Relation between critical current degradation due to pressure in magnets and experimental data

Francesco Bologna
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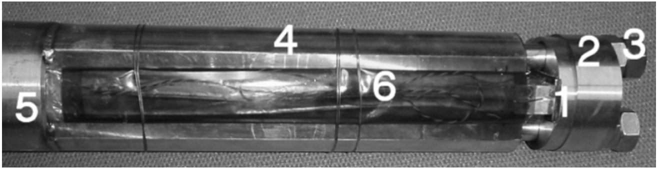
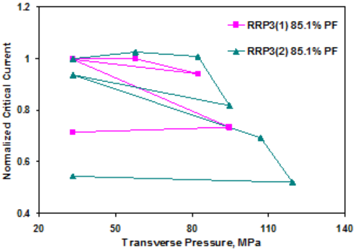
Technical Division, Superconducting Material Department

Outline

FNAL Experimental setup

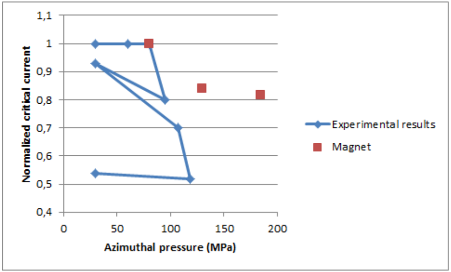




The cable is pressed along transverse direction (i.e. azimuthal in magnets) and critical current is measured.

* *"A Device to Test Critical Current Sensitivity of Nb3Sn Cables to Pressure"*, E. Barzi, M. Fratini, A. V. Zlobin. Advances in Cryogenic Engineering, V. 48, AIP, V. 614, pp. 45-52 (2002).
* *"Effect of Transverse Pressure on Brittle Superconductors"*, E. Barzi, D. Turrioni, and A. V. Zlobin. IEEE Trans. Appl. Sup., V. 18, No. 2, p. 980 (2008).

Experimetal results



Magnet data are plotted against maximum azimuthal stress in the magnet during pre-load.

Experimental data don't seem to be consistent with magnet ones.

Goal of the work

Original goal

Find an equivalent quantity using a simple analitycal model that predicts the behaviour of the magnet.

Problem

Inhomogeneity and anisotropy of the cable make it challenging to produce a single equivalent parameter.

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Find an equivalent quantity using a simple analitycal model that predicts the behaviour of the magnet.

Problem

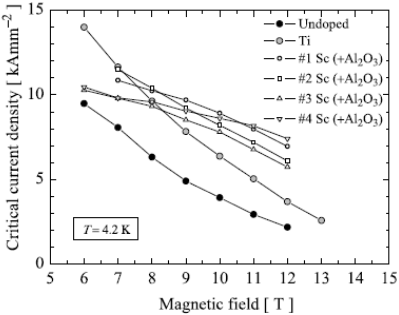
Inhomogeneity and anisotropy of the cable make it challenging to produce a single equivalent parameter.

New goals

- See how different loads can affect the current degradation.
- Try to modify the experimental setup in order to improve experimental data.

* Marco Danuso's Laurea Thesis - 2008, Sant'Anna School, Pisa: *"Parametric Analysis of Forces and Stresses in Superconducting Magnets Windings"*, M. Beghini, A. Zlobin, E. Barzi advisors.

Current degradation due to magnetic field



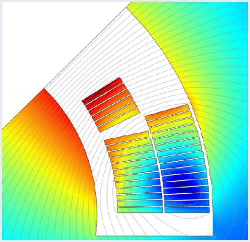
Critical current decreases rapidly with magnetic field.

Bottleneck should be where the magnetic field is higher.

* *"Nb_3Sn research and development in the USA - Wires and cables"*, D.R. Dietderich, A. Godeke.

Field and stress distribution on the magnet

Field distribution



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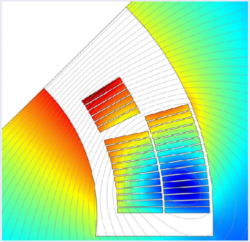

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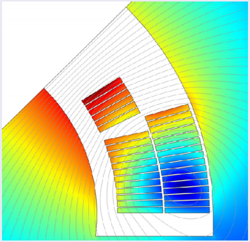
- Magnetic field is high at the pole.
- Critical current bottleneck will be at the pole.
- We must look at stress at the pole.

Field and stress distribution on the magnet

Field distribution



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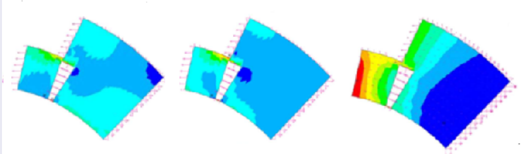
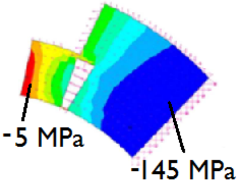
Stress distribution: 300 K, 4.5 K, powered magnet



Stress in the magnet

* *"The Study of Single Nb3Sn Quadrupole Coils Using a Magnetic Mirror Structure"*, G. Chlachidze et al., IEEE Trans. Appl. Sup., V. 21, No. 3, p. 1692 (2011).



Powered magnet

- Small loads on the pole.
- No reversible degradation.
- No permanent degradation.

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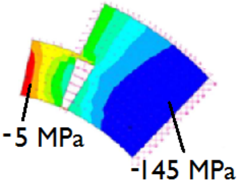

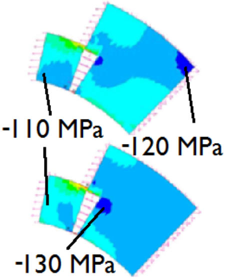

Powered magnet

- Small loads on the pole.
- No reversible degradation.
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Pre-loaded magnet

- No reversible degradation.
- Loads on the pole are higher than before.
- The highest load is still not at the pole.

Comparing magnet behaviour with experimental data

Conclusion

- The interesting degradation is the permanent one, because there will not be any reversible degradation in the powered pole.
- Test results must be compaired with the stress reached on the pole during pre-load.

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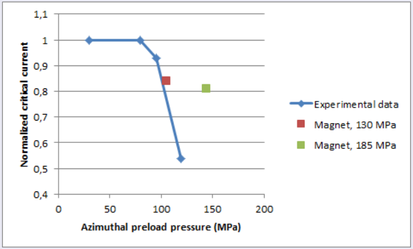
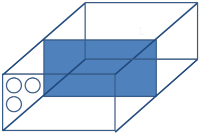
Permanent degradation

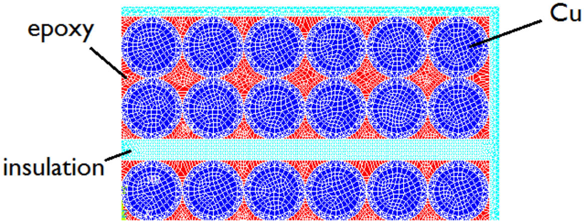


Magnet data are plotted against maximum stress reached where the field is maximum.

Ansys model

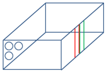
- 2D model of the section.
- Elastic materials.
- No contact elements between strands.





Choice of the elements

In order to choose the correct 2D model, we have to evaluate the behaviour of the sample in axial direction.



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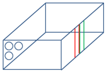
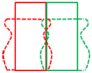


Plane stress does not keep the integrity of the material.



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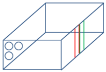

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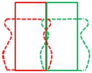
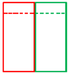


Plane strain does not allow the material to deformate in the axial direction.



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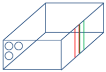

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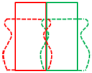

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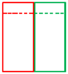
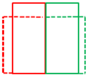
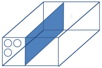


Generalized plane strain forces the axial strain to be constant on the whole section but it does not force it to be zero.



Verification of the model

Simple ANSYS model of an orthogonal section.



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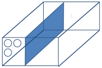

Axial stress is not constant, so plane stress is not correct.

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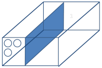


Axial stress is not constant, so plane stress is not correct.

Axial strain is constant (and not zero) along the section, as in the generalized plane strain assumption.

Effect of radial stress

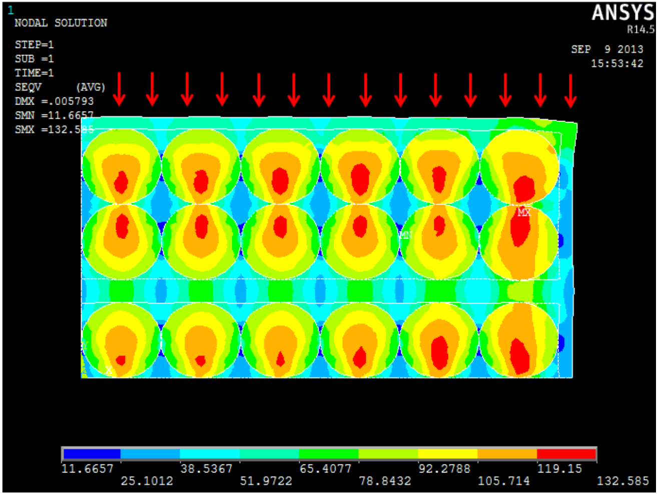
Stress simulated

for $i = 0$ to 15, for $j = 0$ to 15: $\sigma_{\theta\theta} = 10 \cdot i$ MPa, $\sigma_{rr} = 10 \cdot j$ MPa

Von Mises plots shown

1. $\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 0$
2. $\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 40$ MPa

$\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 0$



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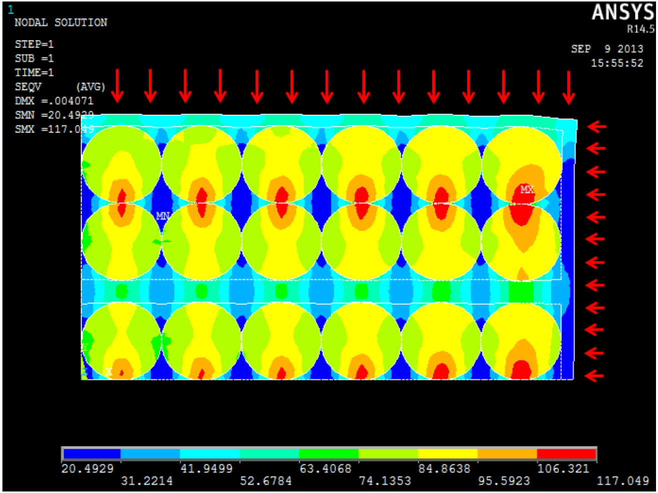
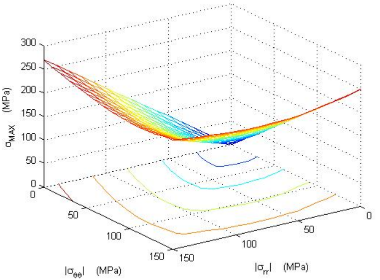
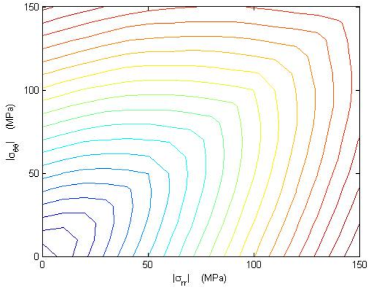


Summary: $\sigma_{MAX}(\sigma_{rr}, \sigma_{\theta\theta})$





Maximum Von Mises stress in the strand while coupling azimuthal and radial stresses is lower than when having no radial stress.

Summary of different configurations results

Configuration	σ_{MAX}	$\sigma_{MAX,or}$	Observations
Epoxy voids	$\sim$ 150 MPa	133 MPa	Singularities
Compact strands	126 MPa	133 MPa	Low stress in center
Compact strands, voids	$\sim$ 150 MPa	133 MPa	Singularities
Nb_3Sn strands	137 MPa	133 MPa	
Side azimuthal load	139 MPa	133 MPa	
Central azimuthal load	135 MPa	133 MPa	
Partial radial load	124 MPa	117 MPa	

Effect of thermal loads

Results can be incorrect if thermal loads are not considered

Different materials in a compound subjected to a temperature variation must expand or contract in the same way, and this induces stress.

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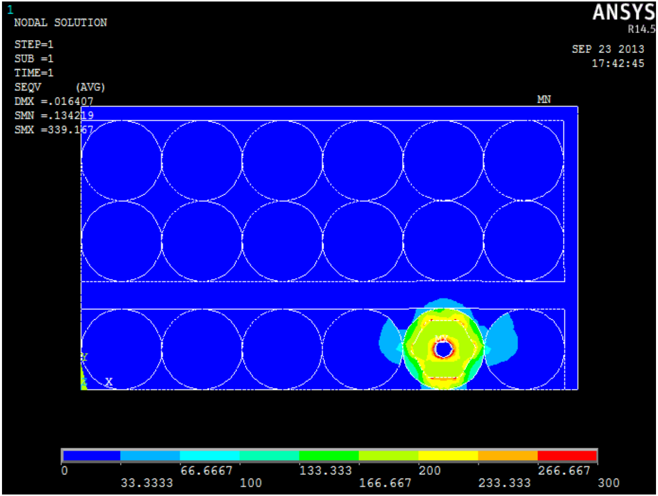
Cable as epoxy-copper compound

Epoxy can not withstand high tensile stress caused by differential contraction; it is going to break locally and follow the deformation of the copper.

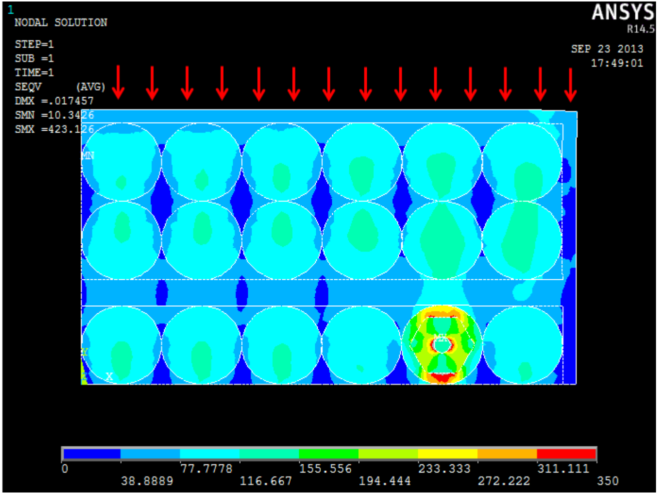
Strand as copper-Nb_3Sn compound

Different thermal expansion coefficient between copper and Nb_3Sn can bring high loads on the material after lowering the temperature.

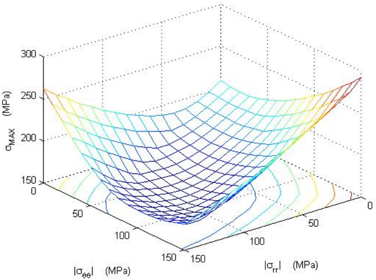
Copper-Nb_3Sn thermal loads

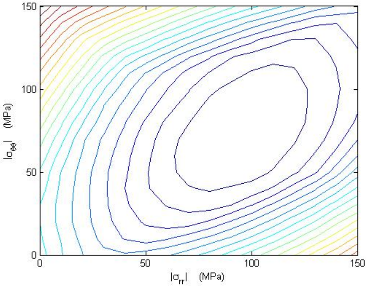


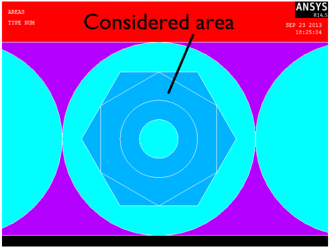
Mechanical and thermal loads



Summary: $\sigma_{MAX}(\sigma_{rr}, \sigma_{\theta\theta})$ with thermal loads

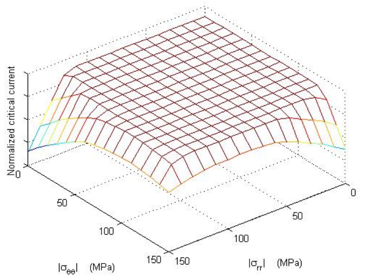




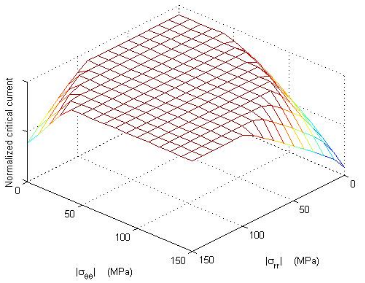


Qualitative prevision of critical current degradation

Warm preload



Cold preload



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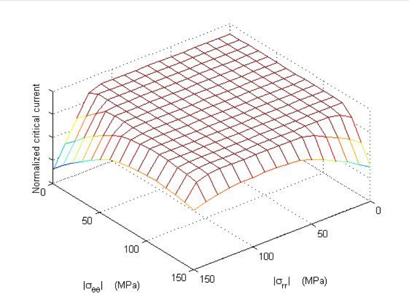

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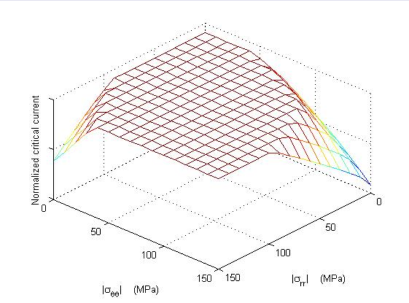

Hypothesis

1. Degradation depends on local Von Mises stress values

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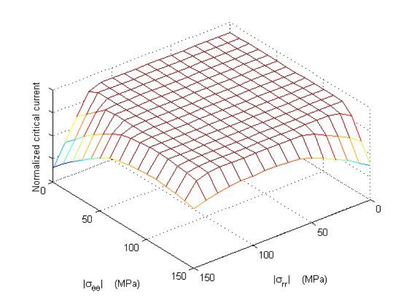

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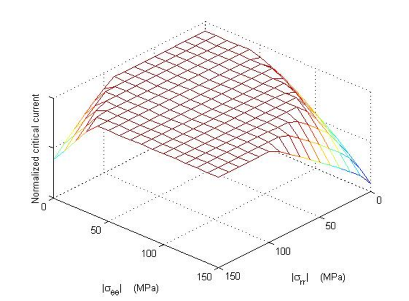
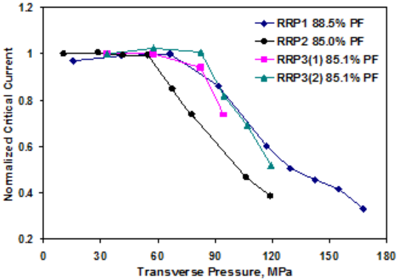


Hypothesis

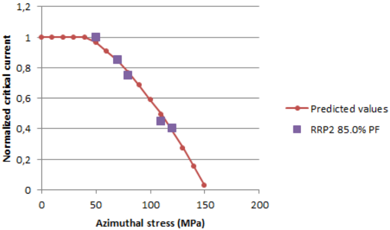
1. Degradation depends on local Von Mises stress values
2. Stress values lower than maximum stress reached in Nb_3Sn at 4.2 K do not give degradation

Fitting on experimental data



Hypothesis

1. $I_c = k\sigma_{MAX} + q$
2. $I_c(\sigma_{MAX}(0, 0, 4.2K)) = 1$



Further developments

- Try to modify the experimental set up.
- Study the differences between applying load at room temperature or after cooling down.
- Study the effect of radial stress and map permanent degradation in terms of both radial and azimuthal stress.

Relation between critical current degradation due to pressure in magnets and experimental data

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