A 2000 GEV SUPERCONDUCTING SYNCHROTRON*

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INTRODUCTION

There are so many unknowns involved in estimating the cost of a superconducting synchrotron that it is largely an academic exercize at the present time. The feasibility of such a machine is strongly dependent on the magnitude of the ac losses produced by the changing guide field, since such losses must be removed at very low temperatures, a notoriously inefficient process. There is relatively little known about how small these ac losses could be made in a practical accelerator magnet, although the subject is being studied extensively. Even if the losses are reduced to a suitable level, the reliability of both the magnets and associated cryogenic equipment has yet to be demonstrated. Despite these deficiencies in knowledge it is possible to make crude estimates of the cost of a 2000 GeV machine based on present experience and reasonable expectations for the future.

MACHINE PARAMETERS

The machine under discussion is assumed to have the following parameters:

Energy	2000 GeV
Injection energy	30 GeV (AGS)
Radius	1.5 km
Aperture	30 cm^2
Peak field	60 kG

The energy was chosen as a suitable next step after the 200 to 400 GeV machine being built at Weston. The injector is assumed to be the AGS, which might conceivably be available for such duties by the time the large machine was built. The radius and field were chosen so that the machine would fit on the present Brookhaven site and the assumption was made that 80% of the ring would be filled with bending magnets. Since the cost of both the magnets and power supply are strongly increasing functions of the aperture size, a circular aperture of approximately 3 cm radius has been chosen as the smallest reasonable size. It is possible that a saving could be made by using an intermediate ring between the injector and final ring so that the aperture could be reduced further in the main ring magnets by injecting at approximately 150 GeV.

MAGNET DESIGN

It is assumed that the accelerator would be of the separated function type consisting of dipoles and quadrupoles arranged in a suitable array.[1]

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1. G.T. Danby et al., IEEE Trans. Nucl. Sci. NS-14, No. 3, 431 (1967).

The magnets would resemble to a considerable degree the high current density dc beam handling magnets being developed at Brookhaven,[2] but would be made with the low loss type of conductor which will be described in the next section. For ease of construction a circular aperture has been chosen, but an elliptical aperture could be used if orbit dynamics require more horizontal than vertical aperture. The required field configuration is obtained by arranging ribbons of conductor around the perimeter of the aperture to form a number of discrete current blocks according to the methods developed by Beth.[3] Shielding of the stray magnetic field is achieved by the use of a laminated iron shield which could also serve as the vacuum jacket of the Dewar. Alternatively, a set of similar windings of lower current density at a larger radius could be used to cancel the external field. The use of iron shielding, sufficiently far from the magnet to prevent saturation, leads to an increase of about 10 kG in the dipole field,[4] while the superconducting shield would lead to a similar reduction in field.

For a dipole field of 60 kG (50 kG without iron), a current of about 8×10^4 A/cm of circumference is required in the high density portion of the windings. This corresponds to a current density of approximately 6×10^4 A/cm^2 for a conductor width of 0.5 in. The quadrupoles would produce a gradient of about 20 kG/cm for the same current density. Figure 1 is a schematic diagram of the magnet cross section.

AC CONDUCTOR

While the losses produced in pulsed magnets using presently available material are rather high,[5,6] it seems possible to reduce such losses by a suitable subdivision of the superconductor.[7] A conductor configuration expected to produce low power dissipation and high current density under pulsed conditions is shown in Fig. 2. This conductor is formed by weaving alternate strands of fine stainless-steel and niobium-tin filaments to form a flat strap. The superconducting filaments are electrically separated by the stainless steel and a ceramic insulator such as boron nitride, and are transposed by the weaving process. The use of such a conductor is expected to lead to a reduction in losses of approximately an order of magnitude over presently available materials. Similar conductors could be made from insulated filaments of NbTi alloy, but they would probably be capable of somewhat lower current densities and would not be as desirable if the magnets were to operate at elevated temperatures in supercritical helium.

COMPONENTS

Magnets. The main ring which consists of 80% dipoles will require about 7.5×10^6 m of superconducting ribbon capable of carrying about 1000 A.

About 2×10^6 m of superconductor would be required for quadrupoles.

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2. R.B. Britton, these Proceedings, p. 893.
3. R.A. Beth, Brookhaven National Laboratory, Accelerator Dept. Report AADD-135 (1967).
4. J.P. Blewett, these Proceedings, p. 1042.
5. W.B. Sampson, ibid., p. 908.
6. G.H. Morgan and P.F. Dahl, ibid., p. 559.
7. P.F. Smith, ibid., p. 913.

Power Supply. The stored energy of the synchrotron is equal to about 100 kJ/m which represents a total stored energy in the ring of some 750 MJ. Since the power supply must be capable of supplying this much energy in a time equal to the rise time, or approximately one half of the cycle time, the power supply must have a rating of:

$$\text{Power supply} = \frac{750 \times 10^6}{t/2} = 300 \text{ MVA for } t = 5 \text{ sec.}$$

It should be noted here that a superconducting synchrotron is especially suited to low repetition rate operation since the energy loss per cycle is independent of frequency (Refs. 5, 6). It is also possible in principle to have very long flat-tops since little or no energy is required to maintain peak field.

It is possible that the cost of the power supply could be reduced by using superconducting technology[8] especially in view of the fact that the additional refrigeration will be relatively inexpensive due to the large installation required for the synchrotron magnets themselves.

REFRIGERATOR

The size of the refrigerator required is determined almost entirely by the ac losses in the magnets since other sources of heat production such as lead loss and beam radiation can probably be made comparatively low by careful design. It is convenient to express the losses produced in the magnets by an effective "Q" defined here as the energy loss per cycle divided into the total stored energy. The losses are then given by

$$\text{ac loss} = \frac{750}{Q} \text{ MJ/cycle} \quad .$$

The "Q" of presently available superconducting coils is approximately 200, and if we assume a factor of ten improvement using special conductor, this should give a "Q" close to 2000. The loss then is 375 kJ per pulse which for a repetition rate of once in 5 sec equals 150 kW of refrigeration.

Assuming the most optimum refrigerator efficiency of 30% Carnot,[8] this machine would require 40 MVA for operation.

CONCLUSIONS

The feasibility of such a machine depends on the possibility of producing a conductor capable of being wound into magnets of very high "Q". If, in addition, such material could be produced at a price lower than $5/m, important savings would be possible.

A point of considerable importance concerning pulsed superconducting magnets is that the loss/cycle is independent of repetition rate. Thus a very high energy machine designed for slow cycling could be used at lower energies with a reasonable cycling time and at very high energies with a few pulses/minute. When it became apparent what sort of physics would be done at very high energies and when the required experimental equipment was more fully developed, the power supply and refrigerator of the machine could be upgraded to improve the repetition rate. The superconducting machine is ideally suited for this type of operation since its power requirements vary linearly with repetition rate.

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8. S.C. Collins, these Proceedings, p. 59.

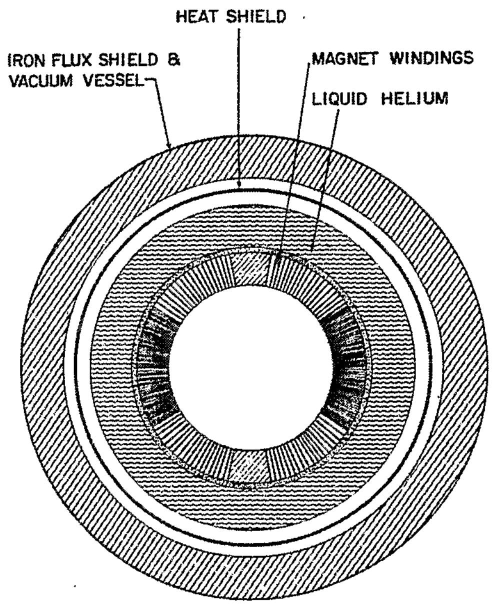

Fig. 1. Schematic drawing of cross section of superconducting accelerator.

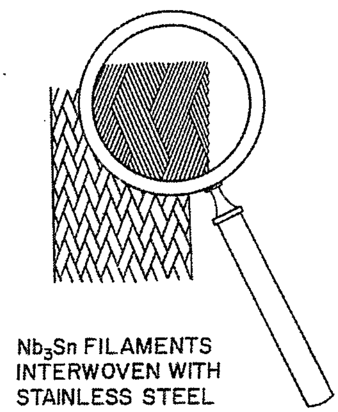

Fig. 2. Low loss ac superconductor.