Mechanical behavior of MQXF cable stacks at room temperature

C. Fichera, G. Vallone, P. Ferracin, M. Guinchard, Ó. Sacristán



Outline

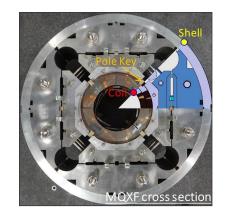
- MQXF and Nb₃Sn cable
- Test campaign planning
- Cable stack production
- Experimental results
- Conclusion



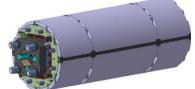
Introduction

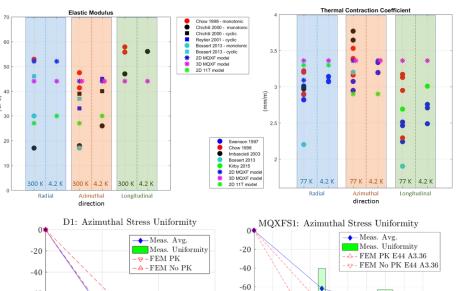
- The coil behavior is a crucial information for the structural assessment of magnets and prediction of conductor performance:
 - Mechanical properties at room and cryogenic temperature
 - Thermal properties from room temperature down to cryogenic
- Knowledge of coil properties shows uncertainty:
 - Different testing configurations (constrains, measurement technique)
 - Different cable configurations (epoxy, fiberglass, Mica, etc.)
 - Large scattering in material properties (thermal/mechanical)
- In FE models bad numerical-experimental comparison with impregnated MQXF coils.

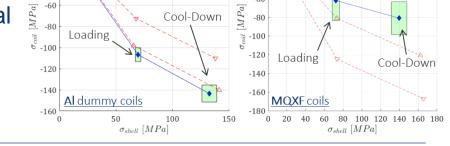
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Test campaign planning

- Where the mismatch between the experimental and the numerical results with real coils comes from?
 - Tolerances (as for dummy coils)
 - Measurement technique (as for dummy coils)
 - Coil properties

How to reproduce the coil response in FE model?	Experimental Test	Sample	Temperature	Loading Direction	Measurements	
 Macroscale approach 				Azimuthal	$E_{yy}, \varepsilon_{yy}, v_{yx}, v_{yz}$	
	Free Compression	PIT 10-stack Reacted + Impregnated	300 K	Radial	$E_{xx}, \mathbf{\epsilon}_{xx}, \mathbf{v}_{xy}, \mathbf{v}_{xz}$	
(Solid block)				Longitudinal	$E_{zz}, \epsilon_{zz}, \mathit{v}_{zx}, \mathit{v}_{zy}$	
			77 K	Azimuthal	$E_{yy}, \boldsymbol{\epsilon}_{yy}, \boldsymbol{v}_{yx}, \boldsymbol{v}_{yz}$	
 Sub-modelling approach 				Radial	$E_{xx}, \mathbf{\epsilon}_{xx}, \mathbf{v}_{xy}, \mathbf{v}_{xz}$	
				Longitudinal	$E_{zz}, \epsilon_{zz}, \mathit{v}_{zx}, \mathit{v}_{zy}$	
		RRP 10-stack Reacted + Impregnated	300 K	Azimuthal	$E_{yy}, \varepsilon_{yy}, v_{yx}, v_{yz}$	
				Radial	$E_{xx}, \boldsymbol{\varepsilon}_{xx}, \boldsymbol{v}_{xy}, \boldsymbol{v}_{xz}$	
 Microscale approach <u>Courtesy by M. Daly</u> 				Longitudinal	$E_{zz}, \varepsilon_{zz}, v_{zx}, v_{zy}$	
			77 K	Azimuthal	$E_{yy}, \boldsymbol{\varepsilon}_{yy}, \boldsymbol{v}_{yx}, \boldsymbol{v}_{yz}$	
				Radial	$E_{xx}, \mathbf{\epsilon}_{xx}, \mathbf{v}_{xy}, \mathbf{v}_{xz}$	
				Longitudinal	$E_{zz}, \varepsilon_{zz}, v_{zx}, v_{zy}$	



Cable stack

- The study of the mechanical properties must be carried out on representative samples of the coil.
 - Dedicated moulds for reaction and impregnation (1.2% width and 4.5% thickness growth considered);
 - Fiberglass: TEX 636, ceramic binder: CTD-1202, epoxy: CTD-101K;
 - 18.7×18.85×150 mm long cable stack (RRP coil 106, PIT coil 203). н.

Parameter	Unit	MQXF
Strand diameter	mm	0.85
Fabrication process		RRP, PIT
Number of filaments		132, 192
Nominal sub-element diameter	um	<50
RRR after full heat treatment		>150
Cu/non-Cu		1.2
Minimum Ic (15 T, 4.222 K)*	А	361
Number of strands		40
Cabling degradation	%	<5
Cable bare width	mm	18.15
Cable bare mid-thickness	mm	1.525
Keystone angle	Deg.	0.55

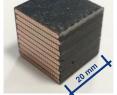


Reaction Mould



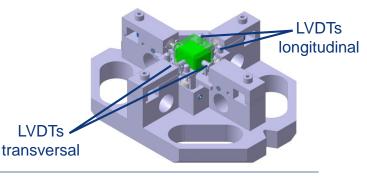
Impregnation Mould

Cutting tool



10-Cables stack

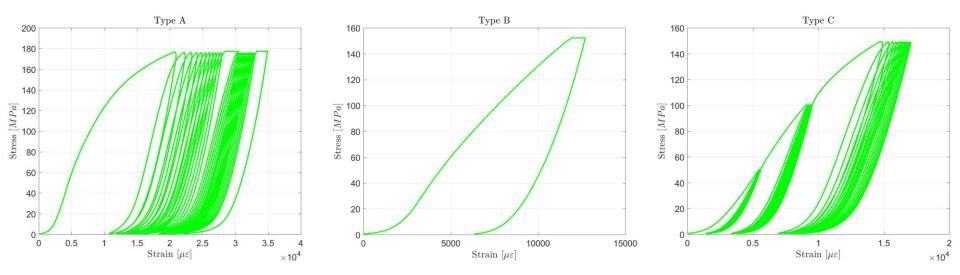
- Dedicated and validated test bench equipped with 8 LVDTs to measure:
 - Stress-strain relationship in all directions;
 - Transverse-longitudinal strain relationship.





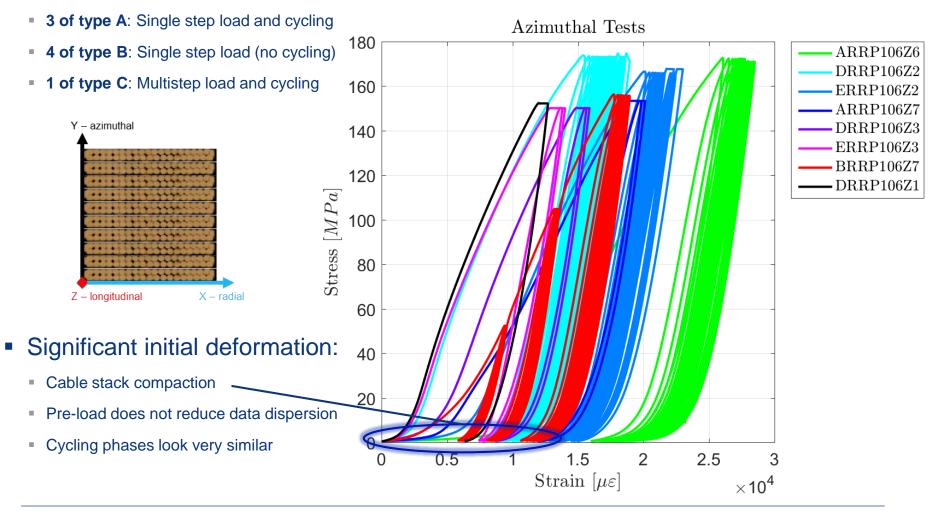
Experimental tests

- Different test typologies to study the cable stack behavior during <u>loading</u>, <u>unloading</u> and <u>cycling</u> phases.
 - Type A: Single step load and cycling
 - Type B: Single step load (no cycling) + load holding
 - Type C: Multistep load and cycling





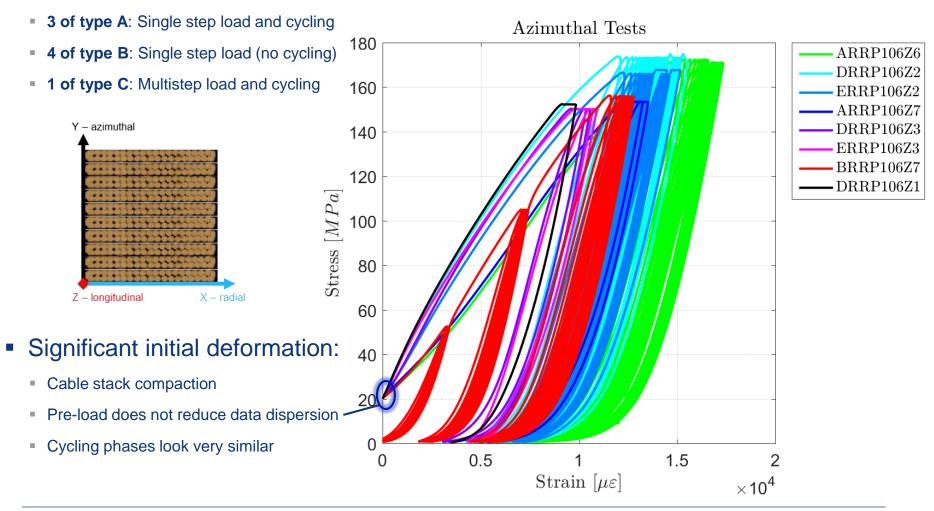
8 tests in azimuthal direction have been performed.





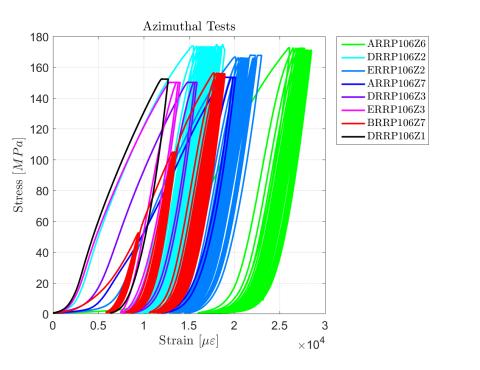
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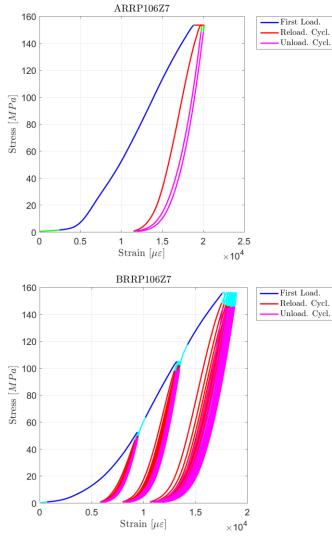
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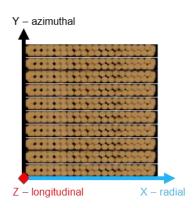


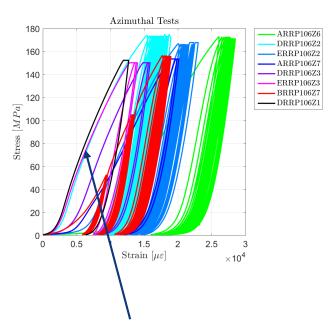
- Splitting the curves in three phases simplifies the data analysis:
 - First loading phase
 - Unloading cyclic phase
 - Reloading cyclic phase









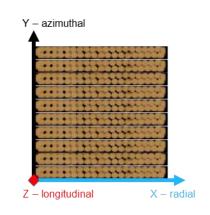


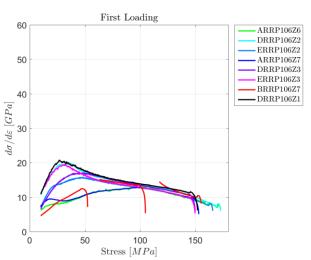
By definition, the material stiffness is the slope of the stress-strain curve:

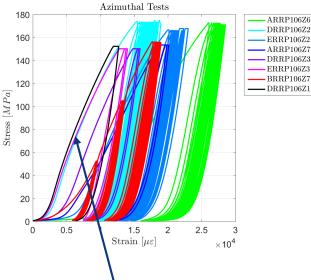
$$K = \frac{d\sigma}{d\varepsilon}$$

If *K* is constant, linear elastic assumption is valid and *K* is known as elastic modulus or Young's modulus (*E*).







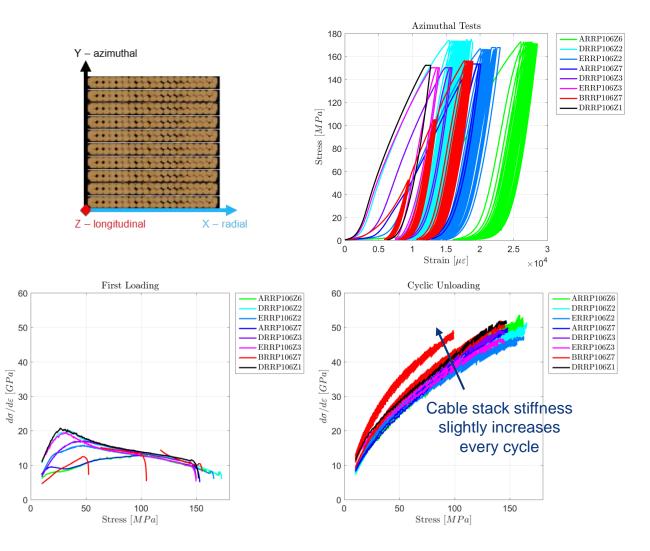


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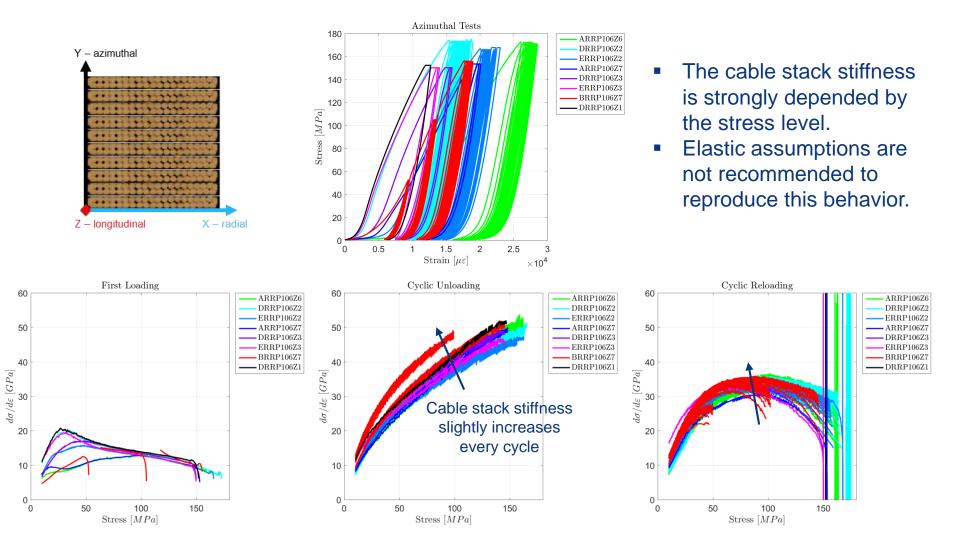
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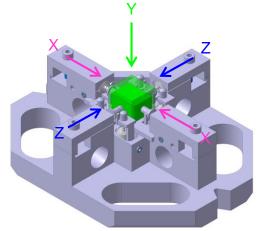


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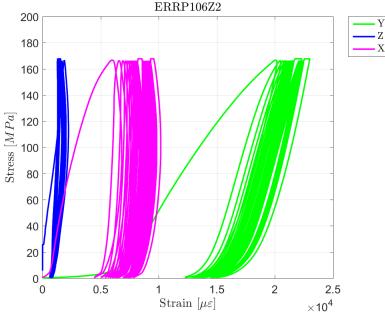
Z – longitudinal X – radial

Y - azimuthal

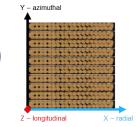
The relationship between the vertical and lateral deformations is commonly defined by:

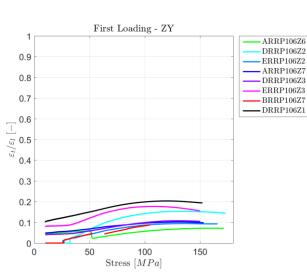
$$\nu_{XY} = -\frac{\varepsilon_X}{\varepsilon_Y}$$
$$\nu_{ZY} = -\frac{\varepsilon_Z}{\varepsilon_Y}$$

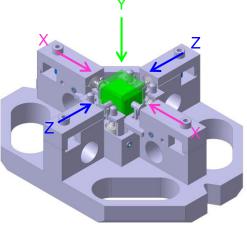
If v is constant, linear elastic assumption is valid and v is known as Poisson's ratio.







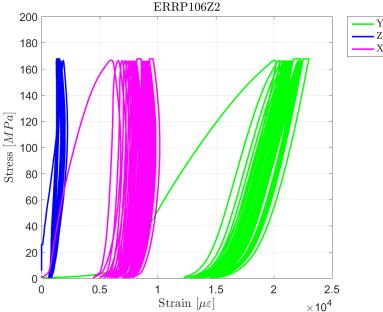




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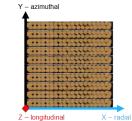




First Loading - ZY Cyclic Unloading - ZY Cyclic Reloading - ZY ARRP106Z6 ARRP106Z6 DRRP106Z2 DRRP106Z2 0.9 0.9 0.9 -ERRP106Z2 ERRP106Z2 - ARRP106Z7 ARRP106Z7 0.8 0.8 0.8 - DRRP106Z3 DRRP106Z3 - DRRP106Z3 - ERRP106Z3 ERRP106Z3 ERRP106Z3 0.7 0.7 0.7 BRRP106Z7 BRRP106Z7 BRRP106Z7 ____ DRRP106Z1 ____ DRRP106Z1 - DRRP106Z1 $\begin{bmatrix} 0.6\\ -\end{bmatrix} \frac{l_3}{l_3} \frac{0.5}{0.4}$ $\begin{bmatrix} 0.6\\ -\end{bmatrix} \frac{1}{2^{j_{3}}}$ $\begin{bmatrix} 0.6\\ -\end{bmatrix} \begin{bmatrix} l \\ s \end{bmatrix}$ 0.4 0.4 0.3 0.3 0.3 0.2 0.2 0.2 0.1 0.1 0.1 0 0 0 50 100 150 0 50 100 150 50 100 150 0 0 Stress [MPa]Stress [MPa]Stress [MPa]

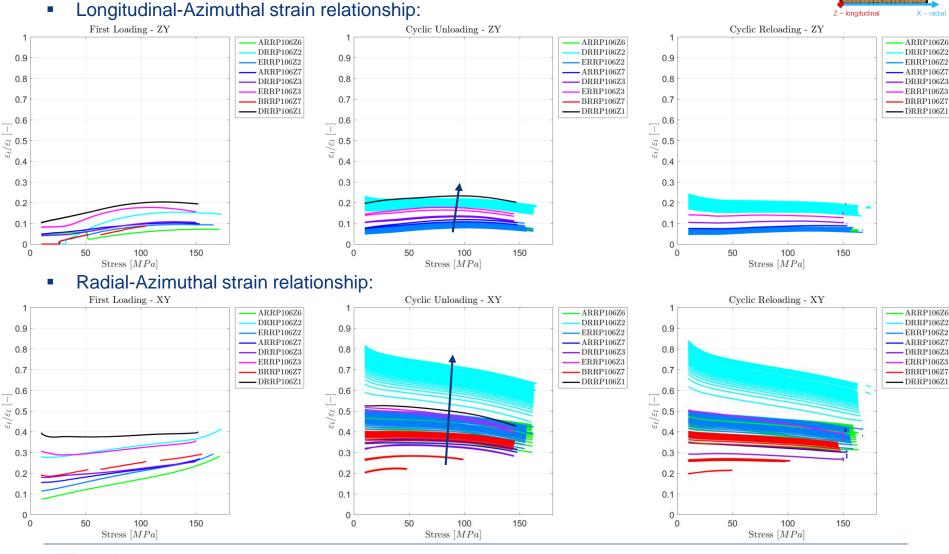
Longitudinal-Azimuthal strain relationship:





ARRP106Z6 DRRP106Z2 ERRP106Z2 ARRP106Z7



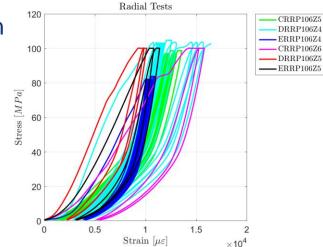


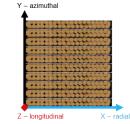
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ENGINEERING DEPARTMENT Workshop on Nb3Sn Rutherford cable characterization for accelerator magnets

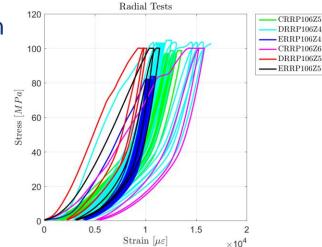
Y - azimuthal

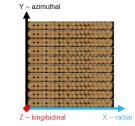
- 6 tests in radial direction have been performed.
 - 3 of type A:
 - Single step load and cycling
 - 3 of type B:
 - Single step load (no cycling)

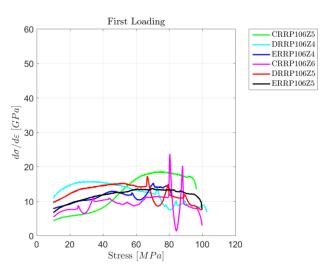




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Radial Tests

Z – longitudinal X – radial

Y - azimutha

3 of type A: 80 Stress [MPa]Single step load and cycling 60 3 of type B: 40 Single step load (no cycling) 20 1.5 0.5 2 Strain $[\mu \varepsilon]$ $imes 10^4$ First Loading Cyclic Unloading 60 60 CRRP106Z5 CRRP106Z5 DRRP106Z4 DRRP106Z4 ERRP106Z4 ERRP106Z4 CRRP106Z6 CRRP106Z6 50 50 DRRP106Z5 DRRP106Z5 -ERRP106Z5 -ERRP106Z5 40 40 $d\sigma/d\varepsilon \ [GPa]$ $d\sigma/d\varepsilon \ [GPa]$ 30 30 20 20 Stiffness slightly 10 ncreases every cycle 10 0 0 0 20 40 60 80 100 120 20 40 60 80 100 120 0 Stress [MPa]Stress [MPa]

120

100

6 tests in radial direction

have been performed.



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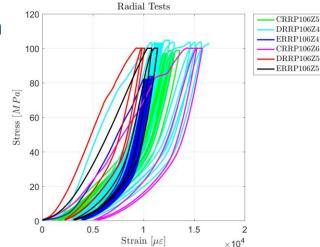
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CRRP106Z5

DRRP106Z4 ERRP106Z4

- CRRP106Z6 - DRRP106Z5 - ERRP106Z5

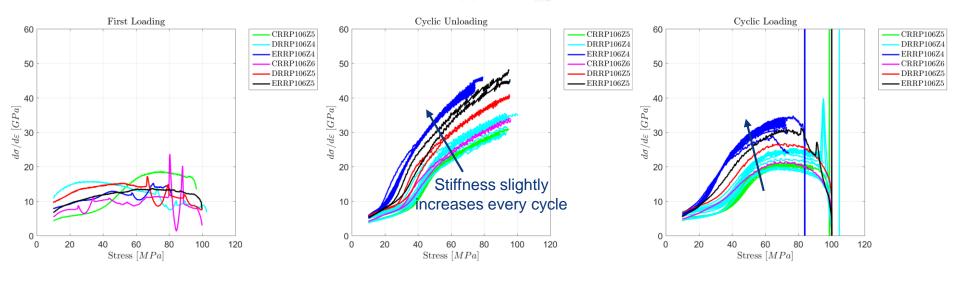
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Z – longitudinal X – radia

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- The cable stack stiffness is strongly depended by the stress level.
- Elastic assumptions are not recommended to reproduce this behavior.
- Cable stack delamination at low stresses.

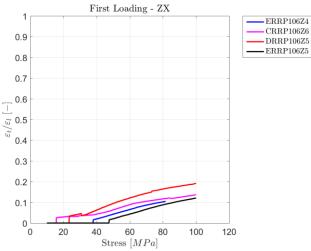


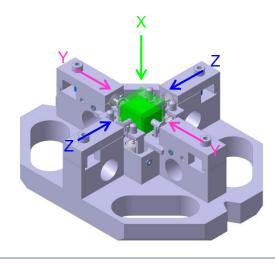


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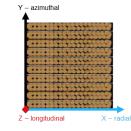
Longitudinal-Radial strain relationship:



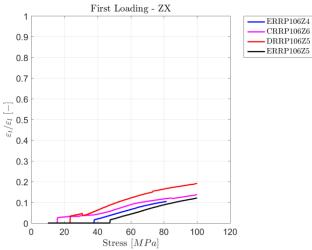


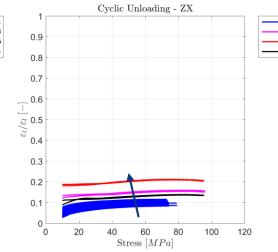


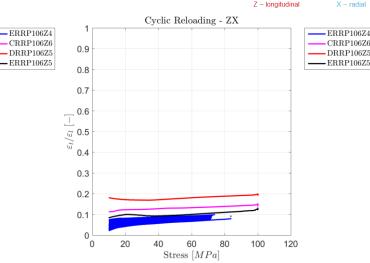


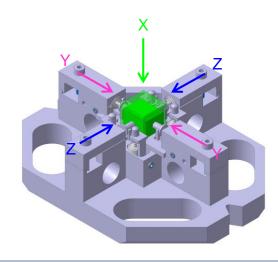


Longitudinal-Radial strain relationship:









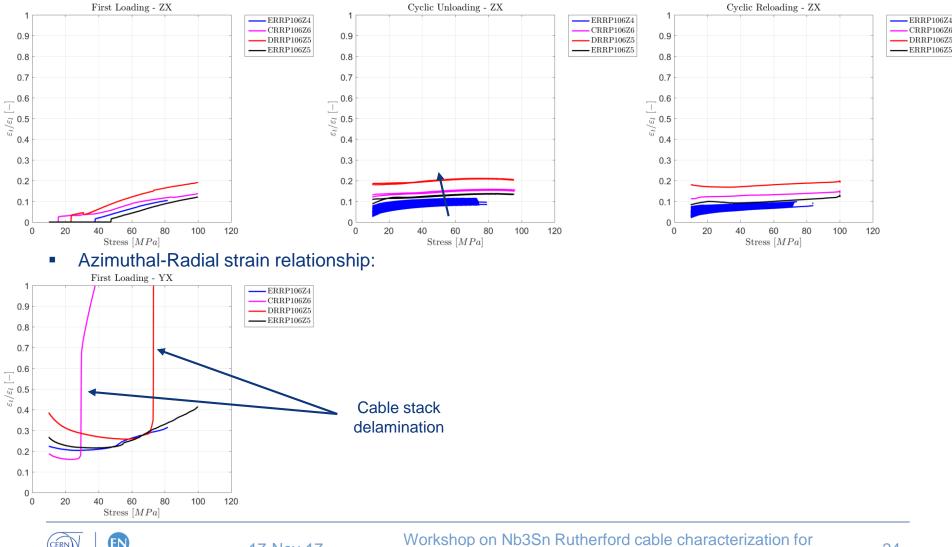


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Longitudinal-Radial strain relationship:

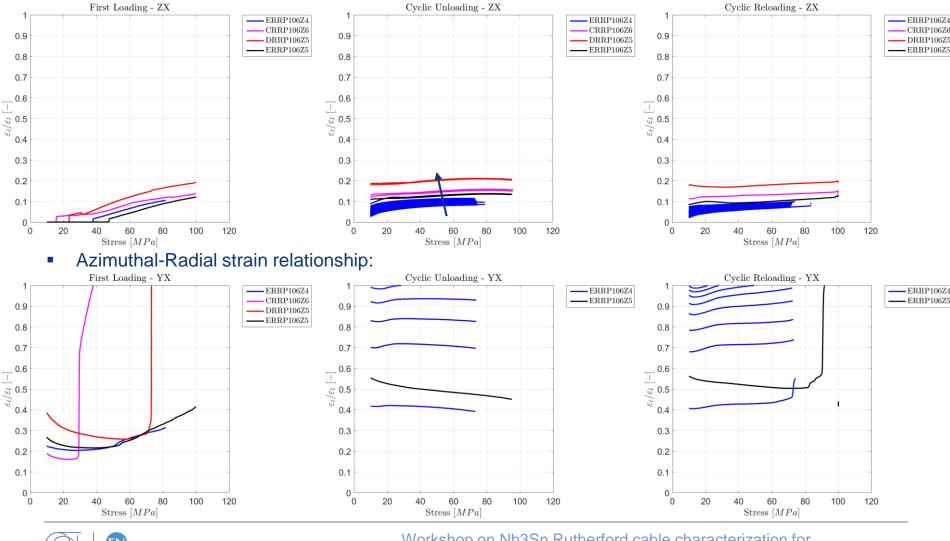


ENGINEERING DEPARTMENT Y – azimuthal

Z – longitudinal

X - radial

Longitudinal-Radial strain relationship:





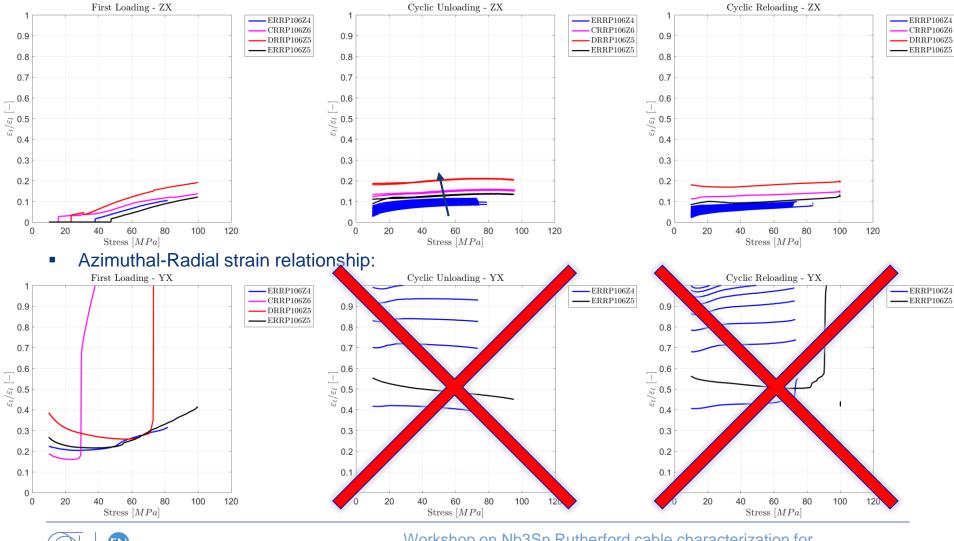
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Z – longitudinal

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Longitudinal-Radial strain relationship:





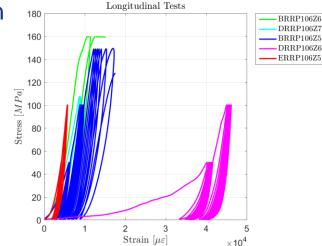
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Z – longitudinal

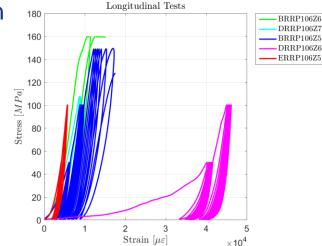
X - radial

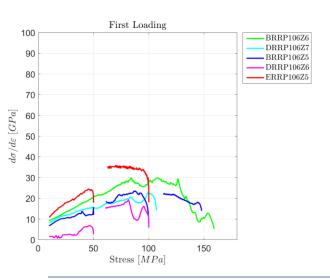
- 5 tests in radial direction have been performed.
 - 2 of type B:
 - Single step load (no cycling)
 - 3 of type C:
 - Multistep load and cycling





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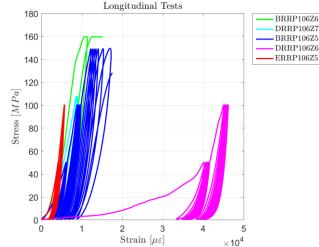


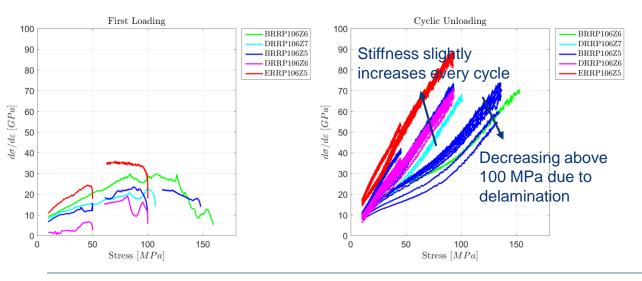




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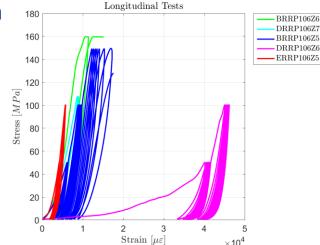
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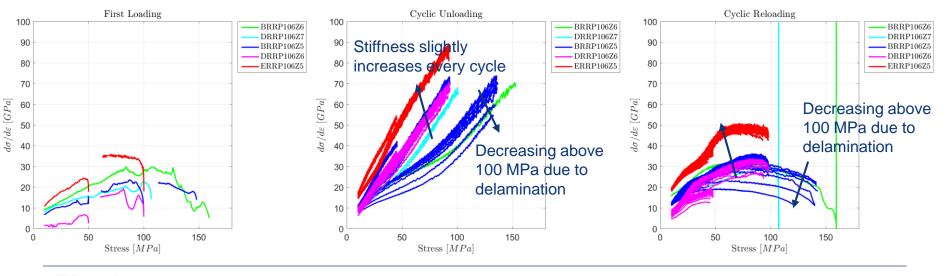
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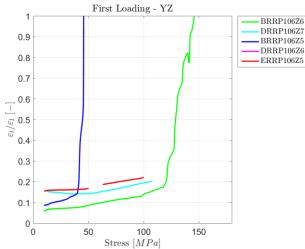
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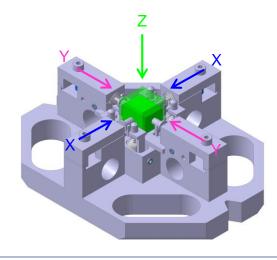


- Y azimuthal
- The cable stack stiffness is strongly depended by the stress level.
- Elastic assumptions are not recommended to reproduce this behavior.
- Cable stack delamination at low stresses.
- Cable stack length could affect the results.



• Azimuthal-Longitudinal strain relationship:







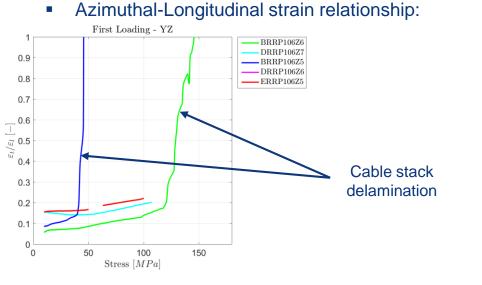


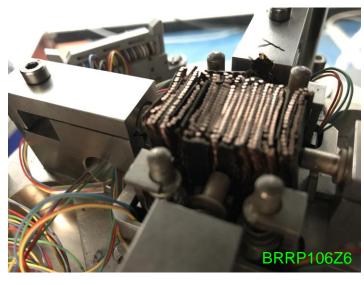
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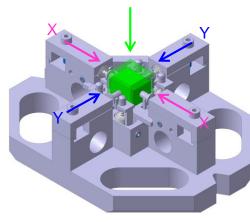
Y – azimuthal

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Z – longitudinal	X – radial

V - azimutha



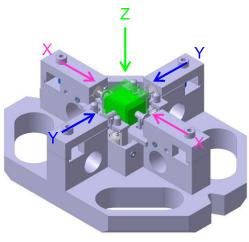




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Azimuthal-Longitudinal strain relationship: Z – longitudinal X - radial First Loading - YZ Cyclic Unloading - YZ Cyclic Reloading - YZ BRRP106Z6 DRRP106Z7 DRRP106Z7 DRRP106Z7 ERRP106Z5 ERRP106Z5 0.9 0.9 0.9 BRRP106Z5 DRRP106Z6 0.8 0.8 0.8 - ERRP106Z5 0.7 0.7 0.7 $\begin{bmatrix} 0.6\\ -\end{bmatrix}^{l_{\mathcal{J}}/l_{\mathcal{J}}} 0.5 \\ 0.4 \end{bmatrix}$ $\begin{bmatrix} 0.6\\ -\end{bmatrix} \frac{1}{2^{1_3}}$ $\begin{bmatrix} 0.6 \\ - \end{bmatrix} \begin{bmatrix} l & 0.5 \\ l & 0.5 \end{bmatrix}$ 0.4 0.3 0.3 0.3 0.2 0.2 0.2 0.1 0.1 0.1 0 0 0 50 100 150 0 50 100 150 0 50 100 150 0 Stress [MPa]Stress [MPa]Stress [MPa]

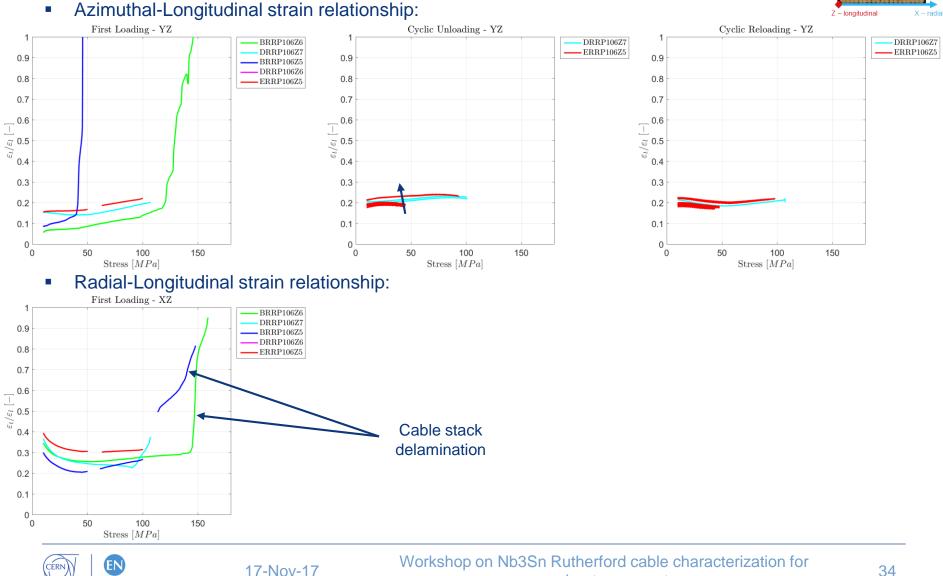




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Y – azimuthal

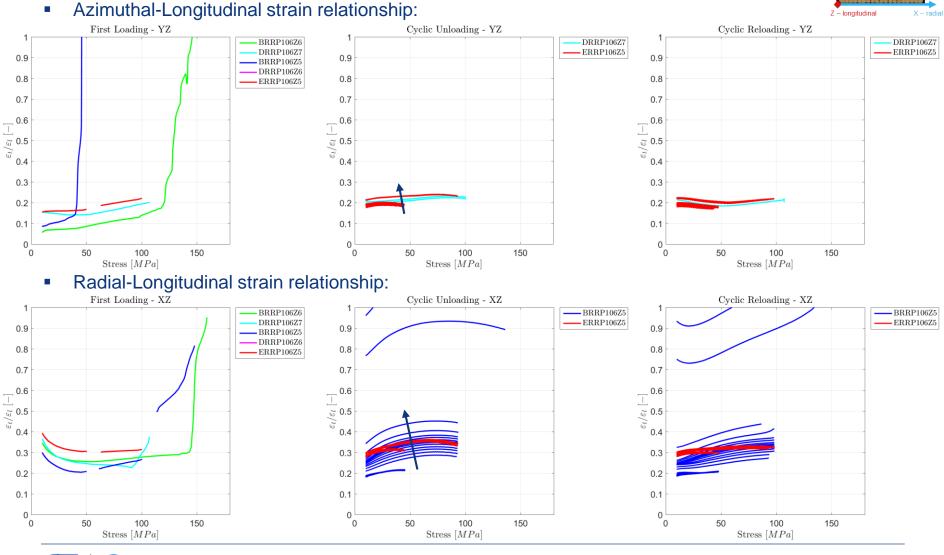


accelerator magnets

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Y – azimuthal



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Y - azimuthal

Conclusion

- An extended test campaign has been carried out at CERN to study the overall behavior of impregnated MQXF cable stacks.
- Stress-strain relationships have been analyzed in free compression tests.
- In all directions (X,Y,Z) the cable stack shows strongly not linear elastic behavior.
- The experimental results give information about the cable stack behavior and different inputs how to reproduce it.

Next

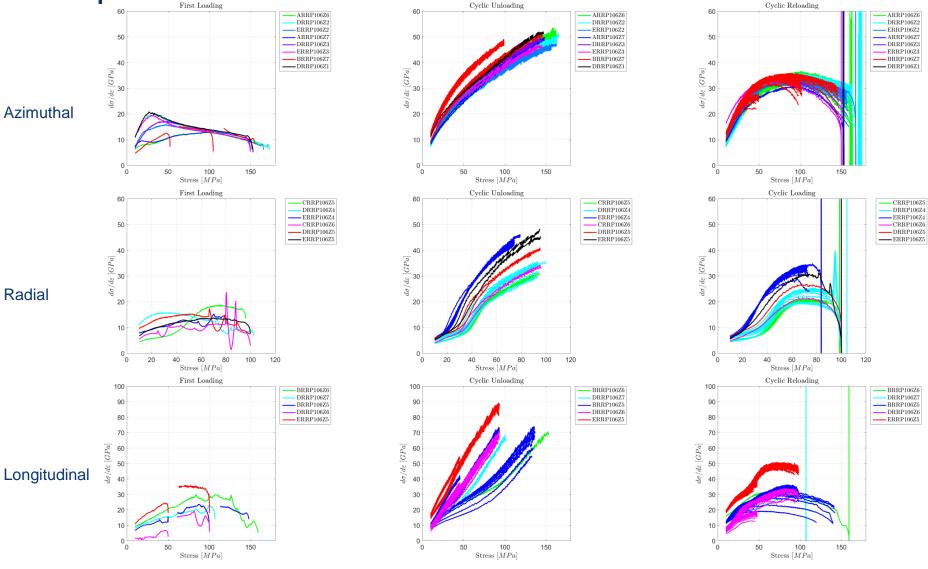
- What about PIT cable?
- What about cryogenic temperatures?
- What about thermal properties?





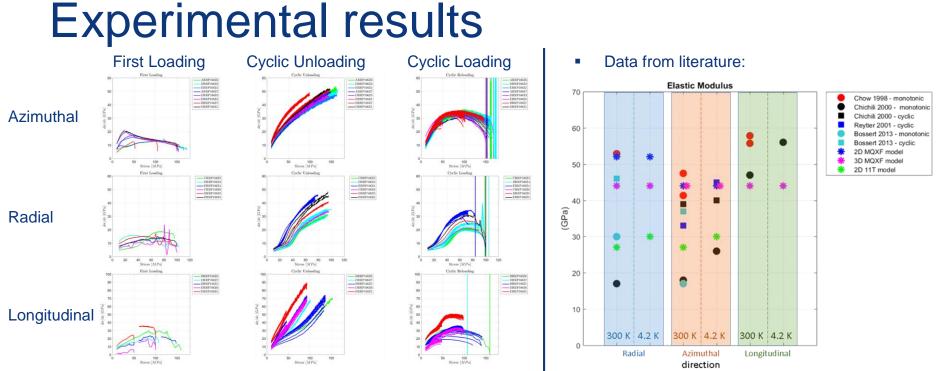
Thank you

Experimental results





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• Summary of the test campaign:

	Azimuthal		Radial			Longitudinal			
	dσ/dε	ε _Ζ /ε _Υ	εχ/εγ	dσ/dε	ε _Ζ /ε _×	$\varepsilon_{Y}/\varepsilon_{X}$	dσ/dε	ε _γ /ε _z	$\varepsilon_X/\varepsilon_Z$
	(GPa)			(GPa)			(GPa)		
First Loading	5÷20	0.05÷0.2	0.1÷0.4	5÷25	0.05÷0.15	~0.2	10÷25	~0.16	0.2÷0.3
Cyclic Unloading	10÷50	0.05÷0.2	0.2÷0.5	5÷40	0.1÷0.2	N/A	10÷70	~0.2	0.2÷0.3
Cyclic Loading	10÷35	0.05÷0.2	0.2÷0.5	5÷30	0.05÷0.15	N/A	10÷35	~0.2	0.2÷0.3



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