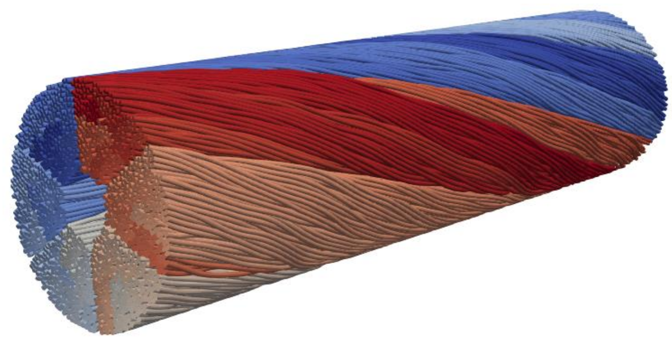
CHATS on Applied Superconductivity 2021

DE LA RECHERCHE À L'INDUSTRIE

Electromechanical modelling of fusion cables

Presenter : Rebecca Riccioli
20/09/2021



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Frédéric Lebon (AMU-LMA)

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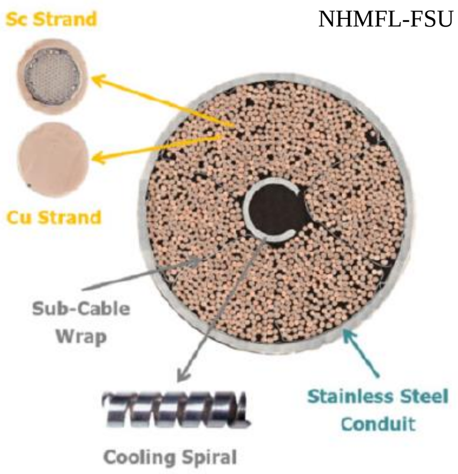
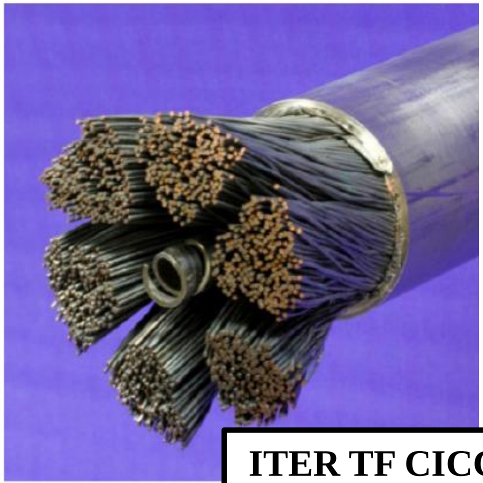
Fusion cables

Superconducting conductors for tokamaks: Cable-In-Conduit Conductors (CICCs)

NHMFL-FSU

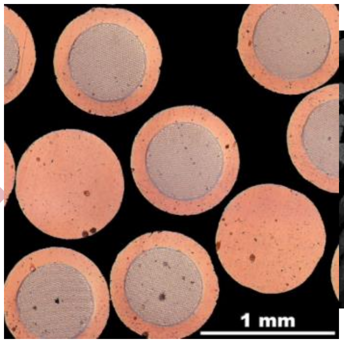




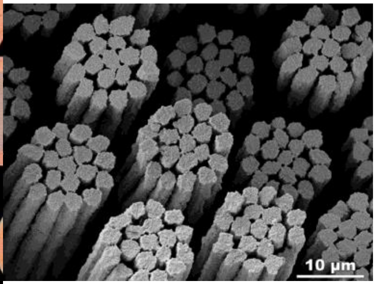
ITER TF CICCs

Taken from: A. Devred *et al* 2014 *Supercond. Sci. Technol.* 27 044001

Composite Nb_3Sn wire



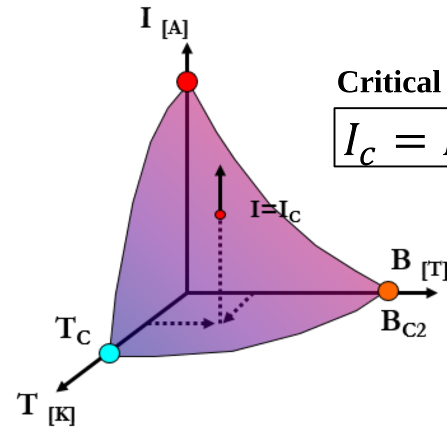
Micro-filaments



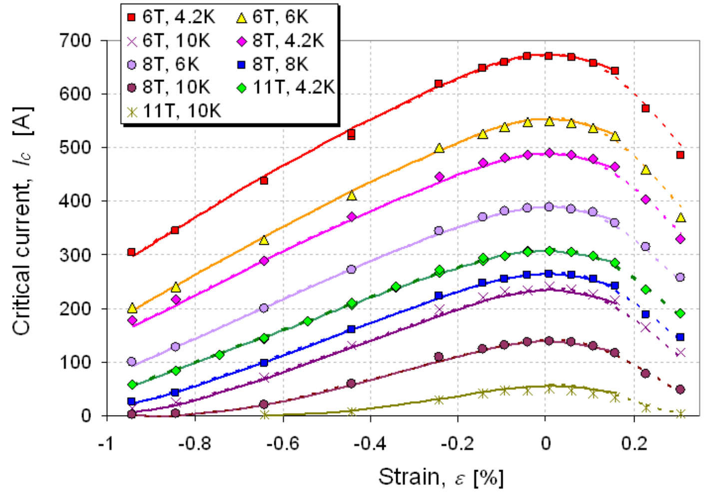
Images of P. Lee & C. Sanabria from NHMFL-FSU

Critical current

$$I_c = I_c(B, T)$$



For Nb_3Sn wires $I_c = I_c(B, T, \varepsilon)$

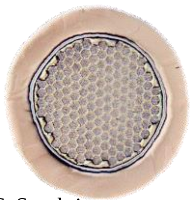


Taken from: Y. Ilyin *et al* 2007 *Supercond. Sci. Technol.* 20 186

Electrical performance

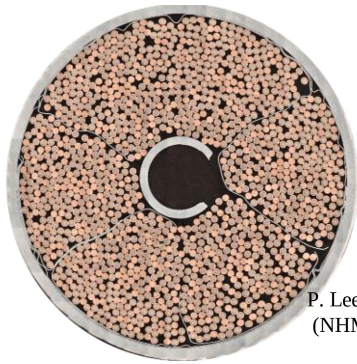
Scaling up from strand to cable ?

Nb$_3$Sn wire

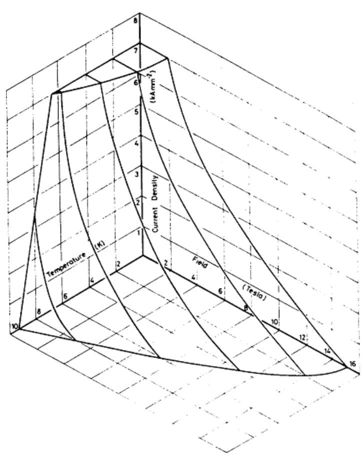


P. Lee & C. Sanabria (NHMFL-FSU)

CIC Conductor



P. Lee & C. Sanabria (NHMFL-FSU)

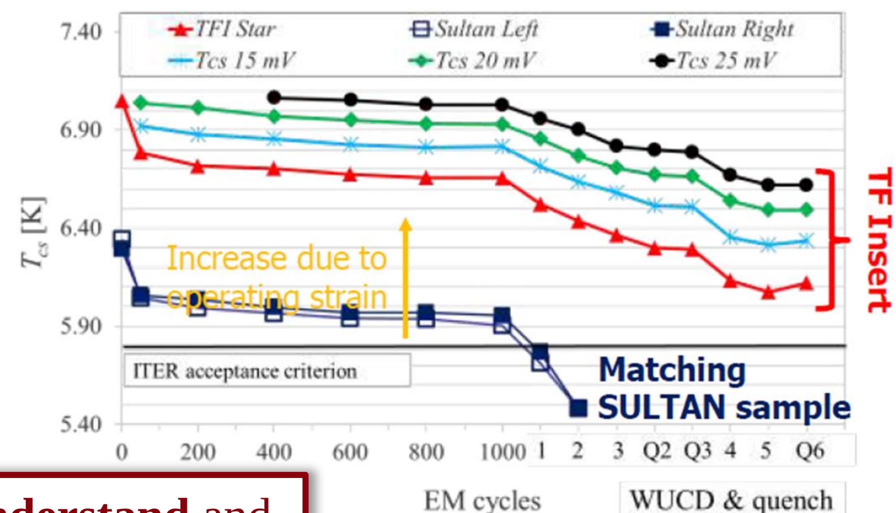


Taken from: M. N. Wilson, *Oxford Science Publications*, 1993

Performance degradation ?

ITER TF CICCs cyclic mechanical loadings due to:

- **Cool-down** after manufacturing (923.15 K to 4.5 K)
- **Warm-up-cool-down** during operation **[~ 50-100 cycles]**
- **Electromagnetic cycles [~ 1000]**
  → Lorentz force (68 kA, 11.78 T) **~ 80 t/m**

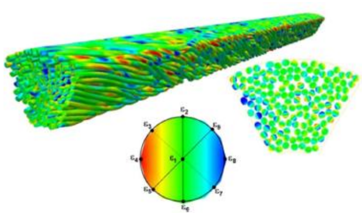


Need for a tool able to **understand** and **predict** the **electrical performance** of a superconducting **fusion cable**

FE mechanical code: MULTIFIL history

2011

H. Bajas Ph.D.



Development of a first mechanical model to simulate fusion sub-cables based on MULTIFIL code developed by D. Durville:

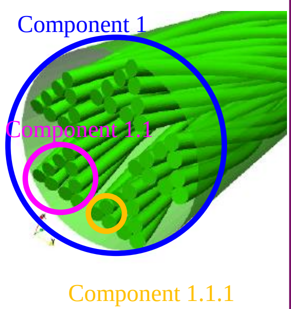
- Material constitutive laws implementation;
- Axial and transverse validation;
- Deep analysis of the ITER CS CICC and main mechanical phenomena.

But missing numerical tools and phenomena: representability ?

2017

MULTIFIL upgrade

Passage from pseudo-periodic BCs to **hierarchical handling of BCs**: Independency of the ends BCs

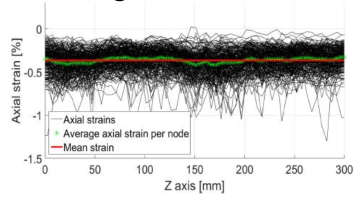


2019

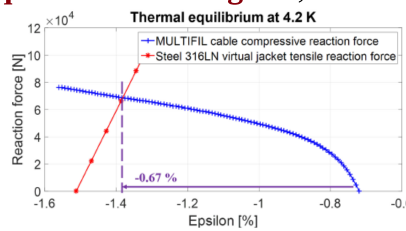
MULTIFIL upgrade & Model improvement

Further developments of the single sub-cable model:

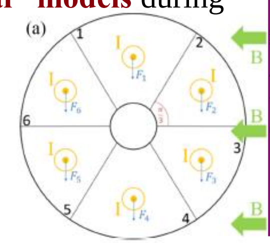
- MULTIFIL upgrade: deformable “jacket” during CD;



- **Jacket-cable thermal equilibrium during CD**;



- **“Multi-petal” models** during EM cycles.



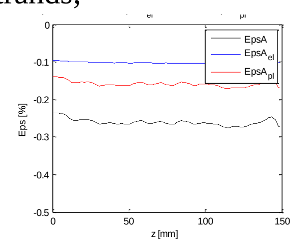
2020

MULTIFIL upgrade & Model improvement

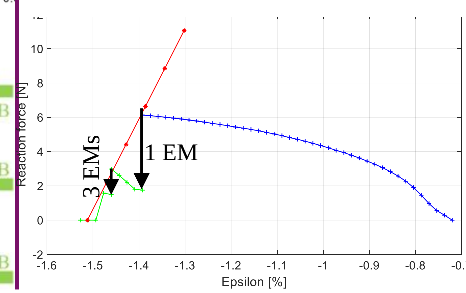
MULTIFIL upgrades:

- **Twisted single sub-cable**;

- Discrimination between plastic and elastic strains over strands;



Adding the **jacket-cable equilibrium for EM cycles**.

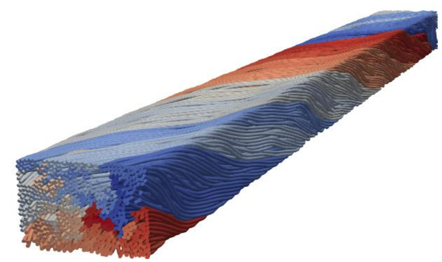


2021

MULTIFIL upgrade & new models

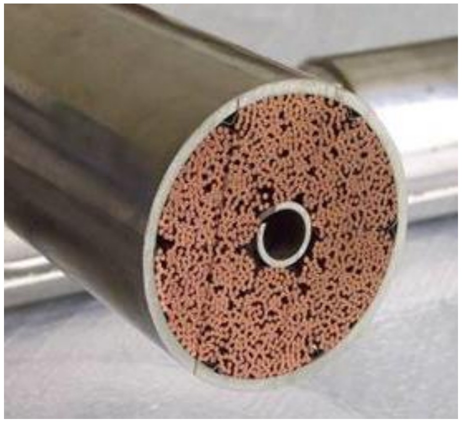
- MULTIFIL upgrade: **full ITER TF CICC simulation**;

- **Other Nb_3Sn cables simulation**: DTT TF cable, JT60SA CS cable, ITER CS STP cable.



ITER TF CICC simulation: *The shaping*

MULTIFIL allows to simulate the main phases of the conductor life starting from the manufacturing, which is here the global shaping of the strands assembly.

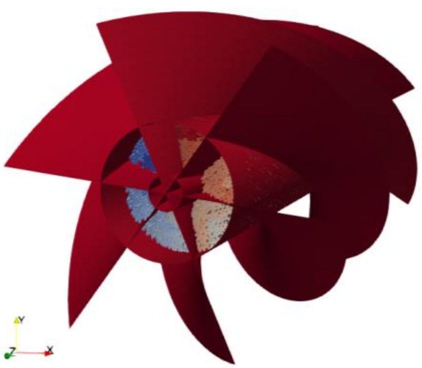


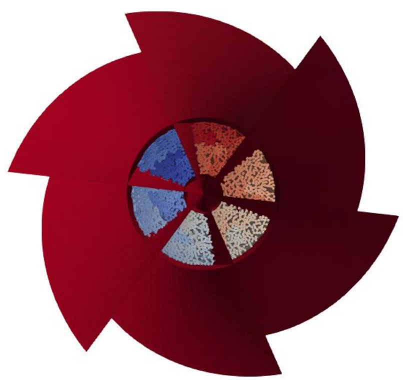
Taken from: M. Breschi *et al* 2017 *Supercond. Sci. Technol. 30* 055007

$6x[(2Nb_3Sn + 1Cu)x3x5x5 + (3Cu)x4)]$

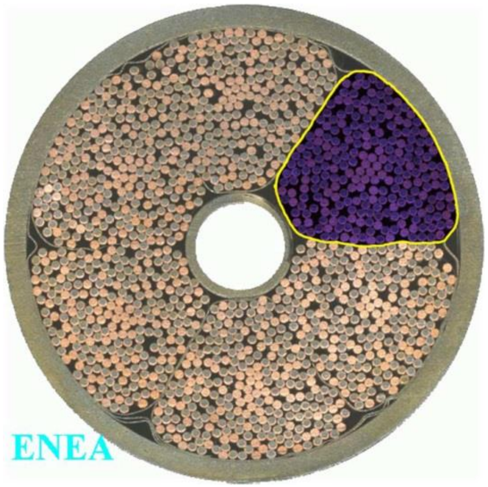
The initial shape is given by the compaction of strands that follow superposed helical trajectories. For each cabling stage, an helix is defined and the result is the superposition of five helices.

The initial trajectories are the result of the compaction by rigid tools





ITER TF CICC simulation: *The shaping*



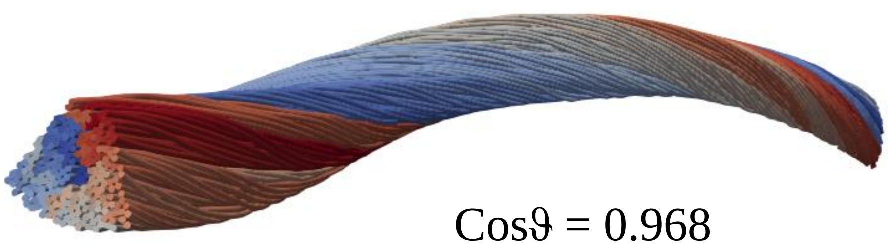
Design:
Cosϑ = 0.97
VF = 29.7 %
Diam = 39.7 mm

Straight Petal (SP)

Cosϑ = 0.988
Diam = 38.44 mm
VF = 29.7 %
Length = 300 mm
STRAIGHT PETAL

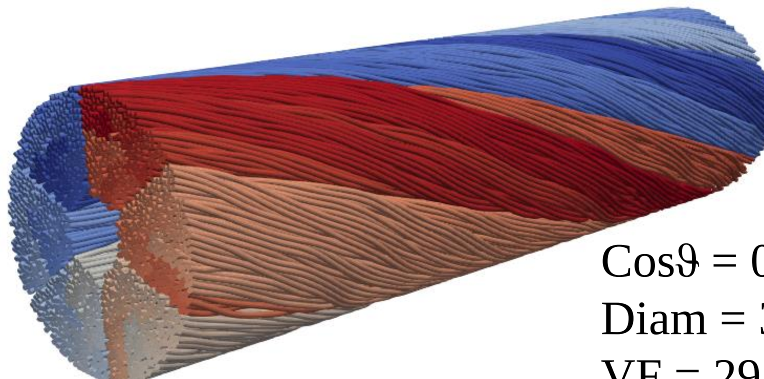
Scaling up of the ITER TF CICC model

Twisted Petal (TP)



Cosϑ = 0.968
Diam = 38.8 mm
VF = 29.7 %
Length = 300 mm
TWISTED PETAL

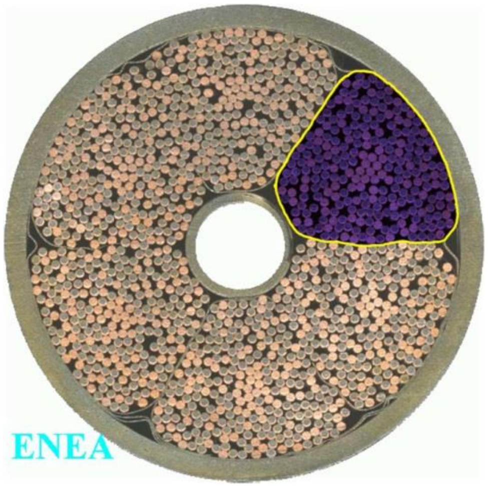
Full Cable (FC)



Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE

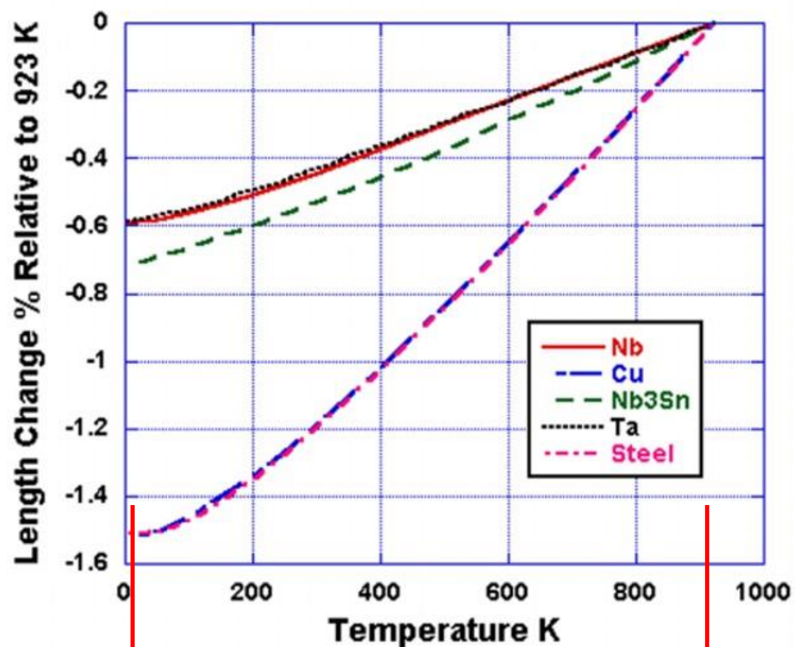
ITER TF CICC simulation: *The loads*

After shaping the other critical phases of the conductor life are the Cool-Down (CD) and the EM loadings.



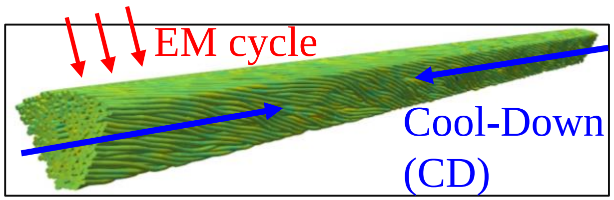
Steel and Nb_3Sn wires have different coefficients of thermal expansion (contraction in this case)

The cable work in a global state of compression inside the conductor



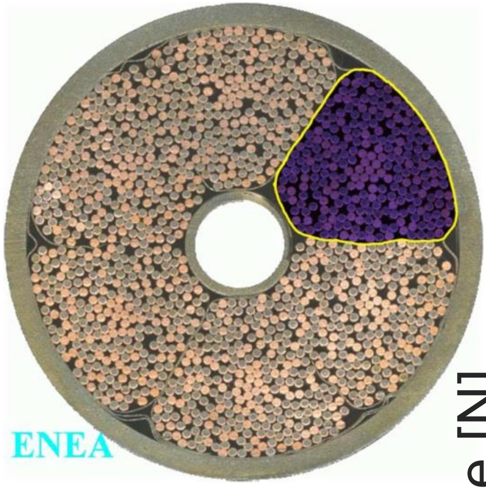
Operating temperature

Heat treatment temperature

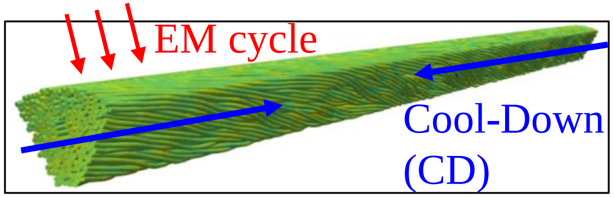


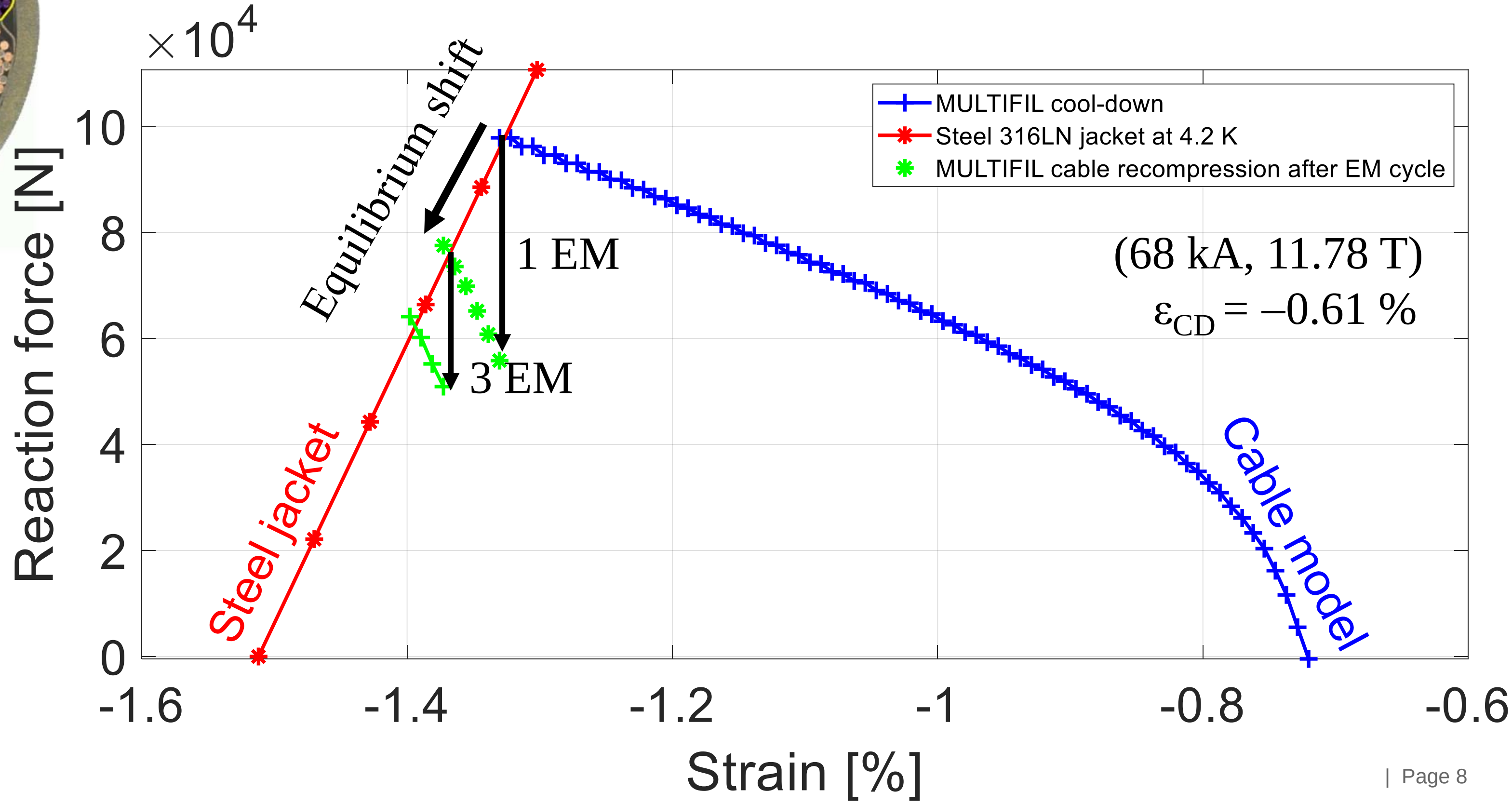
ITER TF CICC simulation: *The loads*

After shaping the other critical phases of the conductor life are the Cool-Down (CD) and the EM loadings.



Gradual compressive shifts of jacket-cable equilibrium due to EM load





The model considers the presence of the jacket even if it is not simulated

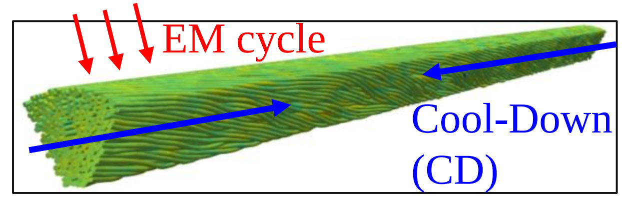
ITER TF CICC simulation: *Phenomenological study*

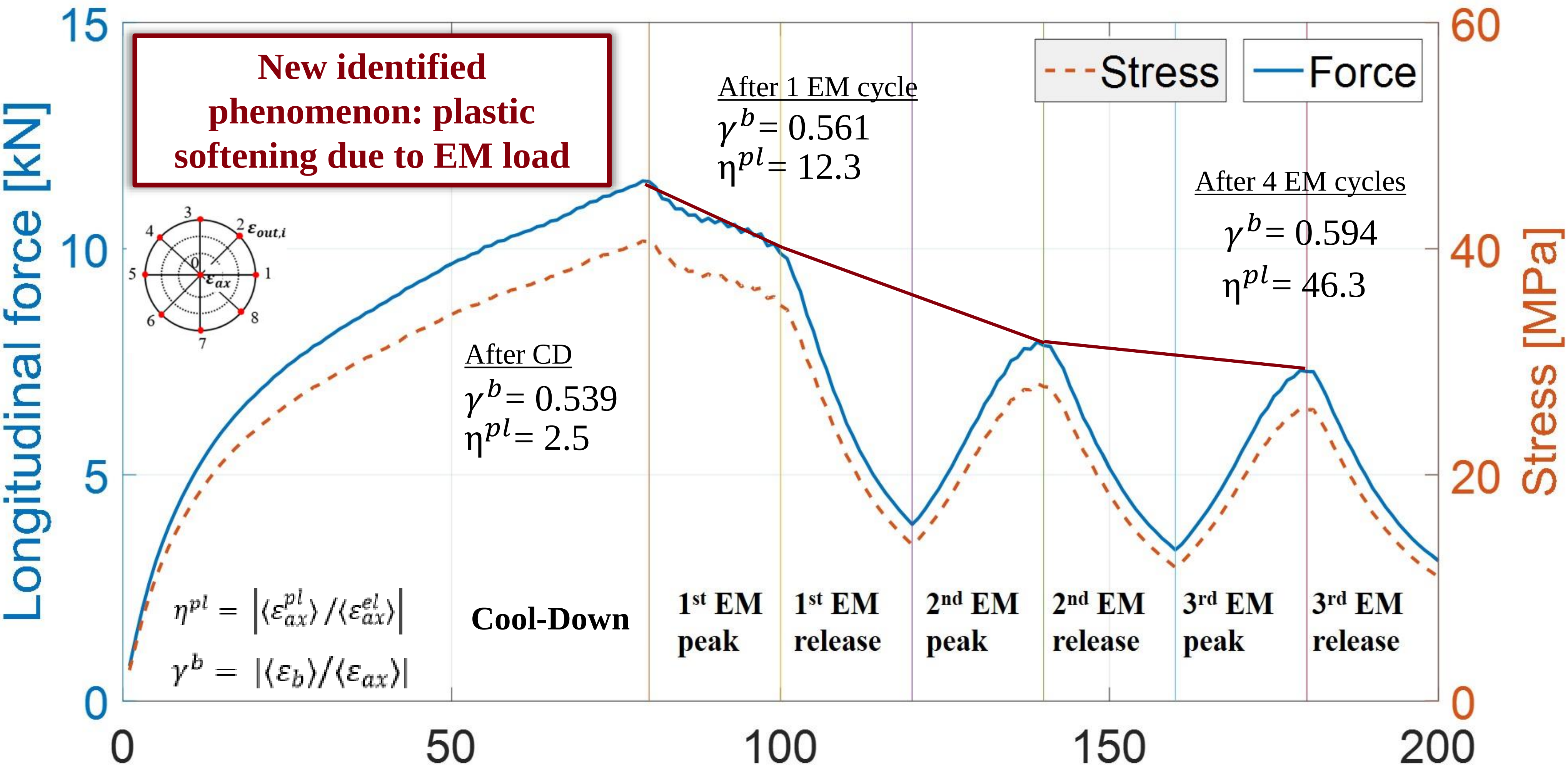
Straight Petal (SP)

Cosϑ = 0.988
Diam = 38.44 mm
VF = 29.7 %
Length = 300 mm
STRAIGHT PETAL

(68 kA, 11.78 T)

$\varepsilon_{CD} = -0.61$ %

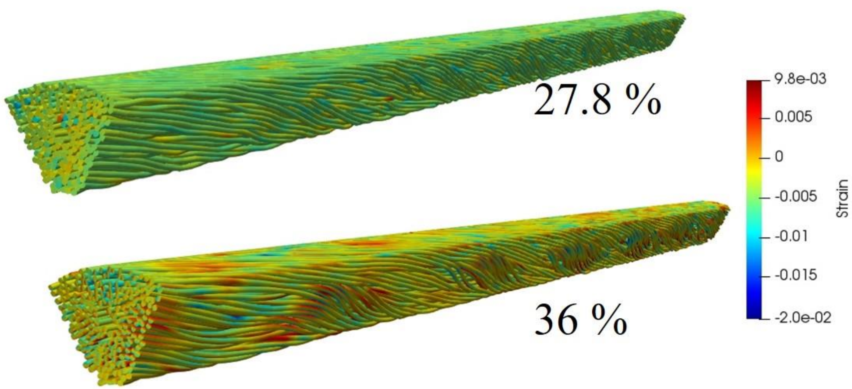




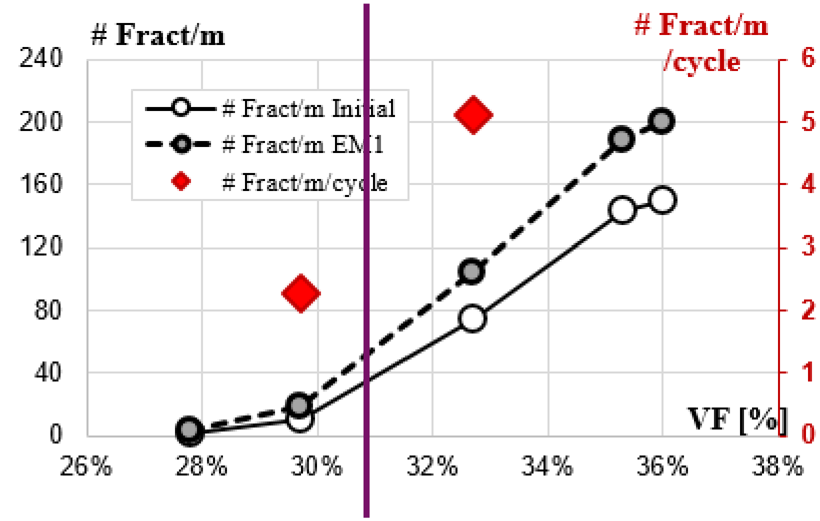
ITER TF CICC simulation: *Parametric study*

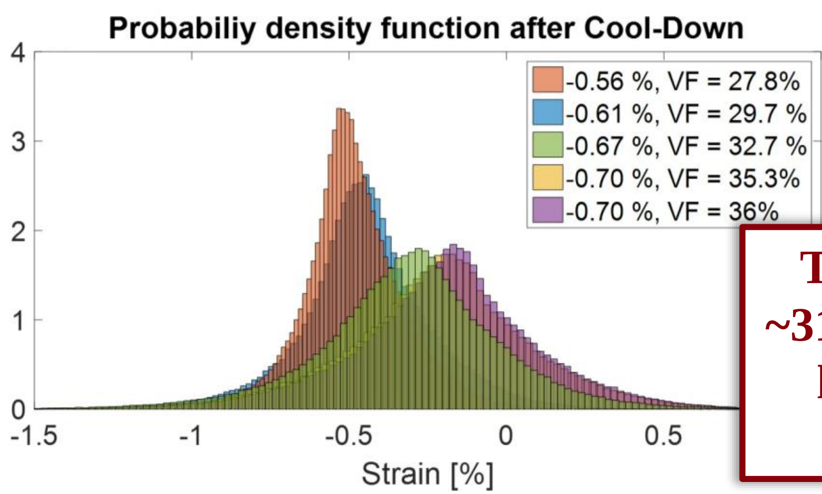
Straight Petal (SP)

Cos϶ = 0.988
Diam = 38.44 mm
VF = 29.7 %
Length = 300 mm
STRAIGHT PETAL

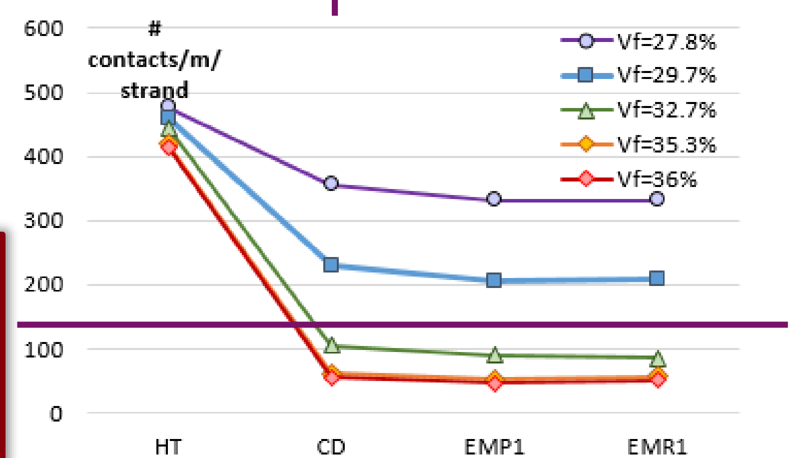


Mechanical exposure to fracture as a function of the VF





Threshold around ~31 % of VF between locked and loose behavior.

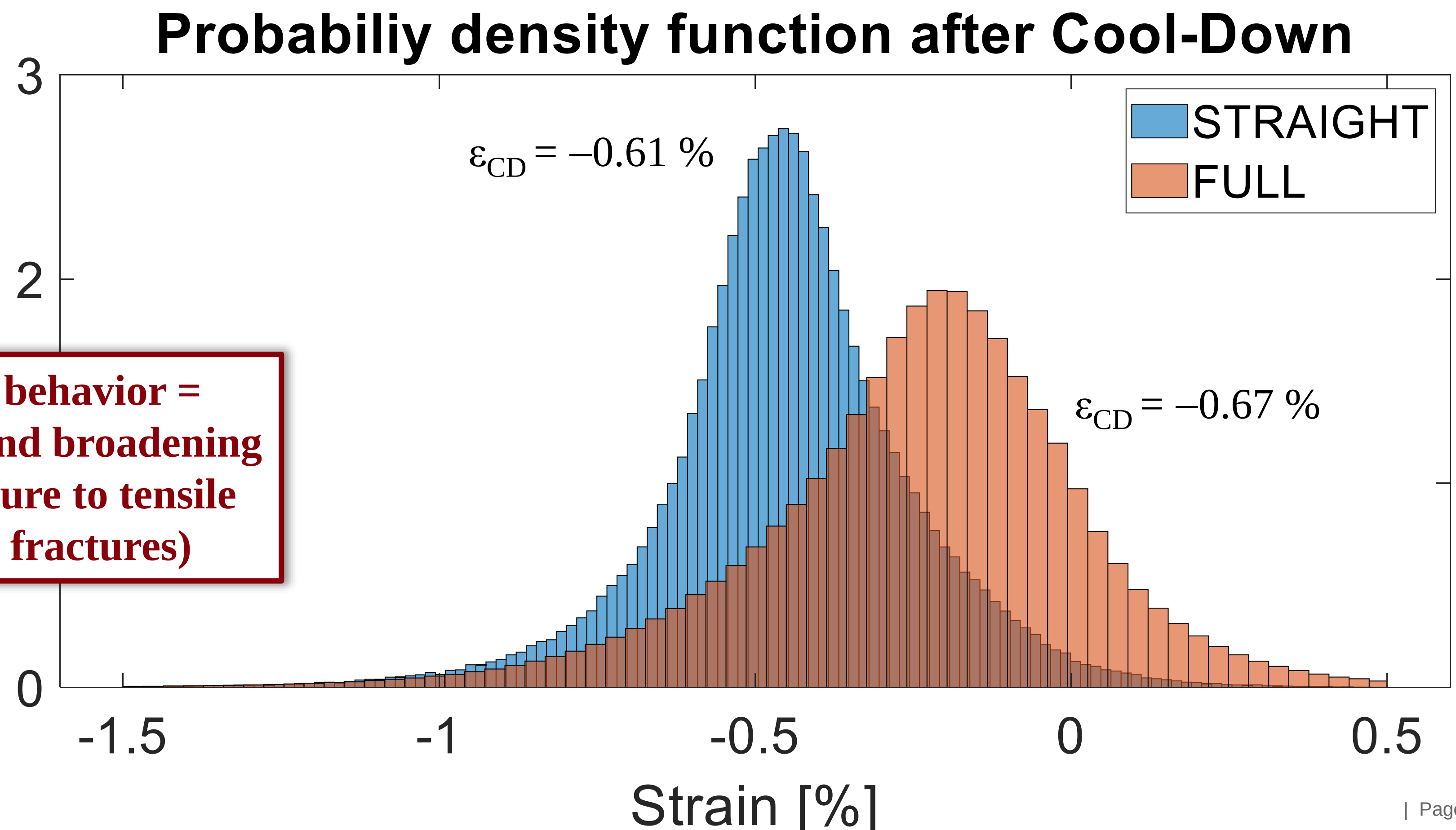


ITER TF CICC simulation: *Scaling-up*

Full Cable (FC)

Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE

Full model VS Petal model mechanical comparison ?



Full cable behavior = tensile shift and broadening (more exposure to tensile strains → fractures)

ITER TF CICC simulation: *EM load on full cable*

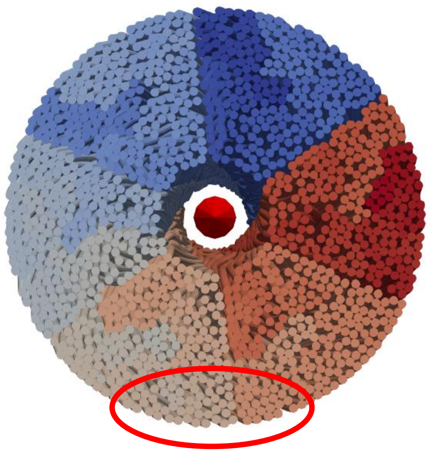
Full Cable (FC)

Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE

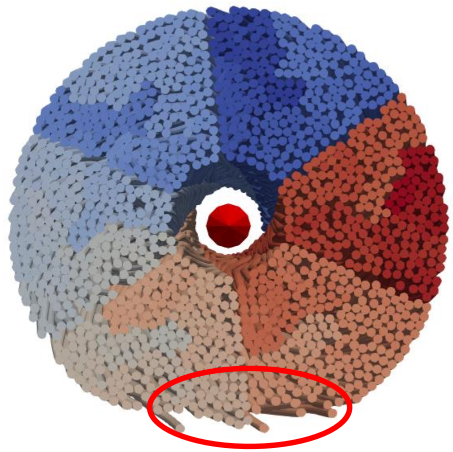
The full cable model shows a large displacement of the wires during the EM cycle in the low pressure side

(68 kA, 11.78 T)
$\varepsilon_{CD} = -0.67\ \%$

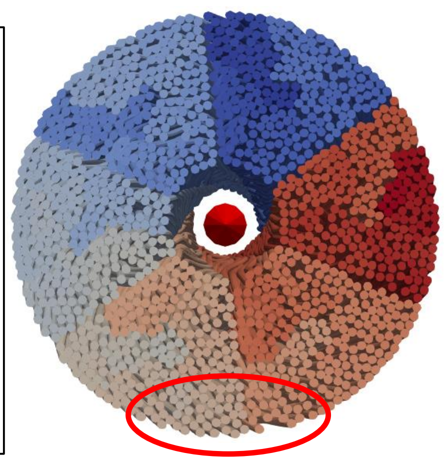
Before EM cycle



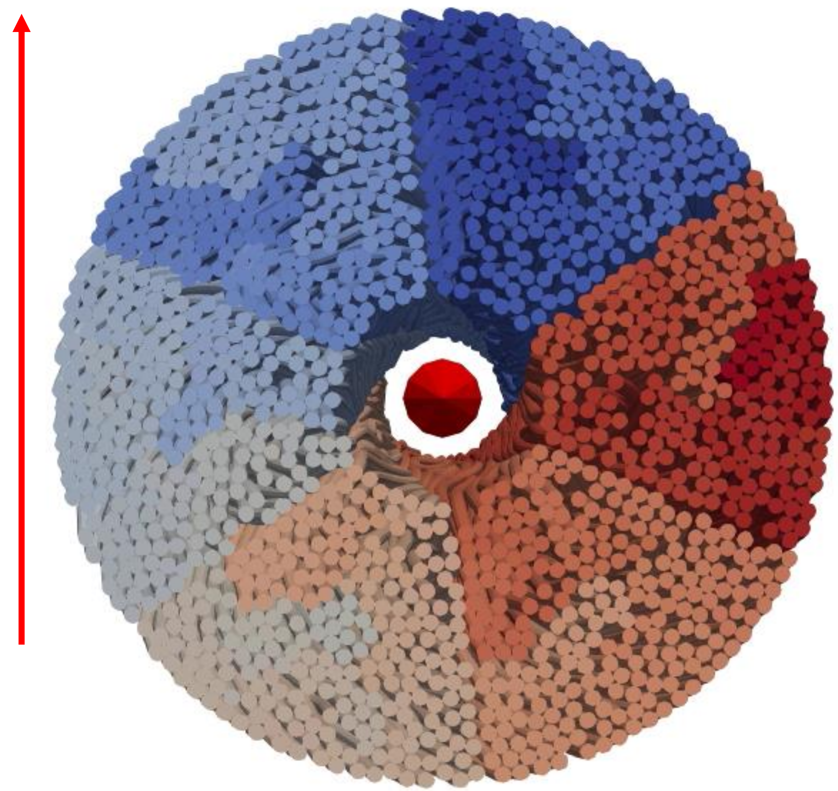
Peak EM cycle

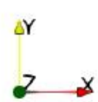


Release EM cycle



IxB





ITER TF CICC simulation: *full cable analysis*

Full Cable (FC)

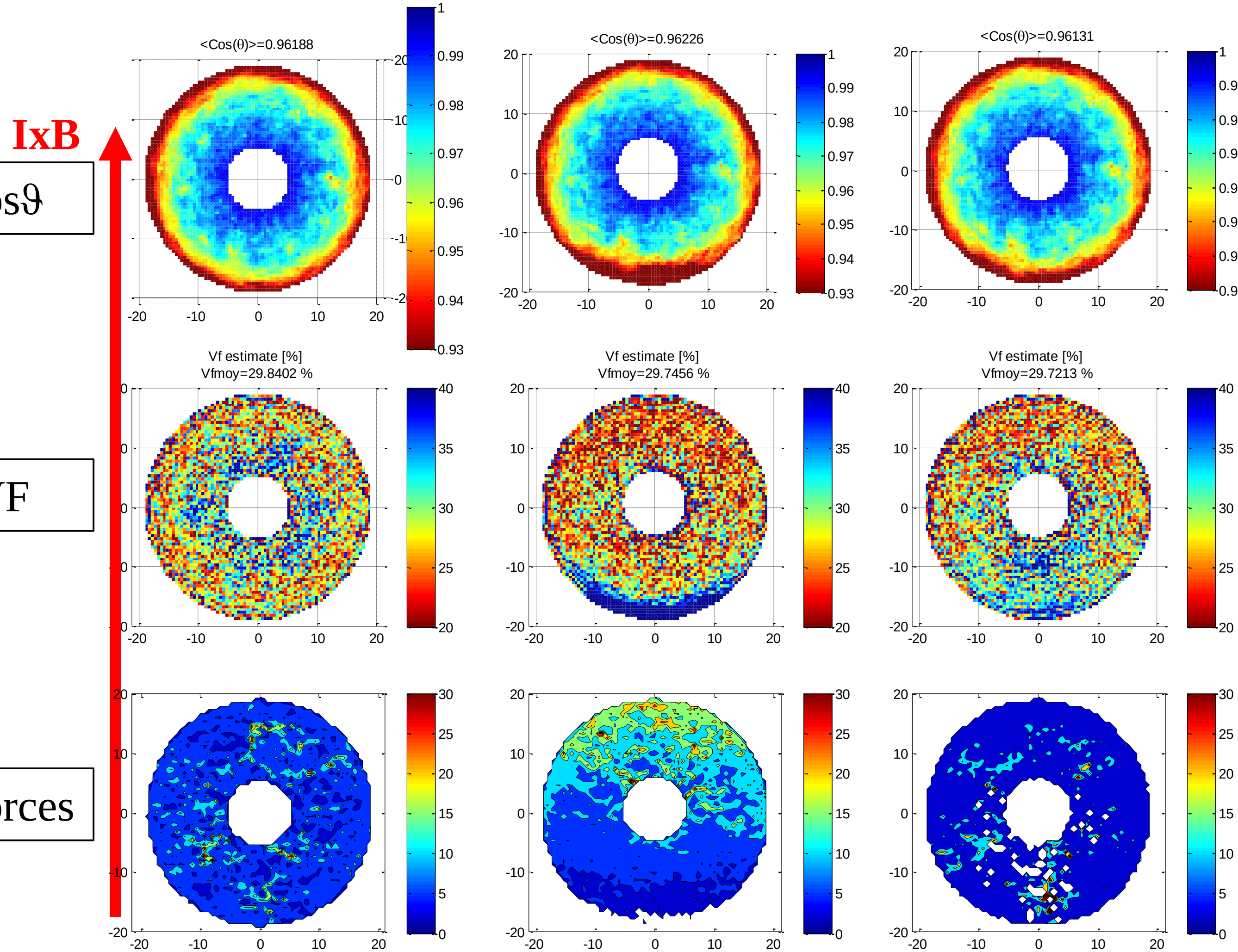
Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE

	Cool-Down 924 K–5 K	EM peak (68 kA, 11.78 T)	EM release

The local twist angle shows a radial gradient — Local cosϑ

The VF increases in the low pressure zone due to the application of the EM cycle — Local VF

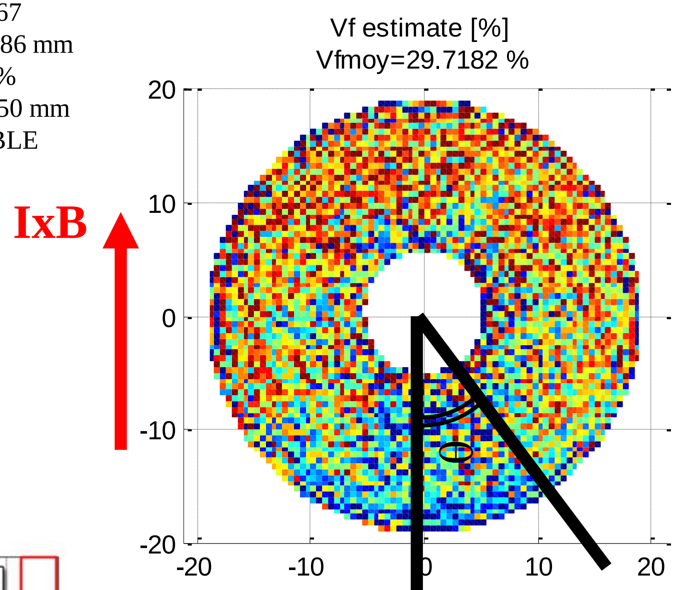
The strong contacts tend to disappear in the low pressure side — Contact forces

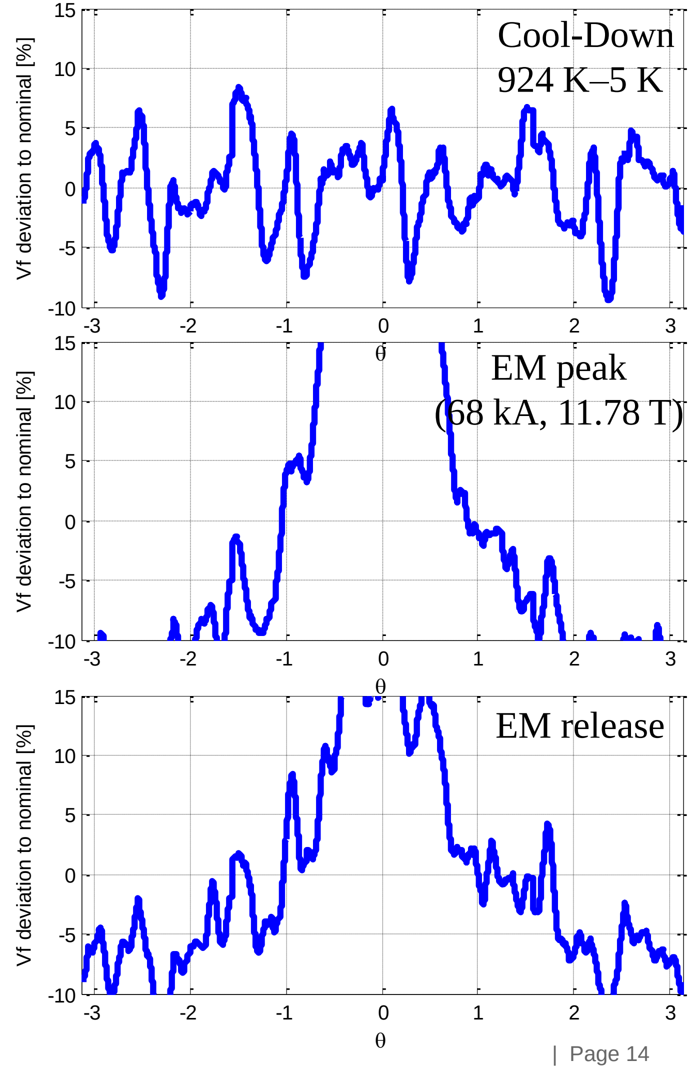


ITER TF CICC simulation: *full cable local VF*

Full Cable (FC)

Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE





Metallographic autopsies of full-scale ITER prototype cable-in-conduit conductors after full cyclic testing in SULTAN: III. The importance of strand surface roughness in long twist pitch conductors

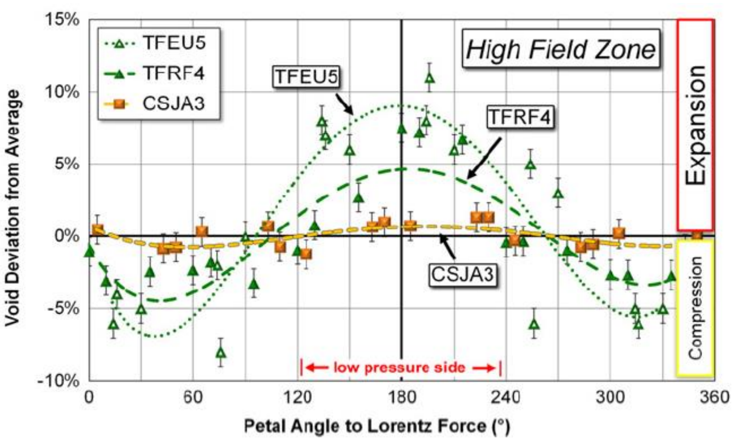


Figure 5. Petal void fraction expansion or compression (from the average of all petals) as a function of petal position which is defined with respect to the Lorentz force. 0° defines the high pressure side of maximum Lorentz force while petals in the vicinity of 180° lie on the low pressure side.

The local VF deviation from average value as a function of the angular position shows very good agreement with the experimental measurements

ITER TF CICC simulation: *full cable plasticization*

Full Cable (FC)

Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE

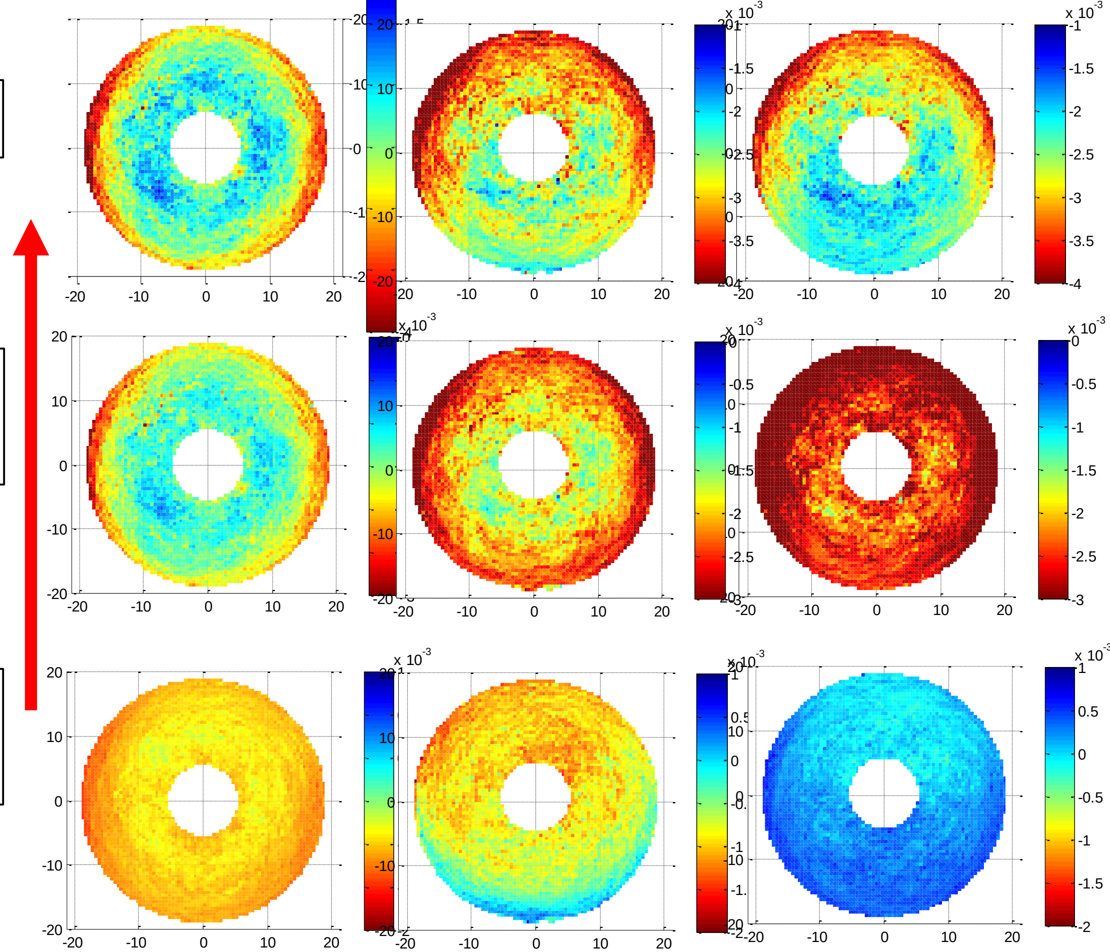
	Cool-Down 924 K–5 K	EM peak (68 kA, 11.78 T)	EM release

Axial strain

Plastic axial strain

Elastic axial strain

IxB



The major effect of the EM cycle is a global plasticization of the strain with major localization in the low pressure side of the cable

ITER TF CICC simulation: *full cable breakage*

Full Cable (FC)

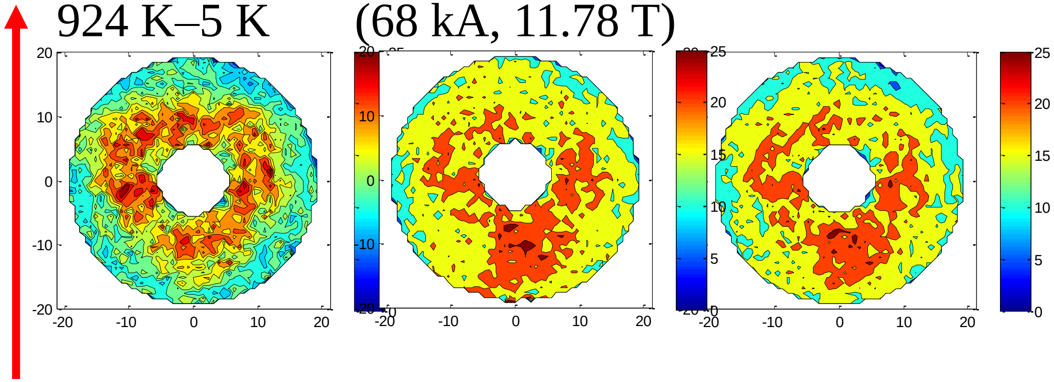
Cosϑ = 0.967
Diam = 38.86 mm
VF = 29.8 %
Length = 150 mm
FULL CABLE

Surface fraction at $\varepsilon > 0$ %

Cool-Down 924 K–5 K

EM peak (68 kA, 11.78 T)

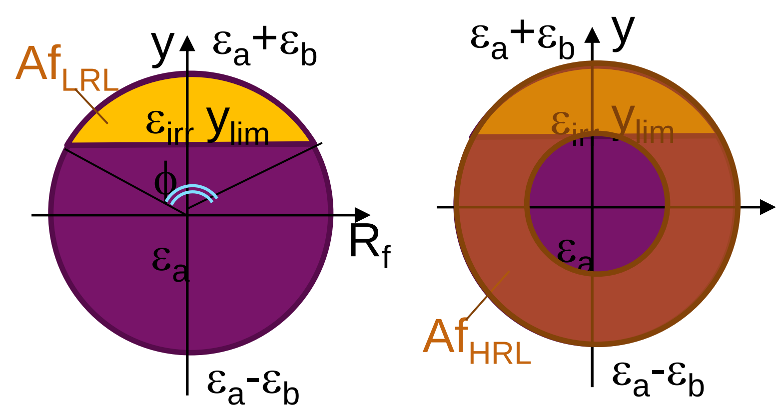
EM release



The low pressure side is characterized by more exposure to fractures and so stronger decrease of Ic.

Breakage models:

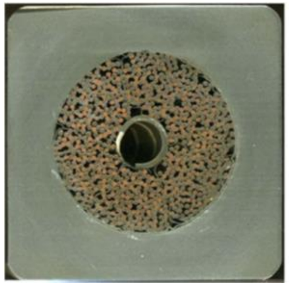
- Low Resistivity Limit: - 10 % Ic
- High Resistivity Limit: - 20 % Ic

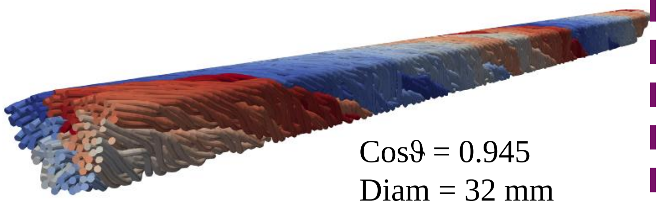


Other conductors

ITER CS STP

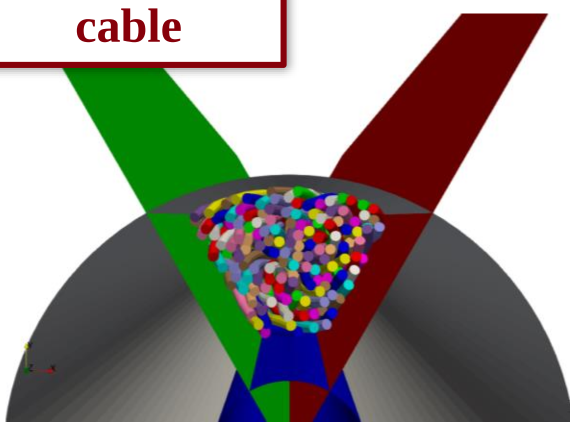
Design:
Cosϑ = 0.945
VF = 33 %
Diam = 32.6 mm





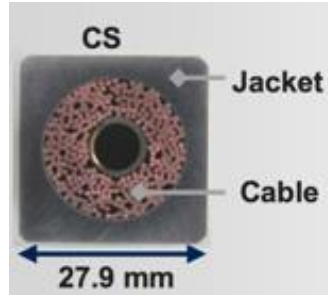
Cosϑ = 0.945
Diam = 32 mm
VF = 33.5 %
Length = 300 mm
STP
STRAIGHT PETAL

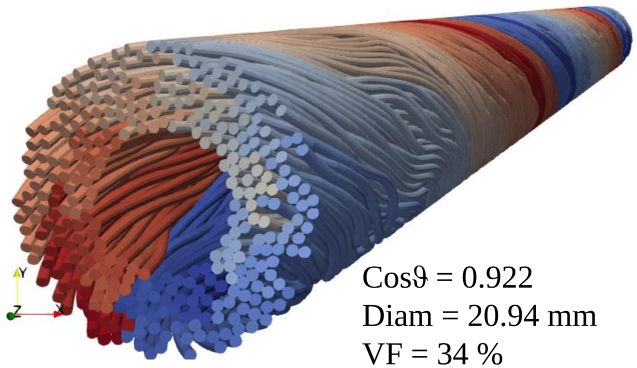
Ready for the scaling-up to full cable



JT60SA CS

Design:
Cosϑ = ?
VF = 34 %
Diam = 21 mm

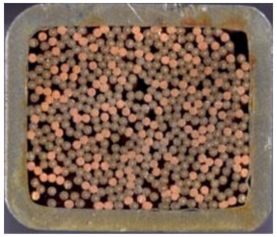




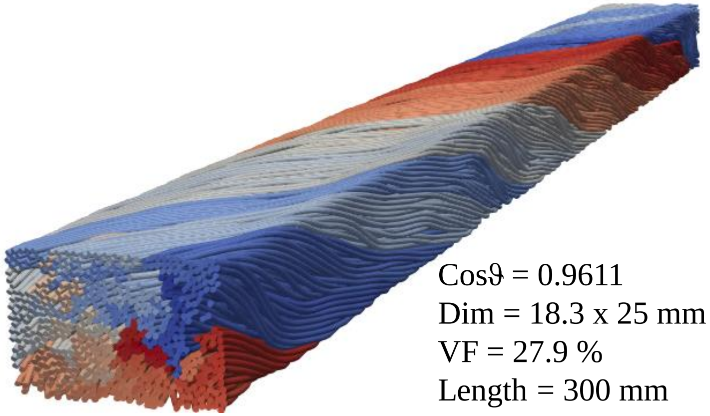
Cosϑ = 0.922
Diam = 20.94 mm
VF = 34 %
Length = 300 mm
FULL CABLE

DTT TF

Design DTT:
Cosϑ = ?
VF = 26.4 %
Dim = 18.3 x 25 mm



Picture of JT60SA TFSL



Cosϑ = 0.9611
Dim = 18.3 x 25 mm
VF = 27.9 %
Length = 300 mm
FULL CABLE

Thank you for your attention !

Questions ??