Electromagnetic and mechanical analysis of a 14 mm 10 period NbTi superconducting undulator

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Abstract--A 14 mm - 10 period NbTi superconducting undulator for the next generation of Free Electron Laser has been studied. The optimum electromagnetic pre-design was carried out using RADIA, an extension module of the commercial software Mathematica. For this pre-design, a variable gap was considered. Additionally, a thermo-mechanical study of one eighth of the superconducting undulator was conducted. A coupled thermo-mechanical model allowed estimating the minimum pre-loading of the coil. This pre-loading ensures that the coil would remain stuck to its pole during cooling. Numerical results are presented for both studies.

This work is a preliminary steps the growing interest of India in upgrading its facility and the interest of Mexico in building a first Mexican light source.

Coupled thermo-mechanical model

A coupled thermo-mechanical 3D Finite Element Analysis (FEA) of the SCU was conducted using the electromagnetic pre-design as geometrical input. Both the thermal and mechanical equations incorporate contact modelling.

Thermal model

The heat balance equation to solve the temperature field of the SCU is given by

$$\nabla.[k\nabla T]=\rho c_p \frac{\partial T}{\partial t}$$

The thermal contact is modelled through an equivalent heat transfer coefficient h = 2800 W/m^2-K.

Mechanical model and coupling

$$G\nabla^2\mathbf{u} + \frac{G}{1-2\nu}\nabla(\nabla.\mathbf{u}) - \frac{E}{1-2\nu}\alpha\nabla(T) = \rho\ddot{\mathbf{u}}$$

Where G, E and ν is the shear modulus, the Young modulus and the Poisson's ratio, respectively. The coupling is carried out through the temperature field. A pre-loading guaranties that the coil does not delaminate from its support during cooling. A situation that often leads to early quenches imàiring the SCU to reach its nominal operation.

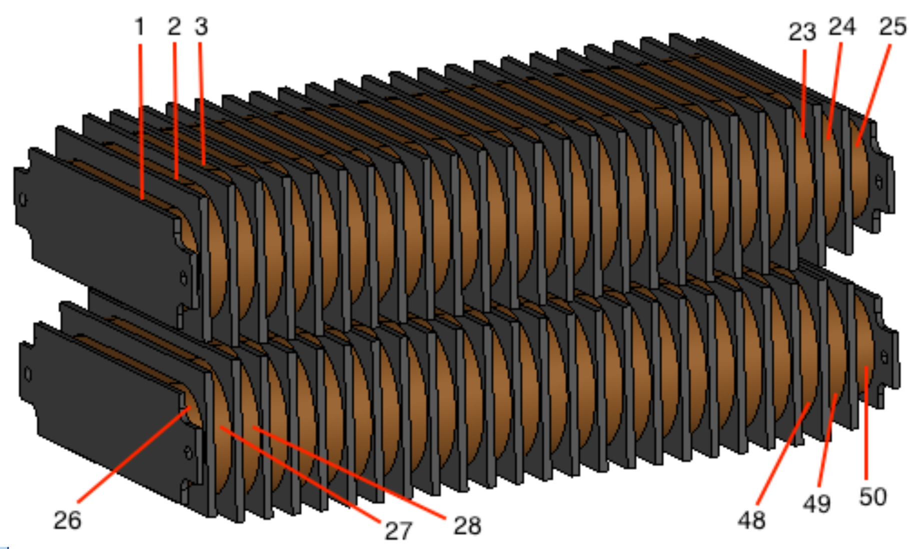


Fig. 1. SCU structure with coil packs.

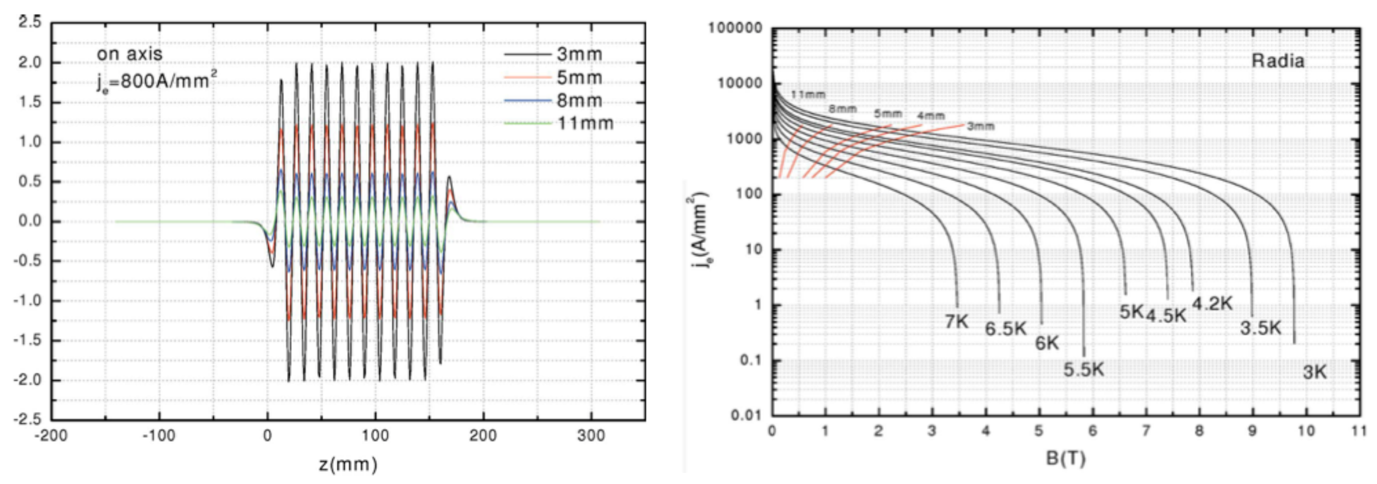


Fig. 3. Pattern of the magnetic flux density generated by the SCU and current margin on the superconductor for different gap.

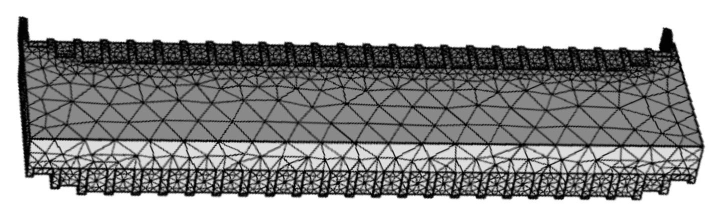


Fig. 2. Meshing of 1/8 th of the SCU.

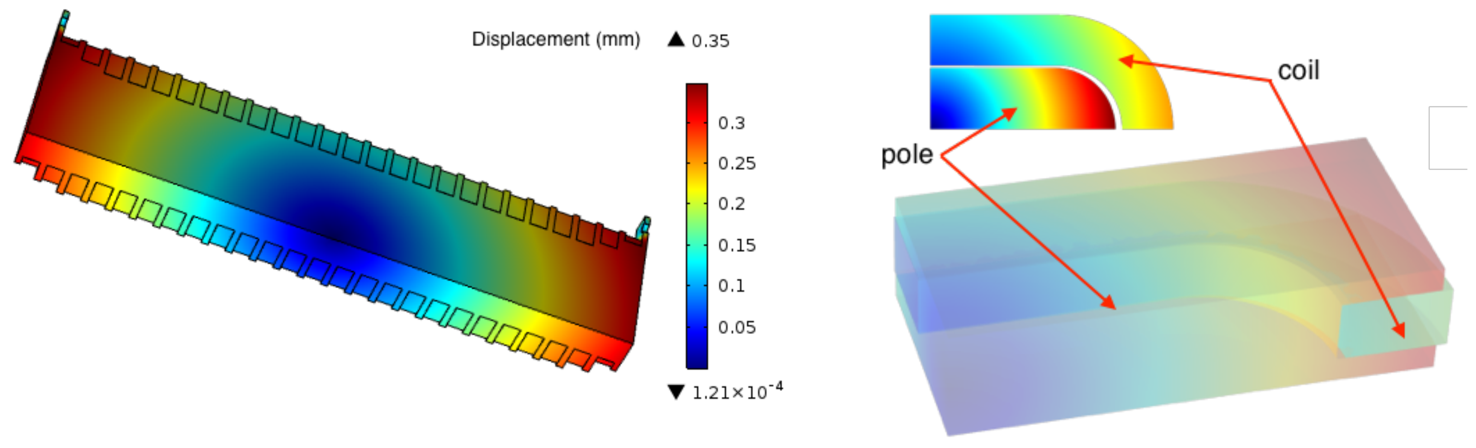
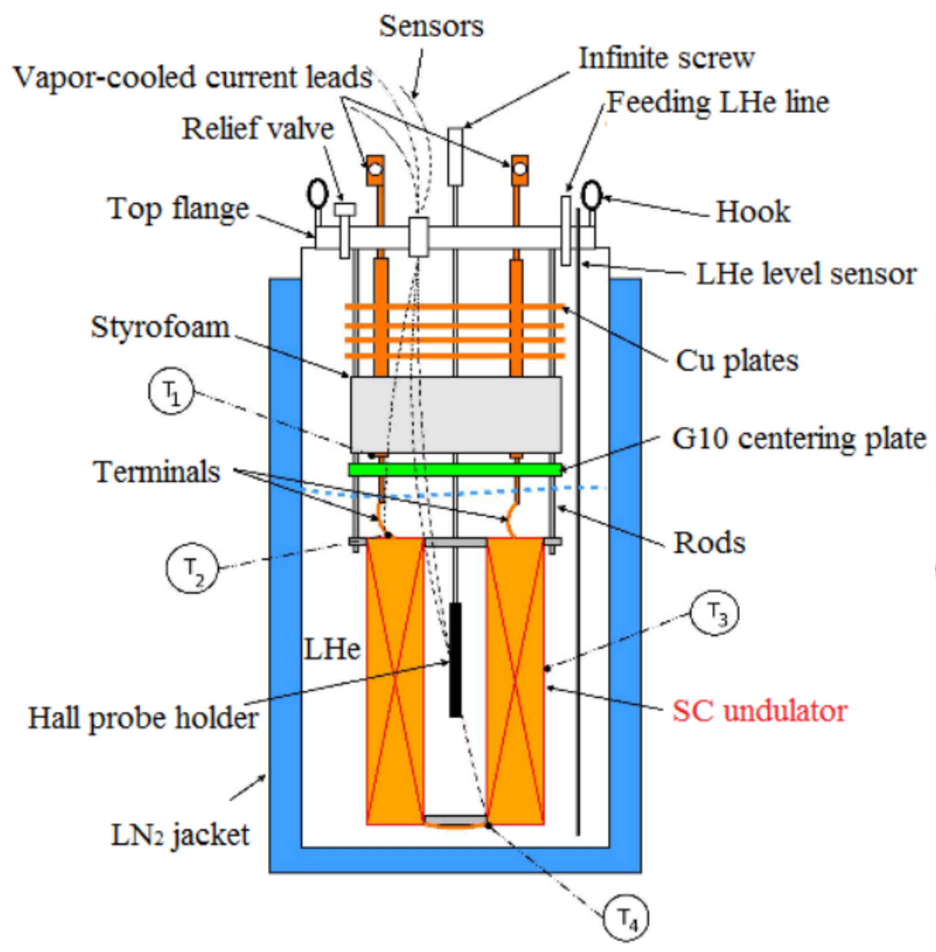
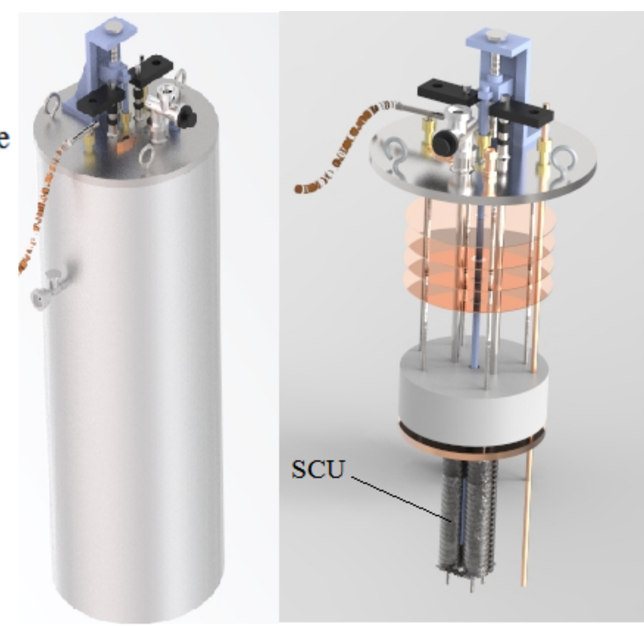


Fig. 4.Left, displacement field. Right, separation between the coil and its support (amplified by a factor of 15).





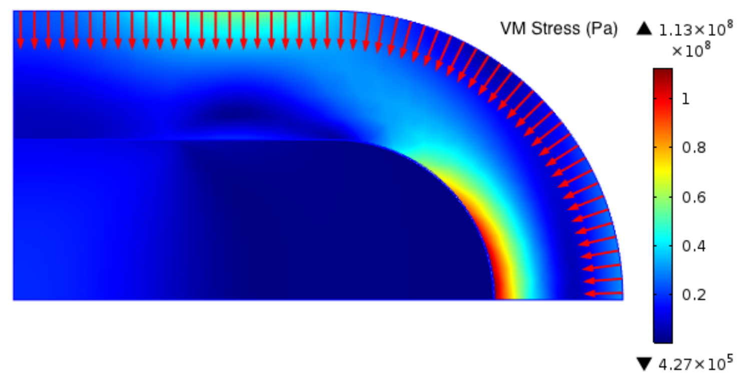


Fig. 5. Pre-loading of 25 MPa to ensure the contact between the coil and its pole.

Results

A rectangular insulated NbTi wire (1 mm x 0.5 mm) is proposed to reach 1 T on axis keeping a current margin of the order of 10% at 4.2 K an a gap of 5 mm (fig. 3).

Assuming that the coil is poorly bonded to its carbon steel support, it is likely to delaminate as shown in fig. 9. A maximum separating of 0.05 mm occurs at the circular portion of the racetrack coil. Over the straight section, the separation amounts to 0.024 mm.

By applying a pre-loading of about 25 MPa, this separation disappears and the stress develop at the contact reaches an admissible value of 113 MPa.

It should be noted that this model, elastic by assumption, does not include phenomena such as cracks and fractures. Therefore, the resulting deformation once the temperature of the SCU reached 4.2 K is independent of the cooling velocity. It is a limitation of the model which can difficulty be overcome without experimental data

Conclusion:

A preliminary mechanical and magnetic study has been conducted to build a NbTi superconducting undulator prototype to be tested at 4.2 K in liquid helium. This first Indian superconducting prototype is expected to be tested at the Insertion Device Development and Measurement Lab of the Devi Ahilya University, Indore, India.

The electromagnetic pre-design targets a 1 T magnetic flux density on axis for a gap of 5 mm.

To avoid the possibility of delamination of the coils during cooling, the magnitude of the pre-compressing force (pre-loading) was estimated to be 25 MPa.

Further works are still necessary to take into the mechanical behavior of the SCU poles during energization. In addition to the thermal forces, the Lorentz force will be added to the mechanical model to get the proper pre-loading.

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