Investigation of the Radiation Effects Upon the Stability of Fusion Magnet Coils

C.T. Yeaw

October 1993

UWFDM-929

Presented at 15th IEEE/NPSS Symposium on Fusion Engineering, 11–14 October 1993, Hyannis MA.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Investigation of the Radiation Effects Upon the Stability of Fusion Magnet Coils

C.T. Yeaw

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

http://fti.neep.wisc.edu

October 1993

UWFDM-929

Presented at 15th IEEE/NPSS Symposium on Fusion Engineering, 11–14 October 1993, Hyannis MA.

Investigation of the Radiation Effects upon the Stability of Fusion Magnet Coils

Christopher T. Yeaw
Fusion Technology Institute, University of Wisconsin
1500 Johnson Dr., Madison, WI 53706

ABSTRACT

The deleterious effects of the D-T fusion radiation environment upon the stability of the cable-in-conduit conductor (CICC) magnet coils have been both qualitatively and quantitatively investigated. Until now, no systematic and accurate analysis of the fluence dependence of the stability of these coils has been performed, and designs have been primarily concerned with the stability of the coils at startup. The analysis presented here shows that stability as a function of fluence (reactor operating time) degrades much more quickly than previously anticipated. This rapid degradation of coil stability has potentially profound design ramifications. The basis for the present analysis has been a code called MagRad, specifically developed for the purpose of predicting the stability of a fusion magnet coil as a function of fluence, given the coil geometry, flow parameters, and initial materials characteristics. Radiation has significant effects upon some of the basic materials parameters of the coils, such as the stabilizer resistivity and the critical temperature and upper critical field of the superconductor. The code, CICC, developed by R. L. Wong, together with the Dresner formulation for the limiting current, have been incorporated as reliable predictors of the stability of the coil at startup, which is used as input for MagRad. Most recent data is used with respect to radiation effects upon the materials properties of the coil. Significantly, inappropriate assumptions used in the semi-analytical form which predicts upper critical field as a function of fluence (which has hitherto been widely accepted and used in stability codes) have been corrected in this present study, and a new and much improved empirical form which represents a fit to the data is presented. That the new form is more suitable than the previous one can be clearly seen in that while the previous form gives a peak upper critical field, B_{c20}, for binary Nb_3Sn of about 63 T at a fast neutron fluence of about 25×10^{18} n/cm^2, the new form mirrors the data which gives a peak B_{c20} of about 25 T at a fast neutron fluence of about 4×10^{18} n/cm^2 (at zero fluence B_{c20} is about 24 T). Additionally, these inappropriate assumptions are discussed in a qualitative manner, and correction is given to the underlying theory. In its primary functional capacity MagRad has been used to analyze the stability of a possible International Thermonuclear Experimental Reactor (ITER) Engineering Design Activity (EDA) coil design, as a function of both fluence and superconducting material.

INTRODUCTION

Stability analysis of CICCs is complicated by the fact that the properties of the materials making up the coil change with fluence. In particular, the superconductor's critical characteristics and the copper resistivity are the most rapidly changing and crucial parameters affected by the radiation environment of the fusion reactor. Most stability studies to date have involved only the analysis of stability at startup. Certainly, if a coil is not stable at startup it is not worth designing, but the more important concern in the design of a coil is whether or not the coil retains its stability with fluence, and, if the stability degrades, at what rate it does so. This area of concern has not been properly addressed. It is the purpose of the code, MagRad, to fill this apparent gap in present analysis. For convenience, MagRad itself has been developed using a spreadsheet software package which is currently widely in use. MagRad incorporates two separate stability criteria, the limiting current formulation first proposed by Dresner [1] and later used in the code CICC [2], and the temperature margin formulation, widely used in stability analyses as a good representative benchmark for the stability of a given coil.

CODE DEVELOPMENT

A. Fluence Dependent Parameters: Data Construction

Critical temperature, T_c, of the superconductor as a function of fluence has been widely studied and is thought to be the result primarily of disorder of the Nb and Sn sublattices. Theory predicts an exponential decay of critical temperature with fluence which is indeed observed. The degradation constant has been taken as a fit to some quite recent data [3]. The standard expression in use up to the present time for the upper critical field as a function of fluence has been the following,

$$B_{c20m}(E_d) = B_{c20m}\frac{\rho_0 + 600E_d}{\rho_0}\exp\left(-\frac{5}{8}E_d\right). \qquad (1)$$

This form, originally given by [4] had been used in all of the codes surveyed. Upon inspection, however, it is seen that this expression grossly overestimates the upper critical field for any conductor of reasonable initial normal state resistivity, ρ_0 (less than 400 nΩm, say). This overestimation is then responsible for the result of an increasing conductor stability with fluence, which has been predicted by other codes as well. In its favor it has a strong plausible theoretical basis, namely that the upper critical field is proportional to the normal state resistivity, the electron specific heat, and the critical temperature. However, using this equation, we find that for an initial resistivity of 160 nΩm (Nb_3Sn) the upper critical field peaks at a damage energy, E_d, of about 1.33 eV/atom, corresponding to an RTNS-II fluence of about 5×10^{18} n/cm^2 (quite high), and has a peak value of about 56 T. This value is obviously much too high. A B_{c20} of about 21.4 T is given in [3] (also the value used for the initial B_{c20} in obtaining the above prediction of 56 T) at zero fluence increasing to a peak of about 22.4 T at a fluence of 0.9×10^{18} n/cm^2. An attempt to modify these results by using a much higher initial normal state resistivity (400 nΩm) was successful in bringing this theoretically based expression closer to the experimental data, but failed to be accurate enough for practical use in MagRad, as will be shown below. Accordingly, until a theoretically based expression can come close to matching the data, the upper critical field has been predicted by simply fitting the data from [3] (including some extrapolated points) with polynomials, taking care to specify the fluence range over which the data are applicable.

Having obtained expressions for both the critical temperature and the upper critical field for the various alloys in consideration, the critical current density, J_c, as a function of fluence was calculated using the scaling law predicted in [5]. These calculated curves were then compared to the data obtained by [3], and the discrepancy was rather crudely incorporated into fluence dependent expressions for the leading coefficient in the scaling law. In this way MagRad correctly predicts critical temperature, field, and current as functions of fluence without in any way making theoretical claims as to the bases of these predictions. Determination of the resistivity of the copper stabilizer at field, or magnetoresistivity, as a function of fluence was made using the expressions given by [6].

B. Stability

Previous work on ITER/CDA CICC simulations [7] have demonstrated that the stability with respect to coil current is a curve with nearly constant slope. Moreover, as the limit is approached of long coil lengths being heated in the prequench phase, the slope of the curve becomes even more nearly constant. The flowpaths involved for the ITER/CDA simulations have already been seen to be very large compared even to the longer heated lengths. That the slope of this curve is very nearly constant is not a surprising result. This result stems from the fact that in ITER, and other coils with similarly long flowpaths, the heating induced convective heat transfer which was so evident in the shorter US-Demonstration Poloidal Coil (US-DPC) [8] type conductors (even giving rise to the double stability phenomenon) is now quite suppressed by the extremely large mass of helium on either side of the prequench heated region. If the heated region were to occur very close to one of the ends of the flowpath we would expect helium expulsion out that end giving rise to a much higher and more sustained induced convective cooling, and thus the stability curve would be characterized by much more structure and not have a constant slope (similar, again, to the US-DPC simulations). This effect of the suppression of the convective cooling in the long ITER coil flowpaths does not, obviously, vary with fluence. The conclusion of the above argument, then, is that the stability curve is very well approximated as having a constant slope with respect to current both at startup and all subsequent times.

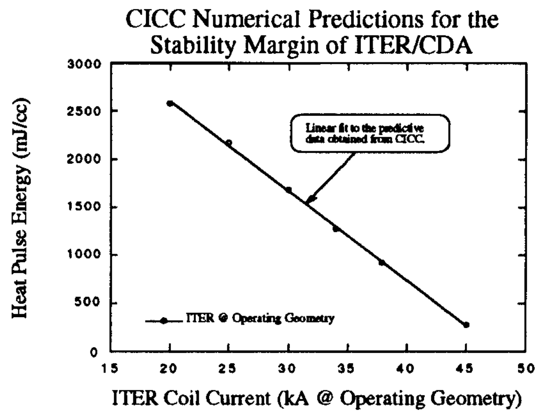

Fig. 1 ITER/CDA stability margin as a function of operating current as predicted by the code, CICC.

MagRad uses the geometry of the stability curve to backsolve for the stability margin at a given coil current from first solving for the limiting current. The limiting current at any fluence may be solved for using Dresner's limiting current expression, given both the availability and validity of the expressions used for the fluence dependent variables such as the copper resistivity, the critical temperature, and the upper critical field. The geometry of the stability curve of a typical long CICC coil is shown in Fig. 1. Due to some theoretical limitations, Dresner's formulation of the limiting current is not valid for long heated lengths (of the order of about 2 m), but earlier studies [7] have shown that the stability curve is nearly coincident with that of the short heated lengths (on the order of about 20 cm). Thus a value of 20 cm for the heated length is used in MagRad. Additionally, MagRad accounts for variation in the slope of the stability line due to different heating durations by using an empirical expression.

STABILITY V. FLUENCE RESULTS

MagRad has been used to predict the stability of two specific coil designs as benchmark cases. Two different criteria for stability have been used: the stability margin as explained above, and the temperature margin. The temperature margin is the difference between the current sharing temperature at operating current and field and the actual operating temperature of the coil. As such, we would expect the temperature margin to qualitatively behave similarly to the stability margin (or limiting current) with a few significant differences. Whereas the stability margin, as given by Dresner, is quite dependent upon the thermal-hydraulic geometry of the case, the temperature margin is heavily dependent upon the critical parameters of the superconductor. Both stability criteria must be looked at to insure that true stability will be achieved at a given fluence. In this way, the designer can make use of the advantages of both criteria, while compensating for the weaknesses of each. The stability margin (more explicitly, the limiting current) has the advantage that it takes into account the geometry of the problem (as well as the copper resistivity, etc.), which has been shown to be a significant factor in stability. On the other hand, the temperature margin has the obvious advantage of incorporating all of the critical parameter changes in the superconductor, instead of just the critical temperature. These advantages will be discussed below. The ITER EDA design is far from complete, and the geometry and operating conditions used in MagRad for this design have been obtained from the ITER Magnet Group meeting held at MIT earlier in the year with the one exception that 12 T is used as the operating field instead of 13 T. It must be reiterated that in using these labels the author is in no way implying a set design or even design direction for the EDA design. This design has the advantage, however, of being well documented and currently relevant.

Of first importance, then, for the designer, it can be seen from the predicted curves in Fig. 2 that the Nb-Ti ternary has the best stability of any of the three candidate materials chosen. It must be pointed out, though, that the binary Nb_3Sn did quite well, and though it did not have as high a startup stability, it retained its stability somewhat better than the ternaries, which was to be expected. Also, the predictions concerning the Nb-Ta alloy may be slightly off, since the data that was used was by necessity older for this material (1987) than for the other two (1991). It is especially striking that,

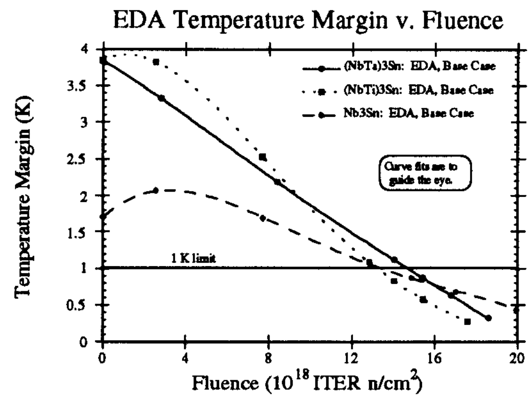

Fig. 3 Temperature margin versus fluence for the EDA base cases.

whereas the effect of a peaking B_{c20} and J_c can be readily seen for the Nb-Ti ternary and the Nb_3Sn, the stability of the Nb-Ta ternary degrades much in the same manner as its B_{c20} degrades, nearly linearly with fluence. In addition to these same results, in the temperature margin curves shown in Fig. 3 it can be seen that the Nb_3Sn has a rather pronounced peak; this is due in large part to the much slower decline in the critical temperature than in the ternaries. As benchmark criteria to determine when these conductors have degraded to dangerously low stabilities, the 100 mJ/cm^3 and the 250 mJ/cm^3 stability limits have been marked off as well as the 1 K temperature margin.

Reassuringly, it seems that these designs will be stable out to about 1.5×10^{19} ITER n/cm^2; well past the designed end of life fluence for ITER. This result must be taken cautiously, though, since the superconductor database for fluence effects was constructed in order to meet the ITER Magnet Group's specifications of critical temperature, field, and current density. The published data is quite lacking as far as the critical field values are concerned (and the critical temperature values for the ternaries). Thus, in using MagRad some technological

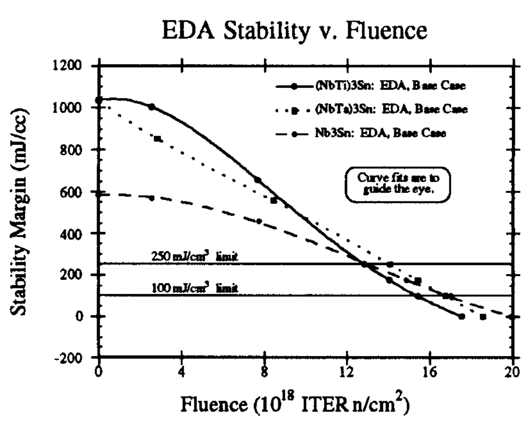

Fig. 2 Stability margin versus fluence for the EDA base cases.

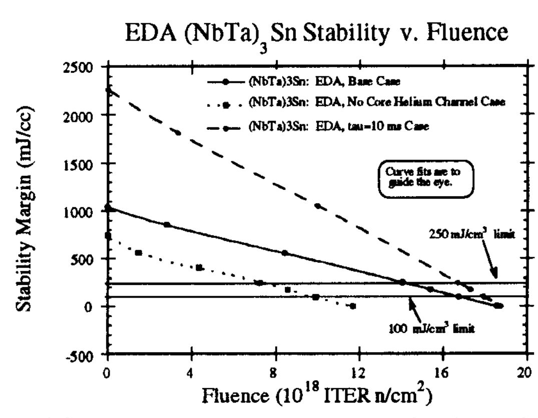

Fig. 4 Stability margin versus fluence for the various EDA non-base cases (no core helium flowpath and low τ).

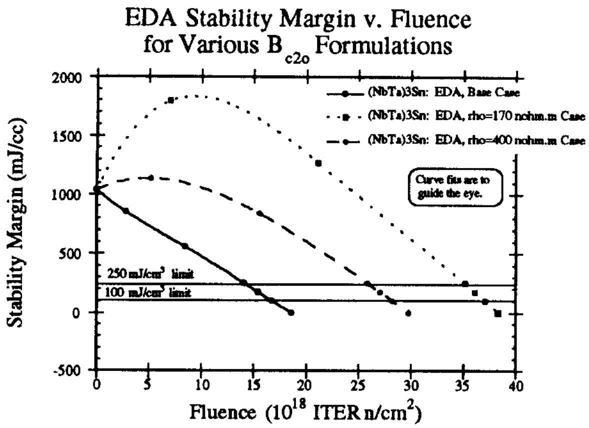

Fig. 5 Stability margin versus fluence for the various EDA B_{c20} formulations.

advancement was assumed prior to the fabrication of the coils.

A couple of final predictions should be noted. In the EDA, Nb-Ta, non-base case scenarios, it was observed that the temperature margin formulation gives no difference between the cases whatever. This is to be expected, since the temperature margin is dependent only upon the bath temperature and the critical parameter values of the superconductor. However, the stability margin, based upon the limiting current formulation, shown in Fig. 4 shows a very significant difference in the behavior of the three cases, a behavior which one would naturally expect to find. This is one example of where it is much more desirable to use the limiting current formulation. Finally, in the curves predicting the stability of the EDA, Nb-Ta base case using three different formulation for determining the value of the critical field at fluence (Fig. 5), it can be seen that there is a very large disparity between the behaviors. The uppermost two curves use the formulation given in [4], but using different values for the initial normal state resistivity. These values are 170 nΩm and 400 nΩm, which fairly bound the previous experimentally determined values. Though most researchers who have looked at fluence effects have used the 170 nΩm value (corresponding to the highest curve), it is instructive to show that even a modification of the initial resistivity (a much 'dirtier' conductor) yields predicted stabilities that are much too high. For this reason, if one were to use this formulation instead of the data (lowest curve) one would be inclined to make the dangerous conclusion that near term reactors will not have any problems with stability.

CONCLUSIONS

It has been shown that magnets fabricated using either binary or ternary alloyed Nb_3Sn may well exhibit good stability at startup, but that stability degrades rather quickly. In particular, this study has shown that, assuming that the superconducting wire meets ITER's specifications, the ITER TF coils should exhibit good stability over the life of ITER. If these specifications cannot be met, however, the coils may not operate well near the end of life fluence. More work must be done concerning this potential problem, but in any case a comprehensive and accurate fluence-dependent stability analysis is highly recommended, since the safety margin at the end of life of ITER has been shown to be much less than previously suspected. The two stability criteria of temperature margin and stability margin (based upon Dresner's formulation) have been shown to be quite consistent, except in the cases of analyzing different thermal-hydraulic geometries and analyzing different initiating energy perturbations, in which case it is safest to use Dresner's formulation. The code MagRad has demonstrated its predictive capability, and can be safely incorporated into a systematic coil design program. Finally, it has been sufficiently demonstrated that all designers should use a set of properly constructed, consistent data for the upper critical field and current density, based upon experimental data, rather than using the theoretically based expression for the upper critical field.

ACKNOWLEDGMENTS

This work was performed under appointment to the Magnetic Fusion Energy Technology Fellowship program which is administered for the US Department of Energy by Oak Ridge Institute for Science and Education, and was jointly supported by the Fusion Technology Institute at the University of Wisconsin.

REFERENCES

[1] L. Dresner, "Parametric study of the stability margin of cable-in-conduit superconductors: theory," *IEEE Trans. Magn.*, vol. 17, pp. 752-755, January 1981.

[2] R. L. Wong, "Program CICC, flow and heat transfer in cable-in-conduit conductors," *Proc. of IEEE 13th Symposium on Fusion Engineering*, vol. 2, pp. 1134-1137, 1989.

[3] P. A. Hahn, M.W. Guinan, L. T. Summers, T. Okada, and D. B. Smathers, "Fusion neutron irradiation effects in commercial Nb_3Sn superconductors," *Journal of Nuclear Materials*, vol. 179-181, pp. 1127-1130, 1991.

[4] L. T. Summers, M. W. Guinan, J. R. Miller, and P. A. Hahn, "A model for the prediction of Nb_3Sn critical current as a function of field, temperature, strain, and radiation damage," *IEEE Trans. Magn.*, vol. 27, no. 2, pp. 2041-2044, March 1991.

[5] D. P. Hampshire, H. Jones, and E. W. J. Mitchell, "An in depth characterization of $(NbTa)_3Sn$ filamentary superconductor," *IEEE Trans. Magn.*, vol. 21, no. 2, pp. 289-292, March 1985.

[6] M. W. Guinan, P. A. Hahn, D. E. Klabunde, and R. R. Coltman, Jr., "Radiation imposed limits on superconducting magnets: a data base for copper stabilizers," *Journal of Nuclear Materials*, vol. 155-157, pp. 1315-1319, 1988.

[7] C. T. Yeaw and R. L. Wong, "Numerical simulation of the stability of long cable-in-conduit conductors for fusion magnets," *Proc. of the ANS 10th Topical Meeting on the Technology of Fusion Energy*, pp. 897-891, October 1992.

[8] R. L. Wong, C. T. Yeaw, S. S. Shen, and J. R. Miller, "Numerical simulation of the stability in a cable-in-conduit conductor developed for fusion-magnet applications," *Proc. of the IEEE 14th Symposium on Fusion Engineering*, pp. 1400-1404, September 1991.