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Publication Date
1982-11-01

LBL-14918

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Accelerator & Fusion Research Division

Presented at the 1982 Applied Superconductivity Conference, Knoxville, TN, November 28-December 3, 1982; and to be published in the Proceedings.

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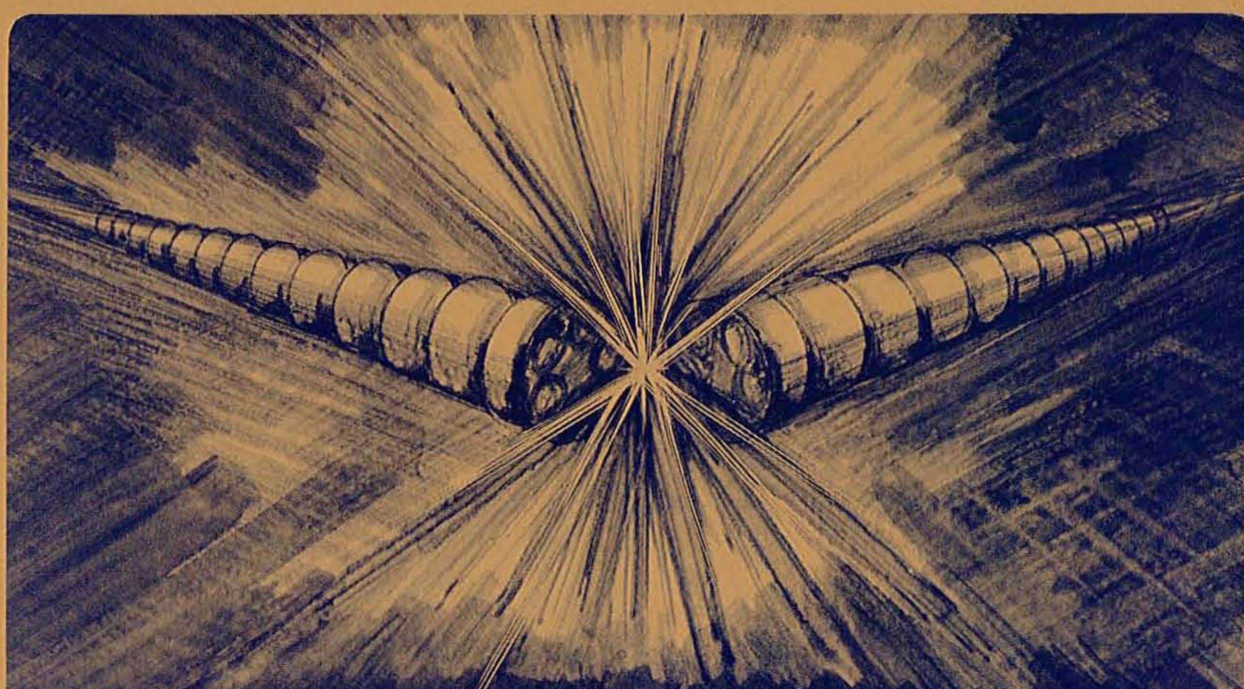

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-14918
SUMAG-76

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

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Summary

Future high energy proton accelerators will likely require very high magnetic fields if the size of the accelerator and associated experimental areas are to be limited to dimensions that can be accomodated by the terrain at convenient sites. Two commercially available superconductors can be used to produce magnetic fields of 10 T or more. The first is Nb_3Sn, which can operate in pool boiling helium at 4.4 K. The second is NbTi, which must be cooled to about 1.9 K in superfluid helium. In this paper the costs of 5 cm bore, 6 m long magnets made of these materials and operating at fields from 5 to 11 T are compared. At 10 T the capital cost of a NbTi coil operating in superfluid helium is 35% less than the cost of a Nb_3Sn coil. The cost of the NbTi coil is still 10% less after the differential operating costs that will be incurred over the life of the accelerator are included. The results presented here are a summary of a detailed analysis of these costs given in a separate report.[1]

Introduction

The Energy Doubler/Saver at Fermilab will produce protons at about 1 TeV, which is almost twice the energy possible in the existing Fermilab accelerator. This energy is possible in the existing tunnel because the superconducting magnets operate at 4 T while the conventional magnets operate at 2 T. Future high-energy proton accelerators will require even higher magnetic fields unless new acceleration techniques are developed or very large expanses of land are used. A 10 T, 20 TeV machine has been proposed as the next step in accelerator development by the ICFA study group. Though it may be possible to use lower fields in a large accelerator, 10 T appears to be a reasonable goal at present considering the capabilities of existing commercial superconductors. Three superconductors may be considered for operation at 10 T. The first is Nb_3Sn operating in pool boiling helium at about 4.4 K. Another is NbTi operating in superfluid helium at about 1.9 K. The ternary alloy, NbTiTa, is a third possibility, but is not considered here because it is expensive and did not appear attractive in an earlier study.[2] This ternary may be effective, however, in a hybrid magnet where it would be used in only the highest field regions in which case the costs developed here would not change significantly.

The detailed design of dipole magnets for future accelerators can only be guessed at, but at fixed field and fixed length, the cost of a dipole magnet will be roughly proportional to the inside diameter of the windings. Though even smaller coils could be built, a 2" bore is possible and is considered here. At present the trade-offs between aperture and beam intensity are not known.

The doubler/saver coils are almost 7 m long and detailed information on component cost has been made available by Fermilab.[3] All the coils considered here are 6 m long and the Fermilab costs are used as directly as possible. The costs developed allow a reasonable comparison of the different types of coils; a comparison that will not change significantly with length. As a further comparison, costs of NbTi coils operating at 4.4 K are included though these coils are limited to a maximum field of about 9 T. In addition, a 5 T coil is included to provide a link to existing accelerator magnets. At 6 m there will be about 10,000 magnets in a 20 TeV machine, clearly reducing this number would be desirable and longer magnets will probably be used in a real accelerator if the problem of protection can be solved.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

Manuscript received November 30, 1982

Superconductor Costs

Good estimates can be made of the production costs of Nb_3Sn and NbTi, which are produced in relatively large quantities. About 10^5 kg of NbTi cable having a copper to superconductor ratio of 1.8 was produced for the doubler/saver by several manufacturers. The raw material and fabrication costs of this conductor are given in Table I. These costs were supplied by Adam et al.[4] but are very similar to costs reported by Fermilab[3] and those obtained from other manufacturers during an economic evaluation of superconducting magnetic energy storage.[5] Recent studies show that some specially processed materials exhibit current densities considerably higher than the Fermilab specifications.[6,7] The special processing includes an additional heat treatment during wire drawing to improve the crystalline structure of the NbTi filaments. These conductors will be somewhat more expensive because of the additional handling; fabrication costs may increase by as much as 15%. Assuming an 82% yield and special processing, the 1.8:1 conductor will cost about $49/lb and the 1:1 about $62/lb.

The fabrication and raw materials costs for Nb_3Sn multifilamentary wire made with the bronze process are given in Table II. The bronze process conductor requires 10 to 30 anneals during processing while the NbTi conductor requires only one or two heat treatments. The fabrication costs in Table II reflect this difference but are slightly less than the actual costs of the LCP conductor.[8]

Several other production methods have been proposed for multifilamentary Nb_3Sn. These methods may

TABLE I: Production costs of NbTi superconductor based on 82% yield of the extrusion

NbTi rod ($\rho = 6.05$)		$80.00/lb
Cu ($\rho = 8.94$)		$3.50/lb
Materials	Cu/SC = 1.8:1	$29.90/lb
	Cu/SC = 1.0:1	$41.90/lb
Fabrication		$17.00/lb
Fabricated Conductor Costs		
FNAL Specification Conductor	1.8:1	$46.90/lb
	1:1	$59.00/lb
High-Current Density Conductor	1.8:1	$49.40/lb
	1:1	$61.50/lb

TABLE II: Production costs for bronze process Nb_3Sn superconducting wire based on large scale production and 80% extrusion yield

Nb rod	(ρ = 8.4)	$80/lb
Nb sheet	(ρ = 8.4)	$80/lb
Cu	(ρ = 8.94)	$3/lb
Bronze	(ρ = 8.7)	$10/lb
Materials	Cu/S.C. = 1.7:1	$21.80/lb
	Cu/S.C. = 1:1	$25.60/lb
Fabrication Cost		$40.00/lb
Fabricated Conductor at 1.7:1		$61.80/lb
Fabricated Conductor at 1:1		$65.60/lb

Table III: Current densities (A/mm^2) in the superconductor

Field	NbTi (4.4 K)		NbTi (1.9 K)		Nb_3Sn (4.4 K)	
(T)	FNAL	Best	FNAL	Best	LCP	Proposed
5	1400	2100	-	-	-	-
7	900	1450	2060	2800	1000	1790
8	660	1200	1710	2300	900	1610
9	340	760	1360	1960	800	1450
10	100	350	1050	1620	700	1250
11	-	-	700	1250	580	1040
12	-	-	380	900	470	840

provide a high current density, and material and fabrication costs may be lower than for bronze process Nb_3Sn. Though a breakthrough is possible, it cannot be predicted, and other costs may be introduced easily to the component costs included here to reevalute total magnet costs.

The costs of superconductors are frequently given in ($/kAm) to reflect the current carrying capacity of the conductor and thus describe conductor value. This cost is based on the working current densities, which are given in Fig. 1 and Table III. The current densities in Table III and the costs in Tables I and II are used to calculate the cost of materials in $/kAm as given in Fig. 2 and Table IV.

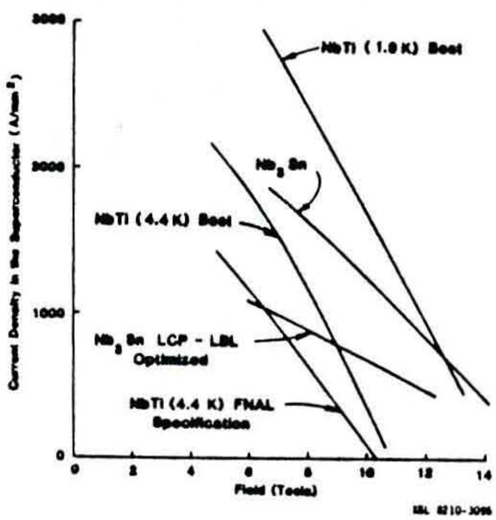

Fig. 1. Short sample critical current expected in bare superconductors used in accelerator magnets.

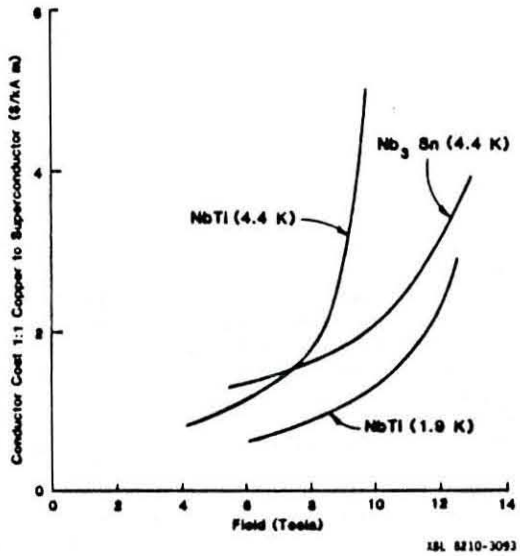

Fig. 2. Unit cost of superconductors proposed for accelerator magnets.

TABLE IV: Conductor cost in ($/kAm) as a function of field for NbTi and Nb_3Sn conductors with 50% stabilizer cross section

Field	NbTi		Nb Sn
(T)	4.4 K	1.9K	4.4 K
5	1.00		
7	1.44	0.75	1.45
8	1.74	0.91	1.62
9	2.75	1.07	1.79
10	5.98	1.29	2.08
11		1.67	2.50
12		2.32	3.10

Superconductor Requirements for Magnets

The amount of superconductor required for a coil depends on the working current density in the conductor, the coil design, and the placement of iron, if it is used. Each of these items is discussed separately below and then the material requirements for specific coil configurations using NbTi and Nb_3Sn are developed.

Though the current densities of Fig. 1 are possible in a short sample, to approach the same current density in a real magnet may be very difficult if not impossible. Thus the working current density is reduced by 20% for Nb_3Sn, and 10% for NbTi. The average current density in the coil windings is less than that in the superconductor because of the space occupied by the stabilizer, insulation, and helium. For the conductors in this study, which have 50% stabilizer, the maximum possible working current density in the winding will be about 38% of that in the superconductor.

The effectiveness of a quantity of superconductor in terms of producing a given field is affected by the coil design. On the average the conductor in the block design[9] is further from the bore than the conductor in the layer design[10]. Assuming the same current density is possible in the conductor, this effect requires that about 5% to 10% more conductor be used for a block coil than a layer coil. In comparing NbTi and Nb_3Sn coils the different conductor characteristics that determine coil geometry become important. Though NbTi can be used in both configurations and the brittle nature of Nb_3Sn may require the block geometry, only layer magnets are considered in this study.

The superconducting dipoles being constructed for the Fermilab doubler/saver ring use warm iron and the Isabelle magnets at Brookhaven use cold iron. Surprisingly, the quantity of iron required to achieve the maximum shielding is almost independent of the distance of the inside of the iron from the coil.[11] This means that the iron can be cold or warm or even some combination of the two and still have about the same cross section, and therefore cost, for a given magnet.

Two, three, and four layer magnet designs were studied to determine the quantity of superconductor required to achieve fields between 7 and 12 T. A single point at 5 T for NbTi at 4.4 K has been included to connect this study to existing accelerator magnet designs. The conductor requirements established by this analysis are shown in Figs. 3 and 4.

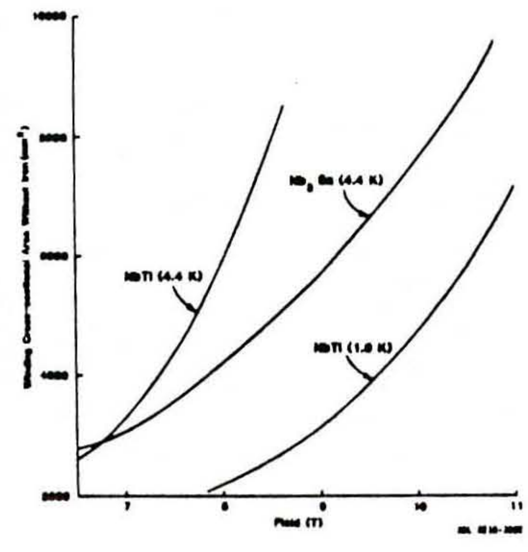

Fig. 3. Cross sectional areas of superconducting windings for 50 mm-bore dipoles without iron.

The conductor costs for 6-m long magnets are found directly by combining the unit conductor costs in Table IV and the conductor requirements in Fig. 3 and are listed in Table V and shown in Fig. 5. Similarly the conductor costs for 6-m long magnets with cold iron are found in Table VI and Fig. 6.

The cost of iron, cryostat, refrigeration system and fabrication for high field magnets can be related to the cost of these items for the Fermilab energy doubler/saver. The approximate cost of each component of the completed FNAL dipole is given in Table VII.

The rationale for adjusting the Fermilab costs to get to reasonable values for high field dipoles are given in detail in Ref. 1 and are summarized qualitatively here.

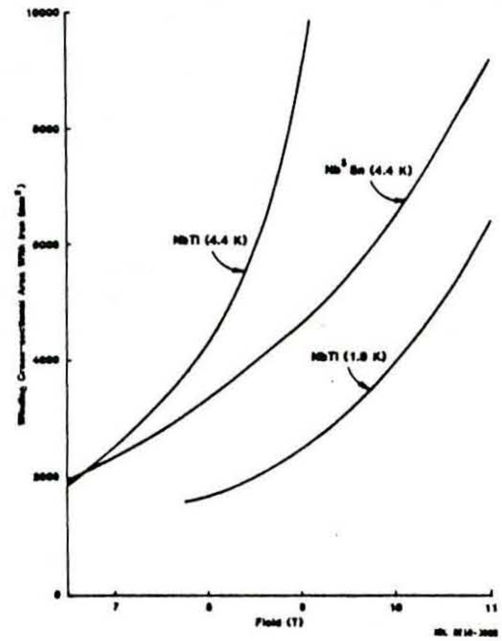

Fig. 4. Cross sectional areas of superconducting windings for 50 mm-bore coils with cold iron.

TABLE V: Cost in dollars of superconductor for 6 m long dipoles without iron

	NbTi	NbTi	Nb_3Sn
Field	4.4 K	1.9 K	4.4 K
5	5640	-	-
7	14170	-	14670
8	25260	9500	20020
9	47190	13610	26850
10	-	20590	36190
11	-	31260	48300

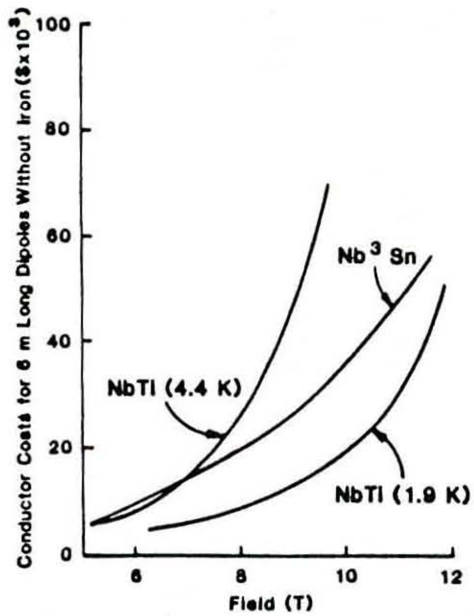

Fig. 5. Conductor costs for 6-m long dipole magnets without iron.

TABLE VI: Cost in dollars of the superconductor for 6-m long dipoles having cold iron

Field	NbTi		Nb_3Sn
(T)	4.2 K	1.9 K	42 K
5	4300	-	-
7	10710	-	11140
8	18370	7210	15550
9	38280	10790	21910
10	-	16870	30950
11	-	27250	43500

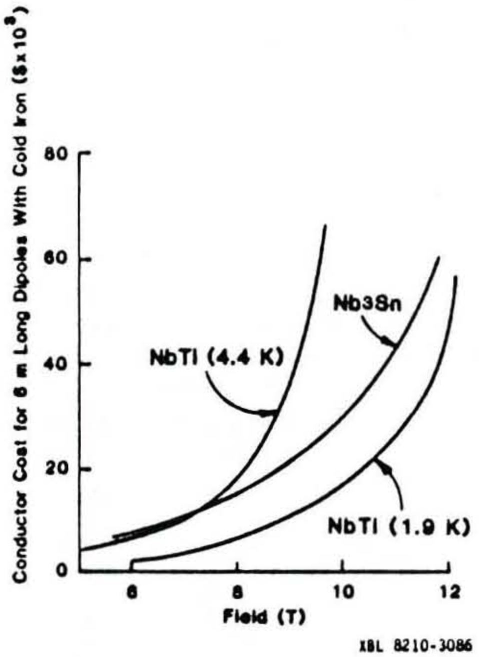

Fig. 6. Conductor costs for 6-m long dipole magnets with cold iron.

TABLE VII: Component costs and manpower requirements for the fermilab energy double/saver dipoles

Conductor	$13,000
Coil Parts	4,800
Cryostat Parts	4,000
Iron	3,500
Misc.	2,000
Total Parts	$27,300
Coil winding and assembly	200
Cryostat assembly	200
Iron assembly	80
Final assembly	120
	600 hrs

The cost of coil parts in the Fermilab magnets are about 37% of the conductor cost. This proportion is used for 4.4 K NbTi coils. The cost of parts for Nb_3Sn coils will be greater because of the lower allowable strains and the need for additional support such as internal structure needed in the block design. This effect is estimated to increase the coil parts cost by at least 30%. In the NbTi coils at 1.9 K the forces will be greater per unit volume of superconductor so the estimated cost increase is 10%.

The cost of the cryostat parts will depend somewhat but not strongly on diameter. The major effect will be due to the use of cold or warm iron and will depend somewhat on field. A 25% increase is assumed for the 1.9 K dipoles. The amount of iron depends primarily on the size of the bore and the coil thickness. Though the quantity of iron required at a given field will decrease somewhat as the current density increases, this is a secondary effect.

The coil winding time will be roughly proportional to the number of layers. Thus Fermilab's 200 hr becomes about 400 hr for a 4 layer coil. An additional 30% is charged to the Nb_3Sn coils to account for the reaction requirements and assembly of the extra support structure.

The costs of the various magnet components, including labor costs at a rate of $20/hr, and the total costs for the different types of magnets are given in Tables VIII, IX and X. In a previous study the effect on refrigeration cost of operating at 1.9 K was shown to contribute about 25% to the total magnet cost. The 1.9 K magnet costs in Table IX are increased by this same factor to obtain adjusted total costs that allow comparison with the other coil costs, as shown in Fig. 7.

TABLE VIII: Cost of NbTi magnets operated at 4.4 K

	5	7	8	9
Conductor	4300	10710	18370	38280
Coil Parts	1590	3960	6800	14160
Cryostat Parts	6000	6400	6600	6800
Iron	3000	4100	4400	4700
Misc.	2000	2800	3200	3600
TOTAL PARTS	16890	27970	39370	67540
Coil winding & assy	4000	5600	6400	7200
Cryostat assy	3300	3900	4100	4300
Iron assy	1600	1760	1840	1920
Final assy	2400	2400	2400	2400
TOTAL LABOR	11300	13660	14740	15820
TOTAL COST	$28190	$41630	$54110	$82820

TABLE IX: Cost of NbTi magnets operated at 1.9 K

Field (T)	8	9	10	11
Conductor	7210	10790	16870	27250
Coil Parts	2960	4390	6870	11090
Cryostat Parts	8250	8500	8750	9000
Iron	4400	4700	5000	5300
Misc.	3520	3960	4400	4840
TOTAL PARTS	26340	32340	41890	57480
Coil winding & assy	6400	7200	8000	8800
Cryostat assy	5130	5380	5630	5880
Iron assy	1840	1920	2000	2080
Final assy	2400	2400	2400	2400
TOTAL LABOR	15770	16900	18030	19160
TOTAL COST	42110	49240	59920	76640
TOTAL w 25% added for Refrig.	$52640	$61550	$74900	$95800

Unit Costs of Accelerator Dipoles

The coil costs given above provide a comparison between different materials at the same field. Another way to compare these magnets is based on the bending power, which is essentially the cost in the units ($/Tm). In this form a comparison can be made

TABLE X: Cost of Nb_3Sn magnets operated at 4.4 K

Field (T)	8	9	10	11T
Conductor	15550	21910	30950	43500
Coil Parts	7480	10540	14890	20920
Cryostat Parts	6600	6800	7000	7200
Iron	4400	4700	5000	5300
Misc.	4160	4680	5200	5720
TOTAL PARTS	38190	48630	63040	82640
Coil winding & assy	8320	9360	10400	11440
Cryostat assy	4100	4300	4500	4700
Iron assy	1840	1920	2000	2080
Final assy	2400	2400	2400	2400
TOTAL LABOR	16660	17980	19300	20620
TOTAL COST	$54850	$66610	$82340	$103260

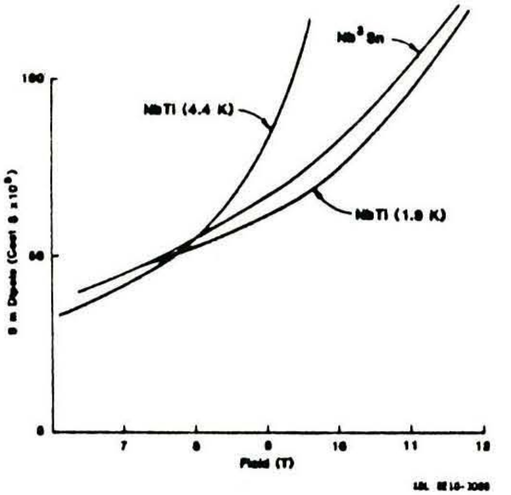

Fig. 7. Total costs of accelerator dipoles

from one field to another not just from one material to another. The unit cost of magnets on this basis are given in Table XI and Fig. 8. The minimum costs are at the lowest fields, but the increased costs of land, trenching or tunneling, piping services, concrete, etc., may offset this effect.

TABLE XI: Unit costs of accelerator magnets in $/Tm.

	NbTi	NbTi	Nb_3Sn
Field	4.4 K	1.9 K	4.4 K
5	940	-	-
7	991	-	-
8	1127	1097	1142
9	1534	1140	1233
10	-	1248	1372
11	-	1452	1565

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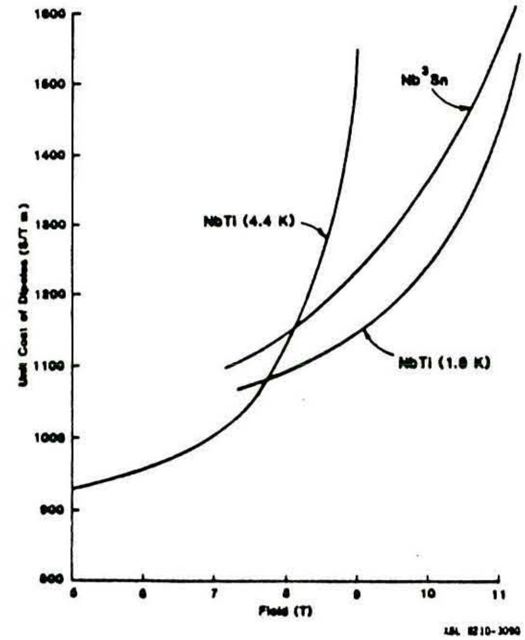

Fig. 8. Unit cost of accelerator dipoles ($/Tm)

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