# Magneto-Mechanical Coupling Analysis of A Hybrid Superconducting Solenoid Using FEM with Different Approaches


***Qiang Hu[1,2], Xingzhe Wang[1], Mingzhi Guan[2], Youhe Zhou[1]***

[1] Key Laboratory of Mechanics on Western Disaster and Environment, Ministry of Education (MoE), College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, China; [2] Institute of Modern Physics of Chinese Academy of Science, Lanzhou 730000, China.


## Background

The high-field superconducting magnet carrying with high current density are commonly exposed to large Lorentz forces leading to the unavoidable deformation in superconducting coils. The deformation will further disturb the magnetic field quality and the operating safety and stability of the magnet. An accurate estimation of the magneto-mechanical behaviors of superconducting coils during excitation is a crucial point.

## Objectives

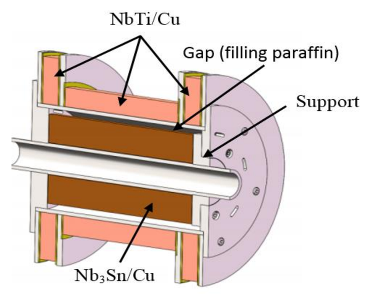
A coupled magneto-mechanical modeling for an hybrid superconducting solenoid was developed, to give a more accurate predictions on the composite structure, the finite element (FE) model utilized different modeling approaches, which include an orthotropic homogenized model to connect the micro-scale of the superconducting filaments to the macro-scale of the superconducting coil with RVE method, and a detailed hierarchical model consists of multilevel structures like superconducting wire, wire insulation and filling material were suggested, and compared with the predictions by an isotropic homogenized model and the experiment measurements.

## Conclusion

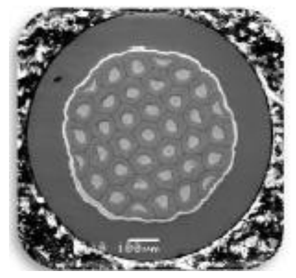
- For the magneto-mechanical behavior predictions, the prediction results of detailed hierarchical model shows the best agreement with the experimental results, the results of orthotropic homogenized model is second, isotropic homogenized model is the worst, especially under the high fields.
- We also found that the maximum stresses all occur within the superconducting wire by means of the detailed hierarchical model, and the simulation results of the detailed hierarchical model could show more details on the stress state of superconducting wire, wire insulation and filling material, one that the isotropic/orthotropic homogenized FE model could never achieve.
- These results would help the high field superconducting magnet designers to numerically predict the magneto-mechanical behaviors of the superconducting solenoid.

## Structure of magnet

A hybrid superconducting solenoid with maximum central magnetic field up to 10 T, consisting of a central $Nb_3Sn$/Cu main solenoid coil, NbTi/Cu solenoid and two NbTi/Cu shield coils.




Cut away view of magnet

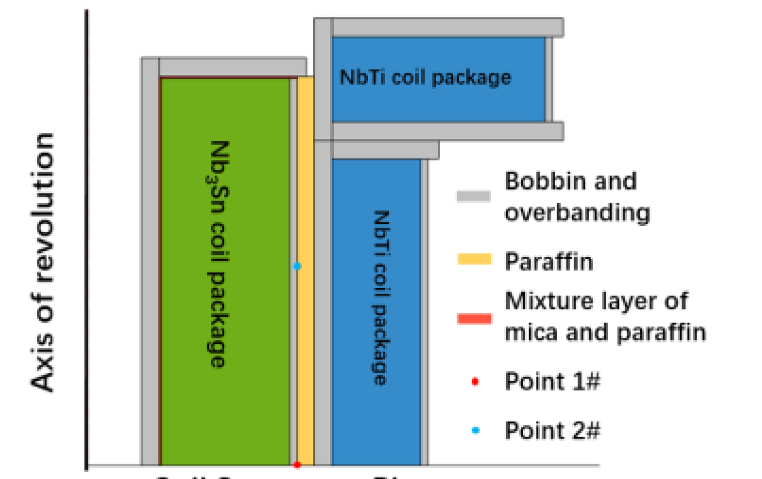


$Nb_3Sn$/Cu wire and microscopic structure

In our study, the central $Nb_3Sn$ solenoid would be main considered, because it sustains high field and the $Nb_3Sn$ filaments are strain sensitive and brittleness.

## Method

### Coupled FE modeling




**Axisymmetric structure and components for the FE model**

The Point 1# and Point 2# are the locations of the strain measurement.

**Maxwell electromagnetic theory**

$$\nabla \times \mathbf{H} = \mathbf{J}, \quad \nabla \cdot \mathbf{B} = 0, \quad \mathbf{B} = \mu_0 \cdot \mathbf{H}$$

**The FEM formulas for magneto-mechanical coupling analysis was implemented based on the following governing equations and constitutes**

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{J}(\mathbf{u}) \times \mathbf{B}(\mathbf{u}) = 0, \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}), \boldsymbol{\sigma} = \mathbf{D} \cdot \boldsymbol{\varepsilon}$$

When the coils deform caused by the Lorentz force, the transport current in the coils and the magnetic field will accordingly alter, which further change the force distribution. Such a coupled problem arises from the electromagnetic forces and structural deformation.

### Isotropic Homogenized Model (IHM)

The isotropic material properties of the superconducting coil was obtained by the rule of mixture

$$E = \sum E_i V_i, \nu = \sum \nu_i V_i$$

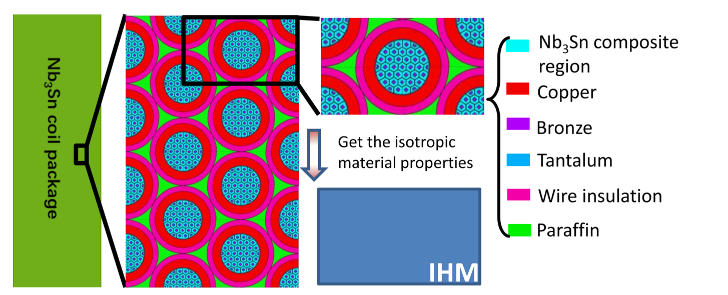



Diagram drawing of IHM of the $Nb_3Sn$ coil package

### Orthotropic Homogenized Model (OHM)

The orthotropic material properties of the superconducting coil was obtained by the RVE method

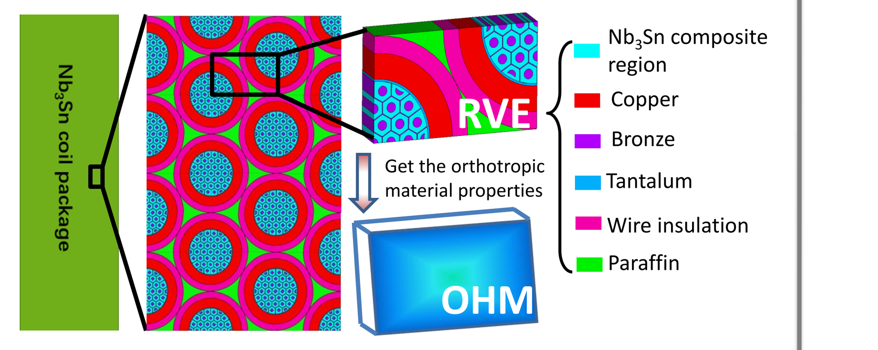



Diagram drawing of the RVE and OHM of the $Nb_3Sn$ coil package

### Detailed Hierarchical Model (DHM)

The detailed hierarchical model, the $Nb_3Sn$ coil package is taken as a composite one, which consists of superconducting wire, wire insulation and paraffin. The superconducting wires were homogenized according to the micro-structure of the composite wire. The exciting currents just only are evenly loaded on superconducting wire.

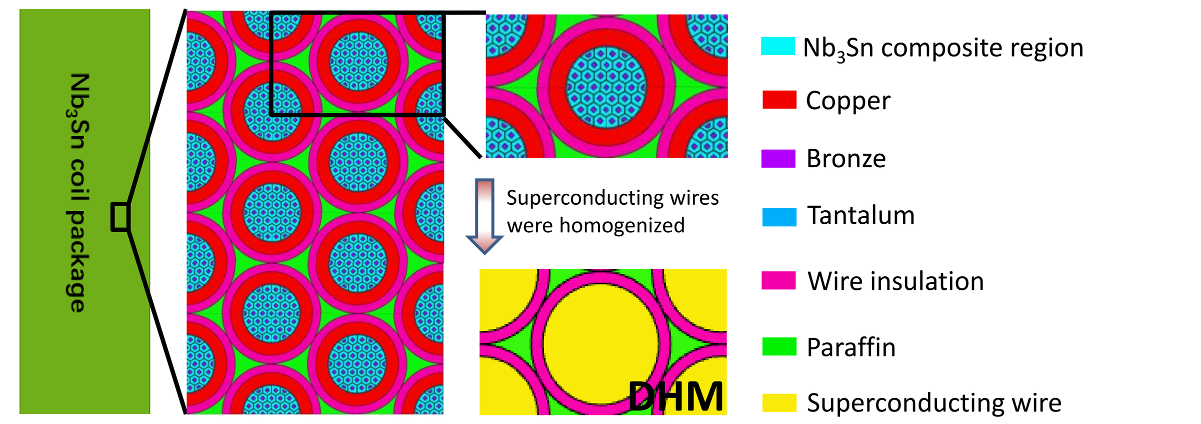



Diagram drawing of IHM of the $Nb_3Sn$ coil package

## Results

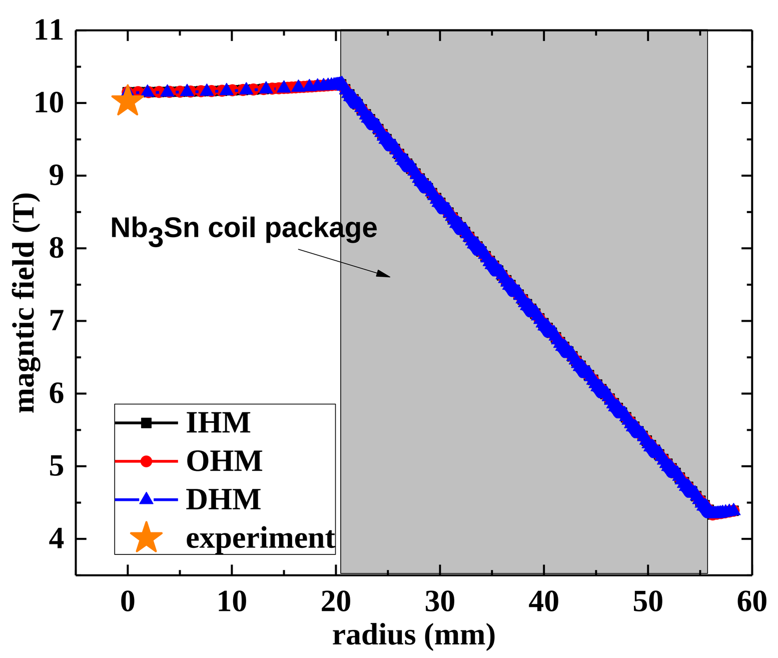



**Fig.1. Magnetic field versus radius at the symmetry plane(@10 T, 122 A)**

- The numerical predictions show an almost linear relation between the magnetic field and radius location at the symmetry plane of the $Nb_3Sn$ coil package.
- The three simulation results are almost coincident, and agree with the experimental value at the central position of the solenoid.

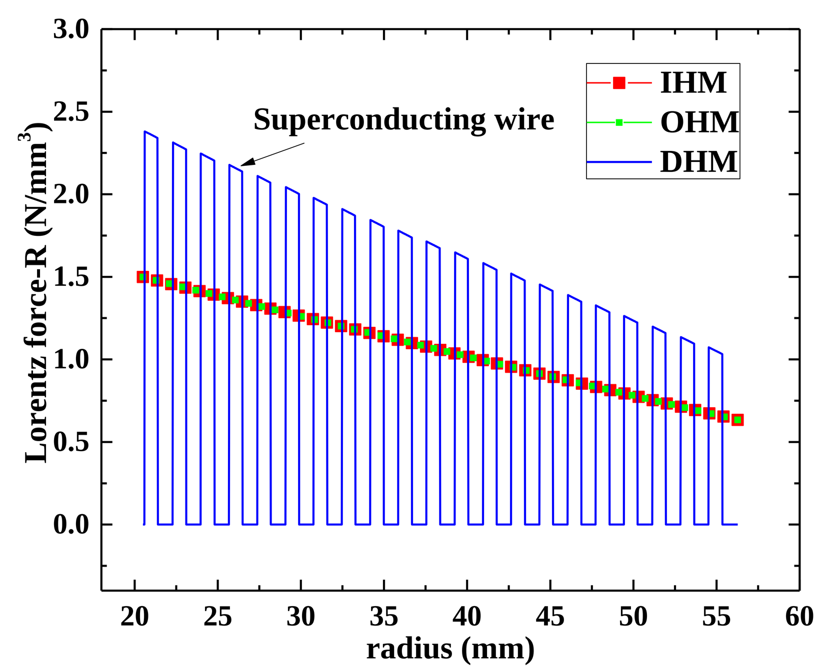



**Fig.2. Radial Lorentz force versus radius at the symmetry plane of $Nb_3Sn$ coil package(@10 T, 122 A)**

- For the IHM and OHM, the Lorentz forces show good continuity along the radial direction of coil package due to the exciting current is evenly/equivalently distributed over the cross section of coil package.
- For the DHM, the Lorentz forces show discreteness and just occur within superconducting wire due to the exciting currents just only are evenly loaded on superconducting wire.

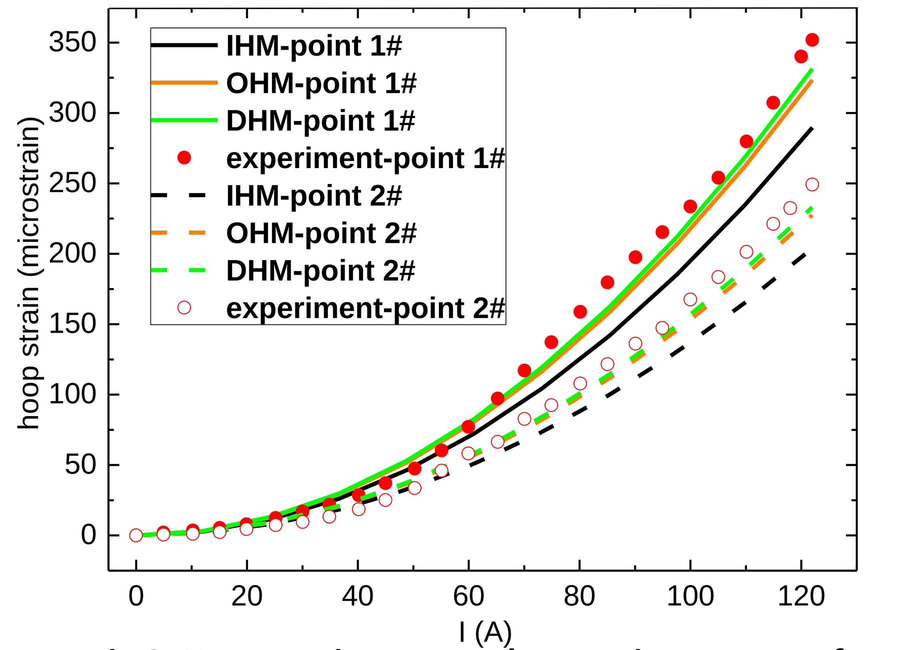



**Fig.3. Hoop strains versus the carrying current of the $Nb_3Sn$ coil package at point 1# and 2#**

- The prediction results of OHM and DHM are almost at the same, and match well with the experimental results at the both locations.
- The results of the IHM have some differences between the predictions and measurements under the higher fields at the both locations.

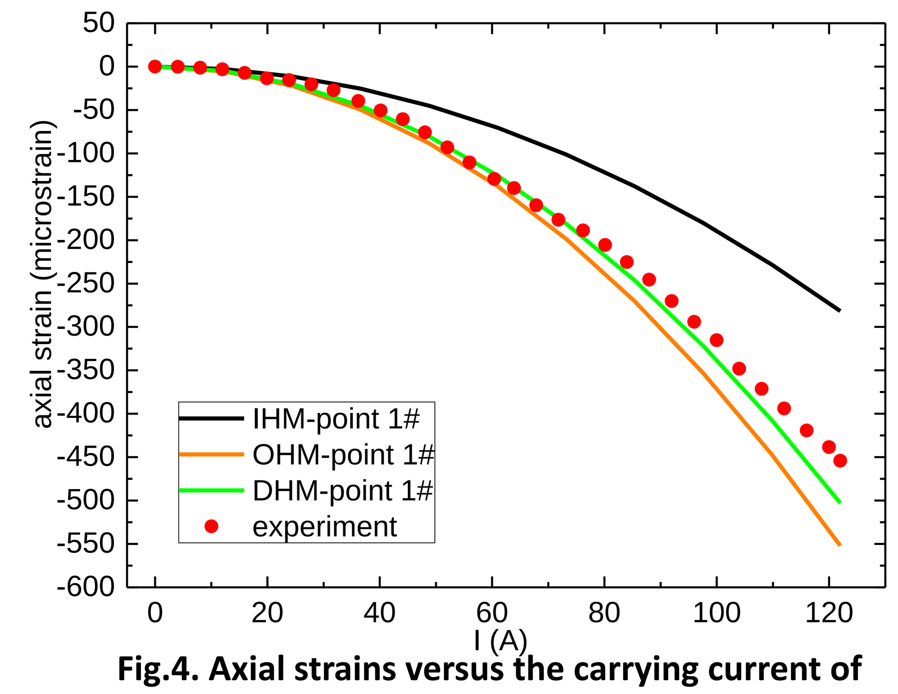



**Fig.4. Axial strains versus the carrying current of the $Nb_3Sn$ coil package at point 1#**

- The prediction of DHM show the best agreement with the experimental results, the results of the OHM is second, IHM is the worst at the point 1# location.
- The OHM overestimates the axial compression strains, the IHM underestimates the axial compression strains at the point 1# location.

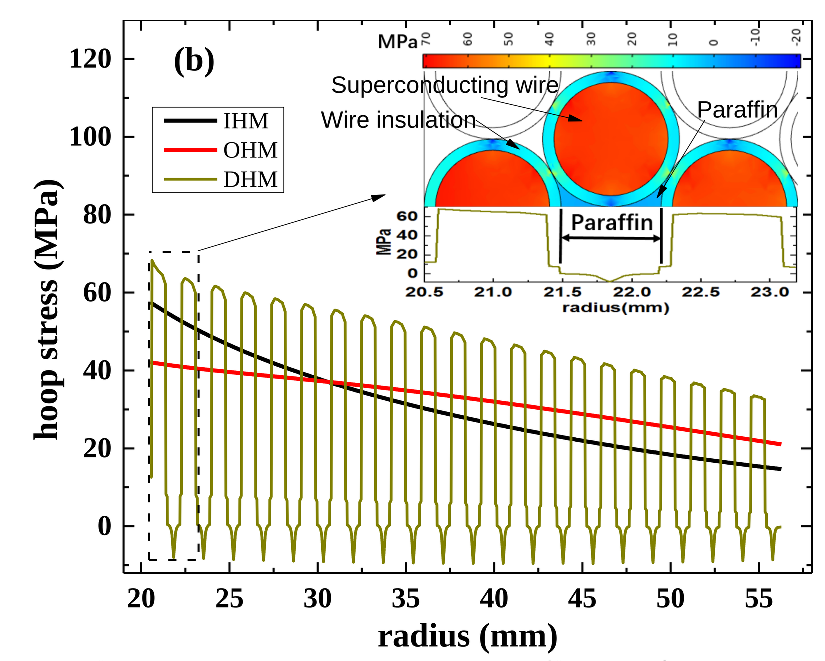



**Fig.5. Hoop stresses versus radius at the symmetry plane of $Nb_3Sn$ coil package (@10 T, 122 A)**

- The curve of DHM presents periodic fluctuation along the radius direction that caused by difference material properties of the component materials.
- From the partial detail picture of the top right corner of this figure, we can see that the maximum stresses are all occur within superconducting wire, the region of superconducting wire and wire insulation are both under tensile stress.

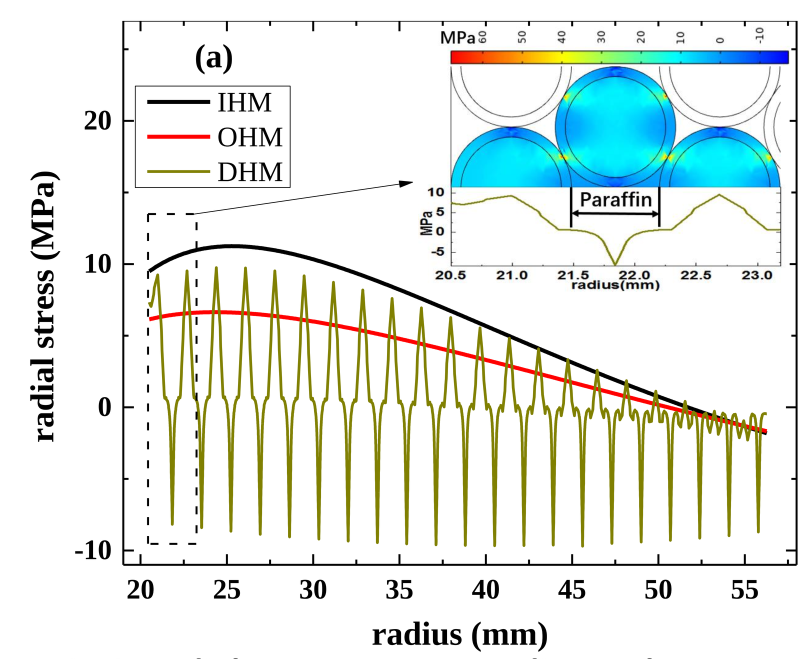



**Fig.6. Radial stresses versus radius at the symmetry plane of $Nb_3Sn$ coil package (@10 T, 122 A)**

- The maximum radial stress all occur within the near the innermost layer of $Nb_3Sn$ coil package.
- From the partial detail picture, we can see that the region of superconducting wire and wire insulation are both under tensile stress, in contrast, the region of paraffin is under compression stress.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