SLAC-PUB-2237
November 1978
(I)

HARMONY IN SCIENCE: SUPERCONDUCTIVITY AND HIGH ENERGY PHYSICS*

Steve J. St. Lorant†

ABSTRACT

Thirty-one days after the disclosure of high field superconductivity in Nb_3Sn, the bubble chamber group at the Lawrence Berkeley Laboratory began a program to apply this discovery to high energy physics. On that day in 1961 a very special relationship was born which, as subsequent events were to show, proved to be one of the most fruitful associations in modern science. Given the well-known high technology content and innovative approach to problem solving associated with high energy physics, it is hardly surprising that significant developments in applied superconductivity took place in accelerator laboratories. Particle physics requires a bewildering array of technologically sophisticated equipment: from the instant when particles are injected into the accelerator through the acceleration process, beam extraction, separation, and steering to the instant of collision and analysis of the interaction products, superconducting devices play a most important role. We examine each step in this process and not only describe how the latest advances in superconductivity have been applied but also discuss why these developments necessarily took place. It is remarkable that, in spite of considerable fiscal restraint, high energy physics is entering a period of major construction activity. Thus if history repeats itself we are about to witness a flood of innovations each intended to alleviate some problem brought on by increasingly expensive power and rising production costs, not to mention the constant clamor for higher accelerator energies and greater resolution of the detection equipment.

INTRODUCTION

In the early fifties when high energy physics was in its infancy and accelerator laboratories were feverishly competing with each other in the energy race, Enrico Fermi indulged in one of his remarkable extrapolations. He noted that, should the energy race continue unabated, the year 2000 would see the construction of a global accelerator having an energy of 10^{15} eV which would be so large as to girdle the earth at the equator. Fermi concluded that, not only would such a machine require the combined industrial resources of the earth, but all its peoples would be occupied with its construction and operation, to the exclusion of all other activities. Thus there would be peace and high energy physics. Unfortunately Fermi did not live to see the advances in the science of superconductivity nor the power of the tool which it gave to the accelerator physicists. The 10^{15} eV machine is no longer an amusing extrapolation but almost a reality, thanks to superconductivity. ISABELLE at Brookhaven will attain an equivalent accelerator energy of 3.4×10^{14}eV, and, appropriately enough, the Tevatron at the Fermilab, should it acquire a storage ring at some future date, will exceed Fermi's predicted energy by a handsome margin. And of course the real estate required by these projects is quite modest.

HISTORY

High energy physics requires a bewildering array of sophisticated equipment and, given this high technology content, it demands an innovative approach to problem solving. As such it represents an ideal breeding ground for significant developments, foremost of which are those in applied superconductivity. Because the past is often a good indication of things to come, let us take a brief look at history. Table I lists some milestone events in applied macro superconductivity which profoundly affected the development of the science and incidentally of high energy physics as well.

Shortly after the discovery of high field superconductivity in Nb_3Sn,[1] a meeting was held at the Lawrence Berkeley Laboratory outlining a program of research and development of superconducting devices oriented towards high energy physics. Not only did this meeting constitute a manifesto for future action, but in its prediction and goals it achieved another first in the art of extrapolation: from Kunzler's data on almost microscopic samples of Nb_3Sn, the Berkeley team produced bold blueprints of 10T-plus magnets for bubble chamber applications! However, the first viable superconducting device used in high energy physics was the Argonne National Laboratory 25 cm HBC magnet.[2] The next two developments, the idea of cryostatic stability[3] and the 12" MHD dipole magnet built on that principle,[4] took place in a commercial research and development laboratory, an unusual event in itself, but not really surprising in view of the enlightened management and the first class technical skills enjoyed by that laboratory. The concept of cryostatic stability of course gave an immense impetus to developments in superconducting magnet technology.

Three years later, in 1968, during the Brookhaven Summer Study we were introduced to intrinsic stability by Peter Smith,[5] followed some months later by a superb publication authored by the Rutherford group[6] detailing their very thorough investigations on superconductor stability. This work very possibly established superconductivity as a practical technology. To end the vintage year of 1968, the 12' bubble chamber magnet became operational[7] and demonstrated, in the words of John Purcell, that "superconductivity is really a very forgiving phenomenon".

By 1972 industrial development, prodded by various government-funded programs, resulted in reliable multifilamentary NbTi conductor. Ironically this period also saw the demise, lamented or otherwise, of numerous small producers of superconductor who thought that they had invented the better mousetrap.

Three more signal events took place in the following years: CERN, with the assistance of Brown-Boveri, developed a hollow superconductor[8] and built the Omega magnet, cooled by circulating supercritical helium.[9] Next, the high

TABLE I

SOME MILESTONE EVENTS IN APPLIED MACRO SUPERCONDUCTIVITY

Event	Year	Where
High Field Nb_3Sn	1961	Bell Telephone Laboratories
ANL 25 cm BC Magnet	1965	Argonne National Laboratory
Cryostatic Stability Concept	1965	Avco Everett Laboratories
12" MHD Dipole Magnet	1966	Avco Everett Laboratories
Intrinsic Stability Concept	1968	Rutherford Laboratory
12' HBC Magnet	1968	Argonne National Laboratory
High Quality M. F. NbTi	1970	Industrial Development
Hollow Conductor (Omega)	1972	C. E. R. N.
Pulsed Magnet Development	1972-present	H. E. Labs in US and Europe
M. F. Nb_3Sn	1976	Industrial Development

*Supported by the Department of Energy under Contract No. EY-76-C-03-0515.
†Stanford Linear Accelerator Center, P. O. Box 4349, Stanford, CA 94305.

(Presented at the 1978 Applied Superconductivity Conference, Pittsburgh, PA, September 25-28, 1978 - Plenary Session D)

energy physics laboratories around the world realized that superconducting pulsed magnets were possible but that success would not come overnight and they launched a major research and development program which resulted in much increased awareness of the problems. Finally, filamentary Nb_3Sn appeared on the market,[10] not necessarily in a convenient form, but at least no longer as fickle in behavior as the tape product.

SUPERCONDUCTIVITY AND ACCELERATOR PHYSICS

From our point of view, high energy physics is a misnomer: we should really call it accelerator physics, for it is there that the action is. Let us illustrate this by referring to a typical accelerator and examining the various functions where superconducting devices are or should be involved. This machine (Fig. 1) is the Googoltron at The Famous National Laboratory. We observe that it has all the essential

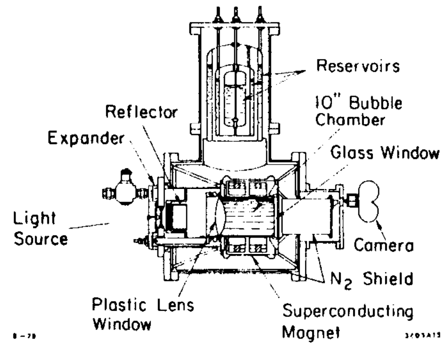

Fig. 2--The ANL 25 cm liquid helium bubble chamber (ca 1966).

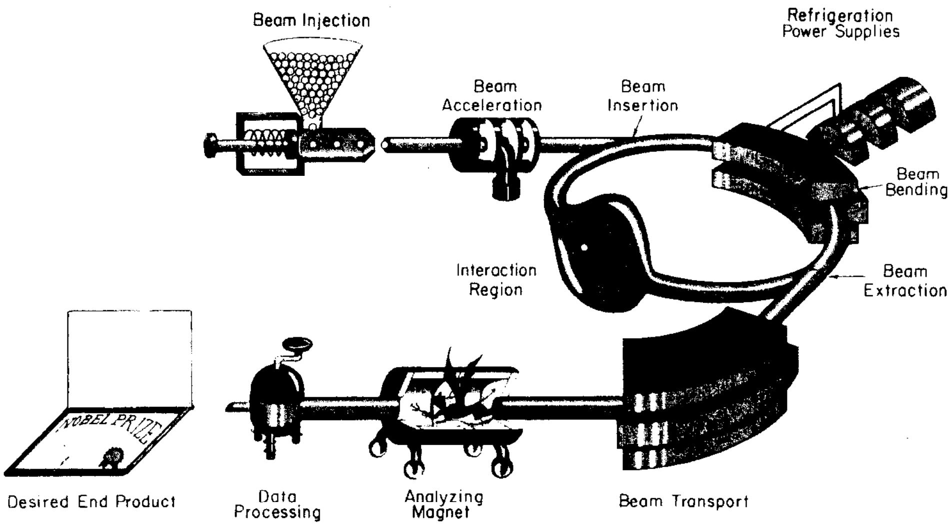

Fig. 1--The Googoltron: a typical accelerator and colliding beam facility.

features of a first class accelerator: injection, acceleration, insertion, and bending of particles; it has an interaction region, an extracted beam, beam transport, an analyzing device with Maxwell's Demon taking care of the physics, a data processing facility, and the desired end product. Now let us collect this catalog of devices and examine each one of them in turn from the point of view of its development, and the role of applied superconductivity in it.

DETECTOR MAGNETS

Initially high energy physics saw in superconductivity a means of achieving large volumes filled with magnetic fields of moderate strength. In the early sixties the major accelerators were completed and so it seemed logical to use superconductivity in detectors, specifically for bubble chambers. And so it came to pass through a combination of serendipitous events that the liquid helium bubble chamber at Argonne acquired a superconducting magnet, as illustrated in Fig. 2.[11] Several types of cable were used in the magnet, which achieved a field of 4.4T with a current of about 500A.[12] And, although the magnet was composed of five sections, some of which were NbTi and some NbZr, it proved to be remarkably stable. Why? In retrospect the explanation is obvious: not only was the conductor cryostatically stable, but its creators made it into a cable which happened to have the correct twist pitch to ensure stability with respect to flux motion. Regrettably the immediate fate of this device is not known: it belongs to the Smithsonian Institution.

It is interesting to note that while this bubble chamber was being built, the ANL 12-foot chamber was in the planning stages and a NbZr superconducting magnet model was constructed to obtain the correct scaling for the water-cooled copper magnet that was to surround the chamber. Fortunately, wise counsel prevailed, the conventional magnet concept was rejected, and the first really large superconducting magnet was built.[7] Incidentally, this device after many years of flawless performance will see further service in its new incarnation as a high resolution spectrometer at PEP, the SLAC positron-electron colliding beam facility.

As high energy physics progressed, larger and larger bubble chambers with increasingly higher magnetic fields were built: the 7' chamber at Brookhaven[13] was followed by the 15' chamber[14] at Fermilab and the monster 3.5m BEBC[15] at CERN. All have superconducting magnets. Soon these relatively slow optical chambers were competing with fast-cycling, electronically triggered chamber systems, in most of which a superconducting magnet provides the magnetic field.[16] To satisfy the thirst for more physics data, magnetic spectrometers with fast electronic readout systems were developed. At first the analyzing magnets were conventional, but as their size and the required field strength increased they soon were replaced by superconducting magnets. Typical of this new breed of analyzing detector, intended for end-of-beam-line service, is LASS at SLAC. Figure 3 illustrates this device. It consists of a superconducting solenoid (1) surrounding a liquid hydrogen target (7) in which the reactions take place, followed by a conventional dipole magnet (4). Every nook and cranny is filled with detection equipment: proportional wire chambers (3), scintillation hodoscopes (5), and Cerenkov radiation detectors (2, 6). The superconducting solenoid,[17] shown in Fig. 4, is no less complex. It consists of four separate solenoids two meters in diameter housed each in its own cryostat, connected electrically in series inside the header tank, and enclosed in massive iron doughnuts which serve the triple purpose of enhancing and homogenizing the magnetic field and reducing its spread. Each coil contains a number of subcoil units with different numbers of turns to achieve the desired field homogeneity both in the axial and in the azimuthal directions. The conductor is cryostatically stable, and, immersed in a generous bath of liquid helium, it operates at an average overall current density of 3800 A/cm^2 at 2.3T. The stored energy is 34 MJ and the inductance of the magnet is 24H. Together with the relatively large volume of helium this represents a system which is very stable both electrically and thermally.

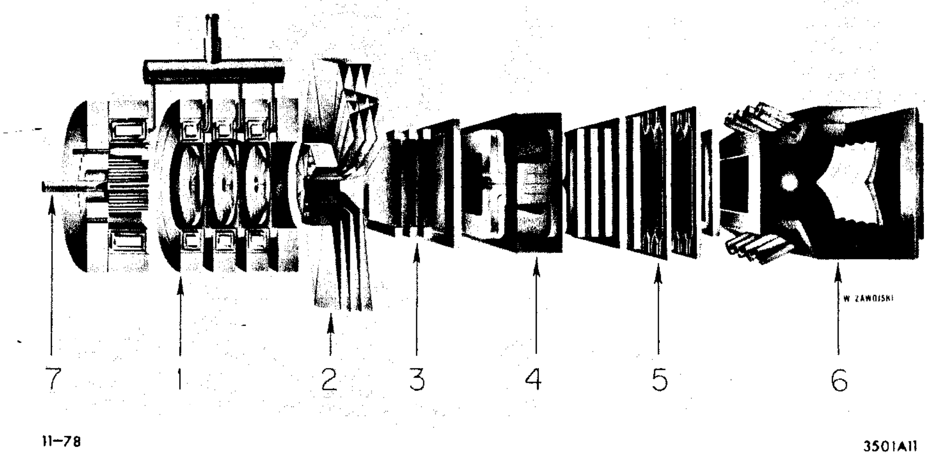

Fig. 3--Large Aperture Solenoid Spectrometer (SLAC 1977).

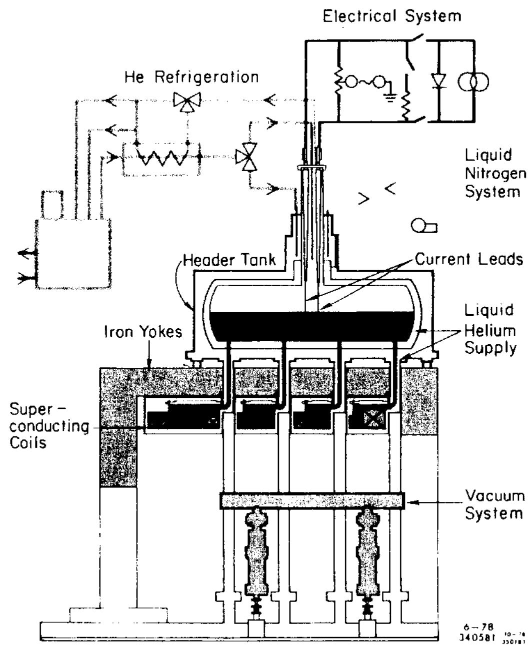

Fig. 4--LASS superconducting solenoid.

Hardly was this magnet operational when new developments occurred: colliding beams of particles stored in accelerator rings were shown to hold tremendous prospects for high energy physics. Detection equipment was quickly devised which naturally also included magnetic fields. By virtue of the colliding beam process these devices differed from all others in that they now became a part of the storage ring: they were no longer tucked away at the end of a convenient beam channel. The first superconducting magnet expressly designed for colliding beam physics was PLUTO, at DESY, a 1.4m diameter, 2.2T cryostatically stable magnet system with an iron yoke.[18] Very quickly it became apparent that the dimensions of such a magnet are too restrictive for physics and the demands for much larger magnetic volumes escalated. Simultaneously it became obvious that to build a PLUTO or a LASS-type magnet with a diameter of perhaps 4 to 5 meters needed to accommodate the detection equipment and with a magnetic field of 1 to 2T would be prohibitively expensive. Yet such magnets would be needed at the second generation of storage rings, at PETRA and at PEP.

Enter the "thin" magnet. Conceived in desperation, the thin magnet concept is a radical departure from accepted practice and it represents a major step forward in the design of superconducting magnets. The "thinness" or preferably "transparency" refers to the amount of material in the path of the particles produced in the colliding beams. The secondaries are energetically capable of passing through the coil without appreciable degradation, to be detected by suitable equipment outside of the magnet. The substitution of light for heavy materials and increasing the current density in the superconductor are the first steps. Figure 5 illustrates this design philosophy taken to its logical if rather radical conclusion. It is a cross section of the TPC magnet[19] proposed for use at SLAC, currently under construction at LBL. In this magnet the superconducting winding has been reduced to two layers and it operates at 1.5T at a current density of 70,000 A/cm^2. Clearly a quench would lead to very rapid destruction of the coil. The magnet is therefore protected by its tight inductive coupling to the aluminum bore tube. In the event of a quench the bore tube will absorb most of the magnetic energy stored in the coil. An added benefit

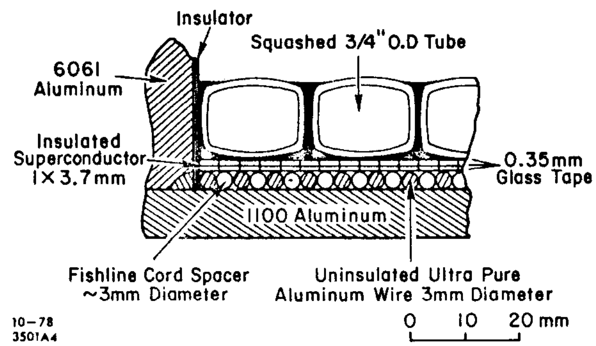

Fig. 5--Cross section of the TPC magnet coil.

is that the bore tube will cause the coil to go normal at a rate much faster than the normal quench propagation. This phenomenon, referred to as "quench back", enhances the conditions for fail-safe operation.

The actual construction of the magnet is as follows:[20] A layer of ultrapure aluminum wire insulated with fishing line is wound on the aluminum bore tube, followed by two layers of superconductor. The pure aluminum serves as a quench-back accelerator so that the magnet will go normal in under 50 milliseconds. Cooling for this structure is provided by a winding of flattened 3/4" o.d. aluminum tubing, which also provides the necessary mechanical support. The coolant is two-phase helium which is pumped through the tubes. The cooling method again sets the magnet apart from all others. This design philosophy has not only been validated by many tests, but has been adopted in various embodiments by other laboratories. For example, the CELLO detector[21] at the PETRA electron-positron storage ring (DESY, Hamburg) achieves the required radiation transparency by a single turn winding of a conductor made up of a rectangular copper-clad NbTi multifilamentary conductor solder-bonded to a strip of high purity aluminum.[22]

ACCELERATOR AND STORAGE RING APPLICATIONS

So far we have considered only the superconducting systems used in detectors. Let us now turn our attention to the accelerating device itself or, more specifically, to a colliding beam device. The rate of proton-proton collisions or the luminosity at an intersection of the CERN ISR is inversely proportional to the local height of the proton beam. This height can be reduced by a factor of 6 by a local insertion and focussing structure of magnetic quadrupoles, which must have a large aperture and a high magnetic gradient. These conditions can be met only by superconducting quadrupoles. Figure 6 shows the cross section through the prototype which has undergone extensive development over the

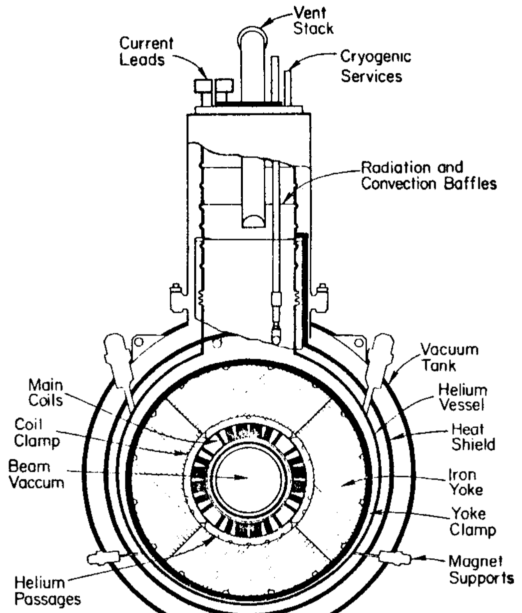

Fig. 6--Precision insertion quadrupole at the CERN ISR.

past several years and which illustrates the degree of sophistication and simplicity which is achievable with good engineering practice.[23] The quadrupole has a warm bore of 173 mm and a magnetic length of 1.24m. In addition to its quadrupole windings it has sextupole and dodecapole correction windings. A gradient of 47 T/m is achievable with a peak field of 6.1T in the main coil. The gradient tolerance throughout the active beam region (130mm) of the magnet is about one part per thousand. An interesting feature of this magnet is that the main coils are not supported radially on their inner circumference: they work as circular or Roman arches stressed from the outside. The segmented iron yoke follows the coil system symmetrically as the latter moves under thermal and magnetic stresses. The yoke is clamped by five shrink-fitted aluminum alloy rings.

Let us now go from the present into the immediate future. It is highly significant that the two largest undertakings of peacetime science in history should both depend crucially on the achievements of applied superconductivity. We refer of course to the Tevatron at the Fermilab and to ISABELLE at Brookhaven. It is a fine tribute to the skills of the research teams at the two laboratories, as well as of the outside help from industry and universities, that the work advances almost simultaneously in both laboratories. Both projects involve hundreds of accurate and reproducible superconducting magnets, kilometers of wiring and plumbing, refrigeration plant of industrial dimensions, and fiscal restrictions of no mean proportions. How the laboratories approached these problems is best illustrated by comparing their respective superconducting magnet systems.

The upper cross section in Fig. 7 represents the Fermilab dipole magnet,[24] while the lower is that of the proposed

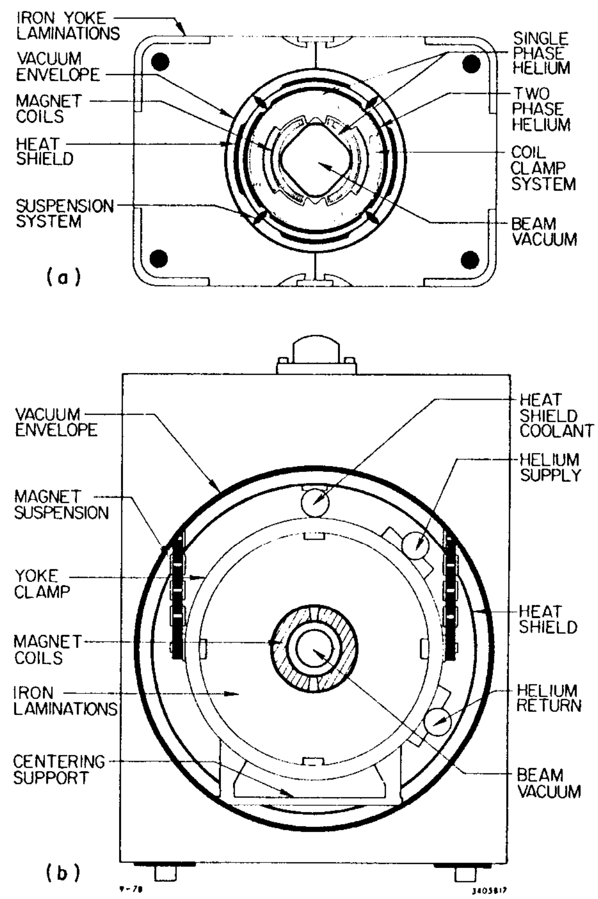

Fig. 7--Comparison of bending magnets:
(a) Fermilab Tevatron dipole
(b) BNL ISABELLE dipole.
(Scale approximate.)

BNL ISABELLE bending magnet.[25] The figure illustrates not only the differences in design philosophy but also the physical differences in the machines for which they are intended. Fermilab has approached the problem from virtually the opposite point of view to BNL, in terms of both development technique and magnet design. For the former, Fermilab elected to produce the magnets according to a preliminary production design which is subsequently refined. The claim is that this enables convincing statistics to be built up on the performance of many magnets so as to sort out the interrelated parameters affecting performance. The Brookhaven team on the other hand decided to develop the perfect magnet and subsequently replicate it as often as required. Although each approach has its critics, it appears to be quite appropriate to the machine to which it is applied. The Tevatron magnets are used in an accelerator: they have a cold beam pipe, multilayer magnet coils, a single phase/two phase counterflow cooling system and a warm iron yoke. The field accuracy is a few parts in 10^4 and any corrections required are taken care of by separate magnetic elements. ISABELLE on the other hand is a colliding beam machine in which counterrotating beams of protons are stored for long periods of time. Its magnets have a warm beam pipe, which is bakeable to 300° C, single-layer magnet coils held rigidly by cold iron, and a cooling system which uses subcooled supercritical helium gas. The field accuracy must be of the order of 10^{-5} and undesirable harmonic perturbations are corrected by integral coils. The vacuum tolerances on the beam are extreme: the present design calls for residual hydrogen pressures of less than 3×10^{-11} torr in the lattice sections and even lower in the insertion and crossing regions.

There is of course one other fundamental difference between the two magnet systems, and that is the ramping time. The duration of the acceleration phase in ISABELLE will be about 3 minutes, which may be repeated quite infrequently, depending on the lifetime of the beams. In the Tevatron on the other hand the magnets will be ramped to their design field of 4.25T in 20 seconds, where they will remain for approximately the cycling time of the beam, which is about a minute. This places unusually severe thermal and magnetic stresses on the magnets and their support systems. It will be most instructive to see how appropriately each design philosophy is matched to its task.

For the statistics-minded, the Tevatron will have 774 bending magnets, each about 7m long, and 240 quadrupole magnets, each 1.35m long. ISABELLE is not far behind, with 732 dipole magnets of various lengths up to 4.75m and 348 quadrupole magnets, the longest of which will be about 1.7m, distributed between two collateral rings.

By and large most magnets of today use niobium titanium as the superconductor. What about other materials? Nb_3Sn, for example? The technology involving these materials is very complex - so much so that only two laboratories - Brookhaven and Rutherford - have extended their experience with relatively small and simple solenoids to larger coils and to more demanding geometries such as provided by straight-sided and saddle-type beam-handling magnets.

At Brookhaven three one-meter long dipole magnets have been built using Nb_3Sn conductor which has been reacted prior to winding. The very rapid degradation of the current-carrying capabilities of Nb_3Sn under very moderate strains led to the adoption of a flat braided conductor with a very high aspect ratio which can thus tolerate limited bending. In fact the geometry of this braid and the method of winding is closely related to that used in the ISABELLE magnets. The latest coil easily achieved a field of 4T at about 8K.[26]

The Rutherford team on the other hand elected to continue development of the more conservative technique of in situ production of Nb_3Sn once the magnet is wound, and to apply it to a very complex magnet geometry, namely to the sextupole shown in Fig. 8.[27]

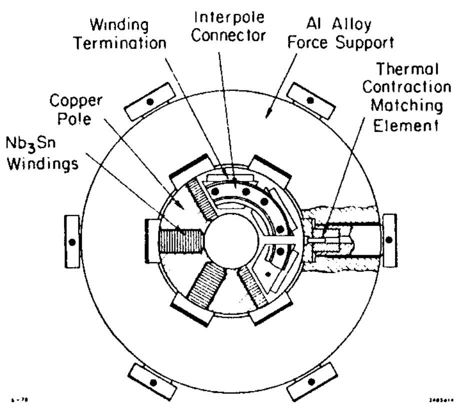

Fig. 8--Rutherford Laboratory Nb_3Sn sextupole magnet.

This is a very interesting magnet, not only because it represents an ambitious extrapolation of Nb_3Sn technology, but also because it is a replica of an existing NbTi sextupole and thus affords a good performance comparison. Notice first of all the absence of iron polepieces. This is due to the difficulty in matching the thermal contraction between the iron and the Nb_3Sn structure. Nevertheless a comparable magnetic field performance can be expected as the higher current density in the Nb_3Sn compensates for the lack of iron. Like the early solenoids the construction uses the wind-and-react sequence in which the Nb_3Sn is formed in situ by heat treatment after the winding phase. For monolithic conductors and relatively small magnets this is currently the only feasible method to avoid strain degradation of the conductor.

The conductor is insulated with glass braid whose abrasion resistance was increased by a treatment with polymethylmethacrylate. The coils are wound in a special fixture and reacted in the impregnation mold. Prior to the final reaction (336 hours or 2 weeks at 650° C) the various binders and adhesives are removed by a vacuum and air heat treatment. Following the reaction, the coils are vacuum impregnated with an epoxy mixture.

Three interesting and not totally unexpected conclusions were reached during the tests:

1. Satisfactory saddle-shaped magnets can be built from multifilamentary Nb_3Sn composites using the wind-and-react technique. Limits to performance appear to be set by the conductor and the relatively fragile insulation rather than by the construction or design.
2. Reproducibility of coils is difficult to achieve but is not impossible.
3. Training problems in Nb_3Sn coils are no different from those in NbTi.

ACCELERATION AND INJECTION

Let us now leave magnets and take a look at the two remaining areas of accelerator design where superconductivity could find important applications: acceleration and injection. Microwave superconductivity applied to particle acceleration has been around for a long time, and, although there are numerous operational devices in various laboratories around the world, it is by no means unfair to say that the initial promise of rf superconductivity has just not been fulfilled. What went wrong? Quite apart from the early optimistic projections resulting from unrealistic extrapolation of results obtained under highly restrictive conditions, the reason for our comparative failure to achieve consistent results is the inherent complexity of the phenomenon. The startling advances in conductor technology somehow obscured the fact that rf superconductivity is a very subtle phenomenon, one which involves to a high degree not only the basic superconducting properties of the metal, but also its surface characteristics and the rf environment.

Furthermore, the sensitivity of the superconducting surface to various, often unrelated effects, each individually capable of destroying the superconducting characteristics of the resonator, has tended to hinder the construction of multicell systems. It is clear that the early hopes of achieving high accelerating gradients in linear structures have evaporated, at least for the time being. On the plus side, energy gradients of 2 to 4 MV/m are now achievable with some regularity[28] and, although much less than those hoped for earlier, they are nevertheless competitive in certain applications where a high duty factor, and high beam quality, stability, and intensity are required. The technical problems of obtaining these in full scale structures are extremely complex and success will be slow in coming.

In view of the many problems in this field it is not surprising that the accelerator community has so far totally ignored a possible application of superconductivity to injection. Considerable interest in this subject has however been demonstrated by the electron microscopists, who for many years have used superconducting electron beam lenses in their devices. Some years ago a group in Germany proposed a high voltage electron microscope with a superconducting microwave linear accelerator and injector, superconducting lenses, and even a cold first stage image detector. Figure 9 illustrates some elements of this ingenious device.[29] The source gun, buncher, and accelerator are combined in one extended rf system fabricated of niobium, while the other components are part of the control system. With an accelerating field of 3 MV/m the design energy of 3 MeV should be readily obtainable in the 1.5m long structure. The magnification of the instrument is variable between 10^4 and 10^6 and the energy

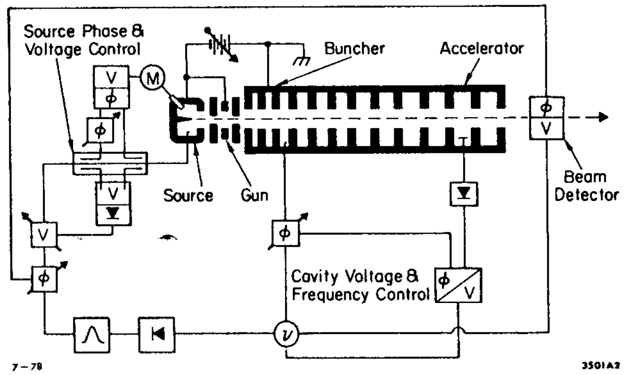

Fig. 9--A proposal: the 3 MeV superconducting linear accelerator for an electron microscope at Karlsruhe.

spread of the beam less than 1 part in 10^5. Unfortunately, though individual components have been built and tested in other systems, the microscope has yet to leave the conceptual design stage. A major current problem, apart from the customary lack of funds, involves the search for a reliable cold field emission source. This microscope[30] is a fascinating device, even if somewhat outside the mainstream of high energy physics, as it illustrates on a small scale potential areas of application of superconductivity to high energy physics.

THE FUTURE OUTLOOK

What will the future bring? The Applied Superconductivity Conference is the bellwether of the industry, so to speak, and the fact that almost 90 papers at this conference deal with superconducting materials not only indicates a desire to improve existing conductors but shows that the search for new superconducting materials continues unabated. The advantages to high energy physics of Nb_3Sn have been mentioned, and the benefits of higher T_c materials would be immense. What are the chances that such materials will be found and developed at a rate which remains in step with the exigencies of accelerator development? We seem to have arrived at a fork in the road, as Fig. 10 shows.

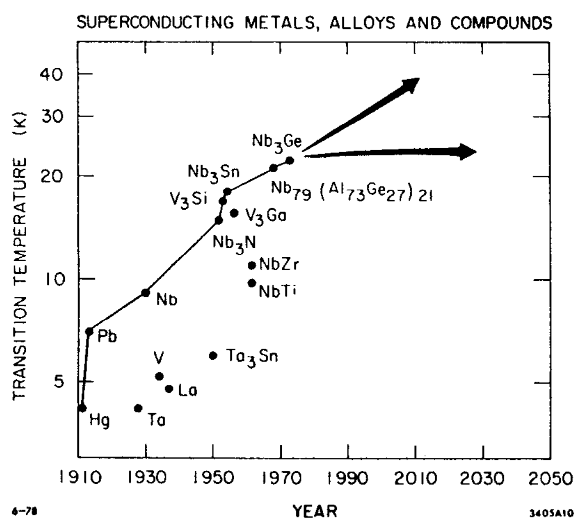

Fig. 10--A study in trends: the transition temperature of some superconductors as a function of the year of discovery.

This is a whimsical plot of the transition temperature of various superconducting elements, alloys, and compounds as a function of the year in which they were discovered. Which way progress?

There is much research to be done with existing materials: the teams at Fermilab and Brookhaven are no doubt fully occupied with their respective superprojects but there are other laboratories. We know that the Rutherford Laboratory is actively studying Nb_3Sn systems and we hear that at LBL the new direction is a systematic program which aims at attaining 6 to 8T magnets with both Nb_3Sn and NbTi cooled with superfluid helium for possible use at PEP, Stage II. At SLAC a modestly cautious program is being launched to answer the rhetorical question of the opening session of this conference[31] and the general feeling is that rf superconductivity for accelerators is not a hollow promise - it will just take much time, ingenuity, and hard work to keep it.

CONCLUSION

Applied superconductivity and high energy physics coexist in a symbiotic association which has brought many benefits to those not directly involved with either science, as illustrated in Fig. 11. It is our belief that every advance

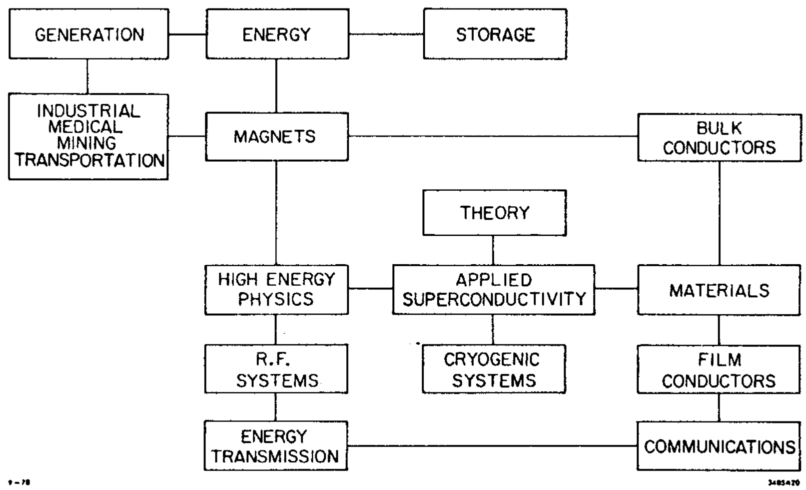

Fig. 11--At the center of the universe: Applied Superconductivity and High Energy Physics.

in our knowledge of superconductivity is carefully scrutinized by the accelerator community and evaluated for possible use. Similarly, high energy physics will turn to its partner when the need arises and will devote much time and energy, not to mention money, to finding and developing the appropriate technology. Beautiful examples of this, if confirmation were required, are the two superprojects at Fermilab and Brookhaven. On the other hand, note that the accelerator community has yet to face the necessity of building a superconducting accelerating structure to meet some goal in high energy physics; so far the "conventional" approaches have been adequate for the task. Should the need appear, however, it is our contention that high energy physics will rise to the occasion with its wonted vigor.

As we remarked at the beginning, applied superconductivity and high energy physics have had a remarkably successful and close relationship in the past; surely all indications are that it will continue in the future.

ACKNOWLEDGEMENTS

I should like to thank the legion of my colleagues who so patiently endured and generously complied with my importunate pleas for information, and to express my gratitude to Ms. E. Bowker and the SLAC Illustrations Department for their understanding help in preparing this manuscript.

REFERENCES

1. J. E. Kunzler, E. Buehler, F. S. L. Hon, and J. H. Wernick, "Superconductivity in Nb_3Sn at High Current Density in a Magnetic Field of 88 kgauss," Phys. Rev. Lett., Vol. 6, No. 3, pp. 89-91, 1961.

2. M. Derrick, T. Fields, L. Hyman, J. Loken, K. Martin, E. G. Pewitt, J. Fetkovich, and J. McKenzie, "The Argonne National Laboratory - Carnegie Institute of Technology 25-cm Bubble Chamber Superconducting Magnet System," Proc. 1966 Int. Conf. Instrumentation for High Energy Physics (Stanford), pp. 264-265, 1966.

3. A. R. Kantrowitz and Z. J. J. Stekly, "A New Principle for the Construction of Stabilized Superconducting Coils," Appl. Phys. Lett., Vol. 6, No. 3, pp. 56-57, 1965.

4. Z. J. J. Stekly, "The Performance of a Large MHD-Type Stable Superconducting Magnet," Les Champs Magnetiques Intenses (Grenoble), pp. 237-246, 1967.

5. P. F. Smith, M. N. Wilson, C. R. Walters, and J. D. Lewin, "Intrinsically Stable Conductors," Proc. 1968 Summer Study on Superconducting Devices and Accelerators (Brookhaven), Part III, pp. 913-919, 1969.

6. Superconducting Applications Group, Rutherford Laboratory, "Experimental and Theoretical Studies of Filamentary Superconducting Composites," J. Phys. D, Vol. 3, pp. 1517-1585, 1970.

7. J. R. Purcell, "The Superconducting Magnet System for the 12-foot Bubble Chamber," Argonne National Laboratory Report ANL/HEP 6813, 1968.

8. N. Schaetti, "Superconductors for the Magnet Coils of the 'Omega' Spark Chamber Magnet at CERN," Brown Boveri Rev., Vol. 59, No. 2/3, pp. 73-77, 1972.

   N. Schaetti, J. M. Rayroux, G. Meyer, and A. Schiller, "Hollow Conductor with Twisted Superconducting Filaments for a Spark Chamber Magnet," Proc. 3rd Int. Conf. Magnet Technology (Hamburg), Vol. MT-3, pp. 1136-1147, 1970.

9. M. Morpurgo, "The Design of the Superconducting Magnet for the 'Omega' Project," Particle Accelerators, Vol. 1, pp. 255-263, 1970.

10. See, for example, Session I, IEEE Trans. Magn., Vol. MAG-11, No. 2, pp. 287-299, 1975.

11. E. G. Pewitt, M. Derrick, T. H. Fields, L. Hyman, C. Laverick, K. B. Martin, J. G. Fetkovich, and J. McKenzie, "The Hydrogen-Helium Superconducting Magnet Bubble Chamber," Proc. XII Int. Conf. High Energy Physics (Dubna), Vol. 2, pp. 465-468, 1966.

12. C. Laverick and G. Lobell, "Large High Field Superconducting Magnet System," Rev. Sci. Instrum., Vol. 36, No. 6, pp. 825-830, 1965.

13. A. G. Prodell, "Large Superconducting Magnets for Bubble Chambers and Other Detectors," Proc. Int. Conf. Bubble Chamber Technology (Argonne), Vol. 2, pp. 1040-1094, 1970.

14. F. A. Nezrick, "The NAL 15-foot Bubble Chamber and the Use of Track Sensitive Targets in Neutrino Experiments," Proc. 1970 Int. Conf. Instrumentation for High Energy Physics (Dubna), Vol. 2, pp. 657-663, 1970.

15. R. Florent, "Status Report of BEBC," Proc. Int. Conf. Bubble Chamber Technology (Argonne), Vol. 2, pp. 703-713, 1970.

    F. Wittgenstein, "Preliminary Test Results of BEBC Superconducting Magnet," Proc. 4th Int. Conf. Magnet Technology (Brookhaven), Vol. MT-4, pp. 295-300, 1972.

16. R. D. Watt, "A Report on Fast Cycling Bubble Chambers at SLAC," Proc. 1973 Int. Conf. Instrumentation for High Energy Physics (Frascati), pp. 44-49, 1973.

17. J. S. Alcorn, H. O. Petersen, and S. J. St. Lorant, "The SLAC Two-meter Diameter, 25-kilogauss, Superconducting Solenoid 'UAMH BINN'," Proc. 1972 Applied Superconductivity Conference (Annapolis), pp. 273-276, 1972.

18. C. P. Parsch, E. Bartosch, F. Böhm, G. Horlitz, G. Knust, S. Wolff, A. Stephan, and D. Hauck, "The 1.4m/2.2T Superconducting Detector Magnet PLUTO for the Electron-Positron Storage Ring at DESY," Proc. 4th Int. Conf. Magnet Technology (Brookhaven), Vol. MT-4, pp. 275-286, 1972.

19. M. A. Green, "Large Superconducting Detector Magnets with Ultra-thin Coils for Use in High Energy Accelerators and Storage Rings," Proc. 6th Int. Conf. Magnet Technology (Bratislava), Vol. MT-6, pp. 429-442, 1977.

20. M. A. Green, P. H. Eberhard, J. D. Taylor, W. A. Burns, B. Garfinkel, G. H. Gibson, P. B. Miller, R. R. Ross, R. G. Smits, and H. W. Van Slyke, "A Magnet System for the Time Projection Chamber at PEP," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session CA, this conference.)

21. H. Desportes, "High Energy Physics Superconducting Magnet Program at Saclay," Proc. 6th Int. Conf. Magnet Technology (Bratislava), Vol. MT-6, pp. 474-479, 1977.

22. P. Genevey and J. Le Bars, "Conductor for a 'Transparent' Solenoid for 'PETRA'," Proc. 6th Int. Conf. Magnet Technology (Bratislava), Vol. MT-6, pp. 1033-1038, 1977.

23. W. Ansorge, J. Billan, K. N. Henrichsen, H. Laeger, P. Lebrun, R. Perin, L. Resegotti, T. Tortschanoff, L. Walckiers, and R. Wolf, "The Prototype Superconducting Quadrupole Magnet for the CERN Intersecting Storage Rings," Proc. 6th Int. Conf. Magnet Technology (Bratislava), Vol. MT-6, pp. 480-486, 1977.

    J. Billan, "Special Techniques in the Fabrication of Coils of High Precision Superconducting Quadrupole Magnets for the CERN ISR High Luminosity Insertion," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session CA, this conference.)

24. A. V. Tollestrup, "Progress Report - Fermilab Energy Doubler," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session JC, this conference.)

    G. Biallas, J. E. Finks, B. P. Strauss, M. Kuchnir, W. B. Hanson, E. Kneip, H. Hinterberger, D. DeWitt, and R. Powers, "The Support and Cryostat System for Doubler Magnets," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session CA, this conference.)

    K. Koepke, G. Kalbfleisch, W. B. Hanson, A. Tollestrup, J. O'Meara, and J. Saarivirta, "Fermilab Doubler Design and Fabrication Techniques," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session JC, this conference.)

25. J. R. Sanford, "Two Superconducting Storage Rings - ISABELLE," IEEE Trans. Magn., Vol. MAG-15,

No. 1, 1979. (Session JC, this conference.)

A. D. McInturff, E. Bleser, P. F. Dahl, J. Kaugerts, K. Robins, and W. Sampson, "BNL Superconducting Storage Ring Magnet Update," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session JC, this conference.)

26. W. B. Sampson, S. Kiss, K. E. Robins, and A. D. McInturff, "Nb_3Sn Dipole Magnets," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session CA, this conference.)

W. B. Sampson, M. Suenaga, and S. Kiss, "A Multifilamentary Nb_3Sn Dipole Magnet," IEEE Trans. Magn., Vol. MAG-13, No. 1, pp. 287-289, 1977.

27. R. Q. Apsey, D. E. Baynham, and C. A. Scott, "Filamentary Niobium-Tin Hexapole Magnet," Proc. 6th Int. Conf. Magnet Technology (Bratislava), Vol. MT-6, pp. 546-550, 1977.

28. K. W. Shepard, C. H. Scheibelhut, P. Markovich, R. Benaroya, and L. M. Bollinger, "Development and Production of Superconducting Resonators for the Argonne Heavy Ion Linac," IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session JC, this conference.)

29. I. Dietrich, K.-H. Hermann, and C. Passow, "A Proposal for a High Voltage Electron Microscope with Superconducting Microwave Linear Accelerator and Superconducting Lenses," Optik, Vol. 42, pp. 439-462, 1975.

30. I. Dietrich, Superconducting Electron-Optic Devices, New York: Plenum Press, 1976, pp. 97-114.

31. M. Tigner, "Rf Superconductivity for Accelerators - Is it a Hollow Promise?" IEEE Trans. Magn., Vol. MAG-15, No. 1, 1979. (Session BA, this conference.)