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FACTORS WHICH WILL AFFECT THE COST OF A SUPERCONDUCTING SYNCHROTRON

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Abstract

This report studies the effect of the more important machine parameters on synchrotron cost. As a start, published cost estimates of the LRL and BNL superconducting synchrotron studies are presented. These costs are compared with published cost data for the NAL conventional synchrotron. Some rough conclusions about the effects of aperture and dipole magnet field can be drawn from these already published cost data.

In order to show more clearly the effects of machine parameters on cost, consistent cost-estimating procedures are applied to a wide variety of machines with various dipole magnetic fields, magnet apertures, and machine cycle times. The cost of machines using a highly advanced nonexistent β tungsten type of material (Nb_3Sn, V_3Ga, etc.) is compared with machines using a practical Nb-Ti material now available. The basic assumptions used in the cost-estimating process are described. The basic machine parameters used in the estimate are discussed. The results of consistent cost calculations using the CDC 6600 computer are presented in tabular and graphical form. The costs for a number of these machines are broken down into component costs so that the effect of various machine parameters can be seen in each of the important machine components. The effect of various machine parameters on the 10-year cost of electric power is also presented.

The report shows that the capital plus power cost of a superconducting synchrotron can be expected to be lower by a factor of 2 or 3 than the best of the conventional synchrotrons. The superconducting machine would also have a gain in energy of 2 or 3 over the conventional machine of the same radius. The lowest-cost machines will have dipole magnetic inductions of the order of 40 to 50 kG, the machine cycle times are likely to be 5 to 15 seconds. The report also makes it clear that no one thing is going to have a dramatic effect on machine cost. In short, one is going to use the best economically justified technology that is available to him at the time of construction of the synchrotron.

Introduction

This report's purpose is to show that one can expect that the cost of a superconducting synchrotron will be lower than or at least competitive with, the cost of the least expensive conventional synchrotron. Furthermore, the report points out the potential savings in operating cost that can be expected. By use of an overall systems approach, the effects of the important synchrotron parameters on cost are investigated. The report points out that if the properties of the superconductor are properly used, substantial reductions in cost can be expected. This, however, may require some change of thought on the part of the high energy physicist. Most important, this report shows that there is no one aspect of machine design that affects the overall cost of the machine greatly. It also shows that superconducting machines that are of minimum cost are not high-field machines (80 to 120 kG dipole) nor are they machines with fast repetition rates. Instead, the minimum-cost superconducting synchrotron will have characteristics that are well within the realm of today's technology.

The earliest reports for superconducting synchrotrons indicated a potentiality for reducing their cost.[1,2] This was particularly true when these costs were compared with the data then available on the cost of conventional synchrotrons.[3] By 1968 it had become clear that the political and technical guidelines for large machine construction in the United States had changed. As a result of these changes, a large reduction in the cost of conventional machines could be realized.[4] Of course, the same political and technical guidelines can and should be applied to superconducting synchrotrons as well.

The first study on the effects of machine parameters on superconducting synchrotron costs was presented in 1968.[5] This study suffered from the fact that much of the cost data was based on earlier machines. The cost data did not take into consideration the advanced technology that was being developed in a number of areas of accelerator development. This early report did, however, point out a number of interesting facts: (1) the cost of a very-high-field machine (say, 70 to 100 k Oe dipole strength) is higher than that of a machine which runs at moderate fields (40 to 50 k Oe); (2) higher repetition rates are expensive. It is economically desirable to have longer cycle times than in conventional machines. This report made it very clear that one must use the properties of the superconductor to best advantage if the machine cost is to be a minimum.

During the last three years a number of machine cost estimates have been made by a number of laboratories.[6-11] The reports have had many interesting things in common besides the fact they point out the potential cost saving possible in a superconducting synchrotron. Some of these cost estimates are discussed and compared with conventional machines in the next section.

A Comparison of Previously Published Cost Estimates of Superconducting Synchrotrons with Previously Published Costs of Conventional Synchrotrons

The cost of four superconducting synchrotrons is compared with the published cost estimate for the National Accelerator Laboratory machine with an energy of 500 GeV. These four superconducting synchrotron schemes have been previously presented. The costs of the various components are compared on the basis of their cost in millions of U. S. dollars per GeV. This cost comparison, along with a list of important machine parameters, is presented in Table I.

All the machines listed in Table I have had the cost of their injectors and experimental areas excluded. Furthermore, the costs of engineering development and contingency have also been excluded. In other words, the machine estimates are for bare-bones main rings only.

Table I illustrates a number of important points. (1) A greater proportion of the cost of a conventional synchrotron will be tunnel, shielding, and plant. (2) The superconducting machine cost will be dominated by the technical components, the most important of which are magnet, power supply, refrigeration, and rf. (3) The cost of operating a superconducting machine (the power cost) is substantially lower than the cost of operating a conventional machine. (4) No one major component cost is glaringly dominant, as the tunnel and plant are for the conventional machines.

For the five synchrotrons listed in the table, there is considerable scatter in the design assumptions and parameters which is reflected in the variations in the unit costs. Since the data in Table I do not show clearly the relation between primary machine parameters and cost, consistent cost estimates are made in the next section to illustrate effects of some basic machine parameters on cost.

The Effects of Machine Parameters on Superconducting Synchrotron Cost

In order to show the effects of basic machine parameters on superconducting synchrotron cost, it was necessary to calculate a large number of cases using consistent cost data. This job was turned over to the CDC 6600 computer for speed and accuracy. Consistent cost factors were applied to a number of machines with varying dipole magnet inductions, varying magnet aperture, and varying cycle times. The effect of the possible development of a highly advanced stable low-ac-loss β-tungsten-type superconducting material is discussed.

Table I. A comparison of cost estimates and machine parameters made by a number of investigators.

	Conventional	Superconducting			
Machine	NAL 500 GeV (1968)[4]	LRL 70 GeV (1970)[9]	CMS 112 GeV (1970)[10]	M.A.Green 1000 GeV (1969)[8]	BNL 2000 GeV (1970)[11]
Basic machine parameters					
Final energy	500 GeV	70 GeV	112 GeV	1000 GeV	2000 GeV
Injection energy	8 GeV	50 MeV	30 GeV	25 GeV	30 GeV
Intensity	1 to 5×10^{12} ppp	2×10^{12} ppp	1×10^{13} ppp	1.5×10^{14} ppp	10^{13} ppp[a]
Dipole induction	22.5 kG	50 kG	40 kG	50 kG	40 to 60 kG[a]
Aperture	2 x 4 in. 1.5 x 5 in.[b]	4 in. D	1.5 in. D	4 in. D	~1.5 in. D[a]
Cycle time	≈ 10 sec	10 sec	4 sec	15 sec	4 to 6 sec[a]
Machine cost estimate (millions of dollars/GeV)	Cost based on original 200 GeV estimate				
Magnets (including cryostats)	0.044	0.050	0.017	0.054	0.020[i]
Power supply	0.012[c]	0.003[e]	0.011	0.024	0.008
Refrigerator	-----	0.047[f]	0.021	0.012	0.018[i]
rf	0.005	0.011	0.002	0.029	0.009[i]
Vacuum	0.005	0.003	-----[g]	0.004	0.002[i]
Control and injection-extraction	0.010[d]	0.009	0.017	0.012	0.005[i]
Enclosure and plant facilities	0.055	0.038	0.003[h]	0.037	0.015
Total capital cost	0.131	0.161	0.071	0.173	0.077[i]
10-year operating cost (power)	0.140[j]	0.060[j]	0.035[j]	0.055[j]	0.035[j]
Capital plus operating cost	0.271	0.221	0.106	0.228	0.112

Table I cont'd on page 4--

Table I cont'd

a. These numbers are not in the report; they are based on conversations with BNL people. There may be considerable error here.

b. Cycle time not clear for 500-GeV operation.

c. Main power grid used as an MG set; add 0.010 M$/GeV or so if an MG set is included for comparison.

d. Some injection and extraction functions are not included; cost not clear here.

e. LRL Bevatron MG set used; add 0.020 M$/GeV if a new power supply is purchased.

f. Refrigerator includes an experimental area refrigerator system.

g. Vacuum cost not presented.

h. AGS tunnel at Brookhaven used; add 0.030 M$/GeV if a tunnel is included for comparison.

i. These costs are based on the average of the estimate given. The whole estimate was rough and not in finished form.

j. This cost estimate is not included in the original report. Cost based on published power consumption figure except that for the 2000-GeV machine the CMS power costs were used. Assumed power cost $0.01/kW hr delivered to the equipment.

The following assumptions are used to estimate the various superconducting machines. (1) The magnet has a circular bore and has coils which step in thickness azimuthally. (2) The iron shield is cold and concentric with the bore of the magnet. The shell is assumed to be unsaturated for aberration-free performance over a wide range of magnet excitations. It should be noted that when the apertures are small this corresponds to the BNL close-in iron construction. (3) Conventional motor-generator power supplies are assumed because of their obvious cost advantages. (4) Simplified mass-produced cryostats are assumed. (5) 4.5^{o}K helium refrigeration is assumed--the efficiency of the machines is assumed to be about 25% of Carnot. It is unrealistic to assume otherwise at this time; besides, it has little effect on economics to assume a more efficient machine. (6) The rf, injection-extraction, and control systems are based on conventional techniques. (7) The high vacuum is supplied primarily through cryopumping on the cold bore of the magnets. (8) An NAL-size tunnel or slightly smaller is assumed. The remainder of the conventional facilities are estimated in a more or less conventional fashion.

Table II. Basic machine parameters used in the computer program which calculates the effect of machine parameters on cost.

Primary fixed parameters	
Final energy	1000 GeV
Injection energy	25 GeV
Intensity	10^{13} ppp
Ratio of machine radius to magnetic radius	1.38
Superconductor strand size	5 μm
Primary variable parameters	
Superconductor[a]	Nb-Ti and advanced β tungsten
Dipole induction[b]	30 to 70 kG for Nb-Ti cases 30 to 80 kG for advanced β tungsten cases
Cycle times[c]	6, 12, and 24 sec
Aperture	1.5, 3.0, 4.5, and 6 in.

a. Nb-Ti material assumed to be comparable to the best of today's material. Coil current density 3×10^4 A/cm^2 at 40°K. Cost \$$3 \times 10^{-3}$/A meter @ 40 kG. The advanced β tungsten material has 2.5 times the current density and 1/3 the cost.

b. Central average induction in the magnet; actual induction in the magnet is higher.

c. Cycle time is divided as follows: rise time and fall time are 1/3 the cycle time each. The front porch is 0.5 sec. The flattop time is equal to 1/3 the cycle time minus 0.5 sec.

The following approximate cost factors are generated by and used in the LRL computer program SUPERA for calculating the costs of a superconducting synchrotron. (1) The cost of superconductor is \$3 x 10^{-3} per ampere meter for the Nb-Ti at 40 kG. The advanced β tungsten material cost is \$1 x 10^{-3} per ampere meter at 40 kG. The magnet current densities with each material respectively are 35 000 A/cm^2 at 40 kG and 75 000 A/cm^2 at 40 kG. The cost of magnet fabrication is about 30% of the total cost for the Nb-Ti case and much higher for the advanced β tungsten case. (2) The power-supply cost is assumed to be about \$35/kW peak power. This cost, which is higher than the Brookhaven estimates, includes the cost of installation and housing. (3) The cost of magnet cryostats is assumed to be about \$1500 per meter.[12] (4) Refrigeration costs are based on the Strobridge data.[13] Recent transfer-line advances are considered.[14] (5) The tunnel cost used was \$3500 per meter, including penetration, shielding, enclosure, and foundation. This is based on NAL experience. The cost of utilities is assumed to be \$100/kW of power handled. (6) The cost of the electric power delivered to the machine is assumed to be \$0.01/kW/hr. More information and cost data can be found in Refs. 15 and 16.

Tables III through VI and Figs. 1 through 3 show the effect of various parameters on superconducting synchrotron cost. It is clear that the magnet parameters do affect the capital cost and the capital-plus-operating cost of a superconducting synchrotron. It is quite clear that there is an optimum field at or near which a synchrotron should operate if it is to be of minimum cost. The magnet aperture does affect the cost of a superconducting machine, but not so much as some people have said. Short cycle times are more expensive than long cycle times. In general, large-aperture long-cycle-time machines are cheaper than short-cycle-time small-aperture machines for given intensity and injection condition. There will be an optimum aperture and cycle time for a minimum-cost machine. It is interesting to note that the results of this machine parameter study are similar to the one done in 1968[5] even though the cost factors used in this study are quite different from those used in the 1968 study.

Tables VII through XII and Figs. 4 and 5 show the effect of various machine components on machine cost. One can see that in machines of interest no one component in the machine dominates the cost. In general, the tunnel and plant facility costs are reduced to the point where they are, although still large, not a dominant factor in the machine cost.

Table III. The capital cost of a 1000 GeV superconducting synchrotron as a function of the dipole induction, magnet aperture, and machine cycle time. The costs are based on reasonable projection of Nb-Ti technology.

Machine cycle time	Magnet aperture	Cost of the main ring (M$/GeV) vs dipole induction			
		30 kG	40 kG	50 kG	60 kG
6 sec	1.5 in.	0.0865	0.0802	0.0889	0.1169
	3.0 in.	0.1036	0.1045	0.1237	0.1581
	4.5 in.	0.1258	0.1384	0.1688	0.2218
12 sec	1.5 in.	0.0747	0.0670	0.0688	0.0874
	3.0 in.	0.0848	0.0814	0.0907	0.1119
	4.5 in.	0.1003	0.1024	0.1184	0.1500
24 sec	1.5 in.	0.0689	0.0605	0.0606	0.0726
	3.0 in.	0.0768	0.0714	0.0748	0.0900
	4.5 in.	0.0865	0.0847	0.0949	0.1156

Table IV. The capital cost of a 1000 GeV superconducting synchrotron as a function of the dipole induction, magnet aperture, and machine cycle time. The costs are based on highly optimistic projections of a highly advanced β tungsten (Nb_3Sn, V_3Ga, etc.) technology.

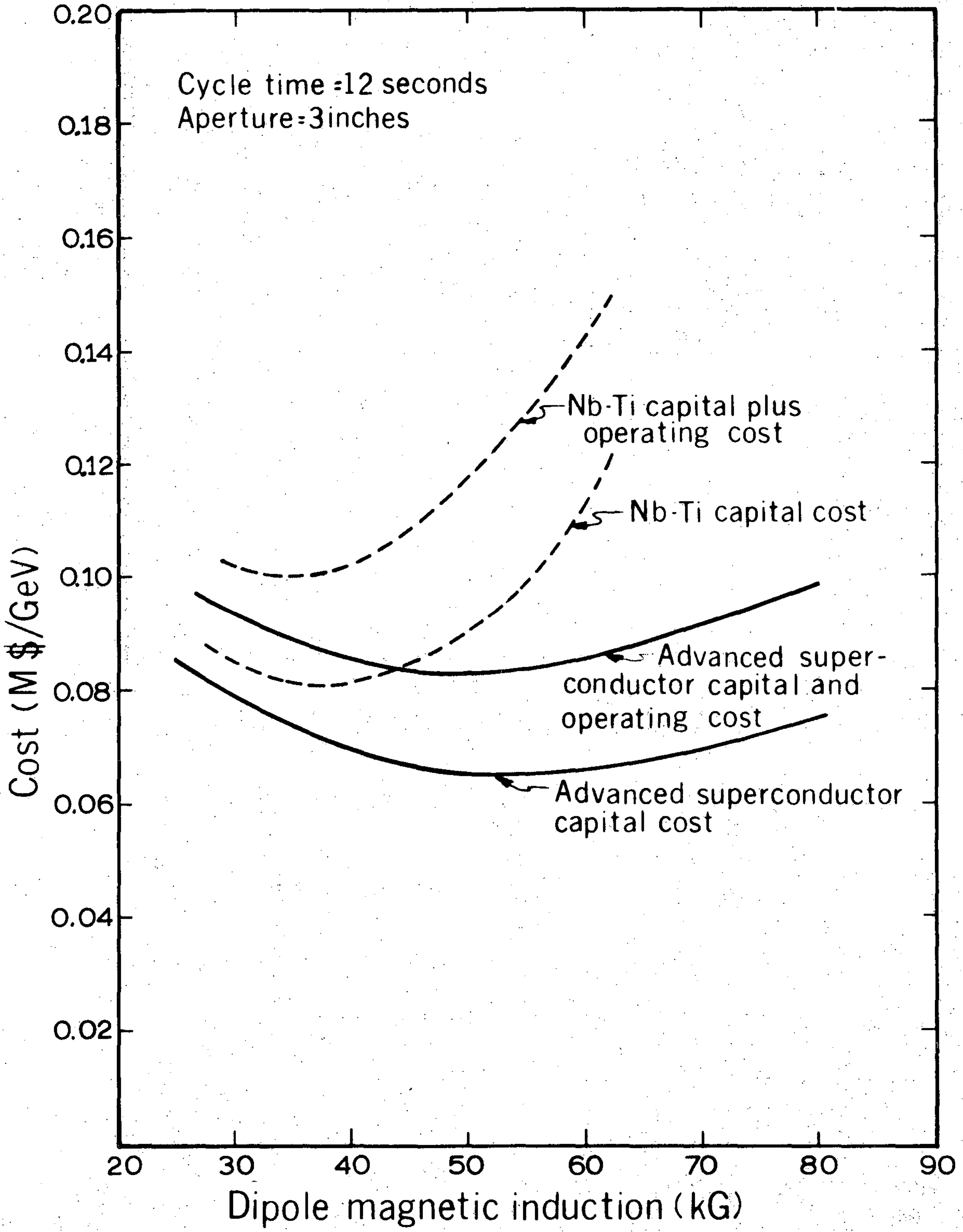
Cycle time	Magnet aperture (in.)	Cost of the main ring (M$/GeV) vs dipole magnet induction					
		30 kG	40 kG	50 kG	60 kG	70 kG	80 kG
6 sec	1.5	0.0815	0.0697	0.0638	0.0612	0.0606	0.0614
	3.0	0.0924	0.0872	0.0858	0.0878	0.0948	0.1015
	4.5	0.1109	0.1115	0.1187	0.1296	0.1435	0.1601
12 sec	1.5	0.0707	0.0590	0.0530	0.0499	0.0487	0.0489
	3.0	0.0781	0.0689	0.0656	0.0656	0.0702	0.0746
	4.5	0.0881	0.0848	0.0853	0.0916	0.0988	0.1104
24 sec	1.5	0.0654	0.0538	0.0476	0.0443	0.0428	0.0427
	3.0	0.0710	0.0611	0.0568	0.0558	0.0570	0.0603
	4.5	0.0780	0.0703	0.0686	0.0724	0.0772	0.0845

Table V. The capital cost plus the 10-year operating cost of a 1000 GeV superconducting synchrotron as a function of the dipole induction, magnet aperture, and machine cycle time. The costs are based on reasonable projection of Nb-Ti technology.

Machine cycle time	Magnet aperture (in.)	Cost of the main ring (M$/GeV) vs dipole induction 30 kG	40 kG	50 kG	60 kG
6 sec	1.5	0.1048	0.1033	0.1218	0.1719
	3.0	0.1319	0.1428	0.1783	0.2399
	4.5	0.1683	0.1978	0.2529	0.3437
12 sec	1.5	0.0868	0.0802	0.0857	0.1134
	3.0	0.1020	0.1022	0.1182	0.1410
	4.5	0.1246	0.1337	0.1605	0.2084
24 sec	1.5	0.0782	0.0695	0.0708	0.0865
	3.0	0.0888	0.0842	0.0902	0.1104
	4.5	0.1023	0.1028	0.1187	0.1456

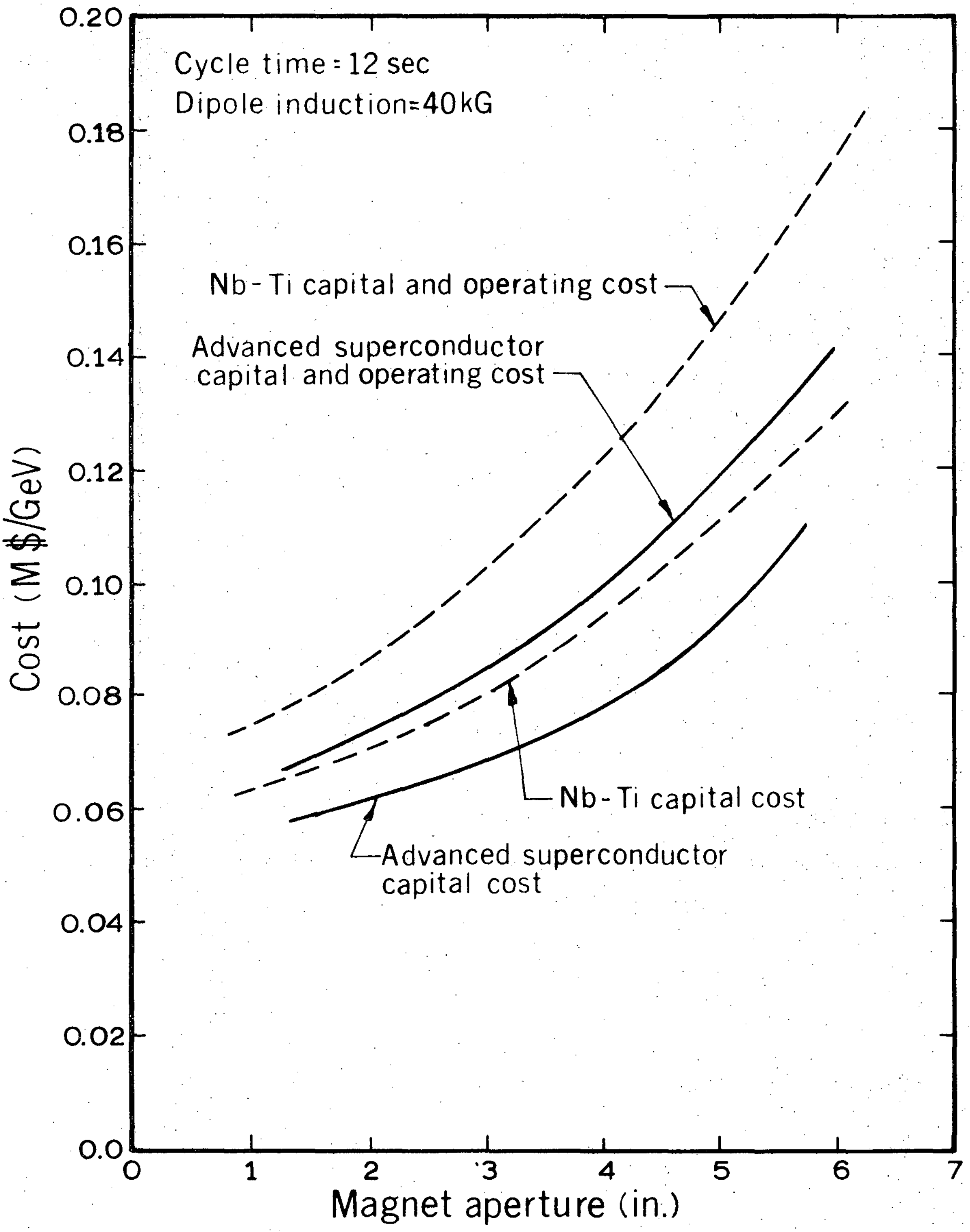
Table VI. The capital cost plus 10-year operating cost of a 1000 GeV superconducting synchrotron as a function of the dipole induction, magnet aperture, and the machine cycle time. The costs are based on highly optimistic projection of a highly advanced β tungsten (Nb_3Sn, V_3Ga, etc.) technology.

Machine cycle time	Magnet aperture (in.)	Cost of the main ring (M$/GeV)					
		30 kG	40 kG	50 kG	60 kG	70 kG	80 kG
6 sec	1.5	0.0973	0.0862	0.0817	0.0809	0.0818	0.0850
	3.0	0.1165	0.1153	0.1184	0.1253	0.1373	0.1491
	4.5	0.1474	0.1567	0.1730	0.1936	0.2167	0.2429
12 sec	1.5	0.0816	0.0693	0.0634	0.0606	0.0600	0.0609
	3.0	0.0934	0.0852	0.0835	0.0855	0.0923	0.0989
	4.5	0.1098	0.1099	0.1143	0.1250	0.1366	0.1528
24 sec	1.5	0.0742	0.0614	0.0577	0.0512	0.0497	0.0497
	3.0	0.0821	0.0718	0.0678	0.0674	0.0694	0.0736
	4.5	0.0925	0.0856	0.0853	0.0909	0.0976	0.1070



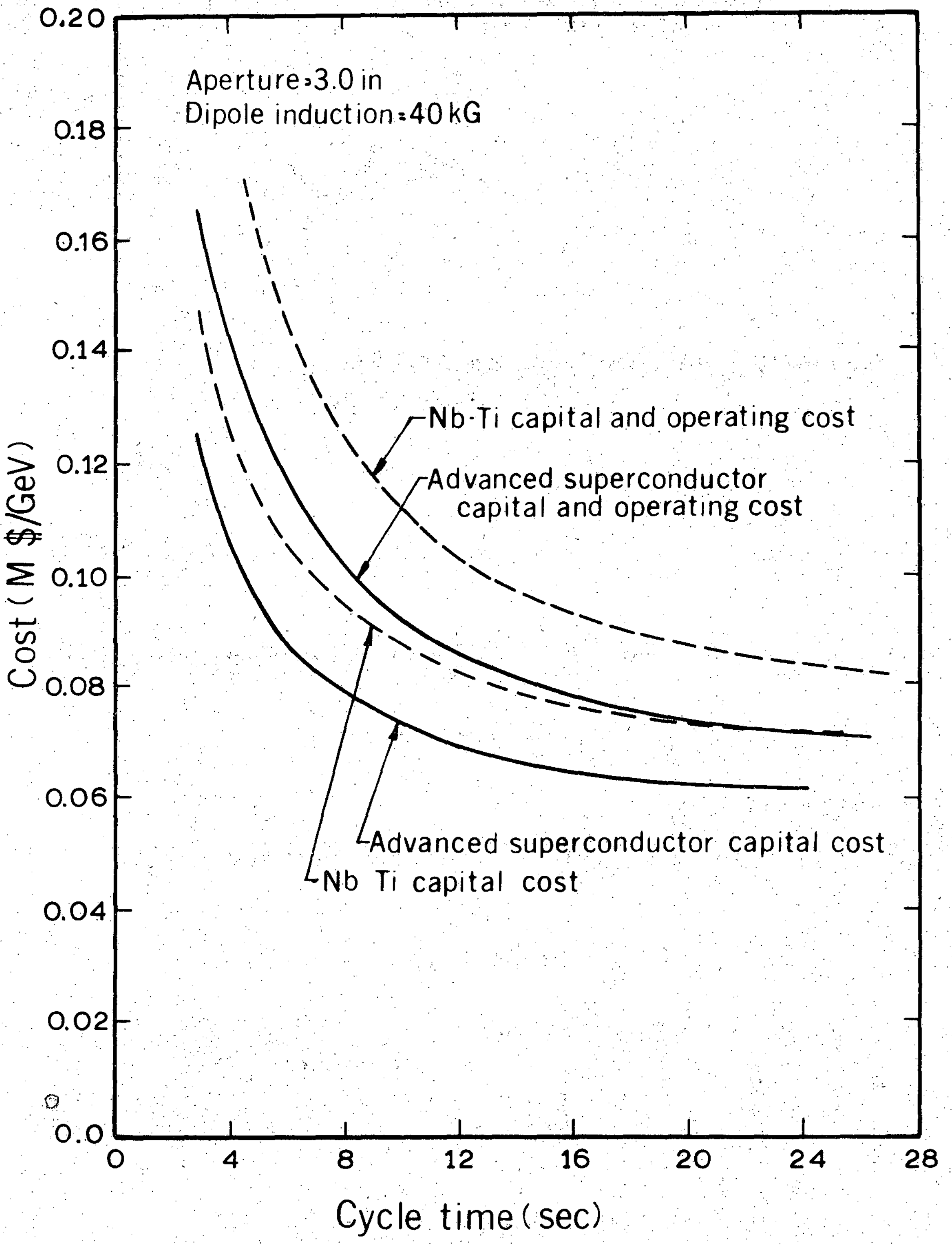
XBL 712 6259

Fig. 1. The effect of dipole magnet induction on the superconducting synchrotron cost.



XBL 712 6261

Fig. 2. Effect of aperture on superconducting synchrotron cost.



XBL 712 6260

Fig. 3. Effect of cycle time on superconducting synchrotron cost.

Conclusions That Can be Drawn from a Superconducting Synchrotron Parameter Study

The first and perhaps the most important conclusion that can be drawn from this study is that changes (even large changes) in one component of the machine construction do not have large effects on machine cost. Contrary to popular belief, new superconducting material, new power-supply technique, new superefficient refrigerators or very small saturated iron magnets will not have the large factor of cost reductions associated with them that some of their proponents have claimed. In short, if you were able to employ all of the above techniques in the best way you know how, you might achieve a 50% reduction of cost below machines designed to use presently available superconducting technology.

A second conclusion--perhaps surprising to those who are not intimately familiar with superconducting magnet technology--is that the use of high field (fields in the dipole greater than 60 k Oe) in a supperconducting machine is not economically justified. In general, one cannot economically justify the use of fields over 45 or 50 k Oe. It should be noted, however, that because of limitations imposed upon the machine size the use of higher-than-optimum fields may be desirable, but one will pay more money per GeV for the use of higher fields in the ring.

A third conclusion is that superconducting machines should and will have lower repetition rates than conventional machines. If high average intensity is required, it is in general better to increase the aperture rather than the repetition rate. Larger aperture (in magnets with unsaturated iron) eases a number of the field uniformity problems associated with the superconducting guide field magnets.

It appears at this time that superconducting synchrotrons will enjoy a cost advantage of 2 or 3 over the best of the conventional synchrotrons. A reduction in power cost can also be expected. It should be noted that the cost of a superconducting ring is only a portion of the cost of a new facility. A superconducting synchrotron will have 2 to 3 times the energy of a conventional machine of the same size. The lowest-cost practical machines will have dipole fields of 40 to 50 k Oe, and cycle times of the order of 10 seconds or more, and apertures of 2 to 4 inches. For technical reasons, fairly high injection energies appear to be needed. It is clear that no dramatic order-of-magnitude change in cost is possible even with the best of material, power supply, or refrigeration techniques. In short, one will use the best economically justified technology that is available to him at the time of construction of the synchrotron.

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Table VII. A breakdown of Nb-Ti superconducting synchrotron cost as a function of dipole induction.

	Dipole magnetic induction (kG)			
Component	30	40	50	60
Magnet	.0092	.0143	.0218	.0343
Magnet cryostat	.0096	.0077	.0067	.0061
Magnet power supply	.0040	.0070	.0114	.0184
Refrigeration	.0085	.0090	.0127	.0177
rf	.0080	.0069	.0062	.0059
Vacuum	.0046	.0034	.0028	.0023
Injection, extraction, and control	.0051	.0051	.0052	.0054
Tunnel, shielding, and plant	.0359	.0280	.0238	.0219
Capital cost	.0848	.0814	.0907	.1119
10-year power cost	.0172	.0208	.0275	.0391
Capital plus power cost	.1020	.1022	.1182	.1510

Magnet aperture = 3.0 inches

Machine cycle time = 12 seconds

Table VIII. A breakdown of Nb-Ti superconducting synchrotron cost as a function of magnet aperture.

	Magnet aperture			
Component	1.5 in.	3.0 in.	4.5 in.	6.0 in.
Magnet	.0082	.0143	.0211	.0288
Magnet cryostat	.0071	.0077	.0085	.0094
Magnet power supply	.0025	.0070	.0141	.0239
Refrigeration	.0071	.0090	.0137	.0206
rf	.0069	.0069	.0069	.0069
Vacuum	.0033	.0034	.0035	.0036
Injection, extraction, and control	.0051	.0052	.0053	.0055
Tunnel, shielding, and plant	.0270	.0280	.0294	.0312
Capital cost	.0670	.0814	.1024	.1298
10-year power cost	.0132	.0208	.0314	.0451
Capital plus power cost	.0802	.1022	.1338	.1749

Dipole magnetic induction = 40 kG

Machine cycle time = 12 seconds

Table IX. A breakdown of Nb-Ti superconducting synchrotron cost as a function of magnet cycle time.

	Machine cycle time		
Component	6 sec.	12 sec.	24 sec.
Magnet	.0143	.0143	.0143
Magnet cryostat	.0078	.0077	.0077
Magnet power supply	.0134	.0070	.0036
Refrigeration	.0165	.0090	.0068
rf	.0136	.0069	.0035
Vacuum	.0034	.0034	.0034
Injection, extraction, and control	.0053	.0052	.0050
Tunnel, shielding, and plant	.0302	.0280	.0269
Capital cost	.1045	.0814	.0714
10-year power cost	.0383	.0208	.0128
Capital plus power cost	.1428	.1022	.0842

Dipole magnetic induction = 40 kG

Magnet aperture = 3.0 inches

Table X. A breakdown of advanced β tungsten (Nb_3Sn, V_3Ga, etc.) technology superconducting synchrotron cost as a function of dipole induction.

	Dipole magnetic induction					
Component	30 kG	40 kG	50 kG	60 kG	70 kG	80 kG
Magnet	.0043	.0062	.0085	.0114	.0151	.0198
Magnet cryostat	.0096	.0077	.0067	.0059	.0055	.0051
Magnet power supply	.0030	.0045	.0060	.0074	.0039	.0104
Refrigeration	.0080	.0079	.0080	.0083	.0109	.0115
rf	.0080	.0069	.0062	.0057	.0053	.0051
Vacuum	.0046	.0034	.0028	.0023	.0020	.0017
Injection, extraction, and control	.0050	.0049	.0048	.0048	.0048	.0047
Tunnel, shielding, and plant	.0357	.0274	.0225	.0194	.0173	.0158
Capital cost	.0781	.0689	.0656	.0656	.0702	.0746
10-year power cost	.0153	.0163	.0179	.0199	.0221	.0243
Capital plus power cost	.0934	.0852	.0835	.0855	.0923	.0989

Magnet aperture = 3.0 inches

Machine cycle time = 12 seconds

Table XI. A breakdown of advanced β tungsten (Nb_3Sn, V_3Ga, etc.) technology superconducting synchrotron cost as a function of magnet aperture.

Component	1.5 in.	3.0 in.	4.5 in.	6.0 in.
Magnet	.0029	.0062	.0098	.0139
Magnet cryostat	.0071	.0077	.0085	.0093
Magnet power supply	.0011	.0045	.0104	.0189
Refrigeration	.0062	.0079	.0120	.0166
rf	.0069	.0069	.0069	.0069
Vacuum	.0034	.0034	.0035	.0036
Injection, extraction, and control	.0049	.0049	.0050	.0053
Tunnel, shielding, and plant	.0266	.0274	.0286	.0301
Capital cost	.0590	.0689	.0848	.1046
10-year power cost	.0103	.0163	.0251	.0370
Capital plus power cost	.0693	.0852	.1099	.1416

Dipole magnetic induction = 40 kG

Machine cycle time = 12 seconds

Table XII. A breakdown of advanced β tungsten (Nb_3Sn, V_3Ga, etc.) technology superconducting synchrotron cost as a function of the magnet cycle time.

Component	Machine cycle time 6 sec.	 12 sec.	 24 sec.
Magnet	.0062	.0062	.0062
Magnet cryostat	.0079	.0077	.0077
Magnet power supply	.0086	.0045	.0023
Refrigerator	.0136	.0079	.0063
rf	.0135	.0069	.0035
Vacuum	.0034	.0034	.0034
Injection, extraction, and control	.0052	.0049	.0049
Tunnel, shielding, and plant	.0289	.0274	.0267
Capital cost	.0872	.0689	.0611
10-year power cost	.0281	.0163	.0107
Capital plus power cost	.1153	.0852	.0718

Dipole magnetic induction = 40 kG

Magnet aperture = 3.0 in.

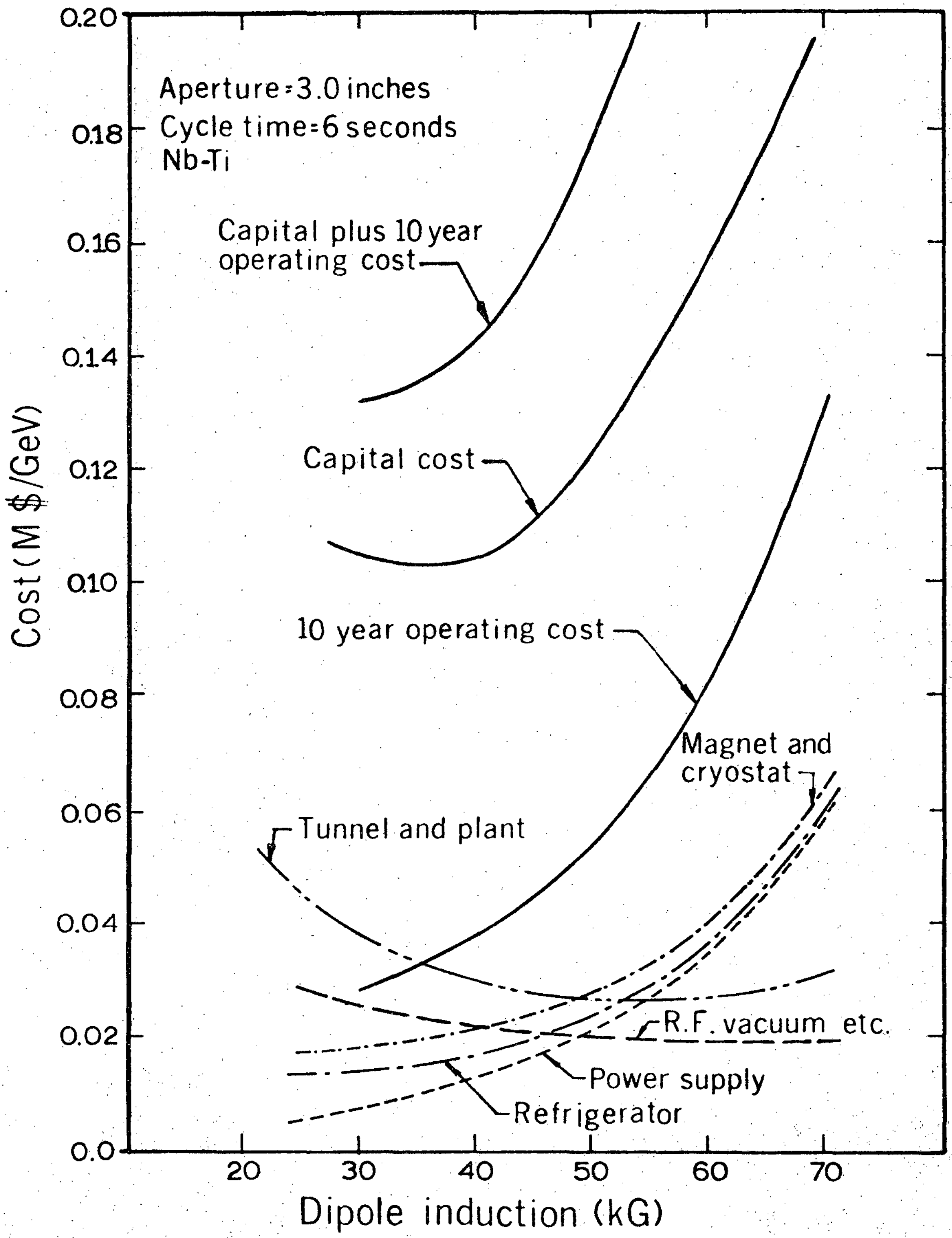

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Fig. 4. A breakdown of machine component costs as a function of dipole induction in a state-of-the-art Nb-Ti superconducting synchrotron.

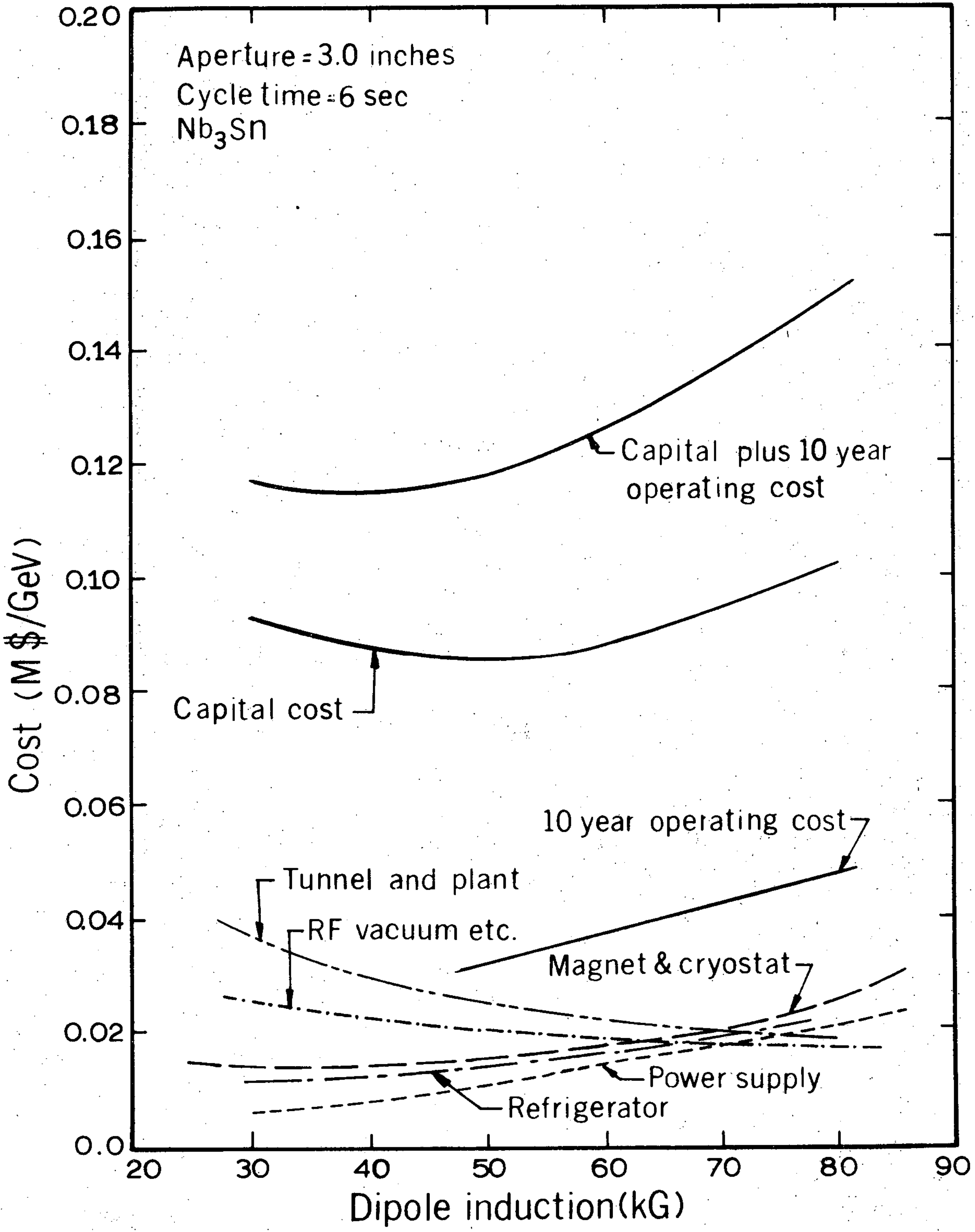

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Fig. 5. A breakdown of machine component cost as a function of dipole induction in an advanced β-tungsten technology (Nb_3Sn, V_3Ga, etc.) superconducting synchrotron.

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