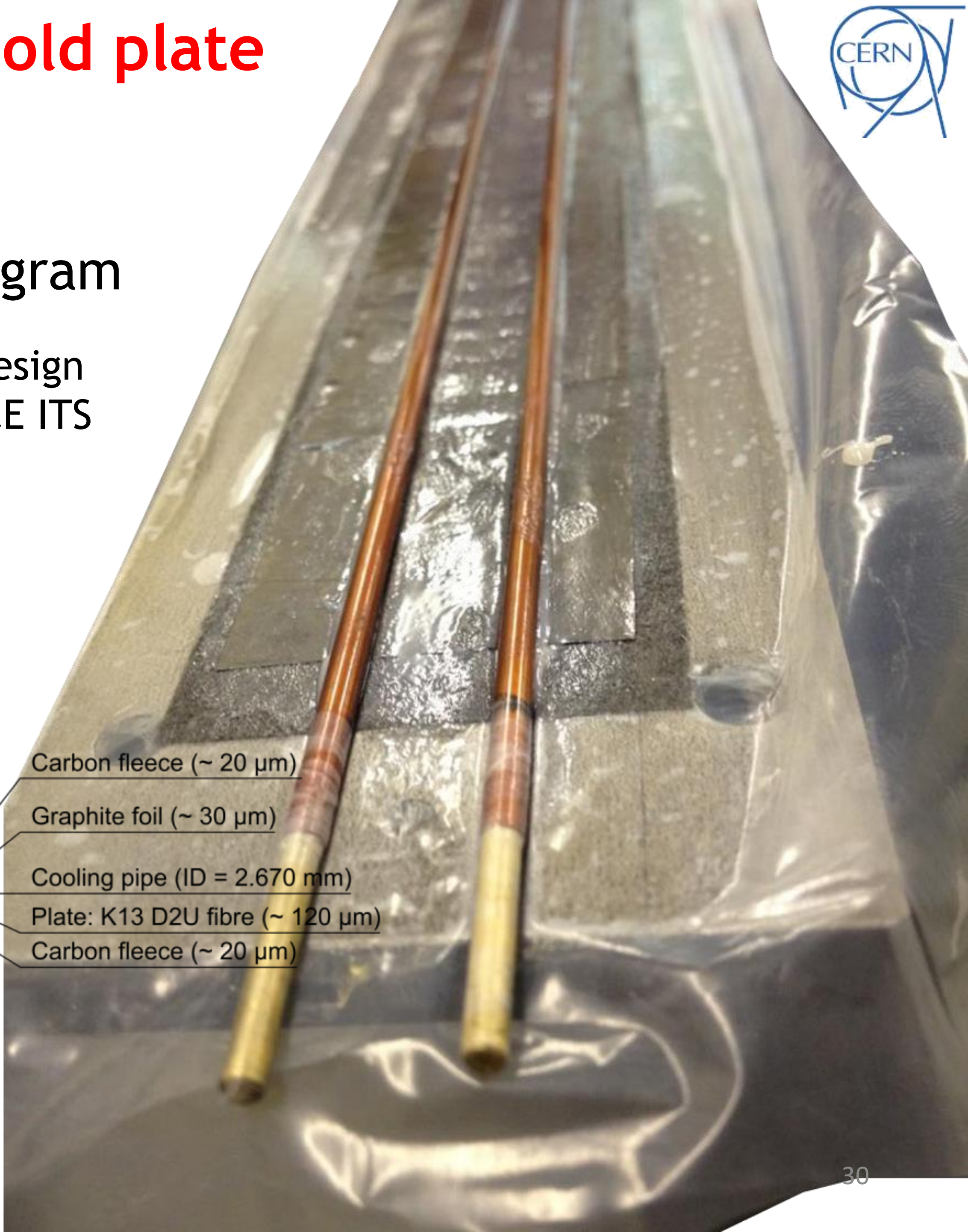
Production Process: Cold plate

1500mm ~22 gram

New innovative design developed fo ALICE ITS Upgrade

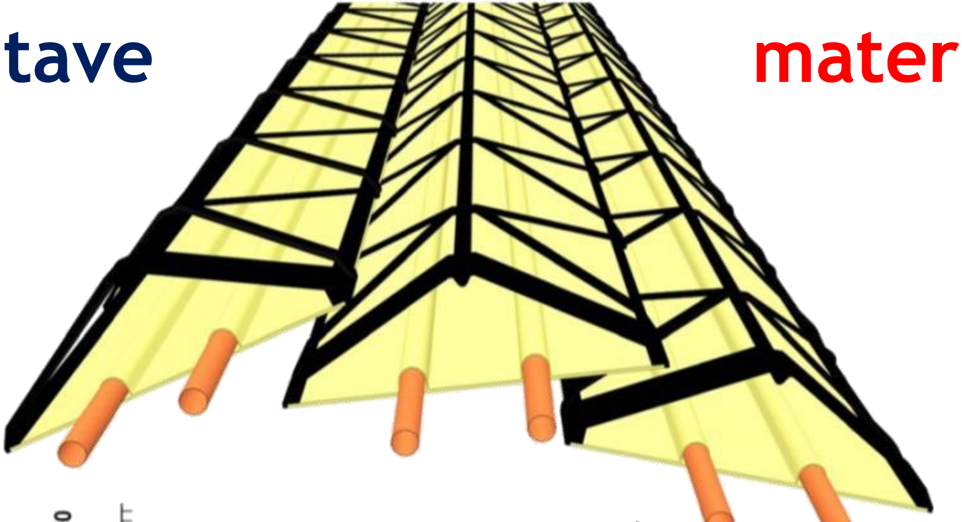
Cold plate transversal section:

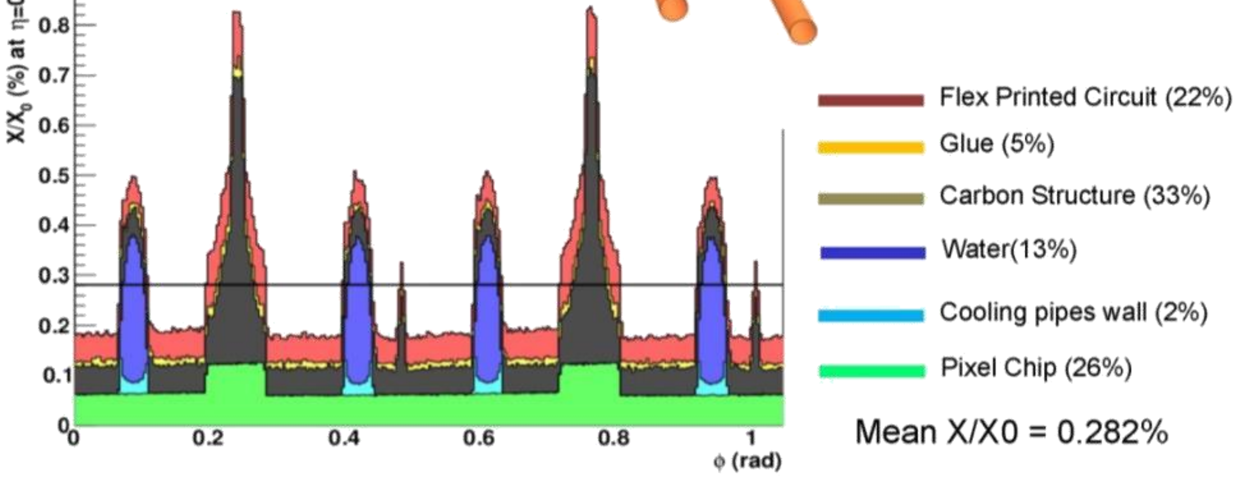




Material budget

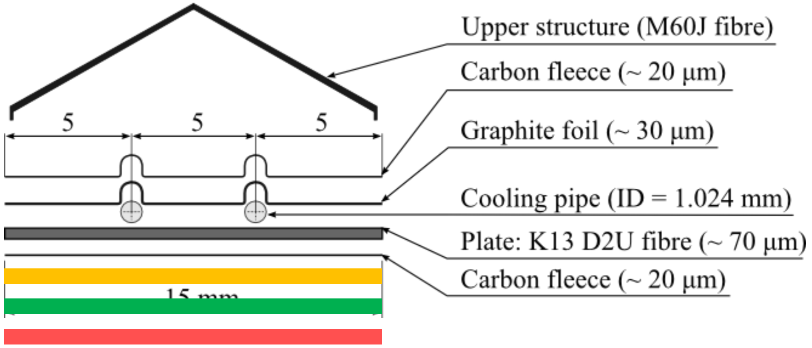
Inner Barrel Stave material budget





Mean X/X0 = 0.282%

Transversal section:



Upper structure (M60J fibre)

Carbon fleece (~ 20 µm)

Graphite foil (~ 30 µm)

Cooling pipe (ID = 1.024 mm)

Plate: K13 D2U fibre (~ 70 µm)

Carbon fleece (~ 20 µm)

Alternative options

Peripheral cooling

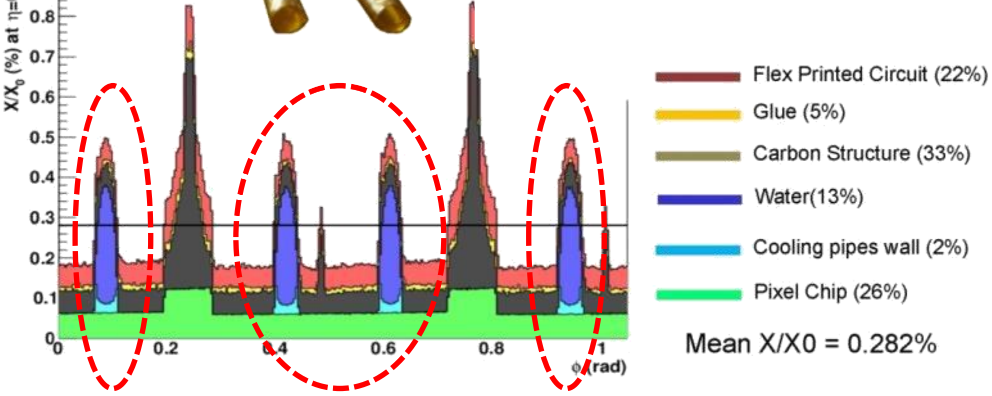
power <30 mW/cm²

HTC CF
Thornel **K1100**

k_{K1100} ~ 1000 W m^{-1} K^{-1}

HTC CF
FGS_003 Amec

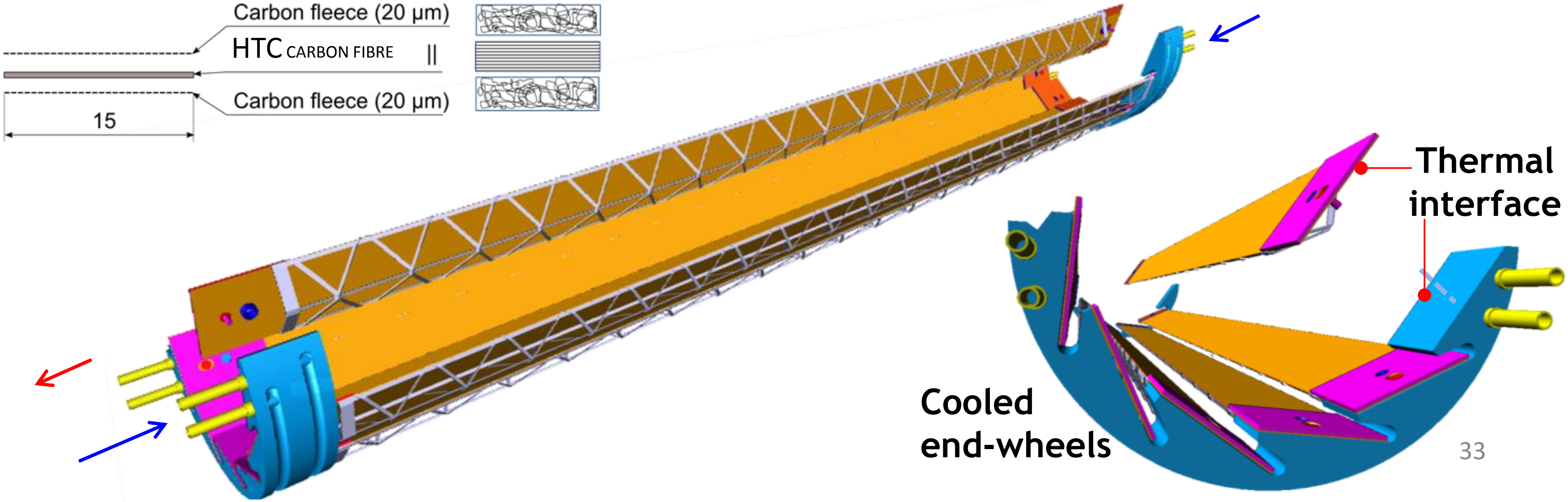
k_{FGS} ~ 1500 W m^{-1} K^{-1}



Mean X/X0 = 0.282%

NO PIPE on the stave to reduce material budget peaks

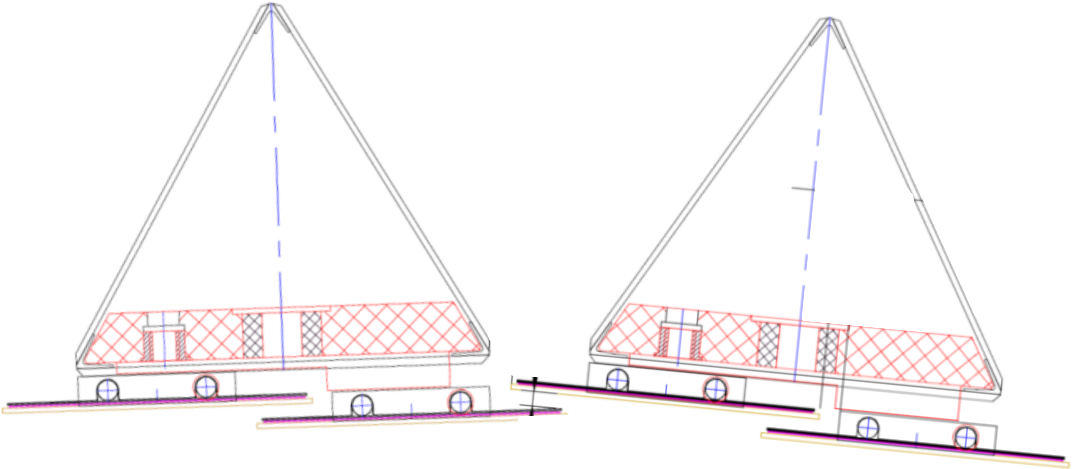
High Thermal Conductive carbon fibres curry the heat to the stave ends, where thermal contact is made with the cooled end-wheels

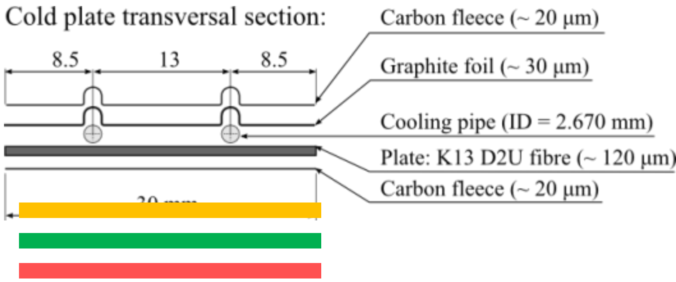


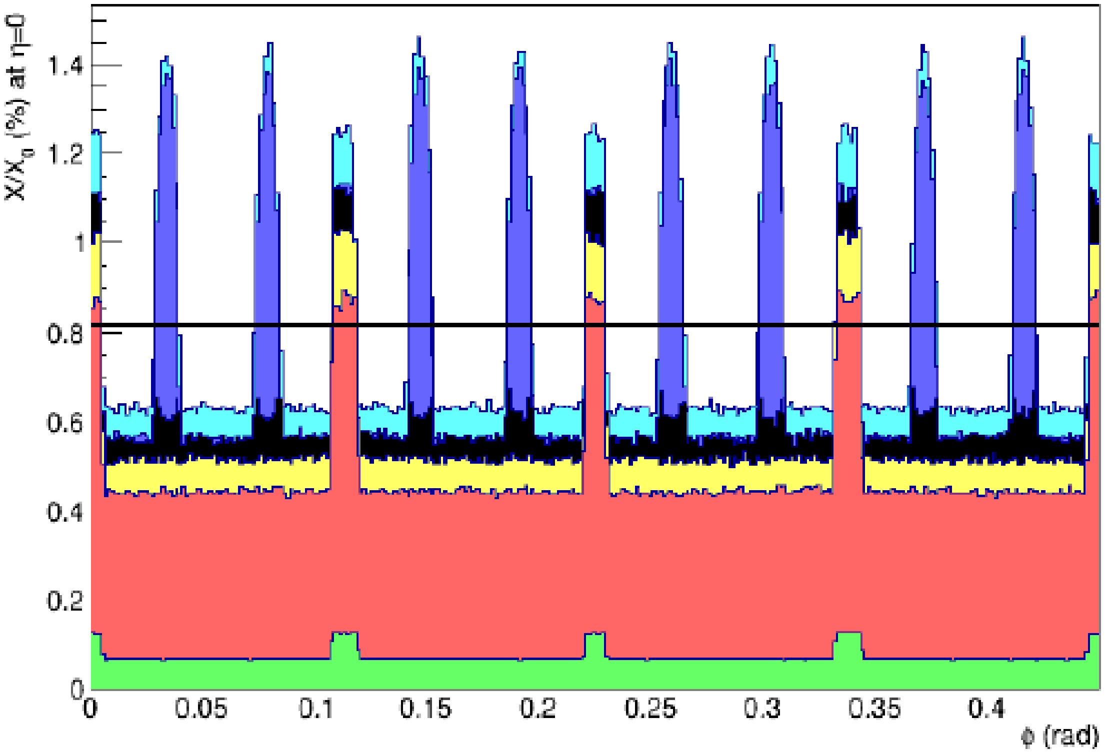
Thermal interface

Cooled end-wheels

Outer Barrel Stave material budget



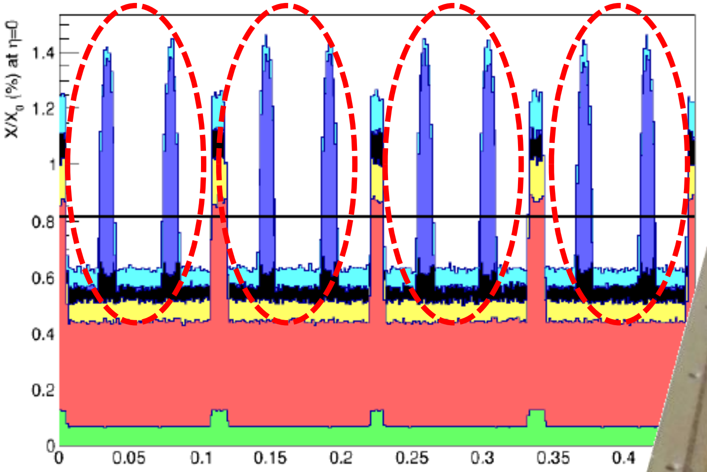




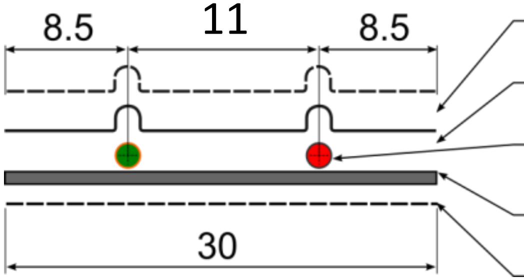
- 🟦 Carbon Structure (9.1%)
- 🟦 Water (14.2%)
- ⬛ Cooling Pipe Walls and Cold Plate (8.0%)
- 🟨 Glue (9.5%)
- 🟥 Flex Cable (50.1%)
- 🟩 Pixel Chip (9.2%)

Mean X/X0 = 0.816%

Alternative options



Beseline



Carbon fleece (20 μm)

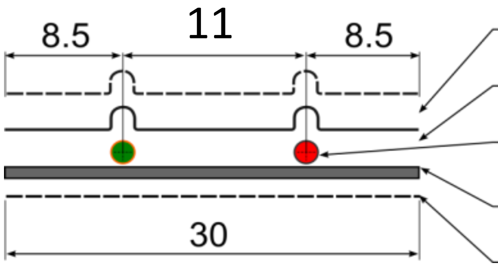
Graphite foil (30 μm) ⊥

Cooling pipe (ID 2.670 mm)

Cold Plate: K13 D2U fibre (120 μm) ⊥

Carbon fleece (20 μm)

Alternative for material budget peak reduction



Carbon fleece (20 μm)

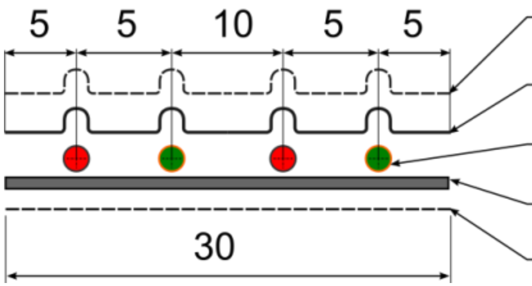
Graphite foil (30 μm) ⊥

Cooling pipe **ID 2.05mm**

Cold Plate: K13 D2U fibre (120 μm) ⊥

Carbon fleece (20 μm)

Alternative for more uniform material distribution



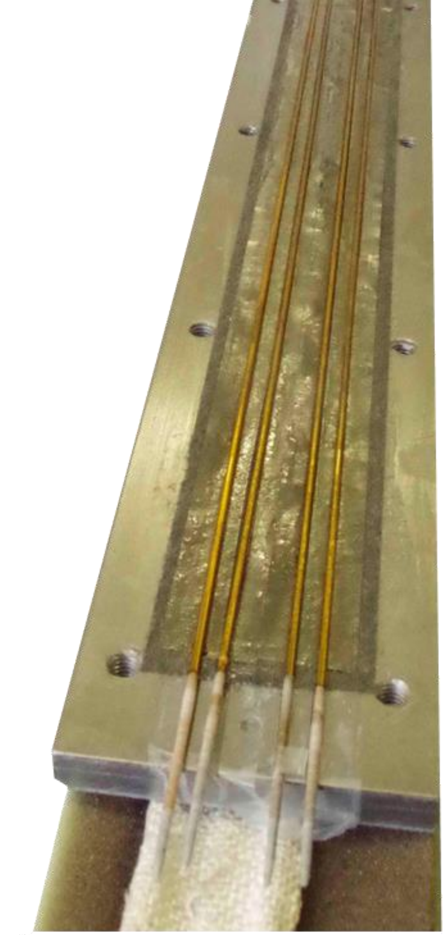
Carbon fleece (20 μm)

Graphite foil (30 μm)

Cooling pipe **4 x ID 1.45mm**

Plate: K13 D2U fibre (120 μm)

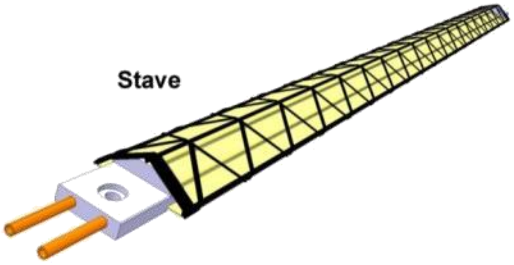
Carbon fleece (20 μm)



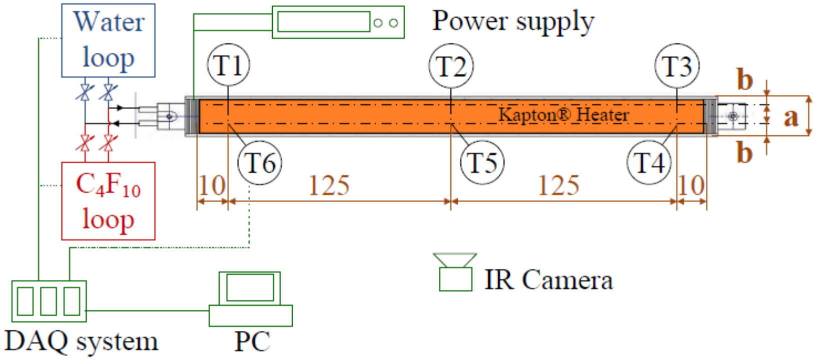
Stave thermal characterization

Thermal characterization

See Manuel presentation



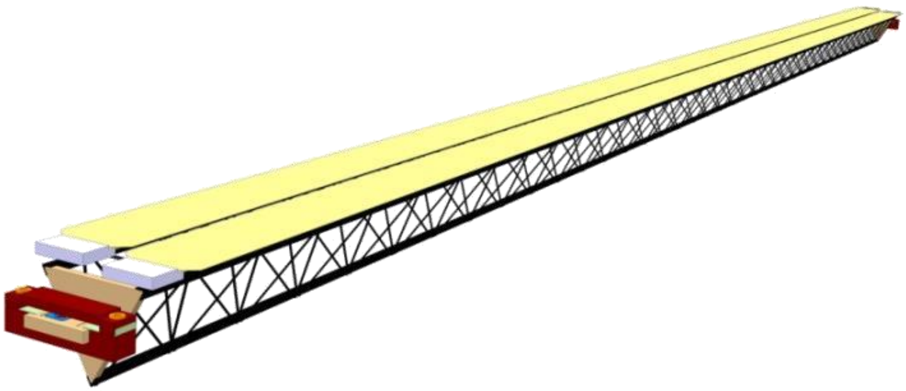
q [W cm^{-2}]	G [L h^{-1}]	$\Delta T_{CHIP\text{-}H20}$ [K]	ΔT_{H2O} [K]	Δp [bar]	v_{H2O} [m s^{-1}]
0.15	3.0	2.4	1.4	0.3	1.0



Water leakless (<1bar) baseline

Water in 15°C--->Tchip <22°C

Pressure drop ΔP below 0.3 bar



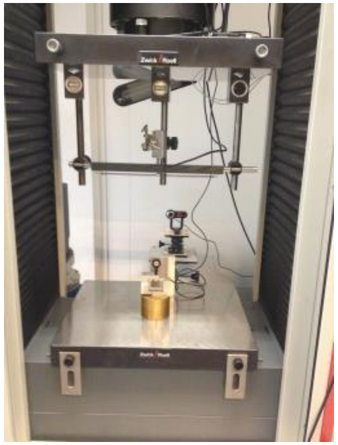
q [W cm^{-2}]	G [L h^{-1}]	$\Delta T_{CHIP\text{-}H20}$ [K]	ΔT_{H2O} [K]	Δp [bar]	$\Delta T_{HEATERS}$ [K]	v_{H2O} [m s^{-1}]
0.15	6.3	6.7	6.9	0.08	4	0.31

Stave mechanical characterization

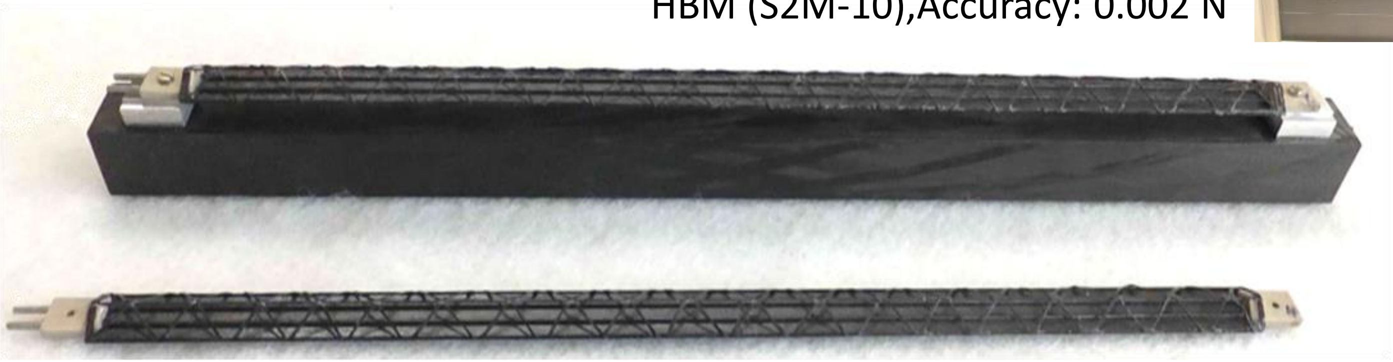
Stiffness: bending test

Objective: evaluate stave sag under Chip+FPC load

3 point bending test results

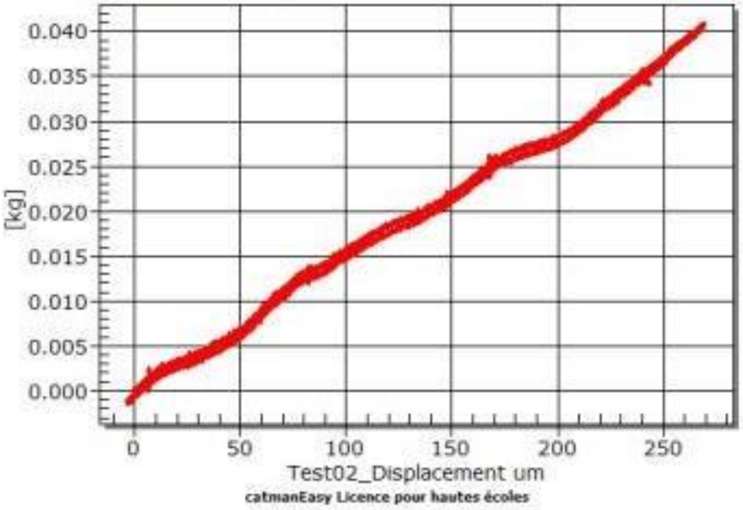


Displacement sensor:
HEIDENHAIN (MT 1201),Accuracy: ± 0.2 µm
Force transducer:
HBM (S2M-10),Accuracy: 0.002 N



INNER Barrel
HIC mass estimate =2 gr

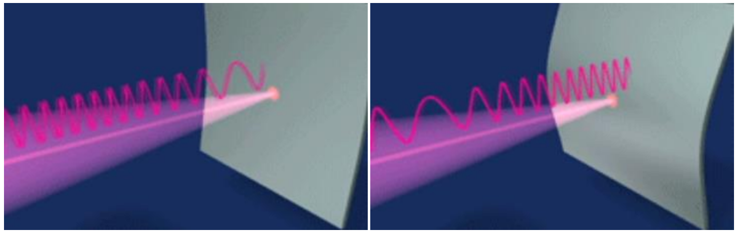
predicted sag 4-9 µm

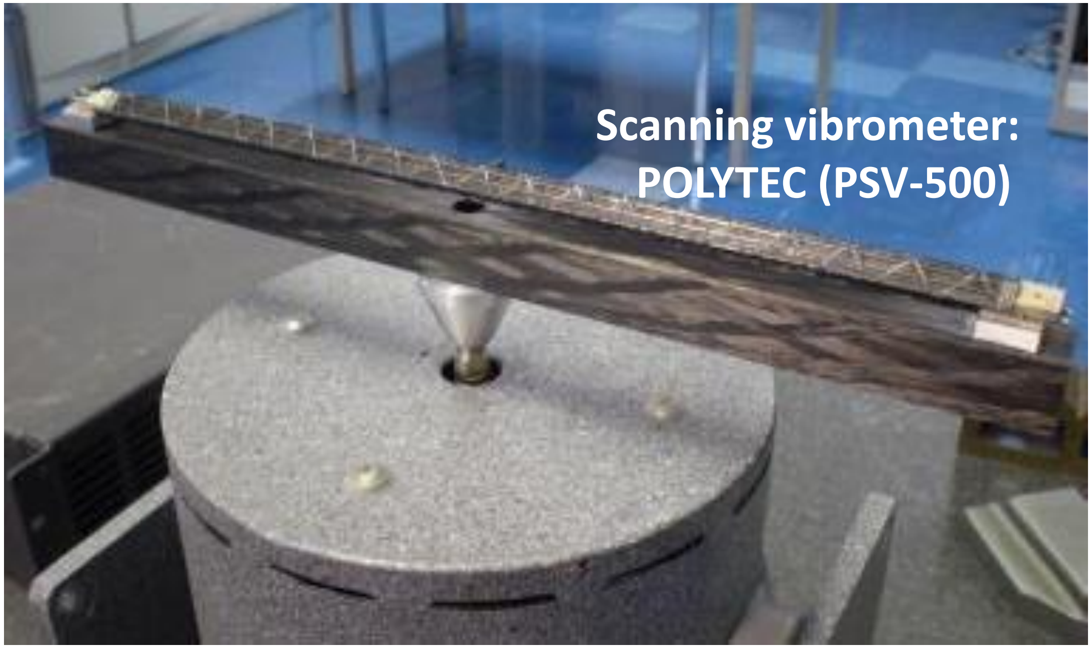


Stiffness: vibration test

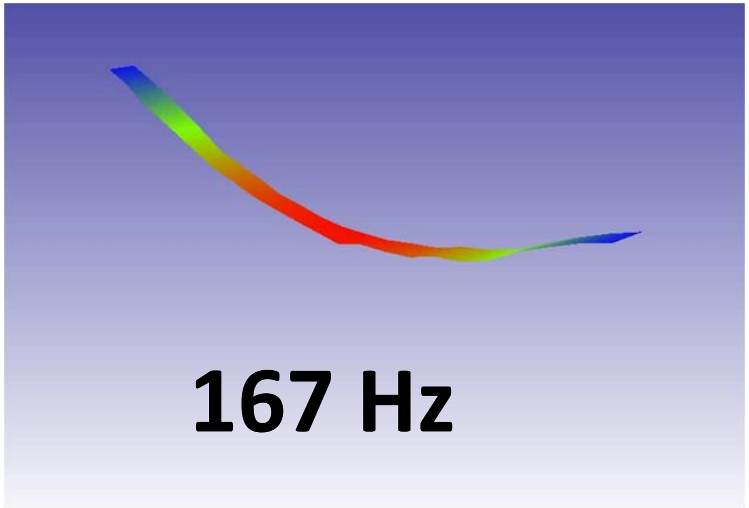
Objective: Determine the natural frequencies of the Inner tracker stave.

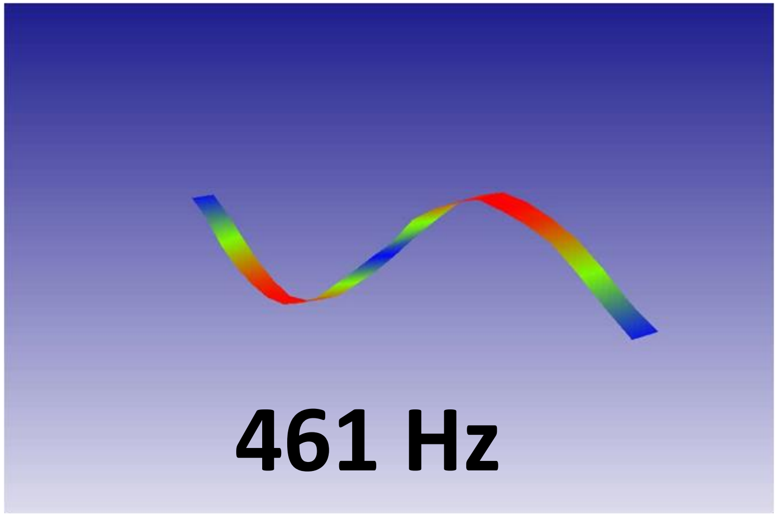
Laser non-contact vibration measurement





Scanning vibrometer: POLYTEC (PSV-500)





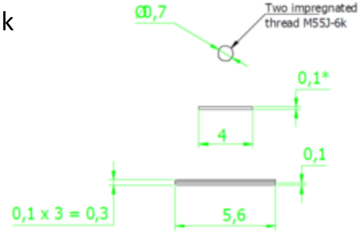
FEA

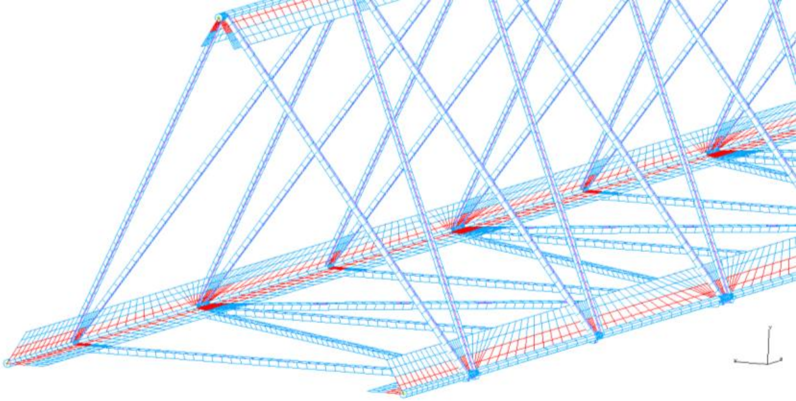
3 impregnated thread M55J 6k

Beam element

Thin shell element

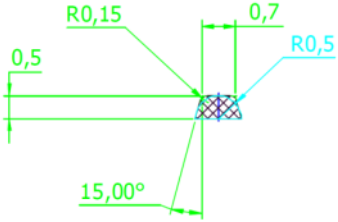
UD prepreg M55J 4 layers





3 impregnated thread M55J 6k

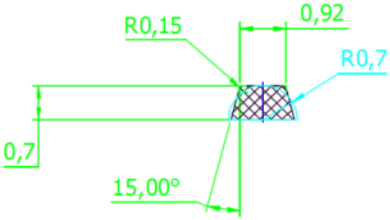
Beam element



Crossection 0,57mm2
Use 3 threads M55J-6k

4 impregnated thread M55J 6k

Beam element



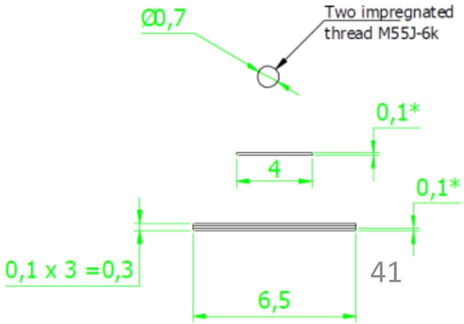
Crossection 0,78mm2
Use 4 threads M55J-6k

3 impregnated thread M55J

Beam element

Thin shell element

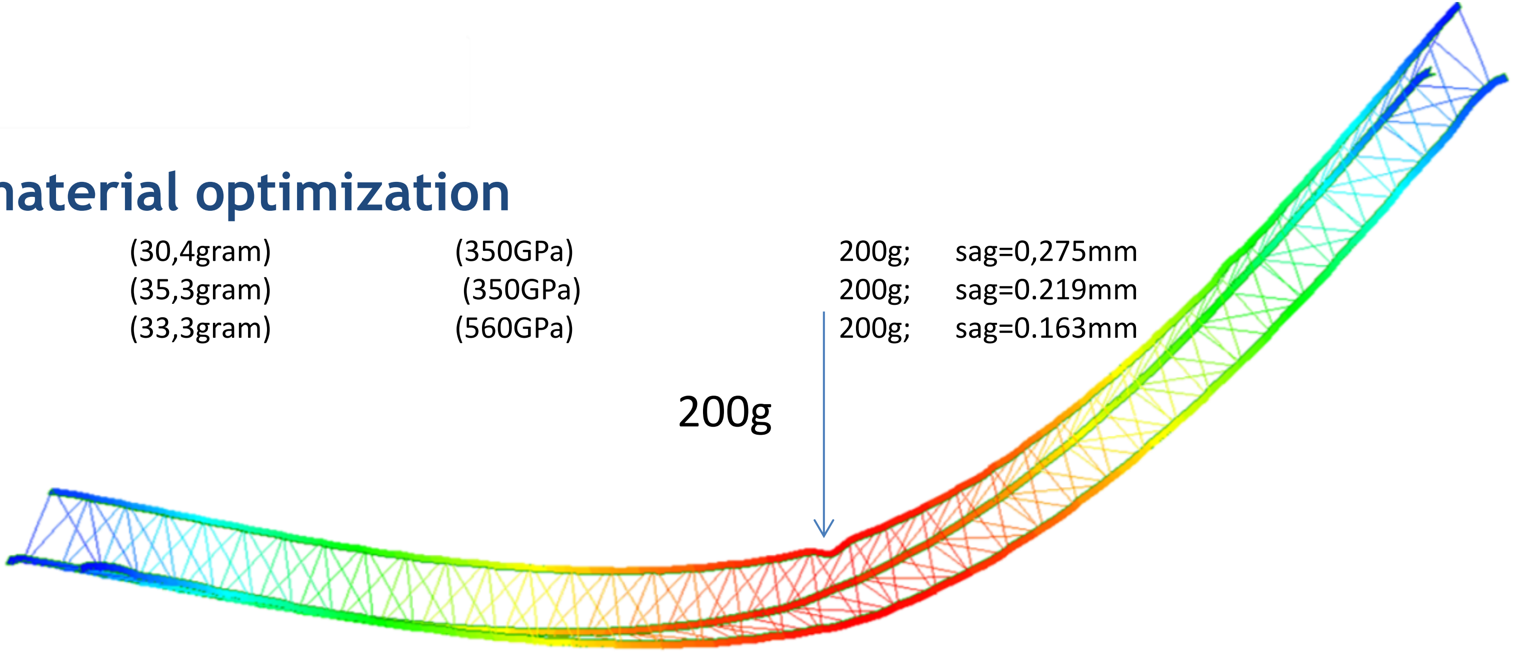
UD prepreg M55J 4 layers



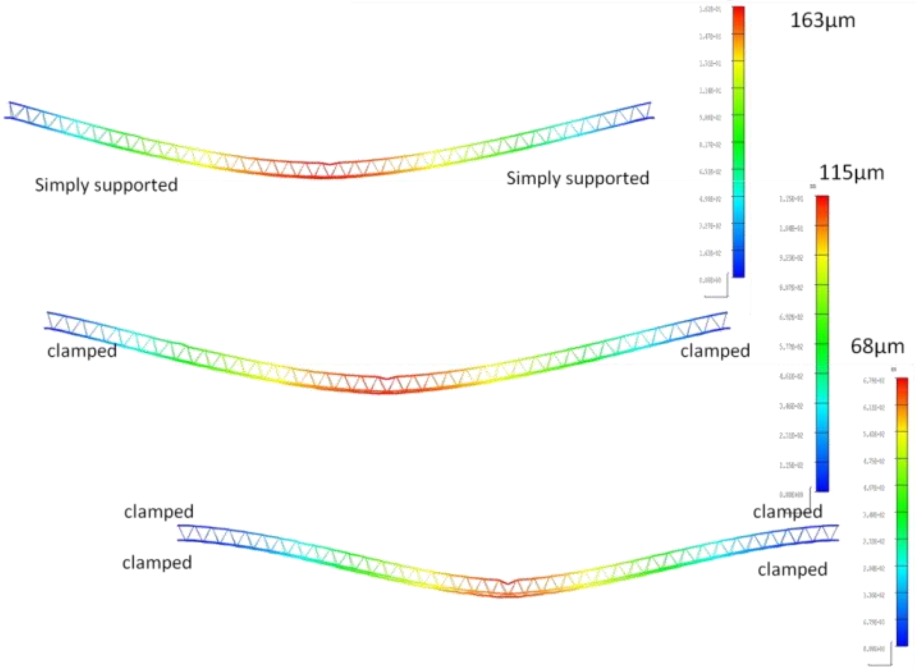
FEA

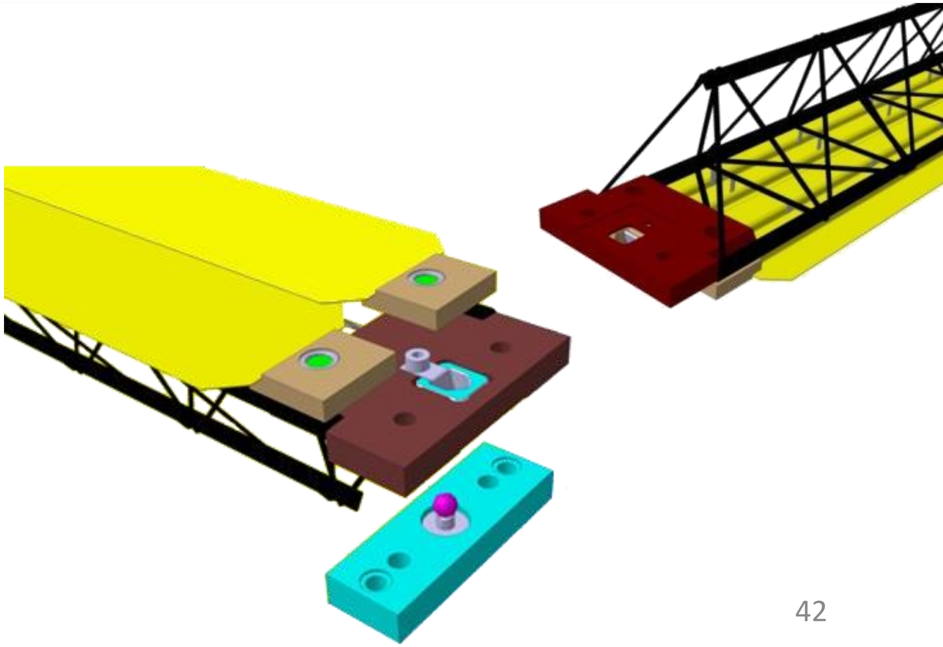
Lay-up and material optimization

M55j	Baseline	(30,4gram)	(350GPa)	200g;	sag=0,275mm
M55j+	Baseline+1 layer	(35,3gram)	(350GPa)	200g;	sag=0.219mm
K13	Baseline with	(33,3gram)	(560GPa)	200g;	sag=0.163mm



Stave connection stiffness design optimization





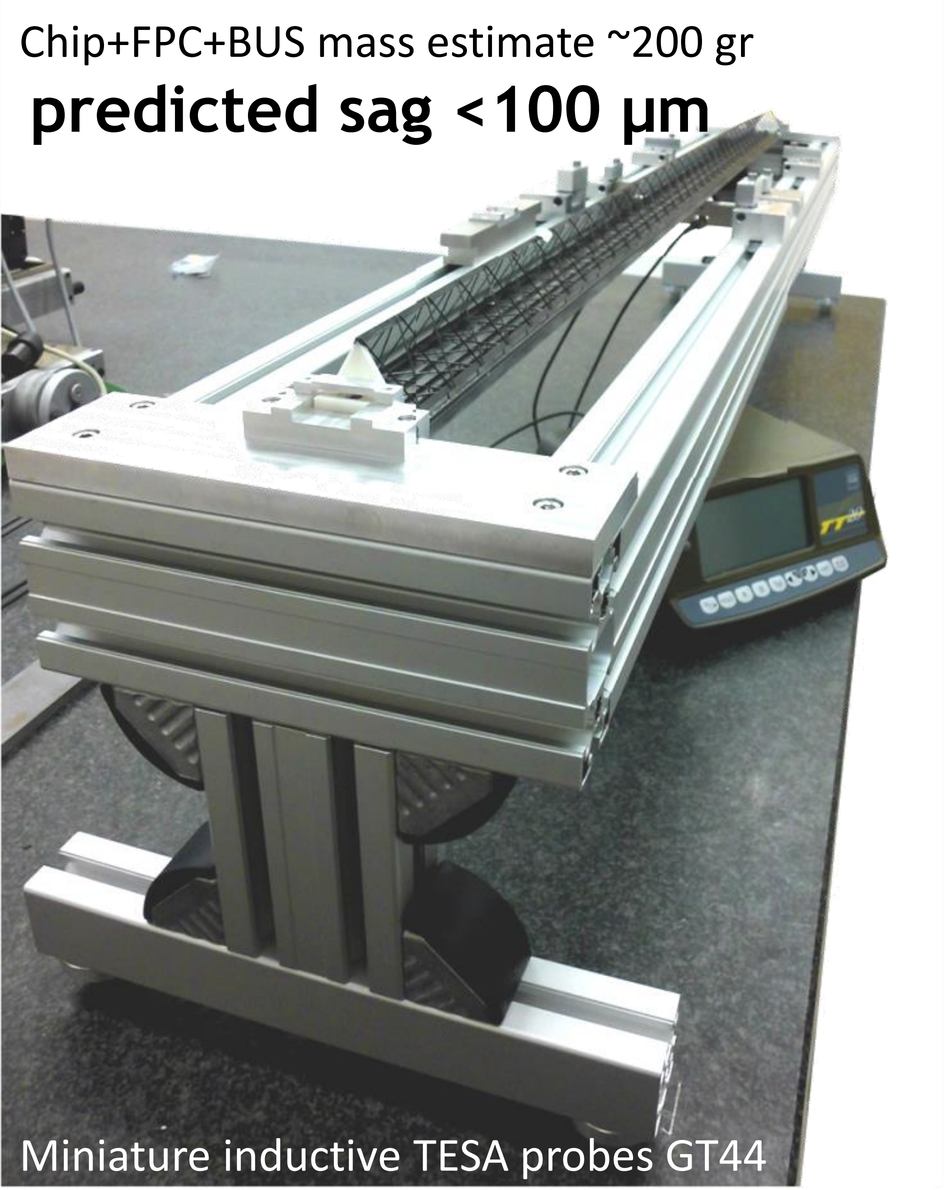
Stiffness test: bending

Objective: evaluate stave sag under Chip+FPC+BUS load

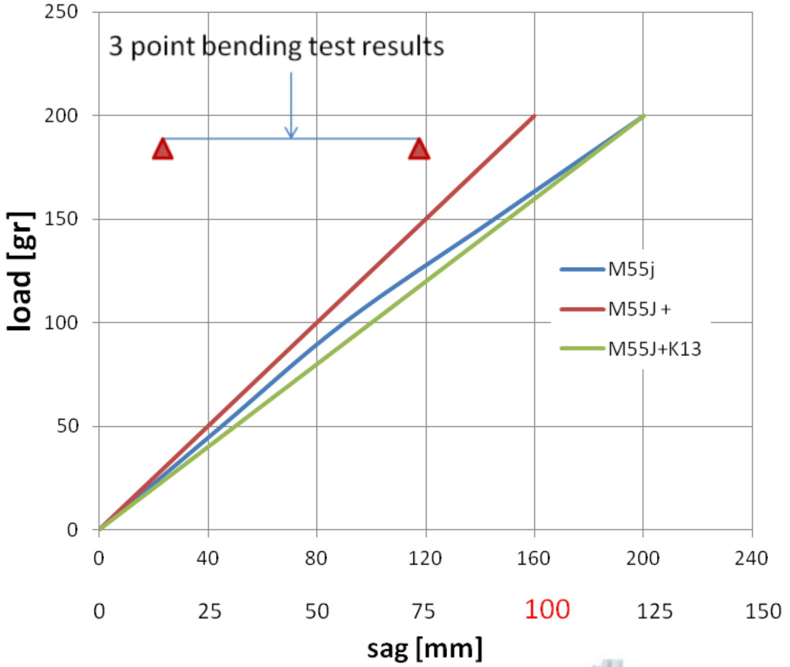
OUTER Barrel stave

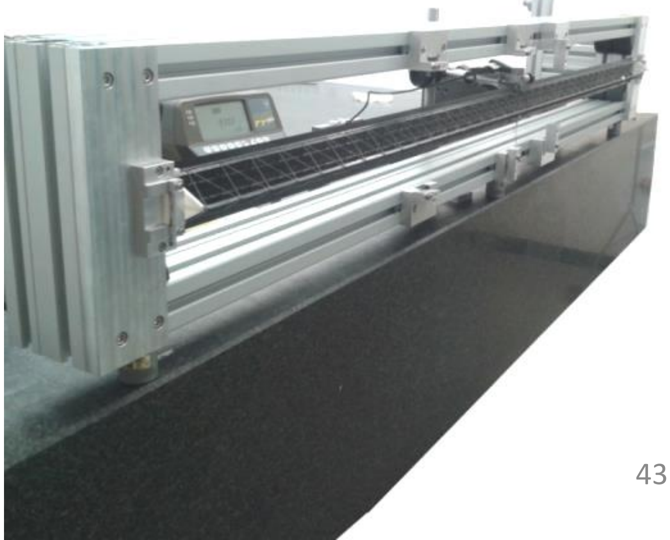
Chip+FPC+BUS mass estimate ~200 gr

predicted sag <100 µm



Miniature inductive TESA probes GT44





Stiffness test: limit load

1.5 kg test (load factror >7)
expected spaceframe payload 200 gram

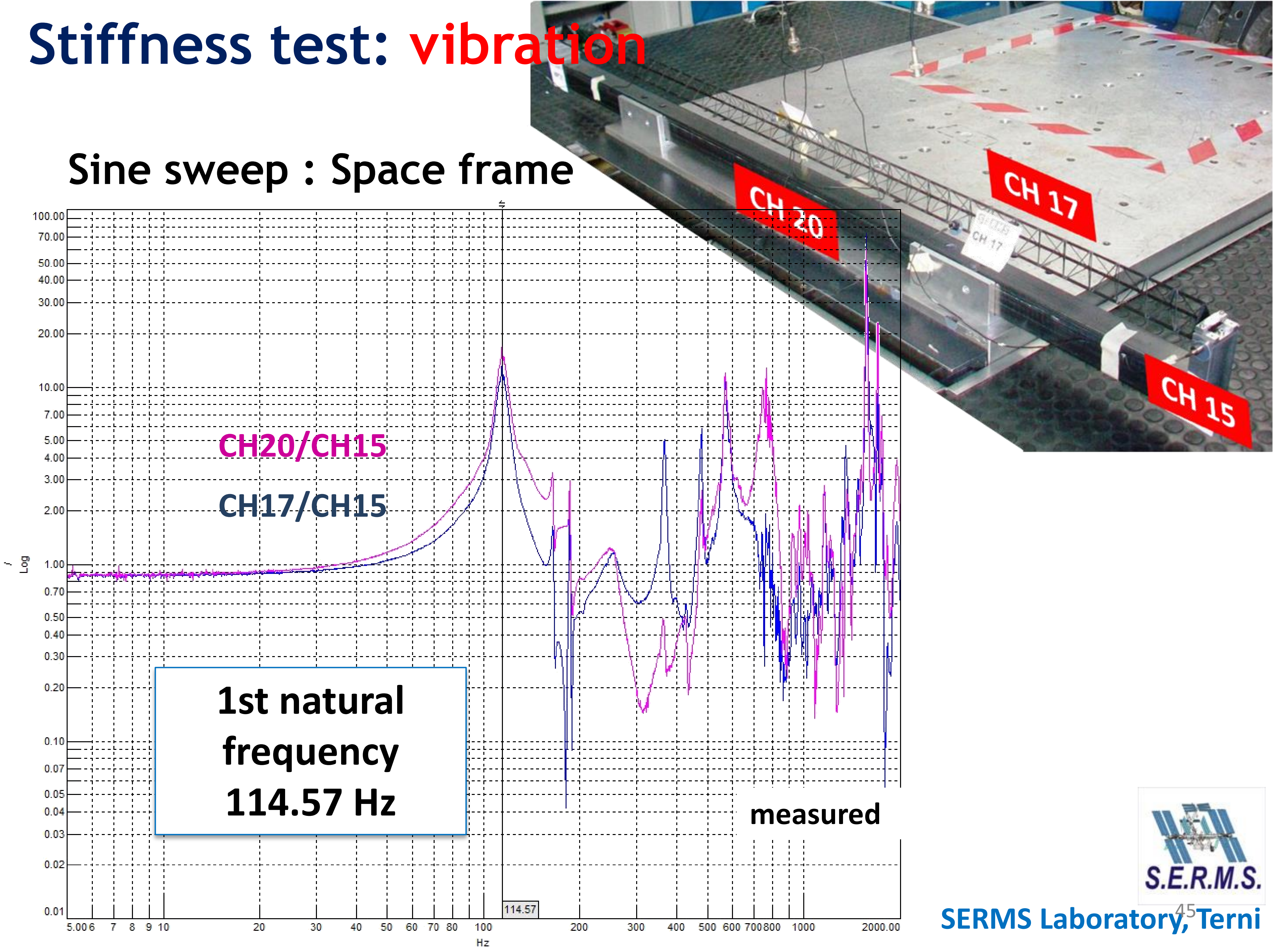
1,5 kg test

1,5 meter

Linear elastic behaviour observed during loading and unloading at several intermediate load steps

Stiffness test: vibration

Sine sweep : Space frame



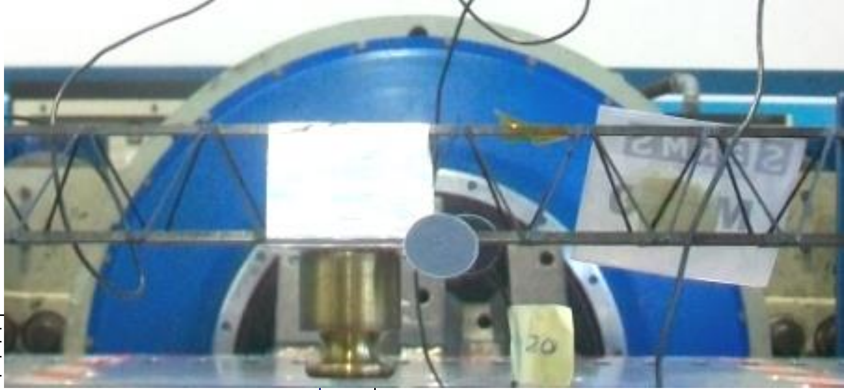
1st natural frequency 114.57 Hz

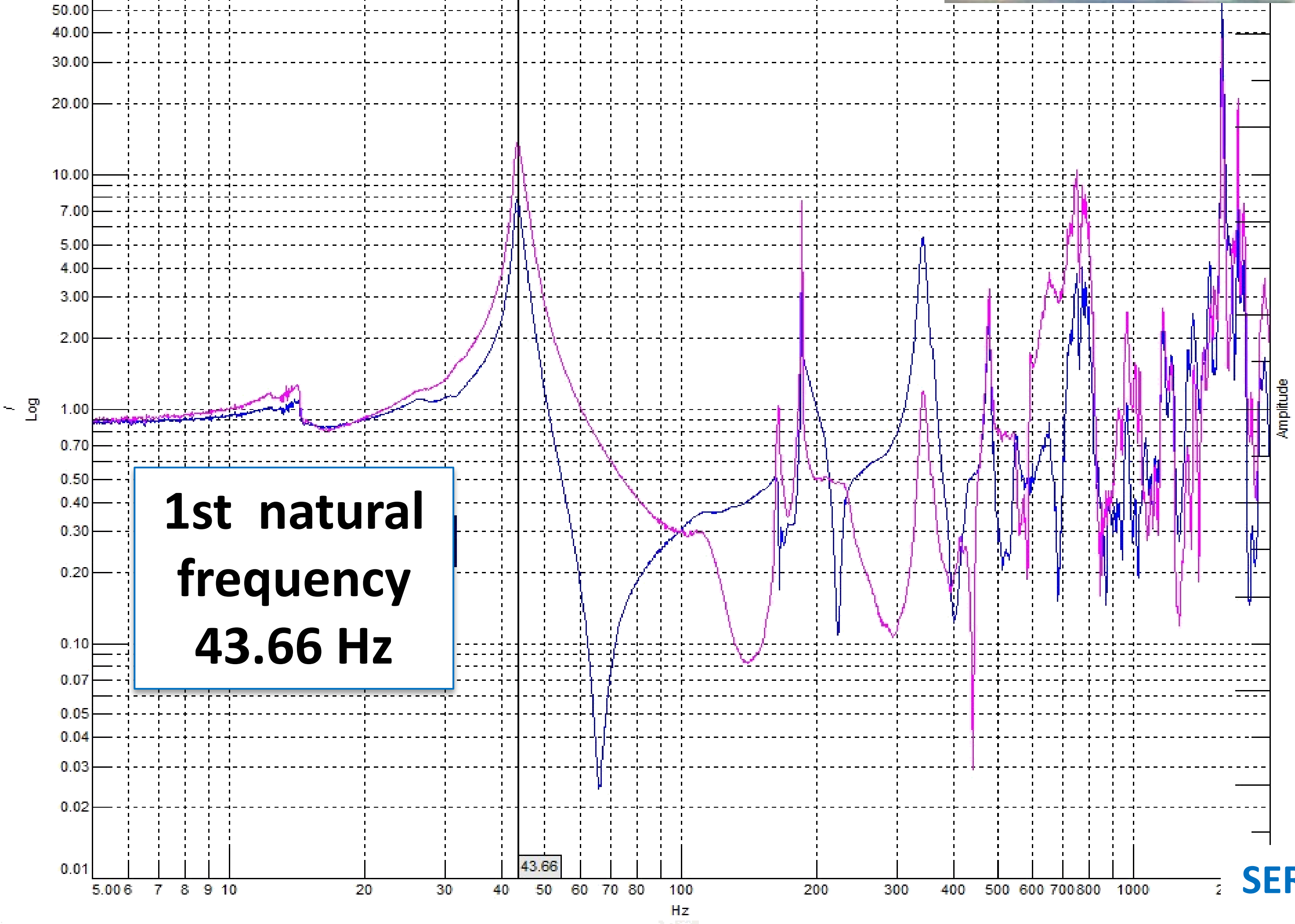
measured

Stiffness test: vibration

Sine sweep:

spaceframe +lumped mass 200gr (FPC, BUS,.)





1st natural frequency 43.66 Hz

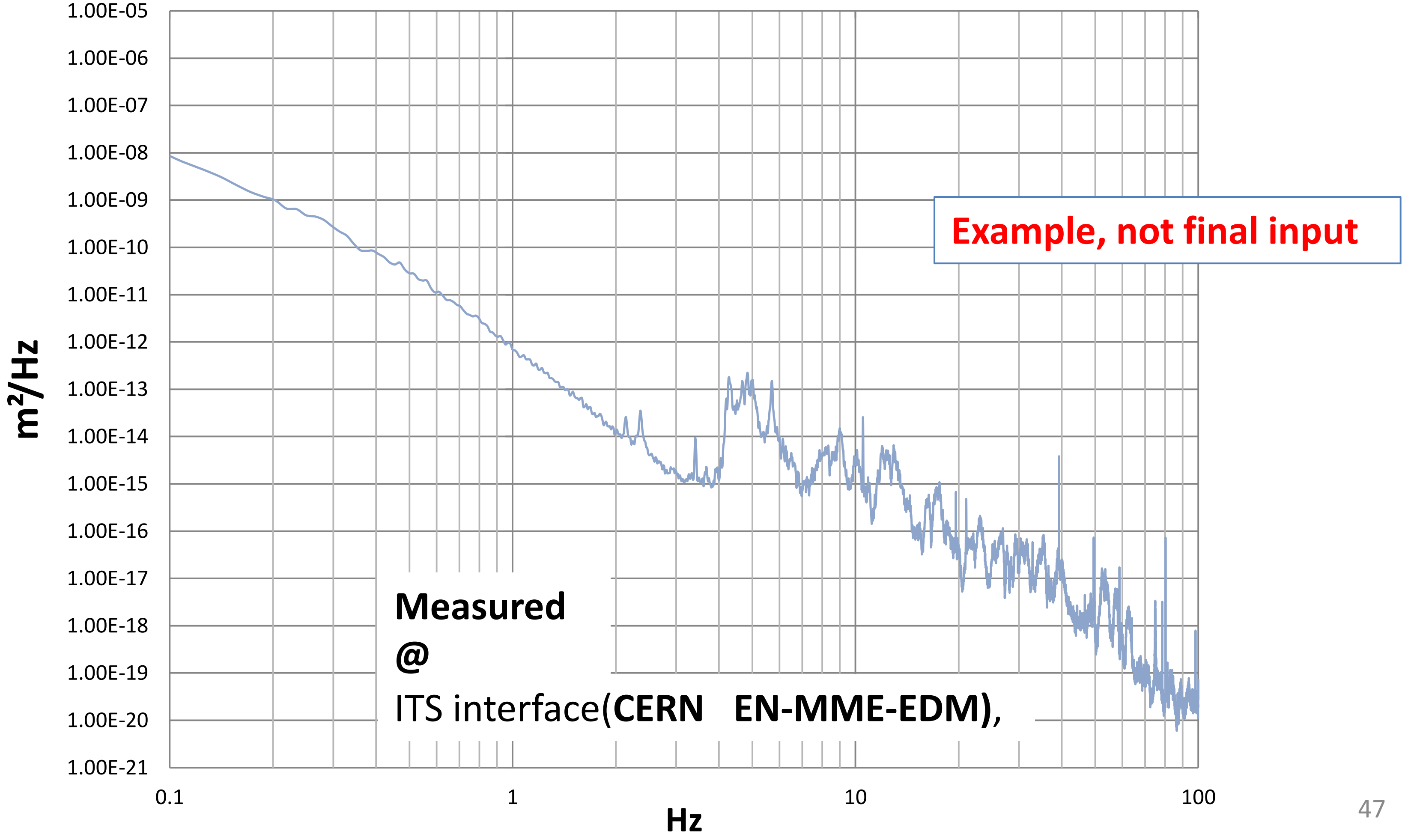
Stave stability: dynamic response procedure

- ✓NEXT Determine vibration INPUT, seismic (<1Hz), cultural (>1Hz), cooling,..

  Ex of PSD to be used as input to evaluate stave response.

  Below PSD is measured at TPC rails (**CERN EN-MME-EDM)**, and is used only as an example of procedure. PSD input need to be evaluated at Stave mechanical intefaces (TPC, Cooling, ...)

x-PSD_Rail_pt_1_Y



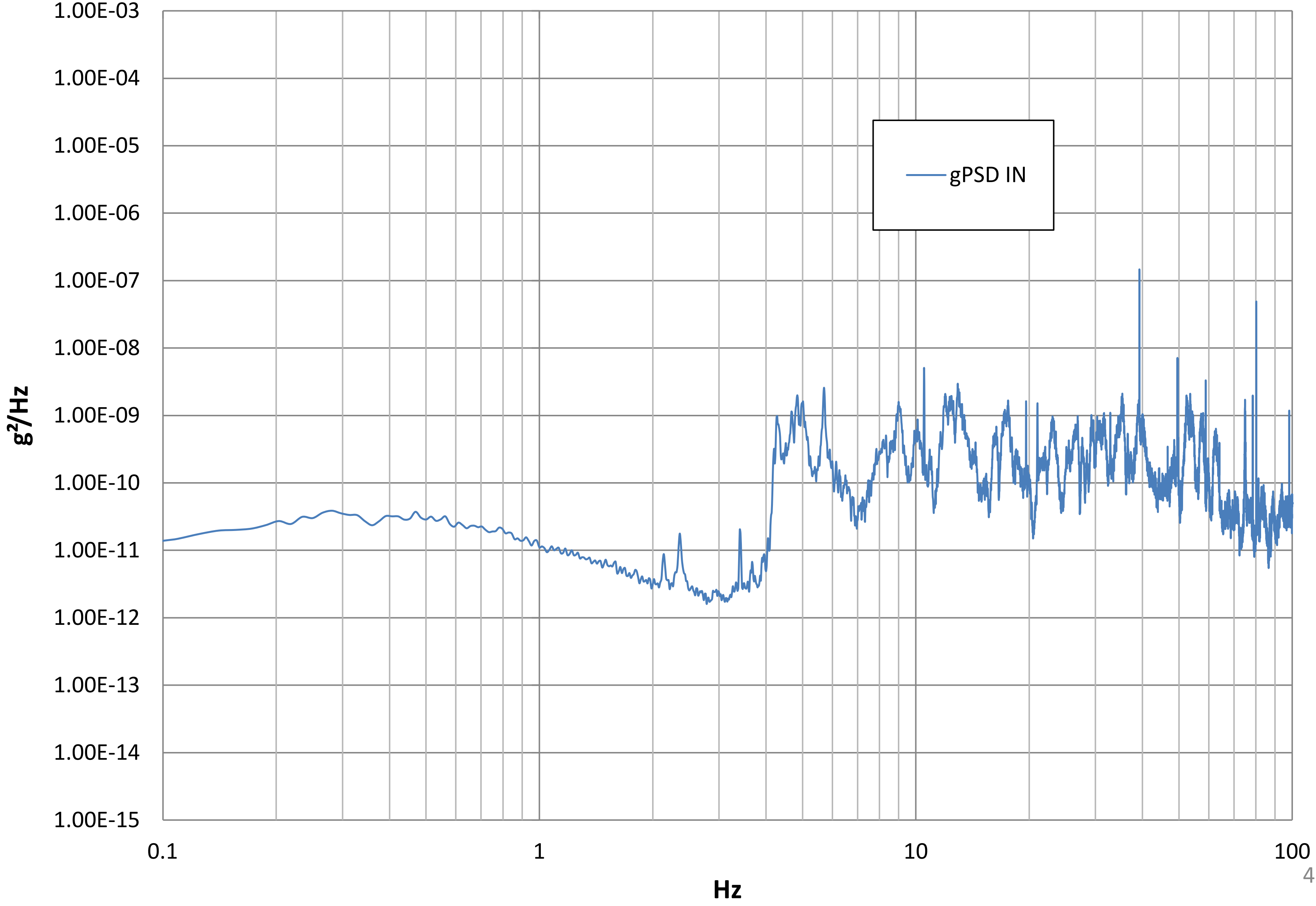
Example, not final input

Measured
@
ITS interface(**CERN EN-MME-EDM),**

Stave stability: dynamic response

$$gPSD = \frac{(2\pi f)^4}{9.81^2} xPSD$$

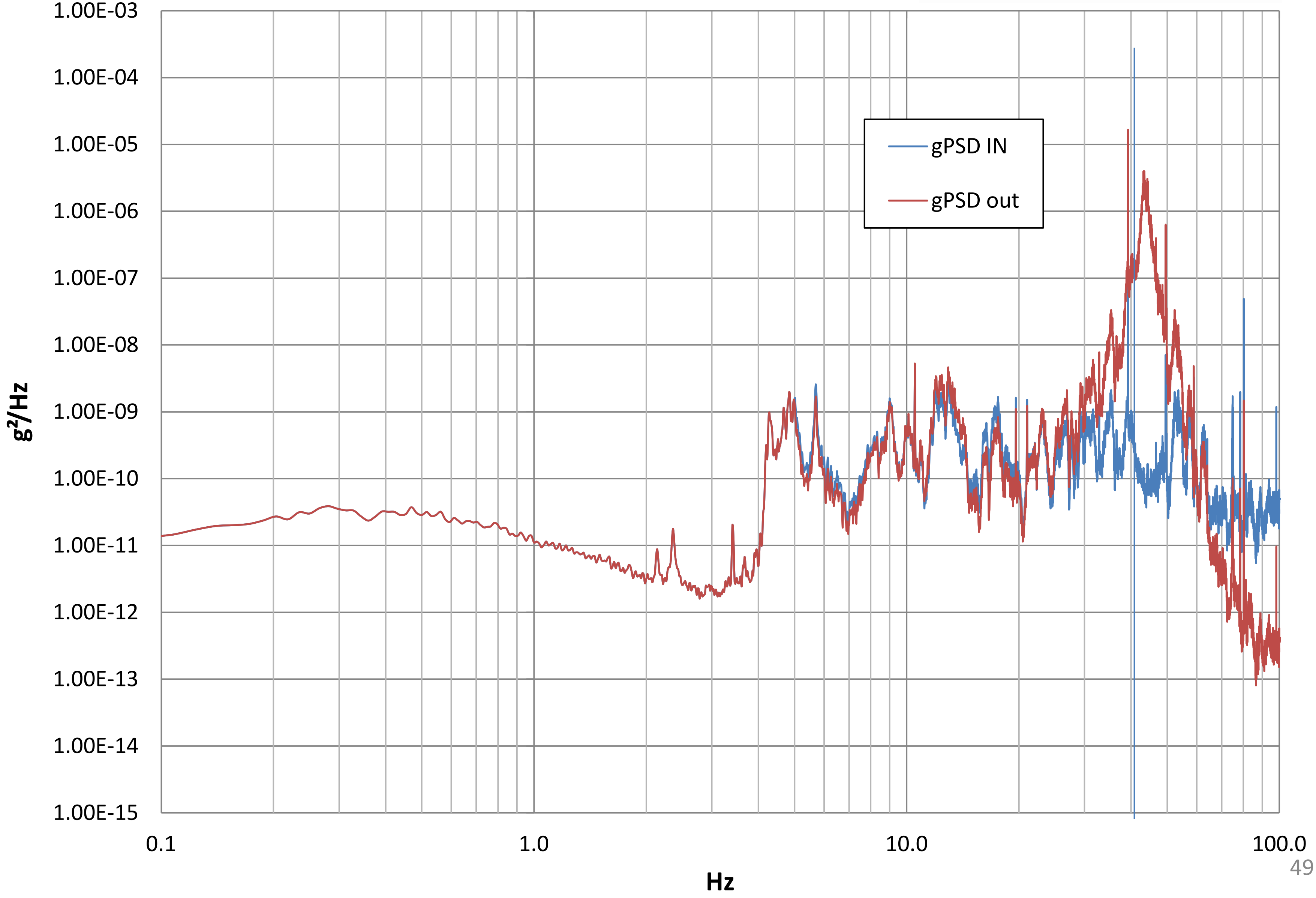
- ✓ From x-PSD to g-PSD **input**



Stave stability: dynamic response

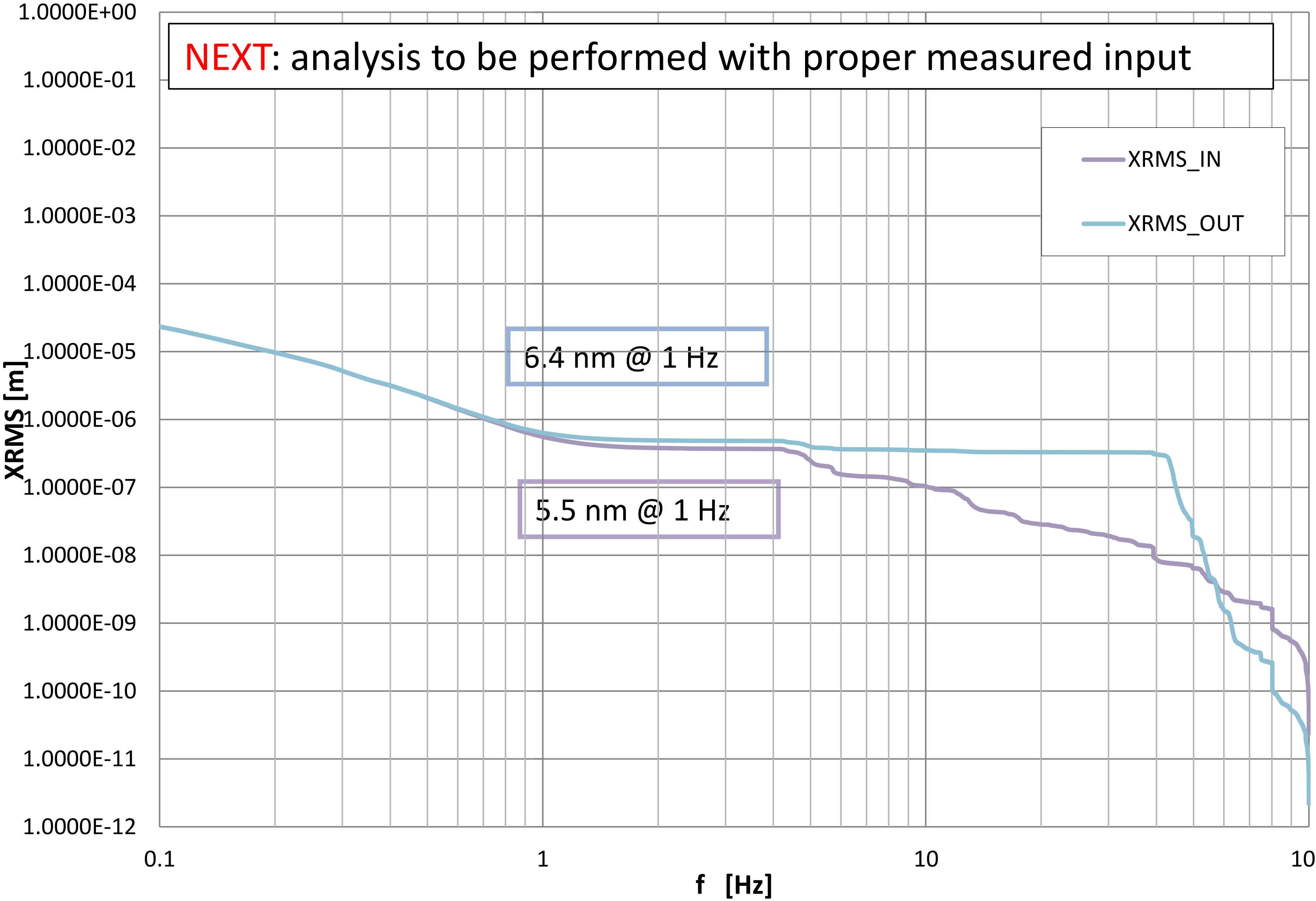
- ✓ g-PSD spaceframe **response**

$$R_Y(f) = |H(f)|^2 R_X(f)$$



Stave stability: dynamic response

- ✓x-RMS of the integrated displacement PSD @ 1 Hz is 6.4 nm



NEXT: analysis to be performed with proper measured input

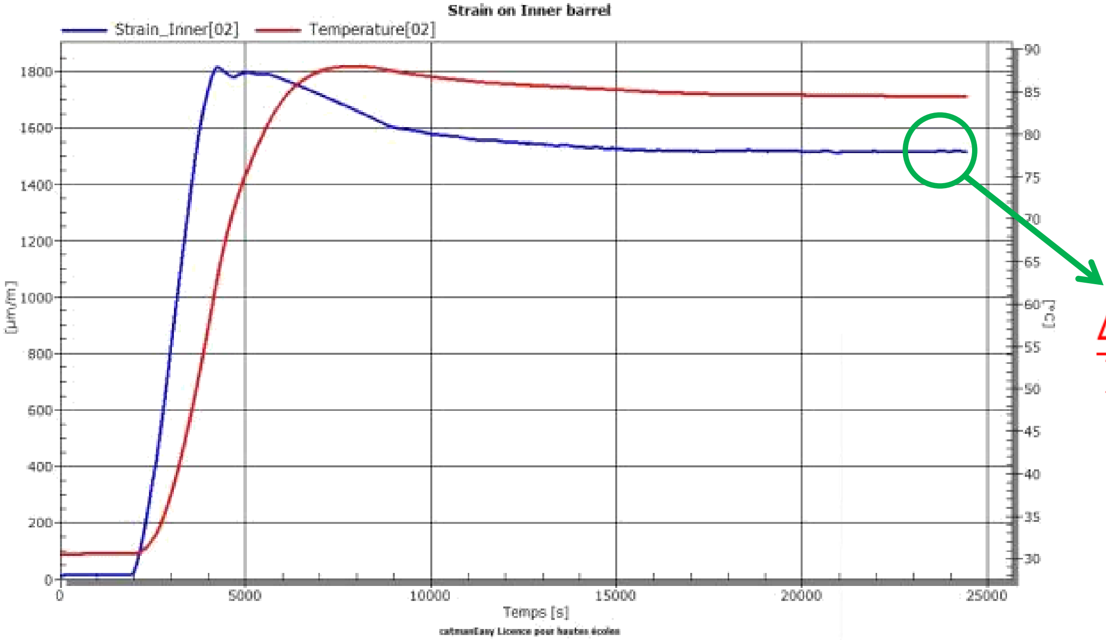
6.4 nm @ 1 Hz

5.5 nm @ 1 Hz

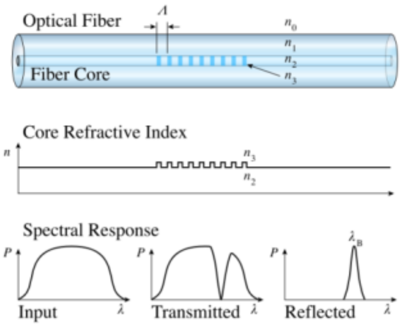
Stave thermo elastic test

Stave stability: thermoelastic behaviour (1)

measured by Fiber Bragg grating



HBM (K-OL)



$$\frac{\Delta L}{L_0} = 1497\ \mu m/m$$

$\Delta T = 55\,^\circ C$

REFERENCE Invar block

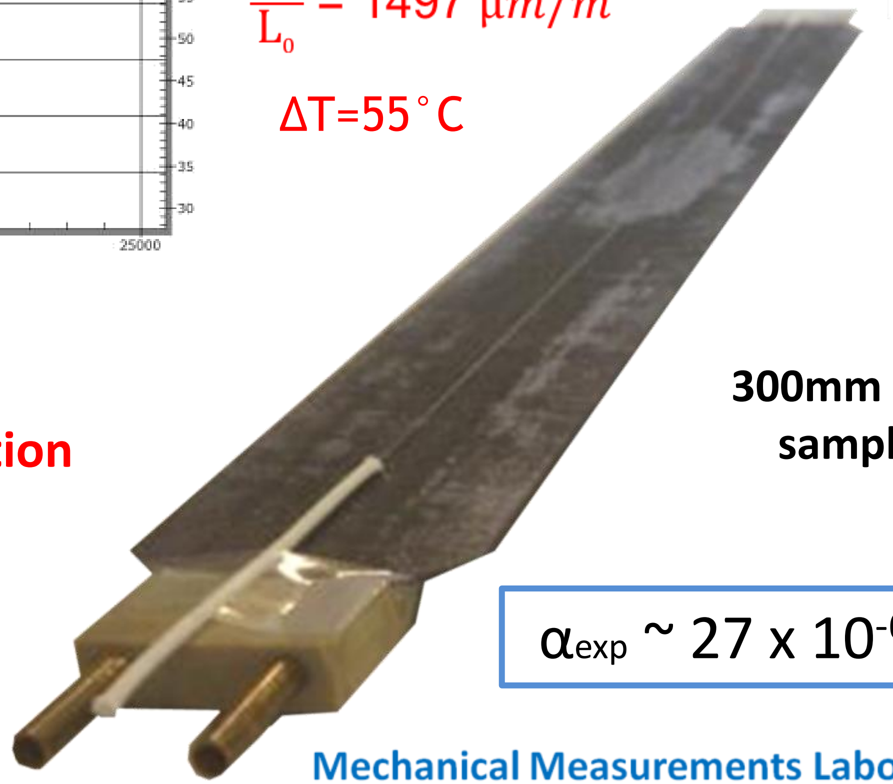
$\alpha_{theoric} \sim 2 \times 10^{-6}\ K^{-1}$

Need further calibration

$\alpha_{exp} \sim 8 \times 10^{-6}\ K^{-1}$

300mm test sample

$\alpha_{exp} \sim 27 \times 10^{-6}\ K^{-1}$



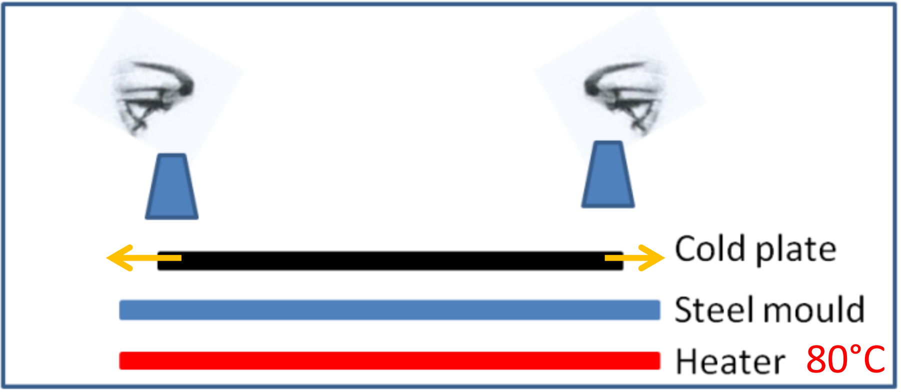
REFERENCE Al block

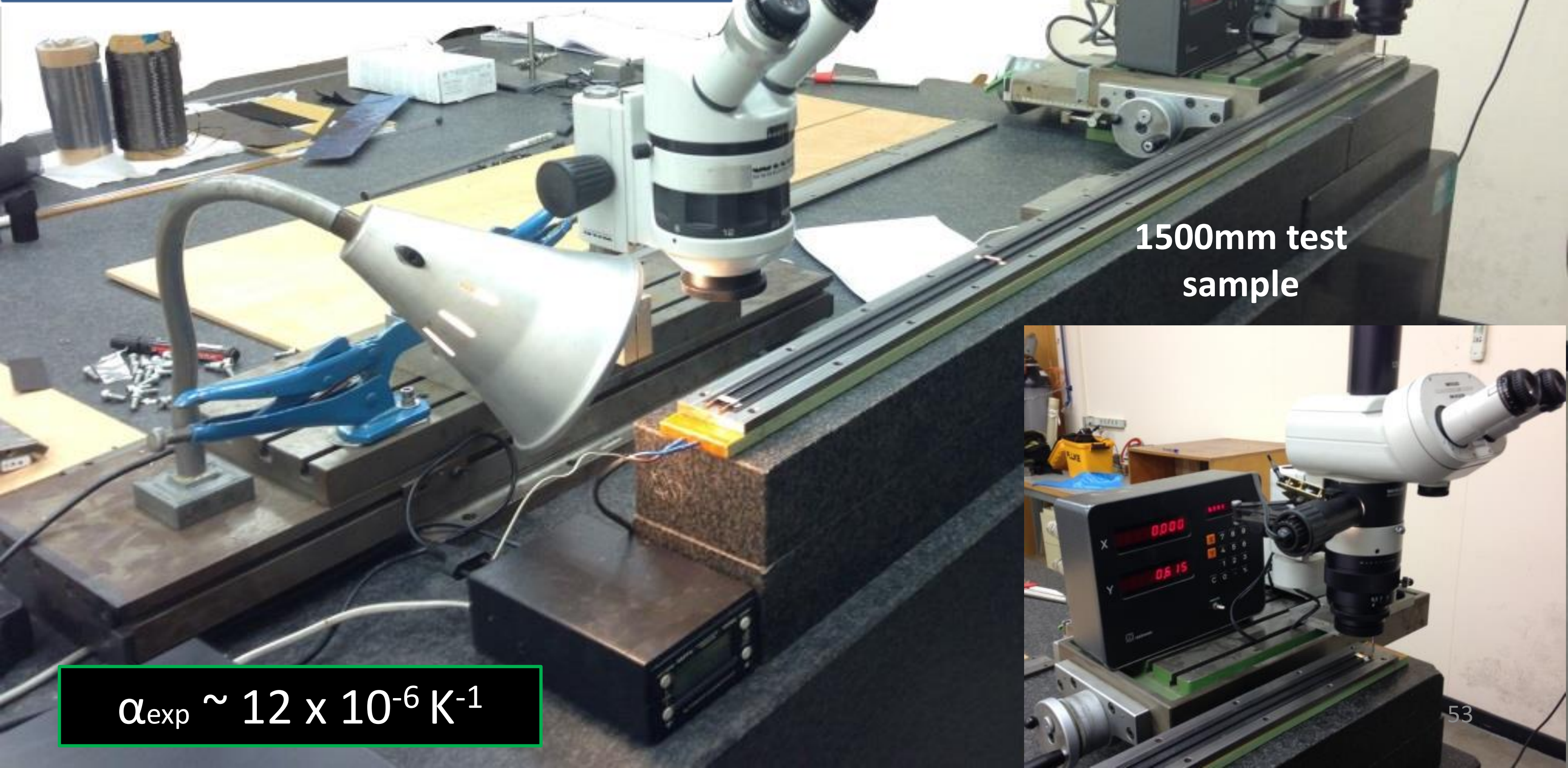
$\alpha_{theoric} \sim 24 \times 10^{-6}\ K^{-1}$

$\alpha_{exp} \sim 31 \times 10^{-6}\ K^{-1}$

Stave stability: thermoelastic behaviour (2)

measured by microscope





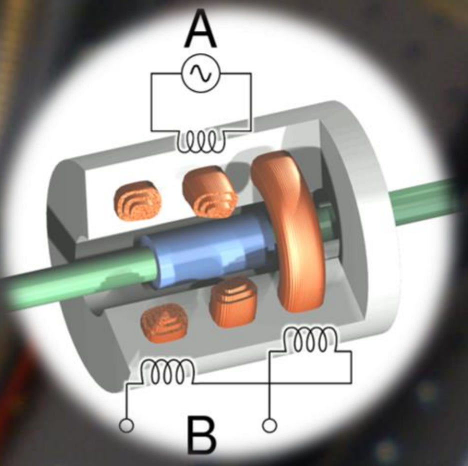
1500mm test sample

$\alpha_{exp} \sim 12 \times 10^{-6}\ K^{-1}$

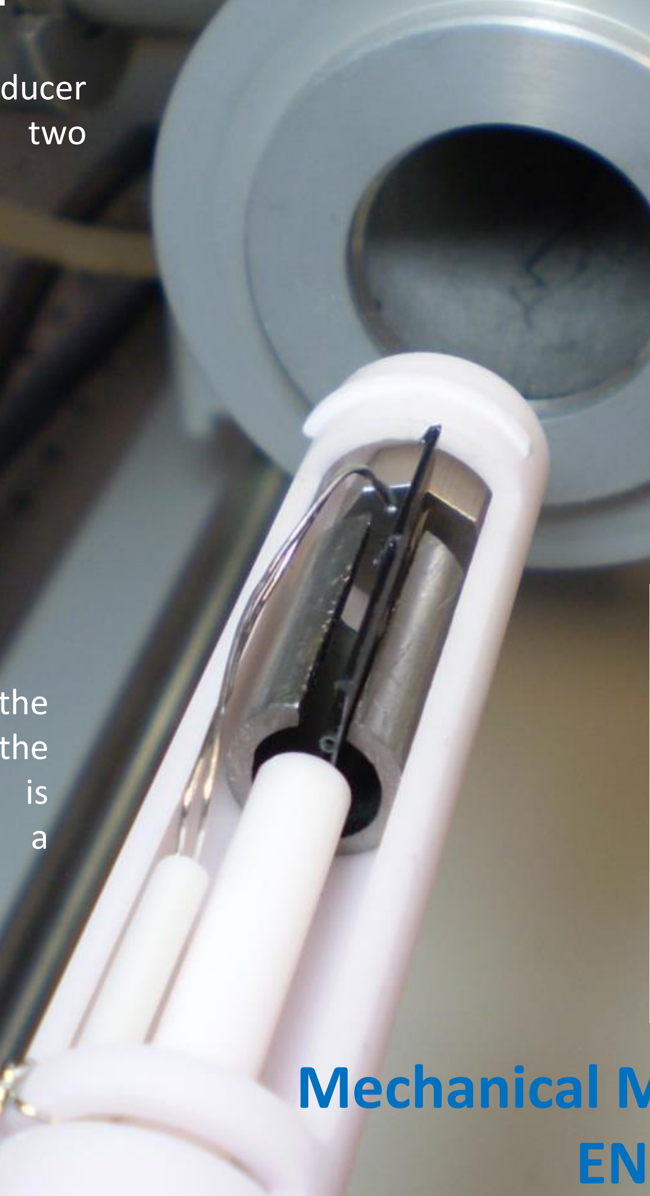
Stave stability: thermoelastic behaviour (2)

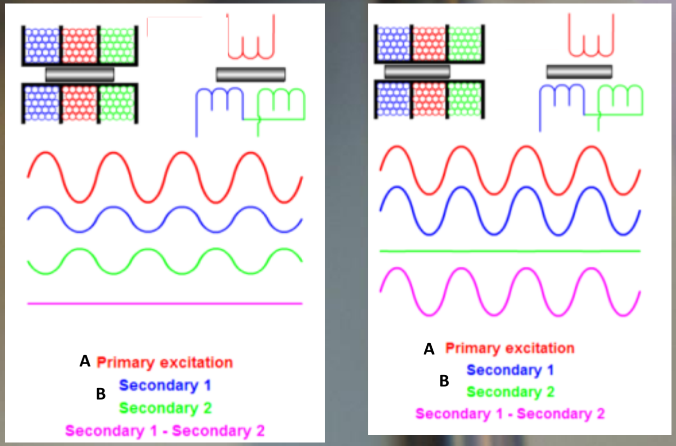
measured by LVDT

An LVDT Displacement Transducer comprises a primary (A) and two secondaries (B) coils



The transfer of current between the primary and the secondaries of the LVDT displacement transducer is controlled by the position of a magnetic core



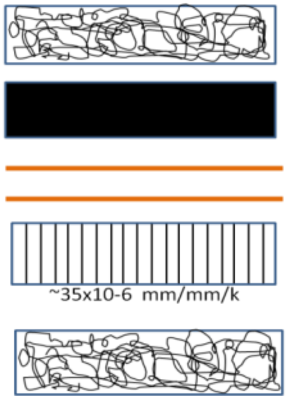


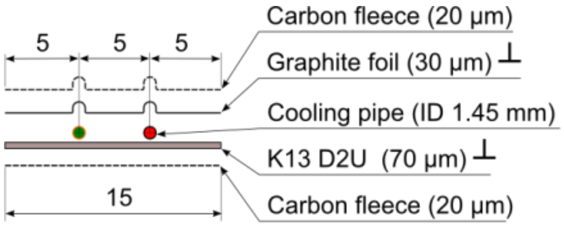
Mechanical Measurements Laboratory
EN-MME-EDM

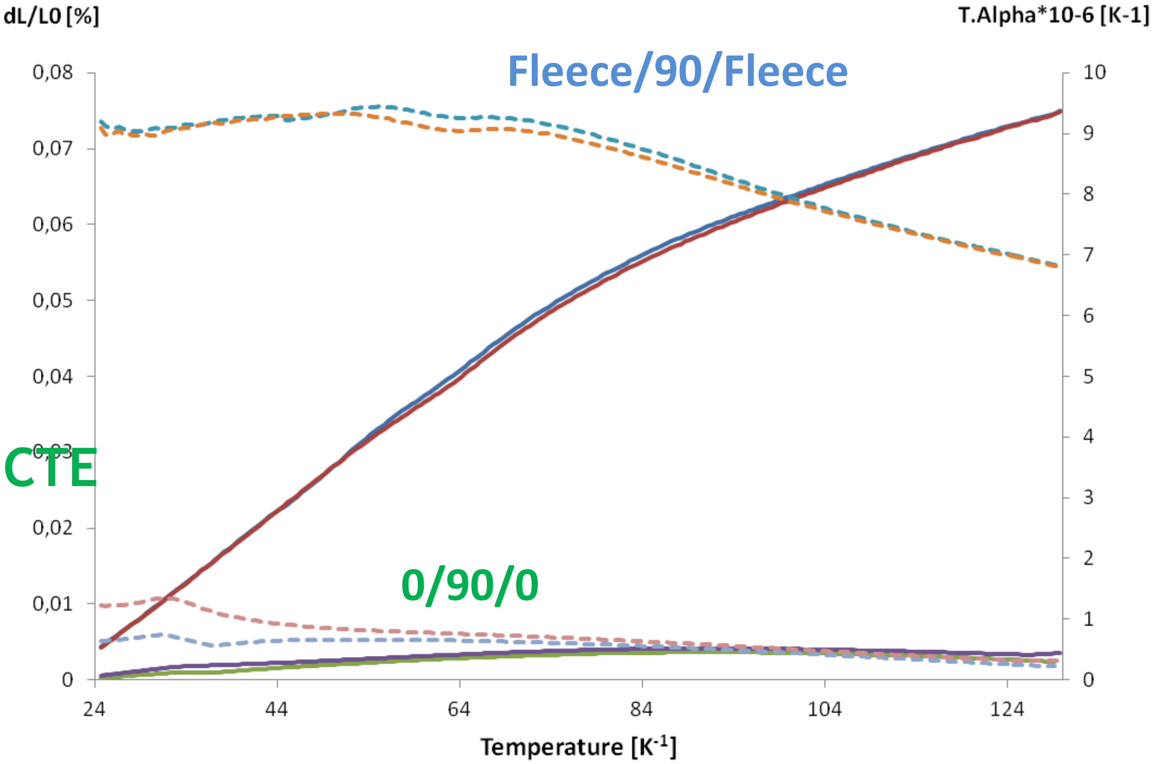
Dilatometer DIL 402 E

Stave stability: thermoelastic behaviour (3)

Measure by LVDT





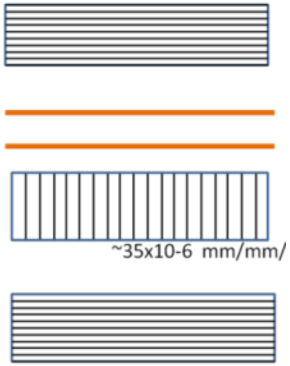


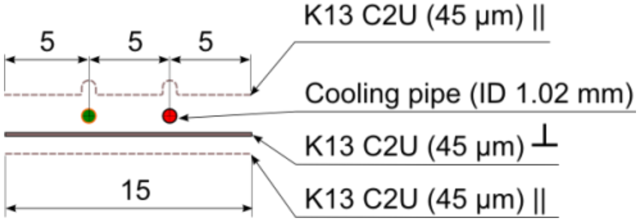
CTE< $10*10^{-6}$ [K^{-1}]

Baseline

Alternative option to reduce CTE

CTE= $0*10^{-6}$ [K^{-1}]





Polymide pipe characterization

Polyimides pipes stability: erosion

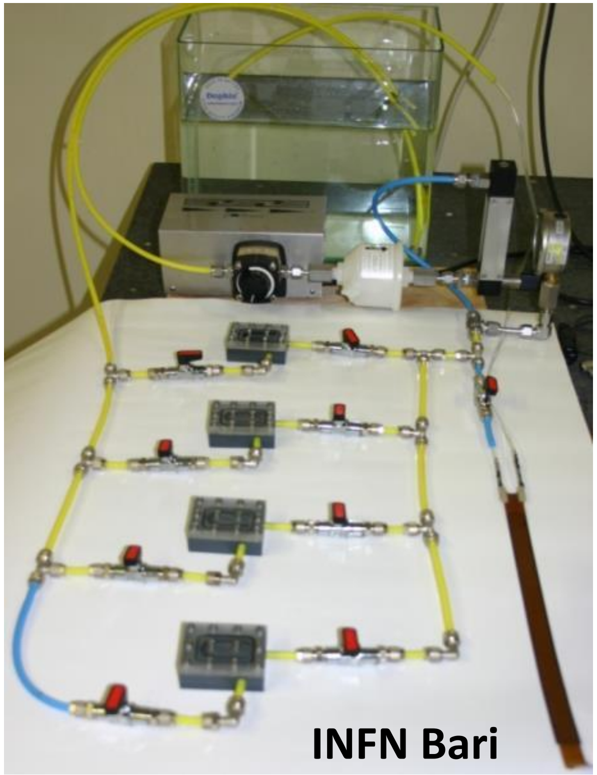
-Long term test with water flow to evaluate erosion effects

-SEM (surface damage) and AFM (surface roughness change) analysis

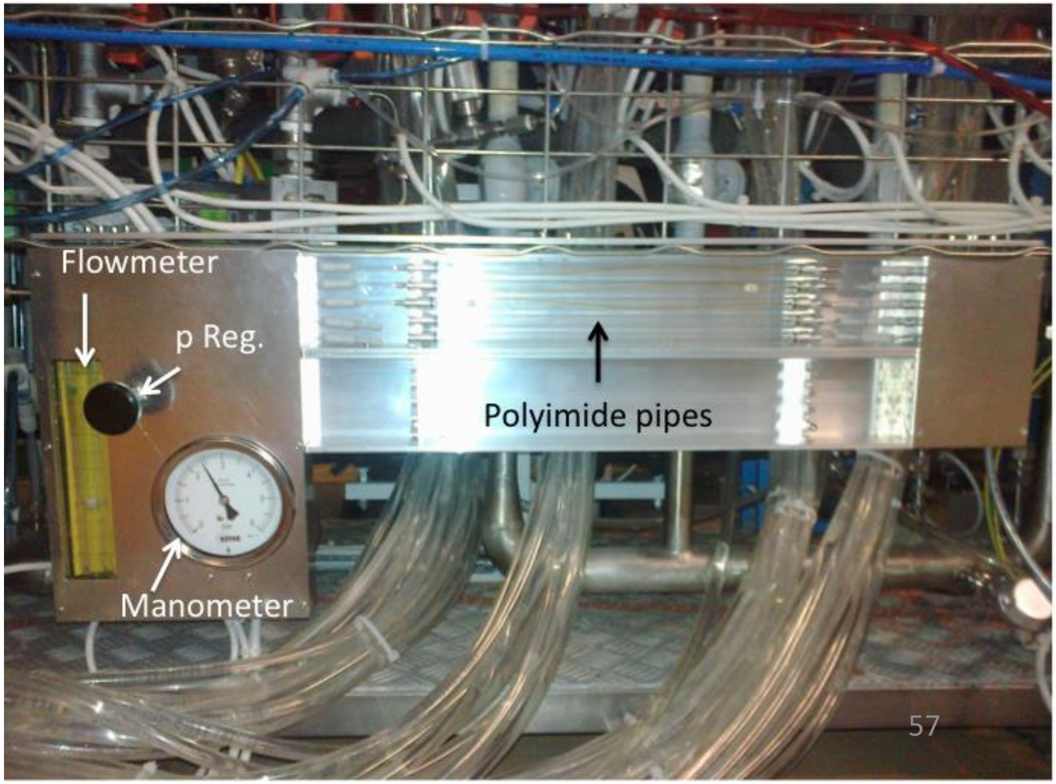
-Sample dimensions: ID =1.024mm
OD=1.075mm
Wt = 0.0254mm
L= 300mm

-Flow rate: 0.3 l/min
-P inlet: 2.30 bar
-T= 20°C

-Test set up on surface



-Test set up in the ALICE cavern



Polyimides pipes stability: erosion

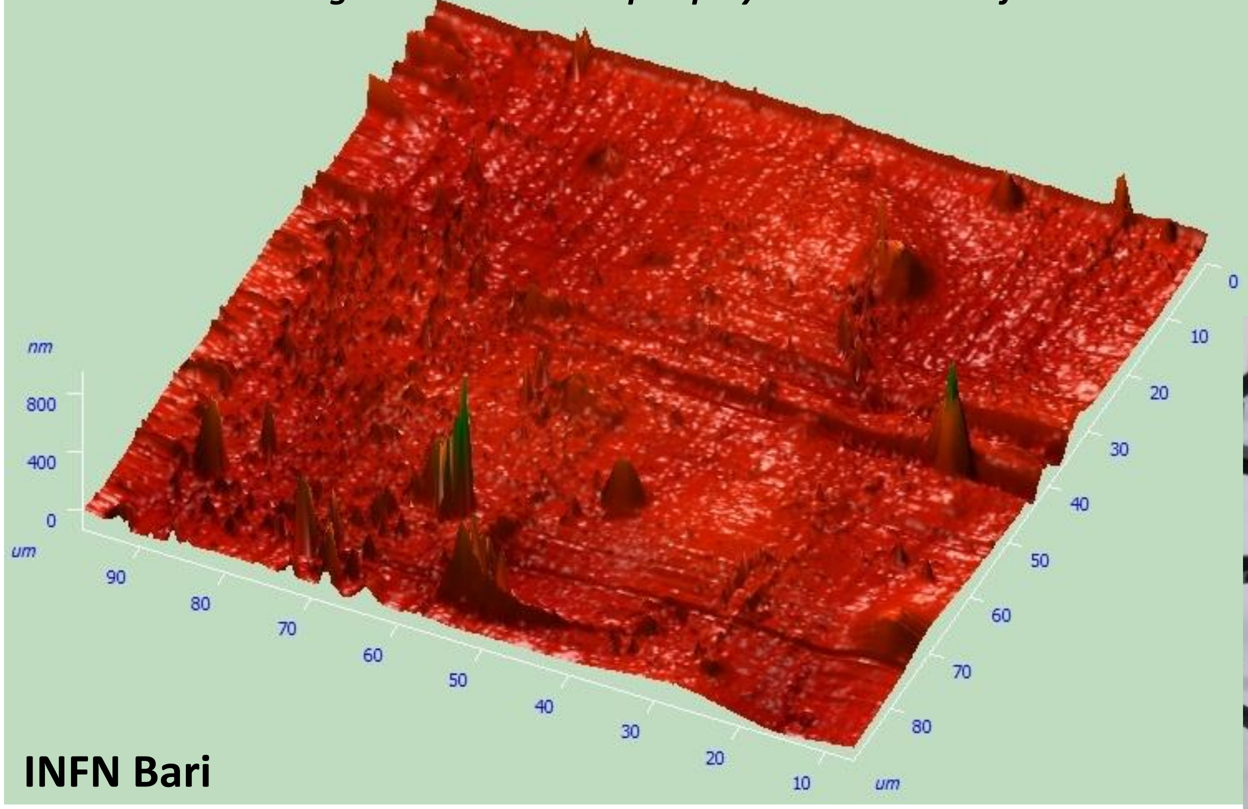
Water erosion effects: surface roughness measurement

A surface roughness measurement was carried out before and after the water erosion test on Polyimide:

The statistical average roughness, on an area of 100 x 90 μm² with 256 x 256 points is 34.94 nm.

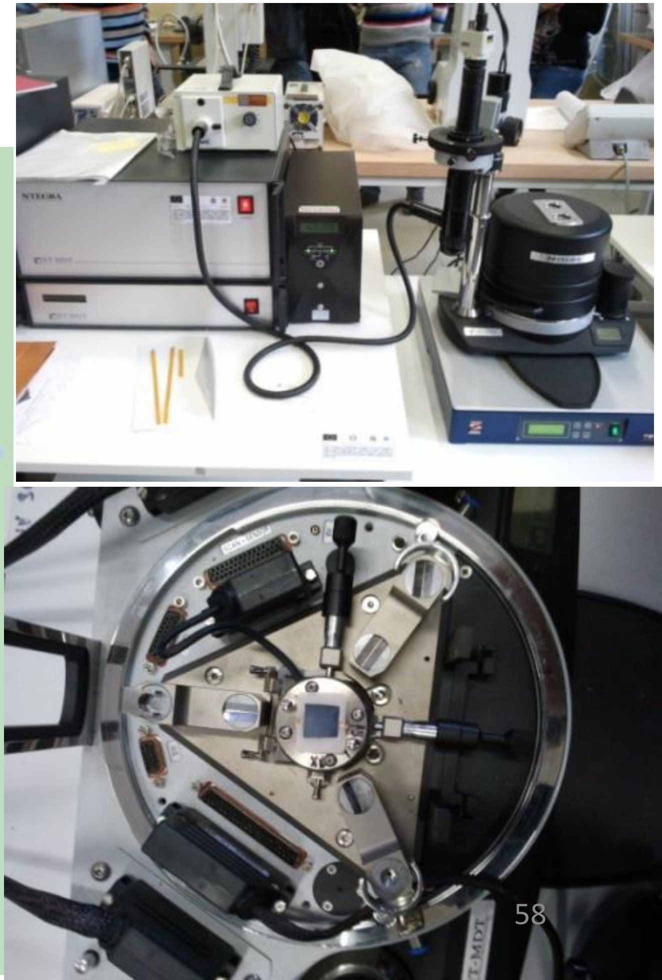
Measure after 10 months of testing : no difference on the average value

3D reconstructed roughness on 100 x 90 μm²polyimide MCHS surface



INFN Bari

Atomic Force Microscope



Polyimides pipes: pressure test

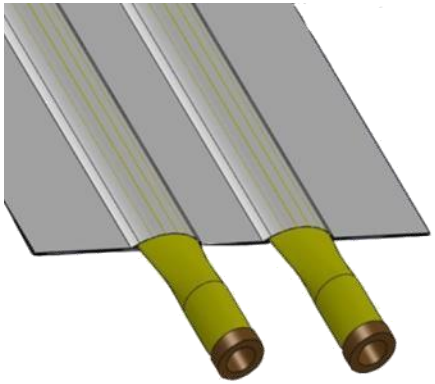
Round pipe

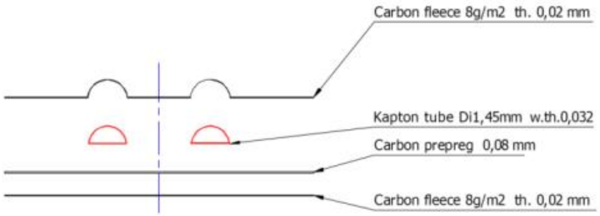
Polyimide Tubing Pressure resistance

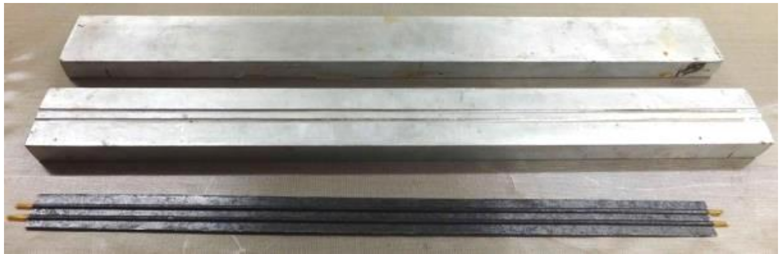
ID [mm]	Wt [mm]	P [bar]
1,024	0,0254	40
1,450	0,032	35
2,050	0,032	25
2,667	0,0635	38

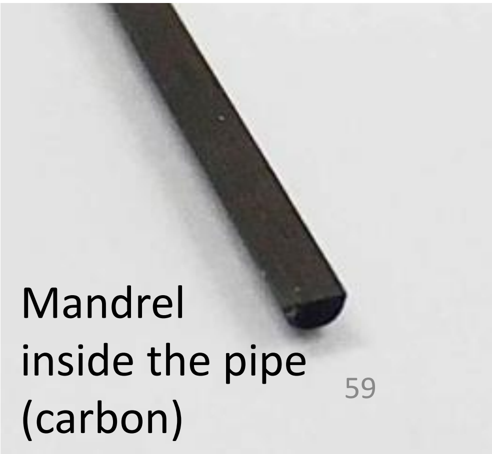
Squizeed pipe

Squeezed pipe to increase contact surface with carbon fiber, remove carbon paper



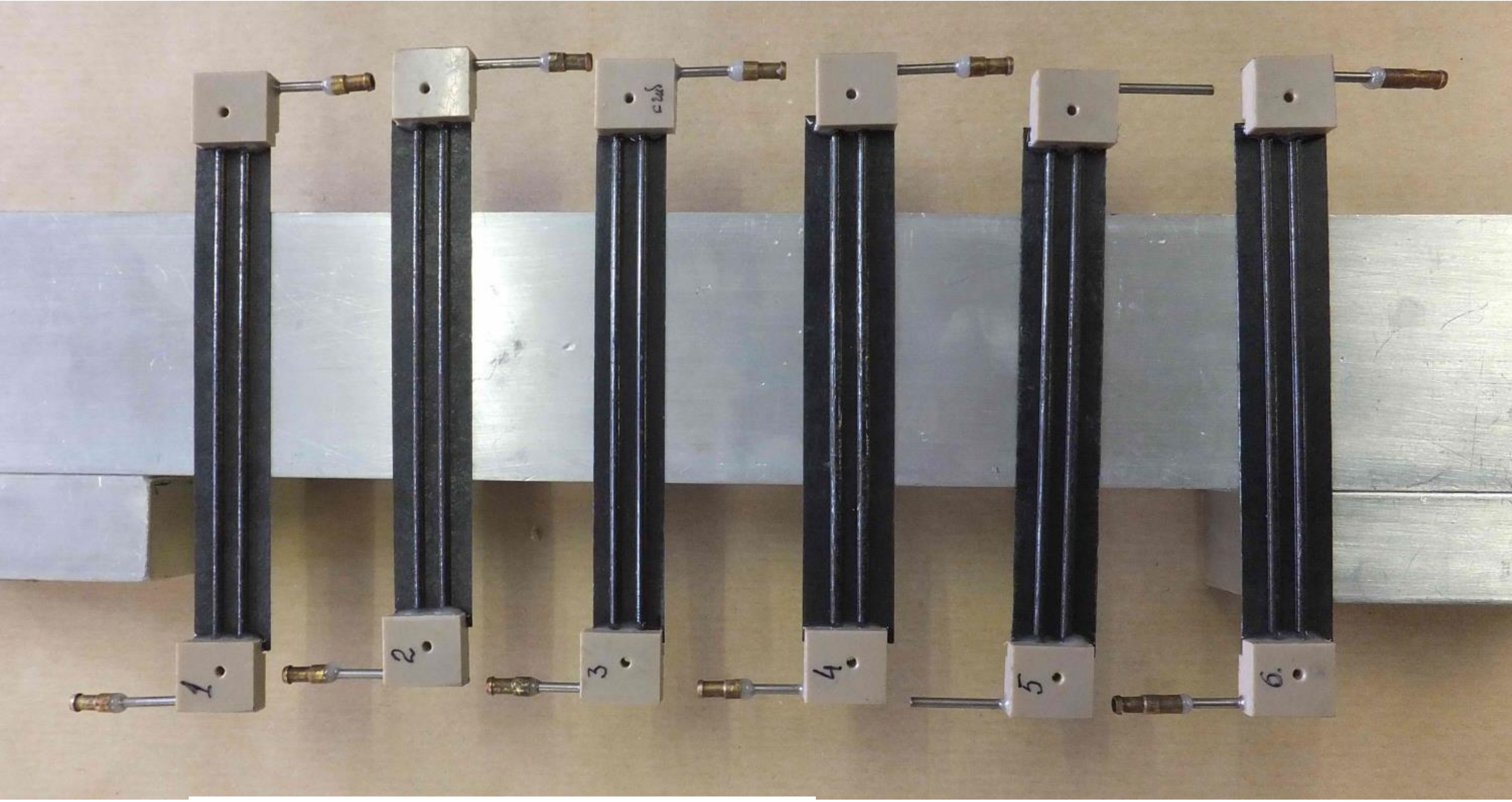


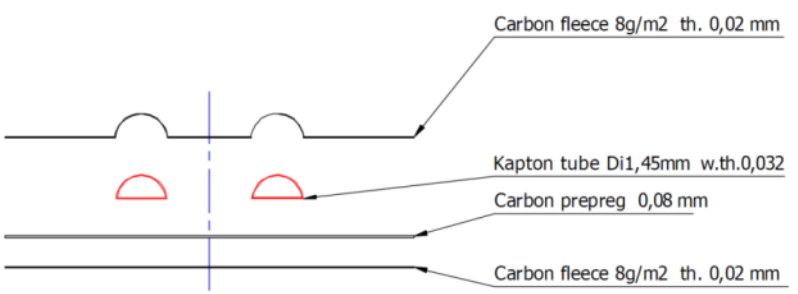




Mandrel inside the pipe (carbon)

Polyimides pipes: pressure test





Objective: verify pressure at which delamination occurs

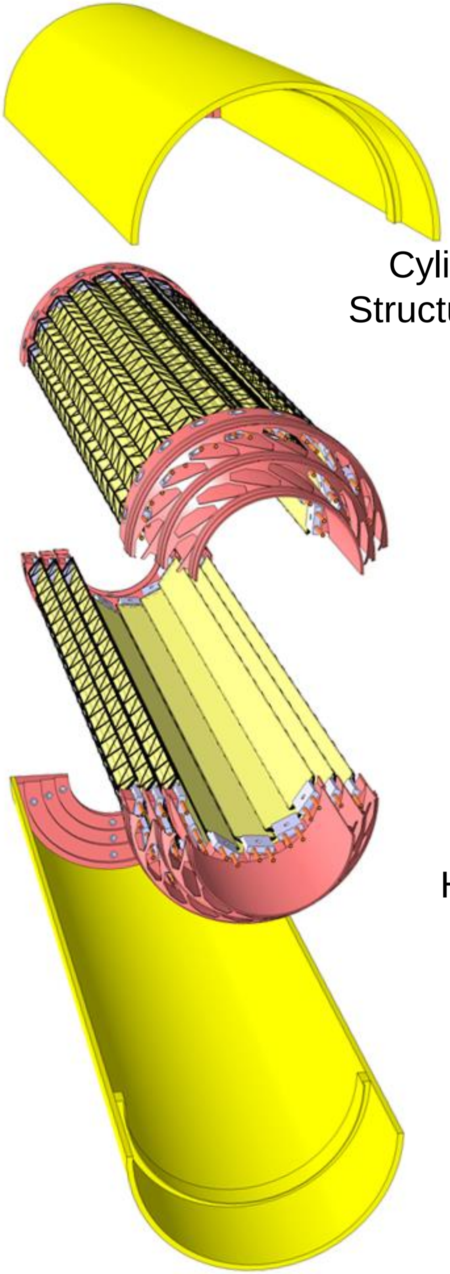
Polyimides pipes: pressure test

№		Delamination Pressure (bar)	
1	resin standard	1,5	
2	resin standard+larger quantity	2,5	
3	resin viscosity increased by a pre-polimerization process (100°C , 25 min)	10	No failure
4	resin+ aerosil 3% (aerosil /resin% weight)	2	
5	resin+ aerosil 5% (aerosil /resin% weight)	3,5	
6	resin+ aerosil 10% (aerosil /resin% weight)	10	No failure

Aerosil, silica compound increases resin viscosity

layers and barrel

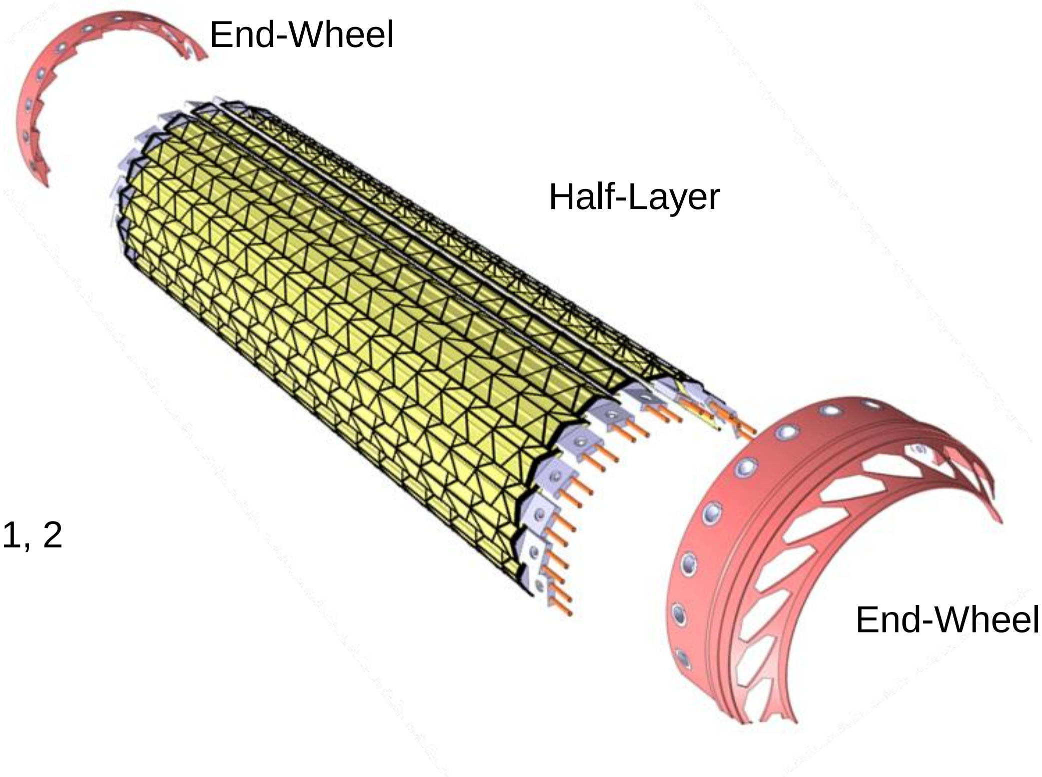
Inner Barrel



Cylindrical
Structural Shell

Layer 0, 1, 2

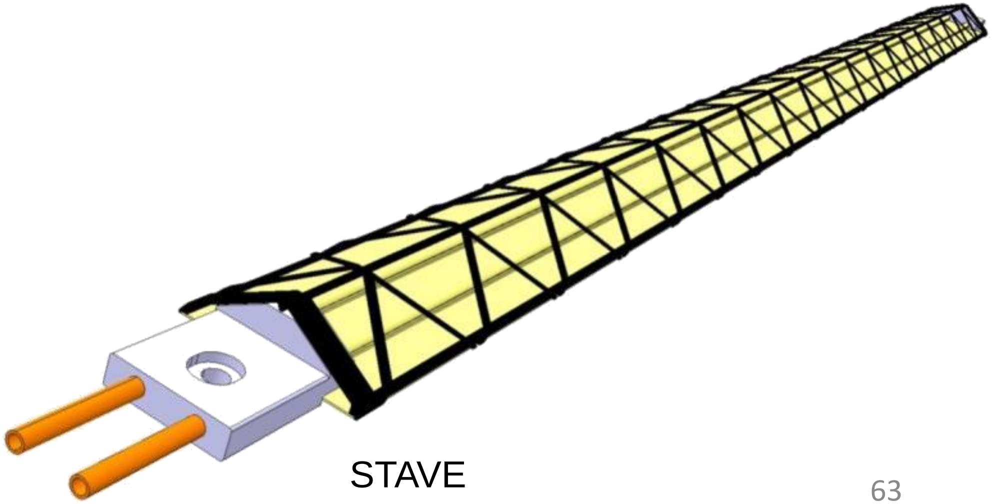
Half-Barrel



End-Wheel

Half-Layer

End-Wheel

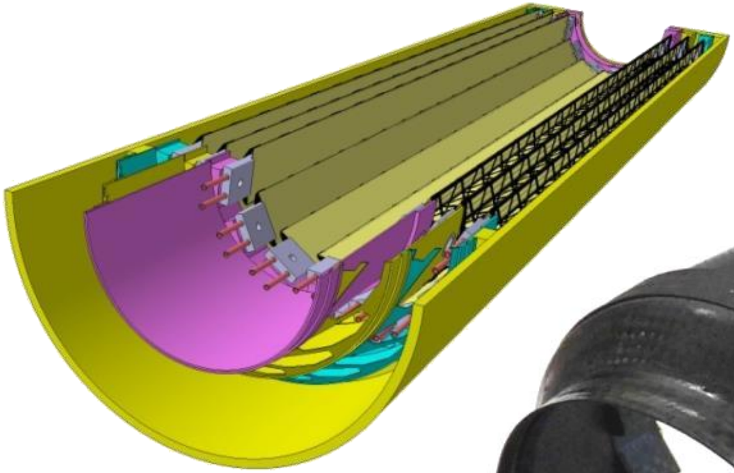


STAVE

End-wheels

	Filaments [K=1000]	E [GPa]	X [MPa]	K [W/mK]	CTE [10^{-6} K^{-1}]
fibre T300	3K	230	3550	418	-0.41

filament diameter= 7µm

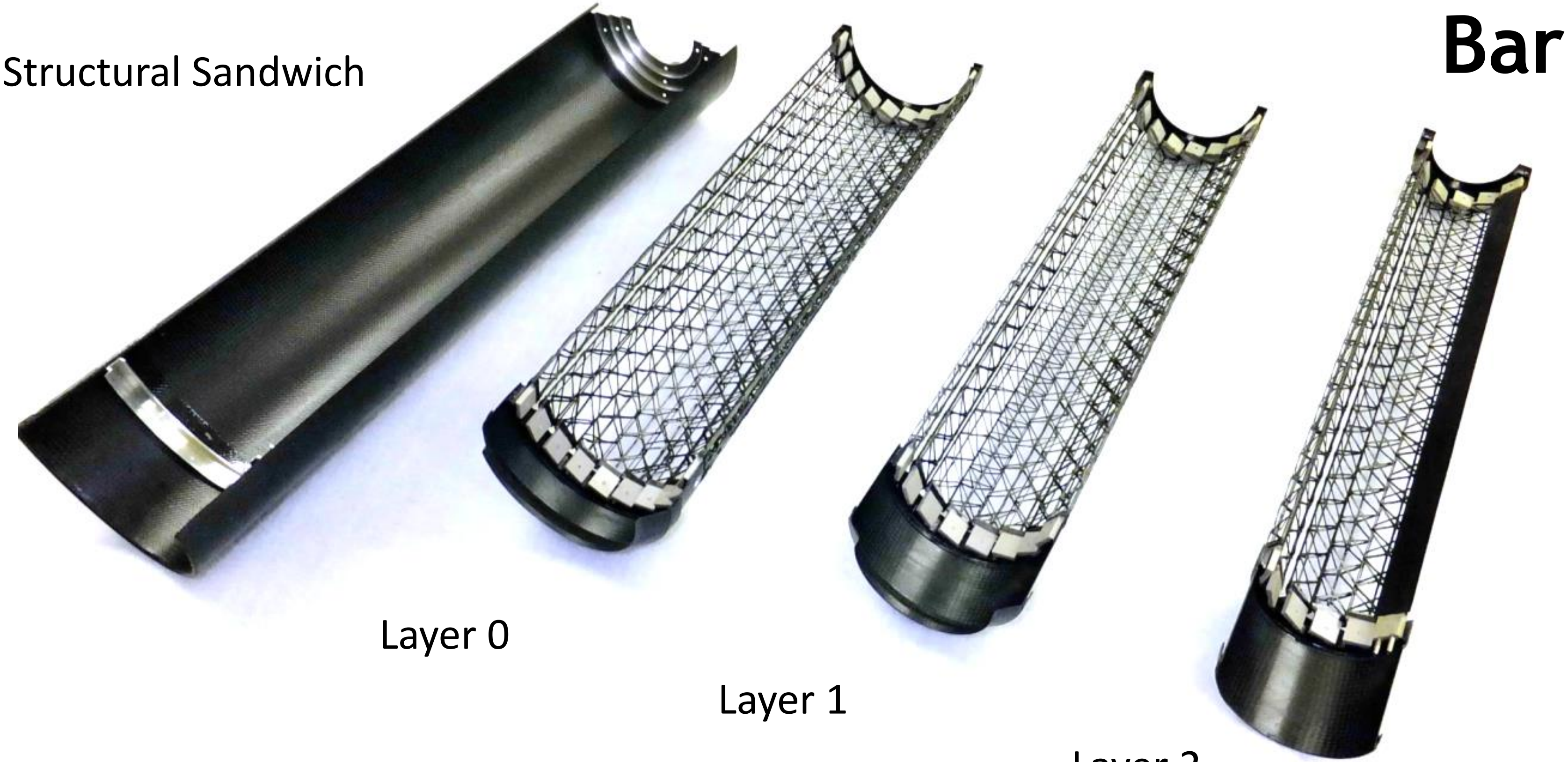


End-Wheel

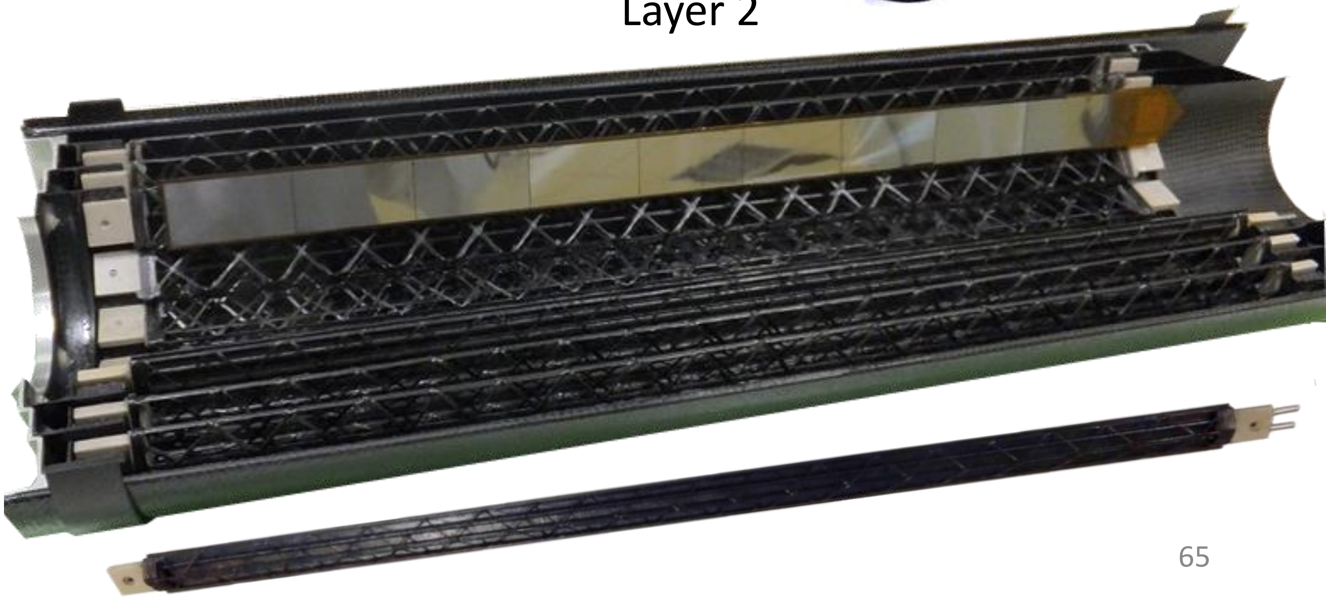
Fabric (0/90)T300

Airex R82.60
(60kg/m3)
closed cell thermolatic
polymer foam

Barrel



Prototype



Production process
moulds & mandrels

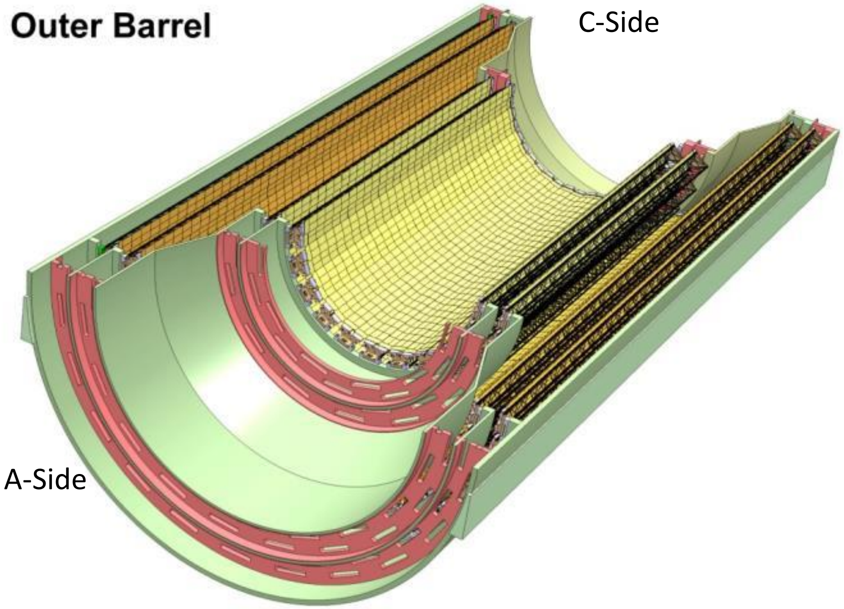
Metallic: steel

Ceramic: Macor

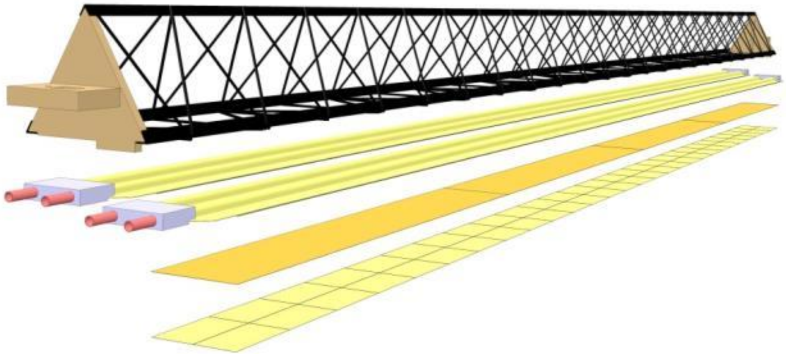
Thermal stability, low CTE

Detector barrel

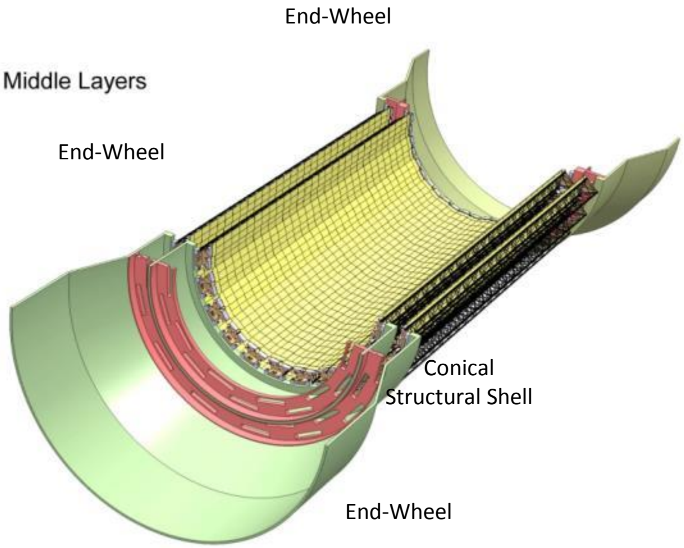
Outer Barrel



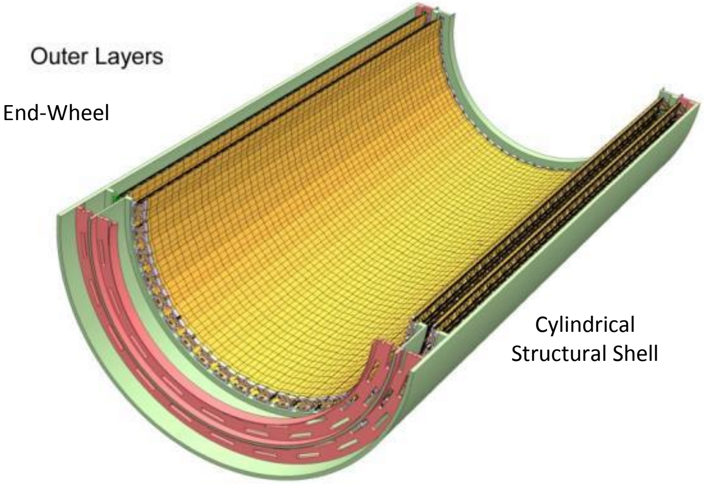
Stave



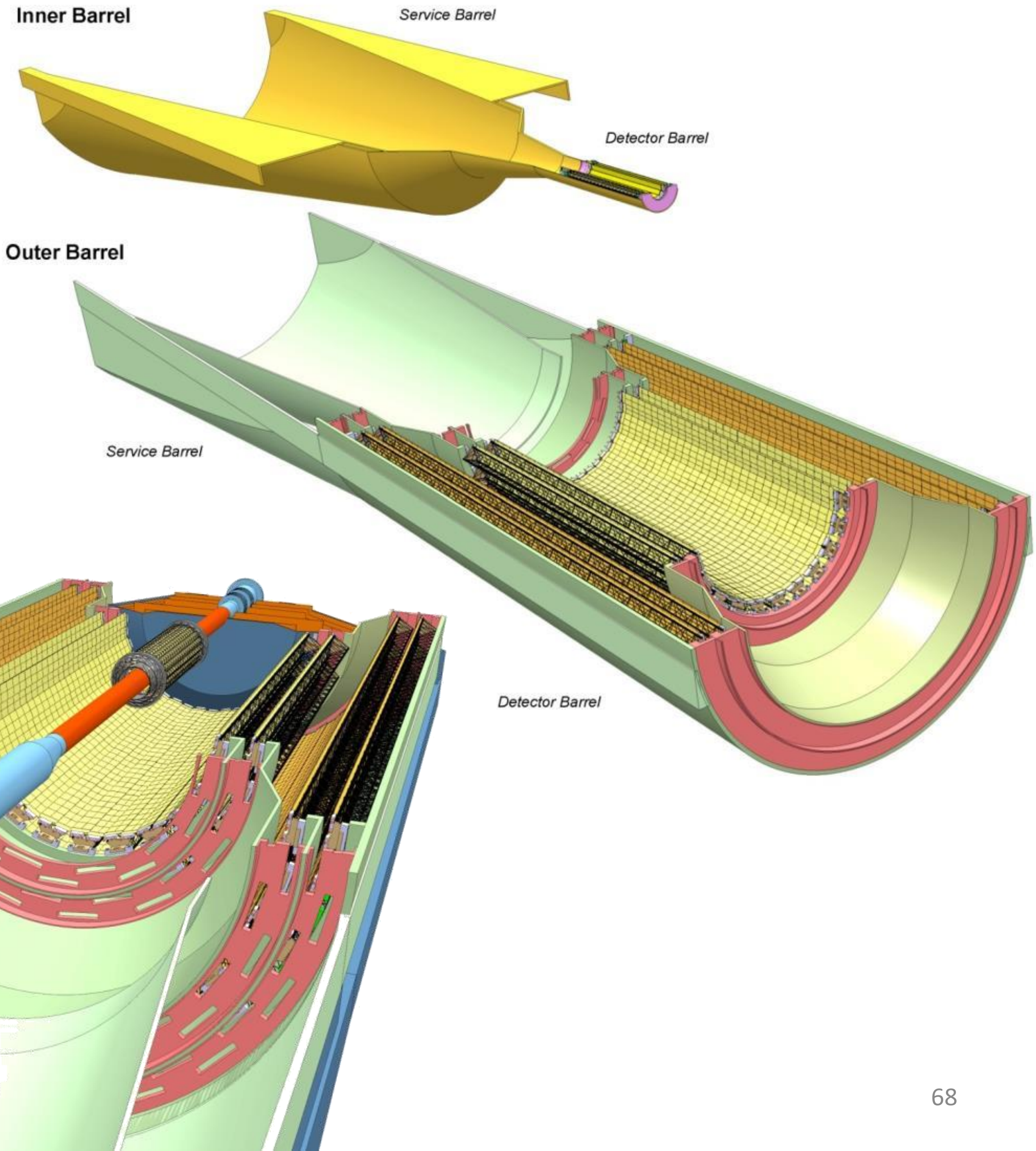
Middle Layers



Outer Layers

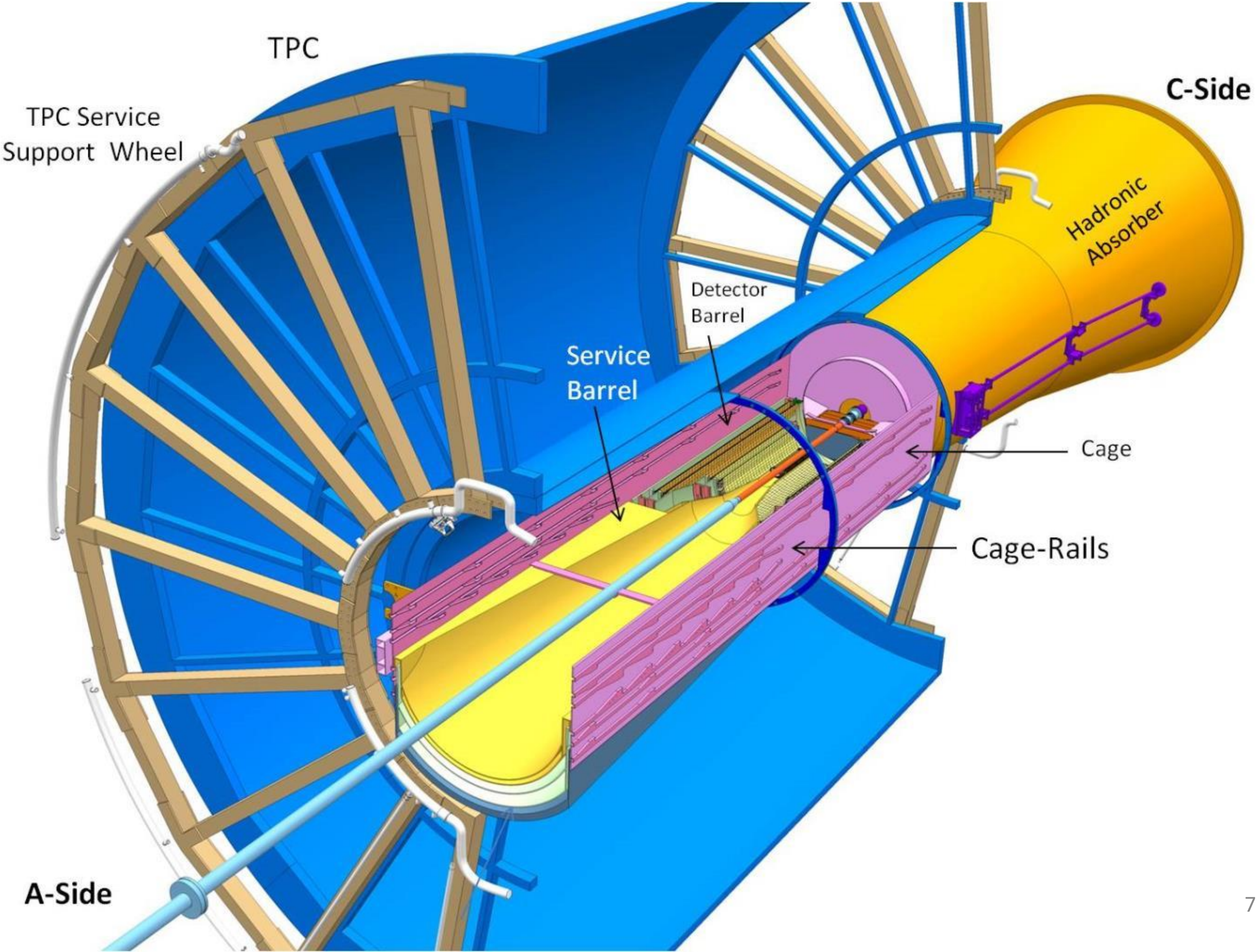


Service barrel



Integration in ALICE

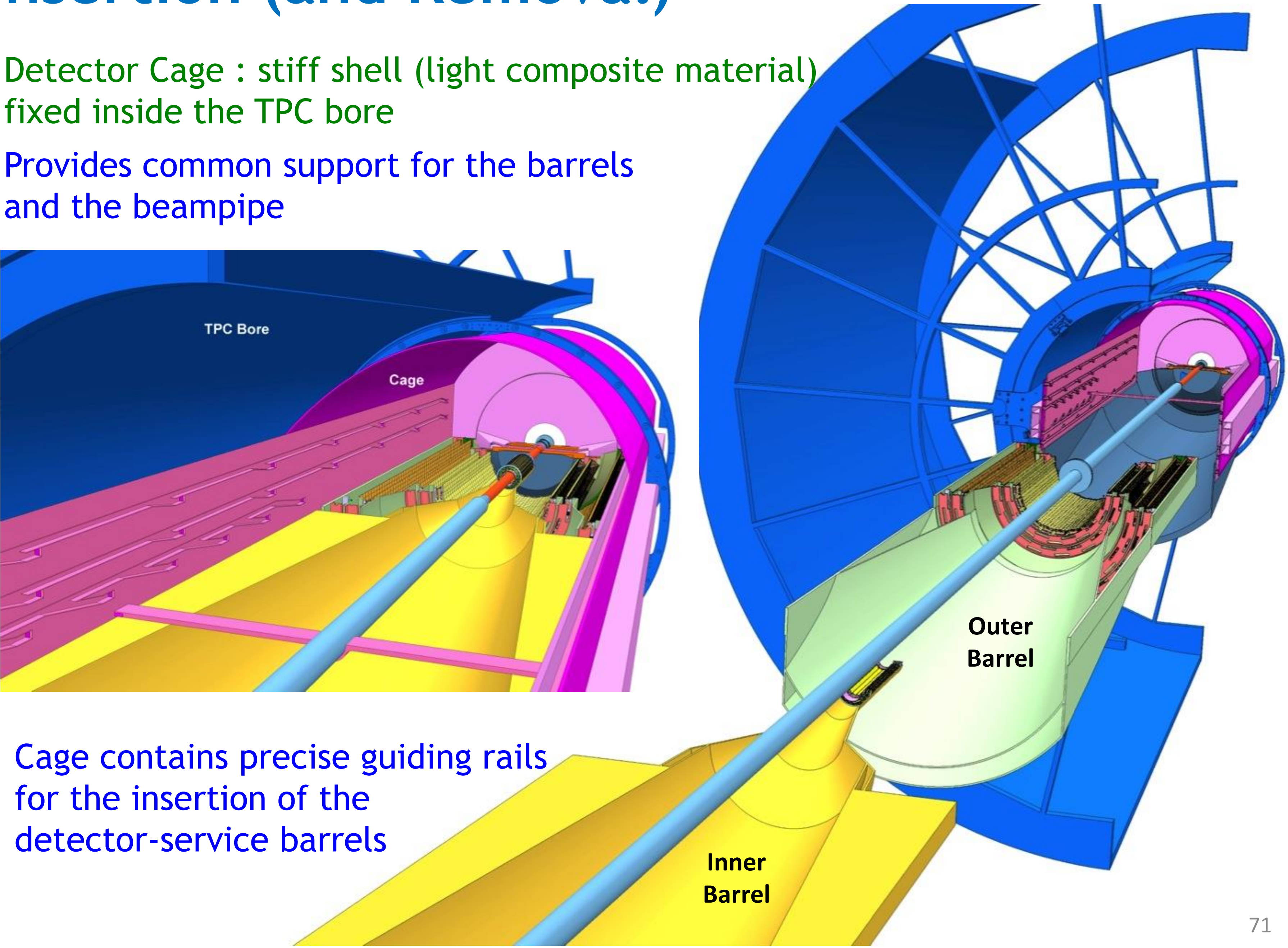
Integration in ALICE



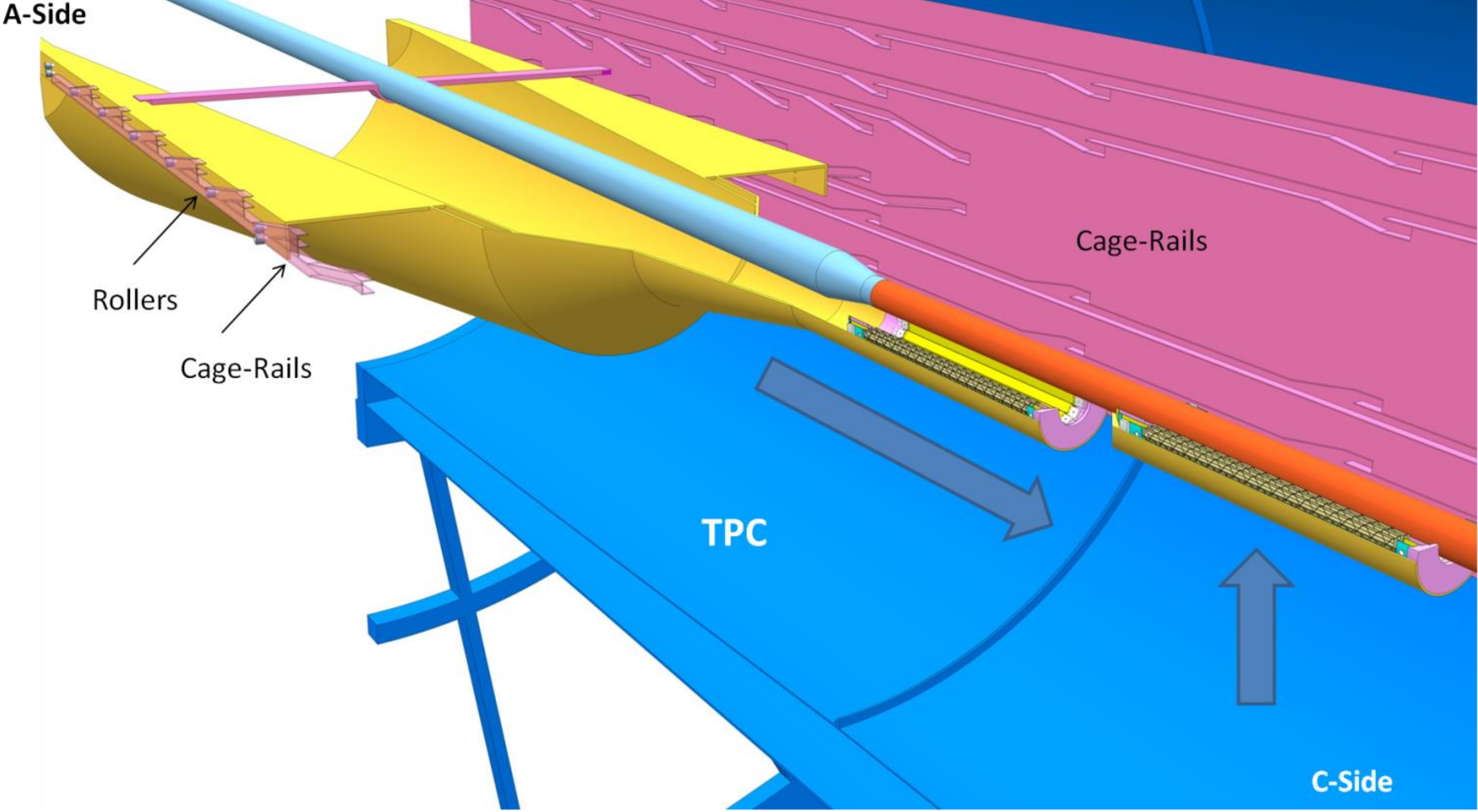
Insertion (and Removal)

Detector Cage : stiff shell (light composite material) fixed inside the TPC bore

Provides common support for the barrels and the beampipe

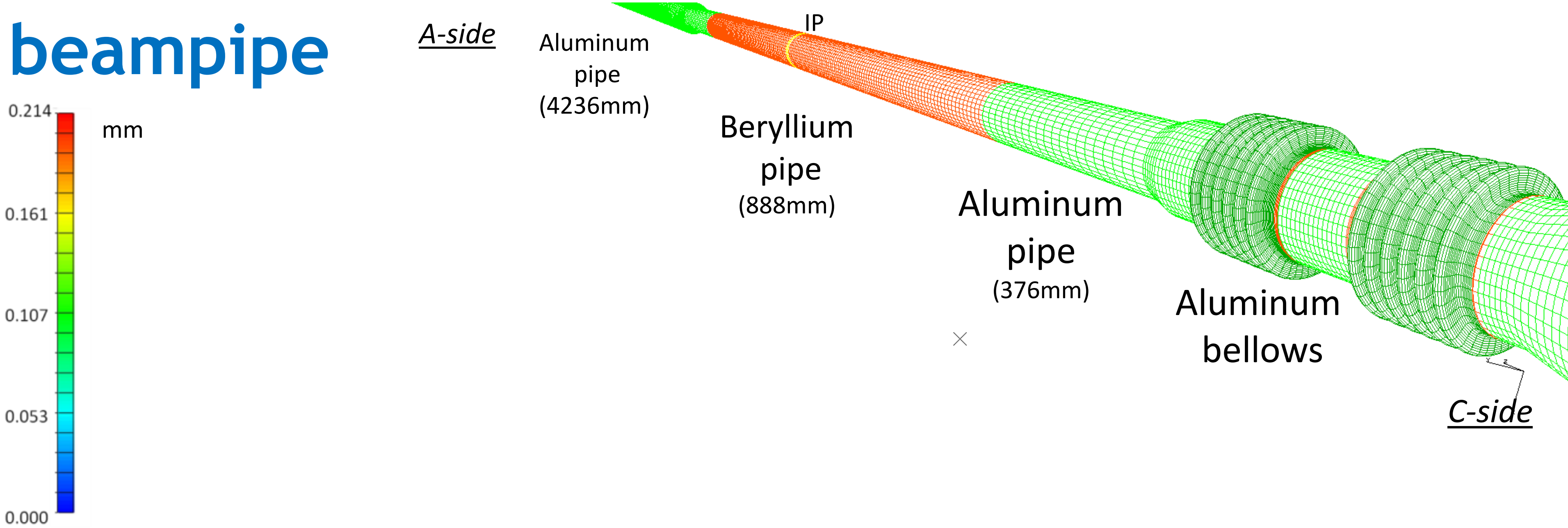


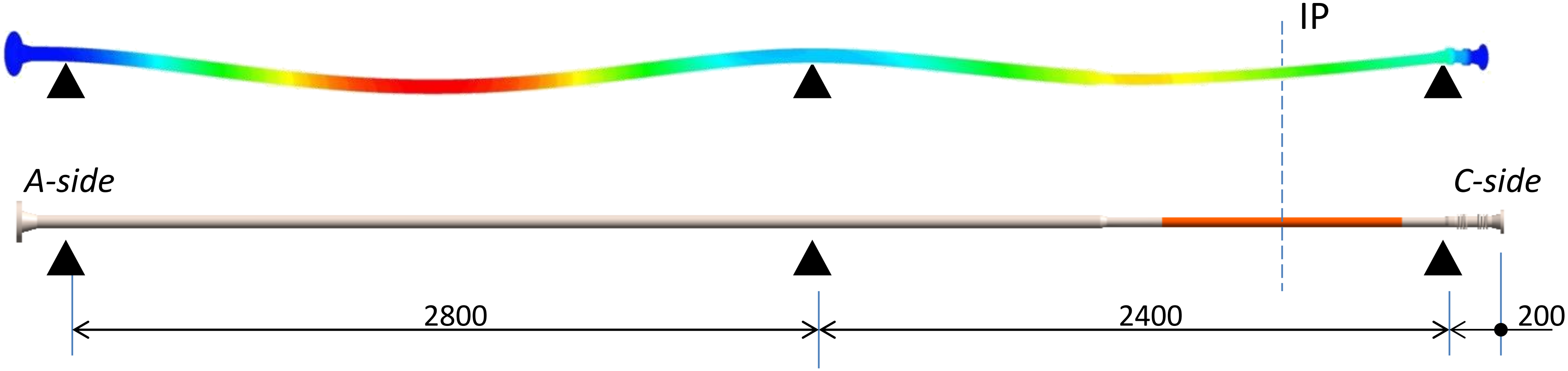
Cage contains precise guiding rails for the insertion of the detector-service barrels

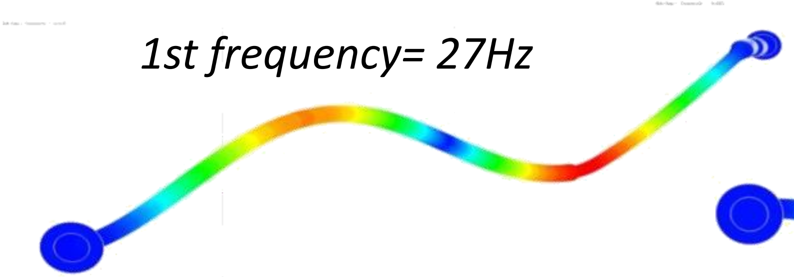


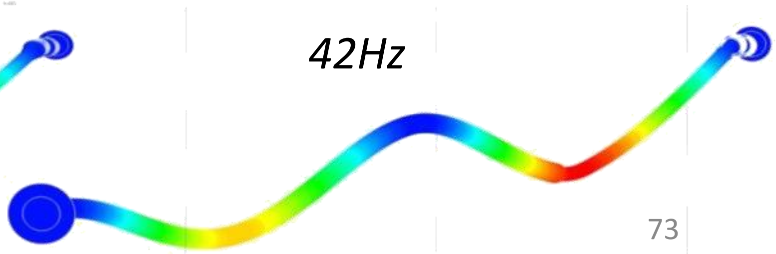
Insertion (and Removal)

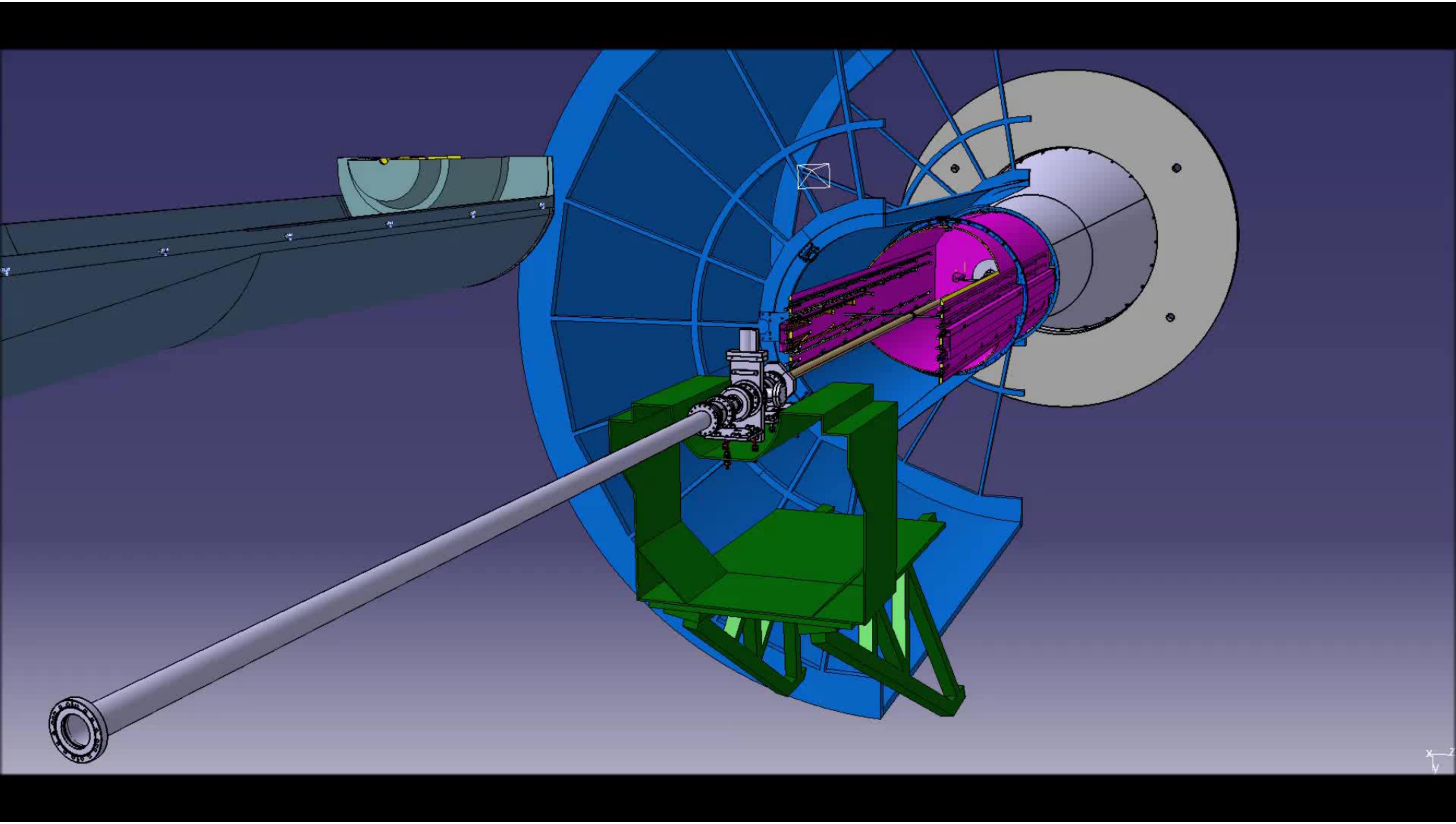
beampipe






1st frequency= 27Hz


42Hz



Insertion (and Removal)

Conclusion

A new design for carbon fibre light structures, with an embedded cooling system, has been developed for the stave of the new ALICE ITS :

-design of a stave for the three Inner Layers 290mm long, ~14 grams
-deisgn of a stave for the four Outer Layers 1500mm long, ~80 grams

Extensive protoyping activity has been curried out to drive the design:

- full scale prototype of the Inner Barrel
- full scale prototype of the Outer Stave

A qualification test campaign is being performed to characterize the stave mechanical, thermal and thermoelsatic behaviour

A new istallation scheme for the new ALICE ITS has been developed

backup

Upgrade goals

Improve impact parameter resolution by a factor of ~3

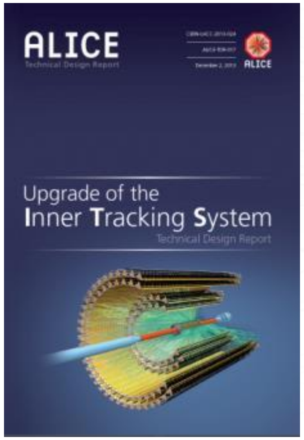
- Get closer to IP (position of first layer): 39mm □22mm
- Reduce material budget: X/X_0 /layer:~1.14% □ ~ 0.3%
- Reduce pixel size: 50μm x 425μm □ target 20μmx20μm

Fast readout

- readout of Pb-Pb interactions at > 50 kHz and pp interactions at > 2MHz

Fast insertion/removal for yearly maintenance

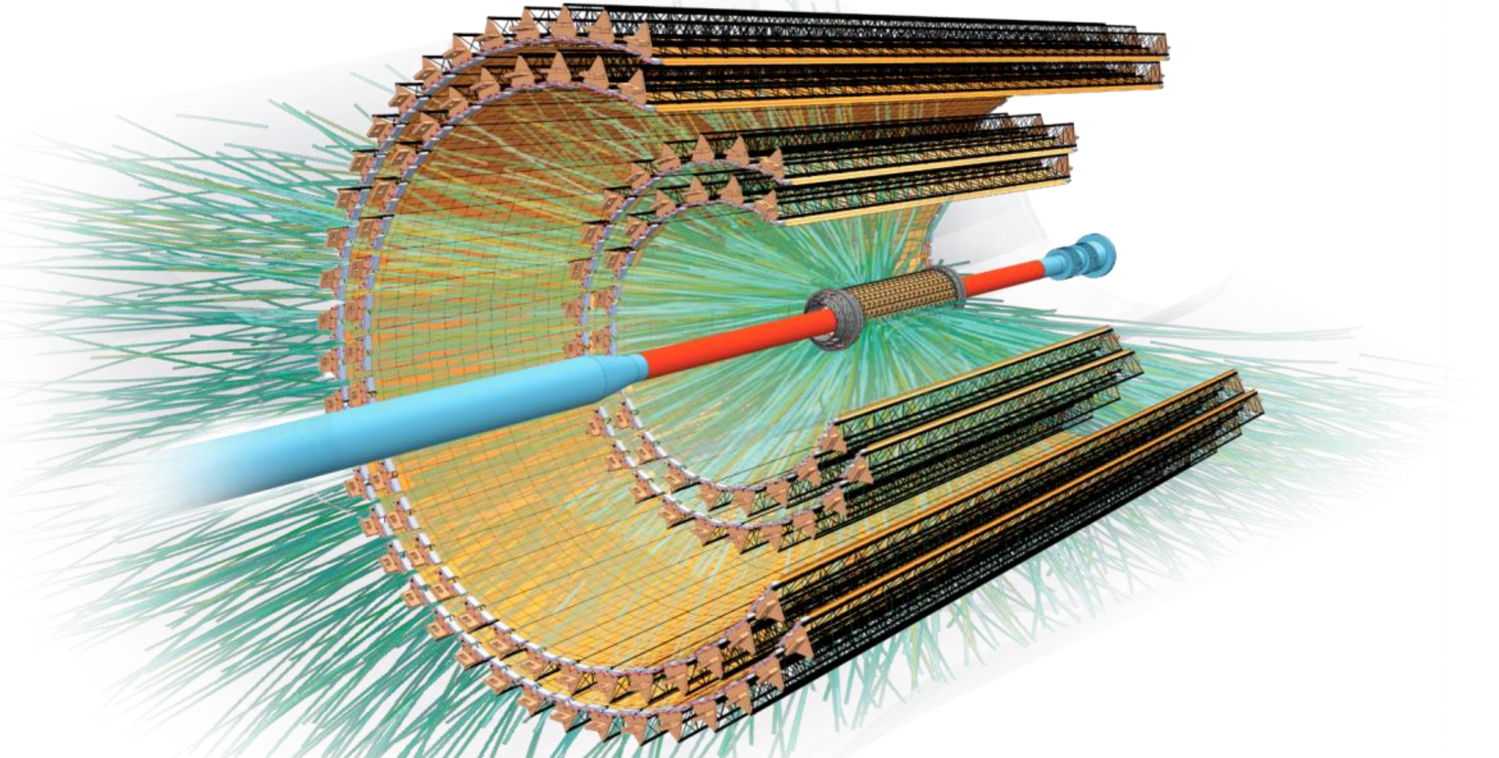
- possibility to replace non functioning detector modules during yearly shutdown



ALICE
Technical Design Report

Upgrade of the
Inner Tracking System
Technical Design Report

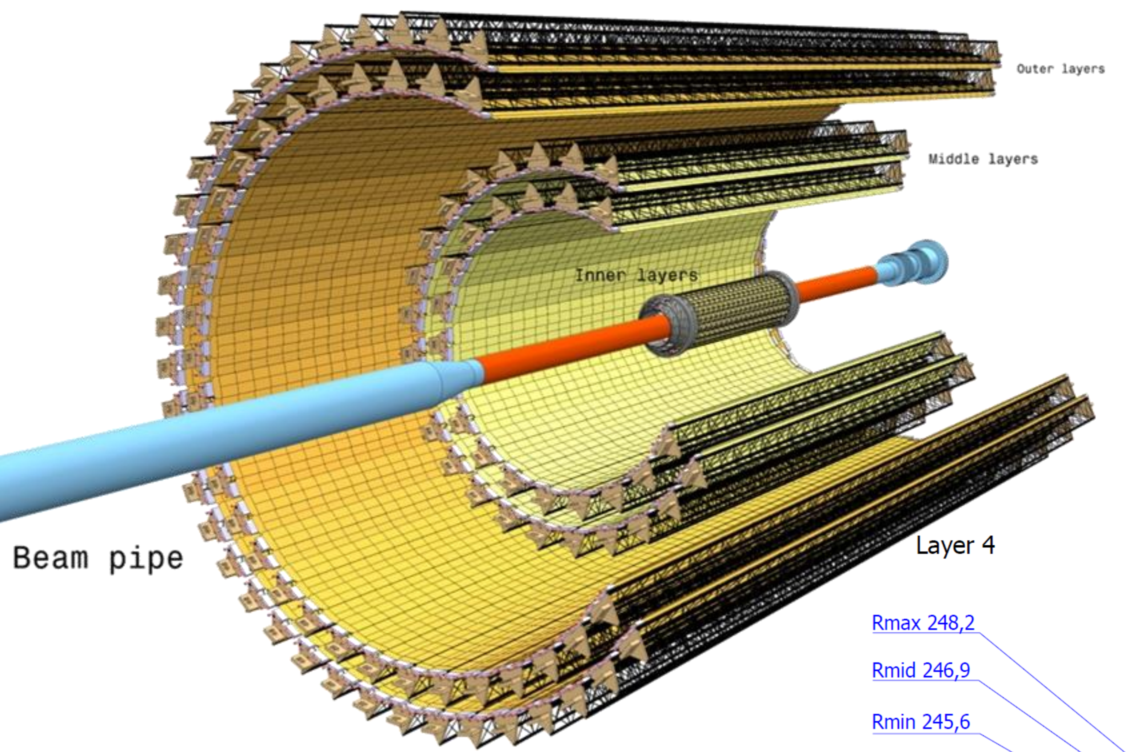
ITS TDR CERN-LHCC-2013-024

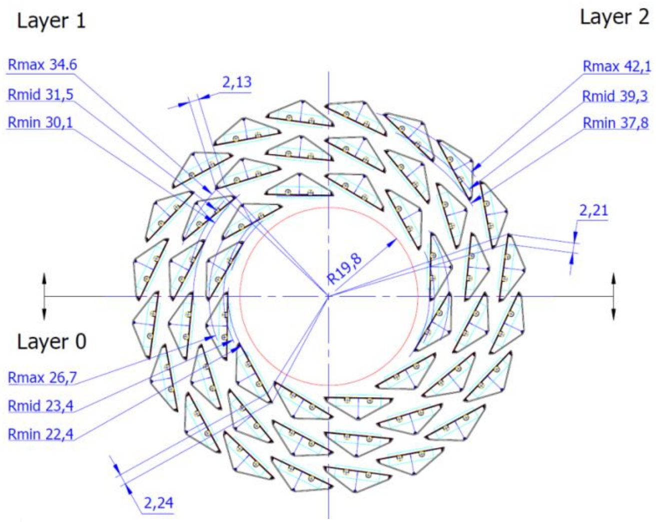


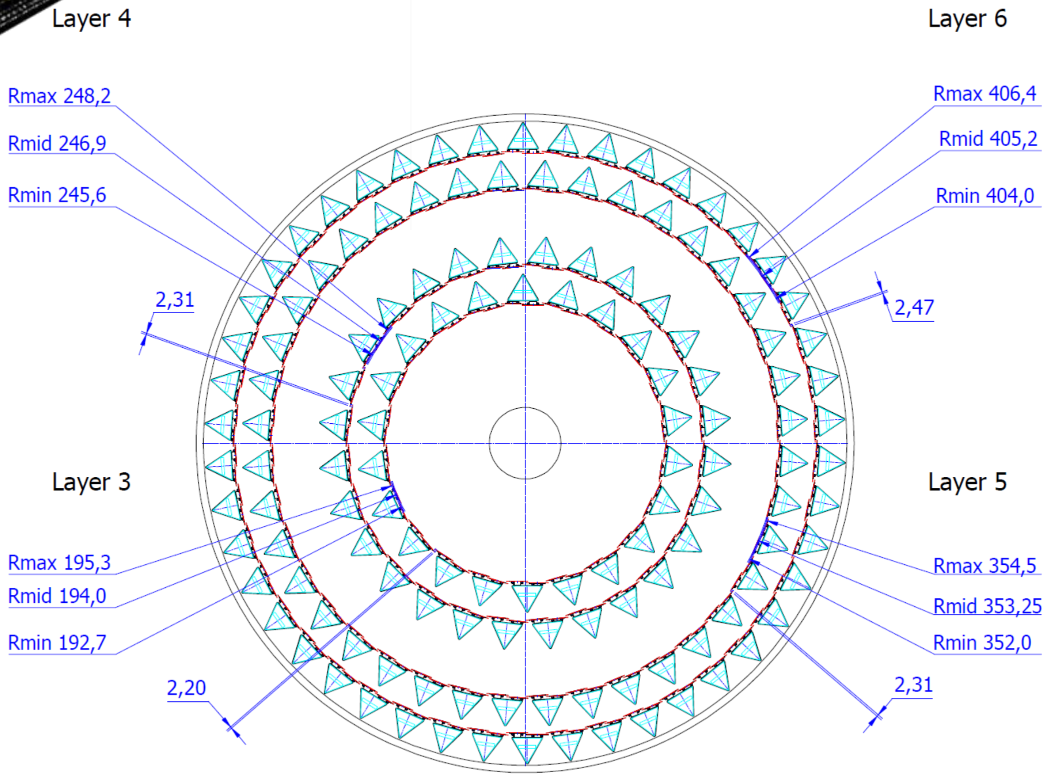
High standalone tracking efficiency and p_t resolution

- Increase granularity: 6 layers □ 7 layers , reduce pixel size
- Increase radial extension: 39-430 mm □ 22– 430(500) mm

layers layout







Inner Barrel (IB): 3 layers pixels

<Radius> (mm): 22,31,39

Length in z (mm): 270

Nr. of staves: 12, 16, 20

Nr. of chips/stave: 9

Nr. of chips/layer: 108, 144, 180

Material thickness: ~ 0.3% X_0

Outer Barrel (OB)

<radius> (mm): 194, 247, 353, 405

Length (mm): 843 (ML), 1475 (OL)

Nr. staves: 22, 28, 40, 46

Nr. modules/stave: 4 (ML), 7 (OL)

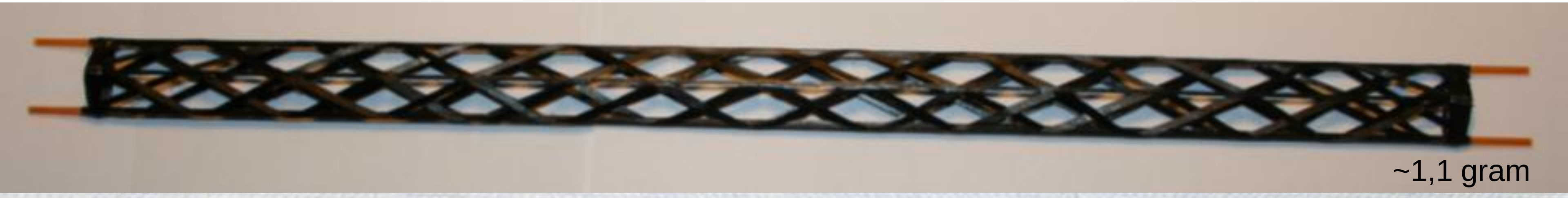
Nr. chips/module: 14

Material thickness: ~ 0.8% X_0

Production Process: Filament winding

Alternative stave design

K13D-2U 2K **K= 800 W/mK**



~1,1 gram

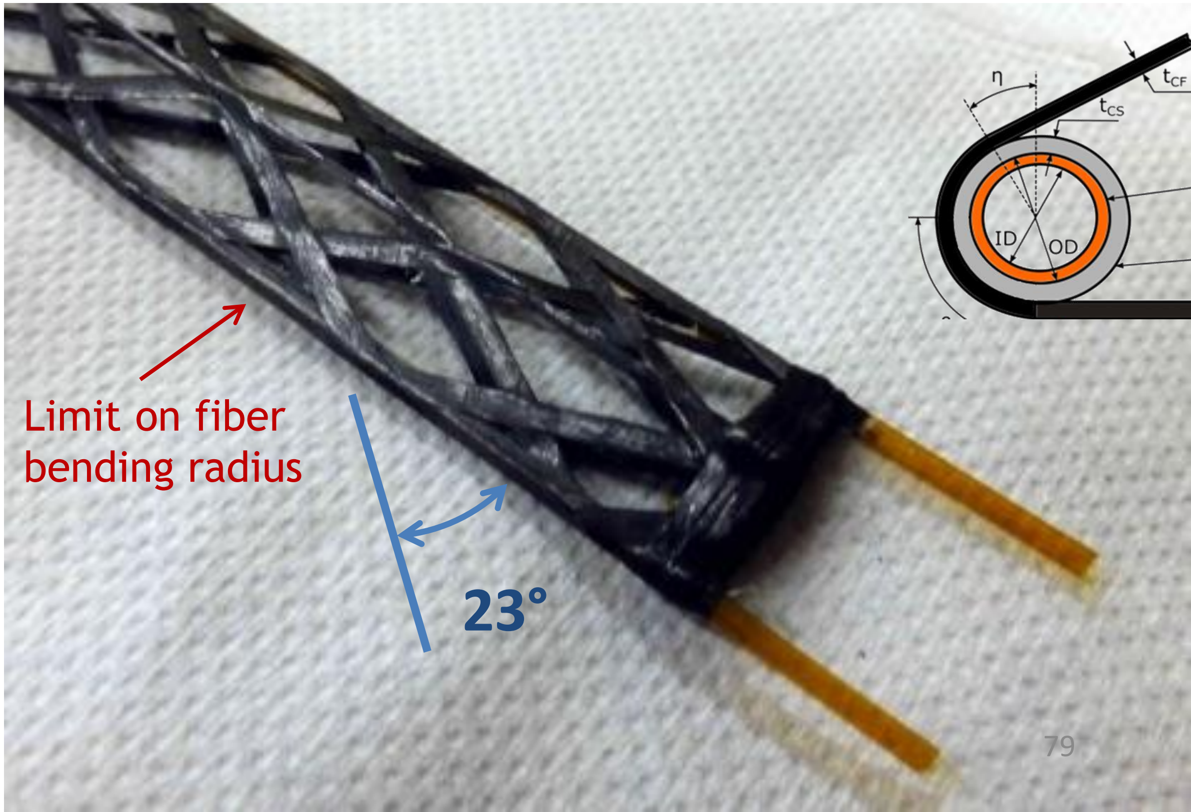
~1,4 gram

Winding angle <23° to avoid fiber break during winding due to fiber High Modulus

E=935 Gpa

Filament radius 11 μm

Carbon Unidirectional Prepreg



Limit on fiber bending radius

23°