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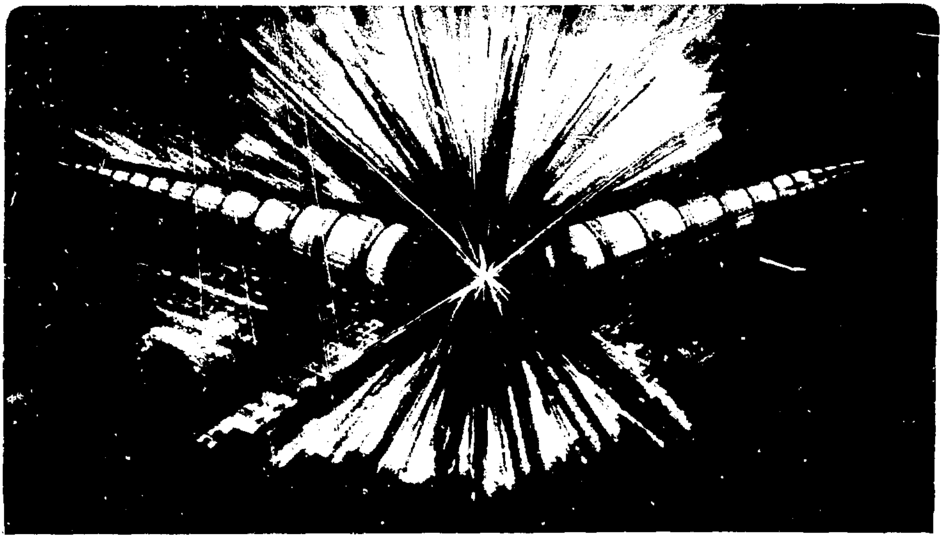

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A COMPARISON OF THE COSTS OF SUPERCONDUCTING ACCELERATOR DIPOLES USING NbTi, Nb_3Sn AND NbTiTa*

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I. *Introduction*

The present study, which is based on the assumption that future, high-energy accelerators will use superconductors, is a comparison of the costs of 5 to 12 Tesla NbTi, Nb_3S_n, and NbTiTa accelerator magnets operating at 4.2 K or 1.8 K, as summarized in Table I. The object of this evaluation is not to determine the actual cost of future accelerators, rather, its purpose is to provide some rationale for research on the next generation of superconducting accelerator magnets. Thus, though the actual costs of accelerator magnets may be different from those given here, the comparisons are valid.

The costs given are based on a "standard", 4-m long magnet with a 0.12-m diam. usable aperture. To establish a base for this study, the effect of aperture and length on magnet cost were used to estimate costs of 5-T, NbTi magnets having apertures and lengths comparable to those of ISABELLE at Brookhaven National Laboratory (BNL), and the Energy Saver/Doubler at the Fermi National Accelerator Laboratory (FNAL). These estimates are usually within 15 percent of the cost and labor figures given by BNL and FNAL and some comparisons are made in the text.

Table I

Superconductors and Operating Conditions Considered in This Study

Superconductor	Operating Temperature	Field Range
NbTi	4.2K	4 - 9T
Nb_3Sn	4.2K	7 - 12T
NbTi	1.8K	7 - 12T
NbTi Ta	1.8K	7 - 12T

II. Superconducting Materials

IIA. Current Densities in Superconducting Materials

The superconductors used in this study were given in Table I. Their current densities as a function of field are given in Table II and are shown in Fig. 1. These current densities are based on recent measurements by manufacturers but are not necessarily for optimized conductors. I.e. it may be possible to increase the current density with a slight variation in alloy or heat treatment. The most significant variations are likely to be in Nb_3Sn where ± 50 percent differences in reported J_c are possible.

Figure 1

SHORT SAMPLE CRITICAL CURRENT IN THE SUPERCONDUCTOR (no stabilizer)

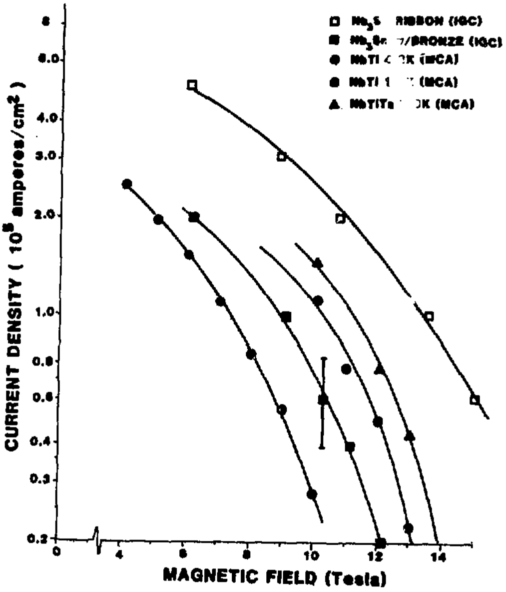

Table II

Current Densities x $10^5 A/cm^2$ of Superconducting Wires Exclusive of Stabilizing Copper

Field (T)	NbTi 4.2K	NbTi 1.8K	NbTiTa(a) 1.8K	Nb_3Sn 4.2K
4	2.6			
5	2.0			
6	1.6	2.6		2.1(b)
7	1.1	2.2		1.8(b)
8	0.8	1.9	2.2	1.4(b)
9	0.6	1.5	1.8	1.0(b)
10	0.3	1.1	1.5	0.7(b)
11		0.8	1.1	0.5(c)
12		0.5	0.8	0.4(c)

a. Data are for 25 percent Ta alloy
b. Data are for Nb_3Sn plus bronze and Ta barrier. IGC
c. Data are for Nb_3Sn plus bronze and Ta barrier. AIRCO

Two techniques have been proposed for fabricating large Nb_3Sn coils having high stresses and strains. One is to wind the coil and then react; the second is to react the conductor and then wind the coil. Because Nb_3Sn is a very brittle material a large degradation can be expected in the coil if the react and wind technique is used in magnets that have high strains. The largest strains invariably occur while winding around the smallest bend radius or in high field regions, which occur together at the ends in dipole magnets. Extra conductor may be

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needed to bring the current carrying capability of wind and react coils in these regions up to that of the rest of the coil. Special care must be taken in any case when Nb_3Sn coils are constructed. This care is ultimately reflected in somewhat higher fabrication costs.

IIB. Costs of Superconducting Materials

The unit cost of NbTi used in this report is based on discussions with conductor manufacturers and the experience of FNAL[1] and BNL[2] (two of the largest purchasers of superconducting wire) and may be considered accurate to ± 10 percent. For copper to superconductor ratios between 1.5 and 2.0 the cost of NbTi is about $75/lb or $166/kg, though $200/kg may be paid for complicated braid conductors.

The costs of Nb_3Sn conductors on the other hand are not so well known. The LCP conductor, of which 20 percent is a stainless steel shell, costs about $220/kg.[3] The cost of the conductor alone (copper and superconductor) would be $250/kg. Much higher costs are expected on small orders. However, there is reason to believe this cost will be reduced, because less of the relatively expensive niobium is required in Nb_3Sn than in NbTi conductors.

The costs of NbTiTa superconductors have not been throughly studied, though Ta is very expensive. The high cost of Ta causes the base cost of NbTiTa alloy with 25 weight percent Ta to be about 520 $/kg instead of 200 $/kg for NbTi. This high initial cost is reflected in a high conductor cost. Estimates range from a factor of 1.5 to 2.0[4] for the ratio of cost of finished NbTiTa conductor to the cost of finished NbTi conductor. This study uses a cost of $360/kg[4] for 25 percent Ta.

III. Magnet System Costs

IIIA. Conductor Cost

The cost of conductor in a magnet is the product of the unit cost of conductor and the quantity of conductor required. The unit costs of conductors used here, as described above, are based on discussions with superconductor manufacturers and reflect current prices paid for superconductor on major projects.

The quantity of superconductor required in a thin dipole coil is given by

$$V_{sc} = \frac{8r\ B_o}{\mu_o} \ ,$$

where r is the mean radius and b is the length, 4 m. For a 0.12 m bore, 5T coil the mean radius of the winding is about 0.10 m. This expression must be modified to include the effect of current density on the radius of the windings. The cost of conductor C_C becomes

$$C_C = C_{sc} \times 2.55 \times 10^3 B(0.7 + 0.18\ C_{sc})$$

where C_{sc} is the unit cost of the conductor in $/kAm at the operating field and is nearly inversely proportional to the critical current.

IIIB. Iron Cost

The cost of iron in a superconducting magnet will depend on the field, the radius of the windings, and whether the iron is cold or warm. Only warm iron coils are considered here and to first order the cost is proportional to the field B. However, the winding radius increases with B causing the quantity of iron to increase. The cost of the iron used in this study is given by

$$C_I = \$1400\ B \times (0.7 + 0.05B)$$

IIIC. Cryostat Costs

The cost of a cryostat is determined mainly by its surface area, $2\pi r$. As the length of the coils is fixed the only variables affecting the cryostat cost are the temperature, 1.8K vs. 4.2K, the mean radius of the conductor, and the forces associated with the weight of the coil and imperfect positioning of the coil in the iron.

The formula used here is

$$C_R = \$1500 + \$900B.$$

IIID. Miscellaneous Costs

Many small items are needed in the construction of a superconducting coil. These include spacer materials, bore tubes, coil form supports, heaters, voltage taps, insulation, and power leads. The formula used here for NbTi coils is

$$C_M = 5520 + 300B + 100B^2.$$

IIIE. Fabrication Costs

The cost of constructing the coil is based on the cost of labor and an estimate of the number of hours required to construct and assemble the coil and cryostat.

$$C_F = \$10000 + \$1600\ B + \$1800\ B^{1/2} + \$240\ B^2.$$

The Doubler magnets are constructed in about 1200 hours and the FNAL labor charge is assumed to be $20/hr giving $24,000. The formula above gives $28,000 for a shorter, larger diameter dipole.

IIIF. Special Costs in a 1.8K Accelerator

Both the initial installation and the operating costs of the refrigeration system for a 1.8 K accelerator will be greater than those of a 4.2 K accelerator. However, only part of the heat load is intercepted at 1.8 K. The major 1.8 K heat source is cyclic hysteresis loss in the coil itself. There will be some radiation and conduction losses at 1.8 K but most of these can be intercepted at a higher temperature, 4.2 K or above. Only about half the heating and losses in an accelerator occur in the bath.

The effect of this increased refrigeration cost on the magnets is best made by comparing the cost of magnets and refrigerators in other accelerators. The ISABELLE is used as an example here as commercial costs are available for this system. The cost of the ISABELLE magnets and cryostats is estimated to be $80 x 10^6 while the cost of the refrigerators and cryogenic distribution system was $20 x 10^6.

An overall cost factor of about 2.5 is expected for 1.8 K systems compared to 4.2 K systems. Applying this cost to half the magnet heat load, the refrigerator cost becomes $35 x 10^6, giving a 19 percent increase. Note that the working field of the superconductor in the magnets increases by 30 percent at the same time.

The cost of operating a 1.8K system will be greater, per Watt of refrigeration, than for a 4.2K system. The power consumption will increase by slightly more than the ratio of the temperatures. The 10 MW of power for ISABELLE would increase to about 16 MW. The present value of this power including investment and operating cost will be $1 to $1.5 per W. This effect will increase the future magnet cost by an additional 7 1/2 to 10 .

Combining these two effects, the increase in refrigeration costs, as reflected in magnet costs will be 25 to 28 percent.

IIIG. Total Magnet Cost

The total magnet cost for a NbTi coil operating at 4.2K is simply the sum of the individual component costs as described above:

$$C_T\ (\mathrm{NbTi},\ 4.2K) = C_C + C_I + C_R + C_M + C_F.$$

This formula for total coil cost was used to obtain Table III. The total cost for NbTi and NbTiTa coils at 1.8K is the sum of the individual component costs but the cryostat cost C_R is increased by 30 percent and the other magnet costs are increased by 25 percent to reflect the increased costs of refrigeration. Two of the individual costs are modified to obtain the total magnet cost for a Nb_3Sn coil at 4.2K. First, for lack of a detailed design, it is assumed that the miscellaneous coil component costs are increased by 30 percent because the coil structure must be more complicated and probably stronger to accomodate strain related degradation of Nb_3Sn. Second, the labor cost for the coil is expected to increase by about 30 percent, which is expressed as a 15 percent increase in total labor cost. These modifications to the formula above for coil cost were used to obtain the Tables IV - VI.

The "Unitized" magnet costs given in Table III to VI are the cost of the system per unit of bending power (Tesla-meter). It is this cost, which increases slowly with field, that should be compared with other costs such as land excavation, and tunnel fabrication to minimize total accelerator costs.

IV. Conclusions and Recommendations

At present the costs of NbTi magnets operated at 4.2 K are most economical for fields up to about 7 T, while the increased current density of NbTi at 1.8 K makes this type of magnet more attractive above 7T. The costs of NbTiTa and Nb_3Sn magnets are higher than those of the NbTi magnets up to 12T as this study indicates. The construction of several model coils and a determination of the effects of compressive loading on coil performance will allow better estimates of Nb_3Sn structural requirements and costs.

Most NbTi alloys and heat treatments are optimized for maximum current density at 4.2 K and intermediate fields. Further optimizations of alloys and process variables may allow improvements in the current density of NbTi and NbTiTa at 1.8 K between 7 and 12T.

References

1. W. Fowler, R. Lundi, Private Communication, FNAL, Sept., 1980.
2. D. Brown, L. Repeta, Private Communication and Main Magnet Cost Estimate, BNL, Sept. 1980.
3. E. Gregory, Private Communication, AIRCO, June, 1980.
4. B. Zeitlin, IGC and T. De Winter, MCA, Private Communication, June 1980 - Feb. 1981.

Table III

Costs of NbTi Magnets Operating at 4.2 K

B (T)	Cost of Conductor $/kAm	Magnet Cost $ x 10^3	Unitized Magnet Cost $/Tm
4	1.25	55	3460
5	1.63	72	3580
6	2.03	91	3810
7	2.96	133	4750
8	3.87	188	5880
9	5.81	322	8940
10	11.60	926	23150

Table IV

Costs of NbTi Magnets Operating at 1.8 K

B (T)	Cost $/kAm	Magnet Cost $ x 10^3	Unitized Magnet Cost $/Tm
6	1.25	093	3880
7	1.48	113	4040
8	1.71	136	4250
9	2.17	169	4690
10	2.96	197	4930
11	3.83	266	6050
12	6.51	536	11160

Table V

Costs of NbTiTa Magnets Operating at 1.8 K

B (T)	Cost of Conductor ($/kAm)	Magnet Cost 4 x 10^3	Unitized Magnet Cost $/Tm
8	2.89	172	5400
9	3.54	223	6200
10	4.24	262	6560
11	5.78	399	9080
12	7.75	628	13080

Table VI

Costs of Nb_3Sn Magnets Operating at 4.2 K

B (T)	Conductor Cost ($/kAm)	Magnet Cost $ x 10^3	Unitized Magnet Cost $/Tm
6	2.62	114	4736
7	3.14	148	5300
8	3.93	202	6300
9	5.50	315	8740
10	7.63	518	12960
11	12.81	1209	27500
12	23.94	3810	79500