Design Notes for Fusion Reactor Magnets

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R.W. Boom and W.C. Young

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Design Notes for Fusion Reactor Magnets*

by

R. W. Boom and W. C. Young
Nuclear Engineering and Engineering Mechanics Departments
University of Wisconsin, Madison

The design of supermagnets for fusion containment is determined more by stress problems than by superconductivity. This emphasis on structure arises because the amount of required structure is proportional to the stored magnetic energy(1) which, for fusion magnets, is a large value such as 10^{10} to 10^{12} joules. A typical magnet turn might be taken as that used for the NAL-Bubble Chamber(2): NbTi filaments in a copper strip wound tightly with strips of stainless steel and mylar. As the current and field in the magnet and conductor are increased the copper and steel expand together sharing the applied hoop stress. Two magnet designs are possible with this conductor, either the copper will be stressed beyond the yield point, in high stress designs, or low stress thicker windings will be used which do not cause the copper to yield.

Case 1. $\sigma_{cu} \lesssim 12000$ psi

The copper stress is held below 12,000 psi, the OHFC yield stress at 4.2°K. Since the steel elastic modulus is twice the copper modulus and the elongations are identical it is impossible to get average stress levels above 24,000 psi. If enough copper is retained for electrical and thermal stability then 16,000 psi is a probable maximum design stress. As an example, replacing a solenoid by a thick wall cylinder with an internal pressure $B_o^2/2\mu_o$, the maximum applied hoop stress is:

$$\sigma_t = \frac{B^2}{2\mu_o} \cdot \frac{\alpha^2 + 1}{\alpha^2 - 1} \qquad (1)$$

where α is the ratio outer radius/inner radius. Equation (1) predicts very thick windings for low σ_t values; using 16,000 psi one gets winding thickness/inner radius ratios of 0.1, 0.48, and 2.4 for central fields of 60, 100, and 160 Kilogauss respectively.

A more accurate numerical analysis of solenoidal layered windings has been made for the above conductor which includes a mylar layer (ignored above) and deformations of the mylar and its copper contact which concentrates compressive stresses on 1/3 the area.$^{(2)}$ The maximum copper hoop stress in psi is:

$$\sigma_c = \left[6774 + 27,660\,\lambda_M - 500\,\lambda_S - 33,300\,\lambda_M\lambda_S + \left\{7355 + 500\,\lambda_M - 3035\,\lambda_S + 10,000\,\lambda_M\lambda_S\right\}\frac{r}{t}\right]\frac{9.947}{1000}B_o^2 \qquad (2)$$

where λ_M and λ_S are the mylar and steel ratios compared to the effective copper in tension, r/t is the inner radius divided by total winding thickness and B_o is the central field in tesla. In addition to the effective copper each copper layer contains an extra 15 percent thickness over a portion of the coil to provide cooling passages. For steel, copper and mylar the moduli of elasticity used were: 30×10^6, 15×10^6 and 1.8×10^6 psi; Poisson's ratio was taken as 0.30, 0.35, and 0.37 respectively. This equation holds for $0.025 \leq \lambda_M \leq 0.075$ and $0.5 \leq \lambda_S \leq 0.65$. The results using equation (2) show that mylar softens up a magnet and increases hoop stresses by as much as 50 percent. The maximum radial stress occurs at about mid-thickness and is about 6 percent of the maximum hoop stress.

Thus the windings for low stress high field magnets seem almost prohibitively thick and heavy with copper and steel completely dominating the superconductor.

Case 2 $\sigma_{cu} \gtrsim$ 12000 psi.

In this case the steel is stressed to 60,000 psi which is below its yield. Then the copper will yield with an elongation of 0.002 and stress levels of about 18,000 psi. The copper should not go into compressive yield anywhere when the magnet is turned off. Thus it does seem possible to thereafter operate with the copper in an elastic region between 18,000 psi tension and something less than 12,000 psi in compression. A 30,000 psi maximum average stress for the steel plus copper would then be realized with considerably thinner windings possible.

It should be emphasized that yielding the copper (or aluminum which is an alternate conductor) is not at all conservative for $100,000,000 magnets. If yielding were to also accidentally occur in compression then on each cycle the magnet could loosen up, insulation abrasion could set in, and electrical resistivities would continue to increase.

1. R. H. Levy, ARS Jour., June 1962, page 787.

2. Private information: H. Desportes, D. Jones, and J. Purcell, Argonne National Laboratory.

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