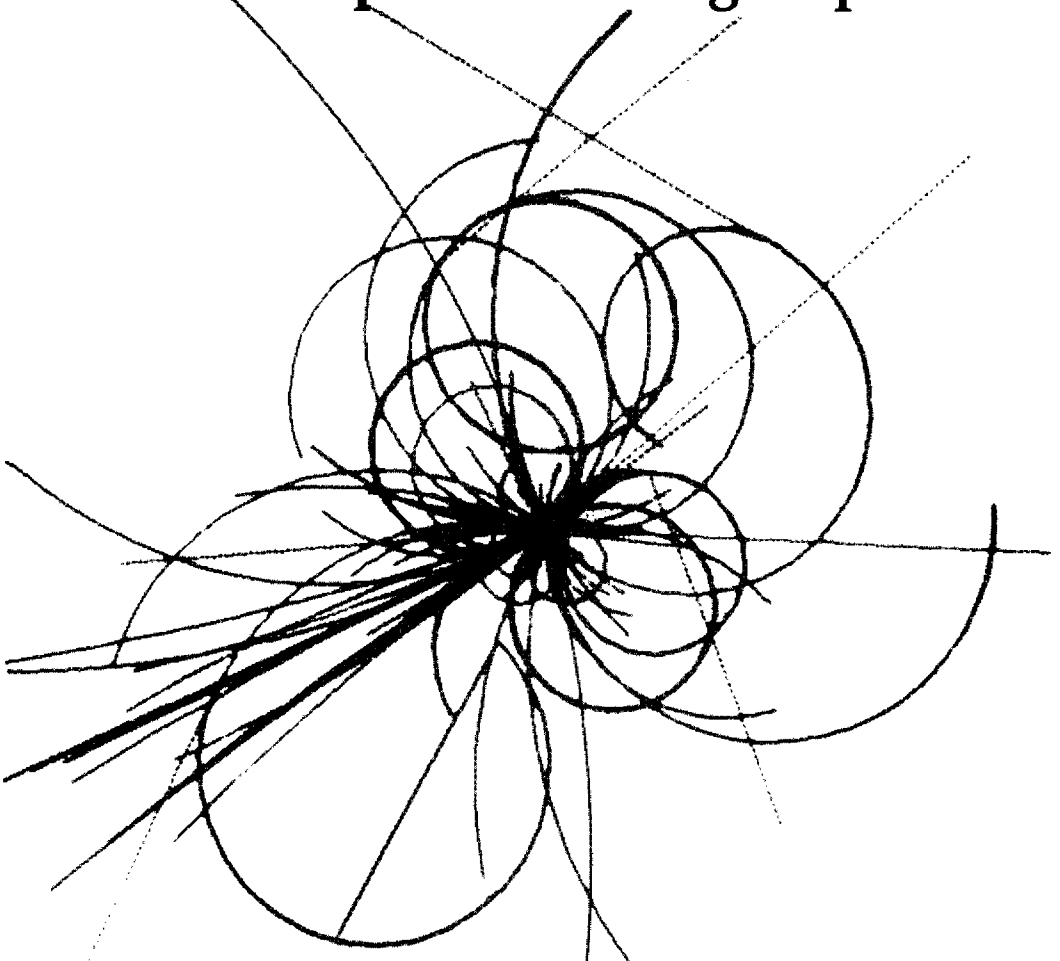
SSC-127

The Superconducting Super Collider



A LIQUID NITROGEN TEMPERATURE SSC

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Summary

Under the assumption that new developments in the science of superconductivity will lead to dipole magnets suitable for the SSC that have the same properties with regard to field, field quality, size and cost as those in the present conception of the collider, but operating at 77 K rather than 4.35 K; the initial cost of the collider facility is found to be less by $213 M out of the $2,000 M actual construction cost for the collider technical systems and the conventional facilities estimated in the Conceptual Design Report. EDI and contingency is not included in these figures

Operation at the higher temperature is not, however, an unequivocal advantage. The beam line vacuum system in the 77 K case presents problems that will require a larger magnet aperture for satisfactory solution. The costs of this together with the costs of the development and construction of the new vacuum system required is estimated to be $156 M. The net capital cost saving associated with the higher temperature operation is thus found to be $57 M or about 3% of the total estimated cost.

In addition it is estimated that the operating cost of the facility will under these conditions be less by $27.5 M per year in the steady-state including an allowance for the greater availability of the simpler cryogenic system.

Introduction

In January of this year the announcement was made of the important discovery of superconductivity in certain oxides at temperatures approaching 100 K. At the present moment very little about the nature and the structure of these materials is known, and even the mechanism responsible for the superconductivity is in doubt. Only an incomplete description of the properties of the materials appeared in the initial publications[1]. What has been clearly demonstrated, however, is that there is a material, yttrium - barium - copper oxide, that has a superconducting transition beginning at 98 K and reaching the zero resistance state in low field at 94 K. It shows a significant Meissner effect, and its critical field at the zero of temperature is estimated to be 190 T.

There is great ferment in this field now, and there are new rumors almost every day[2]. Most important for the present purpose, however, is that it has been shown very clearly that this material will carry supercurrent in a field of 6 T and at a temperature of 77 K[3].

It is important, therefore, to examine the impact that these new discoveries may have on the conceptual design of the Supercollider and on the costs of he project. For this purpose it will be assumed that the development of a new material will result in a dipole magnet of the same size, weight, field level, field quality, operating properties, and cost as the currently conceived niobium-titanium dipole, but operating at a temperature of 78 K rather than 4.35 K. This assumption is clearly drastic and bound to be wrong in all respects, however, the state of knowledge about the new technology will support no other because all detail is lacking. In any case, considering this nitrogen temperature collider will serve to delineate the problems and the costs associated with helium temperature operation.

Magnet Operation at 67 K

Assumptions

The assumptions that form the basis of the cooling concept and of the cost estimates for the 77 K Supercollider are listed below:

1) A superconducting wire requiring a maximum temperature of 77 K is available.
2) The magnet structure consisting of coils, collar and iron is the same as that used presently for the SSC.
3) Cool-down of the magnets requires the same flow areas and cooling channels as presently used for the SSC.
4) The 20 K shield is omitted, and the cryostat is simplified.
5) There will be an 80 K shield, which is used for return of the liquid nitrogen coolant to the refrigerator station and interception of the bulk of the heat flowing from the environment.
6) Heat leak to the magnets is assumed to be the same as for the SSC (.057 W/meter)
7) Synchrotron radiation is .142 W/meter.
8) Heat leak to the nitrogen cooled shield is assumed to be 32 kw per refrigerator (80% of the present value).

Cooling Concept

Liquid nitrogen of a pressure of 3 ata and a temperature of 67 K is pumped into the cooling channels of the magnet. The liquid flows through 4 km of magnet string and is returned through the 80 K shield line to the refrigerator station. There are no recoolers between cells. Liquid is only cooled at the refrigerator station before being pumped around again. Figure I shows the concept.

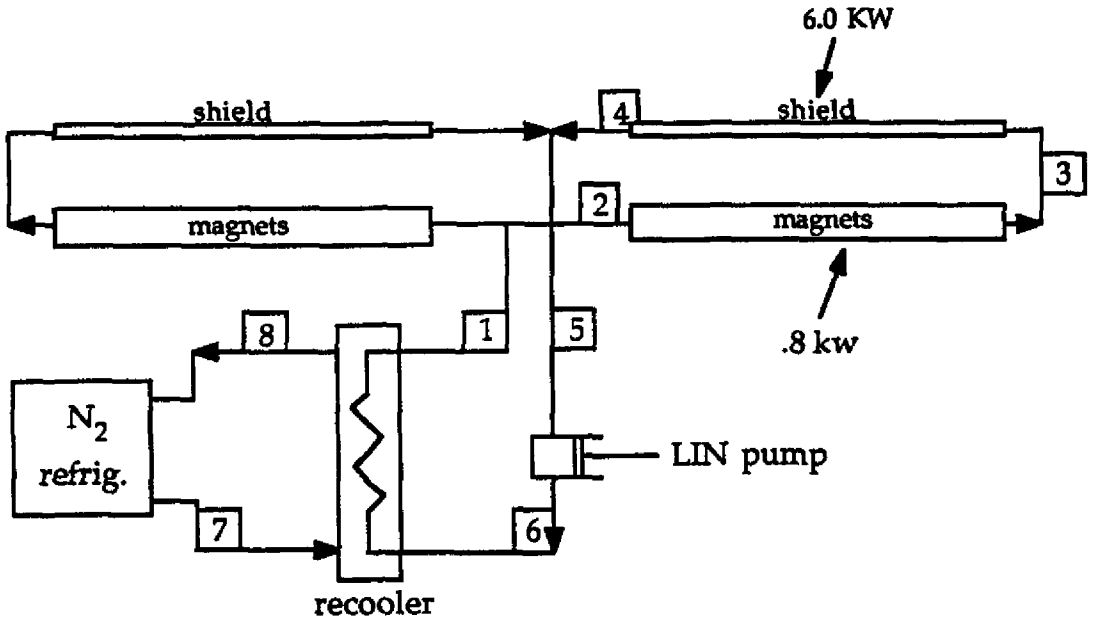

Figure I
Cooling Concept for the Magnet System

Table I
Process Points for Cooling Process of Figure I

Point	Pressure ata	Temp. K	Flow rate g/s
1	3.0	67	617.2
2	3.0	67	308.6
3	2.65	68.3	308.6
4	2.0	77.8	308.6
5	2.0	77.8	617.2
6	3.0	77.85	617.2
7	.2	66.0	74.1
8	.2	66.0	74.1

Magnet Cryostat and other System Components

For the 77 K magnet system a cryostat considerably simplified from the 4 K case has been used for this study. The inner shield is eliminated and the magnet support consists only of the outer one-third of the post in the design of the Conceptual Design Report. Because of the increased stiffness and strength of ths reduced post, the longitudinal struts in the cryostat are eliminated. All of the internal piping of the helium cryostat can be eliminated also, and as a consequence, the cryostat can be reduced to 80%. As described in Figure I, the 80 K shield remains and serves to return the nitrogen coolant flow to the refrigeration station. The shield also intercepts most of the heat load of the system, and as a consequence, the system operates without recooling.

Many other system components - all of the quench relief system and most of the safety valves, U-tube connections, and so forth - also are eliminated. Remaining in the 77 K system are gas-cooled magnet current leads, safety leads, and, of course, all of the correction element systems. The system concepts in the current conceptual design for the interaction region cryogenics are retained, suitably simplified for the higher temperature.

Effects of a Quench

During a quench, approximately 10^6 joules are deposited in the magnet and liquid nitrogen per dipole.

The magnet cold mass is 373 kg/meter. If we assume a specific heat of the cold mass of 121 J/kg - K (iron value = lowest), then a temperature rise of 1 K of liquid plus cold mass requires approximately 750,000 Joules. Total temperature rise is then of the order of 1.2 K. Since the velocity of the liquid in the magnets is of the order of 13 cm/s it takes this quench heat some 10 hours to move through the whole string. Because the nominal operating temperature of the system is some 10 K below the maximum operating temperature of the conductor, the system can absorb the heat of 8 quenches before the maximum permissible temperature is reached. From a cryogenic standpoint the quench is a non-event and special provision for quench recovery is not required.

Cool-Down and Failure Mode operation

Because most of the sensible heat in the iron mass of the magnet is at temperatures above 67 K, the total time for a sector cool-down is not greatly reduced in the nitrogen temperature SSC from the helium temperature case, and the amount of liquid nitrogen needed is roughly the same. Detailed cool-down scenarios for the system pictured in Figure I have not been worked out, and it is assumed for the purposes of costing that cool-down can be done without any components or systems in addition to those needed for steady-state operation. That this is so is not obvious. Cool-down by liquid evaporation in a long system is not a stable process. In addition, the magnets may not be able to tolerate the large transverse temperature gradients inherent in two-phase cooling, and modeling of the cool-down may show that gas cool-down is necessary. Provision for this is not made in the costing done below.

Failure modes for the 77 K cryogenic system have not been considered in detail, however, that the system is quite forgiving is shown by considering the consequences of stopping the coolant flow altogether for some time. During this time the magnets see no flow and the liquid and cold mass warm up from heat leak and the synchrotron radiation. In one hour the temperature rise would be of the order of 4 – 5 millidegrees only. The effect of non-flow is more severe on the cooled shield. Cold mass of the shield is of the order of 9 kg/meter (aluminum), while liquid N_2 inventory is 1.27 kg/meter. Heat capacity of shield and liquid is 5600 Joules/K meter. Heat leak in one hour is 5400 Joules/meter and temperature rise of the shield is approximately 1 K.

It seems likely on this basis that adequate redundancy in the system can be achieved with very little additional cost.

Liquid N_2 Consumption by Power Leads

Liquid N_2 will be vented through the power leads and discharged to the environment. The amount of nitrogen consumed can be evaluated quickly from assuming 60 mV per 1000 A lead. For the total ring, with 2×10^6 A current flow, total cooling requirement will be 120,000 watts. This heat will be removed by boiling liquid nitrogen primarily, and some superheating of the vapor. If we assume 300 Joules/gram as the cooling capacity of the nitrogen, liquid nitrogen consumption will be 400 g/s or 38 tons/day.

In order to handle this, two 35 ton/day liquid N_2 plants will be supplied. Power cost to produce liquid nitrogen is of the order of 600 kWhr per ton. Power consumption will be of the order of 1.0 MW.

Liquid N_2 Refrigerator Station

Equipment present at the refrigeration station will be:

1) N_2 refrigeration plant with a capacity of 45 kW at 66 K. Power required (installed) is 830 kW.
2) Liquid nitrogen storage tank with a capacity of 35,000 gallons (500 tons).
3) Two liquid nitrogen circulating pumps with a capacity of 25 gpm against a differential pressure of 1.5 ata.
4) Two subcoolers to transfer 20 kW each from subcooled liquid N_2 to boiling liquid at 66 K.
5) Miscellaneous piping, instrumentation and valves to move liquid N_2 around for various operating modes.
6) At two out of ten stations, an air separation plant with a capacity of 35 tons/day. Connected power is 875 kw, normal power used is full power until storage is full. Average power consumption is 500 kw.
7) Inventory of the magnet system will be of the order of 40 tons per sector.

Beam-Line Vacuum System

The luminosity lifetime for the collider is determined primarily by two effects: the beam-beam collisions at the interaction points, and residual gas scattering from atoms in the beam line of the two rings. The first is, of course, unavoidable. The second, however, in order that not to place a limitation on the usefulness of the collider sets stringent requirements on the vacuum that must be maintained in the beam lines of the machine. The tolerable partial pressure depends on the molecular weight of the species in question, but for hydrogen, which is the dominant constituent of the residual gas, a pressure of 10^{-8} Torr limits the luminosity lifetime to about 130 hours[4]. The beam-beam effects limit the lifetime to about 100 hours, so clearly a pressure of 10^{-7} Torr would limit the usefulness of the collider in an intolerable way. In addition to the luminosity lifetime limitation, gas scattering at the 10^{-8} Torr level produces a cryogenic heat load of 250 watts per ring and an important amount of the nuclear radiation produced by the beams. Thus it is absolutely necessary to provide a vacuum system for the collider capable of maintaining this 10^{-8} Torr, or much preferably a factor of five below this, under the ring operating conditions including the effects of the synchrotron radiation.

This is a problem that is familiar from the operation of electron storage rings, and the only solution possible is to distribute pumping along the length of the beam pipe inside the dipole magnet. Without this it is not possible

ever to reach the needed pressures in the long, thin beam pipes much less to maintain the low pressure in operation. In the SSC, this distributed pumping is cryopumping provided by the liquid helium cooling of the magnet[5]. It is estimated on the basis of experiments that without the cryopumping, the average pressure in the beam tube under beam operating conditions will be 5.1×10^{-4} Torr[6]. This is so high that under these conditions collider operation of any sort is impossible.

Examining this matter more closely, the pressure quoted above is the length-averaged pressure calculated from measured synchrotron radiation induced gas loads in a beam pipe with zero-pressure local pumping every 100 meters. The average pressure varies inversely as the square of the length between pumps, so even if the magnets of the ring were shortened so that the local pumping could be placed every meter, the average pressure could not be made good enough without also increasing the beam tube size. This illustrates the need for distributed pumping under these circumstances. The pumping must be distributed on the scale of the beam pipe diameter and integrated into the magnet system design.

In the nitrogen temperature SSC cryopumping is not effective for hydrogen, which is the most important component of the residual gas and is produced in the beam tube by the synchrotron radiation, and so some other type of vacuum pumping must be distributed in the beam line. In electron rings this pumping is provided by a continuous sputter-ion pump which is attached to the beam chamber and uses the magnetic field of the dipole for its operation. In this way it is possible to maintain pressures in the low 10^{-9} Torr range after clean-up even with very large synchrotron radiation loads. This technology is not appropriate for the high field magnet of the SSC. The magnetic field volume of the cosine theta magnet is the wrong shape and is too expensive to use in this way. Thus for the vacuum pumping of the beam line in a 77 K SSC some new technology must be developed. What this should be is not at the moment absolutely clear, but perhaps non-evaporable gettering could be applied most easily in this situation. This technology has been chosen for LEP in place of sputter-ion pumping because of the low value of the field in this ring[7]. For the SSC a new type of pump must be developed to fit behind a liner in the magnet bore. The liner is necessary to control the microwave impedance of the beam surroundings; and, because the bore is already chosen to be the minimum prudent size, such a system will require some increase in the bore tube and the dipole magnet size.

It is estimated that an increase of 1 cm in the aperture of the collider involves a cost increase of $140 M in the magnet system[8]. This figure includes only the costs of magnets with the larger aperture. Clearly there are other cost consequences of the size change. The abort system may become more expensive, but the magnet rejection rate will be lower and alignment less costly, for examples. Some account must be made of all of these things, and a quick pass through the Conceptual Design WBS suggests that savings of

$15 M may be realized in this way. These and other estimated system costs are shown in Table II[9].

Table II

Outline of Cost Differentials for NEG-Pumped Beam Line

Cost differential for 5 cm magnet bore diameter	$140 M
Savings associated with the larger magnet size	(15)
Cost differential for lined beam tube with pump	21
Additional costs for support equipment	5
	$151 M
Research, development and testing Costs	5 M
Total Cost Differential	$156 M

The research and development costs here are required to develop a getter material that is optimized for the conditions in the nitrogen temperature SSC and to do testing at a number of stages in the system development. The recent problems in the vacuum system of the TRISTAN ring show how easy it is to have trouble even in situations where the technology is well understood, and how necessary it is to test adequately.

It is easy to overlook the beam line vacuum system in the SSC because with the cryopumping that occurs naturally in the magnet, vacuum requirements do not strongly constrain the design. This is not the case in room temperature storage rings. The beam line vacuum technology in the ISR at CERN or the PEP ring at SLAC, as examples, is highly visible as a driving force in the overall system design, and this technology is the product of a long line of specialized development. In the nitrogen temperature SSC the beam line vacuum problem is a very serious one requiring for its solution a research, development, and testing effort comparable to that already expended on vacuum systems for room temperature colliders. One can expect that the development of this vacuum system would affect the both the design of the collider and its costs in a significant way. The conclusion here is that this cost of providing distributed pumping for the 77 K collider is about $156 M.

Cost Effects

Capital Cost Effect

It is clear that operation of magnets at nitrogen temperature requires a considerably simpler cryogenic system than operation at helium temperature. A concept for such a system has been outlined above. With this concept in mind, the cost estimate for the SSC Conceptual Design[10] has been reviewed

Table III
Changes in cost of Technical and Conventional Systems
Due to 77 K Magnet Operation

WBS Number	Description of System	CDR Cost for Structure No.	77 K SSC Total Cost	Difference
	SSC Total Technical and Conventional Facilities	2,000,426	1,797,242	203,184
.1	Technical Components	1,424,161	1,237,100	187,061
.1.1.4	HEB	107,271	91,831	15,440
.1.1.4.1	HEB Magnets	54,244	48,809	5,435
.1.1.4.2	HEB Cryogenics	13,561	3,556	10,005
.1.2.1	Magnet System	1,001,252	919,362	81,890
.1.2.1.1	Tooling	56,031	55,826	205
.1.2.1.2	Dipole Magnets	746,120	701,344	44,776
.1.2.1.3	Quad Magnets	39,262	35,758	3,504
.1.2.1.4	Spools	78,108	50,753	27,355
.1.2.1.5	IR Magnets	39,168	36,818	2,350
.1.2.1.6	Installation	42,564	38,865	3,699
.1.2.2	Cryogenics	121,137	31,766	89,731
.1.2.2.1	Refrigeration	45,000	5,500	39,500
.1.2.2.2	Station Equipment	25,717	3,231	22,486
.1.2.2.3	LN Plants	8,710	3,915	4,795
.1.2.2.4	Distribution	18,264	10,131	8,133
.1.2.2.5	Amb. Gas Dist.	7,509	1,815	5,694
.1.2.2.6	Inst. & Control	9,750	4,800	4,950
.1.2.2.7	Mag. Testing Syst.	6,187	2,374	3,813
.2	Conventional Facilities	576,265	560,142	16,123
.2.1.4.3	Primary Elect. Dist.	38,521	30,521	8,000
.2.3.4.5	HEB Cryogenic Facility	873	250	623
.2.4.6	Cryogenic Facilities	13,756	6,256	7,500

and changes made where necessary. Table III lists at level 5 the WBS numbers for the technical systems where changes are needed and their magnitudes.

In addition there are savings in the cost of the conventional systems due mainly to reduction in the amount of electrical power, cooling water and floor space needed at each sector station. Estimates of these are also listed in Table I.

To the savings totaled in Table I should be added some allowance for system re-optimization. For example, the cost-optimized nitrogen temperature system may have a different number of sector stations or air separation plants or other savings that would show up only in a detailed re-costing. Savings of something like $10 M might be realized in this way. Therefore the total capital cost savings associated with collider operation at nitrogen temperature is here estimated at about $213 M out of the current total of $2,000 M for technical systems and conventional facilities.

It is argued above, however, that the additional costs associated with the beam line vacuum in the nitrogen temperature case are too great to ignore even in the artificial case being considered here. These costs are estimated to be $156 M. The net capital savings are thus found to be $57 M or about 3% of the total estimated cost of the collider technical and conventional facilities, too small an amount to be significant within the accuracy of the estimate. To first order, savings in EDI, contingency, and management costs will scale, so the conclusion is that the nitrogen temperature SSC would cost 3% less than the helium temperature SSC under the assumptions of this study.

Operating Cost Effect

The most obvious operating cost saving is in electric power. Table IV compares the 77 K concept under consideration here with the helium system described in the Conceptual Design Report (Table 5.3-5).

Table IV
Comparison of Electric Power Requirement
Power in MW

	4 K SSC		77 K SSC	
	Nom.	Inst.	Nom.	Inst.
11 Station plants	29.7	44.0	6.6	9.13
2 Air Separation Plants	6.6	13.0	1.0	1.75
Totals	36.3	57.0	7.6	10.88

Assuming that the helium plants operate for 6000 hours per year with the ring remaining at nitrogen temperature for the remainder, and that in the 77 K ring, the magnets remain at operating temperature all of the time, the power difference is 1.7×10^5 MWhrs/year. Adding 20% for failure mode operation, 10% for transmission and transformer losses, and allowing $50/MWhr, this represents a cost saving of $11.1 M per year. This is about one-third of the power cost projected for the collider operation and one fourth of the total projected steady-state power cost of $44 M/year[11].

An estimate of other operations cost savings can be made by considering the total projected staff and materials and services cost excluding physics support. This number is $103 M per year in the steady-state[12]. To attribute 10% of this to the cryogenic operations would be defensible in view of the estimate above that about 10% of the collider initial cost buys the helium cryogenics. Thus one is lead to a sum of $10.3 M per year staff and materials and services savings. This is probably an overestimate.

In addition to the more or less directly identifiable operating cost savings that have been mentioned above, there should be some allowance for the higher availability of the simpler cryogenic system. Let it be supposed that there would be a 5% greater output of useful collider time due to greater reliability, faster quench recovery, and more efficient cryogenic system manipulation. This can be somewhat arbitrarily translated into cost saving by taking 5% of the total collider operations cost less power and less the $10.3 removed above. This is $6.1 M per year.

The total operating cost savings in the steady-state therefore reaches the total of $27.5 M per year. In projecting the total cost savings over the life of the laboratory pre-operation cost savings must be included. These are projected to total $112.6 for the fiscal years 1991 through 1994[13]. Once again the right order of magnitude of the savings probably is 10%.

Conclusion

In the preceding paragraphs it has been argued that the capital cost savings associated with the use of a liquid nitrogen temperature superconductor in the SSC is about 11%. This represents the cost of the helium cryogenic system. In understanding this number, the most important thing to recognize is that in the cost estimate of the conceptual design, $815 M is estimated for magnets alone. Of this sum, $237 M is for the superconductor alone. This is such a large part of the overall cost of the collider that a new technology if it does not significantly reduce either the number or the cost of the magnets, can have only a relatively small impact on the cost of the facility as a whole. In the case that has been taken as an example above, the effect of the new superconducting materials was assumed to be in the higher operating temperature alone, and the cost savings under these conditions are not great in proportion.

If it is assumed instead that the new materials will allow the construction of dipoles and quadrupoles for the collider that operate at a higher field, say at 13 T rather than 6.5 T, then the possibility exists of reducing the size of the rings and the number of magnets both by a factor of two. This could produce large cost savings assuming that the cost of the magnets does not rise too rapidly with field. The choice of the operating field for the supercollider, however, is a complex one, and many technical and economic factors have a bearing. The magnet aperture that is needed, a principal factor in the magnet cost, is determined through accelerator physics optimizations by injector parameters, field quality, ring size, and the details of the way in which the beams are brought into collision. The field quality is in turn affected by the magnetization properties of the superconducting material and the mechanical properties of the winding under the magnetic forces. Factors of magnet manufacturability and reliability are of considerable importance as well[14]. Accelerator dipoles present a very difficult set of problem for the designer of superconducting magnets. It is noteworthy that niobium-tin materials, although successful in large solenoids, have not been applied in accelerator applications due partly to problems of fabrication and partly to the uncertainties associated with the use of a brittle material with the large cyclic magnetic forces in the mechanically unfavorable geometry of the transverse dipole.

Thus it becomes clear that the true impact of the newly discovered superconductors on the Supercollider can only be assessed when considerable detail about their properties becomes known, detail not only about physical properties, but also about engineering properties as well. The higher temperature operation does not make a qualitative difference in the design or in the cost of the SSC, and other possible advantages will have to be evaluated by detailed technical consideration. Further, because of the very large amount of information and experience that this kind of evaluation, optimization, estimation, and risk assessment requires, the SSC is not an attractive early application for this new technology.

This is not to say that the discovery of high temperature superconductivity has no application in high energy physics technology. The reverse is true. These new materials are a scientific discovery of the greatest importance and very exciting. The technologies that develop from this discovery will, in all likelihood, be very important in continued progress in high energy physics. Certainly it is to be hoped that this is so. Therefore it is appropriate for the SSC to encourage the development of these new materials in every way possible, and there will be areas of application of particular interest to high energy physics that will be slow to develop without encouragement. It would be to the general advantage for the SSC to support and to participate in development in these areas as particular needs are identified.

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[1]J. G. Bednorz and K. A. Muller, Z. Phys. **B64**, 189 (1986)

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M. K. Wu, J. R. Ashburn, C. J. Torng, P.H. Hor, R.L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang and C. W. Chu; Phys. Rev. Letters **Vol. 58**, 908 (1987)

P. H. Hor, L. Gao, R. L. Meng, Z. J. Huang,Y. Q Wang, K. Forster, J.Vassilios, C. W. Chu, M. K. Wu, J. R. Ashburn, and C. J. Torng; Phys. Rev. Letters **Vol. 58**, 911 (1987)

[2]At a meeting of the Physical Society in New York in the middle of March many new results were reported. It is clear that Tc considerably higher than 100 K , and possibly above room temperature, will soon be published. Jc at low field on the order of 10,000 A/sq-cm has been observed in some of the low-Tc materials, but there is less information on Jc at high field. At this early stage of development the samples are probably quite inhomogeneous, and the true critical current of the superconductor is not yet being measured. Magnetization measurements show that these new materials have extreme type II behavior.

[3]This information was presented in a U. C. Berkeley Physics Department Colloquium by Prof. C. W. Chu of the University of Houston on March 2, 1987. Also at the New York meeting a material with europium rather than yttrium was described that has Hc of 30 T at 77K.

[4]D. Bintinger, P. Limon, H. Jostlein and D Trbojevic, "Status of the SSC Photodesorbtion Experiment, SSC - 102 (December, 1986)

[5]Superconducting Supercollider Conceptual Design Report, SSC - SR - 2020 (March, 1986). See sections 4.6.2 and 5.1.3.

[6]D. Bintinger, Private Communication. This value is for hydrogen. Pumping speeds for CO are lower and the scattering cross-section greater, so CO may be as great a problem as hydrogen in the 77 K SSC.

[7]C. Benvenuti, "A New Pumping Approach for the Large Electron-Positron Collider (LEP)"; CERN - ISR - VA/82 - 12 (June, 1982)

[8]SSC Report, "Cost Comparisons for Magnet Dependent Systems", SSC-SR-1012, August, 1985, Appendix C.

[9]D. Bintinger, P. Limon, and M. McAshan, "Concept and Cost Estimate for a NEG-Pumped Beam Line", SSC - N - 326, April, 1987

[10]Ibid. Note 4, Attachment D

[11] Tom Elioff and Ron Yourd; "SSC Operations Projections"; SSC - N -191 (June 12,1986, revised 9/86). The power projections are in Table 6.

[12]Ibid. Tables 5 and 7

[13]Ibid. Table 3

[14]See discussions in the Conceptual Design Report, Ibid. Note 4