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EIGHT-TESLA SYNCHROTRON DIPOLES -- DESIGN ALTERNATIVES

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EIGHT-TESLA SYNCHROTRON DIPOLES -- DESIGN ALTERNATIVES*

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Abstract

Superconducting accelerator bending magnets in the 4 to 5 tesla field range have been, or are being, developed for the LBL ESCAR, FNAL Doubler, and BNL ISABELLE projects and can be considered as state-of-the-art. We are now engaged in a program to develop accelerator dipoles with significantly enhanced performance, into the 8-tesla range.

Analytical design studies, based on idealized configurations, have been done to trace the dependence of stresses within the coil and overall magnet size on the magnet aperture, coil current density, central magnetic field, structural ring stress, and magnetic induction in the iron flux-return yoke.

Our development program includes:

1. Development, and measurement at 4.2°K, of coil structures consistent with the requirements of the analytical design studies.
2. Superfluid helium II at 1.8°K and at atmospheric pressure. Large magnets as well as conductors will be tested.
3. Development and evaluation of aluminum stabilization and various A-15 superconductors.
4. Tests of various model dipoles with instrumentation to measure mechanical motion.

Analytical Design Studies

A wide-range "parameter study" was undertaken,[1,2] using a mini-computer, to see how a variation of certain input parameters affected other output parameters. The model selected has a circular current winding with the current density uniform in radius and varying as cos θ, circular structural rings outside the winding, then the helium vessel and vacuum chamber, and outside of that, the warm-iron flux-return yoke, assumed to have infinite permeability.

In order to minimize the computational work involved, and the amount of output to be digested, the number of variables must be minimized. And for the same reason, rather than investigate all possible combinations, one parameter at a time was varied while all other independent parameters were held constant at their "base values". Not all of the independent parameters affect all of the dependent parameters. The input parameters selected were: Coil inside radius; field in the aperture; field at the inside surface of the iron yoke; average flux density within the iron yoke legs; current density; and stress in the structural rings. The output parameters were: Coil outside radius; structural ring outside radius; iron yoke inside radius; iron yoke outside semi-width; maximum radial stress in the coil; and maximum tangential stress in the coil.

A selected portion of the parameter study is presented here. The results are shown in Table I and in Figures 1, 2, and 3. Figure 1 shows our base-case, 8-tesla dipole, and Table 1 lists the various quantities of interest. Figure 2 shows how the overall magnet width and coil stress vary with central field, for a moderately high current density of 30 kA/cm^2. Figure 3 shows the width and stress for a 8-tesla magnet as a function of coil current density.

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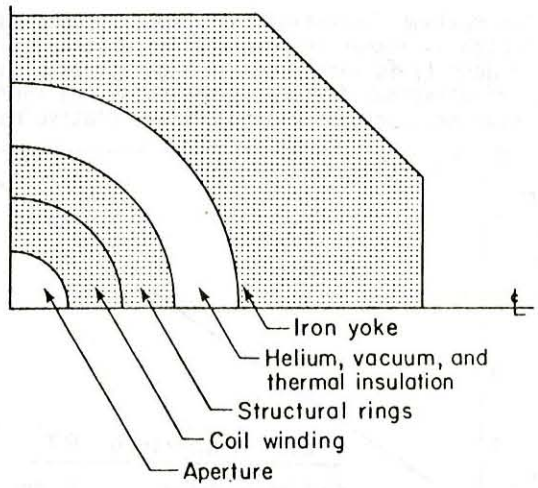


Fig. 1. Computer-generated quarter cross-section of base-case magnet for parameter study.

Table I.

Base Case for Parameter Study

Coil Inside Radius	4.00 cm
Field in Aperture	8.00 tesla
Field at Iron Surface	2.00 tesla
Field in York Leg, Avg.	2.50 tesla
Current Density	30.00 kA/sq cm
Stress in Structural Ring	50.00 kpsi
Coil Outside Radius	7.71 cm
Structural Ring Outside Radius	11.32 cm
Yoke Inside Radius	15.75 cm
Yoke Outside Semi-Width	28.35 cm
Radial Stress in Coil, Max.	6.01 kpsi
Tangential Stress in Coil, Max.	9.07 kpsi

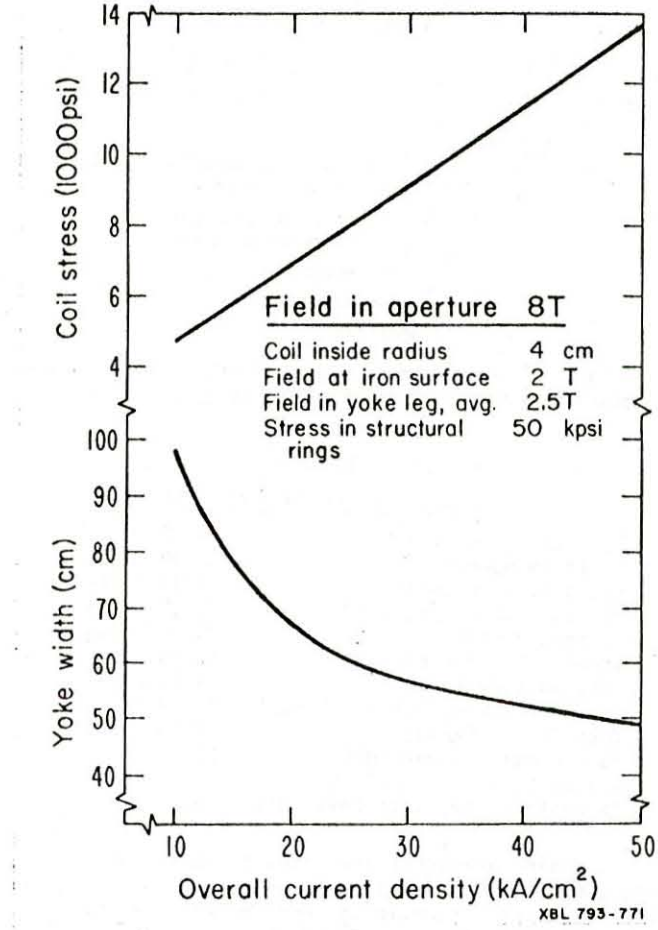
Certain parameters are fixed at reasonably optimistic values. The coil inside radius of 4 cm is for PEP II, a proton ring in the PEP tunnel. The maximum field strength at the iron inside surface is 2 tesla. Previous studies have shown that much higher values can be used before central-field aberrations caused by saturation become a problem, and higher values result in a greater contribution of the iron to the central field. But higher values result in there being insufficient space between the structural rings and the warm iron for helium, vacuum, and thermal insultaion. The average flux density in the yoke legs is 2.5 tesla. This is low enough to avoid harmful effects of saturation on the central field, but might result in excessive stray flux, depending on the particular application.

The maximum stress in the structural rings is 50 000 psi. This is low enough to avoid fatigue failure for cold-worked austenitic stainless steels and even for high-strength aluminum alloys in applications where a life of much less than 10^6 cycles is tolerable. For determining the stresses within the coil and the forces transmitted to the structural-ring system, the coil was considered to be made up of infinitesimal keystone-shaped conductors, bounded by radial and constant-radius lines, and free to slide on each other. Analytical formulas[3] give the stresses directly.

The structural-ring system was considered to cover the entire coil and to extend outward from the outer radius of the coil. Stresses were calculated from exact analytical formulas for a continuous uniform ring.[4] Although the stress was selected as the governing cri-

terion for the sizing of the structural rings, the deflections might well be limiting. Ring distortion leads to aberrations in the central field and may lead to fatigue failure of the coil.

The maximum tangential coil stress becomes distressingly high as either the central field strength or the current density is increased. A high stress might lead directly to fatigue failure of the coil, and there might be a secondary sort of failure due to relative motion, and attendant wear, between parts of the coil, and between the coil and the structural rings. Large coil motion also results in premature quenching, training difficulties, and aberrations in the central field. A high elastic modulus reduces the motion, of course. But even achieving a suitably high modulus for the relatively mild requirements of the ESCAR and FNAL Doubler magnets was a difficult task.



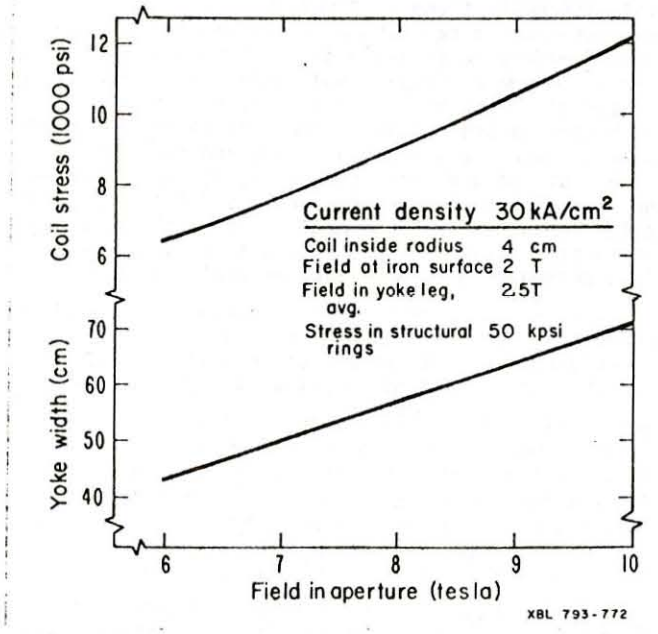


Fig. 2 and 3. The effects of magnetic field in the aperture and coil current density on the overall width and maximum coil compressive stresses.

Coil Structure Development

The mechanical behavior of the built-up coil structure under the Lorentz electromotive and restraint-structure forces have proved responsible for much of the degradation and training observed in high-current-density accelerator dipoles. The requirements for helium coolant passages and electrical insulation usually result in undesirably low compressive moduli. New materials and methods of coil fabrication are constantly being introduced. Mechanical testing of components and models of coil structure are usually done at room temperature.

We have instrumented a 5000-pound testing machine to perform mechanical tests down to 4°K, and soon LBL's Materials and Molecular Research Division will be able to do similar testing at loads up to 50 000 pounds.

Superfluid Helium II, Pressurized at 1.8°K

We have under construction a 150-liter helium II bath that will operate at 1.8°K and one atmosphere. Both superconductor current capacity and the thermal heat transfer are improved in superfluid helium at atmospheric pressure as compared to pool boiling normal helium at 4.2°K. Remarkable increases have been observed in the superconducting stability of short samples. We plan to study the stability margins of sizable magnets -- 1-meter-long dipoles -- in the new facility.

The increase in the current capacity of NbTi at 1.8°K is displayed in Figures 4 and 5, which also plot the current of NbTi at 4.2°K and multifilimentary Nb_3Sn produced by the bronze process. The Nb_3Sn currents are among the highest quoted in the literature[5] but are still somewhat below the values achieved for the older, more developed, tape form of Nb_3Sn. Therefore, some increase in the current capability of multi-filamentary Nb_3Sn might be in the offing. A copper to bronze + Nb_3Sn ratio of 2:; was assumed in generating the overall coil current-density numbers although the amount of stabilitation required for Nb_3Sn is not well established.

The NbTi data are for the best high field alloy tested and reported in the literature.[6] Some data exist for NbTi current densities at 1.8°K and other estimates were generated from data supplied by Robert Schermer of LASL.[7] A rather low ratio of Cu to NbTi of 1:1 was assumed because at high field and 4.2°K the current capacity of the NbTi is quite low. For both the Nb_3Sn and NbTi, the coil space factor, the fraction of coil volume occupied by superconductor plus stabilizer, was taken to be a fairly high 2/3. All the above assumptions are on the optimistic or high-current-density side, and one should probably plan on slightly lower current densities than appear on Figure 5.

The enhanced current capability of NbTi at 1.8°K compared with Nb_3Sn at 4.2°K shows its promise up to at least 12 tesla. Even at 4.2°K, NbTi coils seem competitive with Nb_3Sn up to 8 tesla, but the temperature margin there might be inadequate.

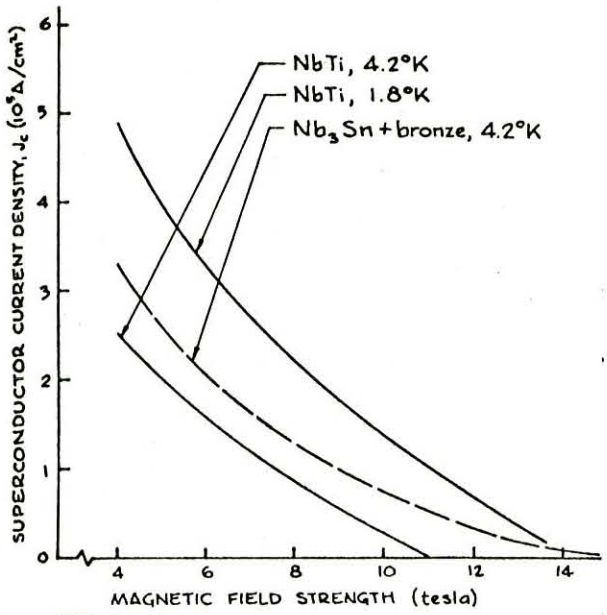


Fig. 4. Critical current density vs. magnetic field and temperature for various superconductors.

Superconductor Development and Evaluation

Aluminum Stabilized Conductor.

The use of ultra-pure aluminum (RRR ≥ 3000) as a stabilizer in composite superconductor allows one, in principle, to have a cryostable conductor at a current density above 10 kA/cm^2. This could eliminate training as a problem and facilitate the design and development of high-field magnets in a timely, predictable, and economical manner. Samples are being fabricated for us, and evaluation experiments are planned.

Nb_3Sn Multi-Filament and Advanced Superconductors.

The advanced superconducting intermetallic compounds are brittle as compared with the NbTi now in general use. Their use requires new fabrication techniques, one of which is to wind the magnet with unreacted conductor, and then form the Nb_3Sn in situ through a high-temperature heat treatment. We have procured some unreacted multi-filament Nb_3Sn and plan to work with the materials specialists in the LBL MMRD division on winding, heat treating, and insulation techniques.

Nb_3Al, Nb_3Ge, $Nb_3(Al, Ge)$ all have superior superconducting properties to those of Nb_3Sn and all have been fabricated by the MMRD materials group group. Possible advantages of fabricating magnets from these materials will be explored.

Design Alternatives

The overall coil current densities, shown in Figure 5, display the alternatives between temperature and materials that one has to work with. Figures 2 and 3 show how these current densities affect the magnet overall size and coil stress. The problems of various development strategies thus become fairly clear, although the solutions are far less so. In addition to the superconductor materials and operating temperature options mentioned above there are also choices of superconductor configurations, insulation, glues, and other materials of construction.

We have also given attention to alternative magnet configurations. Previously, we have built magnets having circular structural rings, to resist the bending resulting from non-uniform radial loads, only on the

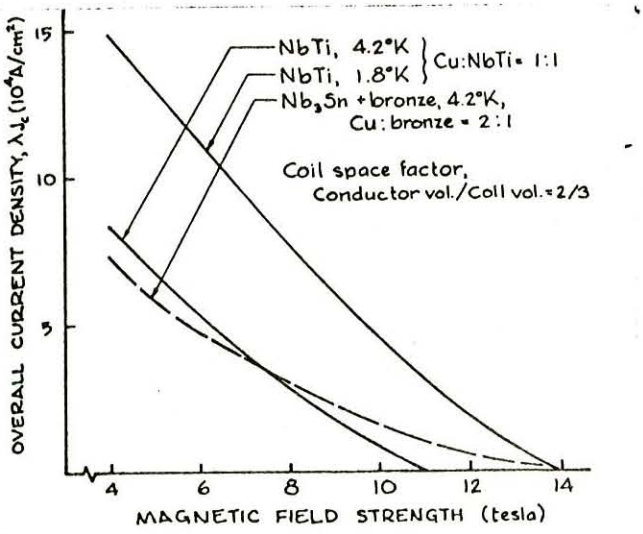


Fig. 5. Overall coil current density vs. magnetic field and temperature.

outside of the coil. We have also built magnets having all of the required bending resistance provided by a tube on the inside of the coil. This works well in cases where the coil thickness is relatively large. For high-field, small-aperture magnets putting all or part of the bending-resistant structure on the inside might be the preferable alternative. We have given some attention to coils with oval cross sections. In principle one should be able to design a coil in such a way that the banding is in pure tension, with no bending moments whatsoever. Attempts at LBL to design such magnets, several years ago, were not successful, but it is possible to reduce the bending to a small value by trial-and-error. Since the design of circular structural rings is dominated by bending, and the direct stress is small, reduction of the bending would certainly be desirable provided the fabrication problems can be solved. The general problem of increasing the efficiency of the structure applies not only to the relatively small-cross-section accelerator dipoles but even more to the large dipoles required in MHD. We are following the development of structural designs in the MHD program.

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