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STABILITY ANALYSIS OF NbTi-Ta-BASED HIGH FIELD CONDUCTOR COOLED BY POOL BOILING BELOW 4 K

MASTER

by

W. Y. CHEN, J. S. ALCORN, Y-H. HSU and J. R. PURCELL

SEPTEMBER 1980

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W.Y. Chen, J.S. Alcorn, Y-H. Hsu and J.R. Purcell
General Atomic Company
P.O. Box 81608
San Diego, California 92138

Abstract

Stability analysis has been performed for cabled NbTi-Ta-based superconductors intended for the high field (12 T) toroidal field coils for a large scale tokamak device such as ETF. Ternary NbTi-Ta was selected as the superconductor because of its superior critical current density at high field as compared to the binary alloy NbTi. The operating temperature was chosen to be 2.5 K or below to optimize the performance of the superconductor. A cabled conductor was selected to minimize the pulsed field losses. The conductor is cooled by pool boiling in a subcooled (~2.5 K, 0.25 atm) bath, or in a superfluid helium (He-II) bath (~1.8 K, 0.02 atm). The analysis was based on numerically simulating the evolution of a normal zone in the conductor. Appropriate superconductor properties and heat transfer characteristics were utilized in the simulation. In the case of subcooled bath, the low bath temperature reduces both the peak nucleate boiling flux (PNBF) and the minimum film boiling flux (MFBF). In the case of He II bath, the heat transfer characteristic is determined by the cooling channel size, bath pressure and the Kapitza resistance. Results indicated that in both cases of cooling the NbTi-Ta-based conductor can be designed to satisfy the commonly followed stability performance criterion for such large coils. In particular, He II cooling was found to offer significant enhancement in the stability performance of the conductor. The implications of the results are discussed.

Introduction

Conductor stability studies have been carried out as one of the tasks undertaken by the General Atomic Company (GA) in its participation in the DOE/OFE/D&T 12 Tesla Coil Development Program.[1] The basic mission of GA's effort in the program is to demonstrate the feasibility of, and establish an engineering data base for utilizing helium bath cooled NbTi alloy based superconductor to generate a peak toroidal field of 12 tesla in a tokamak reactor.

Previous studies have identified the alloy $Nb_{32}Ti_{43}Ta_{25}$ as the most promising candidate for the 12 T application.[2] However, in order to achieve optimum performance, the conductor must be operated at temperatures below 3 K. Two possible modes of operation are: (1) subcooled bath cooling at 2.5 K, with 0.5 K subcooling; (2) saturated superfluid bath cooling at 1.8 K. The heat transfer characteristics in both the above modes are significantly different from that of the 4.2 K saturated bath cooling. Thus, it is important to evaluate the stability performance of the conductor under these cooling modes.

The stability characteristics of the conductor were studied by numerically simulating the evolution of normal zones with finite lengths. Steady state heat transfer data obtained from the literature was used.

Conductor

A three-level uninsulated, unsoldered cable design was selected, in lieu of a monolithic or soldered cable design, for the following reasons:

1. To minimize ac losses from the poloidal field system and plasma disruptions.
2. As a conventional, modular fabrication method for producing high current conductor at reasonable cost, and with good area reduction of the composite superconducting elements.
3. For optimal cryogenic stability, by virtue of its high effective surface to area cooling characteristics.
4. For ease of coil winding by virtue of its flexibility.

Unsoldered, cabled construction would be especially attractive for Nb_3Sn conductor in order to limit both manufacturing and operational strain.

A similar three-level cabled conductor (5 kA current) is employed in the LASL/BPA 30 MJ energy storage coil presently under construction by General Atomic.[3,4] The final conductor design benefitted from an extensive performance and manufacturing development effort by LASL.

Table 1 is a summary of selected TF-coil conductor features. Only the conductor grade intended for 10–12 T operation was studied here. Figure 1 is a sketch of the conductor with the reinforcement structure.

TABLE 1
SUMMARY OF CONDUCTOR FEATURES

CONDUCTOR	
Superconductor materials:	
High field regions	NbTiTa (32-43-25 wt-%)
Low field (0–5 T)	NbTi
Stabilizer:	
Material:	Copper, RRR = 100:1 (minimum)
Maximum current density:	6 kA/cm^2 (coil protection limit)
Operating current:	10 kA
Geometry	Rutherford cable, unsoldered, uninsulated, 3 levels
Number of field grades	Four: 0–5 T, 5–8 T, 8–10 T, 10–12 T
COOLING	
Type:	
(1) Subcooled ℓHe I bath	
Operating conditions:	
Bath temperature	2.5 K
Saturation temperature	3.0 K
Bath pressure	0.25 atm
(2) Saturated ℓHe II bath	
Operating conditions:	
Bath temperature	1.8 K
Bath pressure	0.02 atm
STABILITY RELATED PARAMETERS (1 kA second level cable for 10–12 T region)	
Cross sectional area	0.312 cm^2
Cooled perimeter	1.577 cm^2/cm
ρ_{cu} (B = 0 T)	6.332 x 10^{-8} Ω-cm
Superconductor content	12%
Superconductor J_c:	
6 x 10^4 A/cm^2 at 4.2 K, 9 T	
4.5 x 10^4 A/cm^2 at 2.5 K, 12 T	
7.5 x 10^4 A/cm^2 at 1.8 K, 12 T	

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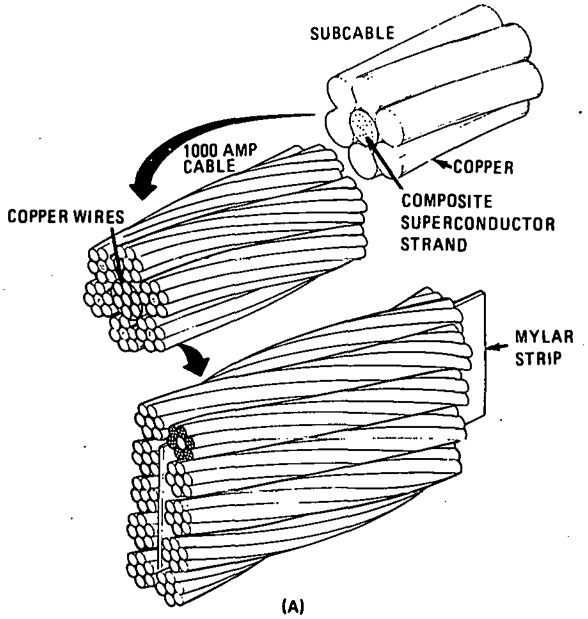
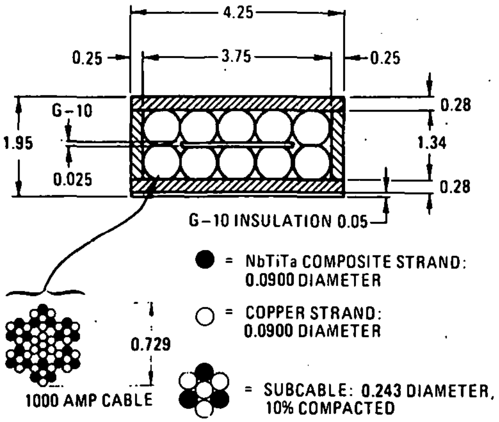
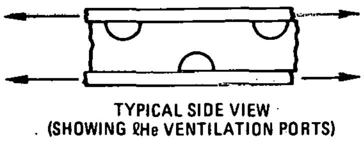


(A)
THREE-LEVEL CABLED CONDUCTOR



ALL DIMENSIONS IN cm

(B)
10 kA CONDUCTOR/SUPPORT MODULE,
HIGH FIELD REGION (10–12 TESLA)



ALL DIMENSIONS IN cm

(C)
CONDUCTOR/SUPPORT MODULES

Fig. 1. Sketch of the cabled conductor

Figure 2 is a plot of the critical current density of the selected NbTi-Ta alloy.[2] Also plotted is the critical current density of the commonly used $Nb_{50}Ti$ alloy. It can be seen that the ternary alloy offers significantly better performance at temperatures below 3 K, which is the primary reason for selecting the low bath temperature.

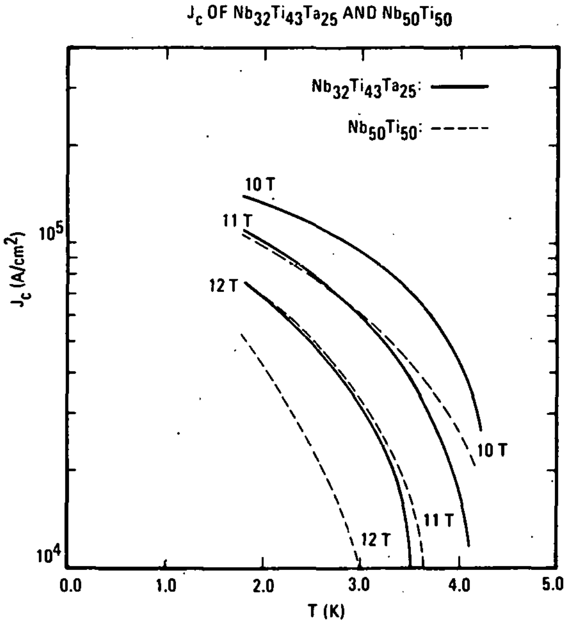


Fig. 2. Critical current densities of $Nb_{32}Ti_{43}Ta_{25}$ and $Nb_{50}Ti_{50}$

Heat Transfer Characteristics

One of the two modes of cooling being considered is subcooled bath cooling at 2.5 K, 0.25 atm, with 0.5 K subcooling. The reason for subcooling the bath is to reduce the amount of vapor generation in the presence of heating in the winding introduced by neutrons or pulsed fields. Subcooling also provides more stability margin in terms of tolerable temperature rise in the conductor.

Although the pool boiling heat transfer characteristics of ℓHe at this temperature/pressure combination has not been actually measured, empirical formulations have been derived for characterizing the heat transfer properties in terms of physical properties of the helium liquid and vapor.[5] In particular, the physical properties involved are the densities, specific heat and the enthalpy difference of the liquid and vapor, and the latent heat and surface tension of the liquid. In the film boiling region, the viscosity and thermal conductivity of the vapor are also involved. Figure 3 is a plot of the estimated heat transfer characteristics at 2.5 K, 0.25 atm, derived

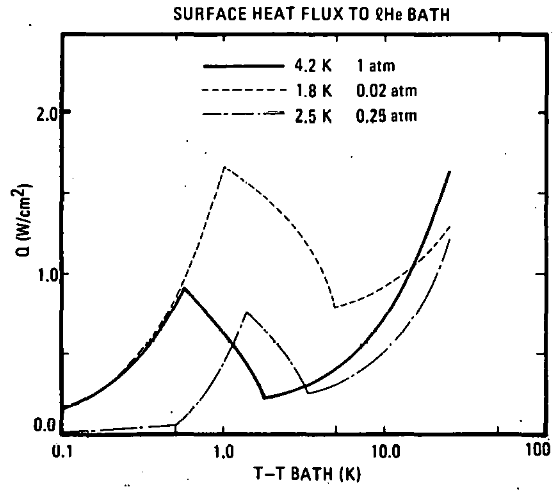


Fig. 3. Heat transfer characteristics of pool boiling saturated He I at 4.2 K, 31.0 atm, subcooled He I at 2.5 K, 0.25 atm, and saturated He II at 1.8 K, 0.02 atm.

from the empirical formulations. Also plotted is the heat transfer characteristics for 4.2 K, 1.0 atm bath. It can be seen that for the 2.5 K case, the values of the heat flux are in general lower than the 4.2 K case, which is the penalty for operating the coil at reduced temperature.

The other selected option is to adopt saturated superfluid ℓHe bath cooling at 1.8 K, 0.02 atm. The heat transfer characteristic is more involved.

Helium II transports heat by conduction mechanism. Heat flow is at least 10^6 times better than that of He I, and greater than 10^2-10^4 times that of annealed high purity copper at comparable temperature. In fact, heat transport takes place so rapidly within He II that it is almost impossible to set up an appreciable temperature gradient; hence all the evaporation takes place from the free surface without forming bubbles. Also, almost all the enthalpy (bath temperature to 2.17 K) in the He II is available to absorb the heating from a local source. Therefore, locally deposited heating can be rapidly dispersed through the entire bath to reduce its impact on the operation of the coil.

The surface heat transfer is much better in He II than that in He I (Fig. 3). Temperature dependence of heat transport in He II, and surface heat transfer has a maximum at 1.8 K. Therefore operating at 1.8 K is the best choice from the stability point of view.

The surface heat transfer characteristic from a solid to He II is determined by:

1. The cooling channel size
2. The bath temperature
3. The bath pressure
4. The immersion depth
5. The state of the surface (in particular by the nature of the material).

It is independent of the orientation of either the heated surface or the channel. This implies a significant increase in the effective cooling perimeter of a conductor.

There are two distinct regions in the surface heat transfer curve:

1. Non-film boiling (Kapitza conductance phenomenon region)
2. Film boiling region.

For the TF-coil under consideration, the coil winding is well ventilated, thus the size of the cooling channel is not a concern. A conservatively selected form of heat transfer characteristic[6] for a saturated He II bath at 1.8 K is plotted in Fig. 3. Although higher heat fluxes have been reported, it will be shown later that a more favorable heat transfer characteristic will not impact the design of large TF-coils because of other considerations.

Although the conductor consists of fine strands of superconducting/copper wires and has a very large total surface area, due to the fact that a high degree of compaction is applied during the cabling process (and therefore very little interstitual spacing exists between the fine wires) it is not realistic to assume that the entire surface area is available for cooling. Based on the results of actual experimental stability studies carried out by LASL on very similar cabled conductors,[7] it was concluded that a realistic estimate of the cooling surface area is one-half of the envelope of the second level cables.

Results and Discussion

The stability performance of the conductor was studied by numerically simulating the evolution of normal zones using a computer program previously described in Ref. 8. Studies were carried out under three operating conditions: (1) 1 atm He I pool boiling at 4.2 K, 9 T; (2) 0.25 atm He I pool boiling at 2.5 K, 12 T; and (3) 0.02 atm He II pool boiling at 1.8 K, 12 T. The operation at 4.2 K at reduced field of 9 T was studied merely for providing a comparison. The reason for selecting 9 T as the ambient field is because at a higher field the conductor performance is limited by its superconductor content rather than by stability. The other two modes of operation at 12 T are the actually proposed conditions for the TF-coil. The analysis was performed on the 1 kA second level cable rather than the 10 kA final cable.

Simulations with initial energy deposition smaller than 10 J were performed with a short initial zone length (~5 cm). Higher energy zones were simulated with a 100 cm initial zone length, which is practically equivalent to an infinite initial zone length due to the small cross sectional area and the large perimeter surface of the conductor.

The stability performance is summarized by plotting the minimum propagating energy at each operating current. The minimum propagating energy (E_{mpz}) is defined as the energy required to drive the conductor into a propagating normal zone.[8] Figure 4 is a plot of E_{mpz} as a function of the operating current I_{op} for the same conductor operated under the three modes described above. It can be seen that by cooling with 1.8 K He II rather than subcooled 2.5 K He I, the stable operating current can be raised by a factor of two. Such a dramatic enhancement in performance is due partly to the increased heat transfer characteristics (Fig. 3) and partly to the increased critical current density in the superconductor (Fig. 2). It can also be seen that operated at 4.2 K, cooled by pool boiling He I, the same conductor can only be used at 9 T ambient field, although the stable current limit is raised as compared to the 2.5 K case due to the improved heat transfer properties and a lower magnetoresistance.

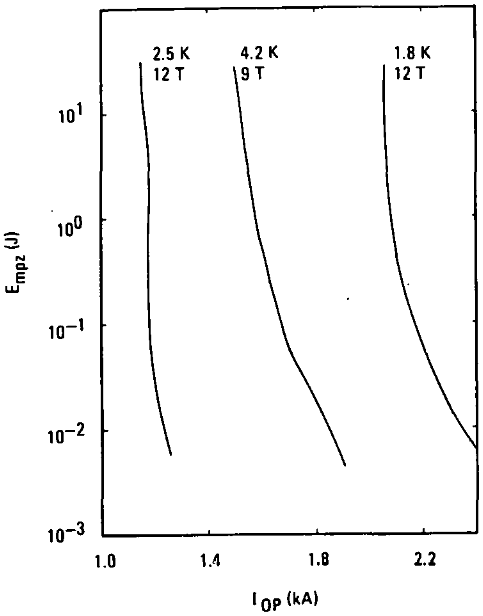


Fig. 4. E_{mpz} of GA/MCA 12 T TF-coil conductor. The initial energy was deposited over a 5 cm conductor section.

Although the above results indicate that by selecting 1.8 K He II as coolant rather than 2.5 K He I, the stable operating current density in the conductor can practically be raised by a factor of two, in actual magnet design other factors must be considered. One important consideration is quench protection of the coil. Studies indicated that the operating conductor current density in a large, high field magnet system must be kept below some safe limit (~6000 A/cm^2) in order to prevent excessive temperature excursions during a coil quench/dumping event.[1,9] Therefore, the gain in current density by He II cooling may not be as impressive as the stability study results alone would indicate. However, for smaller size magnets, the advantages offered by the He II cooling are certainly very impressive.

Conclusions

Results of numerical conductor stability studies clearly demonstrate the superior performance of the conductor when bath cooled by 1.8 K saturated He II over the 2.5 K subcooled He I. Nevertheless, the selected conductor when cooled by 2.5 K He I will be stable against a disturbance of nearly 1 J/cm^3 over a 1 m long section of the conductor even at 11.5 kA. Helium II cooling offers the possibility of significantly increasing the stable current limit of the same conductor based on stability considerations.

The above results also demonstrate the performance enhancement of the NbTi-Ta alloy superconductor operated below 3 K as compared to the commonly adopted 4.2 K operation.

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