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CAS CERN ACCELERATOR SCHOOL

Second John Adams Memorial Lecture

ACCELERATORS AND SUPERCONDUCTIVITY: A MARRIAGE OF CONVENIENCE

Lecture delivered at CERN on 27 November 1986

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ABSTRACT

This lecture deals with the relationship between accelerator technology in high-energy-physics laboratories and the development of superconductors. It concentrates on synchrotron magnets, showing how their special requirements have brought about significant advances in the technology, particularly the development of filamentary superconducting composites. Such developments have made large superconducting accelerators an actuality: the Tevatron in routine operation, the Hadron Electron Ring Accelerator (HERA) under construction, and the Superconducting Super Collider (SSC) and Large Hadron Collider (LHC) at the conceptual design stage. Other applications of superconductivity have also been facilitated—for example medical imaging and small accelerators for industrial and medical use.

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1. INTRODUCTION

It is always a great pleasure to visit CERN, a place where one never fails to meet interesting people or see exciting new developments. On this occasion it is also an honour to be speaking in memory of John Adams, a man for whom I always had the greatest admiration—despite our failure some years ago to persuade him that the SPS should be made superconducting!

What I want to talk about is the relationship between accelerator technology and applied superconductivity. Looking back over the last 25 years one can see quite clearly how each subject has benefited from interaction with the other. The large accelerator laboratories have provided a good environment for people to work on the application of superconductivity and, by setting some very challenging targets, have stimulated many significant advances. In return, superconductivity has provided a powerful new magnet technology which has made it economically feasible to push accelerators to higher energies and also to construct some remarkable pieces of large experimental equipment.

2. HIGH-FIELD SUPERCONDUCTORS

Around the time that John Adams and his colleagues were planning the Super Proton Synchrotron (SPS), people elsewhere, notably at Bell Telephone Laboratories, were working on superconducting materials of a completely new kind. In 1961, some two years after the PS had first begun operation, the application of these new superconducting materials was described in a conference at MIT1). The new superconducting materials differed quite fundamentally from the original superconductors discovered by Kamerlingh Onnes in 19112), which were pure soft metals, such as lead, tin and mercury. These early materials are now known as type 1 superconductors. As well as their obvious property of zero resistivity at low temperatures, type 1 superconductors also display the property of flux exclusion. This is a state of thermodynamic equilibrium, i.e. the superconducting state is characterized by zero magnetic flux within the material, regardless of whether the field is applied to a material already in the superconducting state or the material is cooled down in a pre-existing magnetic field. Flux exclusion raises the potential energy of the material by an amount $B^2/2\mu_0$ per unit volume. Above a certain critical field, it becomes energetically favourable for the superconductor to switch to the resistive state and allow flux to penetrate. Using equilibrium thermodynamics, one may quite simply predict this critical field by equating the increase in free energy coming from flux exclusion to the decrease in energy coming from condensation of electrons into the superconducting state, i.e.

$$B^2/2\mu_0 = {}^1\!/_2 N\Delta^2 \ ,$$

where B_c is the critical field, N is the density of states at the Fermi surface, and Δ is the superconducting energy gap. For typical and rather general properties of known superconductors, the above equation predicts a critical field of about 0.2 tesla. Thus type 1 superconductors will never be any use for high fields; the energy penalty of flux exclusion is simply too high. This fact was discovered experimentally by Onnes in the course of a work programme directed towards the construction of magnets. He records his disappointment at this discovery, but like a good physicist reports that his disappointment was more than offset by the discovery of a new effect, i.e. critical field.

In the early 1950's, people began to find new materials, mainly based on the alloys and compounds of niobium, which could retain their superconductivity up to extremely high fields. It was later realized that such materials belonged to a new class, known as type 2, which are able to admit magnetic flux while still retaining their superconducting state. In this way, they are able to escape the energy penalty of flux exclusion and, for a similar order of condensation energy, remain superconducting up to much higher fields than type 1 materials. Interestingly, the flux is admitted to type 2 materials in the form of quantized flux vortices, each enclosing a flux line of magnitude h/2e. In superconducting materials, Faraday's lines of flux really do exist!

In pure materials which are strain free, the flux lines tend to arrange themselves into a regular lattice, i.e. uniform field and hence zero current density. To produce a technologically useful material which can carry high current densities, it is necessary to produce a flux gradient by means of imperfections such as dislocation cells or precipitates. In fact the metallurgical methods for producing 'hard' superconductors with high current carrying capacity are very similar to those used for producing hard structural materials.

3. CONDUCTORS FOR MAGNETS: PROMISES AND PROBLEMS

In a remarkably short time after their discovery, high-field superconductors were available commercially in a form suitable for winding magnets. The first ductile alloy to be so produced was niobium zirconium, later to be superseded by niobium titanium[3)] which has better superconducting properties and is more ductile. Niobium tin has even better properties and was one of the earliest high-field superconductors[3)]. However, it is a brittle intermetallic compound, whose difficult mechanical properties have given magnet makers problems even to the present day.

Figure 1 illustrates the critical surface for niobium titanium — superconductivity prevails everywhere below the surface and normal state resistivity above it. Most superconducting magnets are operated at 4.2 K, the normal boiling point of liquid helium. For example, at 4.2 K, in a field of 6 T, niobium titanium will carry a current density of around 2000 $A{\cdot}mm^{-2}$ over two orders of magnitude greater than a copper winding in a conventional magnet producing only 2 T.

With such spectacular properties, many were eager to use these materials in magnet construction. High-energy physics laboratories were particularly active, notably the groups at Brookhaven, Argonne and Rutherford, but everyone was in for a great disappointment because the materials simply did not perform in magnets as might have been expected from short-sample testing. Something was happening in the magnet winding to cause a premature transition from superconducting to resistive states at currents far below those expected from the short-sample measurement. This 'degradation' of current seemed to get rapidly worse with attempts to increase the magnet size.

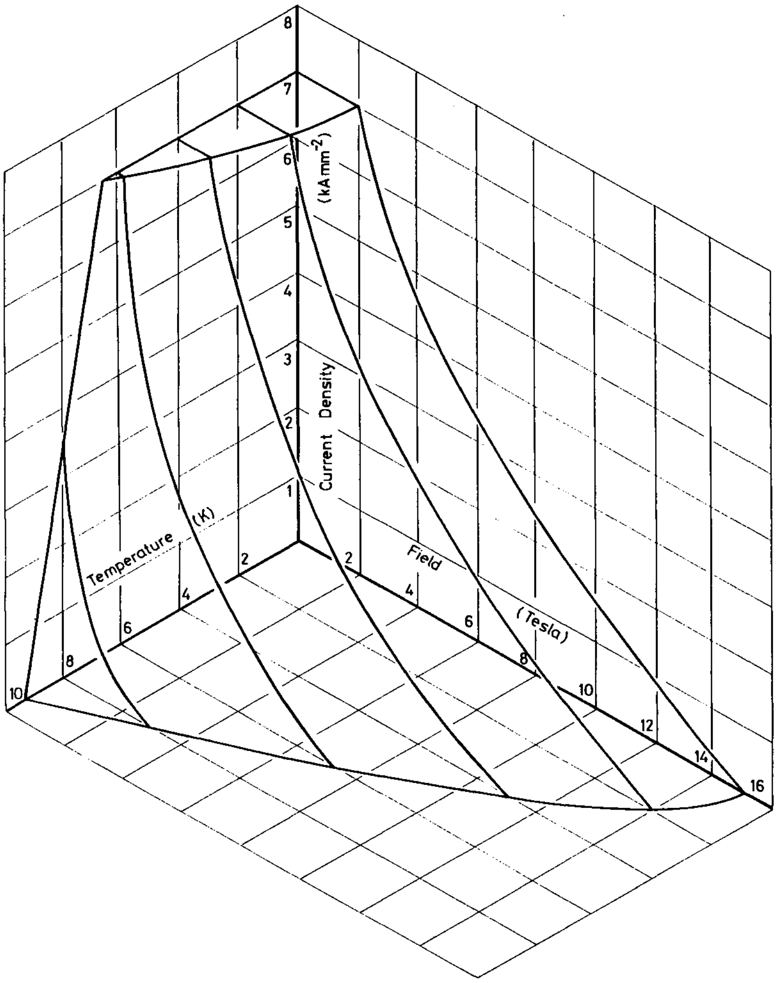
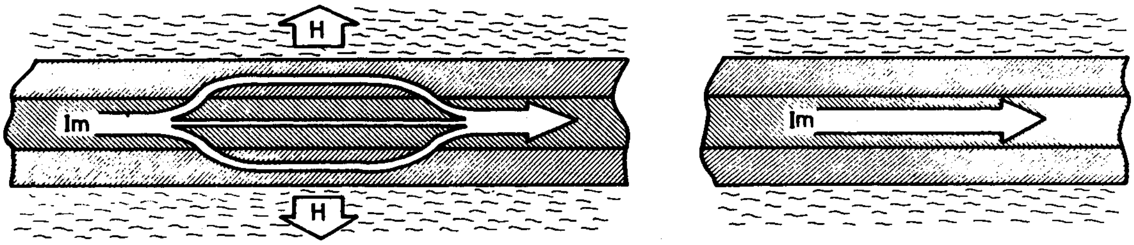


Fig. 1 The critical surface for niobium titanium

4. CRYOSTATIC STABILIZATION: THE FIRST CURE

It would be nice to report that the first cure for this problem came from high-energy physics interest, but in fact Laverick at Argonne was narrowly beaten by Steckley at Avco[4)] in propounding the technique now known as cryostatic stabilization. Nevertheless, high-energy physics laboratories were certainly the first to exploit this technique on a large scale, starting with the first Argonne superconducting bubble chamber, followed by the Brookhaven bubble chamber, and by BEBC and OMEGA here at CERN. As sketched in Fig. 2, cryostatic stabilization consists simply of bonding a copper conductor to the superconductor such that, in the event of the superconductor getting into difficulty, current may divert to the copper. Effective cooling must be provided for the copper, such that the resulting ohmic heating will not cause its temperature to rise above the critical temperature of the superconductor. Provided these conditions are met, the superconductor will be helped over its temporary difficulties and will quickly recover the superconducting state.

Cryostatic stabilization was important because it cut through the mystique which was beginning to surround high-field superconductivity and enabled people to design magnets on the basis of well-known engineering principles of heat transfer, Ohm's law, etc. It made possible the construction of all the large superconducting magnets we know today. However, it did have one big drawback — the large amount of copper required — typically 50 times as much as the superconductor. This dilution by copper, together with the additional space required for liquid-helium cooling channels, was to reduce the overall current density in a superconducting winding from those spectacular levels shown in Fig. 1 to the more mundane level of a conventional magnet. Such current densities were simply not high enough to make acceptable high-field accelerator magnets.



a) b)

Fig. 2 Cryogenic stabilization: (a) following a disturbance, the magnet current I_m transfers from superconductor (centre) to copper (outer), ohmic heat generation H is transferred to liquid-helium coolant; (b) if cooling exceeds generation, temperature falls and current returns to superconductor.

5. FINE FILAMENTS FOR ACCELERATORS

Besides having a low current density, cryostatically stabilized conductors were no use for accelerators because their a.c. losses were too high. As it turned out, these two factors were not unconnected. With further work, it became clear that the main cause of coil degradation was a phenomenon known as 'flux jumping': a rapid and unstable movement of magnetic flux within the superconductor.

Figure 3 shows how the imposition of magnetic field on a superconductor will set up persistent currents which tend to shield the interior of the conductor — just like eddy currents, except that they do not decay because there is no resistance. The magnitude of these currents depends on the critical current density, which itself depends upon the temperature. Imagine now a slight increase in temperature $\Delta\Theta$, which causes a reduction in screening current ΔJ and hence a change $\Delta\phi$ in flux pattern to the dotted line in Fig. 3. This change in pattern means that flux is moving into the superconductor from outside and such a process dissipates energy ΔQ. Naturally, this dissipation of energy raises the temperature, which promotes a further decrease in current density. Electrical engineers will recognize the familiar feedback loop — and the feedback is positive.

$$\begin{tikzcd}
 & \Delta\theta \arrow[dr] & \\
\Delta Q \arrow[ur] & & -\Delta J \arrow[dl] \\
 & \Delta\phi \arrow[ul] &
\end{tikzcd}$$

It was the sudden avalanche movement of flux, resulting from this basically unstable condition, which was causing the degradation of critical current in superconducting magnets. The cure, developed at Rutherford Laboratory5), building on the earlier work of Hancox6), Schwartz and Bean7), and many others, was to divide the superconductor into fine filaments.

As shown in Fig. 3b, the effect of subdivision is to reduce the amplitude of screened field within the superconductor. As a result of this reduction, the flux motion associated with a given change of current density (and hence of temperature) is reduced prorata. This reduction in flux motion $\Delta\phi$, and hence reduction in heating ΔQ, brings about a weakening of one link in the above feedback loop. Below a certain dimension one finds that the thermal runaway process ceases to be self-regenerating and hence the conductor becomes stable against spontaneous flux jumping. For niobium titanium, this stable dimension is about 50 microns.

The only practical way to manufacture and utilize 50 μm filaments of superconducting material is to make a filamentary composite, in which the superconducting filaments are embedded in a normal matrix. If this matrix is made to be a good conductor, such as copper, it can also serve to provide additional stability via magnetic damping and thermal diffusion and can also protect the magnet against burn-out following a quench. Unfortunately however, for any time scale of practical interest, the conducting matrix provides almost perfect magnetic coupling between all filaments in the composite. As a consequence of this coupling the filaments behave in unison, like a single large filament, and the advantages of subdivision are entirely lost. Fortunately, it is rather easy to cancel this coupling effect by twisting the composite, as shown in Fig. 4.

Using arguments about flux motion similar to those outlined above, one may also show that fine subdivision is effective in reducing the a.c. loss of superconductors. Of course, superconductors have no loss whatsoever under d.c. conditions, but in changing fields they experience losses due to flux

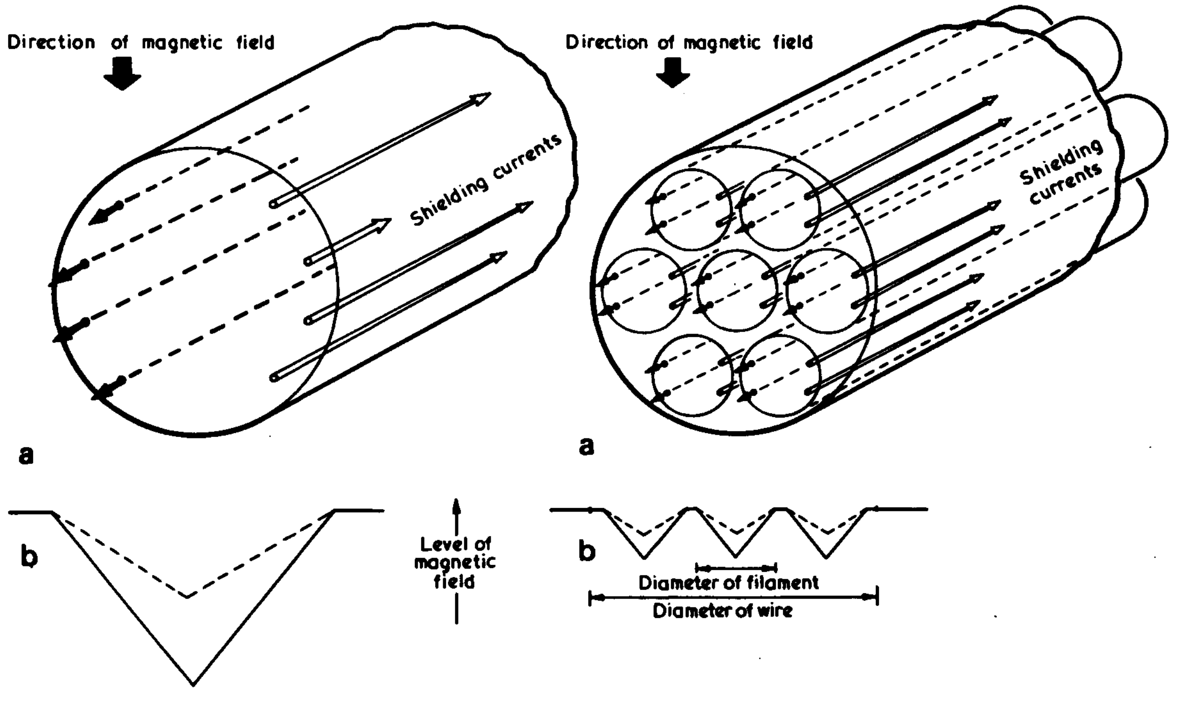


Fig. 3 (a) Screening currents in a single wire and internal field profile resulting from those screening currents; dashed line indicates flux change resulting from change in screening current. (b) Screening currents in finer filaments, showing reduced flux change from a change in screening current density.

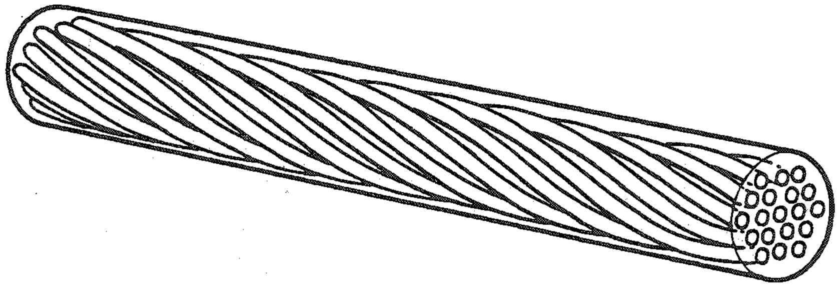


Fig. 4 Twisting a filamentary composite to decouple the filaments magnetically.

motion. Fine subdivision reduces these losses in proportion to filament diameter and, unlike stability, there is no lower limit — the finer the better. This simple fact has given rise to some very elegant metal fabrication work, for example the a.c. superconducting composite shown in Fig. 5

As one reduces filament size for minimum loss, and thereby increases the filament number in a composite, a new coupling effect starts to become noticeable. This is the coupling in self-field, i.e. that component of field due to the current which the composite itself is carrying. Unlike external field, self-field cannot be decoupled by a simple twist; it is actually necessary to transpose the filaments, i.e. central filaments must change places with outer filaments and vice versa. Nobody has yet worked out a way of achieving this in a practical composite and we have had to live with self-field effects, minimizing their effect by restricting the composite wire diameter to about 1 mm.

Single niobium titanium composite wires of 1 mm diameter in fields of ≈ 5 T will carry currents of ≈ 500 A. Such currents are fine for making single magnets of moderate size, but are not suitable for synchrotrons, where one requires high currents so that all the magnets may be connected in parallel without incurring excessive terminal voltages during ramping. For synchrotrons, we need conductors capable of carrying ≈ 5000 A and must therefore use many wires in parallel. Once again, it is essential to avoid coupling, which would produce magnetic instabilities and increased a.c. loss. Superconducting wires connected in parallel must therefore be fully transposed. Figure 6 illustrates three methods which have been used.

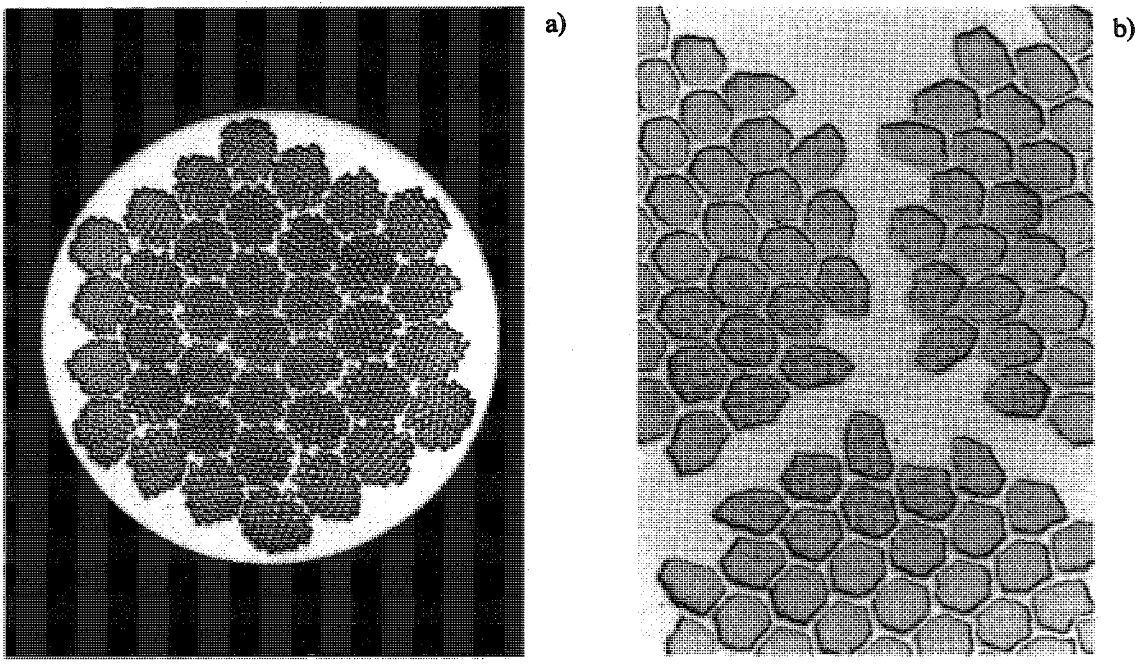


Fig. 5 (a) Cross-section of a 2035 filament 'three component' composite for a.c. use; (b) local view showing the resistive barriers of cupro-nickel alloy around each filament to reduce coupling losses in the matrix. (Courtesy of IMI Titanium Ltd.)

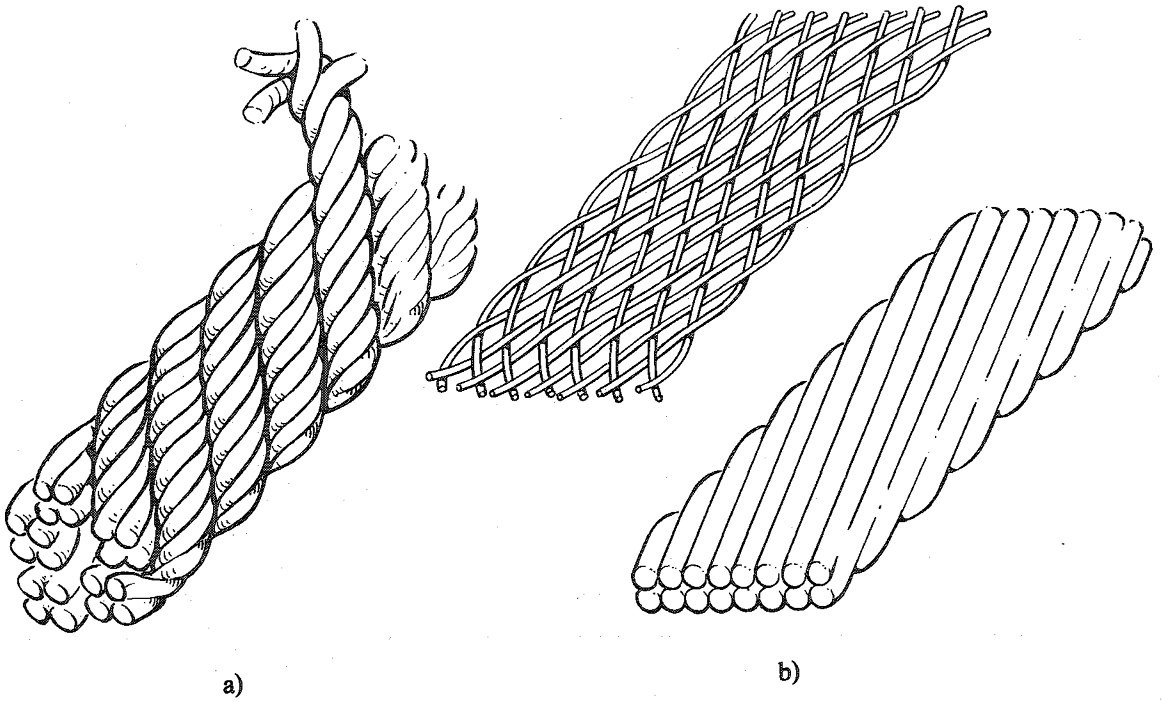


Fig. 6 Three different types of transposed cable: (a) rope, (b) braid, (c) Rutherford cable.

The rope, shown in Fig. 6a, is an obvious derivative of Litz wire and was used at Rutherford for our early synchrotron magnets. It allows very many wires to be connected in a fully transposed configuration, but has the disadvantage of a poor packing factor. Good packing is desirable for maximum overall density in the winding and also for the dimensional stability needed in magnets of good field quality. One may try to increase the packing factor of a rope by compacting it between rollers, but such treatment is likely to damage the individual wires because very high stresses are produced at the cross-over points within the rope. We had some very traumatic experiences of this nature in the early days at Rutherford!

The woven braid, shown in Fig. 6b, is also fully transposed and can accommodate very many wires in a single conductor. It was widely exploited at Brookhaven. Similarly to the rope however, it has a rather poor filling factor and attempts to increase this by rolling are likely to cause damage at the cross-over points. In general, the maximum practical filling factor which can be achieved in braids and ropes is ≈ 65%.

It was problems of compaction which led us at Rutherford to develop the cable shown in Fig. 6c, a sort of hollow tubular cable which is then rolled flat. Because there is no interweaving within this cable, one may compact it very strongly without damaging the individual wires; typical filling factors are ≈ 90–95%. For this reason, Rutherford cable became rather popular and seems to have become the accepted norm for superconducting synchrotron magnets.

We may thus summarize the requirements for a synchrotron conductor. Firstly, it must have fine filaments $\leq 50\ \mu$m to avoid flux jumping, thereby avoiding the need for cryogenic stabilization and permitting operation at high current density. Secondly, it must have even finer filaments $\leq 10\ \mu$m for acceptable a.c. loss during ramping. Thirdly, the composite wire diameter must be less than ≈ 1 mm and many wires must be cabled together to provide the required current-carrying capacity.

6. EARLY SYNCHROTRON MAGNETS

Given suitable conductors, able to carry high currents at high current density with low losses during ramping, many people in high-energy physics laboratories started to think about a superconducting synchrotron. In Europe we formed the Group for European Superconducting Synchrotron Studies (GESSS), a collaboration between Kernforschungszentrum Karlsruhe, CEN

Saclay, and Rutherford. At Karlsruhe, two short dipole magnets of length ≈ 1/2 m were built, named D1 and DT. D1 used single-strand wire conductor, whereas DT had a cable and was able to reach a 4.5 T steady state and a 3.2 T pulsed one. These early prototypes were followed by D2A, a more modern magnet using Rutherford cable, with shrink fitted clamp rings and a laminated cold iron shield; it reached 4.5 T with a rise-time of ≈ 5 s 8).

At Saclay, the first dipole prototype was called MOBY, after the whale-mouth aspect of its end turns; a braided conductor was used. The second magnet, ALEC, was constructed in collaboration with ALSTHOM and used a novel technique for pre-compressing the windings. A rope-type cable was used together with a cold iron shield. ALEC reached a field of 5 T with a ramp rate of 1 $T \cdot s^{-1}$ 9).

At Rutherford, we built AC3 and AC4, both using cables of the rope type. AC3 had no iron shield and was only able to reach fields of 3.5–4 T, but was able to ramp very rapidly, in times of ≈ 1/2 s. AC4 demonstrated a more modern style of design, with cold iron and windings capable of producing a good field shape—not only in two dimensions, but also at the coil ends. Rutherford cable was first used in AC5, a magnet similar to AC4 but incorporating many refinements, notably a rather accurate coil geometry and a shrink fitted supporting structure. Both magnets achieved fields in excess of 5 T 10).

The object of GESSS had been to persuade CERN that the second phase of the SPS could be made superconducting. That objective we failed to achieve—it was probably too early for such a grand scheme. There were of course many other accelerator magnet projects in Europe, notably the low-beta insertions for the Intersecting Storage Rings (ISR) 11), but after the last GESSS magnets the centre of gravity for superconducting synchrotrons tended to move across the Atlantic.

At the Lawrence Berkeley Laboratory, the Experimental Superconducting Accelerator Ring (ESCAR) was a brave attempt to produce a miniature 4 GeV proton ring using 24 superconducting dipoles12). Twelve dipoles, each producing 3.6 T at a cycling rate of 0.1 Hz, were completed before the project was terminated by lack of funding in 1977.

On the East coast, ISABELLE [subsequently renamed the Colliding Beam Accelerator (CBA)] was the Brookhaven project for an intersecting pair of 400 on 400 GeV accelerating proton storage rings13). For many years, the ISABELLE design was based on a braided conductor having the same width as the magnet coil, i.e. a single-layer winding. By inserting spacers between adjacent turns of the winding, a progressive dilution in current density towards the poles was introduced, thereby giving an accurate dipole field shape. Solder impregnation was used to give the braid good dimensional stability and several 'poisoned' solder formulations were developed to provide a good inter-strand resistance—and hence low a.c. losses. Many good prototype magnets were produced, but production magnets suffered from excessive 'training' and from the effects of coupling currents on field uniformity. A latter-day switch to Rutherford cable gave some improvements in performance, but unfortunately these improvements came too late and the CBA project was terminated in 1983 so that resources could be released for the newly proposed Superconducting Super Collider (SCC).

7. THE TEVATRON

It was to be in the mid-West that superconducting accelerators had their first real success story. Work on the Fermilab energy saver/doubler was initiated in the early 70's by Robert R. Wilson. Some ten years later, the Energy Doubler began successful operation as an 800 GeV superconducting proton synchrotron14). Subsequent improvements and the replacement of certain weak magnets have raised this energy to 920 GeV and there are plans to reach 1000 GeV in the none too distant future, thereby justifying a latter-day change of name to Tevatron. Figure 7 shows how the new ring of superconducting magnets has been installed underneath the old conventional magnets in the Tevatron tunnel. The complete accelerator comprises some 774 superconducting dipoles and 216 superconducting quadrupoles. As shown in Fig. 8, the coil windings consist of two layers of Rutherford cable, with the magnetic forces contained by laminated stainless-steel 'collars' which are squeezed tightly around the winding and then welded into position. The laminated iron yoke is situated at room temperature, some distance from the magnet coils.

Extremely reliable magnet performance has been obtained at the Tevatron, with very little 'training' being required to achieve full magnet current. Indeed it was at Fermilab that Rutherford cable really came into its own. My own view is that the excellent performance of Tevatron magnets

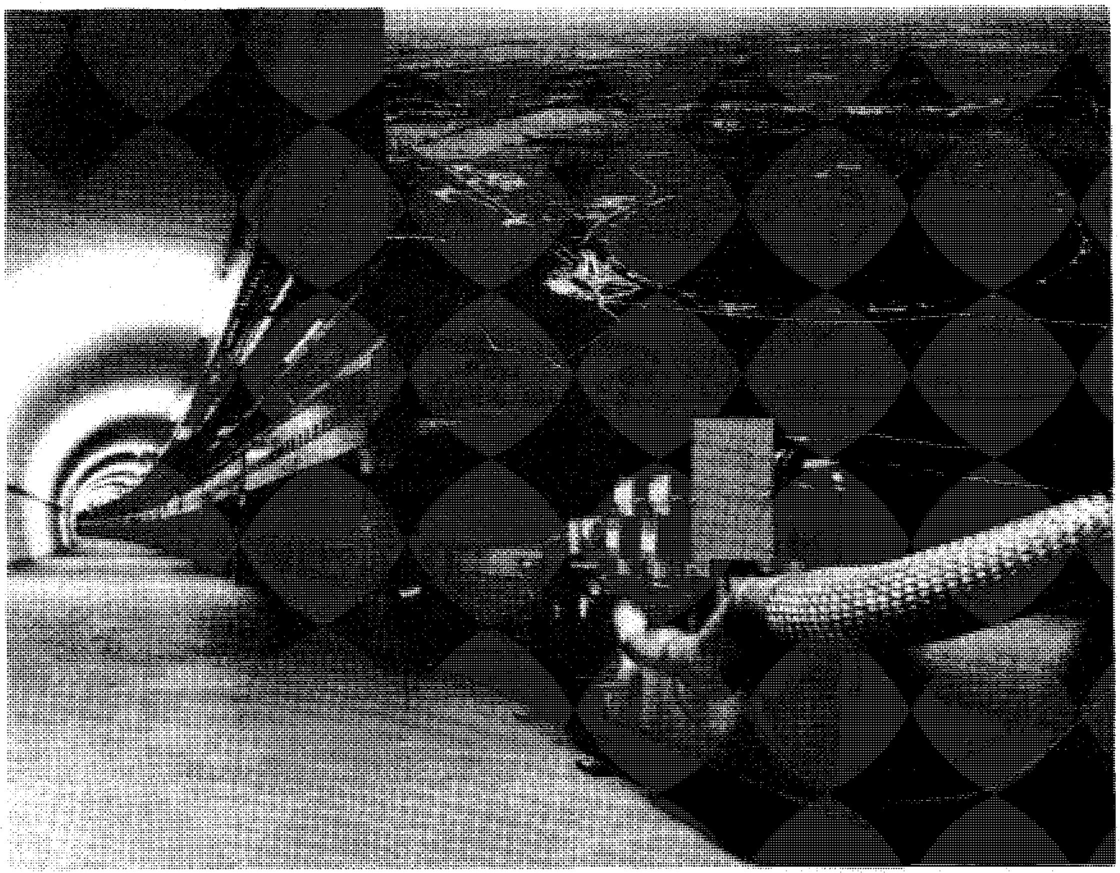


Fig. 7 The Tevatron magnet tunnel showing the ring of superconducting magnets installed beneath the older conventional magnet ring; inset shows the overall site and 2 km diameter ring.

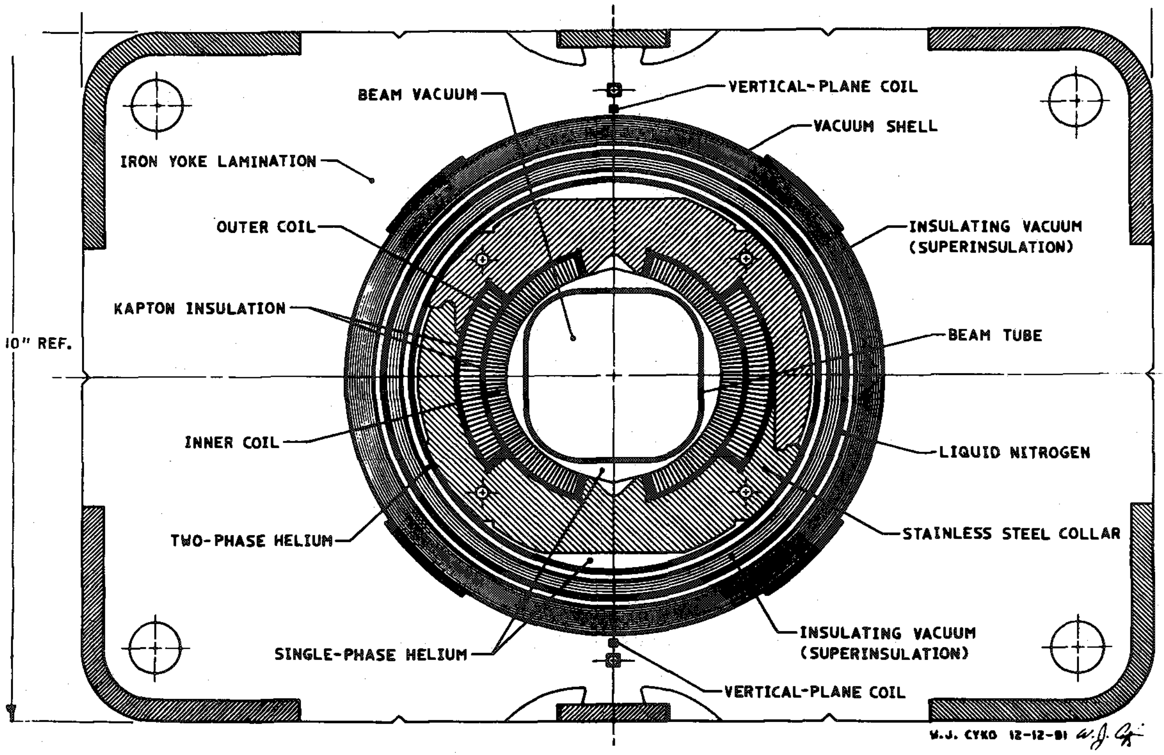


Fig. 8 Cross-section of a Tevatron dipole

came partly from the good dimensional stability of Rutherford cable, but probably more importantly from the fact that Fermilab coils were made porous to liquid helium. Perhaps I may digress for a few moments to develop this point.

We have already seen how fine filaments can eliminate flux jumping, which originally was the main factor preventing magnets from reaching their full current. Unfortunately, it was not the only factor and experience has shown that mechanical effects can also cause problems. If, for example, a winding carrying a current density of 250 A·mm^{-2} in a field of 6 T moves a distance of 10 μm, the field will do work of 1.5×10^4 J m^{-3}. In the most likely event of this work being released as frictional heating, it will raise the temperature of a typical winding at 4.2 K by a couple of degrees—quite sufficient to precipitate a quench. It is very difficult to engineer to a precision of 10 μ m, and many of us have tried to overcome the movement problem by vacuum impregnation with epoxy resin. Unfortunately, epoxy resin (and most other usable insulating materials) contracts much more than the superconducting wire. When cooled to low temperatures, the epoxy therefore finds itself in a state of tension. To make matters worse, epoxy resins become brittle at low temperatures. There is thus a very good chance that the addition of magnetic stresses to the pre-existing thermal contraction stresses will precipitate a crack in the epoxy resin. When this happens the thermal contraction strain energy will be released as heat and one may easily show that this is likely to raise the temperature by many degrees. The net result of these mechanical effects is that coils are likely to 'train', i.e. on first energization the coil will quench at currents well below critical and on subsequent energizations (with luck) the quench current will increase. However, this is a rather random process and coils which require many training quenches are unlikely ever to reach their full critical current.

Various techniques have been developed for pre-loading the coils in order to reduce mechanical training effects, with mixed results. Fermilab coils were pre-loaded by their stainless-steel collars, but in addition, the windings were left porous to liquid helium, which was able to absorb much of the mechanical energy release. It is a little bit like cryogenic stabilization, dismissed many years previously by those of us who had shown that cryogenic stabilization would be completely ineffective at such high current densities, because the ohmic heat generation would be too high. What we had all forgotten was that transient heat transfer to liquid helium can be very much higher than steady state, so that if a conductor can recover quickly from a mechanical energy disturbance, the instantaneous ohmic heat generation can be stable at much higher levels than one might at first think. Figure 9

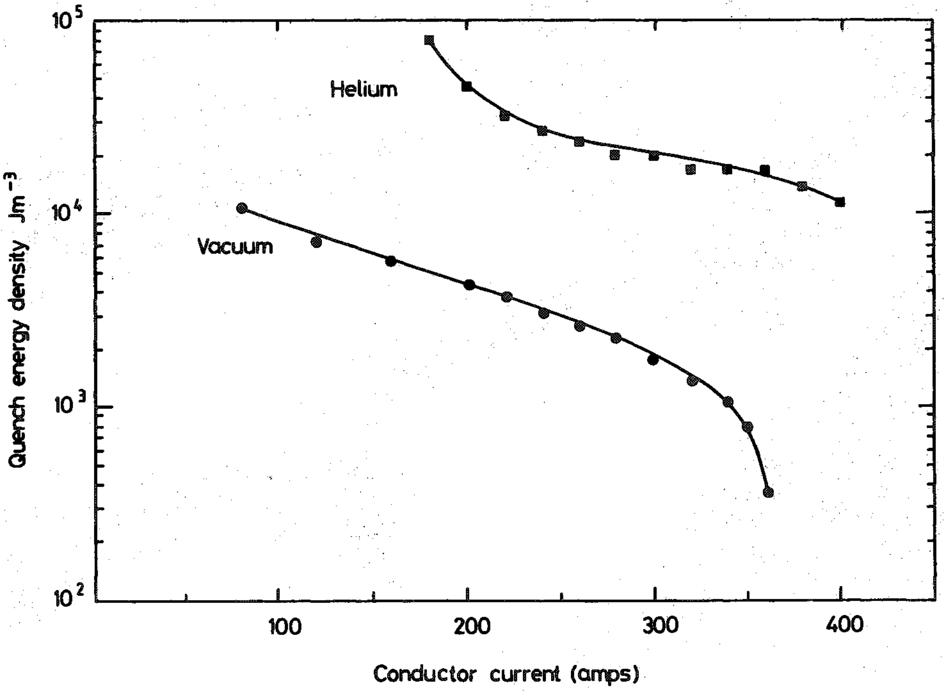


Fig. 9 Magnitude of pulse needed to initiate quenching of the same superconducting wire in thermal isolation or in contact with liquid helium. (Measurements by D.E. Baynham and V.W. Edwards.)

shows some measurements we made at Rutherford, depositing fast energy pulses into a superconductor and measuring the energy density needed to trigger a quench. It may be seen that wires in metallic contact with liquid helium are able to absorb about 20 times as much energy as those which are thermally isolated. Because the process of energy deposition and recovery is very fast, very little liquid helium is involved in the process — no more than the small quantities trapped in the interstices of a Rutherford cable — provided it is not filled with epoxy resin! Although small, this liquid can bring about a substantial increase in the cable's ability to absorb a mechanical energy disturbance without quenching. I have no doubt that this simple fact has contributed greatly to the successful performance of Rutherford cable in the Tevatron and subsequent accelerator projects.

8. HERA

In Europe, the tunnel for the Hadron Electron Ring Accelerator (HERA) is now wending its way beneath suburban Hamburg. HERA consists of a pair of storage rings for 30 GeV electrons and 820 GeV protons[15)]. Superconducting magnets are used for the protons, with 416 bending magnets at 4.68 T central field and of 8.82 m length and 224 quadrupoles of 91.2 $T \cdot m^{-1}$ gradient. Rutherford cable is used for both magnets in a two-layer coil configuration with collar clamping very similar to the Tevatron. Figure 10 shows the laminated aluminum alloy collar clamps, which support the magnetic forces, being fitted to a dipole. Unlike the Tevatron, a laminated iron yoke will be placed close to the magnet, within the helium cryostat. The fourth superconducting dipole has recently been tested, reaching its short-sample current of 6700 A, very comfortably in excess of the design current of 5027 A. Figure 11 shows one of these dipoles in its cryostat. Production of half the dipole magnets by an Italian consortium of LMI, Ansaldo and Zanon has already started, and tendering for the other half is in progress. The quadrupole design was developed at Saclay and orders for series production of these magnets will be placed shortly.

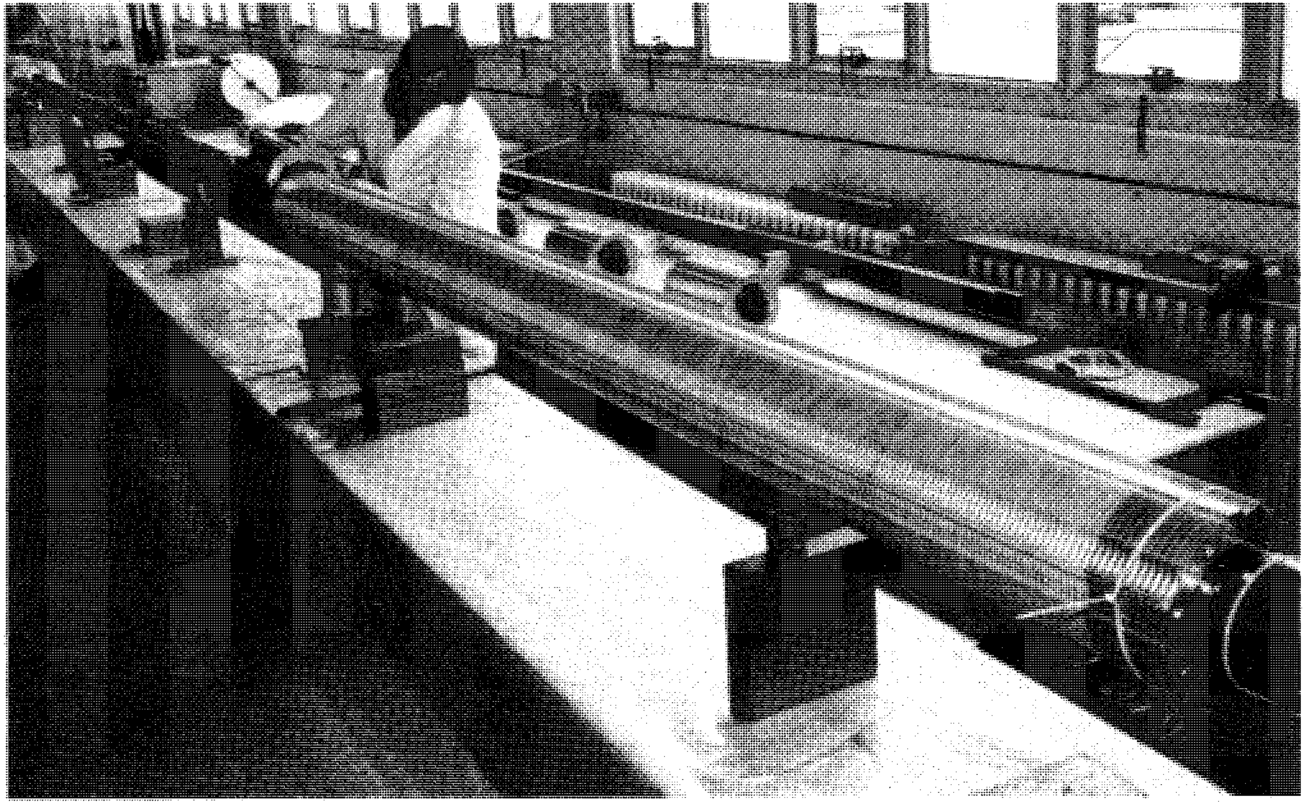


Fig. 10 Fitting the aluminium alloy collar clamps to a HERA dipole

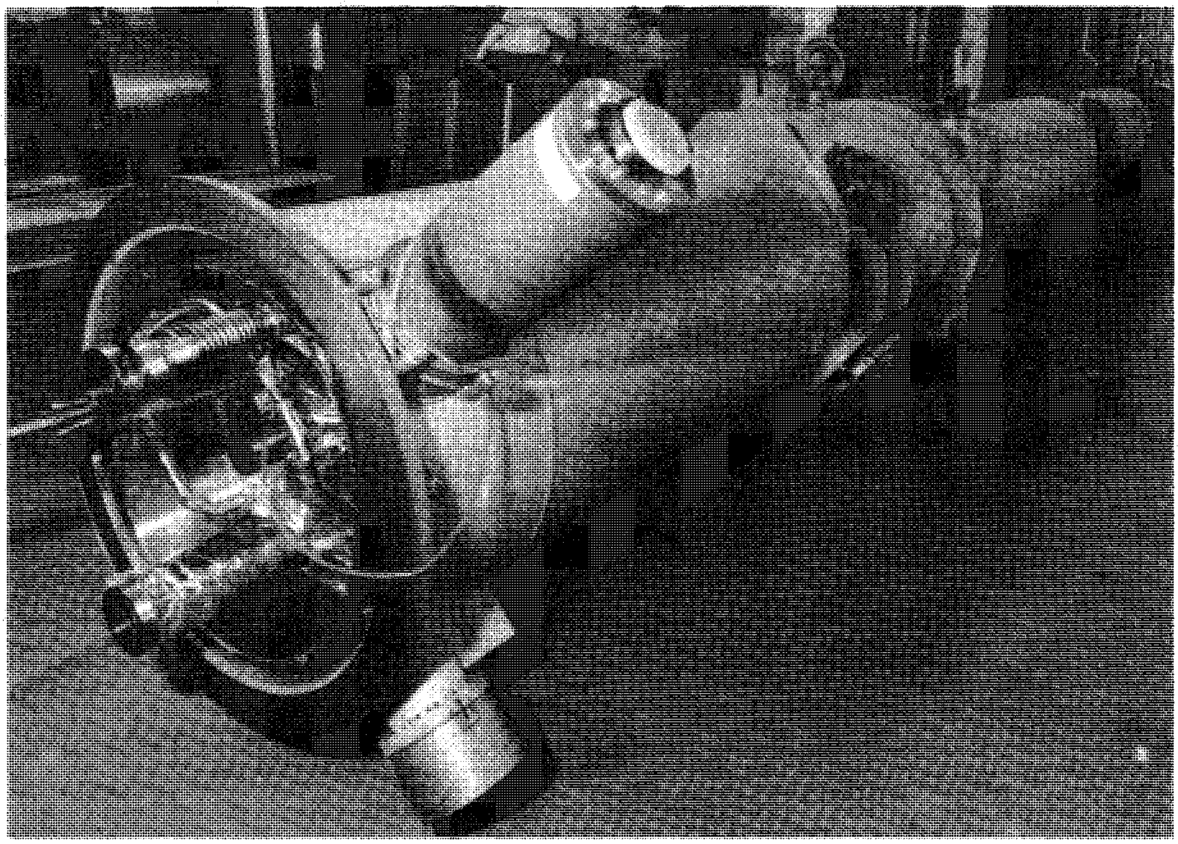


Fig. 11 Complete HERA dipole in its cryostat

9. ACCELERATORS FOR THE FUTURE

Looking beyond the present generation of accelerators, we see brave new plans for the future. In the USA, the SSC waits hopefully for budgetary approval to proceed. It is a pair of 83 km circumference storage rings for colliding 20 TeV protons on protons[16)]. Magnet designs will be very much like those of HERA, but with a field of 6.6 T, a bore of only 32 mm and a length of 17 m. Liquid-helium refrigeration for this enormous cryogenic ring will consume about 30 MW of power, but this should be compared with an estimated 4000 MW which would be required to power a conventional ring of similar size. Development of magnet technology and construction of prototypes is currently under way at Brookhaven, Fermilab, and Lawrence Berkeley Laboratory.

Here at CERN, there are plans for the Large Hadron Collider (LHC) to sit on top of the electron ring in the Large Electron–Positron Storage Ring (LEP) tunnel[17)]. Because LEP obviously has a fixed circumference of 27 km and because it is hoped to reach the highest possible energies, there is a natural desire to achieve the highest possible field in the dipoles. The general consensus seems to be that 10 T should be achievable, either by using niobium tin superconductor or by using niobium titanium at reduced temperatures. Although this is undoubtedly a very difficult target, we may draw some encouragement from results at KEK, where a nominal 10 T dipole has in fact reached an aperture field of 9.3 T, with a peak field of 10.4 T on the magnet windings[18)]. This magnet uses a niobium titanium Rutherford cable working at a reduced temperature of 1.8 K, with the magnetic forces supported by clamping collars of the Tevatron type.

10. OXFORD INSTRUMENTS

Now, I would like to say something about Oxford Instruments, where we make instrumentation for use in basic research, medicine and industry, with special emphasis on the use of superconductivity and cryogenics. In fact we are the world's largest manufacturer of superconducting magnets; they are mainly used to exploit the phenomenon of nuclear magnetic resonance (NMR), in many different types of instrument, spanning a wide range of activities—from unravelling the structure of proteins to monitoring the water content of margarine. In recent years, the use of NMR in medical imaging systems has emerged as the largest single user of superconducting magnets. I know that, in present company, I need have no qualms about using the proper scientific terminology 'nuclear magnetic resonance imaging'—but in these difficult times our marketing people prefer the less controversial title of magnetic resonance imaging (MRI)! Figure 12 shows a typical MRI scan. It may be seen that the image quality is comparable with X-ray computer tomographic imaging, but there are two significant advantages which account for the system's great popularity. Firstly, because it measures the density of protons, the image gives greater contrast to living tissue than to bone. Secondly, as far as we know, there are no harmful effects from exposure to the magnetic fields used. Figure 13 shows the 500th MRI magnet produced by Oxford Instruments. A notable feature of these systems is the careful cryogenic insulation, giving a residual heat leak of 1/4 litre of liquid helium per hour, which I hope the cryogenic experts will agree is quite an achievement for a system of ≈ 2 1/2 metre diameter and length.

Working on a somewhat larger scale, we were pleased to win the contract to build a large solenoid for use in the CLEO II experiment at the Cornell Electron Storage Ring. In view of the large scale and force level we decided to adopt the inside winding technique, so that electromagnetic forces may be supported by the coil shell. There is no liquid-helium cryostat; cooling is provided by an array of pipes attached to the outer shell and cooled by liquid helium flowing under thermo-syphon action from a large storage dewar located about the magnet. Coil bore is 3.5 m and field will be 1.5 T; Figure 14 shows the coil being assembled into the outer vacuum tank of its cryostat. Having established production facilities for large coils of this type at Oxford Instruments, we are now naturally anxious to persuade high-energy physicists away from their traditional 'do-it-yourself' approach to building large solenoids!

Fig. 12 Magnetic resonance image of the brain. (Courtesy of Picker International.)

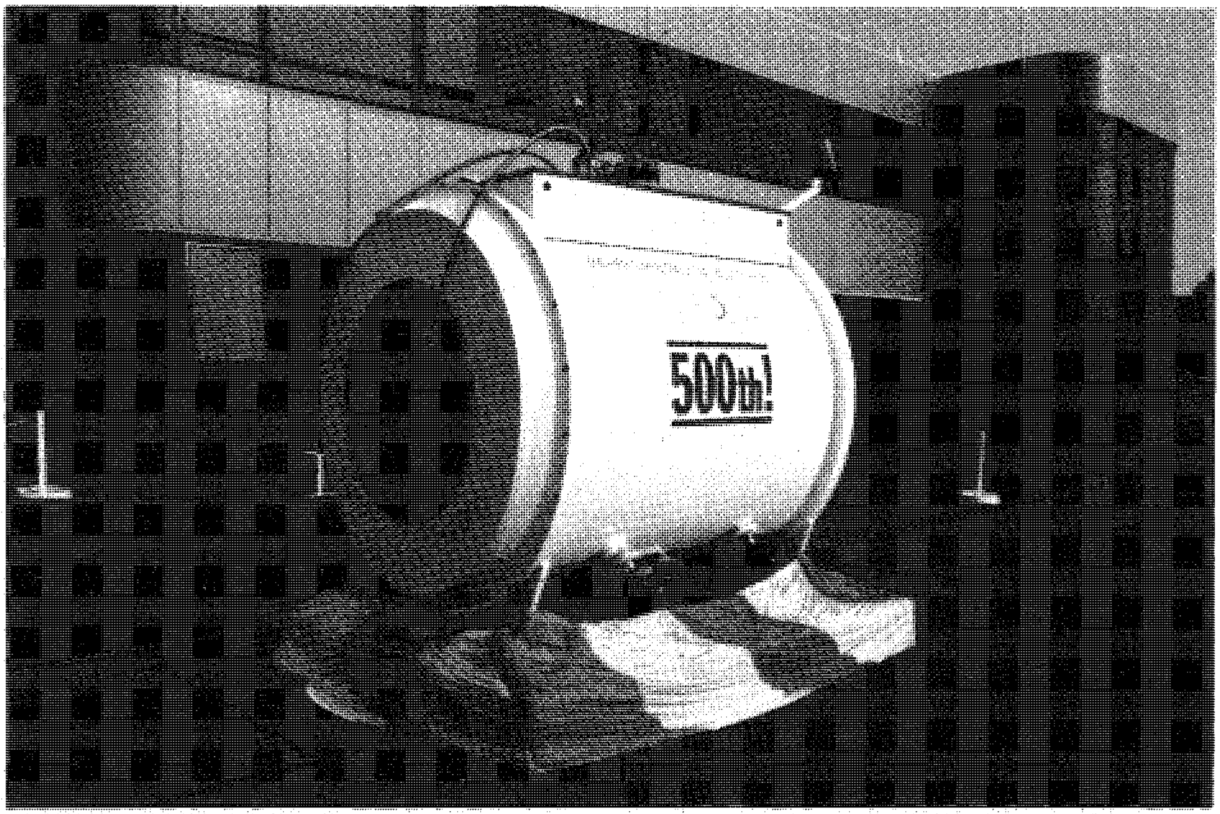


Fig. 13 Superconducting magnet system for magnetic resonance imaging: the 500th produced by Oxford Instruments.

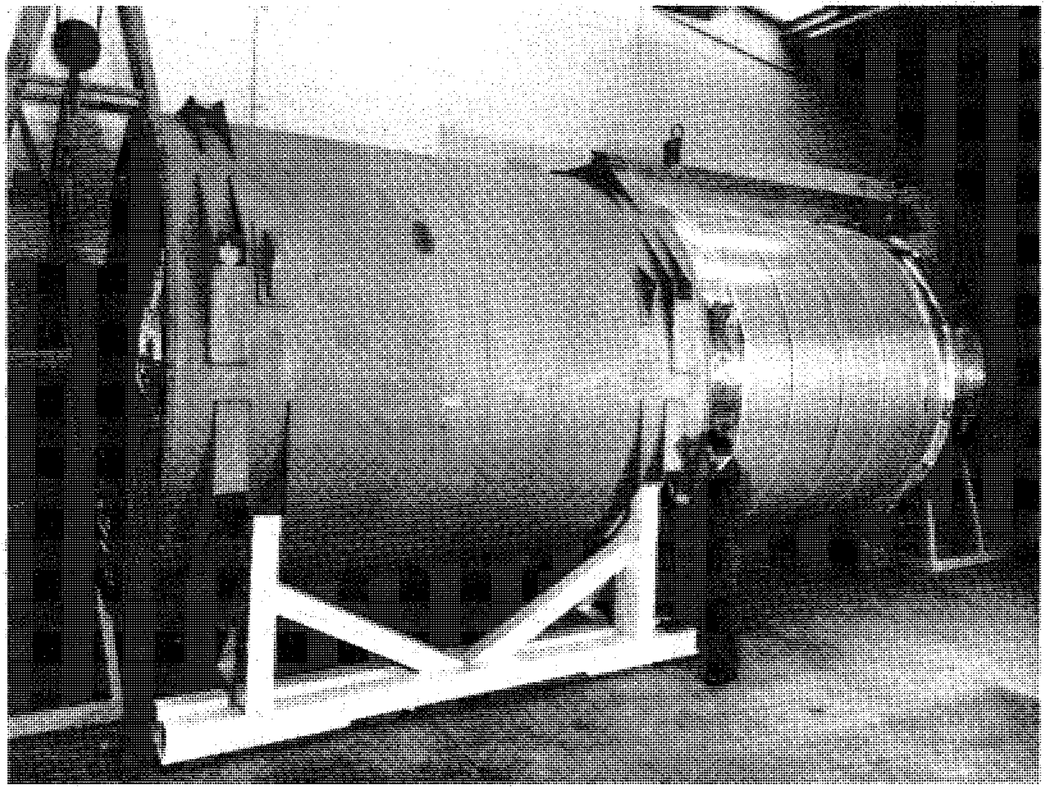


Fig. 14 Assembling the CLEO magnet at Oxford Instruments; superconducting coil at left is about to be inserted within the outer vacuum tank, which already contains the intermediate temperature radiation shield.

11. X-RAY LITHOGRAPHY

Finally, I would like to tell you about a new development which is currently keeping us very busy at Oxford Instruments. It is a compact synchrotron X-ray source, intended as a production tool for the next generation of micro chips. Recent years have seen a veritable explosion in the power that can be obtained from a single VLSI chip. This explosion has been more or less directly linked with the minimum feature size—smaller sizes mean more circuits per chip and faster switching times. Over the last 15 years this feature size has gone down steadily from ≈ 20 μm to the present ≈ 1 μm.

As you probably know, the pattern on a chip is produced by an optical lithography process whereby light is shone through a patterned master mask onto the silicon surface, which is coated with a photo-sensitive material. So far, this process has coped rather well with the continuing demand for reduced feature size—albeit at the expense of some very sophisticated lenses and optical techniques. However, bearing in mind that the wavelength of visible light is ≈ 0.4 μm, it is clear that diffraction effects are now becoming very troublesome and that the ultimate limit cannot be too far away. If you require much smaller linewidths—and there is no doubt that many people do—you must adopt a new technique. There are many possibilities, but the most promising for mass production seems to be a technique which retains the same general idea of shining light through a mask, but which reduces the wavelength. It turns out that the next convenient 'window', where one can have transparent masks but with good contrast absorbers, is in the soft X-ray region at a wavelength of about 1 nm (i.e. 1400 eV photon energy). X-ray lithography has been demonstrated at linewidths down to ≈ 0.3 μm [19] and one can even purchase a commercial X-ray lithography system. However, if X-ray lithography is ever to be viable as a production technique, it will need a much more powerful and well-collimated X-ray source than the electron-bombardment type currently available. In fact there is only one known X-ray source whose intensity is sufficient to achieve the required chip exposure times; that is the electron synchrotron storage ring. Many national facilities, for example, Brookhaven, BESSY, and the Japanese Photon Factory, are now providing X-ray beams for lithography work, but nobody would seriously suggest that such large installations should be built inside a micro-electronics factory. What the lithographers would prefer is a straight replacement for their present light bulb! We are unlikely ever to achieve that but the scaling laws are such that, for the same X-ray intensity and wavelength, one can drastically reduce the size and electron energy of a storage ring by increasing its bending field. Naturally, we again look to superconductivity for that increase of field.

Figure 15 shows our project at Oxford Instruments for a compact superconducting storage ring X-ray source. It is in the form of a racetrack synchrotron with two 180° superconducting bending

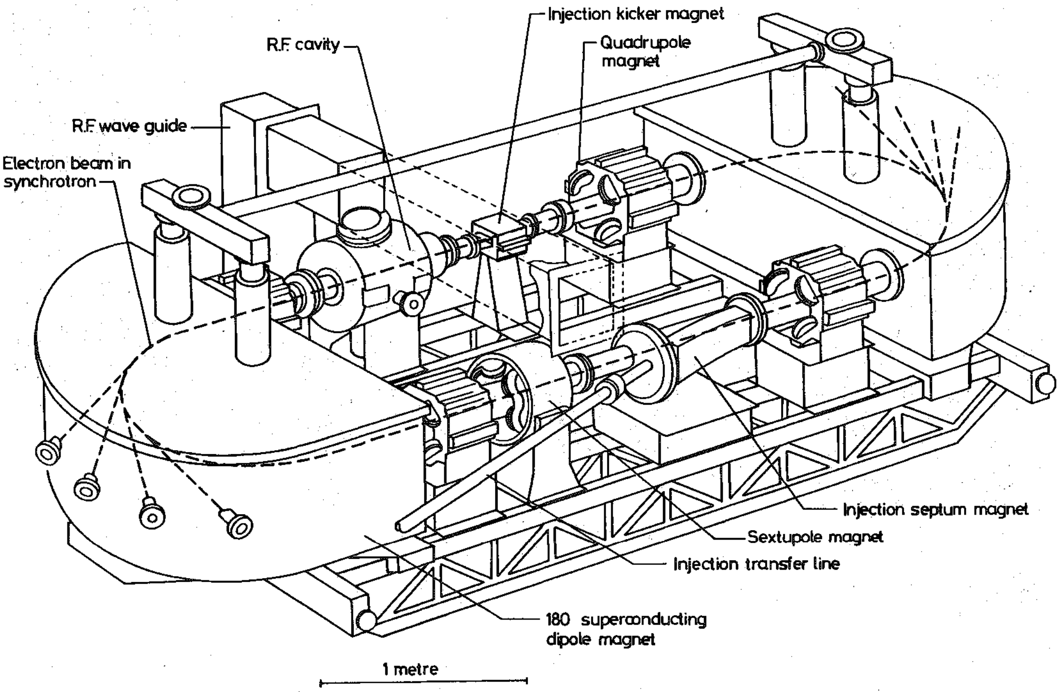


Fig. 15 The Oxford Instruments' project for a compact superconducting storage ring X-ray source

magnets. In the straight sections there are four conventional quadrupole focusing magnets and a sextupole for chromaticity correction. Injection is from a conventional linac, to be supplied by CGR MeV of Buc, France. Power for accelerating the beam from its injection energy, and also to make good the X-ray losses, is provided by a 50 kW, 500 MHz cavity driven by the klystron of a standard TV transmitter. Final energy of the electron beam is 700 MeV, producing an X-ray output power of 8 kW at a critical wavelength of 0.8 nm.

Although the layout is perhaps a little unusual, the only radically new component in this system is the 180° superconducting bending magnet. Design of this component is made difficult by the need to make curved windings and also by the need to leave a completely clear exit slot between the coils for the emerging X-ray beam. Work on developing the necessary technology for this magnet has been in progress for nearly three years at Oxford Instruments and it is good to report that we have recently tested a successful prototype. Encouraged by this success we have now decided to embark on the construction of a complete system with a time scale of about three years from now.

12. CONCLUDING REMARKS

It is interesting to remark that the association of superconductivity and accelerators now seems to be travelling in two directions. For the national and international laboratories, superconductivity has been used to make ever bigger and more powerful machines. In the commercial area, its main interest seems to be in reducing the size of accelerators—incidentally Oxford Instruments also has a project to build a compact superconducting medical cyclotron. At both ends of the spectrum, however, we are continuing to see a mutual benefit of one technology on the other. In fact it really has proved to be a very convenient and agreeable marriage for both partners—and one that seems set to last for many years to come.

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