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SUPERCONDUCTING SYNCHROTRONS*

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Summary

Superconductivity has advanced considerably since the discovery of high-field, type-II superconductors in 1961. During the past two years, superconductivity has at last become a tool of high-energy physics. One may now consider the construction of a superconducting proton synchrotron.

Several laboratories in the United States and Europe are studying the feasibility of superconducting synchrotrons. A realistic look at such a synchrotron requires a study of the machine components and their interaction, and a study of the fundamental properties of such a machine. Economics will be the principal reason for ultimately building such a machine.

Since the magnet system is the primary difference between superconducting and conventional machines, it will be emphasized in the report. There will be a short discussion of magnet coil configurations, superconducting materials, and the use of iron as a magnetic shield and return path. The magnet system consists of a power supply, cryostat, and a refrigeration system. All components are discussed in some detail.

The use of superconducting synchrotron magnets permits one to consider a number of alternative solutions to RF, vacuum, and injection and extraction problems. Changes in the enclosure and other conventional facilities for a superconducting machine are discussed.

A rough cost estimate of superconducting synchrotrons is presented. The effect of field, beam intensity, and repetition rate on cost is discussed. In conclusion, this report shows that a superconducting synchrotron is both feasible and economical.

A Comparison Between Superconducting and Conventional Synchrotrons

In recent years a number of papers have been written about superconducting synchrotrons.[1-5] These papers have suggested that superconducting synchrotrons are both technically and economically feasible. Recent changes in superconducting technology have made these conclusions even more of a reality. A superconducting synchrotron is a strong-focusing, alternating-gradient synchrotron with a pulsed superconducting guide field. A superconducting storage ring is included in this class of accelerator as a special case.

In order to understand the characteristics of a superconducting synchrotron, one must make a comparison with a conventional machine. Table I summarizes the most important differences between conventional and superconducting machines.

Superconducting Synchrotron Magnets

General Comments

A separated-function machine seems preferable to a combined-function machine. Combined-function magnets are more difficult to construct than separate dipoles and quadrupoles. This paper assumes that the synchrotron magnet will consist of dipoles and quadrupoles with a round aperture. The round aperture is preferable because horizontal or vertical apertures cost the same in a superconducting dipole or quadrupole and round-aperture magnets are easier to construct than elliptical-aperture magnets.

A useful magnet aperture of 8 to 10 cm diam appears to be reasonable. The required dipole field uniformity over this region is about ±0.05%. In addition, the field intensities of all bending magnets in the synchrotron must be equal within ±0.1%. A quadrupole tolerance of ±0.1% appears to be needed.[6]

Superconducting Materials

There are many superconducting materials. Only four, however, have enjoyed any commercial success: niobium-zirconium (Nb-Zr), niobium-titanium (Nb-Ti), niobium-tin (Nb_3Sn), and vanadium-gallium (V_3Ga). The Nb-Zr and Nb-Ti are alloys--the Nb-Ti has superior current density and critical field over Nb-Zr. The V_3Ga and Nb_3Sn are β-tungsten compounds of which the Nb_3Sn is the superior material.

Both Nb-Ti and Nb_3Sn have been suggested for use in superconducting synchrotrons. Despite the high field capability of Nb_3Sn, Nb-Ti is the material that was assumed in this study for the following reasons: (1) Nb-Ti is cheaper.[7] (2) Nb-Ti is a ductile material capable of being drawn into fine strands. (3) Nb-Ti is capable of stable high-current-density operation. (4) High fields (> 60 kG) are not desirable from an economic standpoint.[5]

A material with low ac losses is required for use in a superconducting synchrotron. In 1967 Smith[1,8] predicted that a low-ac-loss material would have the following properties: (1) small strands of superconductor ($< 2.5 \times 10^{-3}$ cm); (2) transposition of the strands within a normal matrix; (3) a high-resistivity substrate (Smith has suggested an alloy of copper and nickel). Ac loss measurements taken at LRL and other places

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Table I. A Comparison of superconducting and conventional synchrotrons.

Superconducting synchrotron	Conventional Synchrotron
Synchrotron magnets	
Peak pole field: 40 to 55 kG.	Peak pole field: 12 to 18 kG.
Magnetic field is shaped primarily by the current carried in the coils.	Magnetic field is shaped primarily by the shape of the iron pole.
A round aperture is economically preferable (cost of horizontal and vertical aperture nearly the same).	An elliptical aperture is economically preferable (cost of vertical aperture much greater than the cost of horizontal aperture).
Magnet stored energy: 0.5 to 1.0 MJ/GeV.	Magnet stored energy: 0.1 to 0.3 MJ/GeV.
Synchrotron magnet power supply	
Magnet system Q is high (500 to 2500).	Magnet system Q is quite low (0 to 3; nearly zero for storage rings).
Magnet system Q remains unchanged with repetition rate.	Magnet system Q decreases as the repetition rate decreases.
Storage rings need only a modest power supply.	Large power supply required for storage rings.
Synchrotron magnet cooling system	
Magnets must be maintained at liquid-helium temperatures (4.2 to 4.5°K).	Magnets operate at room temperature.
Helium refrigerator removes heat due to superconductor ac loss, heating due to interaction with the beam, and heat leaking into the cryostat from the outside.	Joule heating in the coils must be removed by a water- or air-cooling system.
Synchrotron vacuum system	
Very high vacuums are easily produced by cryogenic pumping. Most of the machine bore is at liquid-helium temperature.	A separate high-vacuum pumping system is required (diffusion pumps, ion pumps, and separate cryogenic pumps for storage rings).
Synchrotron enclosure and utilities	
Machine radii of 0.9 to 1.5 m/GeV for high-energy machines.	Machine radii of 2.5 to 4.5 m/GeV for high-energy machines.
Machine power consumption 0.01 to 0.2 MW/GeV (lower value for storage rings).	Machine power consumption 0.1 to 0.4 MW/GeV (high-energy machines).

have confirmed Smith's prediction.[9,10,11] LRL is testing materials that have strand diameters of 2×10^{-3} cm and 3.2×10^{-3} cm. The material with the smaller strand diameter is in a cupro-nickel matrix. Both materials are transposed by twisting. One can expect improvements of the material now available. It is quite probable that material with strand sizes in the 10^{-3}-cm range will soon be available.

Electrical insulation within synchrotron magnets should have the following properties: (1) The insulation should withstand moderate voltages without shorting. (2) It should be resistant to breakage and abrasion due to changing magnetic forces. (3) It should have a high thermal conductivity. There may be several solutions which yield a desirable insulation which would include metallic oxide and possibly thin coatings of high-thermal-conductivity plastics.

The cost of today's high-current-density, stranded material is shown in Fig. 1. Large production orders and improved manufacturing techniques will reduce the cost of today's material by a factor of 2 or more (see Fig. 1). The current-density curve shown in Fig. 1 reflects the coil current densities now achievable at LRL. Projections of coil current densities that will be achievable with improved Nb-Ti materials are also shown in Fig. 1.

Superconducting Coil Configurations

Several coil configurations which produce dipole and quadrupole fields are shown in Fig. 2. and 3. Perfect dipole fields can be produced by intersecting-ellipse coils or by current-density variation of $\cos\theta$ around the origin.[12,13] Perfect quadrupole fields may be produced in the same way, except that the angular relations are changed. Since perfect coils are difficult to make, a near-perfect coil can be produced by stepping in layers or in current density. The angle or current density of the steps is varied to eliminate as many of the higher multipoles as possible.[14,15] The $2\pi/3$ dipole and the $\pi/3$ quadrupole represent a case that is common to both methods of uniform field production.

It should be noted that an error in conductor placement will effect the uniformity of the field. The ends of the magnet will have a strong effect on the integrated field through the magnet. It is likely that changes in coil shape will be required to compensate for end effects.

The center of a typical dipole or quadrupole magnet will be more uniform than the outer portions of the magnet. It is not likely that the useful aperture of a synchrotron magnet will exceed 80% of the inner coil dimensions, because of coil configuration inaccuracies.

Two types of dipoles are now under development at LRL Berkeley: a random-wound type and a placed-rectangular-conductor type. Both types of dipoles have coil configurations based on a modified intersecting-ellipse geometry.[16]

Iron Shielding and Return Path

Iron shielding for superconducting dipole and quadrupole beam transport magnets has been investigated by Meuser.[17] The use of iron shielding and return paths appear to be very desirable for synchrotron magnets. Iron shielding around superconducting synchrotron magnets will (1) reduce stray fields and shield the beams from other stray fields, (2) reduce the ampere-turn requirement, (3) reduce magnet-stored energy, and (4) reduce forces on the magnet support structure due to other magnets and nearby iron. The iron shielding and return path would be located outside of the helium cryostat (see Fig. 4 and 5). The iron would be laminated just as in a conventional synchrotron magnet. Saturation and remnant-field effects appear to be quite small because the inside dimensions of the shield are much larger than the useful aperture of the magnet. There is no limitation on the outer boundary shape of the iron as long as the induction in the iron is kept below saturation.

Magnet Parameters and Cost Calculations

Table II describes the basic parameters of a superconducting dipole and quadrupole that could be used in a synchrotron. The magnets described in Table II could be used in the machine shown in Fig. 8 of this report. Table II shows an estimate of the cost of superconducting dipoles and quadrupoles. The methods used to estimate the magnet cost are described in Refs. 18 and 19.

It should be noted that over half of the cost of the superconducting magnet is the superconductor itself. The cost of fabrication will vary depending on the method used to wind the coils. The magnet costs given in Table II do not include engineering, which would increase the cost of the magnet by as much as 30%.

Superconducting Synchrotron Power Supplies

Power-Supply Characteristics

The power-supply characteristics for a superconducting synchrotron are somewhat different from conventional synchrotrons. These differences are tied to the large magnet-stored energies and the low energy losses from the system. The possibility or running the machine at a constant field for extended periods means that low current ripple is important.

The magnet power supply is feeding a nearly pure inductance. Since superconducting magnets are subject to ac loss effects, there is decay in magnet-stored energy as the machine is pulsed. Unlike the conventional synchrotron, the magnet system Q (defined as the ratio of magnet-stored energy to loss per cycle) is constant with repetition rate. In other words, the magnet energy loss is constant per cycle. The stored energy of the magnet system is a factor of 3 or more higher than a conventional magnet system with the same useful aperture. As a result the power supply's primary function is to transfer energy from an energy-storage device to the synchrotron magnets and back again.

Superconducting magnets are well suited for dc operation. Their large inductances and low resistance make the magnet ideally suited for long flat-top operation. Therefore it is quite likely that the power supply will be called upon to supply constant current over long periods of time.

Two Basic Types of Power Supplies

Two basic types of power have been studied for use in superconducting synchrotrons; the conventional motor generator (MG) set and superconducting energy storage supply suggested by Smith in 1967.[20]

The MG set power supply stores the magnet energy in large rotating flywheels. The flywheel stores 10 to 20 times the energy that is transferred in and out of the synchrotron magnets. Energy storage in a flywheel is very cheap (~\$300/MJ).[22] The primary cost of the MG-set power supply is not energy storage but energy conversion. All of the energy passing from the magnet to the flywheel and back must pass through the generator rotor winding and the rectification circuits.[21] The rectification circuits are the most expensive part of today's MG sets. The size of the motor, generator, and rectifier bank all decrease as the cycle time increases. Therefore the cost of an MG-set power supply decreases markedly with cycle time.

Motor-generator sets can be built more reliably than those currently in service. The MG-set power supply systems can be made with a low enough ripple (particularly when they energize a superconducting magnet system) to permit long spills. The two-second-long spill on the Bevatron is evidence of that.[21]

The superconducting energy-storage power supply described by Smith is quite different from an MG set. The energy-storage system becomes the dominant element of the power-supply cost. The rotating power supply described by Smith is basically a 2-phase generator. The field winding

Table II. Synchrotron magnet parameters.

Basic magnet parameters	50-kG dipole	595-kG/m quadrupole
Pole field (kG)	50.0	37.2
Maximum field in the winding (kG)	60.0	44.7
Magnet length (m)	5.5	2.0
Useful half aperture (cm)	5.0	5.0
Inner coil radius (cm)	6.25	6.25

Material-dependent parameters and estimated magnet cost	50-kG dipole		595-kG/m quadrupole	
Material	Present Nb-Ti	Future Nb-Ti	Present Nb-Ti	Future Nb-Ti
Peak coil current density (A/cm^2) See Fig. 1.	1.8×10^4	3.3×10^4	2.5×10^4	4×10^4
Shielding	Iron	Iron	Iron	Iron
Ampere turns required	9.7×10^5	8.2×10^5	9.5×10^5	8.1×10^5
Stored energy (J)	1.6×10^6	1.3×10^6	1.7×10^5	1.4×10^5
Mass of iron shielding (kG)	1.2×10^4	9.4×10^3	4.6×10^3	3.4×10^3
Ampere-meter of superconductor required	1.1×10^7	9.4×10^6	4.0×10^6	3.4×10^6
Superconductor cost factor (\$/ampere-meter) See Fig. 1.	5.8×10^{-3}	2.8×10^{-3}	4.4×10^{-3}	2.4×10^{-3}
Total magnet cost (\$)	8.6×10^4	4.6×10^4	2.6×10^4	1.4×10^4
Cost of magnet/m (\$/m)	1.6×10^4	8.4×10^3	1.3×10^4	7×10^3

(see L_1 in Fig. 6) must have a minimum of four times the stored energy of the magnet system. For most practical cases the stored energy within the field winding is probably 6 to 10 times the magnet-stored energy.

The energy transfer is accomplished by rotating two solenoids whose axes are perpendicular (a 2-phase generator armature, see L_2 and L_3 in Fig. 6) within the field generated by L_1. The field winding power supply L_1 is very cheap if L_1 is a large superconducting magnet. The makeup power to overcome ac losses can be fed in through the interconnection from L_3 to L_4. The power supply in effect moves the energy from L_4 to the synchrotron magnets and back during a magnet pulse.

One of the advantages of the superconducting energy-storage power supply is the low amount of energy lost from the system. The motor on an MG-set power supply must make up for losses in the generator winding and rectifier circuits as well as in the superconducting synchrotron magnets. Since the energy storage elements L_1, L_2, L_3, and L_4 dominate the cost of the superconducting energy-storage power supply, the cost of the power supply changes very little with cycle time.

Power-Supply Parameters and Problems

The type of power supply most attractive for use in a superconducting synchrotron will be dependent on the magnet-system stored energy and the machine cycle time. Both lower stored energy and long cycle times favor the MG set economically. It seems probable that superconducting synchrotrons will be long-cycle-time devices; hence an MG-set-type power supply is used for cost estimates in this paper.

One must consider a number of problems when discussing the power supply of a superconducting synchrotron. One problem is the coupling of more than one superconducting magnet together with superconducting leads. It is undesirable to have high-current leads passing from a room temperature environment to a cryogenic environment at every magnet. Therefore, it appears to be desirable to pass current from one magnet to the next with superconducting leads, yet one does not want the energy from adjacent magnets pouring into a quenching magnet. Other problems include determining the voltage and current suitable for superconducting synchrotron magnets.

Synchrotron-Magnet Cryostats and Refrigeration System

The Magnet Cryostat

The superconducting synchrotron magnets must be maintained at liquid-helium temperatures. The magnet cryostat must rigidly support the superconducting magnet and minimize the flow of heat from the room temperature to the 4°K environment. Rigid support and firm alignment can be obtained using a tension-rod support system. Such a system supports the inner cryostat vessel and its magnet to an outer cryostat vessel by means of support system similar to a bicycle wheel. Such a cryostat has been built and used with a superconducting magnet in a proton beam.[22,23]

Insulation between a liquid-helium environment and room temperature is provided by many sheets of reflective material in a vacuum environment (superinsulation). The rate of heat leak through such an insulation system can be as low as 10 $\mu W/cm^2$. Heat leak can be reduced further by using helium-gas or nitrogen-cooled shields. The magnet cryostat can be rough-pumped with the machine rough-pumping system. High vacuums are maintained in the superinsulation by cryogenic pumping on the liquid-helium temperature inner cryostat wall. The outer cryostat boundary would coincide with the inner boundary of the iron shielding for the magnets (see Fig. 4 and 5). It is estimated that the magnet cryostat cost would average 3 to 4 thousand $/m.[18]

Heat Loads on the Superconducting Synchrotron Refrigeration System

There are three sources for heat deposition in the liquid-helium environment: (1) heat leaks from room temperature; (2) heating due to interaction with the beam; and (3) various kinds of ac losses in the superconducting magnet and the surrounding structure.

Heat entering the cryostat from room temperature will average 2 to 2.5 W/m of magnet length. Roughly half of this heat leak is through the tension-rod support system. It does not appear to be economically wise to reduce the heat leak below the level mentioned above. The helium transport lines are assumed to be high-heat-loss, minimum-cost line. The transfer-line loss is small compared to the rest of the refrigeration required; hence the inexpensive line makes a great deal of economic sense.

Heating due to interaction with the circulating beam could be the most serious cooling problem. The amount of heat deposited is dependent on a number of factors, such as injection and extraction efficiency, beam energy and intensity, and the percentage of beam energy deposited in the 4.2°K region. Several steps can be employed to minimize beam heating in the magnets: (1) eliminate internal targeting, (2) make long straight sections with a phase advance of π or more, with all injection and extraction functions being carried out in these long straight sections, and (3) make injection and extraction processes as efficient as possible. In order to calculate an rms refrigeration load, it was assumed that about 2% of the beam circulating energy is deposited in the 4.2°K region.

The ac loss terms include a hysteresis-type loss in the superconductor and eddy-current-type losses in the superconductor, coil-winding form, magnet structural elements, and the cryostat. I used an equation for ac loss that is based on LRL-measured data. The equation is very similar to the Smith ac-loss equation which states that superconductor ac loss per ampere-meter is directly proportional to magnetic field, frequency, and small-strand diameter. Measurements of ac loss in small-stranded, twisted conductor wound in a solenoid magnet have verified that the above relations are essentially correct.[11]

Eddy-current losses may be due to (1) true eddy currents in the various elements located within the changing field, or (2) high-resistance turn-to-turn shorts. If the magnet winding has a poor insulation system, the latter can be a very serious problem.

The Refrigeration System

The refrigeration system for a superconducting synchrotron is assumed to be several large refrigerators supplying a central receiving transfer line. The use of a large central refrigerator is justified economically[24] because (1) the loads are relatively concentrated, (2) the load in the accelerator system greatly exceeds the transfer-line losses, and (3) the system components are in a fixed location. The refrigeration system is assumed to consist of a small number of large refrigeration units. Each refrigeration unit feeds into a central cold-gas receiving tank and transfer line. Each magnet has its own J-T valve and J-T heat exchanger and draws on the central cold-gas receiving tank for its supply of cold gas (see Fig. 7).

Each large central unit consists of a cold box with its expansion engine system and a compressor station where gas storage and purification take place. The expansion system will reduce the gas temperature from room temperature to about 12 to 15°K. The gas will then be sent to the cold-gas receiving tank.

The cold-gas receiving tank interconnects the large units permitting redundancy, which improves the system reliability. The cold-gas receiving tank acts as a large reservoir of cold gas for use during quick cooldown of a single magnet in the event of a quench. Each magnet would have its own liquid-level control system which controls the magnet's J-T valve. The refrigeration system cost is based on the 1966 Strobridge, Chelton, and Mann estimate of liquid-helium refrigerator cost.[25] It should be noted that the actual cost of large helium refrigerators has been tending somewhat lower than the Strobridge, Chelton, and Mann estimates.[26]

Vacuum System, Injection-Extraction System, RF System, and Other Technical Components

The Vacuum System

There are two fundamental differences between the vacuum system of a conventional synchrotron and a superconducting synchrotron. The superconducting synchrotron magnet cryostats form an integral part of the machine vacuum system. The only places where additional vacuum pipe for the beam is required is in the straight sections of the machine. The second and most important difference is that no high vacuum pumping system is required. Very high vacuums are produced by cryopumping on the 4.2°K surfaces. Very high pumping speeds can be obtained for the air gases without a gettering agent on the walls. Pumping speeds in excess of 2 ℓ/s/cm^2 are obtainable for hydrogen and helium on activated-charcoal or molecular-sieve covered 4°K surfaces.[6] Vacuums of 10^{-9} and 10^{-10} Torr can be obtained by providing the superconducting magnets with a cold bore. Vacuum piping is only needed in those areas that are between the magnets and for the roughing system.

Injection, Extraction, and RF System

The injection and extraction systems would consist of a mixture of superconducting and conventional elements. Beam-transport dipoles and quadrupoles, and septum magnets would probably be superconducting. Kickers and other fast-pulsing elements probably will be of a conventional nature. Septum magnets and beam-transport magnets which are subject to heating due to interaction with the beam can be cooled by using supercritical helium. Thin septa (1 to 1.5 mm) can have bending fields of 15 to 18 kG if they are made superconducting.[27]

The RF system for a superconducting synchrotron probably will have conventional RF cavities, particularly if the injection energy is low. Superconducting RF cavities can be considered. The length of the accelerating structure will be reduced, because accelerating voltages will be a factor of 5 or more lower than for the same-energy conventional synchrotron. There are two reasons for this: (1) the ring diameter is smaller (the beam passes through the cavities more often); (2) superconducting machines are likely to be long-cycle-time machines.

It is probable that the machine control system would be more sophisticated than that of today's machine. There are more components to control, and there is a greater need to monitor and control the position of the beam. The computer will play an important role in controlling the circulating beam.

The Synchrotron, Enclosure and Conventional Facilities

Tunnel, Foundation, and Shielding

The tunnel can be made smaller than many of today's machines because of the reduced physical size of the bending magnets and quadrupoles. A tunnel the size of the 200-GeV machine at Batavia may be very reasonable.[28] It should be noted, however, that a greater portion of the tunnel length will contain penetrations than in a conventional machine of the same energy. The foundation required is highly site-dependent. Shielding requirements will be nearly the same as for a conventional machine of the same energy. The length of tunnel, shielding, earthwork, and foundation scale down with the ring radius. The average unit cost for tunnel, penetrations, shielding, earthwork, and foundation will vary from \$3500/m to \$10 000/m depending on the site and enclosure parameters.[29]

Electric Power and Cooling Water

One reason for considering superconducting accelerators is the expected reduction in electric power. Electric power usage can be divided into the following categories:

1. Electric power for the magnet power supply: An MG-set power supply will require power for makeup of losses in the motor, generator, and rectification system. Electric power requirements will be approximately 6% of the rms power rating of the MG set.[22] The superconducting energy-storage power supply will require makeup power for the magnet-system losses and the power-supply refrigeration system.
2. Power will be required for the refrigerator compressors and the refrigerator control system. Expected power consumption for the refrigerator will be 250 to 450 W/W of refrigeration at 4.2°K. Large refrigerators of the future can be expected to have efficiency in excess of 25%.
3. Power will be required by the RF systems to run the RF stations. This power will be 4 to 5 times the RF beam power.
4. Power will be required for kicker, control, and other conventional magnets.
5. Power will be required for light, ventilation, air conditioning, and pumping cooling water.

In general, one can expect the power consumption of a superconducting synchrotron to be a factor of 2 or more lower than the conventional machine of the same energy. The superconducting storage-ring power requirement will be a factor of 5 or more lower than a conventional machine of the same energy. Cooling-water requirements will be reduced drastically for the superconducting synchrotron. Cooling water will be required for (1) MG-set power-supply rectifier cooling, (2) cooling of the compressed helium gas for the refrigerators, (3) cooling of RF cavities and power tubes, and (4) cooling of conventional magnets and other miscellaneous components. The cost of a water-cooling system will be highly dependent on a number of factors, not the least of which is the site.

1000-GeV Synchrotron Cost Estimate and Other Remarks

Effect of Machine Parameters on Cost

In order to understand the effect of machine parameters on machine cost, it is necessary to estimate the cost of the whole system. After looking at the whole system it becomes clear that some of the machine parameters must be determined by economics rather than by fiat.[5] The primary machine parameters that would normally be set by fiat are machine final energy and average beam intensity. Injection energy would normally be determined by economic considerations. Injection energy, final energy, and average beam intensity are considered the fixed parameters for the purposes of this report.

One should not arbitrarily decide on the machine magnetic field, repetition rate, and aperture by fiat. A number of interesting things can be seen from a look at the whole-system cost. The above-mentioned parameters have a strong effect on machine cost; therefore, it is possible to minimize machine cost by varying these parameters.

There is a machine guide field where machine costs will be a minimum. The field level which results in a minimum cost machine is dependent on aperture and repetition rate. Optimum field values for superconducting synchrotrons are: (1) fast-cycling synchrotrons, 1 to 5 s cycle times, 25 to 35 kG depending on aperture; (2) slow-cycling synchrotrons (5 to 30 s cycle times)

35 to 50 kG, and (3) superconducting storage rings 40 to 55 kG. The higher optimum field level results from slow cycling rates and smaller apertures.[5] It appears that there is no economic gain in using Nb_3Sn material instead of Nb-Ti materials. A breakthrough in Nb_3Sn technology may change this conclusion.

The determination of an optimum repetition rate and aperture go together. The aperture is determined by lattice parameters, beam intensity, and injection emittance. However, if one desires to maintain a constant average machine intensity, one must increase the machine aperture as one increases the machine cycle time. Long cycle times appear to be desirable from an economic standpoint, despite larger aperture requirements. Long cycle times should not have a detrimental effect on many of the physics experiments now envisioned. Development of long-spill techniques is important if long cycle times are to be properly utilized.

Parameters of a 1000-GeV Machine

A 1000-GeV machine is used as an example. The machine lattice is similar to the NAL 200-GeV machine.[28] The synchrotron parameters and coil structure are shown in Table III and Fig. 8.[30] A 1000-GeV machine on a new site was chosen because of the simplicity of its cost analysis. It should be noted that a lower-energy superconducting machine (100 GeV) would be attractive at some of the existing laboratories because of the reduced space requirements for such a machine.

The machine whose cell is shown in Fig. 8 consists of 6 superperiods of 19 cells each; 3 of the 19 cells contain no bending magnets. The 3 empty cells are adjacent and have a phase advance of 0.6 betatron wavelengths. It is assumed that all injection and extraction would occur in these straight sections. Although one may not actually build a machine with this type of straight section, the ratio of straight section to bending-magnet length is probably close to that required in an actual superconducting synchrotron.

The 6.4-m straight section between the focusing quadrupole and the first dipole would be used for beam-correction elements. It should be noted that these correction elements may be conventional magnets. As a result, the space allotted for these elements does not scale downward as the dipole field rises.

The lattice chosen is not the most economical. An increase in the betatron oscillation number is desirable because the machine aperture can be reduced. In order to make the beam round, thus using the cylindrical aperture more fully, the radial oscillation number should be larger than the vertical oscillation number.

Cost Estimate and Concluding Remarks

The cost estimate shown in Table IV includes the magnet system, RF system, vacuum system, injection-extraction system, and conventional facilities. The four most costly subsystems are the magnets, the magnet power supply, the RF system, and the conventional facilities.

In conclusion the following statements can be made. (1) The superconducting synchrotron appears to be technically feasible. (2) The cost

Table III. Parameters of 1000-GeV machines

Machine parameters	Synchrotron (using present Nb-Ti materials)	Synchrotron (using future Nb-Ti materials)	Single storage ring (using future Nb-Ti material)
Final energy (GeV)	1000	1000	1000
Injection energy (GeV)	25	1000	25
Intensity (p/s)	10^{13}	10^{13}	----
Machine radius (m)	1197.5	1197.5	1197.5
Machine magnetic radius (m)	667.8	667.8	667.8
Cycle time (s)	15	15	----
Flat-top time (s)	5	5	----
Magnet useful aperture (cm)	5	5	5
Betatron oscillation number	22-1/4	22-1/4	22-1/4
Number of superperiods	6	6	6
Number of cells	114	114	114
Cell length (m)	66.0	66.0	66.0
Number of dipoles	768	768	768
Number of quadrupoles	228	228	228
Dipole field strength (kG)	50.0	50.0	50.0
Quadrupole gradient (kG/m)	595	595	595
Machine stored energy (MJ)	1280	1030	1030
Power supply rating (MW)	500	410	----
Ac losses (W)	130 000	58 000	----
Refrigeration required (W)	180 000	80 000	25 000
Harmonic number	1260	1260	1260
Injection RF frequency (MHz)	50.37	50.37	50.42
Final RF frequency (MHz)	50.42	50.42	50.42
Beam power (W)	4.78×10^6	4.78×10^6	----
Accelerating voltage (V)	9.78×10^6	9.78×10^6	----
Tunnel length (m)	7524	7524	7524

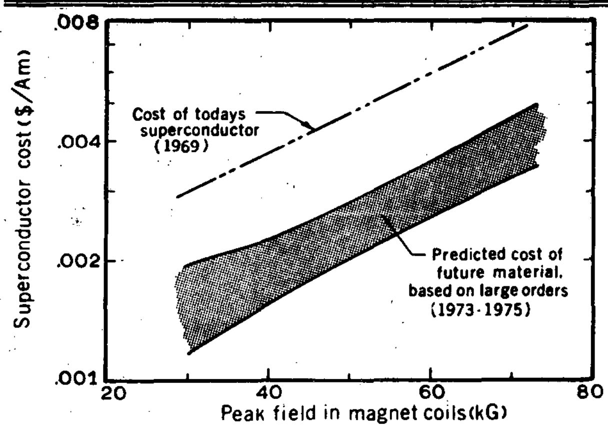
of a high-energy superconducting machine will be lower than for a conventional machine of the same energy. (3) Slow-cycling superconducting synchrotrons appear to be more economical than fast-cycling machines. (4) The optimum dipole magnetic field is under 50 kG for most cases. Changes in technology may alter some of the above conclusions, which are based on today's technology.

The development of low-ac-loss superconductors is important because these conductors are capable of high-current-density operation and will carry current up to the conductor critical current. Equally important is the continuing development of cryogenic systems. Large helium refrigeration systems are now becoming a reality.

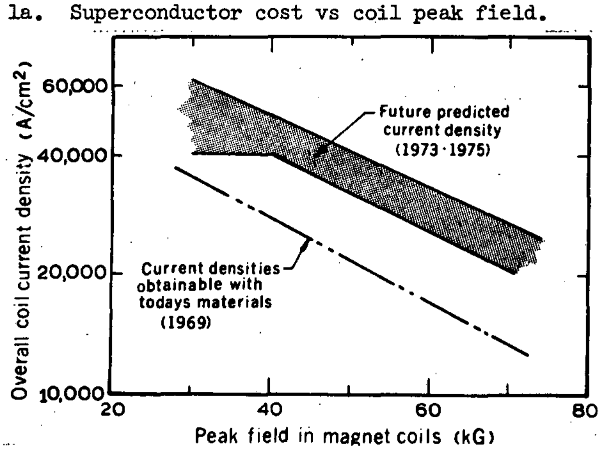
Superconductivity will be necessary for the continued development of high energy physics. The next generation of large accelerators will have superconductivity as an integral part of their makeup. Superconductivity is playing an important role in plasma physics, and is the key to MHD power generation.

Table IV. Estimated cost of 1000-GeV superconducting synchrotrons.

	Synchrotron (based on today's costs	Synchrotron (based on future cost prediction)	Single storage ring (based on future cost predictions)
Machine component costs (M$)			
Magnets	76	42	42
Magnet power supply	42	24	1
Magnet cryostat	15	12	12
Helium refrigerator	21	12	9
RF system	29	29	1
Injection extraction system	5	5	8
Vacuum system	4	4	4
Control system	7	7	7
Enclosure and plant facilities	44	37	37
Total cost (M$)			
Without EDIA and contingency	243	173	121



1a. Superconductor cost vs coil peak field.



1b. Coil current density vs coil peak field.

Fig. 1. The cost and coil current density of fine stranded Nb-Ti superconductor.

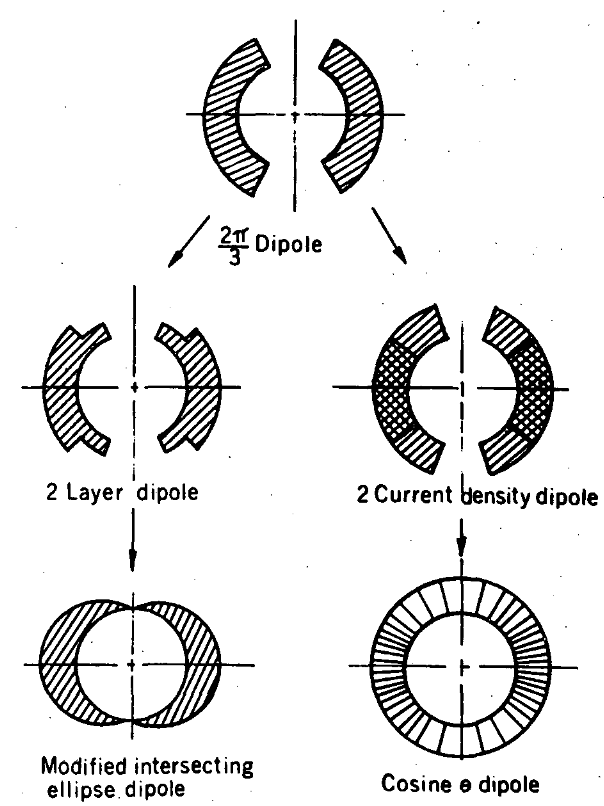


Fig. 2. Superconducting dipole coil configurations.

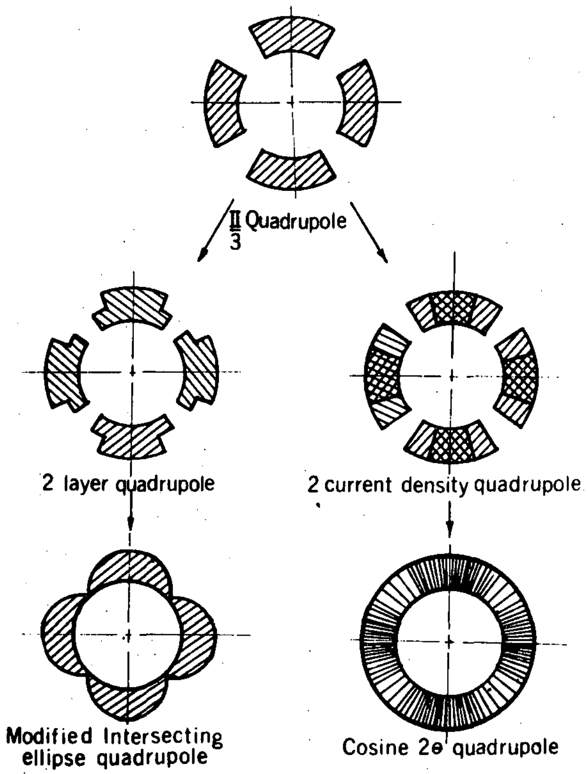


Fig. 3. Superconducting quadrupole coil configurations.

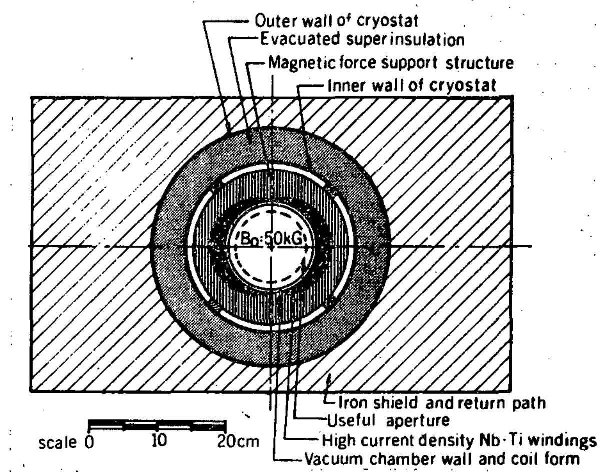


Fig. 4. A cross section of a superconducting synchrotron 50 kG dipole.

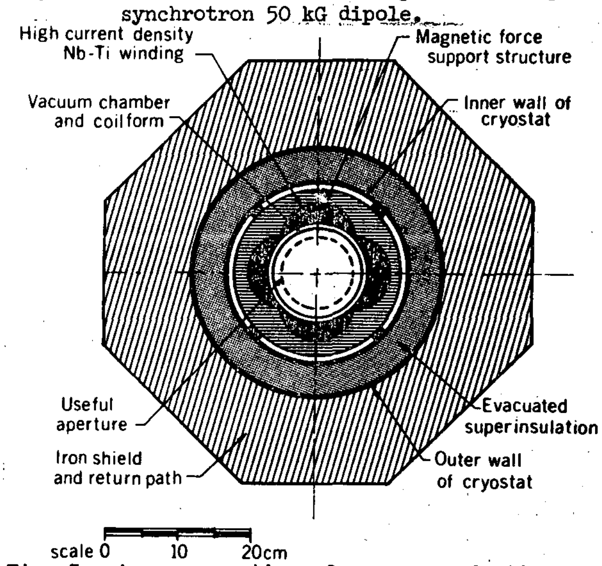


Fig. 5. A cross section of a superconducting synchrotron 595 kG/m quadrupole.

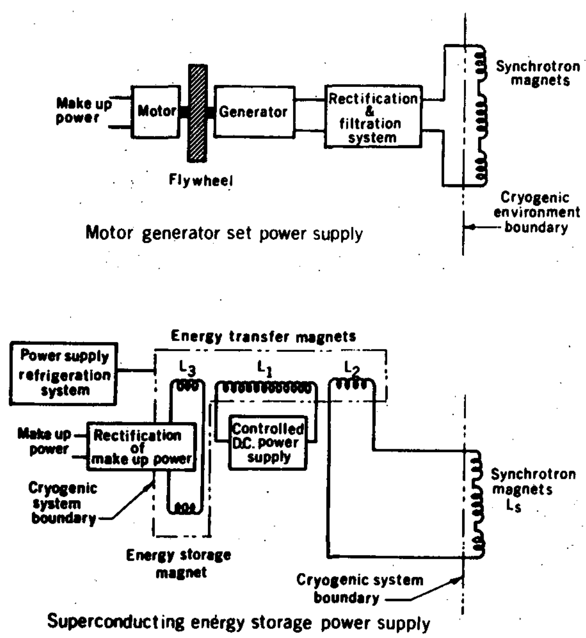


Fig. 6. Two types of superconducting synchrotron power supplies.

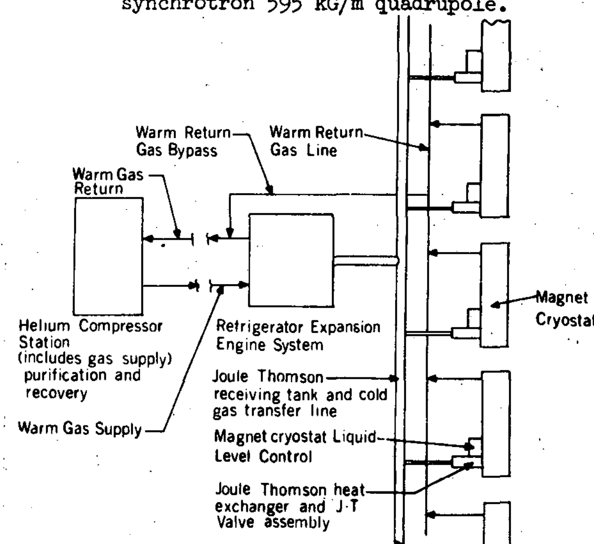


Fig. 7. A superconducting synchrotron refrigeration system.

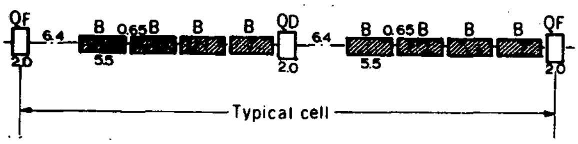


Fig. 8. A typical cell for a 1000-GeV superconducting synchrotron.

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