SUPERCONDUCTING RING ACCELERATORS

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Abstract

An attempt is made to survey the status and prospects of ring accelerators employing superconducting magnets.

Introduction

During the previous International Accelerator Conference there was extensive discussion about superconducting magnets and their application to accelerators. In the intervening two years additional calculations have been made, better superconductors have become commercially available,and, much work has been done in the laboratories. Much of the basic superconductor investigation is done with solenoids. Although the specialists were confident of their long extrapolation from solenoids to accelerators it is now more comfortable to extrapolate from a few dipole models.

Some important points seem clear. Losses in a pulsed superconductor have been brought under control by use of twisted multifilament material, and the measured losses are tolerable in a large ring. The multifilament conductors improve stability against "going normal" and greatly reduce the diamagnetic currents which disturb the field shape - consequently there are no great differences between pulsed and dc magnets of accelerator quality. If the superconducting ring is to be economically feasible the aperture must be small and the current density high.

A number of preliminary designs of cryogenic ring accelerators have been made. One of the first studies in some depth was the Brookhaven CMS (Cold Magnet Synchrotron). The CMS would have energy of order 100 GeV and use the AGS as injector. A detailed study at Rutherford Laboratory considers a rebuilt multi-GeV injector and a pulsed ring extendable to 80 or 90 GeV. The General European Superconducting Synchrotron Study group (GESSS) is examining the addition of a superconducting ring, energy in the range 1000 GeV, to the first 200 GeV stage of the CERN II project. At Brookhaven studies are being made on intersecting storage rings to be filled by the AGS and then slowly pulsed to perhaps 200 GeV. Thus present thinking converges on use of superconductors to extend existing facilities, and use of existing high energy machines as injectors. There have been preliminary examinations of dc storage rings, and serious studies can be expected soon.

Superconductors

Wire for accelerators is made in the form of hundreds or thousands of fine superconductor filaments embedded in a metal matrix. Typically the wire is tenths of a mm in diameter and the filaments for pulsed components are 5-10 μm in diameter. The filaments for dc components will probably be less than 20 μm to ensure stability and to minimise diamagnetic currents. The composite wires are further combined in transposed cables or braids such that the coil conductor contains tens of thousands of filaments and carries maximum current in the range 2-6 kA.

Design of the accelerator is affected in every respect by the characteristics of the superconducting material. The characteristics usually cited are the critical temperature, T_c, and the upper critical field at 4.2^{0}K, H_{c2} . Approximate values for presently considered materials follow (values can vary rather widely with processing) :

	T_c	H_{c2}
NbTi	9^{0}K	> 12T
Nb_3Sn	18^{0}K	> 24T
V_3Ga	15^{0}K	> 20T

However, these are defined for negligible transport current. If the characteristic surface is projected onto the critical current - temperature plane there results a family of roughly straight lines for various applied field strengths.

Niobium-titanium is the only material in volume production in multifilament form and so is the material that must be considered for practical accelerators. Working at 4T its critical current decreases per ^{0}K by 30% of its 4.2^{0}K value, and is zero at 7½^{0}K. Thus if NbTi is at 4T and 90% of its critical current a rise of 1/3^{0}K will send it normal. At 6T the corresponding decrease is 40% per ^{0}K and the current is nil at 6½^{0}K. Thus, use of NbTi, at present necessary, puts severe limitations on current density, maximum field strength, stored energy and cryogenic system temperature.

For Nb_3Sn at 6T the critical current decreases per ^{0}K by 13% of its 4.2^{0}K value, and is zero at about 12^{0}K. Unfortunately, Nb_3Sn is extremely brittle and is a difficult material to process. It is made in tape form, which is not suitable for accelerators, but attempts to prepare it in multifilament composites have thus far not been commercially promising. The most interesting material now seems to be V_3Ga, which responds well to metallurgical treatment and to handling. Multifilament composites of good characteristics have been prepared at Brookhaven and serious consideration of commercial production is being taken in Germany and in Japan. If within one or two years V_3Ga is available in quantity the restrictions on current density, field and stability imposed by NbTi will be measurably relieved.

Magnets

It is necessary to employ an efficient magnetic circuit working at high current density and resulting in small overall size. Two familiar configurations of current produce a uniform field inside: the intersecting ellipse with uniform current density and the circular cosΘ current distribution. If a good approximation of one of these is constructed and an iron cylinder is fitted closely around it an accelerator magnet can be created.

At lower current densities the picture frame type is useful, provided the gap is at least as long as its width. Some time ago there seemed a possibility of using very pure aluminium in the picture frame circuit at current densities of 10-12 kA/cm^2. The magnetoresistance is severe and the thermal losses in aluminium are unfavourable in comparison with present superconductors. The picture frame circuit is comparatively heavy but can be used to 4T if massive correcting currents are applied to cancel the field distortions. The consensus is that aluminium coils should be considered only for specialized applications.

The intersecting ellipse is efficient relative to ampere-turns and stored energy but is difficult to fabricate, particularly at the ends (always the difficult part of a magnet). The cosΘ type magnet requires somewhat more ampere-turns but is not too difficult to fabricate. These configurations are most useful at current densities above 20 kA/cm^2 and with an iron core directly around the coil. The iron core provides needed support for the large magnetic pressures, enhances the field strength and reduces the stored energy (and the stray field as well). The advantages of putting the core directly on the coil far outweigh the disadvantage of having the iron losses within the Dewar. One now can visualize the magnet unit as having a cold bore tube of 5-6 cm diameter, coils working to gross density of 30 kA/cm^2 and iron core of outer diameter 30 cm. The conductors must be a good approximation of the idealized configuration and the iron needs careful proportioning so the higher order field terms will be small and readily correctible. I believe that the peak field strength when employing NbTi should be limited to 4-4,5 T but some of my colleagues,with good reasons, believe that 5T is achievable. If V_3Ga or Nb_3Sn can be obtained the field strength can be put up to 5-6T. Above 6T the magnetic pressures and mechanical stresses present such formidable problems that pulsed units become questionable.

Concerted attacks are being made on the mechanical problems. Units must be fabricated cheaply but must be clamped very tightly, and at 4.2^{0}K, against conductor motion. Minute motion or small local stress relief can readily produce local heating enough to make the coil go normal. Seriousness of this problem is shown by the records. Only a very few dipoles have thus far been so securely restrained that they would go to "short sample" current and field. However, when a dipole performs properly, it does so on both dc and pulsed operation. Precision and permanence of conductor location are an obvious necessity, and closely related to the problem of restraint. Encapsulation with filled epoxy is making steady progress. The poor heat transfer of plastic systems is overcome by use of cooling channels or heat drains. For dc or slowly pulsed systems the cable or braid can be mechanically and thermally stabilized by filling with a soft metal alloy. The very meagre information available on radiation damage and fatigue life indicates that the associated problems can be solved, but accelerator designers must use care on problems of beam loss and "waste disposal". Appreciable beam dump will release enough thermal energy to send units normal. Details of magnet design will be found in numerous papers in this Proceedings.

The Ring Accelerator

The ring may be dc, slowly varied, or pulsed. Since the ring is only a container of 6-dimensional phase space its configuration is similar for the different modes. The auxiliary apparatus is very different for the three modes. One visualizes a circular aperture and a separated function lattice. Due to the mechanical problem a symmetrical structure is indicated while units with large gradients appear difficult. (It should be noted that a dipole and quadrupole can be superimposed without electrical coupling, but the belt of conductors becomes rather thick if intense fields are desired.)

A ring must operate in three regimes - injection, acceleration and extraction. Any accelerator being planned now will require a long flat-top. The storage ring is a special case, requiring a very long flat-top,and perhaps not requiring extraction provision beyond long straight-sections and thin walls.

Injection into a ring requires an aperture which will contain the betatron oscillations, and the perturbations of the central orbit. The latter requirement has been shown by experience of recent years to be only a few mm. If an"injector" of reasonably high energy is available the admittance necessary for a single load of charge is not onerous, but desire for high intensity may lead to stacking and this in turn affects the injection aperture in complex ways. Treatment of this subject alone would require an entire survey paper. A few examples will indicate the order of magnitude of aperture required for injection. It is estimated at Rutherford that injection at 4-5 GeV into an 80-90 GeV ring will require 5-6 cm of aperture. BNL studies of 30 GeV injection into 200 GeV rings estimate 4 cm. The GESSS and Brookhaven studies of 1000 GeV main rings estimate 6-8 cm aperture for 25-30 GeV and 3-4 cm for 150-200 GeV injection. Transverse matching from ring to ring is usually straightforward but matching of longitudinal space upon transfer is difficult. Some novel methods have been suggested but more work is required. A dilution of phase space is usually assumed for the transfer process. Experience with PS-ISR transfer makes an area factor of 1.5 dilution seem reasonable rather than the factor 2 often assumed. High energy injection is quite necessary for use of small aperture and this in turn leads to use of existing high energy machines. A new high energy injector is evidently time consuming and expensive. Residual fields from remanence in the iron and from diamagnetic currents in the superconductor reinforce the desire for high injection energy.

Acceleration puts some demand on radial aperture during capture and during phase transition, if the large ring has injection below transition energy. Carefully matched buckets, synchronous transfer and adiabatic trapping can hold the first demand within apertures cited above. The use of Q-jump and multiple phase switches can reduce radial blow-up at transition to values less than injection amplitude.

There is no longer much doubt that extraction of the beam sets the limits on aperture and on the quality of the magnetic field shape. Resonant extraction needs a large jump per turn at ejection radius. High order (sextupole, decapole, etc) variations in the magnetic field alter the nonlinear motion and can make the protons return towards center before they have reached the ejection radius. The transverse variations of the magnetic field should be within a very few parts per thousand within the aperture. Extensive studies have shown that correcting multipoles must have a high periodicity - preferably the same as the magnet unit periodicity. It is mandatory that the magnet aberrations be small so that programmed corrections can be made, probably on a unit by unit basis, with modest precision. Extraction inefficiency is a potent source of bombardment of machine components. Even with "waste disposal" loss of 2 or 3% may scarcely be tolerable. In order to minimise the extraction inefficiency the first splitter must be at a radius where the radial jump has grown large, and the splitter must be as thin as is feasible. Development of very thin electrostatic splitters is being undertaken at Brookhaven, CERN and NAL and there is a good prospect that 0.05 mm thickness can be employed. High-β sections can also be used to increase the jump at the splitter at the cost of increased aperture in a few of the machine units. Development is also beginning on a "scraping" mode of slow-fast ejection by sweeping the beam across an electrostatic splitter. By application of a little faith it is possible to visualize extraction from a 5 cm aperture.

Since injection requires more radial aperture, extraction can be done vertically in order to make good use of a cylindrical structure. Although a symmetrical structure is desirable, a superconducting magnet could readily be built with more vertical than radial space, unlike the design of conventional magnets.

Auxiliaries

Stored energy in a ring magnet system at constant particle energy and aperture increases approximately as the field strength. The power supply for a dc or slowly pulsed machine is not large, but for a pulsed synchrotron at even slow cycle rate (say 10 sec period) a powerful supply is required. Stored energy of a 1000 GeV 1.1 km radius ring might be reduced to 250 MJ, but estimates have ranged to 600 MJ. (This compares to the order of 15 MJ in the PS or AGS.) Conventional power supplies are possible, but an interesting alternate using superconducting energy storage is under development at Rutherford. The power supply is one of the most exacting technical components of the synchrotron, and can be quite expensive. The power supply must also be subdivided into numerous units in order to keep the voltage to ground small.

An acceleration system for the superconducting ring can follow well developed techniques. The rf system may be non-trivial; 1000 GeV at 3 sec rise and 4.5T peak needs almost 8 MeV per turn.

Vacuum practices are available and well developed. A good vacuum system will be needed to avoid condensation of solid layers of insulating material on the walls and subsequent charge collection.

Refrigeration system components of large size have been built for bubble chambers and for various commercial applications. Pulsed magnet losses and static losses are comparable in magnitude. The total losses at 4.2^0K are estimated, for a pulsed ring at 10 sec cycle length, to be of order 5 Kw per 100 GeV. The power input to the refrigerator at room temperature would then be about 2.5 Mw per 100 GeV. Dc or slowly pulsed machines would have about half the foregoing refrigeration requirements. There is little doubt that development will reduce both dynamic and static losses.

It is probably unwise to print cost figures at this time, but those working in the field are confident that a superconducting ring can be built, and can be built at a cost less than that of a room temperature ring of equal energy. Time scale is even more difficult to estimate, but is less than a few years.

Acknowledgment

The opinions expressed are those of the writer, but are based on the work done at the laboratories active in the superconducting accelerator magnet field. It is pleasant to acknowledge my great indebtedness for information freely shared by colleagues at UCLRL and Brookhaven in the U.S.A. and at Karlsrühe, Rutherford and Saclay in Europe.

DISCUSSION

J.B. ADAMS: Can industry supply the cryogenic systems required for superconducting magnet synchrotrons?

G.K. GREEN: Large units for refrigerators have been built. Compressors as large as 25,000 HP exist and so do large expansion turbines. There is extensive experience with Dewars. One component in need of development is the transfer line - most are expensive and inefficient.

F. SCHMEISSNER: I could add that helium expansion turbines have already been constructed with a cold production of up to 100 kW.

M.H. BLEWETT: How would you align superconducting magnets for a synchrotron?

G.K. GREEN: I would visualize measurement and calibration of each unit, with stable support on something like quartz pillars. Alignment could then proceed from marks on the room temperature side.

W. PAUL: Is there any experience of how stable superconducting pulsed magnets are with time? Has one any feeling if the properties are changed after 10^7 - 10^8 pulses?

G.K. GREEN: There is little or no experience on this point. Careful measurements are required to establish stability and fatigue resistance.

P.F. SMITH: I should like to comment that dipole models constructed so far have been given several thousand pulses with no deterioration of performance. Dipole models planned for 1972/73 will be life tested for more than 10^6 pulses.

N. MARSHALL KING: On the question of stored energy and aperture, there is not so much disparity between the GESS Machine Design Group viewpoint and Dr. Green's as his comments would suggest.

First, the stored energies for the majority of the lattices we have studied lie between 500 MJ and 650 MJ, and refer to an ejection efficiency of 98%. We have pointed out that a reduced efficiency, say 96%, would lead to reduced aperture, hence reduced stored energy; but we have not yet studied the resulting "waste disposal" problems in detail.

Similarly, we have revived the notion of high-β insertion (which originated at NAL) as a means of confining the full energy aperture requirement to the ejection region, and hence making a significant reduction in stored energy. This work is very recent, and so far we have only shown that it is a successful technique for a very special lattice, (a triplet or back-to-back doublet).

With these provisos, we would agree with Dr. Green's comments that dipole apertures might be reduced to about 25 - 30 mm good field radius. Including the bad field radius allowance, say another 10 mm, the resulting stored energies for 1000 GeV would lie in the range 300 - 350 MJ, not the 250 MJ upper limit which was quoted.

K. JOHNSEN: Would the cost be considerably reduced for a d.c. ring?

G.K. GREEN: The cost of power supply, RF system and refrigeration would be reduced for a d.c. ring. Such reduction could be substantial.

J.P. BLEWETT: I would like to make a general comment on high-field magnets. There are many computer programs aimed at establishing the field patterns in iron as it goes into saturation. All make what seems to me to be a questionable assumption - that the B and H vectors remain parallel. We believe that this may result in one or two percent errors in field patterns. We have an experiment in progress to check this point.