ECONOMIC FACTORS INVOLVED IN THE DESIGN OF A PROTON SYNCHROTRON OR STORAGE RING WITH A SUPERCONDUCTING GUIDE FIELD*

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INTRODUCTION

A synchrotron with a superconducting guide field will be justified if the synchrotron can be built and operated in such a way that it ultimately saves money. Although it may be argued that a superconducting facility of high cost is justified because it will speed development of the art, the arguments in favor of a superconducting facility must ultimately be economic ones.

I believe that one must take a careful look at the over-all properties of superconducting accelerators. This paper discusses a number of the important economic considerations that are involved in the design of a superconducting synchrotron or storage ring. This paper shows that a superconducting synchrotron is competitive with a conventional machine even when today's high costs and equipment are used.

A cost estimate of energy expansion of the 200 GeV machine using a superconducting ring was made in 1967.[1] That report showed that it might be feasible to expand the energy of the 200 GeV accelerator at a cost lower than was proposed by some schemes. The most important advantage was that one did not have to commit himself to energy expansion at an early date. The cost figures are comparable with ones that were suggested by Smith[2] and by Smith and Lewin.[3]

This paper discusses the unique properties of a superconducting magnet ring and how they should be utilized. The machine parameters that strongly influence cost are also discussed. The interaction of the various machine components strongly influence cost of a superconducting ring, hence the whole system must be looked at in detail.

UNIQUE SUPERCONDUCTING SYNCHROTRON PROPERTIES

The strong focusing synchrotron with a superconducting guide field is quite different from the conventional AGS machine. These differences affect the design of a superconducting machine. The important differences are:

1. Superconductors are capable of operating at high fields and current densities, which permits high-field air-core magnets to be built.

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*Work performed under the auspices of the U.S. Atomic Energy Commission.

1. M.A. Green, University of California, Lawrence Radiation Laboratory Report UCRL-17862 (1967).

2. P.F. Smith, in <u>Proc. 2nd Intern. Conf. Magnet Technology, Oxford, 1967</u>, p. 594.

3. P.F. Smith and J.D. Lewin, Nucl. Instr. and Methods <u>52</u>, 248 (1967).

2. Superconductors have zero resistance except during charging, hence superconducting storage rings appear to be feasible.

3. The energy lost per cycle in the superconductor is independent of frequency, hence the power consumed goes down as the cycle time increases. (It should be noted that superconducting systems with large eddy-current losses behave in the same general way.) Conventional machines require the same amount of power regardless of the cycle time. Long cycle times and storage rings have much lower power consumption and their costs are not power-dependent.

4. Horizontal and vertical aperture cost nearly the same in superconducting dipoles and quadrupoles. As a result magnets with a round aperture are of interest from both an economic and an engineering standpoint.

It should be noted that superconducting devices have a unique set of problems as well as advantages. The superconducting currents must be carefully placed. The high stress levels in a high-field superconducting magnet make it difficult to insure proper magnet performance. A number of problems are associated with the cryogenic environment needed to produce superconductivity. Control of the magnet stored energy during a quench is also needed. A large number of these problems can be solved only by building a number of model magnets and testing them.

BASIC MACHINE PARAMETERS

A 100 GeV machine is used as an example. It is a "bare-bones" machine with no external beam lines, target areas, or injector. The machine is assumed to be a separated-function machine with a ν value of between 10 and 11. The machine is assumed to have fourfold symmetry with four straight sections that are each one betatron wavelength long. (See Fig. 1.) The straight sections are assumed to have the same quadrupole structure as the bending sections. They are one betatron wavelength long to minimize the radiation dumped into the superconductor during injection and extraction.

The machine parameters are divided into two basic categories, fixed parameters and variable parameters. The primary fixed parameters are final energy, injection energy, and intensity in protons per second. The variable parameters are those determined by economics rather than by fiat. The most important variable parameters are repetition rate or cycle time, aperture, and magnetic field.

The injection energy is assumed to be 5 GeV, the peak or final energy 100 GeV. The study used intensities of 5×10^{12} protons per second. The 100 GeV machine was assumed to have a rather large R/ρ ratio of two because of the low ν value and the one-betatron-wavelength long straight sections. The 1000 GeV examples have a much more reasonable R/ρ ratio of 1.5.

The repetition rate of the machine is directly related to its aperture if the intensity in protons per second is kept constant. There are compelling arguments both from a power standpoint and from a capital cost standpoint to go to long cycle times. Longer cycle times result in larger apertures if a constant average beam current is maintained. The aperture is assumed to be nearly independent of peak magnetic field. This assumption holds if the beam aperture is emittance-limited. Arguments can be made for or against the preceding assumption; as a result, one has to look at a particular machine in order to find out whether the aperture is dependent on the magnetic field. The magnetic field is strongly dependent on economic factors for the machine of lowest cost per GeV. The optimum magnetic field is also dependent on aperture and repetition rate. (It should be noted that one might want to use a nonoptimum field for other reasons, such as physical site limitations.)

A computer program was written to calculate the costs of a large number of superconducting machines.[4] The program calculates the size of and the cost of the following machine components: (1) the superconducting magnet ring, (2) the ring magnet power supply, (3) the magnet cryostats, (4) the 4.2°K helium refrigeration system for the magnets, (5) the rf system, (6) the machine injection and extraction system, (7) the vacuum system, (8) the machine control system, and (9) the conventional plant facilities (including tunnel, earthwork, foundation, and utilities).

THE METHOD OF COST ANALYSIS OF MACHINE COMPONENTS

The detailed equations and assumptions are omitted from this section. One may find these equations and a listing of the program in Ref. 4. The main cost relationships are presented for each of the components.

This paper is relatively conservative in its presentation of costs. Today's costs are used as much as possible. Neither the upward nor downward trend in costs for some products is considered. This paper shows that even at today's costs the superconducting synchrotron can be built more cheaply than the conventional machine.

The superconducting magnet cost can be estimated by knowing the cost of the superconductor, because 70 to 80% of the magnet cost is the superconductor itself. One may calculate the cost of superconductor by calculating the number of ampere meters of superconductor in the system and multiplying it by the cost of the superconductor in dollars per ampere meter. The cost of a typical niobium-titanium and niobium-tin superconducting material is shown in Fig. 2. The cost per ampere meter is a function of winding peak field. It is assumed there is no gradation of the superconductor in the magnet. The number of ampere meters of superconductor is a function of magnet length and ampere turns required. The ampere turns is a function of coil current density, peak central field, and aperture. The coil current density is a function of the peak field in the coil, as shown in Fig. 3.

A 2/3-rule dipole and quadrupole were used as models to calculate the cost of material (see Figs. 4 and 5). Detailed analyses of such a dipole or quadrupole are given by Asner,[5] Bronca,[6] and Halbach.[7] Ampere-turn requirements and stored energy, calculated by using the 2/3-rule model, compare within 10% with those that would be calculated by using a varying current density or intersecting-ellipse models. The use of iron was not considered in the cost estimate.

The magnet cost is one of the largest items in a superconducting synchrotron. Several conclusions can be made that relate magnet cost to machine parameters: (1) The cost of the magnet goes up as the peak central field goes up despite the reduction in magnetic radius; (2) low-current-density magnets require more ampere meters of material than high-current-density magnets; (3) quadrupoles require more material than dipoles of the same peak field and current density.

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[4] M.A. Green, University of California, Lawrence Radiation Laboratory Report UCID 3204 (1968).

[5] A. Asner and C. Iselin, in Proc. 2nd Intern. Conf. Magnet Technology, Oxford, 1967, p. 32.

[6] G. Bronca and J.P. Pouillange, CERN Report CERN/ECFA 67/W62/US-SG1/JPP2 (1967); and ECFA Utilization Studies for a 300 GeV Proton Synchrotron (CERN, 1967), Vol. 2, p.203.

[7] K. Halbach, Lawrence Radiation Laboratory, private communication.

The power supply is assumed to be a conventional motor generator set such as the ones used on today's synchrotrons. The cost of the power supply is proportional to the magnet stored energy and inversely proportional to the machine rise time. The magnet stored energy goes up as the peak central field to the N power, where N is greater than unity. The power supply costs also go up with aperture to the m power, where m is somewhat less than 2.

There appear to be several schemes which may result in large decreases in power supply cost; one such scheme has been advanced by Smith of the Rutherford Laboratory.[8] This scheme may be particularly promising for short-cycle-time machines. Long flattops will require an extremely low ripple factor. Today's power supplies have too high a ripple factor to permit long beam spills. However, superconducting magnets can be made to run in the persistent mode, which is essentially ripple-free.

The magnet cryostat cost is a function of its length, hence is inversely proportional to the peak central field. The cryostat is assumed to be as simple as possible, because the high heat leak found in the simplified Dewar is dominated by other loads in the system. The cryostat is estimated to cost about $3000 per meter.

The liquid helium refrigeration system would consist of one or more large refrigerators and the appropriate transfer lines. The large system is applicable for an accelerator[9,10] because: (1) the loads are relatively concentrated, (2) the load in the accelerator system greatly exceeds the transfer line losses, (3) the system position is fixed. The system is assumed to consist of a group of central refrigerators with cold gas transport. The J-T (Joule-Thomson) valves and final J-T heat exchangers are located at the Dewar (see Fig. 6).

There are three primary sources of heating in the 4.2°K region: (1) heat leaks from the outside through the Dewar and power supply leads, (2) heating due to energy loss from the beam, (3) various kinds of ac losses.

Heat leaks into the system are roughly proportional to the cryostat length. It is assumed that 10% of the beam is lost at extraction and 5% of the beam is lost during injection. It is further assumed that 20% of the lost beam energy is dumped into the 4°K region. There could also be a severe local heating problem; it can be reduced by the long straight sections and the use of special quadrupoles in these sections. It is desirable to have as high an extraction and injection efficiency as possible to reduce the beam heating.

The ac losses are divided into two basic terms, a hysteresis-like loss and an eddy-current-type loss. I use Smith's[2] ac loss equation, which is being experimentally confirmed by work at LRL,[11] Brookhaven,[12] Rutherford,[13] and other places. I have assumed that the basic wire dimensions are 0.0025 cm (0.001 in.). There is strong

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8. P.F. Smith, in <u>Proc. 2nd Intern. Conf. Magnet Technology, Oxford, 1967</u>, p. 589.

9. M.A. Green, G.P. Coombs, and J.L. Perry, report by 500 Incorporated, a subsidiary of Arthur D. Little, Inc., Cambridge, Mass. (1968).

10. M.A. Green, G.P. Coombs, and J.L. Perry, these Proceedings, p. 293.

11. W.S. Gilbert, R.E. Hintz, and F. Voelker, University of California, Lawrence Radiation Laboratory Report UCRL-18176 (1968).

12. W.B. Sampson, R.B. Britton, G.H. Morgan, and P.F. Dahl, in <u>Proc. Sixth Intern. Conf. High Energy Accelerators, Cambridge, Mass., 1967</u>, p. 393.

13. P.F. Smith, these Proceedings, p. 913.

evidence that such a material can be made in a high-resistance substrate. Work is proceeding on such an NbTi material. The same dimensions are used for both the NbTi and Nb_3Sn cases. An eddy-current term is included in the program. Prevention of eddy-current losses will require extensive use of high-resistivity metals and nonmetallic materials in the $4^{\circ}K$ region.

The refrigeration cost is based on the Strobridge, Chelton, and Mann[14] estimate. It is assumed that there is one refrigerator at each point where leads leave the enclosure. The cost of each refrigerator can be calculated by using the relationship

$$\text{Refrigerator cost} = \$3720\ (\text{Power @ } 4.2^{\circ}\text{K})^{2/3} ,$$

where the $4.2^{\circ}K$ power required is greater than 100 W. The above relationship fits the Strobridge, Chelton, and Mann curve very well. The actual cost of large units is tending to be somewhat lower than the cost predicted by the above relationship.[15]

The rf system cost is primarily a function of rf power, which is a function of the beam power. The injection extraction system consists of fast kickers, thin septums, deflectors, and magnet to get the beam into and out of the machine. The cost of injection and extraction elements is a function of the injection and extraction energies respectively.

The vacuum system consists of vacuum piping in regions where there are no magnet cryostats, vacuum joints, a roughing pump system, and high-vacuum cryogenic pumps using liquid helium. The cost of the vacuum system is roughly proportional to the ring radius. The accelerator control system is assumed to be 5% of the sum of the accelerator cost.

The cost of tunnel, earthwork, and plant facilities is an extremely important part of the cost analysis. The computer program is capable of calculating the conventional facilities cost for three types of sites: hard sites with cut-and-fill methods used, soft sites with cut-and-fill methods used, and a hard-rock bored tunnel site. The soft site was used for the 100 GeV example. The cost of enclosure, shielding, foundation, and earthwork is estimated to be about $7400 per meter. The tunnel is much like the LRL 200 GeV design study tunnel[16] (see Fig. 7), which may be larger and more expensive than needed. The utilities or plant facilities cost consists of an electric power distribution net and a cooling water system (cooling water is required for the rf system and refrigerators). The cost of the utilities is about $100 per kilowatt fed into the power consuming systems. The machine subtotal cost is the sum of all the systems. An additional 50% was added for engineering development, civil engineering, architecture, and contingency. The latter was added to make the estimate comparable to today's actual conventional machine costs.

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[14] T.R. Strobridge, D.B. Mann, and D.B. Chelton, National Bureau of Standards Report 9229 (1966).

[15] G.P. Coombs (500 Incorporated, a subsidiary of Arthur D. Little, Inc.), private communication.

[16] 200 BeV Accelerator Design Study, Vol. II, University of California, Lawrence Radiation Laboratory Report UCRL-16000 (1965).

THE EFFECT OF MAGNETIC FIELD, APERTURE, AND CYCLE TIME ON TOTAL MACHINE COST

A number of interesting things can be seen from looking at the whole system cost. The variable parameters have a strong effect on machine cost, therefore it is possible to minimize machine cost by varying the variable parameters.

Figure 8 shows clearly that there is a field for which the machine cost is minimum. Also shown in Fig. 8 is the effect of cycle time on both the optimum field and the optimum machine cost. The machine aperture affects the machine cost at all cycle times (see Fig. 9). The difference in cost between NbTi and Nb_3Sn machines is greater for larger apertures.

The optimum field increases as the cycle time increases (see Fig. 10). The Nb_3Sn systems at long cycle time have a higher optimum field than the NbTi systems. The optimum field at long cycle times is strongly affected by the current density in the magnet coils. Today Nb_3Sn coils have a larger coil current density than NbTi except at very low fields. A factor of two increase in current density for NbTi, which will be achieved within a year, will result in higher optimum fields and somewhat lower costs than shown in Figs. 9 and 10.

There is also an aperture and repetition rate which will result in a minimum-cost machine for a given average beam current and duty factor. Table I illustrates that the slow-cycle large-aperture machine may be very attractive from a cost standpoint. A 100 GeV storage ring was included for comparison with the accelerators. A more detailed cost breakdown of the machines shown in Table I is given in the Appendix.

A 1000 GeV accelerator and storage ring are shown in Table II. The 1000 GeV machines have a ratio of average radius to magnetic radius of 1.5 instead of 2.0. The ν value for the 1000 GeV machine is approximately 100, hence the long straight sections do not take up a large part of the machine circumference. It should be noted that the 1000 GeV accelerator has an injection energy of 25 GeV and an aperture diameter of 8 cm. A storage ring is also shown in Table II for comparison with the synchrotron.

GENERAL CONCLUSIONS AND THE EFFECT OF FUTURE DEVELOPMENTS

A number of conclusions can be drawn from the studies that have been made on the economics of superconducting synchrotrons. These conclusions will be greatly affected by changes in cost and technology of superconductors and other equipment.

This paper shows that niobium-titanium alloys are promising from a cost standpoint. If high fields are required (greater than 50 kG), Nb_3Sn appears to be the cheapest material, particularly if the aperture of the magnet is small. It is not inconceivable that the quadrupoles may use Nb_3Sn while the dipoles are made of NbTi. Ductility and the ability to form NbTi into a large variety of shapes are very advantageous. There are NbTi materials that could be used in storage rings today. It is quite evident, however, that more work is required on magnet design so that reliable, uniform magnets are built. Current densities achievable in NbTi materials can be expected to double in the next year or two (to 40 000 A/cm^2 or more in 60 kG coils). As a result NbTi will become increasingly attractive at 50 or 60 kG. There has been a downward trend in material cost, due primarily to improvement in manufacturing techniques, and the possibility of running these materials at their critical current. No definite material choice can be made at this time.

TABLE I. Cost breakdown for two 100 GeV synchrotrons and a storage ring.

	Short-cycle machine	Long-cycle machine	Storage ring
MACHINE PARAMETERS			
Final energy	100 GeV	100 GeV	100 GeV
Injection energy	5 GeV	5 GeV	---
Beam intensity	5×10^{12} P/sec	5×10^{12} P/sec	---
Magnetic field	30 kG	40 kG	45 kG
Cycle time	2.0 sec	20 sec	---
Aperture	5.0 cm	12.5 cm	12.5 cm
Material	NbTi	NbTi	NbTi
MACHINE COMPONENT COST			
Magnets	1.9 M$	6.6 M$	8.3 M$
Magnet power supply	7.9 M$	6.3 M$	0.2 M$
Magnet cryostat	2.5 M$	2.1 M$	1.9 M$
Helium refrigeration	7.1 M$	3.2 M$	1.5 M$
Rf system	2.9 M$	2.9 M$	0.2 M$
Injection-extraction system	1.0 M$	1.0 M$	1.0 M$
Vacuum system	0.8 M$	0.6 M$	0.5 M$
Control system	1.2 M$	1.1 M$	0.7 M$
Enclosure and plant facilities	12.3 M$	8.7 M$	7.1 M$
SUBTOTAL COST	37.6 M$	32.5 M$	21.4 M$
TOTAL COST with EDIA and contingency	56.4 M$	48.7 M$	32.1 M$
YEARLY POWER COST	1.55 M$	0.65 M$	0.11 M$

TABLE II. Cost estimate for a 1000 GeV synchrotron and a storage ring.

	Synchrotron	Storage ring
MACHINE PARAMETERS		
Final energy	1000 GeV	1000 GeV
Injection energy	25 GeV	----
Beam intensity	3.3×10^{12} P/sec	----
Magnetic field	40 kG	45 kG
Cycle time	30 sec	----
Aperture	8.0 cm	8.0 cm
Material	NbTi	NbTi
MACHINE COMPONENT COST		
Magnets	44.3 M$	56.9 M$
Magnet power supply	29.6 M$	1.0 M$
Magnet cryostat	19.2 M$	17.9 M$
Helium refrigerator	14.8 M$	7.3 M$
Rf system	28.7 M$	0.4 M$
Injection-extraction system	4.6 M$	4.6 M$
Vacuum system	3.8 M$	3.4 M$
Control system	7.2 M$	4.6 M$
Enclosure and plant facilities	63.4 M$	52.7 M$
SUBTOTAL COST	215.6 M$	147.9 M$
TOTAL COST with EDIA and contingency	323.4 M$	216.6 M$
YEARLY POWER COST	3.95 M$	0.82 M$

This study indicates that the magnetic field for a minimum-cost machine is lower than what is talked about by Smith[2,3] and Sampson.[17] Fields of 60 kG are high for today's technology. However, changes in material cost, superconductor current density, and the power supply may make the 60 kG field level practical (particularly for long-cycle-time machines) from an economic standpoint. It should be noted, however, that if tunnel cost and cryostat cost can be reduced below the numbers given in this paper, the optimum magnetic field will also be reduced.

This paper indicates that long cycle times are attractive even when the aperture is increased to accommodate a larger beam current. A long flat-top adds very little to the cost, but the ability to produce long beam spill has to be perfected. Superconducting magnets can be made ripple-free if they are run in the persistent mode, which may help solve long spill problems. Short cycle times are desirable for some kinds of experiments. Changes in power supply technology may make shorter cycle times more attractive. It is clear that some thought is required to find a solution that is best with respect to both physics and economics.

In conclusion the following statements can be made. (1) Superconducting technology has advanced far enough that storage rings are possible to build. (2) It appears that costs for a 50 to 100 GeV superconducting synchrotron are competitive with today's conventional machines. (A conventional bare-bones machine would cost 0.7 to 0.8 million dollars per GeV.) (3) A large economic advantage is likely to be gained when machines in the TeV (trillion electron volt) range are built. (Machine costs should be reduced by a factor of 2 or more.) (4) Changes in superconducting technology, cryogenics, and power supply technology should have a favorable effect on the projected cost of a superconducting synchrotron.

Superconductivity has a bright future, but a great deal of realistic thinking and hardware development is required before superconductivity becomes a tool of high energy physics instead of a plaything. The full utilization of superconductivity in high energy physics will require both money and manpower. We must commit ourselves to superconductivity if we are going to realize its promise.

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[17] W.B. Sampson, these Proceedings, p. 998.

APPENDIX

A DETAILED COST BREAKDOWN OF THE 100 GEV MACHINE SHOWN IN TABLE I

Table A. 100 GeV machine parameters

Parameter	2-second cycle accelerator	20-second cycle accelerator	Storage ring
General parameters			
Peak final energy	100 GeV	100 GeV	100 GeV
Injection energy	5 GeV	5 GeV	---
Average proton intensity	5×10^{12} P/sec	5×10^{12} P/sec	---
Peak dipole field	30 kG	40 kG	45 kG
Aperture diameter	5 cm	12.5 cm	12.5 cm
Cycle time	2 sec	20 sec	---
Detailed parameters			
Machine average radius	224.2 m	168.2 m	149.6 m
Dipole magnetic radius	112.1 m	84.1 m	74.8 m
Superconducting material	NbTi	NbTi	NbTi
Superconductor cost	$\$2.55 \times 10^{-3}$/Am	$\$3.48 \times 10^{-3}$/Am	$\$4.07 \times 10^{-3}$/Am
Coil current density	31 400 A/cm^2	23 000 A/cm^2	19 600 A/cm^2
Dipole ampere turns	3.57×10^5	1.04×10^6	1.23×10^6
Peak magnet stored energy	25.5 MJ	170.5 MJ	210.2 MJ
Peak MG set power	84.7 MVA	68.0 MVA	---
Magnet rise time	0.6 sec	5 sec	500 sec
Magnet flat-top time	0.7 sec	7 sec	---
Injection time (front porch)	0.1 sec	3 sec	---
Number of refrigerators	4	4	4
Refrigeration required	27 300 W	7600 W	2000 W
Rf power required	504 kW	605 kW	~ 20 kW
Accelerating voltage	1.49×10^6 V/turn	1.34×10^5 V/turn	---
Injection efficiency	95%	95%	95%
Extraction efficiency	90%	90%	90%
Total power required	19.0 MW	8.5 MW	1.5 MW
Type of site	Soil	Soil	Soil

Table B. The cost of various machine components for the 100 GeV machine shown in Table I (costs in thousands of dollars)

Component	2-second cycle accelerator	20-second cycle accelerator	Storage ring
1. Magnet system			
Dipole cost	1634	5301	6608
Quadrupole cost	104	713	958
Correction magnet cost	174	601	757
Total magnet cost	1912	6615	8323
2. MG set power supply			
Generator cost	1012	788	18
Motor cost	131	1103	7
Rectifier cost	4113	3232	60
Flywheel cost	9	60	74
Leads and bus bar cost	1314	1031	21
Installation cost	1316	1045	40
Total power supply cost	7895	6259	220
3. Magnet cryostat cost	2549	2113	1885
4. Refrigeration system			
Refrigerator cost	6553	2806	1157
Transfer line cost	549	426	385
Total refrigeration system cost	7102	3232	1542
5. Rf system cost	2861	2906	183
6. Injection-extraction system			
Injection system cost	270	270	270
Extraction system cost	725	725	725
Injection-extraction system cost	995	995	995
7. Vacuum system			
Vacuum piping	235	166	147
Vacuum joints	151	122	109
Cryopumps	180	129	114
Roughing pumps	211	159	141
Total vacuum cost	777	576	511
8. Control system cost	1205	1135	683
9. Tunnel earthwork and plant facilities			
Tunnel cost	4651	3488	3100
Earthwork cost	3946	2960	2631
Foundation cost	1832	1374	1221
Utilities cost	1903	846	132
Total plant cost	12 332	8668	7084
Machine subtotal cost	37 628	32 499	21 426
50% EDIA and contingency	18 815	16 250	10 716
Total machine capital cost	56 443	48 749	32 140

Table C. Operating power and annual power cost for the 100 GeV machine shown in Table I

	2-second cycle accelerator	20-second cycle accelerator	Storage ring
Power required by the accelerator			
MG set power	3776 kW	2936 kW	50 kW
Refrigerator power	13 643 kW	3783 kW	975 kW
Rf station power	1890 kW	1428 kW	160 kW
Tunnel power (includes air conditioning, lights, etc.)	423 kW	317 kW	282 kW
Total power required	19 032 kW	8464 kW	1477 kW
Annual power cost @ $0.01/kWh delivered to the equipment (cost in thousands of dollars per year)	1553	645	106

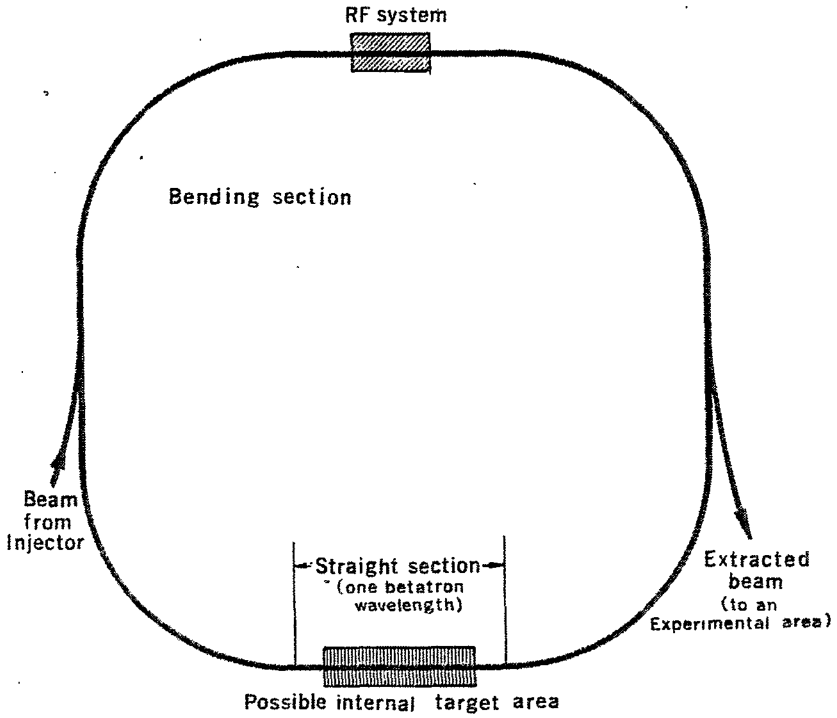


Fig. 1. A superconducting synchrotron with fourfold symmetry.

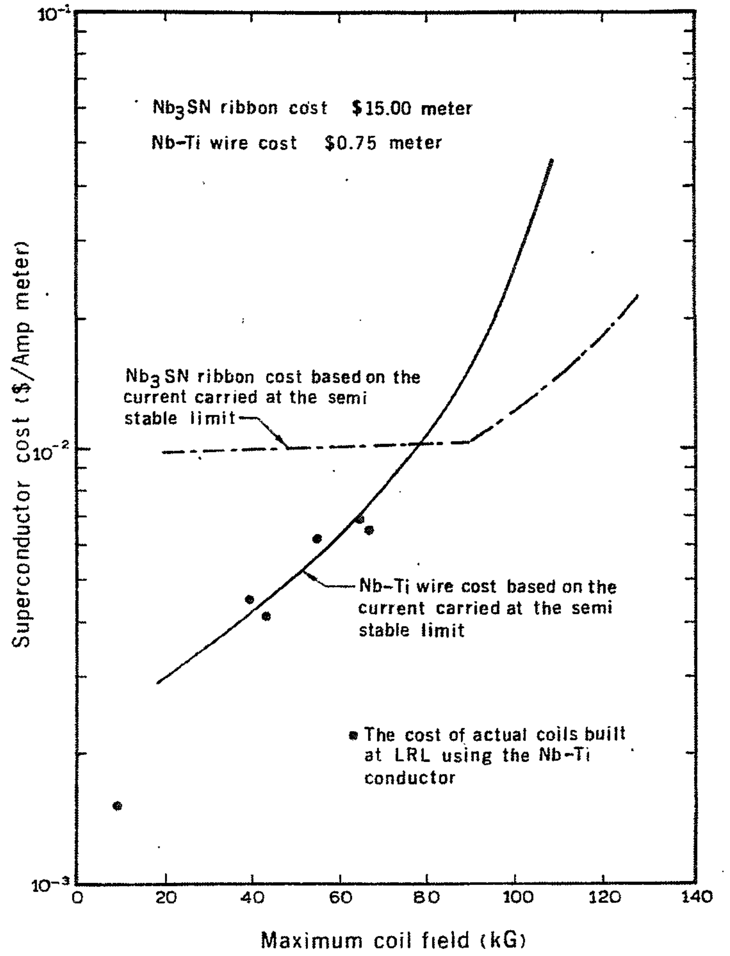


Fig. 2. The cost of a superconductor vs the maximum field in a coil winding.

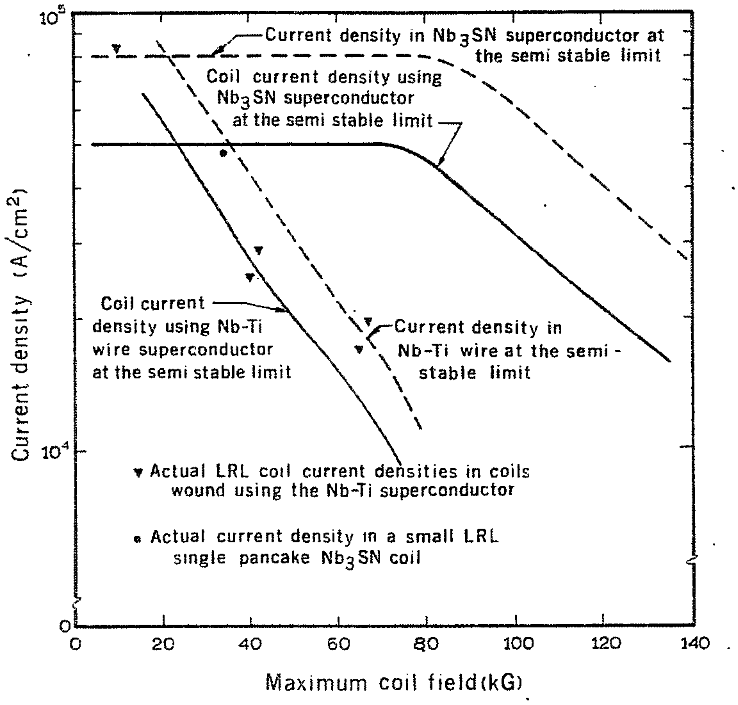
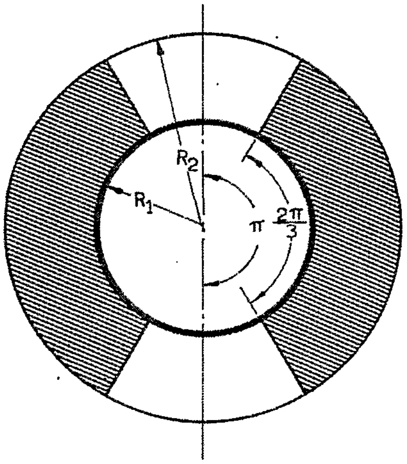


Fig. 3. Coil and superconductor current densities using NbTi and Nb_3Sn high-current-density superconductors.

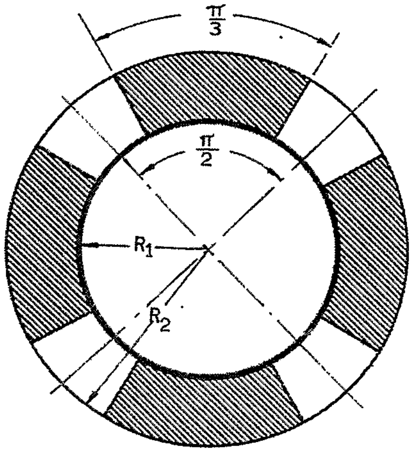


$$B_0 = \frac{\sqrt{3}}{\pi}\ \mu_0\, J_0 \left(R_2 - R_1 \right)$$

$$Ni = \frac{\pi}{3} \left(R_2^2 - R_1^2 \right) J_0$$

$$Am = 2 \left[L_D + \frac{\pi^2}{6} \left(R_1 + R_2 \right) \right] Ni$$

Fig. 4. A dipole cross section based on the 2/3 rule.



$$G = \frac{B_1}{R_1}$$

$$G = \frac{\sqrt{3}}{\pi}\ \mu_0 J_0\ \ell N \left(\frac{R_2}{R_1} \right)$$

$$Ni = \frac{\pi}{3} \left(R_2^2 - R_1^2 \right) J_0$$

$$Am = 2 \left[L_Q + \frac{\pi^2}{12} (R_1 + R_2) \right] Ni$$

Fig. 5. A quadrupole cross section based on the 2/3 rule.

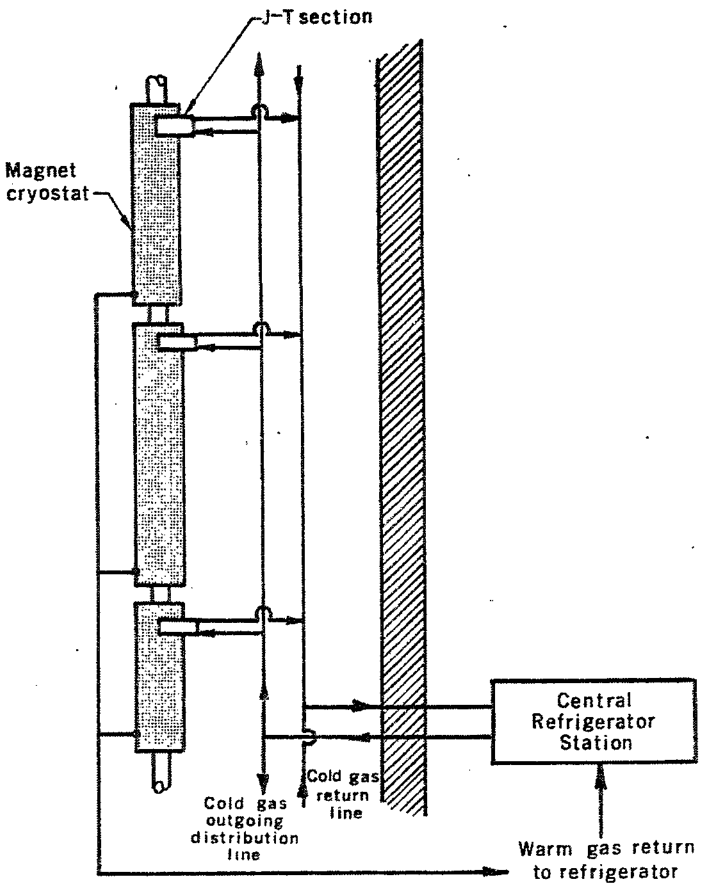


Fig. 6. A superconducting synchrotron refrigeration distribution system.

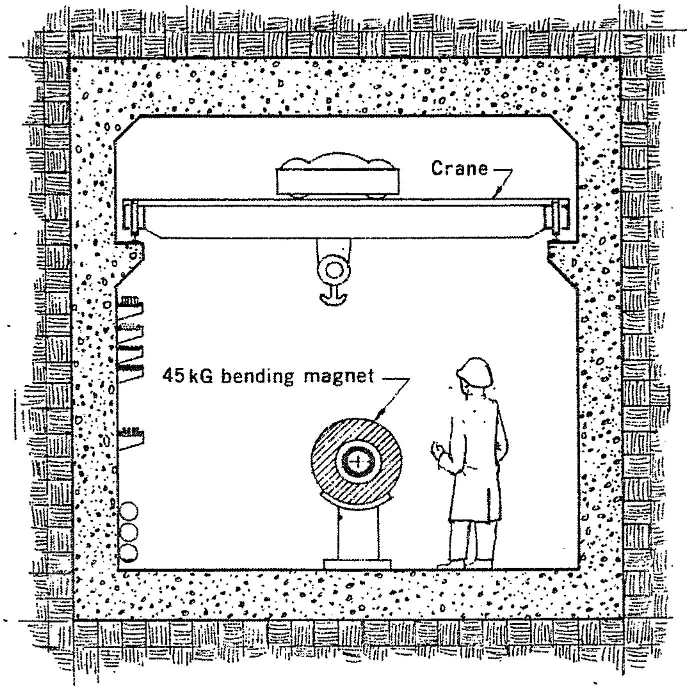


Fig. 7. A typical tunnel cross section showing a 45 kG magnet installed in the tunnel.

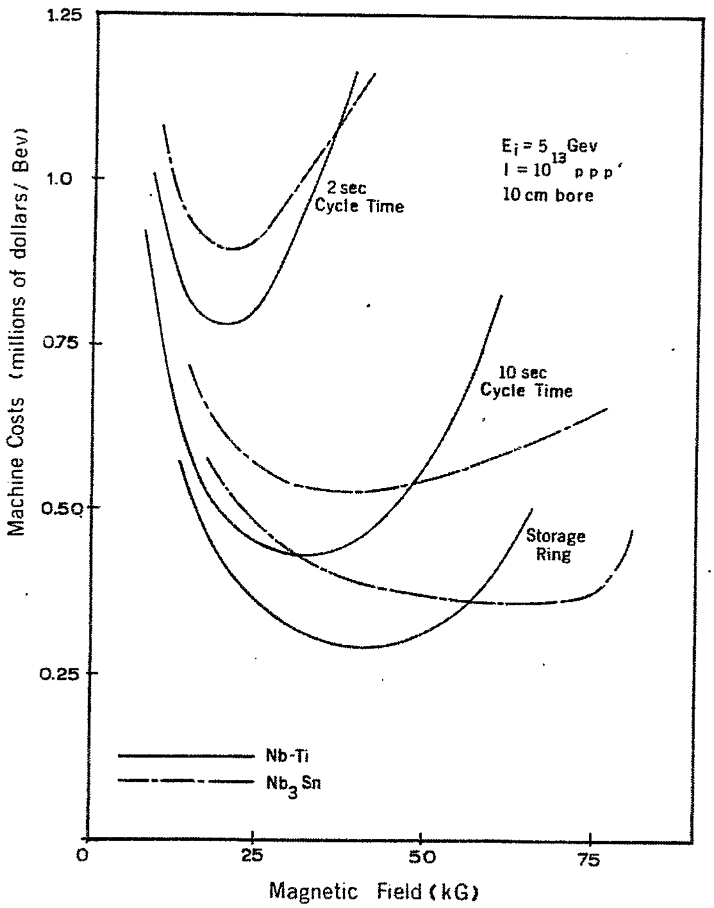


Fig. 8. The cost of a 100 GeV synchrotron vs the bending magnet field.

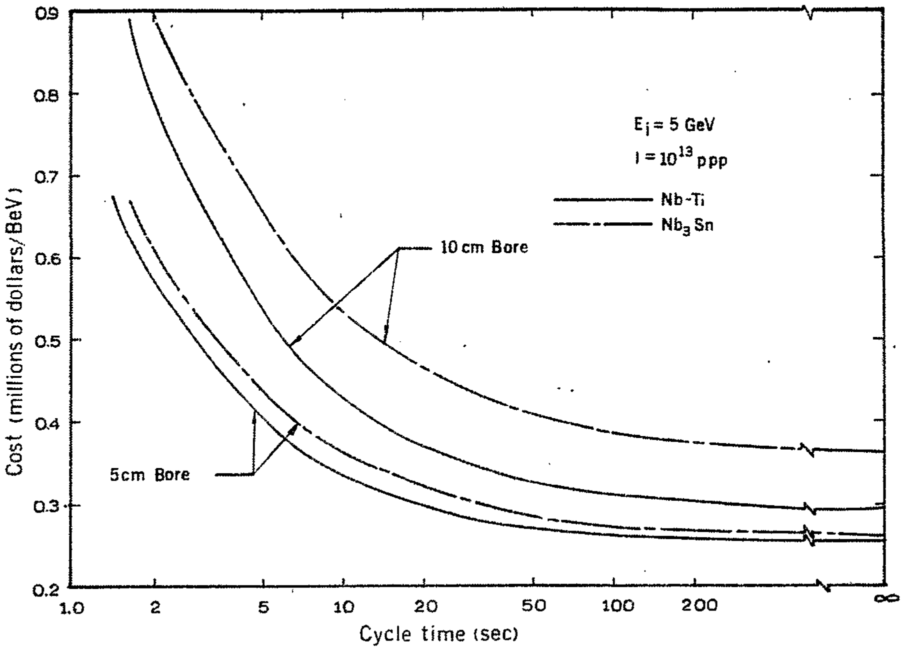


Fig. 9. The cost of a 100 GeV superconducting synchrotron at optimum magnetic field vs cycle time.

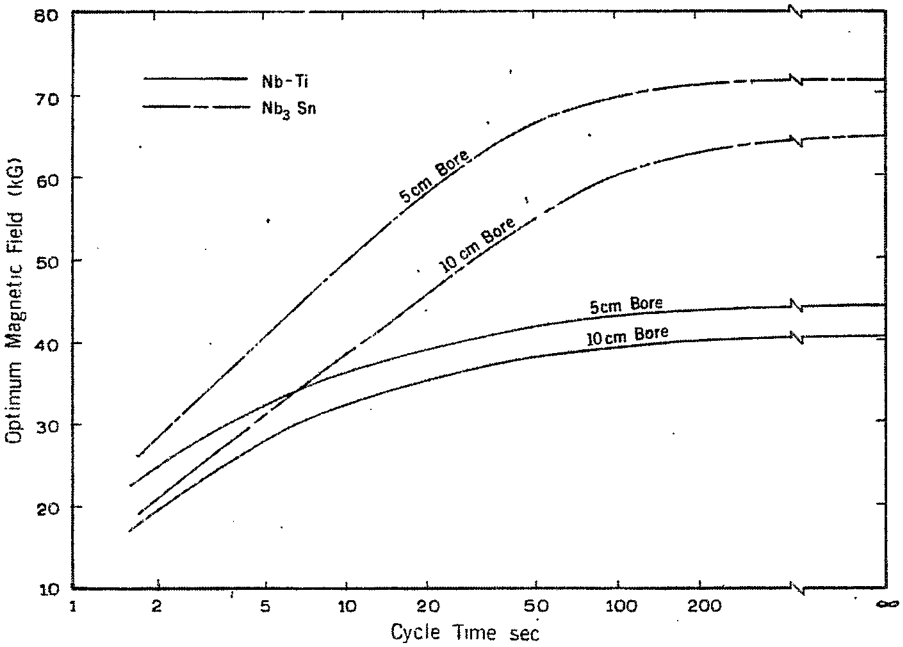


Fig. 10. Optimum magnetic field vs cycle time.