SUMMARY OF SIXTH WEEK OF 1968 SUMMER STUDY

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The topic of the sixth and last week of the 1968 Summer Study was "Accelerators and Storage Rings using Superconducting or Cryogenic Magnets." The first two days and a small part of the third day were devoted to design studies and cost estimates for accelerators using superconducting magnets. Storage rings were mentioned in passing but it soon became evident that there has been virtually no serious work on superconducting storage rings. The third day was "FFAG day" when Brookhaven and Argonne design work on superconducting FFAG machines was presented. On the fourth and last day of this session cryogenic magnets using pure, but not superconducting, metals were introduced.

SUPERCONDUCTING SYNCHROTRONS

The week began with a discussion by Peter Smith of the Rutherford Laboratory on superconducting proton synchrotrons. His presentation was divided into four parts. The first was on costs, a subject which he considered in a paper in Nuclear Instruments and Methods last year. There he had shown that the cost of a superconducting 300 GeV machine could be 10-20% lower than that of a conventional, room-temperature machine. Optimum bending fields appear to be of the order of 60 kG. The main change in the picture since last year is the imminent solution of the problem of high losses in superconductors. This led into the second part of the lecture which was on ac losses and was a summary of a presentation by Smith given in the preceding week. At that time he described the design of a superconducting cable that consists of a large number of 1 mil or 2 mil strands of NbTi embedded in a high resistance alloy. Smith and others have shown that, if this cable is twisted around its axis at a rate of about one turn per inch, it should be free of flux jumps and should also have very low ac losses. This conductor has been fabricated in a variety of combinations and dimensions by IMI and is just now under test at the Rutherford Laboratory. Although the tests are not complete, the results to date seem to bear out the theoretical predictions and so are very encouraging. This probably is one of the most important revelations of the Summer Study. It should open the field of ac and power applications to low temperature operation.

The third part of Smith's presentation was devoted to design problems, of which there appear to be many. The straightforward problems of coil design, choice of aperture, magnet length, etc. involve educated choices from available techniques. Heating effects and removal of heat are more difficult. Heat may be generated by ac losses, eddy currents, or particle beam loss. Probably the cryostat must be nonconducting. Stray fields outside of the coil probably must be shielded.

The magnet power supply might consist of units rated at about 3000 A, 5000 V distributed around the ring. In a separate talk, Smith described some ingenious ideas for storing energy in superconducting coils. He showed that energy can be transferred from one inductance to another by making mechanical changes in the coupling coefficient and finally he described a rotating system in which energy could be transferred from a superconducting energy storage coil to a superconducting synchrotron without introduction of any external energy source.

Finally Smith described a few projects that are under consideration at the Rutherford Laboratory. These include conversion of the 7 GeV Nimrod accelerator to 40 GeV by replacement of Nimrod's room-temperature magnets with superconducting magnets. Another project involves a more modest increase in Nimrod's energy to about 25 GeV at which energy it would serve as a booster injector for a 100-200 GeV ring. In Smith's words "the costs are so low as to be unbelievable."

Some of the theoretical analyses presented by Smith were not followed completely by all members of the audience so when this presentation was completed, John Lawson, also of the Rutherford Laboratory, attempted to revive the sagging confidence of those who had been left behind. He wrote Maxwell's equations in appropriate form on the blackboard and showed how simple is the fundamental approach. As he said it is "the sort of thing you can do on the platform while you are waiting for trains." Later, it was said that nothing is involved but Ohm's law; it was stated that "Ohm's law is all you need to know, but you must know it very well." This statement was referred to more than once during the week.

A second paper primarily on costs of superconducting synchrotrons was presented by Michael Green of the Lawrence Radiation Laboratory. This was a carefully considered study of the consequences of redoing the original LRL 200 GeV study using superconducting magnets distributed around the LRL circle of 690 m radius. He made a number of rather conservative assumptions and used a computer to look for optimum parameters. These assumptions essentially concerned parameters that were close to the present state of the art. His first conclusions included the following:

- The push to high field may not be justified; the economic considerations seem to point to lower than maximum fields.
- High current density <u>is</u> important.
- Elliptical beam geometry may well change to circular geometry for superconducting systems.
- The cost of superconducting machines probably will decrease with time.

Green then proceeded to a cost study of a "bare-bones" 100 GeV machine, a machine which included no experimental facilities; indeed, it did not even include an injector.

A number of pertinent conclusions emerged from this study. The cost of the magnets, using present superconductor costs, was 70-85% accounted for by the cost of the superconducting ribbon or wire. At low fields NbTi is cheaper but, at about 100 kG, Nb_3Sn was cheaper. Power supplies were estimated on conventional systems "bad as they are." Cryostats were to be of simple design with high heat leak but of high reliability. No liquid nitrogen shielding was included. Cost was estimated at $2000-$3000 per meter.

Refrigerators would be large units since cost of refrigeration seems to vary with about the two-thirds power of the refrigeration power required.

Other systems would be conventional with the exception of the vacuum system, which would use cryopumping.

Green's conclusions were somewhat surprising. For a 2 sec cycle his economic optimum occurred at a peak field of 25 kG (slightly higher for Nb_3Sn superconductors). For a 10 sec cycle the optimum is at 35-40 kG.

Perhaps the main impact of Green's presentation came from the conclusion that, even at such modest increases in field, the cost of a superconducting synchrotron would be about half of that of a conventional machine for the same energy.

Sampson of Brookhaven then presented a combined paper. Under his chairmanship the previous week's session on superconducting magnets was so crowded that he postponed a paper of his own on pulsed superconducting magnets which was now coalesced with a study on superconducting synchrotrons.

Sampson and his associates have shown experimentally that:

- Loss per cycle is independent of frequency.
- Loss correlates with total field swing regardless of bias.
- Loss correlates even better with the rms value of field normal to the tape surface (Nb_3Sn tape was used in all cases).
- For the same change in field, loss is independent of current.
- Loss is proportional to the Nb_3Sn content of the tape used.
- Loss is influenced by the winding density.

Sampson emphasized a point made earlier in the session by Howard Hart of General Electric that attempts to increase current carrying capacity by increasing the thickness of a layer of Nb_3Sn can be self-frustrating since, from our experimental results, the low thermal conductivity of Nb_3Sn can make it impossible to remove the heat generated in ac losses in a thick layer of this superconductor.

Sampson then presented a few cost estimates for a modest accelerator of 2000 GeV using superconducting magnets. This is to be a machine of 1.5 km radius with a peak field of 60 kG. The aperture is assumed to be 6 cm in diameter. About 80% of the ring will be full of magnets. Stored energy in the ring has a peak value of about 750 MJ. Injection would be at 30 GeV, which happens to be available from Brookhaven's AGS.

From Brookhaven's ac measurements it seems that a ratio of stored energy to loss per cycle of about 200 is presently achievable. Sampson assumed that this can be increased to about 1000, an assumption that, in view of Smith's work, seems pessimistic. He then made cost estimates that were even more encouraging than those of Michael Green.

STORAGE OF ENERGY IN SUPERCONDUCTING MAGNETS

Smith's proposals for power supplies for superconducting synchrotrons already have been mentioned. Another energy storage project in progress in France was reported by G. Bronca of Saclay. In an attempt to simulate conditions encountered by satellites on re-entry into the atmosphere, the ONERA laboratory in France is planning storage of about 50 MJ in superconducting coils for release in 20-50 msec. Pilot tests for this experiment are in progress at Saclay.

AC LOSSES IN SUPERCONDUCTORS

LRL work on this topic was presented during the fourth week by F. Voelker. New work since that date was described by W.S. Gilbert, also of LRL. For those who did not hear Voelker's paper the earlier results were reviewed. New results on pancake coils of 0.5 in. Nb_3Sn ribbon were presented. The rather high losses observed precipitated a discussion of the significance of short circuits in test coils.

In conclusion Gilbert expressed considerable optimism about the possibility of operating at high over-all current densities.

IRON SHIELDING FOR SUPERCONDUCTING MAGNETS

A short paper was presented by the writer on iron shielding for cosine wound circular dipoles and quadrupoles. Analytic expressions were written for a coil of finite thickness surrounded by a cylindrical shield of inner diameter large enough so that the external field of the magnet has fallen below the saturation value for iron. It was shown that such a shield will not distort the field in the useful aperture but that its value will be increased to some extent. In the case of dipoles the dipole field can be increased by about 10 kG for no change in current.

RADIATION EFFECTS ON SUPERCONDUCTING MAGNETS

This subject was attacked by H. Brechna of SLAC who, in typical Brechna fashion, injected a few stimulating introductory remarks. These remarks were aimed at the general attitudes toward superconducting devices. He drew a picture of a classical scales. One pan of the scales included a package of "uncertainty about superconducting magnets + room temperature magnets." The other pan was filled with "experiments + optimism." It was his feeling that, in the present atmosphere, the former pan might move rapidly downward.

Brechna emphasized a few of the problems facing the designer of high field magnets — fatigue, for example, about which at this early state of knowledge little is known.

On the question of radiation effects, this talk was divided into five sections. These sections fell, very logically, into the following categories:

- Induced radioactivity. As an example, figures were presented for a magnet 5 m downstream from a target at SLAC. This magnet would receive 3 W of gamma rays, 1 W of neutrons, and 0.4 W of protons.

- Radiation effects on type II superconductors. The usual effects of radiation — lattice distortions, changes in mechanical properties, ionization effects, etc. can be expected. For Nb_3Sn changes of critical current in either direction can result. It should be noted that an increase in critical current, although apparently desirable, may make a stable superconductor unstable. NbTi and NbZr can both be expected to deteriorate slightly in their superconducting properties as a result of radiation.

- Radiation effects on nonsuperconducting metals. The usual metals used for stabilization — copper, silver or aluminum — can be expected to lose mechanical strength and to increase in electrical resistivity under intense radiation.

- Radiation effects on insulation. These also are uniformly bad. Insulation can be expected to become conducting and so to deteriorate the flux jump pattern. Many insulators evolve large quantities of gas. For example, teflon at 9×10^8 rad gives off 9 mg per gram of material. The gas is predominantly fluorine.

- Radiation effects on helium. Here, offhand, one does not expect serious difficulty. But, of course, the three isotopes of hydrogen will be produced and could freeze and obstruct the cooling system. At SLAC in intense radiation areas hydrogen can be produced from helium at a rate of one liter every three hours.

Wednesday was FFAG day. The topic was introduced by George Parzen of Brookhaven. Parzen described the procedures for choosing parameters in an FFAG accelerator. At MURA, because of the very large range of momentum to be included, the proposed machine had an enormous (4 m) radial aperture. But if the momentum range could be held to a factor of three (for example, 200 MeV to 1 GeV or 300 GeV to 1000 GeV) the radial aperture could be held to 15 cm regardless of the energy level. Vertical apertures would be about 2 cm.

Problems with the FFAG mentioned by Parzen included:

- The field ratio between the useful field in the median plane and the maximum field at the windings. This could approach a factor of two. If a maximum field of 60 kG is tolerable at the windings the maximum usable field would be 30 kG.
- Magnet design, which at best is very complicated. End effects of return windings may be troublesome and are barely calculable.
- Field-free straight sections of any appreciable length cannot be tolerated in an FFAG machine. Thus injection, ejection and rf acceleration systems become very difficult to design.

The design of a magnet for an FFAG accelerator was described by P. Gerald Kruger of the University of Illinois. Kruger has been for many years a consultant to Brookhaven. Using the computer at the Urbana campus Kruger has shown that air-core superconducting coils can be designed to provide the fields required for a superconducting accelerator. The structures that he described, although complicated, appeared to be quite feasible. Kruger presented a comparison between cost estimates for a pulsed synchrotron and an FFAG machine indicating that the dc operation of the FFAG accelerator might make it somewhat cheaper.

G. del Castillo of Argonne presented design ideas evolved at ANL and emphasized a number of mechanical problems that remain unsolved for FFAG and, indeed, for all types of superconducting machines. He emphasized the problems of aligning structures in cryostats at 4°K and of measuring magnetic fields at low temperature with the high precision required. He presented three possible cryostat designs, including means for making the necessary measurements, but it cannot be said that he appeared confident that any of his designs was completely satisfactory.

del Castillo then discussed plans for FFAG developments at Argonne. Room-temperature tests of a coil configuration proposed at Brookhaven indicated that such a configuration might be useful. Kruger pointed out the fact that this configuration, although initially intriguing, had very bad end effects.

Plans at Argonne include construction of a superconducting coil which would represent an element of an FFAG system. Attempts will be made with this coil to measure fields to 0.01% to check detailed computations of field patterns. The relation between field and current will be checked and the effects of field induced forces up to 200 tons will be observed.

A paper not in the program was introduced on Wednesday by W. Herrmannsfeldt of SLAC. After a few pungent remarks about cost estimates, Herrmannsfeldt discussed the possibility of converting the two-mile linear accelerator to a superconducting machine yielding 100 GeV. This would require acceleration rates of 10 MeV per foot which is somewhat above current acceleration rates. If this could not be achieved, SLAC proposes that the electron beam should be magnetically deflected back to the injection end of the machine and reaccelerated. A couple of intriguing problems raise their heads. The geometry of the return path is adversely affected by a new Freeway which is under construction and which crosses the two-mile machine on a bridge. The second problem is that of energy loss by radiation in the curved sections of the returned beam. Here it is quite possible to lose half of the energy in the accelerated beam. These rather formidable problems do not appear to have frightened the indefatigable group at SLAC.

The last day of this week's session was a departure from superconductivity to a consideration of nonsuperconducting metals at cryogenic temperatures. Here pure aluminum appears to be the most promising material. It can be operated in the temperature range between 4^{o} and $30^{o}K$. The properties of very pure aluminum were outlined by Vincent Arp of the Bureau of Standards at Boulder. The resistance of aluminum is made up of a sum of components due to impurities, lattice defects, grain boundaries, lattice vibrations, etc. The larger are these components the higher will be the value of the temperature at which a sample reaches an asymptotic value of resistance when cooled — further reduction of temperature will cause no further decrease in resistance. By removing impurities, the ratio of resistivity at room temperature to that at $4^{o}K$ can be increased to values as high as 45 000. Values as high as 15 000 are commercially available — these samples are purified by zone refining. This process, however, leaves traces of transition metals. A new German process is now available which involves electrolytic deposition of aluminum from aluminum triethylene, a very inflammable and explosive substance. The electrolyzed aluminum has many impurities but does not include transition metals. It can then be zone refined to produce the highest purity yet attained.

The resistivity of aluminum rises sharply if it is strained beyond its yield point. The low value can be restored, however, if the sample is annealed at room temperature or at a somewhat higher temperature.

A desirable property of aluminum is a relatively low value of magnetoresistance. At about 10 kG the resistivity reaches a value approaching about three times its zero field value, but at higher fields the resistivity shows no further increase.

Aluminum samples show a variety of size effects when used in ac applications. These size effects depend on the relative magnitudes of the sample diameter, the classical skin depth, and the electron mean free path.

The possible use of aluminum in cryogenic accelerator or beam transport magnets was discussed by Gordon Danby of Brookhaven. Danby pointed out the fact that "picture frame magnets" for very high flux densities suffer from the relatively low current density attainable in copper in conventional room-temperature magnets. For fields much above 20 kG the winding becomes absurdly large. But for materially higher current densities Danby has shown that fields in iron core magnets can be pushed to 40 kG and above. Field distortions of sextupole or higher order become surprisingly low if the magnet gap is increased to be of the same order as the separation between the windings. The models thus far have included copper windings cooled by liquid nitrogen but Danby will soon have obtained some aluminum strip with a resistance ratio of 15 000. With this he hopes to attain current densities of the order of 10 000 A/cm^2.

Danby then turned to consideration of a 2000 GeV accelerator using cryogenic magnets, operated at 40 kG. He would propose operation at $27^{o}K$ using liquid neon as a coolant, although in the subsequent discussion it appeared that operation as low as $10^{o}K$ might be advantageous. At $27^{o}K$ resistive losses would amount to about 60 W/ft. Eddy current and hysteresis losses would increase the total loss to about 66 W/ft.

At this early stage it is not at all obvious whether cryogenic or superconducting magnets will be preferable for use in synchrotrons. Very preliminary cost estimates give comparable results for the two cases. They do, however, indicate that major savings should be possible for the super-energy synchrotrons of the future.