Computation of the Reversible Critical Current Degradation in Superconducting Nb_3Sn Coils

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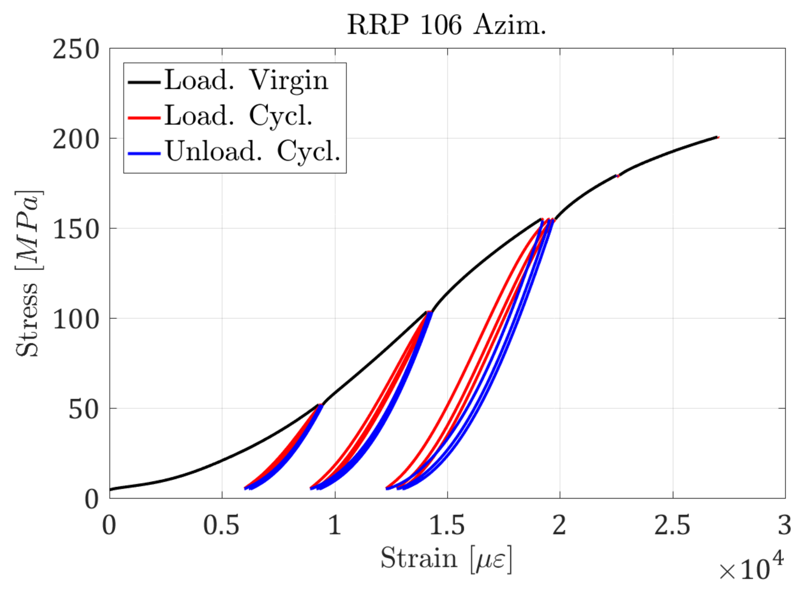
Introduction

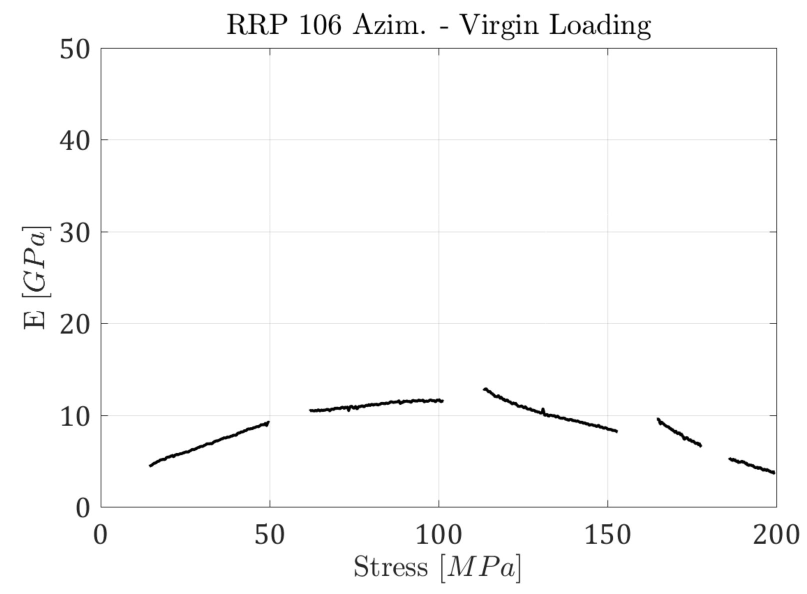
Strands:

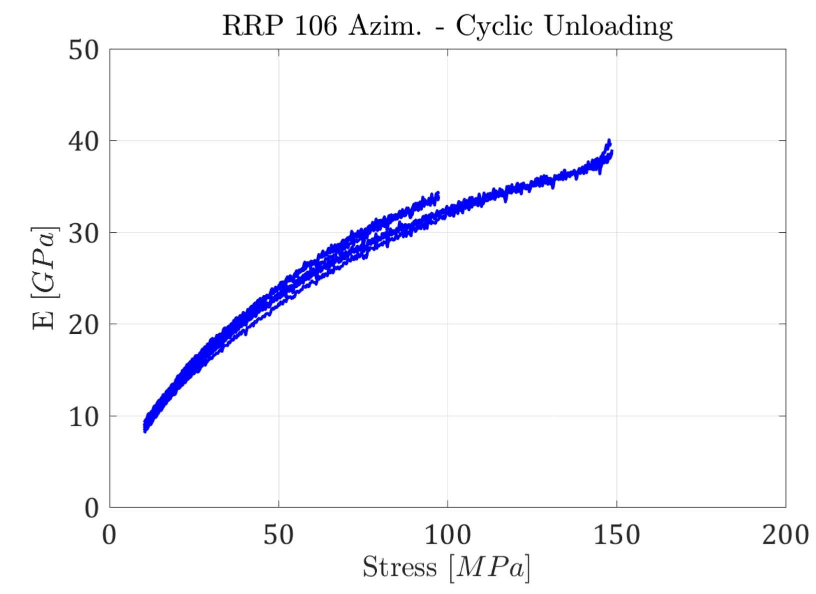
Nb_3Sn strands are prone to **critical current degradation** under the effect of mechanical **strains**. This degradation can be produced with both **axial** and **transverse** strain. Axial strains measurements were used to define **laws** governing the critical current degradation due to the applied axial strain. It was shown that they can also be used for strands under transverse pressure.

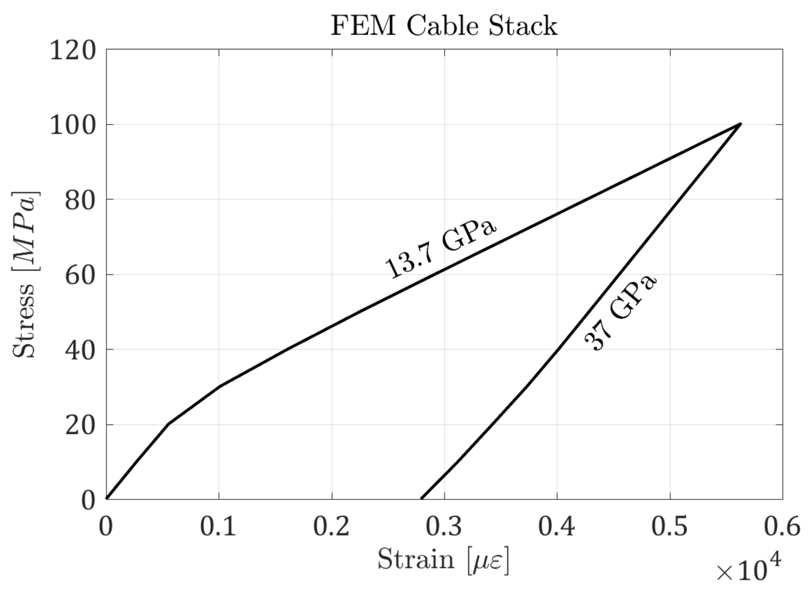
Accelerator Magnets Coils:

The degradation resulting from high strains inside the windings may compromise **magnet performances**. However, clear limit conditions are not available. Magnet mechanics are simulated approximating the windings as a **uniform block** with averaged mechanical properties. An **empirical** equivalent stress **limit** of 150-200 MPa is used at the moment.









Cable Stacks Under Transversal Pressure

Coils mechanical properties can be measured on **stacks** of impregnated cables. A detailed **stack FE model** was validated against the measured data. Strands were modelled as concentric **octagons** of copper and Nb_3Sn. The geometry was defined compatibly to the filling factor and the copper to non-copper ratio definitions. Material properties were extracted from literature.

$$e_o = \sqrt{\frac{h_o w_o - A_c \eta_f / N_s}{2}} \qquad \eta_f = \frac{N_s \pi (d_s/2)^2}{A_c \cos \beta_t} \qquad \alpha = \sqrt{\frac{1+\gamma^2}{1+\eta_{cu}}}$$

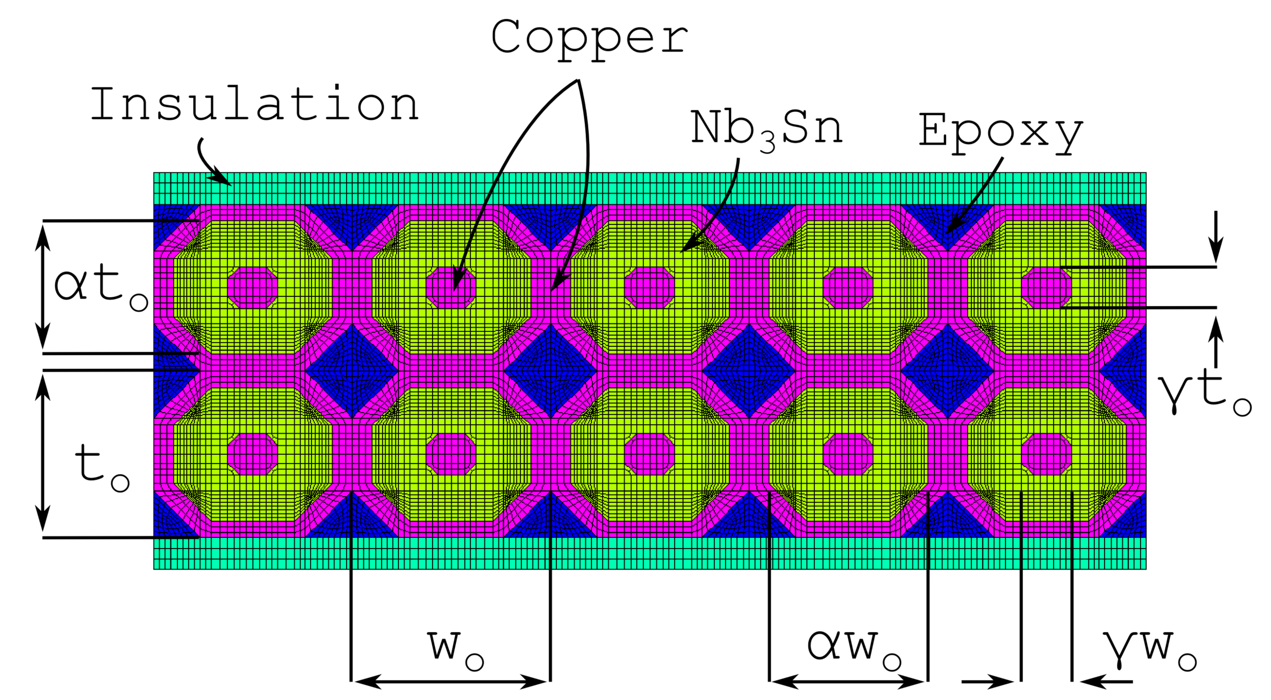


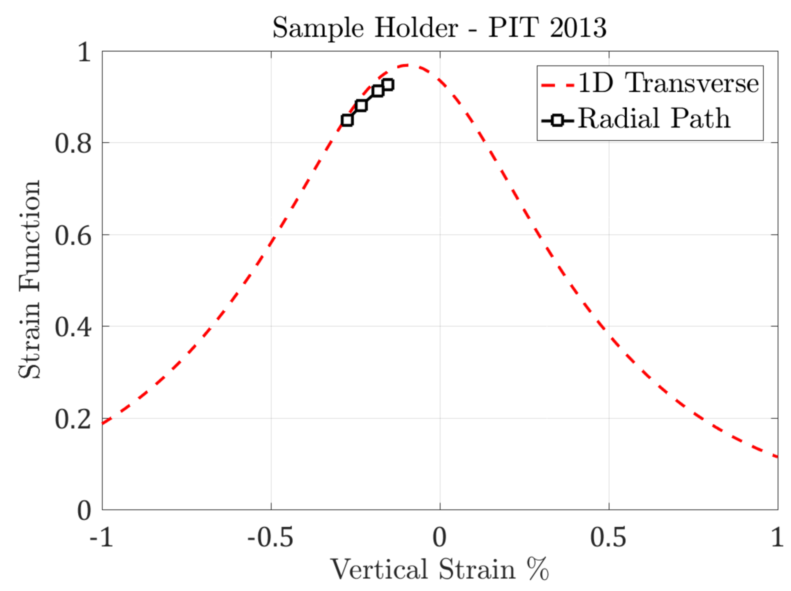
TABLE I
CABLE PARAMETERS

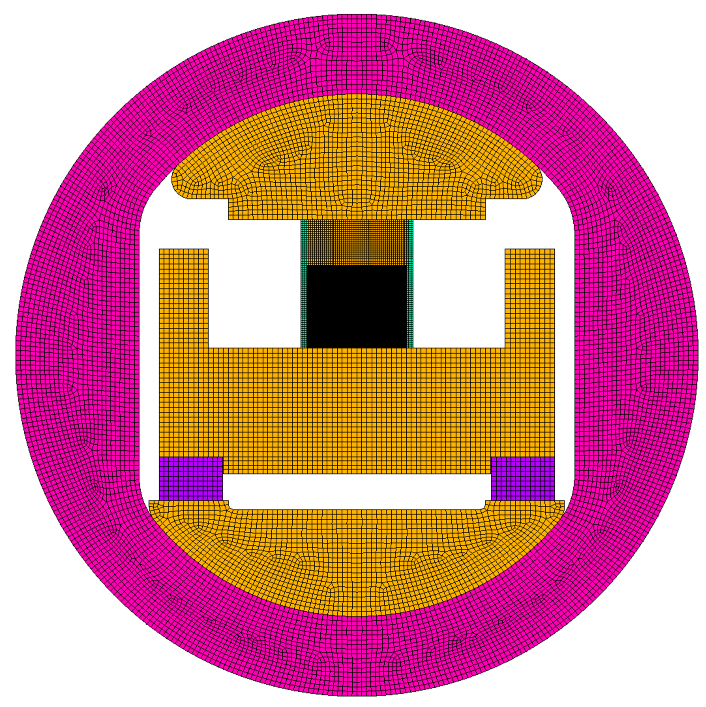
Parameter	Unit	Value - A†	Value - B‡
Strand	/	RRP 108/127	PIT 288
Strand diameter	mm	0.85	1.25
Number of strands in cable	/	40	18
Copper to non-copper	/	1.2	1.22
Twist Pitch	mm	14	63
Cable Bare Width	mm	18.15	10
Mid Thickness	mm	1.525	1.81
Keystone Angle	degrees	0.40	0

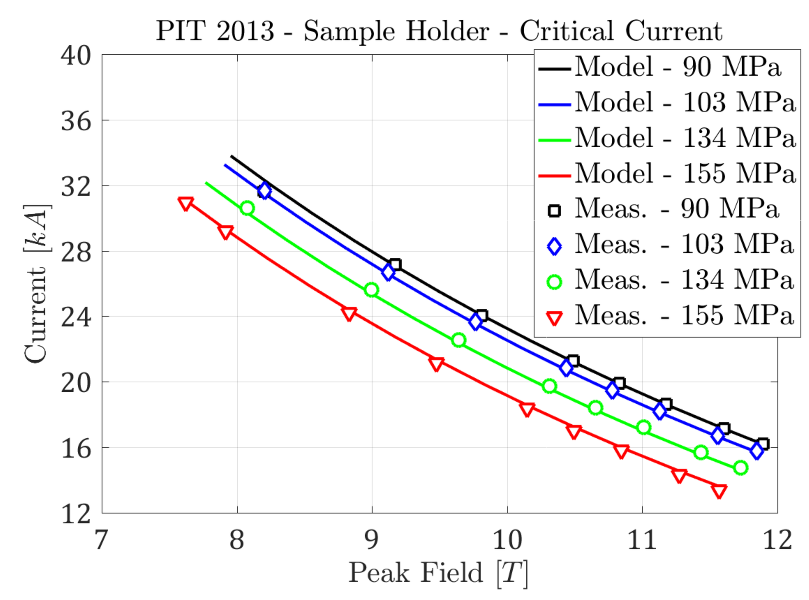
† 10-stack cable (MQXF [13]) - E measurements.
‡ Sample holder cable [3] - Critical current measurements.

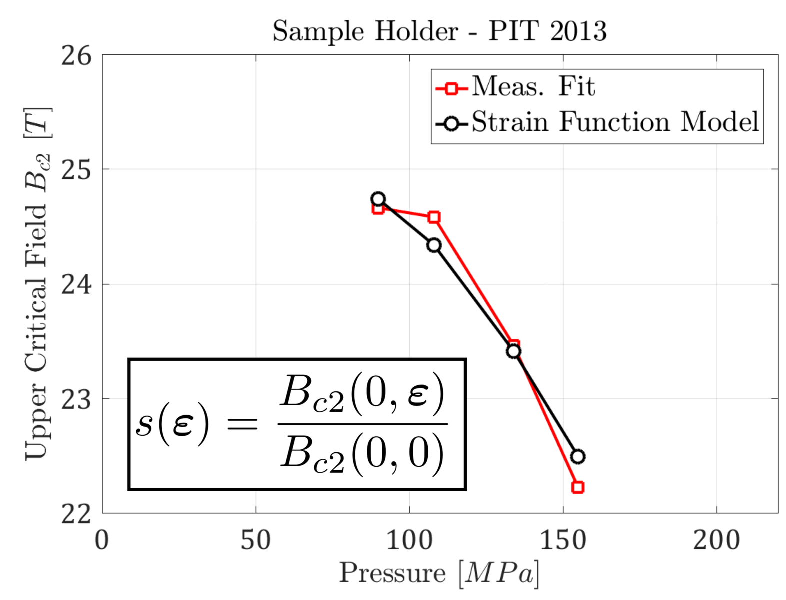
TABLE II
MATERIAL PROPERTIES

Parameter	Unit	Value
Copper Elastic Modulus (R.T.)	GPa	110
Copper Elastic Modulus (4.3 K)	GPa	120
Copper Yield Strength	MPa	30
Copper Tangent modulus	GPa	5
Nb_3Sn Elastic Modulus (R.T.)	GPa	100
Nb_3Sn Elastic Modulus (4.3 K)	GPa	70
Epoxy Resin Elastic Modulus	GPa	5
Impregnated Insulation Elastic Modulus	GPa	13









Critical Current Degradation

1. Effective Strain:

The strain computed in a detailed cable stack model has to be corrected considering the contribution of the **differential thermal contraction** of the strand components. The horizontal and vertical strain were also multiplied for a constant factor to account for the **stress amplification** at the **filament** level. The factor was found to be equal to 1.65. 3D models show that part of this factor (0.2) is due to the stress variation across the sample length.

2. Strain Function:

Because of the **twist pitch** of the **cable**, one can assume that all the strands will be subject to the same strains and field along the length of the sample. Also, since also the **filaments** are twisted, one can consider that all the elements at the **same distance** from the strand center will be in turn subject to the **same strain** and **field** condition. The strain function was then averaged along the strand radius. For the PIT 2013 sample strain function values were: 0.93, 0.91, 0.88 and 0.85.

$$s(\varepsilon) = \frac{e^{-C_1 \frac{J_2+3}{J_2+1} J_2} + e^{-C_1 \frac{I_1^2+3}{I_1^2+1} I_1^2}}{2} \qquad s_\mu(\theta) = \frac{1}{\Delta R} \int_{R_i}^{R_o} s(\varepsilon(r,\theta))dr$$

3 .

Magnetic Field:

The magnetic field inside the strand was computed as a sum of the background field and the self-field. As the strands are twisted, they will all be subject to the maximum field along the sample.

$$\vec{B}(x,y) = \vec{B}_{bg} + I\vec{K}(x,y)$$

4. Critical Current:

Ramping the applied current one can verify if a **critical condition** is reached or not. Remarkable **agreement** was found with measured values. However, the computed values for the most severe load are slightly higher than the measured ones. This may be due to a small percentage of **irreversible** degradation.

$$F_p = J_c(B, T, \varepsilon) \times B = Cg(s(\varepsilon))h(t)b^p(1-b)^q$$

Conclusion

The procedure proposed demonstrated the possibility of reproducing the measured critical current degradation on cable stacks under **transversal pressure** in the **reversible region**. This required **only one tweaking factor**, reasonably justified by the problem mechanics. This result suggests for the first time that the exponential **strain function** can be applied also to **Rutherford cables**. As these cable stacks should be mechanically very similar to **coil windings** (at least in the straight section), the result should be applicable without major corrections also to accelerator magnets. The methodology has the great advantage of not requiring the modelization of the **filaments**, which could be prohibitive in a magnet winding modeling. Clearly, a direct validation on superconducting magnets would require extensive testing.

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