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ULTRA-HIGH-FIELD SUPERCONDUCTING MAGNETS

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INTRODUCTION

Recent advanced mirror fusion reactor studies indicate a trend towards using very high-field barrier solenoid coils. Indeed, the Mirror Advanced Reactor Study (MARS) and the FPD study 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 in a high-radiation environment pose many problems. 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 superconducting materials, compiled up to and including 1981, shows that our present 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:

- o Low critical-current densities in Nb_3Sn , at fields $> 15 \text{ T}$.
- o The increased stabilizer resistivity due to higher magnetoresistance requires more stabilizer, thus lowering the overall current density.
- o Additional stabilizer in the coil pack lowers the overall current density still further, resulting in a need for more turns and larger magnets.

- Neutron shielding is required between the plasma and the superconductor to limit radiation damage and nuclear heating losses in the coils. This again increases the magnet's diameter.
- Large magnets and high fields produce enormous electromagnetic forces, which create prohibitive strains on an unreinforced superconductor.
- The critical current density of advanced high-field superconductors, such as Nb_3Sn , is strain sensitive. This compound is also extremely brittle and, in a multifilamentary conductor, fractures at a strain of about 0.8% elongation.
- Using an internal strengthening structure in the coil pack (e.g., an interleaved, stainless-steel strip) decreases the coil's overall current density, again increasing its size.

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 as long as one tries to independently solve each problem. Some means must therefore be found to simultaneously satisfy the following conditions:

- 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

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

- 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.
- Using Nb_3Sn at 1.8 K appears to enhance its critical current capacity at high fields (from 12 to 17 T) by 40 to 200% over the normal operating values at 4.2 K.
- Significantly better current-carrying capability at high fields ($B > 14$ T) can be achieved by using a new compound ($\text{Nb}_3\text{Sn:Ti}$).
- 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.
- By using $\text{Nb}_3\text{Sn:Ti}$, Nb_3Sn , and Nb-Ti, a typical coil can be subdivided radially to provide current grading, which satisfies both field variations and electromagnetic hoop forces.
- Two new computer programs for solenoid magnet design, CONDUCTOR and ADVMAGNET, developed by the 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. Our starting point was to examine the critical-current characteristics of the new compound, $\text{Nb}_3\text{Sn:Ti}$. Several current-density vs field curves are depicted in Fig. 1. The data for these plots were obtained by McDonald and Larbalestier^{2,3} for fields of up to 18.5 T. We have extrapolated the best sample curve out to 20 T, resulting in an expected critical current density of $2500 \text{ A}\cdot\text{cm}^{-2}$. This value is small compared to J_c at 12 T. However, the data indicate that this compound can be used for up to 20-T operation.

Figure 2 shows additional good news. These are J_c vs field curves for Nb_3Sn , taken at 4.2 and 2.39 K by Hong and Larbalestier.⁴ The 20-T point has again been extrapolated, this time from 19 T, and the numbers written above the curves refer to the percentage increase in J_c between the two temperatures. At present, we expect to find a similar J_c -temperature enhancement for $Nb_3Sn:Ti$, and investigations are continuing on this compound.

The sensitivity of the critical current density to conductor strain is another important concern in designing high-field magnets, particularly for Al5-type compounds at field values > 12 T. Figure 3, adapted from Ekin's results,⁵ illustrates this for standard "bronze-type" multifilamentary Nb_3Sn for fields up to 19 T. Most manufactured conductors have internal prestrains (due to differential thermal contractions between the composite's components) of from -0.5 to -0.3% of the yield stress. Measurements of J_c for short samples therefore yield results which are somewhat lower than the peak value (J_{cmax}) obtainable at optimum strain. Our coil designs are based on J_c values with zero externally-applied strain, and an operating electromagnetic strain that is limited to approximately +0.35% of the yield stress, which is therefore on the conservative side. Figure 4, also from Ekin,⁶ suggests that the acute sensitivity of Nb_3Sn at fields near 20 T is reduced at lower temperatures. Although these curves were obtained at 10 T, we expect that a reduction in temperature from 4.2 to 1.8 K at 20 T will produce a more favorable strain dependence. Once again, additional investigations are required to ascertain whether these results are also true for the $Nb_3Sn:Ti$ compound, which (like Nb_3Sn) belongs to the same Al5-class crystal structure.

Heat transfer from conductors to pressurized (1 atm)⁷⁻¹¹ He-II has been extensively studied by Claudet, Seyfert, Van Sciver, Caspi, and others. Their general results are that He-II possesses a number of desirable coolant properties compared to normal He-I. Some of these are:

- He-II at 1.8 K has an effective thermal conductivity that is several thousand times that of copper.

Fig. 1. Critical current density of $\text{Nb}_3\text{Sn}:\text{Ti}$.

Fig. 2. Critical current density of Nb_3Sn .

Fig. 3. Strain sensitivity of Nb_3Sn .

Fig. 4. Strain sensitivity of Nb_3Sn at various temperatures.

- The effective thermal diffusivity of He-II is also thousands of times that of copper.
- No gas bubbles are formed in He-II (at heat fluxes of less than 8 to $10 \text{ W}\cdot\text{cm}^{-2}$), but heat transfer is accomplished by the convective motion of helium atoms condensed in both the superfluid and normal liquid states.
- Experiments have shown that the conductors in magnet coil packs can be operated with wetted-perimeter heat fluxes of at least $1 \text{ W}\cdot\text{cm}^{-2}$. This has not been established as being the upper limit, so values of $2 \text{ W}\cdot\text{cm}^{-2}$ or more may therefore be possible. (For purposes of comparison, the MFTF yin-yang coils operate at $0.19 \text{ W}\cdot\text{cm}^{-2}$ in He-I.)
- Superfluid Helium has a vanishing viscosity (analogous to the vanishing of resistivity in superconductors). This property greatly simplifies calculations of heat-transfer, since frictional and gravitational effects make only small contributions, even in complex coolant-channel geometries.

CONDUCTOR REINFORCEMENT

A few comments should be made about the parallel winding of stainless steel with the conductor. The force produced on the conductor is equal to the cross product of the current density and its surrounding field value. We would like to limit the resulting strains to values that do not degrade the conductor's J_c properties; usually to about 0.35% (see Fig. 3). But, we also want as high a coil-pack current density as possible, to limit the coil's overall size (volume). This requires selecting a material with a high elastic modulus even at high strains, i.e., the material must have a yield strain higher than 0.35%. Work-hardened copper does not meet this criterion, since its modulus of 17.6×10^6 psi rapidly falls to 3×10^6 psi for strains in excess of 0.2%. A stainless steel such as 304 LN is much better. However, since its yield stress is approximately 100 kpsi, if we operate at two-thirds of this value, this implies only being able to load the 304 LN to 66 kpsi, corresponding to a strain of 0.24%. For these reasons, we have selected

21-6-9 stainless steel (with a yield stress of 196 kpsi at 4.2 K) for the conductor reinforcing material. Although producing reliable welds in thick sections of 21-6-9 is difficult,¹² the reinforcing strips for the coils discussed in this report will not be thicker than 0.64 cm (0.25 in.), and should not therefore present any difficulties.

THE COMPUTER PROGRAMS "ADVMAGNET" AND "CONDUCTOR"

The increasing complexity of advanced high-field magnet designs has warranted our developing additional analytic tools. Existing computer programs, such as EFFI,^{13,14} MAGF, and STANSOL, could calculate such parameters as the magnetic field and the forces resulting from input current distributions and coil geometries. But, 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, in order to limit both the maximum permissible magnetic field and the strain induced on the superconductor. To assist in these calculations, two new computer codes for designing superconducting magnets have been developed. The conductor windings, insulation, stainless-steel reinforcing, and coolant flow channels are designed by CONDUCTOR. The coil-pack current densities are input into ADVMAGNET, which designs the graded subcoil geometries for producing a required central on-axis magnetic field. A unique feature of ADVMAGNET is that the total volume of the subcoils is minimized: for the given current densities, the smallest system of coils is designed for producing the given magnetic field. These designs have generally shown that He-II allows large-bore, high-field magnets to operate at higher current densities than were ever possible with He-I.

Earlier, we listed several engineering design problems associated with the design of high-field solenoids for use in future experiments, such as MARS and FPD. The most serious ones are:

- Internal stainless-steel substructure must be included in the coil winding pack to react against the large electromagnetic hoop stresses.

- The conductor and its neighboring cooling channels must provide cryostatic stability in He-II.
- The stress and magnetic field variations in the coil dictate that smaller magnets be achieved by grading the current density within the winding pack.

To provide adequate protection for the superconductor, a strip of stainless steel reinforcement is wound in with the conductor. Expressions are needed for calculating the amounts of stainless steel and stabilizer that are required. Figure 5 shows the geometry of a repeating conductor pack element with its associated interturn and interpancake insulation. CONDUCTOR models such parameters as the wetted perimeter, operating heat flux, insulation thickness, and the conductor aspect ratio from this figure. It also calculates the thicknesses of the copper stabilizer and stainless-steel strip needed for cryostatic stability and for limiting the strain to a permissible level.

Current-density grading usually requires dividing the magnet into several subcoils, since the amount of grading can be as large as a factor of 2 or 3 (typically, about $1000 \text{ A}\cdot\text{cm}^{-2}$ to $3000 \text{ A}\cdot\text{cm}^{-2}$ between the bore tube and the outer radius). Therefore, we decided to model a given superconducting coil as a system of three subcoils. The inner two are $\text{Nb}_3\text{Sn}/\text{Ti}$, and the outer coil is Nb/Ti , all with differing coil-pack current densities. Figure 6 shows the model of this three subcoil 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 ($\alpha = R_o/R_i$, $\beta = 1/2 R_i$), which are functions of the inner bore radius and magnetic field boundary conditions, are unknown. ADVMAGNET sums the three subcoil volumes and finds a solution for the coil geometries (α 's and β 's) that will produce the necessary central field, while satisfying each subcoil's peak field requirement and minimizing the total coil volume. The designs that result should yield coils that use the least amount of superconductor to produce the desired central field.

Before ADVMAGNET can be run, it needs three values produced by CONDUCTOR; the coil-pack current densities in the three subcoils. CONDUCTOR determines these values by calculating the amounts of copper needed for cryostability and the amounts of stainless steel for limiting the strains on the conductors. These are found (for a given field and range of radial thicknesses) as a function of the operating current, I_0 . The curve for the overall current density vs I_0 that results produces a rather broad maximum coil current density over a range of subcoil radial thicknesses. In general, we pick a conductor configuration that gives both the maximum overall current density and a practical conductor aspect ratio. These current densities are inserted into the ADVMAGNET Program to determine the final geometry of the subcoil system.

Fig. 5. Conductor pack repeating element.

Fig. 6. Magnet subcoil system model. The α 's and β 's are ratios:

$\alpha = R_o/R_i$, $\beta = 1/2 R_i$. B_m represents the maximum permissible field values at the coil location.

EXAMPLE: DESIGNING A 20-T, 2-m BORE SOLENOIDAL COIL

In order to elucidate the preceding discussion, we have included a summary of the steps used to produce a design for a 20-T, 2-m-bore-diameter solenoid coil.

Step 1. Estimate the overall winding-pack size for the three-coil system.

This is done by modeling the coil as a single constant-current-density solenoid. From prior experience with these large bore coils, we can estimate that the average coil current density will be nearly $1300 \text{ A}\cdot\text{cm}^{-2}$. Then,

$$H_0 = j\lambda F(\alpha, \beta) ,$$

in which H_0 is the central field, $j\lambda$ is the average coil-pack density, a is the inner coil radius, and $F(\alpha, \beta)$ is the corresponding Fabry geometrical factor. For this coil:

$$F(\alpha, \beta) = \frac{20 \times 10^4 \text{ gauss}}{(1300 \text{ A/cm}^2)(100 \text{ cm})} = 1.54$$

Since we want to minimize the volume of the final coil set, the single coil should also have a minimum volume. From the Fabry plots shown in Fig. 7, we find that: $\alpha = 2.85 = R_0/R_1$, and $\beta = 1.70 = 2/2R_1$. These values imply that a single coil will produce a field of 20 T if it has a current density of $1300 \text{ A}\cdot\text{cm}^{-2}$, and the following dimensions: $R_1 = 100 \text{ cm}$, $R_0 = 285 \text{ cm}$, and $l = 340 \text{ cm}$. Of course, this coil is only an approximation, since the final design will be a three-subcoil system, with spaces between them for current leads and substructure. Each subcoil will also have a different current density, because the peak strain on each conductor must be limited to a particular value.

Fig. 7. $F(\alpha, \beta)$ for a solenoid with a uniform current density.

Step 2. Divide the single constant $j\lambda$ coil into three radial sections with the following field boundary conditions at their inner and outer radii:

Coil No. 1:	$R_i = 100 \text{ cm}$	$B_{in} = 20 \text{ T} = B_o$
	$R_o = 160 \text{ cm}$	$B_{out} = 15 \text{ T}$
Coil No. 2:	$R_i = 150 \text{ cm}$	$B_{in} = 15 \text{ T}$
	$R_o = 220 \text{ cm}$	$B_{out} = 9 \text{ T}$
Coil No. 3:	$R_i = 220 \text{ cm}$	$B_{in} = 9 \text{ T}$
	$R_o = 280 \text{ cm}$	$B_{out} = -2 \text{ T} = -10\% B_o$

Note that all of the subcoil radii are only approximate guesses (except for the inner 100 cm bore requirement), and that J_{pack} for this first iteration is also only a guess, based upon the single-coil winding-pack envelope ($J_{pack} = 1300 \text{ A}\cdot\text{cm}^{-2}$). If we cannot achieve a final average pack current density as high as $1300 \text{ A}\cdot\text{cm}^{-2}$ for the three-coil system, then the final coil set may have to be larger.

Step 3. Use CONDUCTOR to design the detailed coil pack for each of the three subcoils. The input parameters are:

- R_i and R_o -- the inner and outer subcoil radii.
- Q_w -- the wetted perimeter heat flux in He-II.
- B_{in} and B_{out} -- the inner and outer subcoil magnetic fields.
- L_s -- the total width of the conductor and parallel-wound stainless-steel strip.
- W_t and W_l -- the interturn and interlayer insulation thicknesses.
- S_f -- safety factor on the amount of active superconductor in the composite. This equals $(I_c/I_{op} - 1) \times 100\%$, where I_{op} is the operating current and I_c is the critical current.

- ρ_{Cu} -- copper matrix resistivity, as a function of the magnetic field.
- J_c -- critical-current density for the active superconductor plus bronze cross section, as a function of the peak field present on each subcoil.
- E_c and E_s -- Young's moduli for the conductor and stainless steel.
- ϵ_{max} -- maximum permissible strain allowed on the conductor.
- σ_{ss} -- two-thirds of the yield stress for the type of stainless-steel used in the parallel winding.

The outer radius (R_o) for each subcoil is only approximately known, as stated earlier. The operating current (I_{op}) is unknown. Both R_o and I_{op} are input as guesses into DO loops within the program. The computer output is displayed as pages of tables. Each table tabulates the results for a given radial thickness, for a particular subcoil. The first column of each table contains a list of possible operating currents, while subsequent columns list the dimensions of the components depicted in Fig. 5. To provide cryostatic stability and adequate structural support, the sizes of the conductor and stainless-steel strip are calculated so as to limit the strain on the conductor (without also exceeding two-thirds of the stainless-steel strip's yield strain).

For each subcoil outer radius, the output contains a table of I_{op} and:

- A_{cond} -- the total conductor area that is required. This includes the active superconductor composite and the copper stabilizer.
- A_{steel} -- the area of stainless steel that will limit the strain on the combined conductor and stainless-steel elements to ϵ_{max} . (Both elements will have the same width.)

A_{total} -- the total cross-sectional area of a coil pack repeating element. (This includes the cross-sectional areas for the stainless steel, conductor, insulation, and the coolant-channel.

J_{pack} -- the subcoil pack current density. This equals I_{op}/A_{total} .

λ -- the packing fraction of conductor to the total cross-sectional area. This equals A_{cond}/A_{total} .

σ_{cond} -- the stress on the conductor producing ϵ_{max} .

σ_{steel} -- stress on the stainless strip producing ϵ_{max} .

An example of an output page for the innermost (20 to 15 T) subcoil is given in Table 1. Note that this table assumes an outer radius of 160 cm. The outer subcoil radius, for each coil, is generally varied in 10-cm increments to produce several such tables. We can then scan these tables for the I_{op} and pack configuration that gives the maximum overall pack-current density. Or, we can select the I_{op} and conductor combination that gives a more favorable aspect ratio for winding or manufacturing the conductor. In our present example, we would like to limit the winding strains on the conductor to less than 0.3% at a bending diameter of 2 m for the innermost turns. This corresponds to a maximum conductor thickness of 0.6 cm. The conductor is reacted on a mandrel, so that the part of the conductor which will be wound onto the coil former (i.e. the highest field) will have zero strain at that bend radius. This means that there will be some additional strain in the outer turns due to bending, but these outer turns are in a lower field and will therefore be able to carry a much higher current. For example, the field variation over the innermost subcoil is 20 T to 15 T. At 1.8 K, the critical current at 15 T is about four times that at 20 T so that considerable additional strain is acceptable.

The conductor must be straightened during the winding process, so

Table 1. A Sample Computer Output Page for the Innermost (20 to 15 T) Subcoil.

THIS PROGRAM SIZES THE CONDUCTOR AND STAINLESS STEEL COMPOSITE FOR BOTH THE STRAINS AND OBTAINING CRYOSTATIC STABILITY IN HELIUM II COIL

FOR THE CASE WHEN THE OUTER RADIUS = 150 CM
 INNER RADIUS = 100 AND HEAT FLUX = 1 W/CM**2
 INNER MAGNETIC FIELD = 200000 OUTER MAGNETIC FIELD = 150000 GAUSS
 CONDUCTOR SIDE LENGTH = 2.54 CM

IOP (AMPS)	ACOND (CM**2)	ASTEEL (CM**2)	ATOTAL (CM**2)	JPACK (A/CM**2)	PACKING FRACTION (KSI)	CONDUCTOR STRESS (KSI)	STAINLESS STRESS (KSI)
1000	.503492	.265948	1.37803	71.136	.361377	13.0496	97.9963
1100	.560712	.291627	1.46249	75.111	.382099	13.0496	97.9963
1200	.618932	.317174	1.55782	77.31	.391308	13.0496	97.9963
1300	.678096	.342595	1.64906	788.328	.411201	13.0496	97.9963
1400	.738151	.367897	1.74113	804.072	.423947	13.0496	97.9963
1500	.799049	.393087	1.83401	817.882	.435685	13.0496	97.9963
1600	.860743	.418171	1.92762	830.041	.446532	13.0496	97.9963
1700	.923189	.443155	2.02193	840.781	.456588	13.0496	97.9963
1800	.986344	.468045	2.11691	850.297	.465936	13.0496	97.9963
1900	1.05017	.492845	2.21251	858.752	.474651	13.0496	97.9963
2000	1.11463	.517561	2.30871	866.285	.482793	13.0496	97.9963
2100	1.17969	.542197	2.40546	873.012	.490419	13.0496	97.9963
2200	1.24531	.566758	2.50275	879.034	.497577	13.0496	97.9963
2300	1.31147	.591247	2.60053	884.434	.504307	13.0496	97.9963
2400	1.37813	.615669	2.69879	889.287	.510647	13.0496	97.9963
2500	1.44527	.640028	2.7975	893.656	.516631	13.0496	97.9963
2600	1.51287	.664326	2.89663	897.596	.522286	13.0496	97.9963
2700	1.58089	.688567	2.99616	901.155	.52764	13.0496	97.9963
2800	1.64932	.712754	3.09607	904.373	.532715	13.0496	97.9963
2900	1.71814	.73689	3.19634	907.289	.537533	13.0496	97.9963
3000	1.78732	.760977	3.29695	909.932	.542113	13.0496	97.9963
3100	1.85685	.785018	3.39789	912.332	.546471	13.0496	97.9963
3200	1.9267	.809015	3.49913	914.513	.550624	13.0496	97.9963
3300	1.99687	.83297	3.60067	916.497	.554585	13.0496	97.9963
3400	2.06734	.856886	3.70248	918.303	.558366	13.0496	97.9963
3500	2.13809	.880764	3.80456	919.949	.561981	13.0496	97.9963
3600	2.20911	.904606	3.90689	921.449	.565439	13.0496	97.9963
3700	2.28039	.928415	4.00946	922.817	.568751	13.0496	97.9963
3800	2.3519	.95219	4.11226	924.066	.571925	13.0496	97.9963
3900	2.42366	.975935	4.21527	925.207	.57497	13.0496	97.9963
4000	2.49563	.99965	4.3185	926.248	.577893	13.0496	97.9963
4100	2.56781	1.02334	4.42192	927.199	.580701	13.0496	97.9963
4200	2.6402	1.047	4.52553	928.068	.583402	13.0496	97.9963
4300	2.71278	1.07063	4.62932	928.862	.586	13.0496	97.9963
4400	2.78554	1.09424	4.73328	929.588	.588502	13.0496	97.9963
4500	2.85849	1.11783	4.83741	930.25	.590913	13.0496	97.9963
4600	2.93159	1.14139	4.94169	930.855	.593237	13.0496	97.9963
4700	3.00486	1.16493	5.04613	931.407	.595479	13.0496	97.9963
4800	3.07829	1.18846	5.15071	931.911	.597644	13.0496	97.9963
4900	3.15186	1.21196	5.25543	932.37	.599734	13.0496	97.9963
5000	3.22557	1.23544	5.36028	932.788	.601755	13.0496	97.9963

The conductor must be straightened during the winding process, so the strain must be limited at that time to prevent damage. If the conductor thickness is limited to 0.6 cm, the maximum strain will not exceed 0.3%. Therefore, for a conductor width of 2.54 cm, its maximum total area must be less than $2.54 \times 0.6 = 1.524 \text{ cm}^2$. The sample table shows that this value is satisfied by the entry for $I_{op} = 2600 \text{ A}$ with a corresponding J_{pack} of $897 \text{ A}\cdot\text{cm}^{-2}$. Using either of the two selection procedures for I_{op} just mentioned, a plot (Fig. 8) is constructed showing the resulting coil-pack current density as a function of the assumed outer radius of each subcoil. In general, all of the curves show a lower radial-thickness region in which J_{pack} is relatively insensitive to the coil's outer radius. Finally, as the coil's thickness increases, the resulting electromagnetic forces require using increasingly thicker stainless-steel strips. This causes a rapid drop-off in the overall pack-current density. These plots actually show us how a subcoil's J_{pack} should be graded, as a function of coil radius, to limit the strains on the conductor and stainless steel to less than ϵ_{max} . Note that the outer Nb-Ti subcoil should not need grading, as long as it has an R_o of from 200 to 300 cm. For the two inner coils, the J_{pack} is more steeply dependent on radius. This complicates the selection of a permissible constant current-density for these coils. For the second subcoil, we will tentatively guess that the final outer radius of this coil will be less than 220 cm and will select a possible J_{pack} of $1390 \text{ A}\cdot\text{cm}^{-2}$, based on our approximate guess of Step 2. We have selected an operating pack current density of $900 \text{ A}\cdot\text{cm}^{-2}$ for the inner subcoil, assuming that its outer radius can be limited to less than 160 cm.

Given $J_{pack 1}$, $J_{pack 2}$, and $J_{pack 3}$, a three-subcoil magnet is sought that will produce the required central field and have the smallest possible total volume. The solution must also satisfy the maximum field values for the different superconductor types, as indicated in Fig. 6. ADVMAGNET solves this problem, and uses the following input parameters:

Fig. 8. Current density grading for the 2-m diameter bore, 20-T coil system.

B_{in} -- the required maximum field that the conductor will be exposed to at the inner radius of each subcoil.

B_{out} -- the required field at the outer radius of each subcoil, except for coil No. 3.

B_C -- the required central magnetic field. The B_C and B_{in} values for the inner subcoil must be carefully chosen, since:

$$\frac{B_{in} \text{ (Coil 1)}}{B_C} = K(\alpha, \beta) .$$

This value depends upon the size of the coil bore, and on the overall coil-pack size. Using our single-coil constant-current minimum model, it is possible to estimate K from solenoid plots, such as the one in Fig. 9. For $\alpha = 2.85$ and $\beta = 1.7$, K can be estimated as 1.055, resulting in a B_{in} coil 1 of 20 T and a B_C estimated at 19 T. Due to the 7.5-cm thick stainless-steel case and the closeout spaces between each coil pack, our final coil system will be slightly larger. Because of this, we estimate that K will be somewhat smaller, yielding a B_C of perhaps 19.6 T.

With these values as the input, ADVMAGNET's output contains:

FV -- the total volume of the three subcoil system.

α_i -- the values of α for each subcoil in the system:
 $\alpha = (R_O/R_i)$.

β_i -- the values of β for each subcoil in the system
 $(\beta = l_{coil}/2R_i$, where l_{coil} is the subcoil's axial length).

Fig. 9. K vs α and β .

C_i -- the differences between the input magnetic field values at several radial locations within the system, and those actually calculated for the final coil geometry determined by the program. Usually these differences are less than 0.1%.

The resulting parameters for this coil design are tabulated as follows:

Total System Volume = $8.743 \times 10^7 \text{ cm}^3$.

Subcoil No. 1:	$\alpha_1 = 1.530$	$R_i = 100 \text{ cm}$	$R_o = 153 \text{ cm}$
	$\Delta R = 53 \text{ cm}$	$\beta_1 = 2.502$	$\ell_1 = 500 \text{ cm}$

Subcoil No. 2:	$\alpha_2 = 1.256$	$R_i = 160.5 \text{ cm}$	$R_o = 201.6 \text{ cm}$
	$\Delta R = 41.1 \text{ cm}$	$\beta_2 = 1.726$	$\ell_2 = 554 \text{ cm}$

Subcoil No. 3:	$\alpha_3 = 1.239$	$R_i = 209 \text{ cm}$	$R_o = 259 \text{ cm}$
	$\Delta R = 50 \text{ cm}$	$\beta_3 = 1.319$	$\ell_3 = 552 \text{ cm}$

The results of this iteration, particularly the values for the outer radii of the three subcoils, are compared to the plot of Fig. 8 to check for agreement between the estimated and actual coil radial thicknesses. If ADVMAGNET gives subcoil thicknesses much larger than estimated (in Step 2), our input J_{pack} values will be too large to assure strain protection for the conductor: the induced strains will be larger than ϵ_{max} . We would then have to return to Step 1 and assume a smaller $J_{\text{pack}} = J\lambda$ for the next iteration. However, if the resulting coil thicknesses are much smaller than our estimates, then the coil solution is acceptable: the strains on the conductor will be much less than ϵ_{max} . Indeed, a still smaller coil could be made by increasing the pack-current density in Step 1.

It is instructive to compare the final coil system volume with that of our simple single-coil model. Both are minimum volume

coils. However, the three subcoil system has 7.5-cm radial gaps between the first and second, and the second and third, subcoils. These gaps lower the overall current density from the single-coil value of $1300 \text{ A}\cdot\text{cm}^{-2}$, resulting in a larger size for the final coil system. In this case, there is an approximately 15% volume increase due to the presence of these gaps.

Step 5. The resulting designed coil-current-densities and subcoil dimensions are verified by their being input into the MAGF and STANSOL computer programs. Figure 10 shows an output plot of the coil shapes and resulting field line contours for the 20 T, 2-m coil design. In addition, MAGF also calculates the coil inductances, hoop, and axial pressures acting on sections of the winding packs. STANSOL enables us to model the individual coil pack components of a central pancake of each subcoil. This code actually calculates the hoop and radial stresses and strains imposed on each of the four winding components. Figure 11 displays the STANSOL output for the total strain (electromagnetic and winding pre-stress) on the materials in the three coils of the winding pack. The numbers in the graphs refer to the four winding components; (1) bore tube, (2) insulation, (3) conductor, and (4) stainless steel. The agreement between the conductor strains calculated by STANSOL and CONDUCTOR ($\leq 0.35\%$) is amazing, especially since STANSOL operates on large main-frame computers (such as the CRAY-1) and CONDUCTOR runs on a home microcomputer.

After completing Step 5, several goals have been accomplished. We have not only demonstrated the feasibility of designing a 20-T, 2-m solenoid coil, but we have:

- Established its overall coil-pack size and operating-current densities;
- Computed the complete design of its internal coil pack features, interpancake insulation, turn-to-turn insulation, stainless-steel winding substructure, and conductor geometry; and

Fig. 10. 20-T, 2-m coil pack and field plot.

Fig. 11. Hoop strain in Specimens 1, 2, and 3.

- Demonstrated that the parallel winding of stainless steel can indeed react the electromagnetic forces, even for high-field coils of this size.

20-TESLA, 1.5- and 2.0-METRE-BORE COILS

In this section, we have tabulated the coil-design parameters for two coil systems operating at 20 T, with 1.5 m and 2.0-m bore diameters. These coils were designed by using the 5-step method just outlined.

Cost estimates were obtained from current material and fabrication prices. The total cost is equally split between the material and fabrication items, at approximately $\$0.45/\text{cm}^3$ ($\$26/\text{lb.}$) each. The cost breakdown for materials is:

- $\text{Nb}_3\text{Sn-Ti}$ conductor -- 62% of the total cost;
- Nb-Ti conductor -- 32%;
- Epoxy G-10 insulation -- 2%; and
- Stainless-steel winding strip, bore tube, and coil case -- 4%.

Figures 10 and 12 show the coil packs and field-line contours for these coils, and Fig. 13 displays a plot of the coil system volume and cost as a function of the inner-bore diameter. The point at 50 cm in Fig. 13 resulted from an earlier 20-T coil design with a 50-cm bore. Note that this graph approaches an asymptotic limit at an inner-bore diameter of approximately 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 large sizes of these coils. The first is the low critical-current density of even $\text{Nb}_3\text{Sn-Ti}$ at 20 T. This forces the inner subcoil, which generates the final 15- to 20-T field, to occupy approximately one-fourth to one-third of the entire system's volume. The second factor is due to the large turn radii in the outer subcoil. Here, the hoop stresses from the electromagnetic forces are so large that nearly

Fig. 12. 20-T, 1.5-m coil pack and field plot.

equal amounts of conductor and stainless steel are needed for reacting against them. The stainless-steel that is added to the winding pack lowers the overall current density, resulting in the need for an even larger coil. Eventually, this runaway condition produces the asymptote indicated in Fig. 13.

Another asymptotic phenomenon is clearly indicated in Fig. 14, which shows plots of the minimum-volume coil size with an inner bore diameter of 260 cm that will be required to produce a given central magnetic field. The coils that are represented use three different materials for their parallel windings: one-half hard copper, 304 LN stainless steel, and 21-6-9 stainless. For all of these combinations, the maximum permissible electromagnetic strains on the conductor are limited to:

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

where $2/3 \sigma_y$ is two-thirds of the reinforcement material's yield stress, E_m is its modulus, and ϵ_{max} equals 0.35% strain. As indicated by the graph, the low modulus and yield stress of copper limits its use in a coil (at this bore diameter) to a field of 14 T. Even the usefulness of 304-LN stainless becomes limited at 17 T, while the greater yield stress of 21-6-9 allows the production of 20 T.

ADDITIONAL CONSIDERATIONS AND FUTURE RESEARCH DEVELOPMENT NEEDS

Coil Size and Conductor Properties

We are seeking ways for further optimizing and investigating these coil designs. Our foremost consideration is to reduce the size of the magnets. Currently, these coils are a minimum volume "geometrically." ADVMAGNET determines the smallest envelope size that will generate a given central field for the three given subcoil current densities, which are limited both by forces and superconductor $J_c(B)$ characteristics. Therefore, any effort to reduce the size of these coils must concentrate on increasing the coil-pack

Fig. 13. Coil volume for a 20-T coil and cost vs the inner bore size.

Fig. 14. Minimum volume requirement for 260-cm diameter bore coils with reinforced parallel windings.

current densities. By examining Tables 2 and 3, we can see that the major contributor to the size of these coils is the low current density of $\text{Nb}_3\text{Sn:Ti}$ in the 15- to 20-T region. If the J_c of the compounds were higher, the size of subcoil 1 would decrease. The sizes of subcoils 2 and 3 will follow suit, since their smaller radii would also require less stainless-steel substructure.

In this report, we are using a J_c for $\text{Nb}_3\text{Sn:Ti}$ of $2500 \text{ A}\cdot\text{cm}^{-2}$ times a low temperature enhancement factor of 1.4 (the increase of J_c upon going from 4.2 to 1.8 K). We feel that this is a conservative enhancement factor, and that it seems to apply fairly well to Nb_3Sn at 12 T. Since starting this report, additional data obtained by Suenaga, Ekin, and Tachikawa indicate that the true enhancement is between 200 to 300%. Several sample measurements¹⁵⁻¹⁶ have yielded J_c values of $7000 \text{ A}\cdot\text{cm}^{-2}$. A sample recently measured by Kamata¹⁷ produced $10\,000 \text{ A}\cdot\text{cm}^{-2}$. Figure 15 is a plot of J_c vs the percentage of titanium added to the niobium filament cores to produce the $\text{Nb}_3\text{Sn:Ti}$. These values, obtained by Suenaga for 20-T operation at 4.2 and 1.8 K, show the large temperature enhancement. They also show that the optimum titanium wt. % addition is ~1.5%. These results have given most conductor developers confidence that material with J_c values of $20\,000 \text{ A}\cdot\text{cm}^{-2}$ at 1.8 K and 20 T will shortly become available.

A second possible optimization can be made in the third outer subcoil, since this coil uses a Nb-Ti conductor operating at up to 9 T. The Nb-Ti conductor, unlike Nb_3Sn , is relatively insensitive to strain. Therefore, the 0.35% maximum strain limit is no longer applicable. If this subcoil were to be designed with a 0.5% maximum strain criterion, it would need less stainless-steel substructure and have a higher overall current density in the pack. Recent data obtained by Ekin and Tachikawa have shown that $\text{Nb}_3\text{Sn:Ti}$ is also less strain sensitive than ordinary Nb_3Sn , a property that is particularly advantageous at high fields (see Fig. 3).¹⁵⁻¹⁷ The effects of these optimizations are currently under study by our group.

Axial Forces on the Coil

Tables 2 and 3 show that the coil systems have axial lengths of 476 and 552 cm for the 1.5-m bore and 2.0-m bore coils, respectively. There is a net

Fig. 15. Effect of titanium additions to Nb_3Sn .

Table 2. 20-T, 1.5-Metre Diameter Bore Coil System.

PARAMETER	SUBCOIL NO. 1	SUBCOIL NO. 2	SUBCOIL NO. 3
R_i	75 cm	130 cm	175 cm
R_o	122 cm	168 cm	223 cm
ΔR	47 cm	38 cm	48 cm
Length (coil)	432 cm	476 cm	467 cm
B_{max} (at winding)	20 T	15 T	9 T
B_{max} (on axis)	19.7 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)	$2333 \text{ A}\cdot\text{cm}^{-2}$	$23\ 333 \text{ A}\cdot\text{cm}^{-2}$	$37\ 333 \text{ A}\cdot\text{cm}^{-2}$
I_{op}	4000 A	4600 A	5500 A
J_{op} (conductor)	$1603 \text{ A}\cdot\text{cm}^{-2}$	$3917 \text{ A}\cdot\text{cm}^{-2}$	$4940 \text{ A}\cdot\text{cm}^{-2}$
J_{op} (coil pack)	$992 \text{ A}\cdot\text{cm}^{-2}$	$1494 \text{ A}\cdot\text{cm}^{-2}$	$1814 \text{ A}\cdot\text{cm}^{-2}$
Area (conductor)	$5 \times 0.5 \text{ cm}^2$	$2.54 \times 0.462 \text{ cm}^2$	$2.54 \times 0.447 \text{ cm}^2$
Area (steel)	$5 \times 0.15 \text{ cm}^2$	$2.54 \times 0.461 \text{ cm}^2$	$2.54 \times 0.460 \text{ cm}^2$
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)	202 439 ft (61 703.4 m)	180 446 ft (54 999.9 m)	300 756 ft (91 670.4 m)
Ratio (Cu/ superconductor)	0.46	5.0	5.9
No. double pancakes	40	87	85
Length (conductor)/ double pancake	5061 ft	2074 ft	3538 ft
Turn-to-turn insulation	$2.54 \times 0.2\text{-cm}$ ladder	$2.54 \times 0.2\text{-cm}$ ladder	$2.54 \times 0.2\text{-cm}$ ladder
Layer-to-layer insulation	0.2-cm snowfence	0.2-cm snowfence	0.2-cm snowfence

Total coil stored energy = 4.5 GJ

Total coil-pack volume = $5.74 \times 10^7 \text{ cm}^3$ Estimated weight at $7.86 \text{ g}\cdot\text{cm}^{-3}$ = 497 tonsEstimated cost at $\$0.90 \times \text{cm}^{-3}$ = \$52 million

Table 3. 20-T, 2.0-Metre Diameter Bore Coil System.

PARAMETER	SUBCOIL NO. 1	SUBCOIL NO. 2	SUBCOIL NO. 3
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 A·cm ⁻²	35 000 A·cm ⁻²	50 000 A·cm ⁻²
J_{op} (superconductor)	2333 A·cm ⁻²	23 333 A·cm ⁻²	33 333 A·cm ⁻²
I_{op}	2600 A	4600 A	5500 A
J_{op} (conductor)	1719 A·cm ⁻²	3793 A·cm ⁻²	4849 A·cm ⁻²
J_{op} (coil pack)	898 A·cm ⁻²	1395 A·cm ⁻²	1725 A·cm ⁻²
Area (conductor)	2.54 x 0.596 cm ²	2.54 x 0.462 cm ²	2.54 x 0.447 cm ²
Area (steel)	2.54 x 0.262 cm ²	2.54 x 0.541 cm ²	2.54 x 0.517 cm ²
Q_w (conductor)	1 W·cm ⁻²	1 W·cm ⁻²	1 W·cm ⁻²
ϵ_{max} (electromagnetic)	0.35%	0.35%	0.35%
Length (conductor)	239 204 ft (72 909.4 m)	256 786 ft (78 268.4 m)	417 190 ft (127 159.5 m)
Ratio (Cu/ superconductor)	0.39	5.0	5.9
No. double pancakes	91	101	101
Length (conductor)/ double pancake	2629 ft (801.3 m)	2542 ft (774.8 m)	4131 ft (1259.1 m)

Total coil stored energy = 7.8 GJ

Total coil-pack volume = 8.74×10^7 cm³

Estimated weight at 7.86 g·cm⁻³ = 757 tons

Estimated cost at \$0.90 x cm⁻³ = \$79 million

attractive force acting on each conductor turn, which tends to compress the windings toward the axial center. For long high-field solenoids, the final accumulated compressive pressure on the central pancake turns might degrade the J_c properties of the conductors. The 1.5- and 2.0-m bore coil systems will generate maximum midplane axial pressures of 13.8 and 15.3 kpsi, respectively. These stresses correspond to an $\sim 0.35\%$ compressive strain on the superconductor composite. Currently, all of the strain-critical current-density degradation studies have been performed with the conductor placed in tension along its length. What remains to be investigated is any possible further decrease of J_c with compressive loads directed normally to the conductor's width and thickness. Our group is planning to adapt the LLNL tensile testing facility to perform these experiments on $Nb_3Sn:Ti$. However, it seems that the most probable resolution will be to design the coil pack so that these axial stresses are completely transferred from the conductor to the stainless-steel strips. This can be done by making the conductor's width slightly less than that of the stainless-steel strip.

Effect of Radiation on the Coil Systems

There are two concerns associated with neutron and gamma irradiation effects in the high-field solenoid coils. The first is the possible degradation of the $Nb_3Sn:Ti$'s J_c at neutron fluences of $>10^{18} \text{ n} \cdot \text{cm}^{-2}$ (which has been reported for Nb_3Sn).¹⁸ The second is the problem of radiation-induced heating in the coils, heat which must be removed by the He-II coolant at 1.8 K. At present, the sensitivity of this compound to radiation damage is not known; further investigations are pending. We have calculated that the total resistive-joint heating rates (within the conductor) for both the 1.5 and 2.0-m-bore coil systems are less than 60 W. Additional heat loads will arise from the radiation field and conduction losses to the 1.8-K environment. Presently, He-II refrigeration systems have been built with 380-W capacities at 1.8 K (e.g., Karlsruhe and the proposed Tore Supra facility).^{19,20} Therefore, removing heat loads of several-hundred watts should be possible with present-day technology. Figure 16 shows that an order-of-magnitude calculation of the expected heating rate induced in a high-field solenoid coil system for the FPD reactor is a function of the inner shield thickness. The curve marked with the shield thicknesses for the 1.5- and 2.0-m diameter bore coils indicates that the neutron and gamma radiation heating levels are acceptable.

Fig. 16. Heating in the FPB choke coil vs shield thickness (an order-of-magnitude estimate).

Helium-II Transient Heat Transfer and Coil Protection

We are continuing our investigations of the coolant properties of pressurized He-II. Its performance under transient-heat-input conditions is of particular interest. A related problem is associated with coil protection during a superconducting-to-normal quench. Currently, the problem can be solved for coils cooled with pool-boiling LHe, by mathematically modeling the coils with computer programs such as QUENCH. This program needs modification to account for the quench propagation velocity of $\text{Nb}_3\text{Sn:Ti}$ at high fields, and for the thermal properties of superfluid He. The experimental and analytical investigations of these phenomena are envisioned as being part of our group's tasks during the next few years.

CONCLUSIONS

We have studied the technology required for producing large high-field coils and have found that, with some extensions to our present technological base, feasible designs can be achieved. The resulting magnets could well play a paramount contribution to the national mirror-fusion endeavor.

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