IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Invited poster presentation 3A-LS-O1.7 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
Submitted to *IEEE Trans. Appl. Supercond.*

Coupled Mechanical and Electrical Modeling of Nb_3Sn Strand Critical Current under Bending

D. Ciazynski[1]***, A. Torre***[1]***, S. Li***[2]***, and G. Lenoir***[3]

[1] CEA, IRFM, F-13108 Saint Paul-lez-Durance, France
[2] Ecole Centrale Lyon, France
[3]Ecole CentraleSupélec, Paris, France

INTRODUCTION

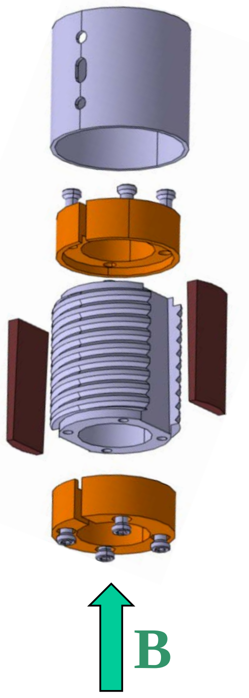
Strain dependence of Nb_3Sn superconducting properties is known to be responsible for the degradation of transport current capability of large steel jacketed cable-in-conduit conductors (CICCs). The mechanical deformations of the strands in the cables, due to both cool down after heat treatment and Lorentz force during operation, are the main sources of strand-in-cable critical current degradation. The complete modeling of a CICC relies first on the modeling of the single strand with its superconducting filaments then on the modeling of the strands in the cable.

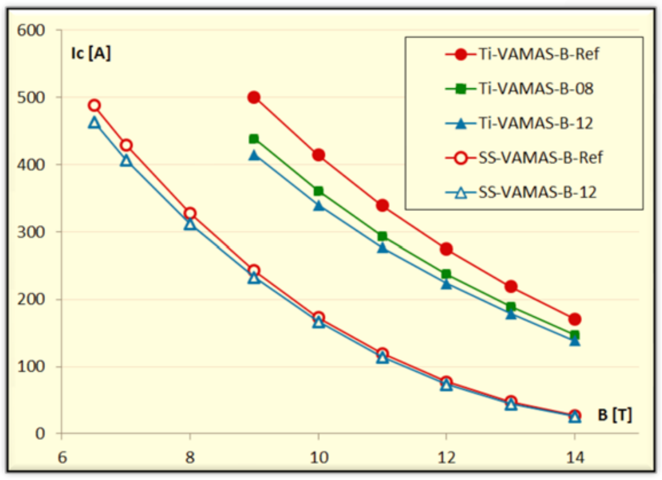
A collaborative action has been launched between CEA/IRFM and Ecole CentraleSupélec, ECS/LMSSMat where CEA takes in charge electrical modeling and measurements whereas ECS is responsible for mechanical modeling and characterizations. The coupling between mechanical and electrical models is made through the build of a strain map in the strand cross-section along each strand which is used as an input to compute the Nb_3Sn critical current density in the electrical model.

I. STRAND CRITICAL CURRENT UNDER BENDING

A simple, compact, VAMAS-like sample-holder was designed and manufactured at CEA-IRFM to measure strand critical current under bending in an industry-compatible test facility. The strand is free to bend, under the centripetal Lorentz force generated by the strand current under the applied magnetic field, in dedicated unsupported lengths over its helical trajectory. Titanium or Stainless Steel (with SS ring) mandrels are used in order to vary the thermal strain.

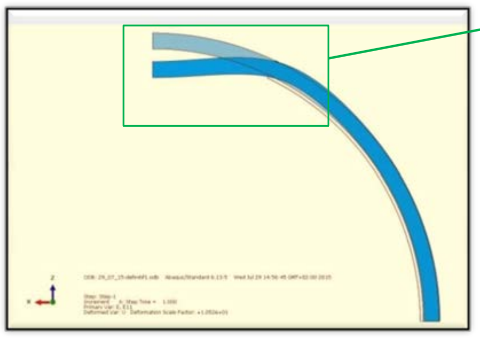
SAMPLE-TYPES TESTED	
Name	Unsupported length (per half turn)
Ti-VAMAS-B-Ref	0
Ti-VAMAS-B-08	8mm
Ti-VAMAS-B-12	12mm
SS-VAMAS-B-Ref	0
SS-VAMAS-B-08	8mm
SS-VAMAS-B-12	12mm

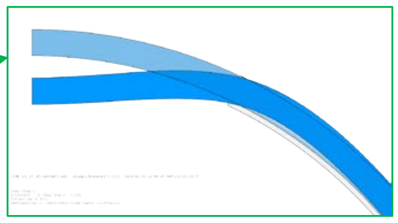




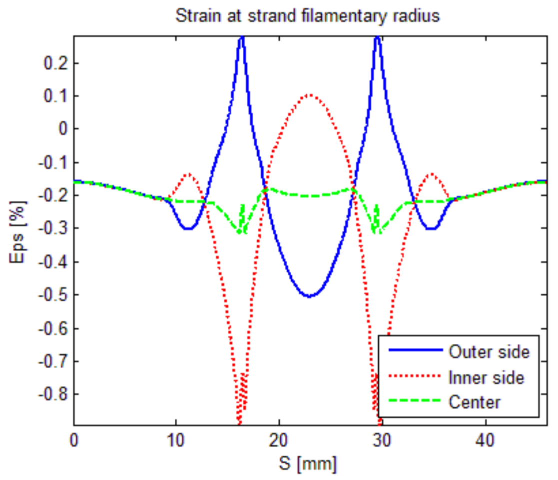
II. STRAND MECHANICAL MODELING

Mechanical modeling performed by ECS using the $Abaqus^{TM}$ code to analyze a **quarter of a turn** of the strand on its mandrel with symmetries at both ends. The strand (∅ 0.81 mm) was modeled as a homogeneous medium according to previous ECS analyses.





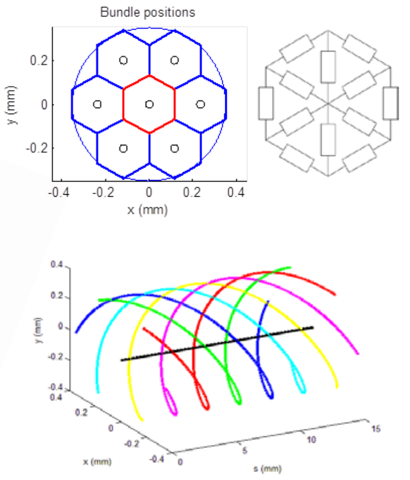
Strand deformation (x10) for a Lorentz force of 4 kN/m (maximum value during the tests) and for a free length of 12 mm.



Axial strain map built from the computed strain along the strand inner and outer radii on the mandrel (free 12 mm length at middle).

- ❑ Linear variation of strain along the radius in the cross-section assumed
- ❑ Addition afterwards of a thermal strain of -0.10% (on Ti mandrel)

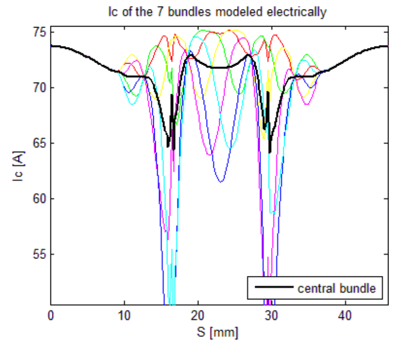
III. STRAND ELECTRICAL MODELING



Simplified 7 (six twisted around one) filament bundles model built in CEA CARMEN code

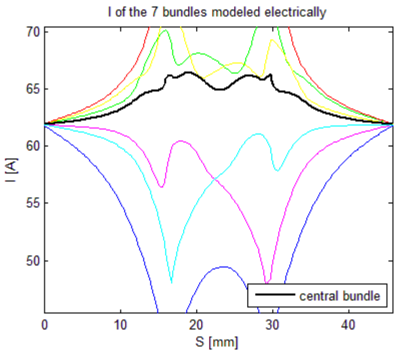
- ❑ Strand length of half a turn modeled w/ the 12 mm free length at middle
- ❑ Inter-bundle resistances computed from the transverse resistivity ρ_{tran}
- ❑ At each strand end, all bundles connected to a common node through high series resistances ➔ ensure uniform current distribution at ends
- ❑ Twist pitch = 14.6 mm
- ❑ Computation step over the length = 0.2 mm.

IV. RESULTS OF CARMEN SIMULATION (1/2)

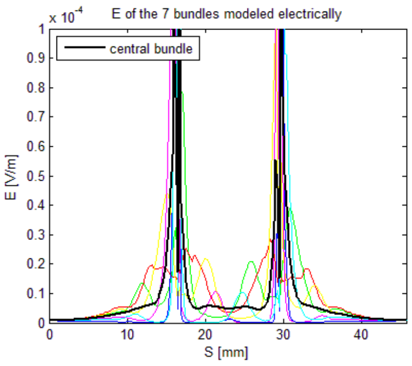


B = 9 T
T = 4.22 K
n = 20
ρ_{tran} = 3.0 10^{-11} Ω.m

- ❑ Low local critical currents due to either high compression or tension
- ❑ 'Resonance' between the twist pitch and the high strain areas distance



- ❑ Strand critical current defined as close as possible to the measurement with:
  $<E> = E_C = 10\ \mu V/m$
- ❑ 2 mm removed at each end to eliminate ends effect



- ➢ **Bundle currents change ov small scales following critic current thanks to low ρ_{tran}**
- ➢ **However, this transfer is nc strong enough to avoid hig electric fields up to 40-50 E**

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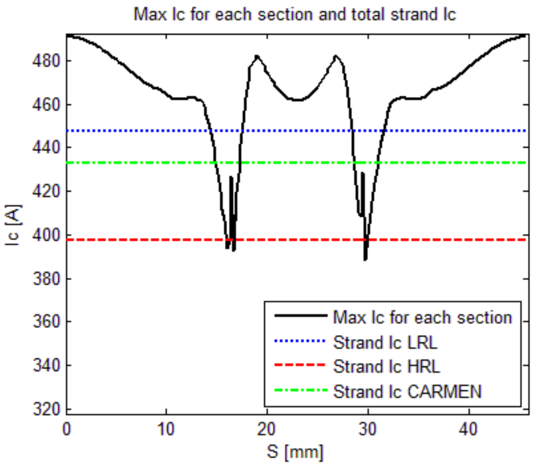
V. RESULTS OF CARMEN SIMULATION (2/2)



- Insulated bundles = high resistivity limit (HRL)
- In CARMEN, strand I_C depends on ρ_{tran}

Measurement: I_C = 410 A

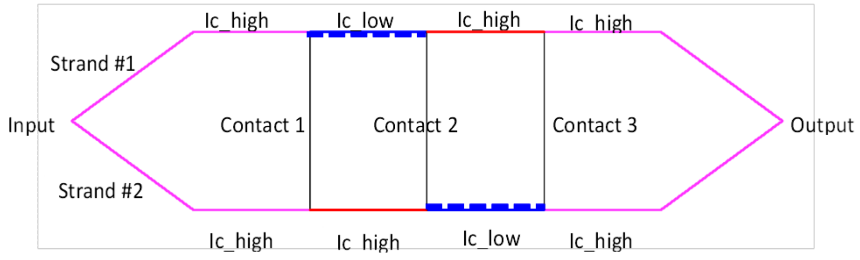
3.0 10^{-10}	I_C (A)
∞ (HRL)	398
3.0 10^{-9}	**372**
3.0 10^{-10}	419
3.0 10^{-11}	432
0 (LRL)	448

☞ *Simulation result may be lower than the HRL due to the boundary conditions in CARMEN model: current distribution among bundles is forced to be uniform at strand ends, which is not imposed in the HRL.*

ith very low end resistances, one gets: I_C = 411 A for ρ_{tran} = 3 10^{-9} Ω.m !

VI. CURRENT TRANSFER IN A TWO-STRAND CABLE

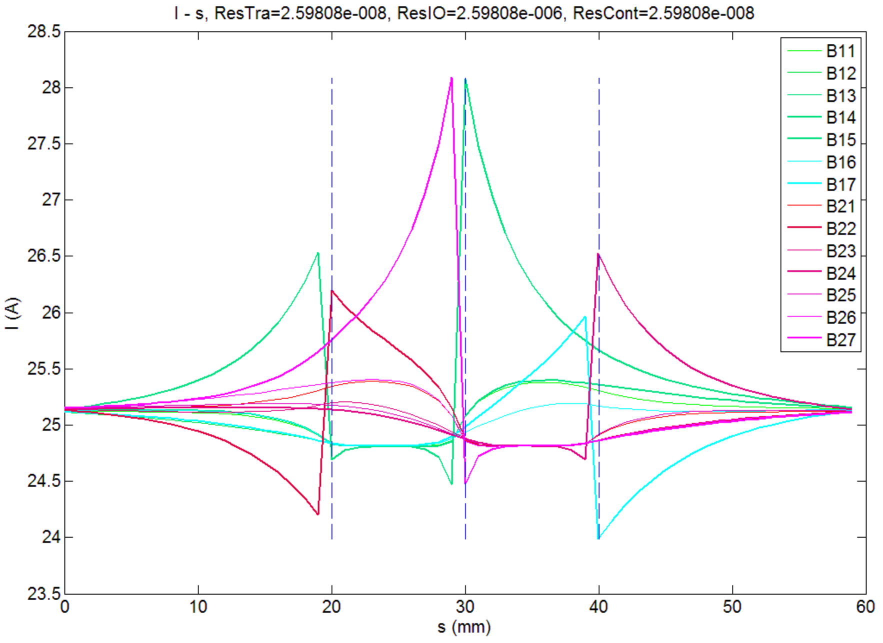
- ❑ Simple two-strand (6+1 bundles per strand) electrical CARMEN model
- ❑ 3 interstrand contacts (1 connected bundle per strand)
- ❑ Two weak lengths between contacts (i.e. I_C = 24 A vs. 30 A per bundle)



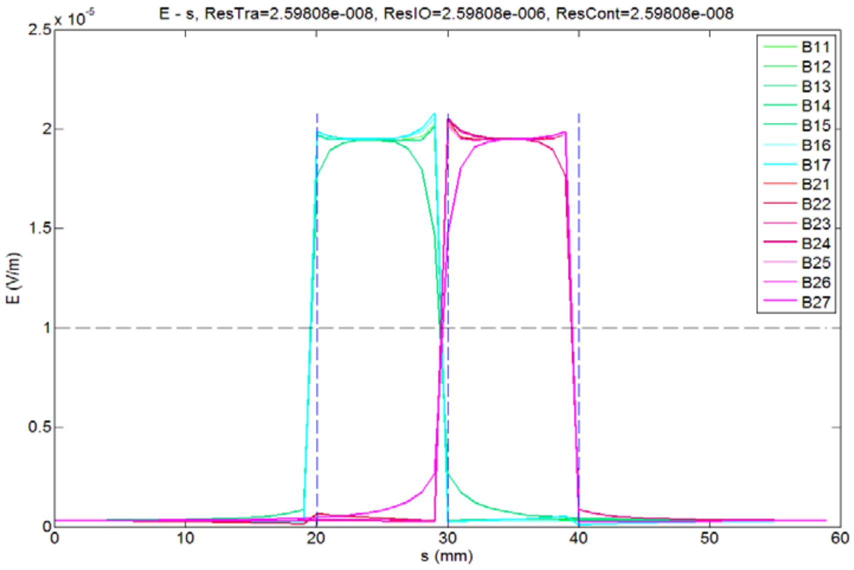
Contact #	Strand #1	Strand #2
1	B15	B22
2	B14	B27
3	B17	B24

VII. TWO-STRAND CABLE CRITICAL CURRENT

Bundle currents (Bjk = k^{th} bundle in strand #j)



Electric field along bundles



- ➢ Current transfer between strands acts to decrease the current (and so the electric field) in the weak lengths
- ➢ Inter-bundle current transfer in strands must be involved prior or after any inter-strand current transfer so as to maximize the contact current ➔ tends to limit contact resistance efficiency
- ➢ Electric field on the weak bundles is only slightly reduced (compared to the value of 2×E_C needed to get <E> = E_C with E = 0 on strong lengths)
- ➢ Contact resistance R_{cont} plays on cable I_C (see Table, R_{trans} = interbundle resistance over 1 mm)

R_{cont}/R_{trans}	I_C (A)	I_{cont1} (A)	I_{cont2} (A)	I_{cont3} (A)
10	**348.0**	0.2	-0.5	0.2
1	**351.9**	2.2	-4.5	2.2
0.1	**361.2**	7.8	-15.9	7.8
0.01	**363.9**	10.1	-20.2	10.1

VIII. EQUIVALENT TWO-BUNDLE CABLE MODEL

- ❑ Simple ‘two-bundle’ CARMEN macro model to simulate two-strand cable
- ❑ 3 interstrand contacts
- ❑ Two weak lengths between contacts (i.e. I_C = 168 A vs. 210 A per strand)
- ❑ Effective contact resistance depends on R_{trans}

$$R'_{cont} = R_{cont} + \alpha * R_{trans}$$

R_{cont}/R_{trans}	0 (initial)		0.24 (optimal)	
R_{cont}/R_{trans}	I_C (A)	I_{cont2} (A)	I_C (A)	I_{cont2} (A)
10	**348.0**	-0.5	**348.0**	-0.5
1	**352.4**	-5.0	**351.6**	-4.0
0.1	**373.2**	-29.5	**360.6**	-13.7
0.01	**377.9**	-40.5	**363.9**	-17.5

CONCLUSIONS

A coupled mechanical and electrical modeling has been set to analyze Nb_3Sn strand bending experiments on dedicated VAMAS-like mandrels. The first results have shown that the strain map was more complex than expected and that high local strain could lead to strong peaking of local electric field pushing significant current transfer between filaments. First results look promising but both mechanical and electrical models still need to be improved in order to better represent the experiment.

First modeling of current transfer between strands in a CICC performed using a simple two-strand model have shown the complexity of the current transfer at contact points involving inter-filaments current transfer inside connected strands which requires increasing the effective contact resistance when using strand macro models.

This work was supported in part by the French Agence Nationale de la Recherche within the Cocascope project.