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INTRODUCTION

Recent advanced mirror fusion reactor studies indicate a trend toward using very high-field barrier solenoid coils. Indeed, the MARS and FPD studies call for solenoid magnet peak fields of 24- and 20-T, respectively. During these studies, most of the investigators and magnet designers felt that only a portion of these fields could be obtained by using superconducting magnets, with the remainder being supplied by inner, copper, resistive coils. Such coils pose many problems in a high-radiation environment. It is therefore desirable to generate as much of the field as possible with superconductors, thus minimizing or eliminating the resistive coil problems by making the coils smaller. The data base on the material properties of superconductors, compiled through 1981, shows that superconducting magnet technology also has problems at high fields. The main factors limiting conceptual superconducting coil designs to peak field values of approximately 15 T are:

1. Low critical current densities in Nb_3Sn at fields $> 15 \text{ T}$.
2. The increased stabilizer resistivity, due to higher magnetoresistance, requires the use of more stabilizer, thus lowering the overall current density.
3. Large magnets and high fields produce enormous electromagnetic forces, which create prohibitive strains on an unreinforced superconductor.

4. The critical current density of advanced high-field superconductors, such as Nb_3Sn , is strain sensitive. This compound is also extremely brittle and fractures at a strain of about 0.8% in a multifilamentary conductor.

These problems are all interrelated. As additional stainless steel is used in the coil pack, the magnet grows, creating larger forces than in the initial design. This positive feedback continues for as long as one tries to solve each problem independently. Means must therefore be found to simultaneously increase the superconductor's current density, provide better cooling to the conductor (thus decreasing the amount of stabilizer needed), and use the coolant and stabilizer space thus saved for additional support against the electromagnetic forces.

SUPERFLUID HELIUM FOR ADVANCED MAGNETS

Since the spring of 1982, we have endeavored to apply emerging technologies to solve the four problems just outlined. Several developments look promising:

1. Using superfluid helium (He-II) at 1.8 K and ~ 1.25 atm for cryostatically stabilizing superconductors. The effective thermal conductivity and diffusivity of He-II is several thousand times that of copper, so less stabilizer is needed.
2. Using Nb_3Sn at 1.8 K appears to enhance its critical current capacity by 40 to 200% (from 12 to 17 T) over the operating values at 4.2 K.
3. A new compound ($\text{Nb}_3\text{Sn:Ti}$) has significantly better current-carrying capability at high fields ($B > 14$ T).
4. The STANSOL¹ program shows that winding stainless-steel strip in parallel with the conductor provides an adequate internal substructure for reacting against the large electromagnetic forces.
5. By using $\text{Nb}_3\text{Sn:Ti}$, Nb_3Sn , and Nb-Ti, a typical coil can be radially subdivided to provide current grading, which satisfies both field variations and electromagnetic hoop forces.
6. Two new computer programs for solenoid magnet design, CONDUCTOR and ADVMAGNET, developed by LLNL's Superconducting Magnet Development Group can design conductor winding packs with current grading and different types of conductor. Each radial subcoil is designed to produce a known contribution to the central on-axis field, while controlling the maximum

strain on the superconductor and meeting conductor stability requirements.

Armed with these six new developments, we set out to design the highest-field, advanced superconducting coils currently envisioned. First, the critical-current characteristics of the new compound $\text{Nb}_3\text{Sn:Ti}$ are examined. In this report, we use a $\text{Nb}_3\text{Sn:Ti}$ J_c of $2500 \text{ A}\cdot\text{cm}^{-2}$ times a low-temperature enhancement factor of 1.4 (the increase in J_c upon going from 4.2 to 1.8 K operation). Since starting this report, additional data indicate that the true enhancement is between 200 to 300%. Several sample measurements have yielded values^{2,3} for J_c of $7000 \text{ A}\cdot\text{cm}^{-2}$. A recently measured sample⁴ gave $10\,000 \text{ A}\cdot\text{cm}^{-2}$. Figure 1 plots J_c vs the weight percentage of titanium added to the niobium filament cores to produce the $\text{Nb}_3\text{Sn:Ti}$ conductor. These values, obtained for 20 T operation at 4.2 and 1.8 K, show the large temperature enhancement and that the optimal titanium wt.% addition is ~1.5%. These results make most conductor developers feel confident that material will shortly be available with J_c values of $20\,000 \text{ A}\cdot\text{cm}^{-2}$ at 1.8 K and 20 T.

The sensitivity of the critical-current density to conductor strain is also important in the design of high-field magnets, particularly for Al_5 -type compounds at field values of $>12 \text{ T}$. Most manufactured conductors have internal prestrains (due to differential thermal contraction between the composite's components) of from -0.5 to -0.3%. Therefore, short sample J_c measurements yield somewhat lower results than the $J_{c\text{max}}$ value obtainable at optimum strain. Our coil designs are based upon the J_c values with zero externally-applied strain, and the operating electromagnetic strain is limited to approximately +0.35%, which is therefore on the conservative side. Elkin's results suggest that the acute sensitivity of Nb_3Sn at fields near 20 T may be reduced at lower temperatures.^{5,6}

Fig. 1. Effect of adding titanium to Nb_3Sn .

CONDUCTOR REINFORCEMENT

The cross product of the current density and its surrounding field value gives the amount of force on the conductor. We want to limit these strains to a value that does not degrade the conductor's J_c properties; this is usually about 0.35%. But we also want as high a coil pack current density as possible, to limit the coil's overall size (volume). This means selecting a material with a high elastic modulus even at high strains; it must have a yield strain higher than 0.35%. Work-hardened copper falls short of this criterion, since for strains above 0.2% its modulus of 17.6×10^6 psi rapidly falls to 3×10^6 psi. A stainless steel such as 304 LN is much better. But, 304 LN's yield stress is approximately 100 kpsi. If we operate at two-thirds of this value, we can only load it to 66 kpsi (0.24% strain). For these reasons, we have selected 21-6-9 stainless steel (with a yield stress of 196 kpsi at 4.2 K) for reinforcing the conductor.

THE COMPUTER PROGRAMS "ADVMAGNET" AND "CONDUCTOR"

The increased complexity of the advanced high-field magnet designs warranted our using additional analytic tools. Existing computer programs, such as EFFI,^{7,8} MAGF, and STANSOL, can calculate such parameters as the magnetic field, and the forces resulting from input current distribution and coil geometry. However, there are occasions when we do not know the required input values. This is particularly true when the coils must be subdivided for current-density grading, to limit the maximum permissible magnetic field and the induced strain on the superconductor. Two new computer codes have been developed to assist in these calculations. CONDUCTOR designs the conductor windings, insulation, stainless-steel reinforcing, and coolant flow channels. ADVMAGNET takes the coil-pack current densities given by CONDUCTOR, and derives the graded subcoil geometries for producing the required central on-axis magnetic field. A unique feature of ADVMAGNET is that the total volume of subcoils is minimized. Thus, for a specific current density, ADVMAGNET designs the smallest system of coils that will produce a given magnetic field. Generally, the results show that using He-II allows large-bore high-field magnets to operate at higher current densities than were ever possible with He-I.

To give adequate protection to the superconductor, the stainless-steel reinforcement is wound in as a strip, along with the conductor. Expressions are needed for calculating the required amounts of stainless steel and stabilizer. Parameters, such as the wetted perimeter, operating heat flux, insulation thickness, and the conductor aspect ratio, are modeled in CONDUCTOR, which calculates the thicknesses of the copper stabilizer and stainless-steel strip.

We decided to model a given superconducting coil as a system of three subcoils with differing peak current densities. The inner coils are made of Nb₃Sn:Ti and Nb₃Sn, and the outer coil of Nb-Ti. In the modeling of this system the inner radius and central field are known, along with the peak fields on each subcoil winding (as determined by the limiting current densities for each conductor type). The parameter ratios of α 's and β 's ($\alpha = R_o/R_i$, $\beta = l/2 R_i$), which are functions of the inner bore radius and magnetic field boundary conditions, are unknown. Program ADVMAGNET sums the total volume of the three subcoils and finds a solution for the coil geometries (α 's and β 's) that will produce the central field and satisfy the peak field requirements of each subcoil, while minimizing the total coil volume. The resulting designs should yield coils that utilize the least amount of superconductor to produce a desired central field.

Before ADVMAGNET can be run, it needs three values produced by CONDUCTOR: the coil pack current densities for the three subcoils. CONDUCTOR determines these values by calculating the required amounts of copper for cryostability, and stainless steel for limiting the conductor strains. For a given field and radial thickness range, these are found as a function of the operating current (I_o). The resulting overall current density vs I_o curve produces a rather broad maximum coil current density over a range of subcoil radial thicknesses. We generally pick conductor configurations having a maximum overall current density and a practical conductor aspect ratio. These current densities are used in ADVMAGNET to determine the subcoil system's final geometry.

A SAMPLE COIL DESIGN: 20-T, 2-m DIAMETER BORE

Several high-yield coil designs have been created by this technique. Table 1 contains the parameters for a 20 tesla, 2-m inner-bore diameter coil system.

The total cost estimate for this coil was obtained from current material prices and fabrication costs. The total cost turns out to be equally split between materials and fabrication, at about $\$0.45\text{-cm}^{-3}$ or $\$26/\text{lb.}$ each. The material cost breakdown is: Nb₃Sn:Ti conductor, 62% of the total cost; Nb-Ti conductor, 32%; Epoxy G-10 insulation, 2%; stainless-steel winding strip, bore tube, and coil case, 4%.

Figure 2 shows the coil pack and field-line contours for this coil. Figure 3 plots several coil system volumes and their costs as a function of the inner bore diameter (the points at 50 and 150 cm come from earlier coil designs). Note the approach toward an asymptotic limit at an inner bore diameter of 300-cm. Attempts to build coils larger than this will not only become quite costly, but

may in fact be impossible with the technology discussed in this report. Two major factors contribute to the coils' large sizes. First, the low critical current density (even of $\text{Nb}_3\text{Sn:Ti}$) at 20 T forces the inner subcoil, which generates the final 15 to 20 T field, to occupy approximately 25 to 33% of the system's total volume. Second, the electromagnetic forces from the outer subcoil are so large that nearly equal amounts of conductor and stainless steel are needed to react against hoop stresses. The additional stainless-steel in the winding pack lowers the overall current

Table 1. A 20-tesla, 2.0-metre inner-bore diameter coil system.

PARAMETER	SUBCOIL NO. 1	SUBCOIL NO. 2	SUBCOIL NO. 3
Conductor type	$\text{Nb}_3\text{Sn:Ti}$	Nb_3Sn	Nb-Ti
R_i	100 cm	160.5 cm	209 cm
R_o	153 cm	201.6 cm	259 cm
ΔR	53 cm	41 cm	50 cm
Length (coil)	500 cm	554 cm	552 cm
B_{max} (at winding)	20 T	15 T	9 T
B_{max} (on axis)	19.6 T	---	---
J_c (superconductor)	$3500 \text{ A}\cdot\text{cm}^{-2}$	$35\,000 \text{ A}\cdot\text{cm}^{-2}$	$50\,000 \text{ A}\cdot\text{cm}^{-2}$
J_{op} (superconductor)	$2333 \text{ A}\cdot\text{cm}^{-2}$	$23\,333 \text{ A}\cdot\text{cm}^{-2}$	$33\,333 \text{ A}\cdot\text{cm}^{-2}$
I_{op}	2600 A	4600 A	5500 A
J_{op} (conductor)	$1719 \text{ A}\cdot\text{cm}^{-2}$	$3793 \text{ A}\cdot\text{cm}^{-2}$	$4849 \text{ A}\cdot\text{cm}^{-2}$
J_{op} (coil pack)	$898 \text{ A}\cdot\text{cm}^{-2}$	$1395 \text{ A}\cdot\text{cm}^{-2}$	$1725 \text{ A}\cdot\text{cm}^{-2}$
Area (conductor)	$2.54 \times 0.596 \text{ cm}^2$	$2.54 \times 0.462 \text{ cm}^2$	$2.54 \times 0.447 \text{ cm}^2$
Area (steel)	$2.54 \times 0.262 \text{ cm}^2$	$2.54 \times 0.541 \text{ cm}^2$	$2.54 \times 0.517 \text{ cm}^2$
Q_w (conductor)	$1 \text{ W}\cdot\text{cm}^{-2}$	$1 \text{ W}\cdot\text{cm}^{-2}$	$1 \text{ W}\cdot\text{cm}^{-2}$
ϵ_{max} (electromagnetic)	0.35%	0.35%	0.35%
Length (conductor)	239 204 ft	256 786 ft	417 190 ft
Ratio (Cu/ superconductor)	0.39	5.0	5.9
No. double pancakes	91	101	101
Length (conductor)/ double pancake	2629 ft	2542 ft	4131 ft

Tot. coil stored energy = 7.8 GJ Tot. coil-pack vol. = $8.74 \times 10^7 \text{ cm}^3$
 Wt., at $7.86 \text{ g}\cdot\text{cm}^{-3}$ = 757 tons Est. cost, at $\$0.90 \text{ x cm}^{-3}$ = \$79M

Fig. 2. 20-T, 2-m coil pack with field plot.

Fig. 3. 20-T coil volume and cost vs the inner bore size.

density, resulting in a need for an even larger coil. Eventually, the runaway condition produces the asymptote indicated in Fig. 3.

Another asymptotic phenomenon is indicated by Fig. 4, which plots the minimum volume coil size for producing a given central magnetic field with an inner bore diameter of 260 cm. These coils use various materials for the parallel winding technique; one-half hard copper, or 304 LN or 21-6-9 stainless steels. In all uses, the maximum permissible electric magnetic strains on the conductor are limited to:

$$\epsilon_{\text{conductor}} < \frac{2/3 \sigma_y}{E_m} \leq \epsilon_{\text{max}}$$

where σ_y is the reinforcement material's yield stress, E_m is its modulus, and ϵ_{max} equals 0.35% strain. Figure 4 indicates that the low modulus and yield stress of copper limits its highest field coil (at this diameter bore) to 14 T. Even 304-LN stainless becomes limited at 17 T, while the greater yield stress of 21-6-9 allows 20-T production.

ADDITIONAL CONSIDERATIONS AND FUTURE RESEARCH DEVELOPMENT NEEDS

In seeking to further investigate and optimize these coil designs, our foremost consideration is to reduce the magnet's size.

Fig. 4. Minimum volume requirement for 260-cm diameter bore coils with reinforced parallel windings.

Currently these coils are a minimum volume "geometrically," since ADVMAGNET determines the smallest envelope for generating the given central field with the three given subcoil current densities (which are limited by the forces and superconductor $J_c(B)$ characteristics). Therefore, any effort to reduce the coils' size must concentrate on increasing the coil-pack current densities. By examining Table 1, we can see that the size of these coils is mainly due to the low current density of $Nb_3Sn:Ti$ in the 15 to 20 T region. If the compound's J_c were higher, then the size of subcoil 1 would decrease, with subcoils 2 and 3 following suit, since smaller radii require less stainless substructure.

A second optimization is possible in the third outer subcoil, with its Nb-Ti conductor operating at up to 9 T. Unlike Nb_3Sn , Nb-Ti is relatively insensitive to strain, so the 0.35% maximum strain limit no longer applies. Perhaps this subcoil could be designed with a 0.5% maximum strain criterion, resulting in less stainless-steel substructure and a higher overall pack current density. Recent data²⁻⁴ have also shown that $Nb_3Sn:Ti$ is less strain sensitive than ordinary Nb_3Sn , a property that is particularly advantageous at high fields. We are currently studying the effects of these further optimizations on reducing the coil-system size. A more detailed paper⁹ tabulating the various design steps, and describing the computer programs and formulas, is available from the authors.

CONCLUSIONS

Our study of the technology required for producing large high-field coils has shown that, with some extensions to our present technological base, feasible designs are achievable. The resulting magnets could well make a paramount contribution to the national mirror-fusion endeavor.

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