# Development of a 40 T Compact Hybrid Magnet

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| journal or publication title | IEEE Transactions on Magnetics |
| volume | 32 |
| number | 4 |
| page range | 2470-2473 |
| year | 1996 |
| URL | http://hdl.handle.net/10097/47210 |

doi: 10.1109/20.511373

# Development of a 40 T Compact Hybrid Magnet

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**Abstract — A 40 T compact hybrid magnet consisting of a 16 T outer superconducting magnet and a 24 T inner resistive magnet is conceptually designed. A highly strengthened superconducting magnet with a 360 mm room temperature bore can be made using newly developed $(Nb,Ti)_3Sn$ wires with Cu-Nb or Cu-$Al_2O_3$ reinforcing stabilizer, and as a result the coil weight is outstandingly reduced by about 70 %. A poly-Bitter resistive magnet which generates 24 T in a 14 mm room temperature bore is realized consuming 8 MW power.**

## I. INTRODUCTION

The projects of hybrid magnets with flux densities in excess of 40 T have been recently performed in the world [1-3]. High field superconducting magnets inevitably require employing $Nb_3Sn$ superconducting wires. In a wide bore superconducting magnet for a hybrid magnet, the electromagnetic force at the windings increases with the strength of a field. The superconducting properties of $Nb_3Sn$ wires have a weak point for applied stress, and the critical current of $Nb_3Sn$ wires without reinforcement degrades easily under the large stress. Practically reinforced superconducting wires have been realized by means of an external reinforcement. Heat-treated and fully reacted $Nb_3Sn$ wires are surrounded with housings of cold-worked hard Cu [4]. Since Cu stabilizer with a large cross section must be utilized as housings to overcome the huge stress, the average current density of the coil is extremely reduced. As a result, high field superconducting magnets with a wide bore tend to become larger and larger. A superconducting magnet with heavy weight and large size needs the inconveniently large scale cryostat and refrigerator system. From the aspects of manufacturing and operating costs, such a large scale superconducting magnet system is undesired to widely promote the advanced research in high fields.

In order to reduce the coil weight and size, a very compact superconducting magnet has to be developed employing the highly strengthened $(Nb,Ti)_3Sn$ superconducting wires with the minimized volume. This paper describes the project of a 40 T compact hybrid magnet which consists of a remarkably light 16 T superconducting magnet using $(Nb,Ti)_3Sn$ superconducting wires reinforced with Cu-Nb or Cu-$Al_2O_3$ and a 24 T water-cooled resistive magnet with an 8 MW power supply.

## II. DEVELOPMENT OF $(Nb,Ti)_3Sn$ WIRES WITH REINFORCING STABILIZER

Figure 1 shows cross sectional views of newly developed multifilamentary $(Nb,Ti)_3Sn$ wires with Cu-Nb or Cu-$Al_2O_3$ reinforcing stabilizer. The former $(Nb,Ti)_3Sn$ wire reinforced

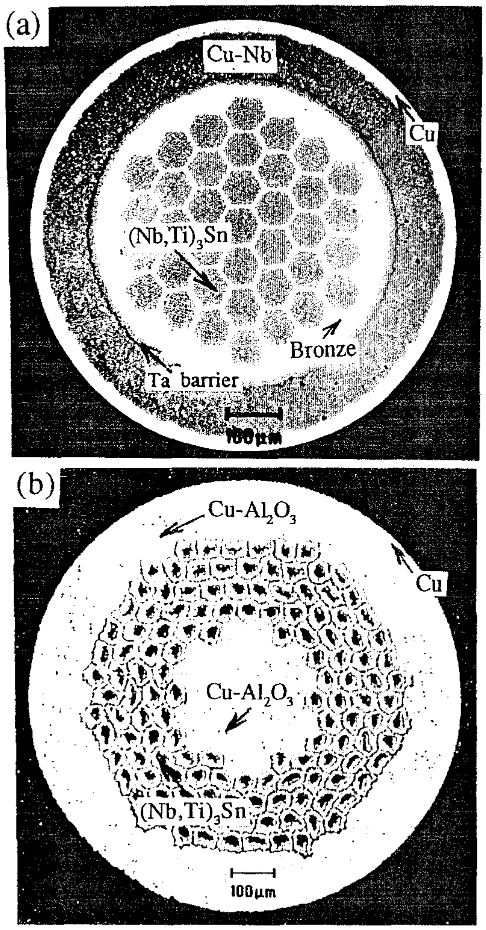

Fig 1. Internally reinforced superconducting wires. (a) Bronze processed multifilamentary $(Nb,Ti)_3Sn$ wire with Cu-Nb reinforcing stabilizer and (b) Nb-tube processed multifilamentary $(Nb,Ti)_3Sn$ wire with Cu-$Al_2O_3$ reinforcing stabilizer.

Manuscript received June 13, 1995.

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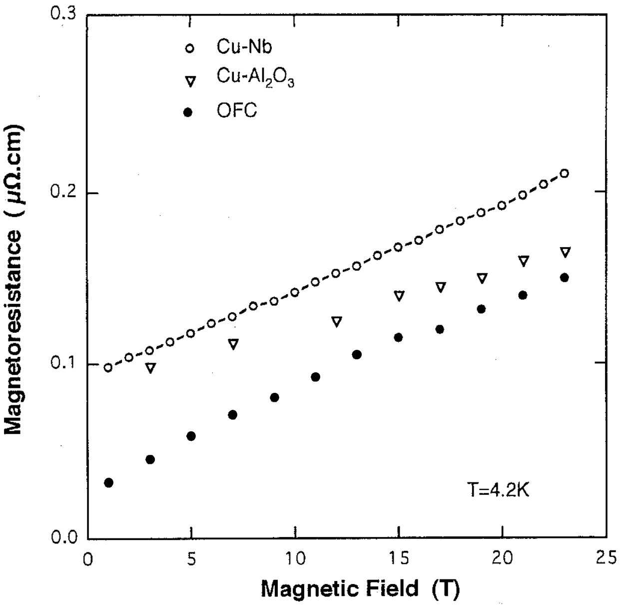

Fig. 2 Magnetoresistance as a function of magnetic field at 4.2 K. Oxygen free copper (OFC) and $Al_2O_3$ dispersion copper (Cu-$Al_2O_3$) were annealed at 720 ℃ for 50 hours, and Cu-Nb conposite at 670 ℃ for 200 hours.

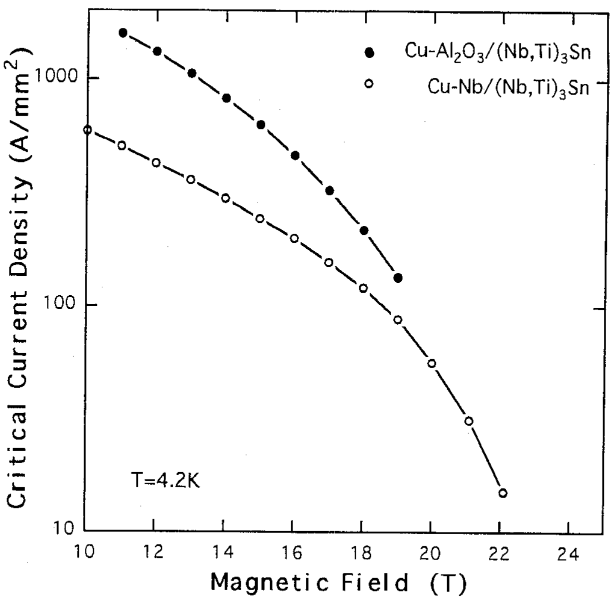

Fig. 3 Comparison of non-Cu $J_c$ at 4.2 K in high fields for Cu-$Al_2O_3$/(Nb,Ti)$_3$Sn and Cu-Nb/(Nb,Ti)$_3$Sn.

with Cu-Nb composes of the wire parameters : 0.8 mm outer diameter, 3.4 μm filament diameter, 5587 filaments, and Cu/Cu-Nb/non-Cu ratio of 0.14/0.67/1. The latter wire with Cu-$Al_2O_3$ has a 1.0 mm outer diameter, 52 μm filament diameter, 132 filaments, and Cu/Cu-$Al_2O_3$/non-Cu ratio of 0.94/0.86/1. It is important to know the resistivity of the reinforcing materials used instead of Cu stabilizer. Figure 2 shows the magnetoresistances of the stabilizer materials measured in high fields at 4.2 K after the heat treatment. Cu-14.6 at.% Nb and Cu-0.4 at.%$Al_2O_3$ composites exhibit the low magnetoresistivity of 0.15-0.17 μΩ·cm at 16 T and 4.2 K, which is merely a factor of about two higher than that of Cu stabilizer. Therefore, these reinforcing materials are expected to play the role of a stabilizer. Bronze processed multifilamentary (Nb,Ti)$_3$Sn wires stabilized with Cu-Nb reinforcement, Cu-Nb/(Nb,Ti)$_3$Sn [5], and Nb-tube processed multifilamentary (Nb,Ti)$_3$Sn wires stabilized with Cu-$Al_2O_3$ reinforcement, Cu-$Al_2O_3$/(Nb,Ti)$_3$Sn [6], have been successfully demonstrated. The heat-treatments to form A15 compounds were carried out at 670℃ for 200 hours in Cu-Nb/(Nb,Ti)$_3$Sn and at 720 ℃ for 50 hours in Cu-$Al_2O_3$/(Nb,Ti)$_3$Sn. Both reinforcing (Nb,Ti)$_3$Sn superconducting wires give characteristic points such as mechanically strong properties and electrically good conductivity even after heat-treatment at about 700℃. From the stress-strain curve measured at 4.2 K, it was found that the yield stress defined as the 0.2 % proof stress is 310 MPa at 4.2 K for Cu-Nb/(Nb,Ti)$_3$Sn [5]. On the other hand, the yield stress for Cu-$Al_2O_3$/(Nb,Ti)$_3$Sn is more than 300 MPa at room temperature [6]. When these value are compared with that of ordinary (Nb,Ti)$_3$Sn wires without reinforcement, it is clear that the strength of such reinforced (Nb,Ti)$_3$Sn wires is significantly improved and is twice as high as that of ordinary ones.

Figure 3 exhibits the critical current densities in a non-Cu area section (non-Cu $J_c$) in high fields at 4.2 K for the highly strengthened multifilamentary (Nb,Ti)$_3$Sn wires. The reinforced (Nb,Ti)$_3$Sn wires usually indicate the slightly lower $J_c$ values than the ordinary wires without reinforcement, because of larger residual strain. In an applied strain state due to the Lorentz force, the critical current density becomes closer to the $J_c$ properties in a strain free state, since the residual compressive strain decreases with increasing the electromagnetic tensile strain axially applied to the wire. For Cu-Nb/(Nb,Ti)$_3$Sn wires, the residual strain at 4.2 K was measured to be about $\varepsilon \approx 0.5$ %. The non-Cu $J_c$ values obtained for the bronze processed Cu-Nb/(Nb,Ti)$_3$Sn wire show the good performance even in 0.5 % prestrain state, and in addition, for the Cu-$Al_2O_3$/(Nb,Ti)$_3$Sn wire fabricated by Nb-tube process the non-Cu $J_c$ is splendidly high. From these results, both Cu-Nb/(Nb,Ti)$_3$Sn and Cu-$Al_2O_3$/(Nb,Ti)$_3$Sn wires are considered to have an enough potential for the highly strengthened superconducting magnets.

## III. HIGHLY STRENGTHENED SUPERCONDUCTING MAGNET FOR 40 T COMPACT HYBRID MAGNET

The highly strengthened $(Nb,Ti)_3Sn$ wires mentioned above enable us to design a very compact high field superconducting magnet with a wide bore for a 40 T hybrid magnet. In order to perform an outstanding design of a new superconducting magnet, we adopt the advanced conditions as follows :

1) A superconducting magnet generates 16 T in a center of a 360 mm room temperature bore.
2) The superconducting magnet may quench, if the insert resistive magnet fails.
3) The coil weight is as light as about 3000 kg, and a Philips PGH105 cryogenerator with two refrigeration powers of 50 W at 20 K and 115 W at 80 K is conveniently available for precooling the coil from room temperature and for radiation shielding.
4) The mechanical properties are extended to be less than 250 MPa for a tangential tensile stress of the coil and less than 100 MPa for a transverse stress of the coil.

The optimization calculation of a highly strengthened superconducting magnet which will be made using epoxy impregnation techniques is still being performed. The conceptual design parameters are presently listed in Table 1. This magnet consists of four grades coils which are designated S1, S2, S3, and T1 from the inside out. The S coils are wound using highly strengthened multifilamentary $(Nb,Ti)_3Sn$ superconducting wires, and the T coil employs a conventional NbTi superconducting wire. When the size of conductors is adopted to be 7.6×3.7, 7.6×3.7, 7.0×3.4 $mm^2$ for S1, S2, and S3 coils, respectiely, the critical current as a function of magnetic field is obtained for $Cu-Al_2O_3/(Nb,Ti)_3Sn$ wires, for instance. Figure 4 shows the load lines for S1, S2, and S3 coils of the 16 T superconducting magnet, and the designed operation current corresponds to 90.4 %, 84.2%, and 80.9 % $I_c$ on the load line, respectively. The innermost coil experiences the maximum field of 17 T at 4.2 K at the windings. As a safety margin, the hoop stress considering the sum of the coil body forces is 200 MPa. This stress value gives a lower strain value than that of the strain free state of 0.5 % in highly strengthened $(Nb,Ti)_3Sn$ superconducting wires. It is worthy of note that the total conductor weight employed in this design is less than about 2,900 kg. This results in the large reduction of magnet size and weight. According to the conventional design using $(Nb,Ti)_3Sn$ wires with external reinforcing housings, the total conductor weight reaches more than 10,000 kg. Therefore, an extremely compact high field superconducting magnet with a wide bore whose weight is about 1/3 in comparison with the ordinarily made magnet can be realized.

Table 1. Coil parameters of a 16 T compact superconducting magnet with a 360 mm room temperature bore for a 40 T hybrid magnet.

| coil grading | S1 | S2 | S3 | T1 |
|---|---|---|---|---|
| inner diameter [mm] | 420 | 498 | 628 | 806 |
| outer diameter [mm] | 498 | 608 | 786 | 936 |
| coil height [mm] | 680 | 680 | 680 | 680 |
| operation current [A] | 1640 | 1640 | 1640 | 1640 |
| central field [T] | 16.0 | — | — | — |
| maximum field [T] | 17.0 | 14.8 | 11.8 | 6.6 |
| effective current density [A/$mm^2$] | 53.8 | 53.8 | 63.0 | 131 |
| hoop stress [MPa] | 200 | 200 | 200 | 100 |
| conductor length [m] | 1260 | 2120 | 4590 | 9680 |
| conductor size [mm×mm] | 7.6×3.7 | 7.6×3.7 | 7.0×3.4 | 4.8×2.3 |
| stabilizer / non Cu ratio | 1.5 | 2.6 | 7.2 | 1.2 |
| total conductor weight [kg] | 2880 | — | — | — |

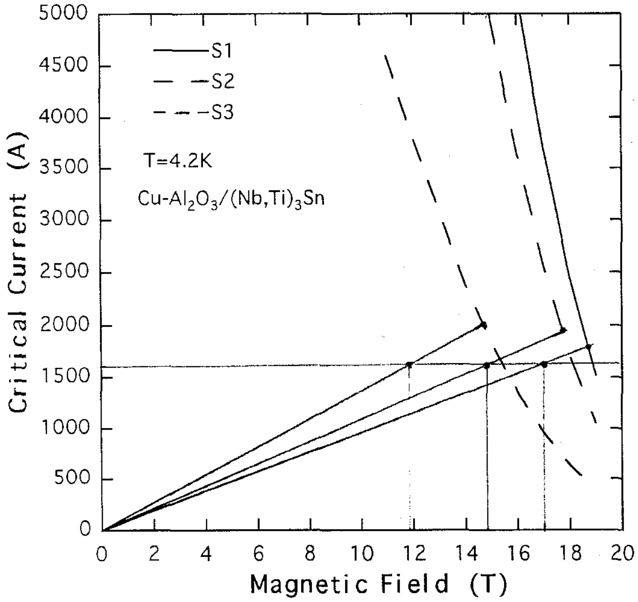

Fig. 4. $I_c$-vs-B properties for $Cu-Al_2O_3/(Nb,Ti)_3Sn$ superconducting wires, and the load lines of a 16 T superconducting magnet.

## VI. 24 T POLI-BITTER MAGNET WITH 8 MW POWER SUPPLY FOR 40 T COMPACT HYBRID MAGNET

Strengthened materials such as Cu-0.9 at% Cr (yield strength of 400 MPa and electrical conductivity of 90 % IACS) and Cu-0.4 at.% $Al_2O_3$ (460 MPa and 89 % IACS) have been used for water-cooled resistive magnets. Since high field resistive magnets require more highly strengthened materials, the more largely equipped power supply system is needed. The resistivity of a reinforced material increases with increasing strength. That is the reason why the large power supply systems of 15-25 MW have been installed for

Table 2. Coil parameters of a 24 T poly-Bitter magnet with a 14 mm room temperature bore for a 40 T hybrid magnet.

| | inner dia. [mm] | outer dia [mm] | coil height [mm] | operation current [kA] | power [MW] | generated field [T] | max. hoop stress [MPa] | max. disk temperature [°C] |
|---|---|---|---|---|---|---|---|---|
| 1 | 220 | 320 | 250 | 23 | 2.78 | 4.21 | 416 | 95.3 |
| 2 | 142 | 217 | 155 | 23 | 2.02 | 4.16 | 478 | 52.4 |
| 3 | 72 | 137 | 145 | 23 | 1.84 | 6.76 | 513 | 58.5 |
| 4 | 20 | 68.0 | 145 | 23 | 1.37 | 8.46 | 529 | 76.6 |
| Total | | | | 23 kA | 8.0 MW | 24 T | | |

resistive magnets in new high field facilities [1-3]. Recently developed Cu-50 at.%Ag materials with yield strength of 700 MPa and electrical conductivity of 85 %IACS [7] attract strong attentions as a suitable material of a resistive magnet. We concentrate on this Cu-50at.%Ag with extremely high yield strength to introduce a 24 T resistive magnet with 8 MW power supply for a 40 T compact hybrid magnet. A poly-Bitter type resistive magnet is designed under the conditions of the DC power of 8 MW (23 kA and 350 V) and the cooling ability of 350 $m^3/h$ which have already been equipped at High Field Laboratory for Superconducting Materials, Tohoku University [8]. Table 2 presents the typically designed poly-Bitter resistive magnet which generates 24 T in a 14 mm room temperature bore [9]. The objective of a 40 T compact hybrid magnet is to provide both electrical resistivity and magnetization measurements, in order to explore the physical properties in high fields for thin films and single crystals, for instance. These research will require the experimental cold bore of 8 mm at least (a room temperature bore of 14 mm). These results obtained for the poly-Bitter resistive magnet encourage us to challenge for highly strengthened magnet design, and lead to the realization of a 40 T compact hybrid magnet.

## VII. CONCLUSION

Newly developed multifilamentary $(Nb,Ti)_3Sn$ superconducting wires with reinforcing stabilizer such as Cu-Nb or Cu-$Al_2O_3$ enable us to design a highly strengthened superconducting magnet. A high field and wide bore superconducting magnet without external housing reinforcement can be made by adopting an epoxy impregnation technique, and as a result, a very compact superconducting magnet with the large over-all current density is realized. In a conceptual design of a 40 T hybrid magnet, the weight of a 16 T outer superconducting magnet with a 360 mm room temperature bore is reduced to about 1/3 in comparison with the ordinarily made magnet. Moreover, a 24 T inner resistive magnet with a 14 mm room temperature bore is designable using a poly-Bitter concept with an 8 MW power supply of 23 kA and 350 V.

## ACKNOWLEDGMENTS

We would like to thank Professors K. Katagiri and K. Noto of Iwate University for useful discussions on highly strengthened materials. Cu-Nb/$(Nb,Ti)_3Sn$ wires were prepared by Fujikura Ltd.

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