STRESS COMPUTATION IN THE C400 SUPERCONDUCTING COIL USING THE OPERA-2D STRESS ANALYSIS MODULE

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Abstract

A tender for the study and construction of a large superconducting split solenoid for the C400 carbon therapy cyclotron was issued by IBA in March 2008 and awarded to Sigmaphi. Although the current density is moderate, the large radius and average field imply quite a high level of hoop stress. Simple formulas range between 140 and 180 MPa and, with such large values and uncertainties, it was felt necessary to perform a finite element analysis of the structure. Average fields in a cyclotron are very well modelled using an axially symmetrical structure and the stress was therefore studied using the stress module of the Vector Fields Opera2d suite. Different models were tried with different levels of details. A comparison is made between them as well as with the analytical results.

INTRODUCTION

The C400 cyclotron for carbon therapy [1] has a split pair superconducting coil to generate the magnetic field in the machine. Sigmaphi s.a. will conduct the full study and construction of the coil and its associated cryogenic structure. The 2134 mm average radius, approximate 200 x 200 coil is made of 1344 turns -1000 A "wire in channel" type conductor in epoxy resin, making it one of the largest compact composite/copper epoxy impregnated structure to date. Being close to the cyclotron iron yoke, it experiences rather high fields, thereby generating high stresses in the coil structure. The present paper describes ongoing studies on these stresses.

2D MODELLING OF THE CYCLOTRON

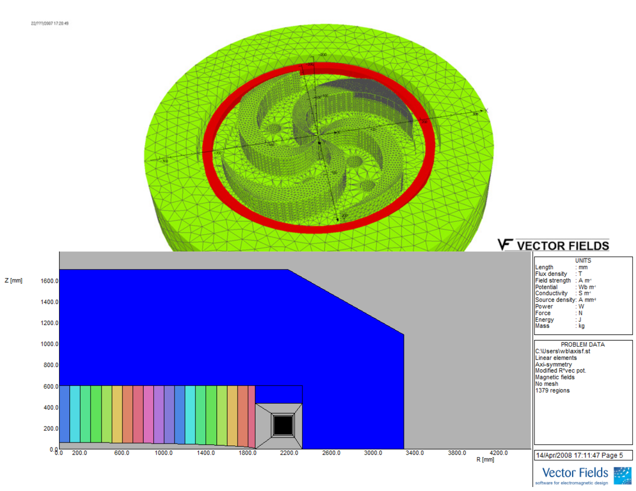

Figure 1: 3D view and 2D modelling of the cyclotron.

Figure 1.shows the inside layout of the cyclotron. Although a very tri-dimensional structure, the strong iron saturation allows an adequate 2D modelling using stacking factors. The azimuthal split between regions of high and low fields is mimicked by downgraded material B-H properties rated by the angular ratio of hills and valleys. Those pseudomaterials have B-H curves given by

$$B_{pseudo} = \mu_0 H + k.(B - \mu_0 H)$$

with k, the stacking factor is the proportion of the full circle occupied by iron.

With such a model, the fields at the coil location are very close to the fields from a 3D model and a 2D stress study can be performed.

STRESS STUDIES

Stress in the Insulation

Because all resins become brittle at 4K, it is important to avoid tensile stress in the insulation, which often occurs in thick coils. Simple criteria are based on plots of radial stress as a function of coil geometry, using the parameters α = outer radius / inner radius and β = inner field / outer field. With α = 1.10 and β = -4.71, such diagrams as presented in [2] show that our coil is very well inside the fully compressive region both in radial and axial stresses and should raise no problem to the resin.

Stress in the Conductor

The axial component of field produces a radial force on the conductor which results in a tensile hoop stress. Simple formulas ignoring any strength in the insulation and assuming all the stress is taken by the metal of the conductor deliver values ranging between 140 MPa (Wilson's infinite solenoid [2]) and 180 MPa (Iwasa's mean field at mean radius [3]) but the clearly pessimistic approach of the unsupported turn gives a very high 440 MPa. These values are too much on the high side and too scattered to rely on them and it is highly desirable to conduct a finite elements study.

The Simplest Finite Elements Model

The coil is analyzed using the Opera2d-sa stress analysis module (ERA Technology Ltd formerly Vector Fields Ltd). The first model is used to check that the values are found within the expected range. It features a coil with average properties derived from the parallel mixtures rule as given by Iwasa [3] where the Young modulus of the composite is the sum of the modulus of each component weighted by its fractional area.

This model delivers a coil that is in compression in both radial and axial directions. It also delivers a hoop stress of 105 MPa, much lower than the semi-analytical values. This reflects its inability to properly take into account both the correct current density and the correct geometry at the same time. Indeed, the coil cross-section is considered filled with conductor and the current density is decreased accordingly to get the proper field values. However, the actual conductor filling factor being ~78%, the real stress is thus ~105/0.78 = 135 MPa, in much better agreement with the expected values.

A Better Model – Macro Conductors

The actual cross-section should look as depicted in figure 2 but as one of the main concerns is about the resin, we can't believe an answer where the resin is meshed with only one layer of elements.

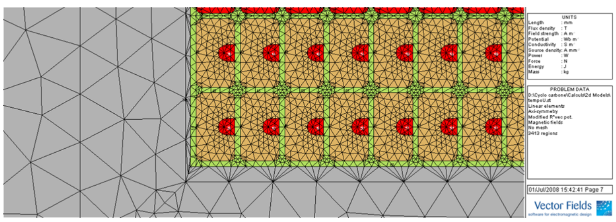

Figure 2: Realistic cross-section of the coil.

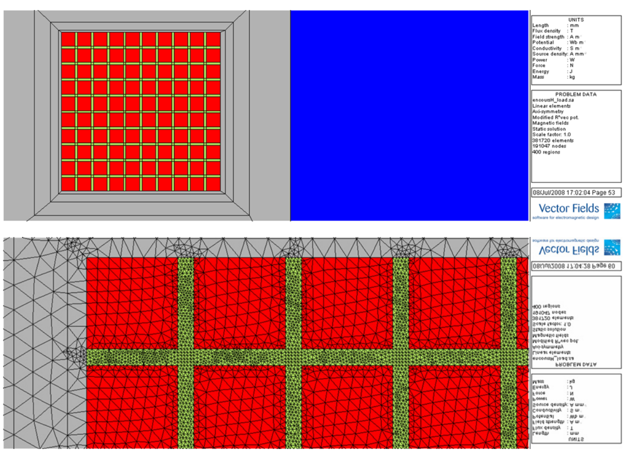

Figure 3: Subdivision in macro conductors with dense meshing in the resin.

As resin layers are very thin compared to copper, a simple model is first studied with the coil material shared in 10 sections instead of describing all conductors in detail. Using such "macro-conductors", fine meshing can be made (Figure 3). A 137 MPa maximum hoop stress is found (figure 4). Its distribution along radius as well as its magnitude is now in very good agreement with the simple formulas. The coil is found to radially displace by 2.1 mm. The model also points out a small trend towards tensile axial stress on the coil top. A restraint plate which is needed to cope for a repulsive force between the coils at low currents during power up, will keep the coil top in compression

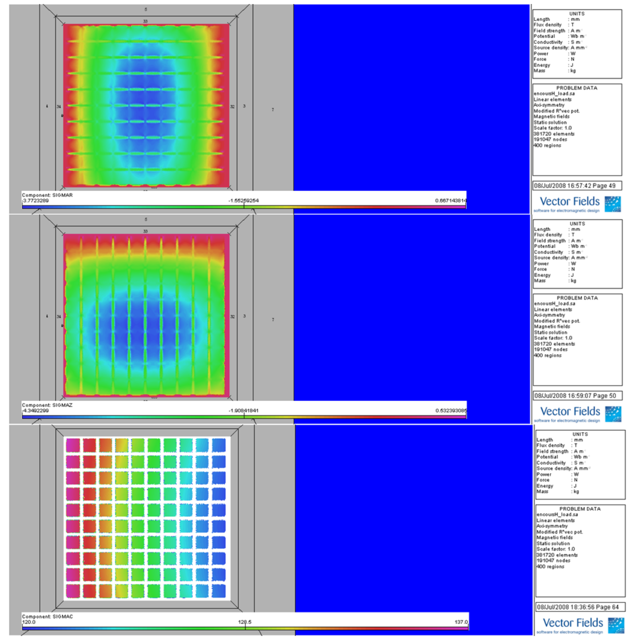

Figure 4: Radial, Axial and Hoop stresses in the macro-conductors model.

This model is also used to study the variation in hoop stress as a function of the mechanical characteristics of the insulating material (figure 5)

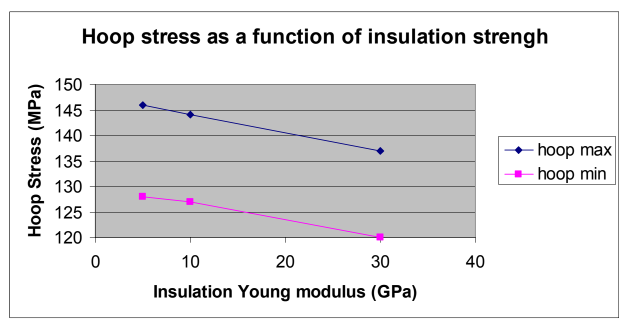

Figure 5: Hoop stress versus insulation strength.

Full Model with Support

As a split pair, there is a strong attraction force between the coils across the median plane In all previous models, the coil is prevented from displacing axially by boundary conditions and is only allowed radial displacements. Unfortunately, the real world doesn't allow such a Harry Potter's feature and a real support must be taken into account together with its interactions with the coil. All the coil features are now described as accurately as possible and 2 support geometries, flat and tilted, are studied.

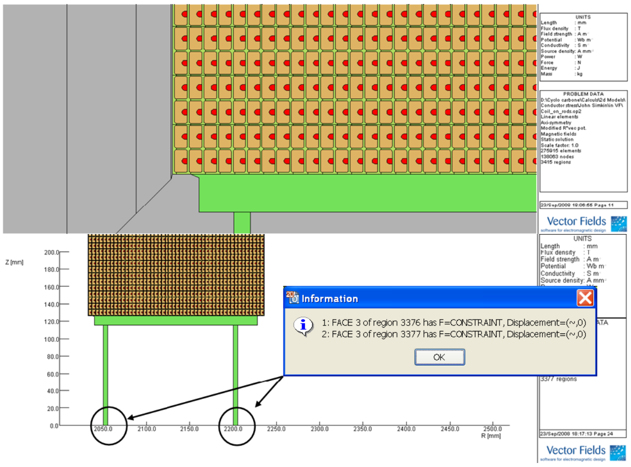

Figure 6: Full model with supports with axial boundary conditions on the support pillars.

The materials properties are listed in the table below. The shear modulus G is derived from the Young modulus E and the Poisson ratio in the limit of homogeneous isotropic linear elastic materials as

$$G = \frac{E}{2(1+\nu)}$$

Table 1: Material properties used in the model

	Density (kg/dm^3)	Young E (GPa)	Poisson ν
Cu	8.933	150	0.33
SC	8.698	160	0.32
G10	1.100	20	0.28
Support	0.800	8	0.30
Buffer	8000	0.001	0.30

The support and buffer materials have such rather awkward characteristics so that the support is strong enough but able to sink and the buffer can be completely squashed while at the time providing an interface that allows the coil nodes to slide with the support nodes remaining fixed. Figure 7 displays a 1mm support tilting.

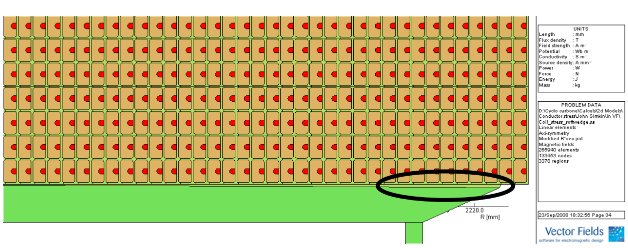

Figure 7: Tilted support modelling.

Figure 8 compares radial stress, axial stress and coil displacement for a flat (left) and tilted (right) support.

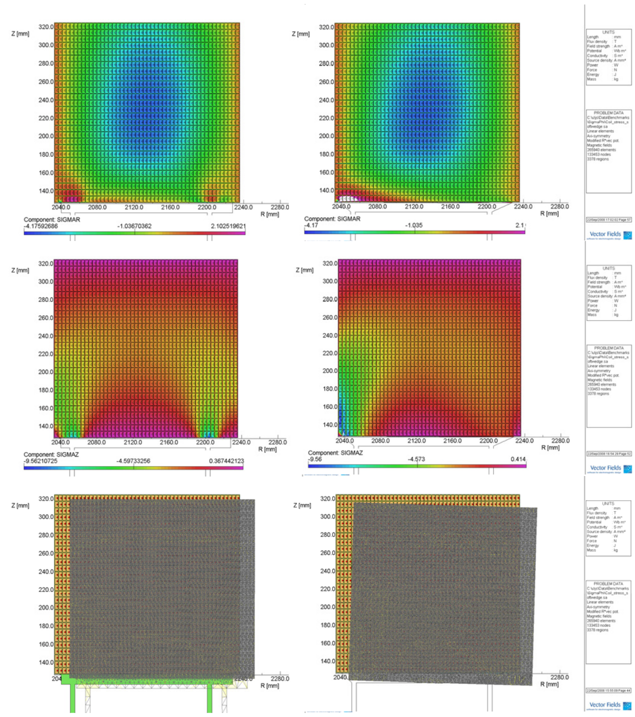

Figure 8: Comparison of radial stress, axial stress and coil displacement for a flat and tilted support.

The radial stress pattern is very similar to those observed in other models and the values are very small compared to allowed maxima. However, radial stress pattern features small tensile zones on the inner side of the pillar where the coil has a tendency to lag behind while moving. The axial stress pattern is very different from previous models. As expected compressively constrained zones are observed on top of the supporting pillars while a slightly tensile zone develop above the centre of the support if it is not rigid enough. The appearance of tensile axial stress on the top of the coil is confirmed and needs to be dealt with using compression plates. Tilting the support doesn't change things too much on the average but since larger tensile zones develop, such coil tilts must be kept very small.

Small zones of shear stress also develop close to the support. They will need more care since maximum tolerable values are much smaller in shear than in radial or axial and values above 40 MPa should be avoided

REFERENCES

[1] Y. Jongen et al., "IBA C400 Cyclotron Project for Hadron Therapy", 18th Int. Conf. Cyclotrons and their Applications, Giardini-Naxos, Italy, Oct 1-5 2007, and other papers on C400 at the same conference

[2] M.N. Wilson, 'Superconducting Magnets', pub Oxford Science Publications, Clarendon Press, Oxford (1983), reprint 2002

[3] Y. Iwasa, "Case Studies in Superconducting Magnets Design and Operational Issues", Plenum Press (1994)