PULSED SUPERCONDUCTING MAGNETS

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Abstract

The possibility of using superconducting magnets to increase the energy of present accelerators or to get very high energy in new facilities, has been studied in many laboratories all over the world. We review in the present paper the work which is made concerning the theoretical aspect of the behaviour of superconductor in pulsed field, the present conductor status, the field tolerances and correction, the magnet construction problems and finally the experimental results obtained recently in testing coils of different sizes and shapes.

I. Introduction

In the general line of the applications of superconductivity to magnets, the field of the pulsed magnets for accelerators was quite intensively studied in the past years. As soon as the theoretical studies showed the necessity of using a few micron twisted filaments to reduce the hysteretic losses and when these conductors were obtained from industries in long enough quantity and with good quality, many projects were made. Two kinds of facilities were studied : with the first one it will be possible to increase the energy or the intensity of present or being built machines (Argonne, Batavia, CERN II) by a factor of 2 to 3 using the same tunnel. The second possibility is to design a new machine with a higher energy than that existing now, the use of superconducting magnets giving new performances and or lower costs (ISABELLE).

In these machines the new aspect will be the magnetic system and its environment, namely the multipolar magnets, their cryostats and their electrical and cryogenic supplies. The main characteristics of the machines, mainly the magnets, are studied and discussed in the laboratories working in this field : National Accelerator Laboratory (Batavia), Argonne National Laboratory, Lawrence Berkeley Laboratory, Brookhaven National Laboratory in USA, the Radiotechnical Institute (Moscow), the Electrophysical Institute (Leningrad) in USSR , and the Institute für Experimentelle Kernphysik (Karlsruhe), the Rutherford Laboratory and the Departement Saturne (Saclay) in Western Europe.

The dipoles which will be the largest part of the magnets will be discussed in the following chapters, many results being also applied to the focusing quadrupoles and higher order correcting lenses.

The maximum field value which has been considered varies from 4 T to 6 T. It should be clearly understood that for a given total radius the energy of the machine is proportional to the field but that construction problems and cost will also increase for a higher field. When the final energy has been fixed some economical studies show an optimum field value around 4.5 T to 5 T. However as usual, this optimum is quite flat and the choice of the field is still open.

The bending magnets must have a homogenous field. Homogeneity is defined through the field integral performed along the magnet for different positions in the bore. The tolerances which are stated now is a relative field integral difference of a few 10^{-4} in all the region where particles will circulate.

One should add some space to take into account magnet construction tolerances to this useful region defined by the beam width, particle oscillation, injection and extraction conditions. Finally the coil aperture we are led to, corresponds to a diameter of 5 to 6 cm for the Batavia doubler, about 8 cm for the ISABELLE project whereas the European laboratories are designing magnets of 8 to 11 cm diameter for the CERN II superconducting alternative.

The last point to be mentioned concerns the cycle duration. The basic value corresponds to the 8 to 10 s pulse duration of the European 400 GeV conventional magnet version. However it is clear that increasing this value to 30 to 60 s will help in solving many problems such as magnet technology, low temperature losses, refrigeration, power supply, etc. The choice is still being discussed in Europe while it is clear that the cycle duration for ISABELLE will be a few minutes.

We will review now the work made in the past years in the study the design and the construction of pulsed superconducting magnets.

II. The production of the field

In this kind of magnet, the conductors give the dominant part of the field; so, the location of the currents is most important ; consequently, the coil configuration must be carefully designed and, during the construction, the location of the conductors must be sufficiently accurate so as not to be an important source of inhomogeneity.

Studies taking into account the magnetic iron shielding are however necessary to calculate its contribution to the field and to minimize the saturation effects.

For all the sources of inhomogeneity tolerances are prescribed so that their effect may be corrected by systems of small dimensions.

1. The shape of the coil

In two dimensions, one can analyse the complex field inside the aperture of a coil by a Taylor series :

$$B = B_x - i\,B_y = \sum_{n=1}^{\infty} c_n\, z^{n-1} \qquad (1)$$

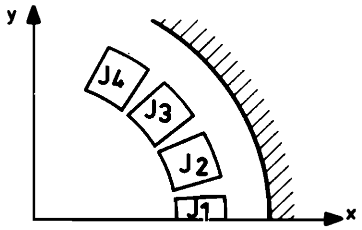
where

$$z = x + iy \qquad (2)$$

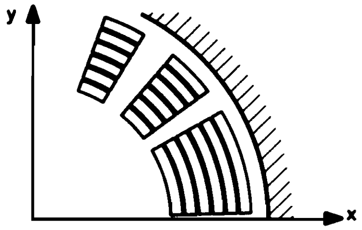
The c_n are called multipole coefficients.

For a perfect dipolar symmetry shape, the dipolar coefficient C_1 and its odd harmonics (C_3, C_5, ...) are only present; these coefficients are all imaginary.

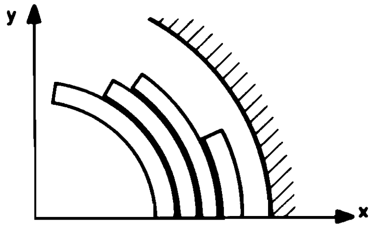
Starting from the two configurations giving a pure dipolar field (intersecting ellipses and $\cos\theta$ current density distribution on a circular or an elliptical boundary), one has to make practically windable approximations. Studies made in different laboratories,[1,2,3,4] lead to configurations producing a field homogeneity of a few 10^{-4} into 60 to 80 per cent of the aperture (fig. 1).



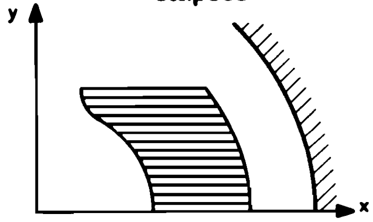
Approximation of $J_0 \cos\theta$ by four blocks



Approximation of $J_0 \cos\theta$ by spaced sectors of constant current density



Concentric layers of constant current density approximating either $J_0 \cos\theta$ or intersecting ellipses



Approximation of intersecting ellipses by shaped blocks of constant current density

Fig. 1. Shapes of coils under construction in differents laboratories.

These results may be obtained either by the cancellation of several multipole coefficients or by balancing their effect in the median plane (fig. 2).

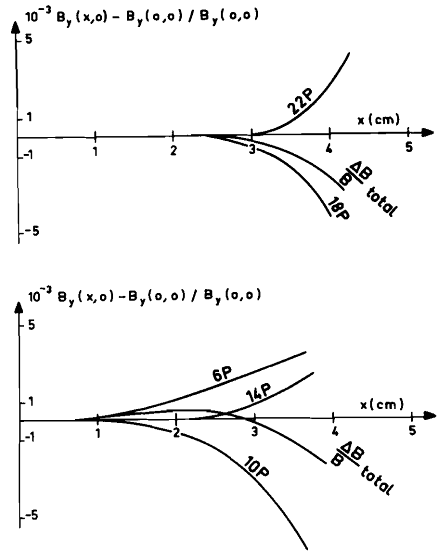


Fig. 2. Production of a good field homogeneity either by cancellation of several multipole coefficients (above) or by balancing their effect in the median plane (below)

One can also possibly conceive window-frame or H-type superconducting magnets[5]; the shape of the coils is then very simple but one has to shape the shielding to minimize the sextupolar coefficient at low field and to set additional corrections to minimize the saturation effects at high field (fig. 3).

Practically, one has to take into account the finite length of the magnet and its ends, wound as to keep free the vacuum chamber. The results given in two dimensions for B_x and B_y are also valid in three dimensions for the field integrals K_x and K_y along the azimuthal axis s :

$$K_x\ (x,y) = \int_{s=-\infty}^{s=\infty} B_x\ (x,y,s)\ ds \qquad (3)$$

$$K_y\ (x,y) = \int_{s=-\infty}^{s=\infty} B_y\ (x,y,s)\ ds \qquad (4)$$

One can write :

$$K = K_x - i\ K_y = \sum_{n=1}^{\infty} d_n\ z^{n-1} \qquad (5)$$

that is to define the multipole coefficient of a coil as its integrated value from $s = -\infty$ to $s = \infty$. Calculations have shown that it is possible, to minimize these coefficients d_n, by shaping the ends.[6,7,8,9,10] However, these end effects are small for the long dipoles that one bears in mind now (≠ 6 m for the superconducting version of CERN II).

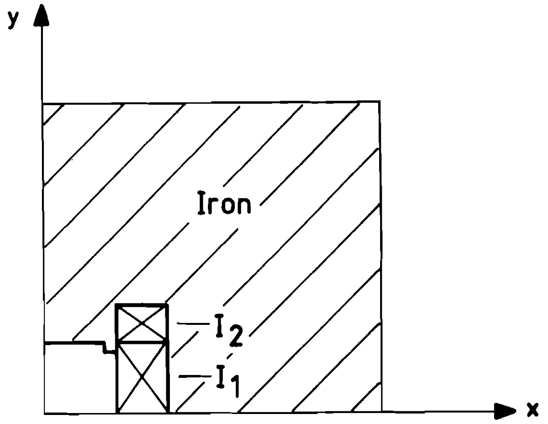


Fig. 3. H-type dipole (Brookhaven National Laboratory).

2. The iron shielding

First conceived to canalize the magnetic flux, the iron shielding is also such that it increases the field and it reduces the stored energy ; the magnitude of these two effects depends on the location of the shielding ; most laboratories put the shielding inside the cryostat (cold iron) in order to make the best of these advantages. Typically, for a field of 5 T in an aperture of 10 cm, the contribution of the iron shielding is about 1.5 T with a consequent reduction of the stored energy.[11]

This laminated iron shielding can be of circular or rectangular shape. The present computer programs such as GRACY, LINDA, MARE, MAGNET, POISSON, TRIM enable one to locate and to shape the iron shielding in order to minimize saturation effects ; eventually, one can take into account these saturation effects to cancel one multipolar coefficient ; but this result is valid for only one field value.

Neglecting the saturation effects, one can prove analytically that a circular and well centered iron shielding around a circular symmetry coil improves the field homogeneity ; for a non circular symmetry coil, the iron shielding can generate harmonics which were not present for the coil alone.

3. Construction errors

Other sources of inhomogeneity than those coming from the conception of the magnet (reference shape of the coil, finite length, ends, saturation, ...) must be taken into account. They result from the winding of the coils and from their location in the iron shielding. All these sources may be listed into three types :

- systematic errors for all the magnets.
- random errors from one magnet to another (they affect the field and its homogeneity).
- random errors inside one magnet (they affect the field homogeneity).

The sources of inhomogeneity due to the conception are of the first type and the sources due to the winding and the location are of the three types ; one can distinguish :

- location of the conductors inside the coil, especially those on the boundaries.
- location of one half coil compared with the other.
- location of the whole coil into the iron shielding.

The accepted tolerances in order to get a few 10^{-4} in the field homogeneity in 70 per cent of an aperture of 10 cm are :

- random location of the conductors with a root mean square value of about 0.3 mm.[12,13,14]
- location of one half coil compared with the other with a rms of 0.05 mm.[13,15,16]
- location of the whole coil inside the iron shielding with a rms between 0.1 an 0.5 mm.[13,16]

Copper models have shown that these tolerances may be kept.[2,3,17]

4. The "bad-field" margin

For all the sources of field inhomogeneity, let us say again that it is of first importance to distinguish the systematic and the random ones. For an accelerator with a great number of magnets the whole effect on the beam of the random errors will be less important than the effect of the random errors in one magnet,due to compensation ; for the systematic errors, the whole effect will be the same as the effect for one magnet.

The distinction is however delicate because it often depends on the construction process ; on the other hand, for most errors of construction, one part is systematic and the other one erratic.

Whether one attributes the errors to one magnet or to a great number of magnets, the useful aperture, defined by $|\Delta B/B \text{ total}| \lesssim$ a few 10^{-4}, is between 60 to 80 per cent of the aperture.[13,15,18] Other definitions of the useful aperture are possible but lead to the same results,[15] that is a margin of 10 to 20 mm between the end of the useful radius and the conductors for a total aperture of 10 cm.

5. The "remanent" field

Due to the nature of the superconducting wires, diamagnetic and circulating currents with very long time-constant are generated in the wires after a first field-rise. These currents generate a conductor diamagnetic field with a strong sextupolar term and so disturbing during the injection.

The theory,[19] in reasonable agreement with measurements,[20,21] shows that one has to reduce the size of the filaments and the critical current density for zero field ; incidentally, the higher the injection energy is, the weaker this disturbing effect is.

New theoretical results[22] have shown that this effect is variable during the accelerator cycle ; the figure 4 shows the calculated perturbation due to the remanent field during a triangular cycle up to 5 T for the dipole MOBY with its iron shielding ; the penetration of the superconducting material and the fact that the critical current Jc in the superconductor is a function of the maximum field are taken into account.

This variable effect enables us to correct this disturbing residual field with dynamic correcting devices.

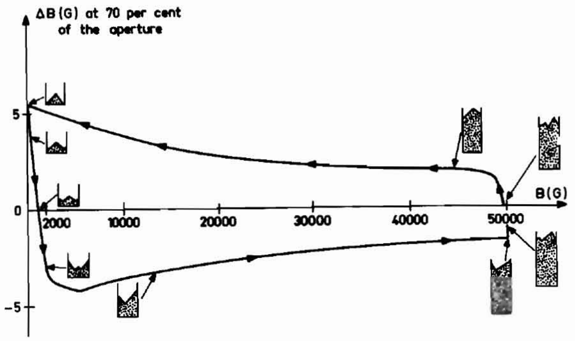


Fig. 4. Perturbation due to the remanent field during a triangular cycle (profiles of penetration of the superconducting material are shown at different moments of the cycle.)

6. Correcting devices

Several correcting methods are possible to improve the field homogeneity :

- correcting lenses independent from the magnets

- multipolar corrections made of N blocks regularly located within the main coil aperture ; these corrections are supplied independently of the main coil[23]

- corrections made with short-circuited windings ; they are located within the aperture and the induced currents correct instantaneously the unwanted harmonic during the whole cycle.[13] Experimental results with a sextupolar symmetry device (fig. 5) have shown a reduction of a factor 6 of the sextupolar term.

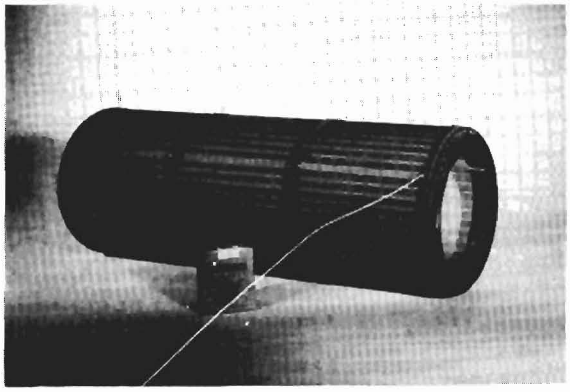


Fig. 5. Self correcting device. (CEN-Saclay)

The variable aspect of the conductor diamagnetic field enables one to use this method for its correction.

III. Conductor

1. Theory

Building pulsed superconducting magnets implies using composite conductor made of thin superconducting filaments embedded for mechanical reasons in a normal material matrix and twisted for electrical reasons. The effects of such a configuration were studied theoretically from both points of view : hysteretic losses in the conductor with transport current and stability (flux jumps, wire movements etc...).

If twisting the conductor may be considered as a perfect transposition with respect to the uniform external field, it is clear that it is not the case when one considers the field due to the current in the conductor itself, namely the self field. This imperfect transposition leads to a change in the current sharing between filaments which has been analysed both theoretically and experimentally.[24,25,26,27]

The calculations show that, close to the maximum transport current for the given field, the dissipated power grows rapidly. This effect will have practical consequences on the design of the coil cooling.

Contrarily to what was believed some years ago self field effects do not lead to important extra losses[25,28,29] and instability. However, the stability remains slightly lower than one thought according to simple theory.[30] However it appears that, for a given matrix to superconductor ratio, increasing the total number of filaments means a larger twist pitch due to a larger strand diameter and consequently more losses ; equally the adiabatic composite stability is lower. It seems that an upper limit will be reached for a conductor of several ten thousand of filaments.[26] On the other hand a conductor made of filaments located only in the composite outer part should be more stable than a conductor where the filaments are uniformly located.

The non orthogonality of current and field due to the twist gives actually a local increase of the current density j_c. The measured change in j_c when taken into account could show in particular cases only a very slight increase of the losses.

The influence of the temperature on the losses was studied.[25] Higher temperature means lower current density and local change of the electrical field. The effect is an increase or a decrease of the losses depending on which one of the phenomena is the most important. It has been checked qualitatively.[1,32]

2. Critical current density

The only superconducting material now being used for pulsed magnets is the niobium-titanium alloy. Depending on the alloy characteristics and heat treatment, the critical current densities are quite different, typically for a 6 T field the average value is 1.2 10^9 A/m2. Higher values can be obtained with particular heat treatments and impurity but then the mechanical properties lead to fabrication difficulties (breaks) during wire drawing.

One must remember that for a 6 T field no current will flow in Nb-Ti wire; if its temperature is 6.5°K the corresponding value is 7.5°K for a 4 T field ; stated in other words a 0.2°K temperature increase of a conductor in a 6 T field means a 10 % decrease of its critical current density. From this point of view the materials being studied now : filamentary Nb_3Sn, V_3Ga, Nb_3Ga are quite promising for the future.

3. Multifilamentary conductor topology

Losses and stability considerations called for reducing the filament size down to a few microns.

The need of a many thousand ampere intensity in the magnets leads to a total number of 5 to 10 μ filaments of about 10^5. Today a strand is made of 300 to 1000 of these filaments embedded in a normal matrix, the 0.5 mm diameter strands being then assembled together (fig. 6). Very new conductors are tested with a high number of filaments per strands.[33]

A higher number of filaments allows the use of a higher conductor which will facilitate the fabrication of the final conductor and give a larger average current density in the coil. However there will arise, as already stated, stability and losses problems due to self field effects. This will limit very likely the number of filaments to a few ten thousand.[26]

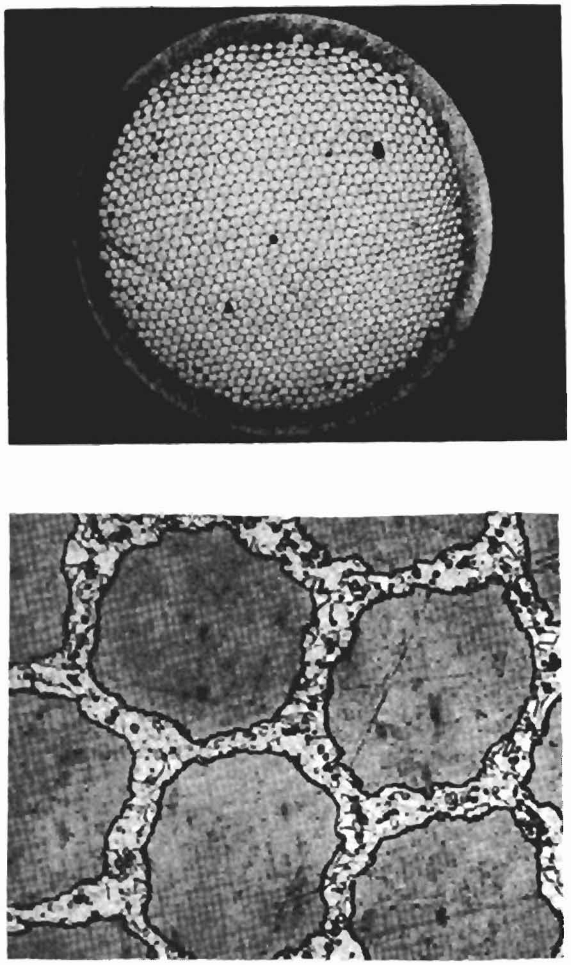


Fig. 6. Typical superconducting composite conductor (above) and filament (below).

4. Matrix material

The choice of the matrix material is determined by contradictory requirements. Copper which has good stabilisation properties does not always limit enough the induced currents. Due to its high resistivity, cupronickel exhibits lower extra-losses (smaller induced currents) or for a given percentage of total losses allows longer twist pitch and eventually bigger strand diameter. However coils made of cupronickel matrix conductor were less stable.[26] A good compromise should be given by a two component matrix, where each filament is directly surrounded by copper, and then embedded in cupronickel; this conductor is not very stable (it has not enough copper) and quite difficult to draw out. Conversely when a very small amount of cupronickel around each filament and the copper is the matrix the conductor is stable but induced currents between filaments located for one from the other, are important and extra losses may be obtained for big conductors.

A more sophisticated solution is being tested[33] (fig. 7). Almost all the laboratories studying low rise time field magnet using conductors with less than 1000 filaments prefer now copper matrix. Many discussions are still important in this field; the solution will depend also on the strand assembly difficulties.

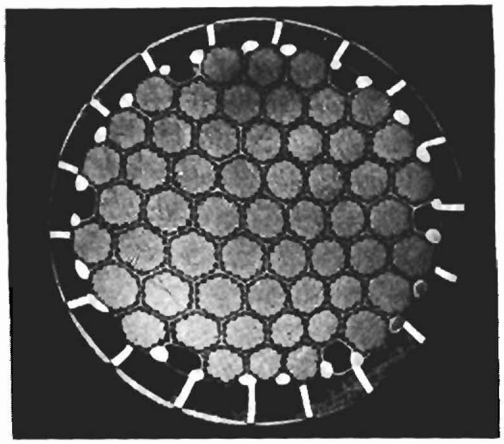


Fig. 7. Transverse section of the 13 255 filament composite (I.M.I.)

Whatever the choice of the matrix will be, the matrix to superconductor ratio which was reduced down to 1 to 1 to allow high average current density is now usually chosen between 1 to 1 and 2 to 1 after experimental results on small coils showed some instabilities for too low ratios.

5. Strand assembly

As long as a 10^5 filament conductor has not been constructed with good coils performance, it will be necessary to continue strand perfect transposition to get the final high intensity conductor. Braiding or cabling methods can be used in one or many stages (fig. 8). It always gives low filling factors (50 to 70 %) even with high compaction and obviously low average current density. One gets in the final conductor a current density of about 25 000 A/cm2 at 4 T field and 16 000 A/cm2 at 6 T field.

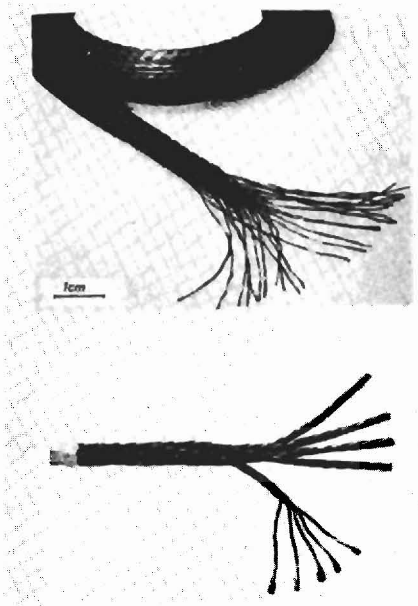


Fig. 8. Typical superconducting braid (above) and cable (below).

Whatever the assembling process is, the conductor is more or less subject to strand movement which leads to degradation and lower effective current in the coil. Such a trouble can be overcome by impregnating the conductor itself with an epoxy or a metallic filling material (Pb-Sn, In-Th, Ag-Sn, ...) and also the whole coil with an epoxy. Both the strand varnish insulation, and the epoxy having bad thermal conductivity properties, a good and efficient cooling must be designed to avoid a temperature increase. When the strand is insulated, the experimental results show no extra losses due to current between strands, but sometimes degradation and very often training was obtained.[1,17] Moreover it is hard to compact efficiently the conductor without shorts between strands. Very recent tests using polybondex insulation seem to be promising.[1]

The presence of a solder shows a very high increase of the measured losses as obtained with badly insulated strands, but heat treatement bring them back to a acceptable level. So, it could be accepted as a solution when the field rise rate is low (few kG/s) as the degradation due to the high losses rate, is not important. It should also be noted that the solder improves the stability by enthalpy effect.

Another proposed solution[21] consists in insulating each strand made of a complex matrix by an oxide layer. Due to its resistance, the layer will limit the induced currents between strands and then the extra losses while allowing an efficient high temperature compaction. It is still necessary to understand which of the high resistivity material in the matrix or the oxide would be the most efficient barrier. In the same line, work is done at Brookhaven[34] to reduce the induced currents by having a highly resistive bronze layer being formed around each strand by a heat treatment. It appears to be efficient only if the layer is thin enough. From the frequency dependance losses one can conclude that soldered conductor will be used only for small field rise rate.

Finally impregnation of the whole coil prevents degradation due to conductor or coil movements but sometimes degradation was observed and may be due to stresses appearing during the cooling down.

With today's knowledge, the choice of the number of filaments, type and matrix ratio and assembly (insulation, compaction, filling material, etc.) is still being discussed within the groups. The laboratories are engaged in different experimental lines due to different preliminary choices concerned with field rise rate, size of conductor, coil design etc. It seems very likely that comparing the work which will be done in the two coming years will lead to the right conclusion for each project.

IV. Construction problems

1. Coil

Whatever the shape of the approximation (starting from $J_0 \cos\theta$ distribution or intersecting ellipses), one has to build the coil very accurately and bend up the ends. The winding process must fit the conductor size (1000 - 5000 A) and its shape. A very flat and wide braid enables us to wind coils with one turn per layer (up to about 4 T ; for higher field, practical considerations lead to use more than one such coil). A square cable (or rectangular with an aspect ratio close to 1) lends itself to a winding in pancakes or double pancakes directly on cylindrical shape former (saddle shape)[21,35] (fig. 9).

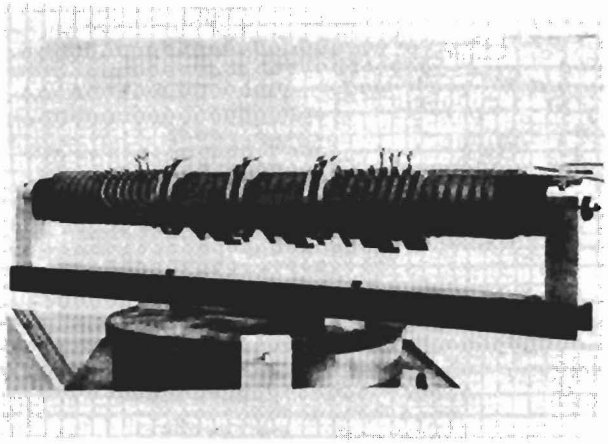


Fig. 9. Trial coil winding of a double layer pancake coil of AC4. (Rutherford Laboratory)

Special shapes[4,35,36] with a constant length of turn per layer, give a stable mechanical winding with only one piece of conductor per pole (no joints), (fig. 10 and 11). Generally one bends up the ends during the winding process but for some magnets[3] pancakes are wound flat, each end being bent up afterwards (fig. 12).

Construction tolerances require sophisticated equipments to be reached and numerous copper models, up to one meter long, have been carried out[3,35] to check the effects of construction errors on field map.

Although these models are still far from an industrial version, it is generally thought the required tolerances can be achieved.

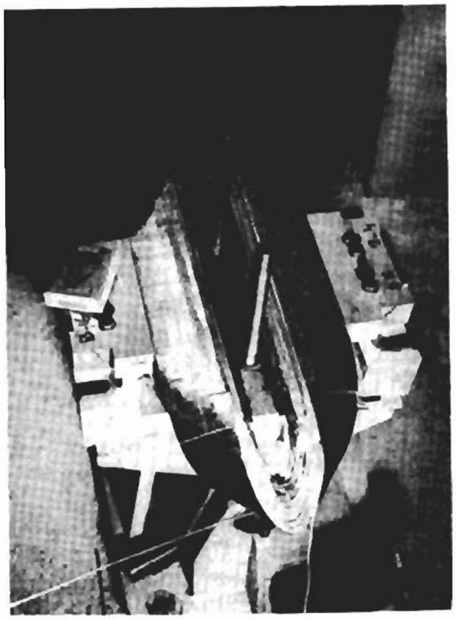


Fig. 10. Coil winding of MOBY dipole (CEN/SACLAY).

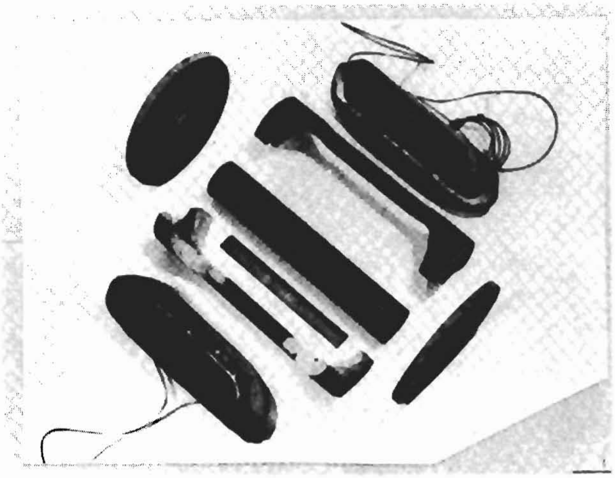


Fig. 11. Coil winding of dipole number 8 (Lawrence Berkeley Laboratory).

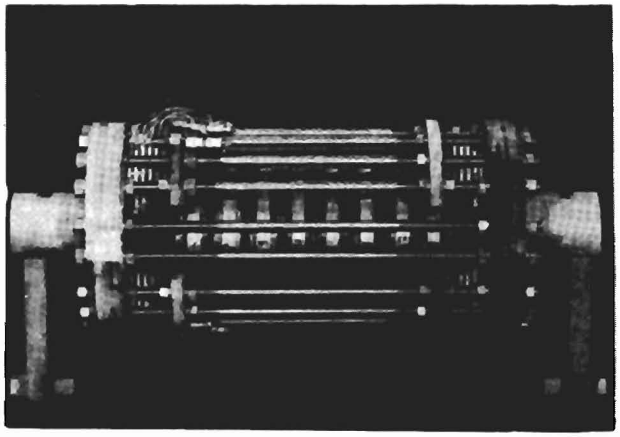


Fig. 12. D1 dipole magnet (IEKP Karlsruhe).

With copper to superconductor ratios close to 1 : 1 needed to reach high current densities, the conductor becomes very sensitive to wire movement and the coils are often impregnated to avoid these movements. Impregnation materials are usually filled or not epoxy resins. The impregnation is made either during winding directly on the conductor, or under vacuum for each pancake, or also under vacuum for the completed coil ; the conductors are generally kept in place during winding by a little amount of thermosetting material for the last two cases. Special effort is made to build very compact coil in order to get an equivalent Young modulus as high as possible and consequently to minimize deformations under stresses. Deformations of the coil give rise to change of the field map, extra losses and quenches. Cooling is obtained either by means of helium passages between layers[2,35] or by means of heat drains stuck to the layers[4,21] to drive the heat from within the coil to the helium bath.

The direction of the cooling passages varies according to the design, vertical passage being much better from heat transfer point of view. Some coils[1] using a very flat and wide braid are just cooled along their edges. Coils with heat drains have their drains protruding different ways from the coil into the helium bath.

For impregnated coils and heat drain coils the thermal contact behaviour between superconductor and resins is very important. This contact must remain good for the lifetime of the magnet and many studies are going on this subject.[21,37]

Provided thermal contact remains good for the life time of the magnet, heat drains have the advantage of giving a good packing factor and to equalize the temperature within the coil. In case of quench they make the propagation of normal state through the whole magnet easier, avoiding any hot point which could burn and destroy the coil.

2. Choice of the current

Many designers of pulsed superconducting magnets choose currents close to the ones used in conventional magnets ; this would enable us to use a similar voltage division along the tunnel for a superconducting synchrotron. It is also thought that with big conductors a better filling factor can be achieved for the coil winding. However, as it has been said previously one needs for the moment several stages (2 or 3) for the conductor assembly process and this leads to a poor packing factor of the conductor. Therefore the question can be asked whether a one stage low current conductor with a slight smaller filling factor during winding could result in a higher overall current density. The current lead problems would be much easier and the voltage division along the tunnel could be probably changed without difficulty.

3. Iron shielding

For the time being, the tendency is to locate the shielding as close as possible to the coil in order to get the maximum increase of the magnetic field and to reduce the stored energy. The only limit to this close position is saturation problems.

This solution makes the cryostat design much easier, its outer wall being then no more subject to variable field. In addition no other force than the weight has to be held through the cryostat.

In some designs, one thinks of using the shielding directly to contain the bursting forces of coils (typically 200 t/m for 5 T and Ø = 10 cm); it would then serve for both magnetic and mechanical purposes. The shielding is designed from the magnetic point of view and is too large from mechanical point of view, but as silicon laminations have to be used to reduce hysteretic losses and as these laminations become fragile at low temperature, the large mechanical dimension is in fact useful. Another advantage of large mechanical dimensions, is the very small deformations under stresses keeping a constant field homogeneity as the field increases (fig. 13 and 14).

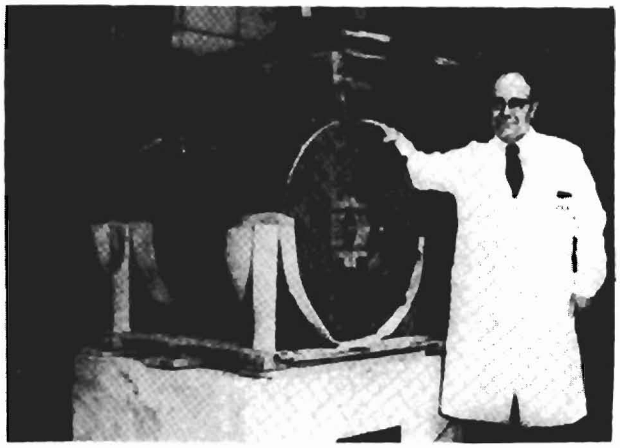


Fig. 13. Iron shielding of MOBY dipole. (CEN/Saclay).

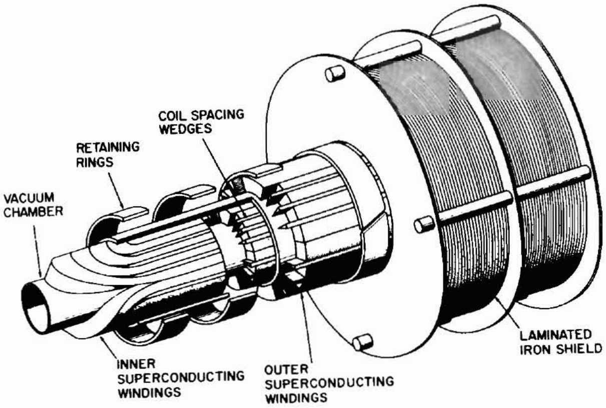


Fig. 14. Coil structure of a two-layer dipole.
(Brookhaven National Laboratory)

The thermal contractions of the coil and of the silicon steel are different and for that in some magnets one prefers not to use directly the shielding to contain the bursting forces. The shielding is then cut in two parts and must be supported by an external clamping structure.(fig. 15). Stainless steel tie rods are used to join the clamps together. Disc springs under the nuts of the tie rods serve to take up differential thermal contraction and thus keep the coil always in a state of compression, but unfortunately in using springs under stresses, this structure can move by a little amount.

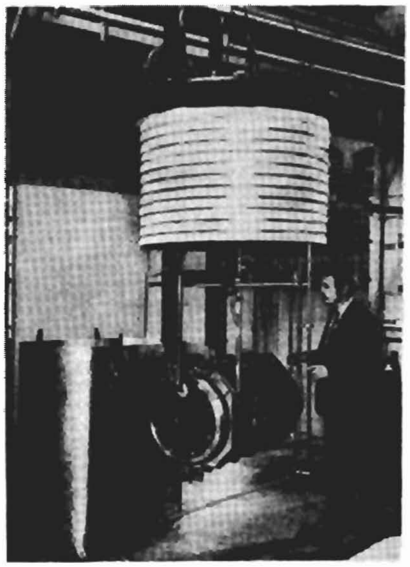


Fig. 15. AC4 dipole magnet. (Rutherford National Laboratory)

Important mechanical problems remain to realize stacking of laminations several meter long at low temperature and very few solutions which satisfy all requirements are coming out.

The main drawback of putting the iron shielding at helium temperature, in addition to the necessity of cooling down a big amount of material, is the hysteretic losses.

Taking as a basis magnetic measurements made at Brookhaven[38] (at 2 T and He temperature), losses of 5.10^{-2} J/cycle/kG are found for silicon steel (3.25% Si). This gives typically for a 5 T and 10 cm aperture dipole 90 J/cycle/meter which is roughly the superconductor coil losses if 10 μ filaments are used.

At same field but smaller aperture the amount of iron losses compared to the coils losses is less but still important The higher the maximum field in a constant aperture is, the higher the amount of iron losses is.

Of course, the comparison is still worse if 5 μ or less filaments are used. These figures are only calculated and one has to wait realistic measurements to check them.

4. Cryostat

The cryostat design is considerably simplified if the iron shielding is at helium temperature[17] ; then only the inner wall is under variable field. The losses per meter in such a tube are :

$$P = \left(\frac{dB}{dt}\right)^2 \pi r^3 \frac{e}{\rho} \qquad (6)$$

r = radius of the inner wall tube,

e = thickness of the wall,

ρ = resistivity,

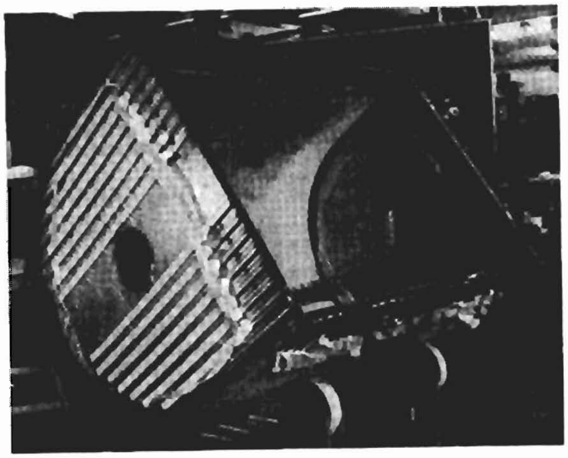
$\frac{dB}{dt}$ = speed of field variation.

With $\frac{dB}{dt} = 1$ T/s ; $r = 5$ cm ; $e = 1$ mm and $\rho = 5.10^{-7}$ m (stainless steel) one obtains $P = 0.8$ W/m which is not negligible ; non metallic tube, or corrugated stainless steel tube should be used if the rise rate is kept fast.

Very few cryostats working horizontally for pulsed magnets are under construction[17] (fig. 16) ; a special effort must be made to keep the overall dimensions small and for that, welded solutions have to be used extensively.

The magnet support system must be designed to have low heat leaks and to give a reproducible position of the magnet with regard to the cryostat after each cooling down in order to know from the outside where the magnetic axes are.

Whether to have current leads for each cryostat or for several of them is not solved, the first solution allowing an easier replacement in the accelerator tunnel. Studies made on the cooling system applied to a whole accelerator[39] seem to give a tendency where the magnets would operate in boiling helium bath, the cryostats being cooled by distributed refrigerators.



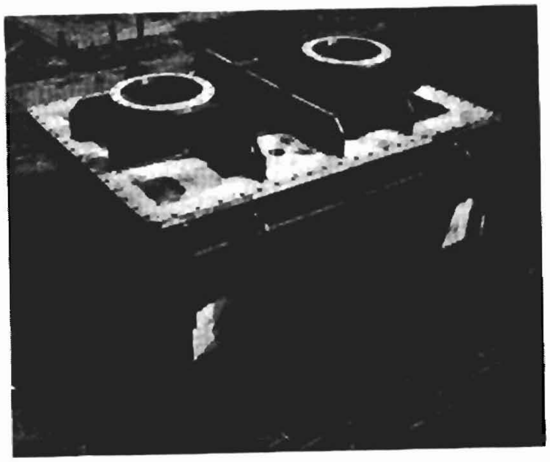


Fig. 16. Cryostat of MOBY (CEN/Saclay) : the nitrogen shielding (above) and the vacuum tank (below). (ALSTHOM Company)

5. Estimate of losses

For a 5 T dipole with an aperture of 10 cm which could be used on a 1000 GeV range synchrotron, the losses are estimated as a function of the cycle duration, on the following table 1. The filament size is assumed to be 10 μ .

This table shows that for a cycle duration of more than 30 s, the losses due to the cryostat and the supply are predominant ; so, it is not necessary to reduce below 10 μ the size of the superconducting filaments.

Table 1 : Estimated losses

Cycle duration (s)	5	10	20	30	60
S c losses (W/m)	18	9	4.5	3	1.5
Iron losses (W/m)	18	9	4.5	3	1.5
Cryostat losses(W/m)	4	4	4	4	4
Supply losses (W/m)	4	4	4	4	4
Total (W/m)	44	26	17	14	11

6. Radiation effects on materials at low temperature

Three types of problem arise :

- damage of materials (change of properties, destruction)
- increase of refrigeration power
- local temperature rises sufficient to make the magnet quench.

Typically,for a 1000 GeV synchrotron, 10^{13} particles per cycle of 10 seconds , a beam loss of 2% during extraction would give a mean dose of 10^7 - 10^8 rads per year and a peak dose of up to 10^{11} rads per year. This peak dose would occur downstream of the extraction region and is not tolerable because it would lead to a lifetime smaller than a year for insulants and anyway the temperature rise would be 10 to 100°K.[35] Therefore it is clear that one will have to shield these more exposed magnets.

Radiation effects on superconducting material result in change of properties but everything is not yet clear in this subject. Decrease of 5 to 10 % on critical current was observed on Nb-Ti along with the increase of the copper matrix resistivity up to a factor 50[40].

V. Experimental work

1. Assembly

As long as many thousand ampere intensity will be needed in magnets and high filament number conductor (> 5000) is not yet available, braiding or cabling a large number of wires with a perfect transposition will be necessary. But such transposed conductor have a low filling factor and a high compaction is needed to get suitable large current density. This compaction sometimes breaks or damages the wires and gives cross-over points.

For example in compacting a 24 insulated wire braid filling factor as low as 50%, we have had several breaks and a great number of shorts;[17] also a cable of oxide insulated wires had four broken wires (compaction 60%). These considerations favour a conductor with a low number of wires; nevertheless improvements in compacting are expected in the future.

2. Typical coil characteristics

Many solenoids have been built to understand the superconductor behaviour and to measure losses.

The characteristics of some recent coils are listed below as an example.

TABLE 2

Laboratory	Brookhaven[34]		Karlsruhe[41]	L. B. L.[42]	Saclay[17]	
Coil name	42	24		75	M1	M3
Coil						
inner diameter (cm)	2.5	2.5	2.4	6	3.90	3.90
outer diameter (cm)	7.5	7.5	8.4	10	12.3	12.3
length (cm)	4.5	4.5	5.3	6	8.20	8.20
B > at I_c (T)	5.3	5.3	5	-	6.9	6.6
potted	-	yes	no	-	yes	yes
Composite						
Cu/Sc	1.3	1.3	3 : 1	-	1.0	1.0
filament diameter (μ)	7	7	13.	11	10	10
filament number	210	210	361	-	1000	1000
composite diameter(μ)	200	200	0.5	279	440	440
twist pitch (mm)	2	2	0.4	-	2	2
Conductor						
type	braid	braid	-	braid	braid	braid
number of wires	33	33	1	48	24	24
transposition length (mm)	70	-	-	-	60	60
insulation	metal.	formvar	-	copper oxide	formvar	formvar
I_{DC}/I_c	1.0	0.7-0.9	1	-	0.95	0.96
I/I_c	1.06	0.6	1	-	0.23	0.94
for rise time (s)	-	-	-	-	2	2

Many other solenoids have been built in other laboratories but their characteristics have not been published or have not been available in time to be listed here.

3. Degradation

Insulated wire assembly :

In almost all the laboratories the organically insulated wire coils exhibited erratic behaviour. Some coils had a high degradation (I/I_c = 0.5 to 0.7), a few of them worked correctly. Depending on the particular case the reasons of their behaviour could be different. For example with a three wire cable (Cu/Sc = 1 : 1), the coil was improved (no more degradation) when it was tightly rewound. The wire movement is for a part the reason of the observed training. In an other experiment, a slightly modified loss measurement apparatus gave the overall magnetization curve of the coil showing up the conductor movement.[21] Besides the wire is more movement sensitive when the copper to superconductor ratio is low (close to 1 : 1). In a more general way a better behaviour was noticed when the Cu/Sc ratio is nigher.

A typical example of impregnated organically insulated wire coil behaviour was observed on coil M3 using a 24 insulated strand braid.[17] In a first test a high degradation was obtained (I/I_c=0.49) and by measuring the currents in each wire (this measurement tending to make them all equal) higher degradation was noticed ($I/I_c = 0.25$). It was found that two wires had lower current and by disconnecting these wires almost no degradation was observed ($I/I_c = 0.96$) even at a $\dot{B} = 2$ T/s. A possible explanation is that these two wires were broken and that their current was transferred through the cross over points to the other wires then heating the conductor. These troubles would have been avoided if the wire insulation had not been locally destroyed.

Coupled wire assembly :

Coupled wire conductor behaves as a wire having a large number of filaments because it allows current transfer between wires. It should be more stable than insulated wire conductors. Moreover as it is fully transposed, it is perhaps less sensitive to self field instability that a more than ten thousand filament conductor will be. The metal filled conductor allows this coupling but does not limit the induced currents and leads to loss increases. The use of oxide insulation or intermetallic layer lowers this trouble keeping about the same stability. The experimental results of AC3 oxide insulated conductor ($I_{DC}/I_c = 0.95$)[21] and metal impregnated conductor coil ($I/I_c = 1$)[34] seem to agree with that explanation. It is also the case of coil M1 made of the same braid as M3 but during winding, the insulation was destroyedby the alumina charged epoxy allowing a high coupling between wires. Small degradation was observed ($I_{DC}/I_c=0.95$) even with three broken wires but in pulsed condition the extra losses lead to an important degradation ($I/I_c = 0.3$ to 0.4) due to temperature increase.

In general channel or heat drain cooled coils exhibit no degradation in DC condition but depending on the loss level heat drain coils may chiefly have some degradation in pulsed condition due to temperature increase.[21,43]

4. Losses

The magnetization losses are now well understood and experimental measurements agree with theory within a factor 1.3 to 1.6. The extra losses due to self field do not appear experimentally to be as important as one thought a few years ago.[28] However current sharing between wires is very much disturbed when the conductor is not fully transposed.[44] With no coupled (insulated) wires there are only losses in the composite itself (superconductor and copper) and mechanical losses but cabling, compacting and winding may introduce shorts. With coupled wires, extra losses are due to current loops between wires. Theoretical approach may be made in the same way as for multifilament wires.[42,45]

With metal impregnants, suitable heat treatment producing intermetallic layer at the surface and small transposition length, the coupling may be lowered so that the extra losses with small $\dot{B}$ (few kG/s) are of the same order as with organic insulation.[34] Figure 17 shows the influence of different intermetallic layers and transposition lengths . The coil 42 A has no intermetallic layer and coils 42 A through 42 D have progressively thicker layers. Coils 42 D and 43 are identical except for the conductor which has different transposition length (5.2 cm for coil 43 instead of 7 cm).

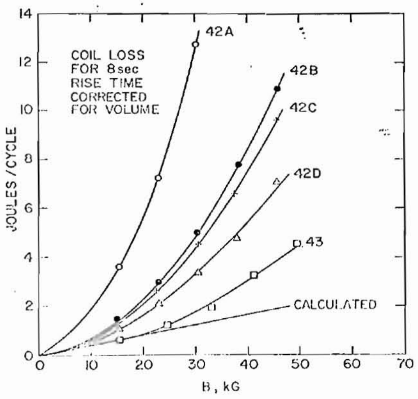


Fig. 17. Solenoïd coil losses vs field for various heat treatment and metallized conductor. (Brookhaven National Laboratory)

Figure 18 gives the measured losses for different rise times.

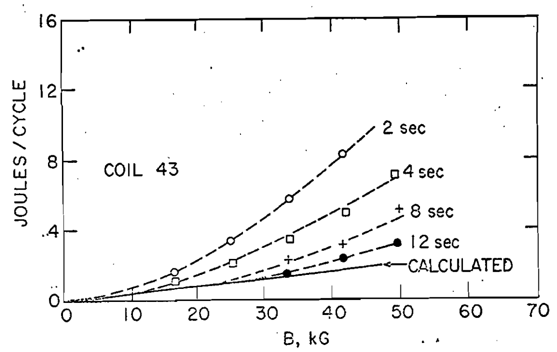


Fig. 18. Solenoïd coil losses vs field for various rise times. (Brookhaven National Laboratory)

The oxide insulation seems sufficient to obtain the resistance needed to limit the induced currents. Experimentally it was shown that such an insulated braid had, at 1 T/s and 3 T max field, losses 1.5 time the losses at $\dot{B} = 0$; and with a three component wire cable the losses at 1 T/s and 3 T maximum field are 1.2 time the losses at $\dot{B} = 0$.

All the experimental results are not yet fully understood and are difficult to compare, the experimental conditions being not well known ; however it seems today that a poorly coupled conductor (oxide or any resistive layer) which allows a good stability and low extra losses is the preferred solution.

VI. Superconducting dipole

Pulsed superconducting magnets have been built in different laboratories for over five years.

The development of those pulsed magnets have been pushed up by the projects of superconducting accelerators. If some of these projects seem to be withdrawn the others are quite promising.

1. Europe

In the project of the 300 GeV machine it was involved the use of superconducting magnets to increase the energy to about 1300 GeV ; two solutions have been proposed:

a) the missing magnet solution :

after the 200 GeV stage is completed, superconducting magnets would be installed in the gap of the lattice rather than conventional magnets. The energy being uprated to 500-600 GeV and perhaps 700-800 GeV if it is possible to supply conventional and superconducting magnets simultaneously.

By replacing in a second stage conventional magnets, the energy will be uprated to 1000-1300 GeV.

b) the separate ring solution :

a separate superconducting ring is built either in the same tunnel above the 200 GeV ring, or in an adjacent tunnel, the injection energy being 200 GeV.

The main parameters are listed in table 3.[35]

Three European laboratories (IEKP Karlsruhe, Rutherford HEL, CEN Saclay) are engaged in the development of suitable prototype dipole magnets. The GESSS (Group for European Superconducting Synchrotron Studies) collaboration coordinates the work of these laboratories.

The main parameters of completed and in project dipoles are listed in table 4.

Karlsruhe dipoles

DT (fig. 19) has a flat race-track coil wound on resin bonded fiber glass former and is not potted in resin. The high level of losses (13 W at 5 s rise time) is due to eddy currents and filament couplings in soldered cable. This magnet will be soon tested with the same coil but potted in epoxy resin.

The coil D2 and D3 will have the same saddle shape with the ends shaped so as to cancel high multipole coefficients in field integral. Both will have the same field and aperture but D3 will be twice longer. For D3, the choice of the conductor is not frozen yet.

TABLE 3 - Different options for superconducting synchrotrons

Solution	Missing magnet			Separate Ring
	1st Stage	2nd Stage	2nd Stage Higher Energy Variant	
Machine Energy (GeV)	500	1 000	1 330	1 000
Injection Energy (GeV/c)	10	10	10	200
Magnetic field in dipoles (T)	4.5	4.5	6	4.5
Diameter of magnet aperture (mm)	100 - 110	100 - 110	100 - 110	70 - 80
Stored Energy in dipoles (MJ)	450	900	1 800	500
Machine cycle time* (s)	11	22	44	12
Average flux (protons/s)	9×10^{11}	4×10^{11}	2×10^{11}	8×10^{11}

* Machine cycle time assumed to be 3 times magnet ramp time.

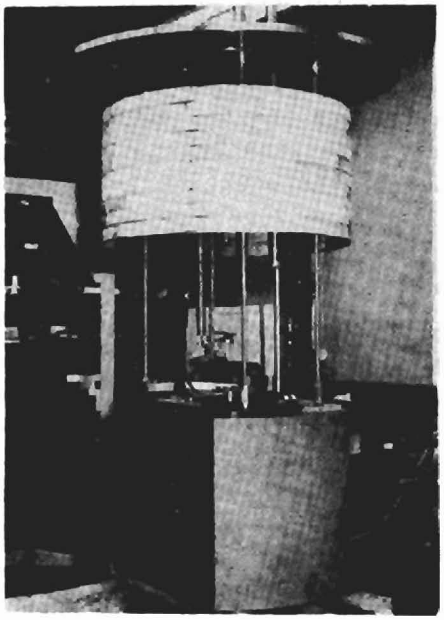


Fig. 19. DT dipole magnet.
(IEKP Karlsruhe)

Rutherford dipole

AC3 : (fig. 20, 21)

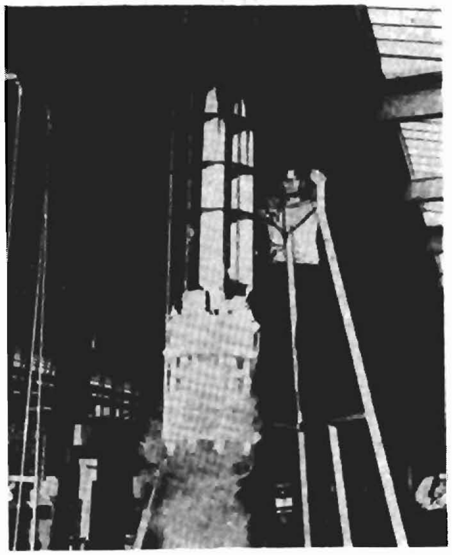


Fig. 20. AC3 dipole magnet.
(Rutherford National Laboratory)

TABLE 4

GESSS laboratory	Karlsruhe			Saclay	
Designation Year of completion	DT 1972	D2 1972	D3 1973	MOBY 1972	ALEC 1973
Magnet					
coil aperture or diameter (mm)	80 x 40	80	80	100	110
length (m)	0.4	1.4	2.8	0.5	1.5
pulsed field achieved (T)or specified	3.2	4.5	4.5	6.0	5.5
at field rise time (s)	5	10 - 20	3 - 10	5 - 15	5 - 15
cold iron	yes	yes	yes	yes	yes
Conductor					
type	cable	cable	cable	braid	cable
No of strands	10	12	-	24	36
individual strand diameter(mm)	0.5	0.54	-	0.44	0.5
filament by strand	1045	1000	1000	1000	1000
filament size (μ)	10	12	-	10	10
Nb-Ti : Cu : Cu-Ni	1:1.5:0.2	1:1.1:0	-	1:1:0	1:1.6:0
cable filling	solder	solder	-	resin	resin
operating current (A)	1035	1520	-	1500	2500
coil cooling	channel	channel	channel	heat drain	heat drain

TABLE 4

GESSS laboratory	RUTHERFORD			
Designation Year of completion	AC3 1971	AC3 modified 1972	AC4 1972	AC5 1973
Magnet				
coil aperture or diameter (mm)	100	75	90	90
length (m)	0.4	0.4	0.8	1.5
pulsed field achieved (T) or specified	3.5	4.1	4.5	4.5
at field rise time (s)	1	1	3	3
cold iron	no	no	yes	yes
Conductor				
type	cable	cable	cable	cable or flattened cable.
No of strands	90	90	25	5 - 15
individual strand diameter(mm)	0.4	0.4	0.85	1.1 - 0.7
filament by strand	1045	1045	2035	10.000-20.000
filament size (μ)	8	8	12	5
Nb-Ti : Cu : Cu-Ni	1:1.3:0.2	1:1.3:0.2	1:1.3:0.2	1:1.3:0.2
cable filling	resin	resin	resin	resin
operating current (A)	5100(DC)	4500(DC)	5400	4000
coil cooling	heat drain	heat drain	channel	channel

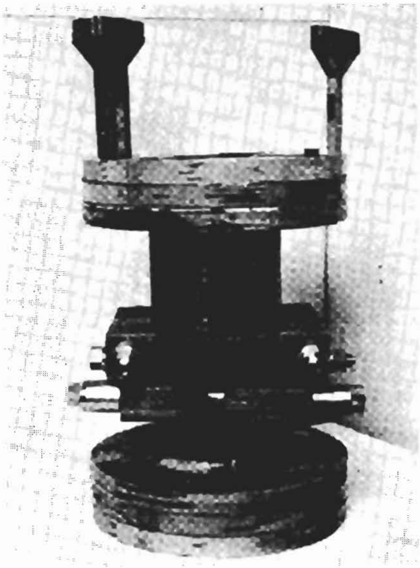


Fig. 21. AC3 winding.
(Rutherford National Laboratory)

The winding is made of six double pancakes connected in series. It reached 3.5 T central field (3.9 T peak field) at a current of 4580 A. Two additional pancakes, reducing the aperture diameter from 100 mm to 75 mm, has allowed to reach a central field of 4.1 T (4.7 T peak field) at a current of 4000 A. Particular attention was paid to minimize the losses (44 J in charging the magnet to 3 T and discharging). Less attention was paid to field homogeneity and industrial winding.

AC4[44] (fig. 9,15) has two double layers of winding per pole. A split iron yoke is used, the two halves being held by a cylindrical stainless steel clamp. The expected field homogeneity is 4.10^{-4} over 60 mm diameter.

AC5[44] is based on the AC4 design. It would have six double pancakes rather than four to allow safety margin on operating current. The conductor will be either a rectangular 5 to 7 strand cable with about 20.000 filaments per strand or a flattened cable of 9-15 strands with less filaments by strands. A solid laminated iron yoke is studied. The dipole will be tested horizontally.

Saclay dipoles

The so-called constant perimeter method is used for winding each layer. This technique allows to build an entire pole without internal joint in a very compact way. MOBY[17] (fig.10,13) is the highest field magnet under construction. Its expected field homogeneity is 10^{-3} in 50% of the coil aperture. ALEC has a greater length(1.5 m) but a slightly lower field. The design field homogeneity is 4.10^{-4} in an aperture of 70 x 40 cm. The iron yoke is located further to avoid saturation effects. Considerable industrial participation is involved in the construction of ALEC.

MOBY and ALEC will be tested in a cryostat with a horizontal bore axis.

2. U.S.A.

200 GeV intersecting storage accelerator ISABELLE (Brookhaven National Laboratory).

Those intersecting storage accelerators will use the AGS as an injector. The ring consists in two interlaced racetracks each made of two half circles with a regular lattice and two long experimental straight sections. The orbits in the regular lattice are separated by 0.2 m in the vertical plane.

The main-parameters are listed below (table 5)[46,47]

TABLE 5

Average radius of curved section (m)	220
Experimental straight section length (m)	285
Total circumference length (m)	1 937
Injection energy (GeV)	30
Each ring proton energy (GeV)	216
Equivalent proton energy(GeV)	10^5
Accelerator rise time (s)	120
Each ring stocked protons	6.10^{14}
Injection dipole field (T)	0.6
Maximum field (T)	4
Field variation (T/s)	0.03
Length of dipole (m)	3.2
Aperture diameter (mm)	80

The first approach for the dipole field was an arrangement of magnet coils to allow one coil to use the return flux of the other.[47]

Because of the slow rise time, BNL is developing a metal filled superconducting multifilamentary braid.[34] The winding shape results from the cos θ distribution and uses a single layer for a 4 T dipole.[48] The characteristics of dipole models being studied now are listed in table 6.[49]

TABLE 6

Name	2 P	2 G
Insulation	poly-bondex	metal filled
Filament size (μ)	10	7
Cu/Sc	2 : 1	0.8 : 1
Wire diameter (μ)	200	200
Conductor type	braid	braid
Wire number	132	132
Conductor dimensions (mm x mm)	13.2 x 0.4	13.2 x 0.4
Minimum rise time (s)	1	20
Current at maximum field (A)	2 270	2 780
% of short sample $(10^{-12}\,\Omega.\mathrm{cm})$	95	100
Current density (kA/cm2)	24	31
Obtained maximum field in aperture (T)	3.4	4

It is planned to build four more models to check construction tolerances and test newer metal filled braid.

Two I S A dipole models are planned, of similar design but 8 cm aperture, 90cm length and six current blocks (3400 A). Each unit will be tested in a vertical dewar then mounted end to end horizontally to be tested for an extended period. The first one will be ready for testing in September 1972.

Lawrence Berkeley Laboratory

Although the main program aimed at the use of superconducting transport elements for bevatron areas, an extensive program of development work is also directed towards the construction of superconducting magnets for possible proton synchrotron applications.

The magnets have in each quadrant two conductor blocks of the same width but with different current densities. The technique used is the so called constant perimeter. The main characteristics of the dipole (fig. 11, 22) are listed in table 7.[50,51]

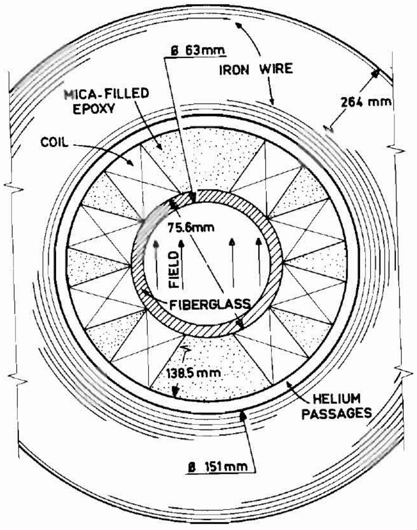


Fig. 22. Pulsed dipole n° 8.
(Berkeley National Laboratory)

TABLE 7

Name	n° 8
coil aperture (mm)	63.5
length (m)	0.40
operating current (A)	1 920
DC field (T)	3.9
max. field in end (T)	4.5
pulsed field achieved (T)	3.5
at field rise time (s)	0.5
coil cooling	channel
coil iron	yes (soft iron wire)
Conductor	
type	cable
No of strands	133 (19 x 7)
strand diameter (mm)	0.2
cable filling	Ag-Sn solder

The channels are formed with the B stage coated epoxy insulation wrapped around the conductor. In the next test the soft iron will be replaced by laminated iron yoke.

A new magnet with a length of about 1 m is planned to be constructed and tested in an horizontal cryostat cooled by a helium refrigerator.

Superconducting stretcher ring for the zero gradient synchrotron (Argonne National Laboratory)

A superconducting stretcher ring has been proposed[52] to increase the intensity of the Z G S. The beam duty cycle would be about 100% and a factor of five higher rate of acquiring data would be possible in many experiments. The average intensity of the Z G S would be doubled (the A G S operating without flat top). Although the magnets will not be optimized for pulsing they will be pulsable with a long rise time (20 to 30 s).

The main characteristics of the dipoles (fig. 23) are listed in table 8.

TABLE 8

inner diameter (cm)	10
length (m)	1.45
maximum field (T)	2.9
operating current (A)	500
current density (kA/cm2)	15 to 20
Conductor	
type	cable
strand number	7
filament number	700
filament diameter(μ)	10

The dipole are wound of flat pancakes with turned up ends.

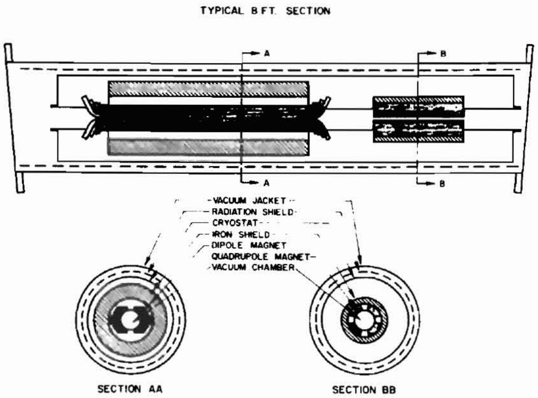


Fig. 23. Proposed dipole for the Z G S (Argonne National Laboratory)

National Accelerator Laboratory

An energy- doubler concept has been proposed to uprate the energy to 1000 GeV [53,54]. This superconducting ring would be mounted 700 mm above the main ring in the same tunnel. The superconducting magnets would have very small bore (5 cm) and the field would be used from 2.2 T to 4.5 t; this simplifies the magnet technology.

A quadrupole[55] has been tested. Its characteristics are listed in table 9.

TABLE 9

bore (cm)	2.5
length (m)	0.5
current (A)	800
gradient (T/m)	40
% of J_c at B_{max}	57
Conductor	
number of strands	121
Cu/Sc	3 : 1
insulation	formvar

3. U.S.S.R.

At the Radiotechnical institute (Moscow) the study of high energy synchrotrons has been carried out for several years, the aims of the program being a synchrotron of energy higher than 1000 GeV. The general principle given at Erevan conference is the uprating of a 1000 GeV.[56] The main characteristics are listed in table 10.

TABLE 10

	1st step	2nd step	3th step
Proton energy (GeV)	500	1 000	4 000 5 000
Intensity (proton/s)	2.10^{12}	3.10^{13}	10^{13}
Diameter (m)	5,435	5,435	5,435
Max.field (T)	0.8	1.6	6.0-8.0
Aperture (mm)	40x66	40x66	Ø 66
Pulse duration (s)	6	3	12
Injection energy (GeV)	6	18	18

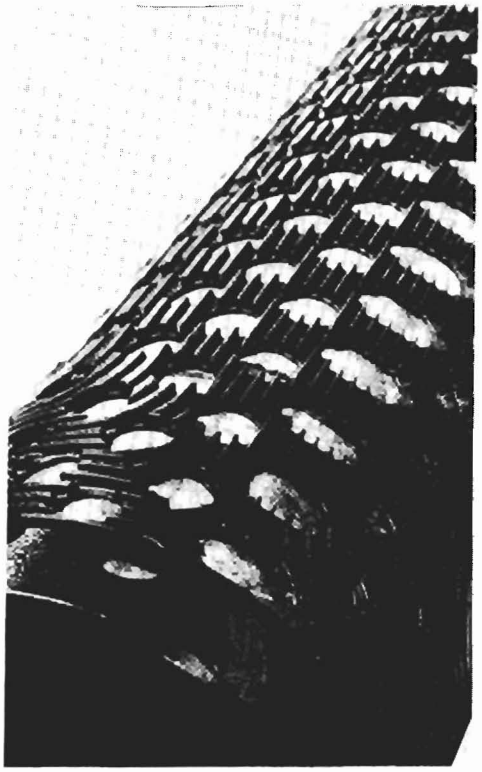


Fig. 25. Dipole cylinder with grooves for the superconducting cable. (Radiotechnical Institute Moscow)

The two first steps use conventional magnets but all the plans are made to be able to replace these magnets by superconducting ones keeping the same ring. An other way is a multistage scheme.[57] The dipole length will be about 6 m. A model dipole of 6 cm aperture and 70 cm length had been completed.[58,59,60] The technique is a cosine distribution of 2 mm diameter wire arranged in thin stainless steel grooves (fig. 25). The magnet is placed horizontally in a fully demountable cryostat (fig. 26). The study of this type of magnet is continued by an epoxy impregnated version.[59]

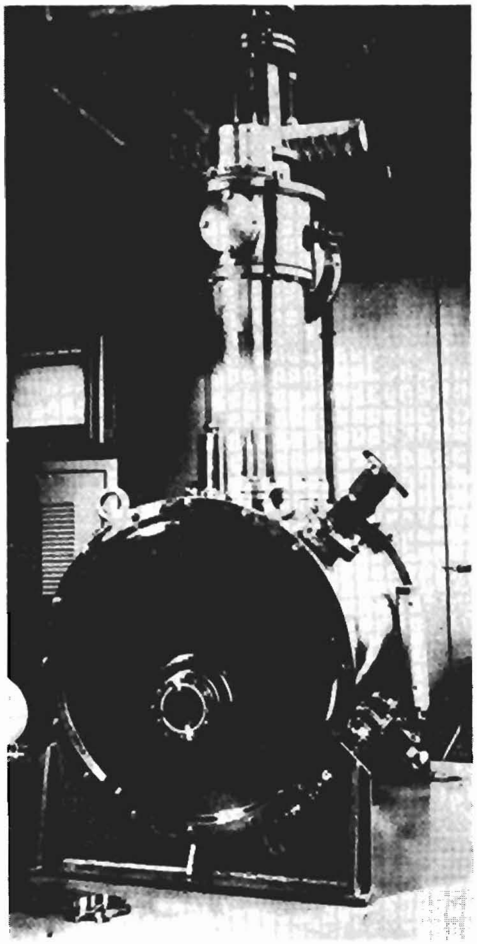


Fig. 26. Horizontal cryostat. (Radiotechnical Institute Moscow)

VII. Conclusion

More knowledge is today available for the design of new machines. Both the requirements and the methods to fulfil them did not yet reach a complete agreement between all the laboratories. On the other hand so many experiments have been made that it is not possible up to now to compare all their results and to draw a final precise conclusion. However considerable progress has been made in the two past years in the understanding of the behaviour of pulsed coils.

Our feeling is that in the coming months a large effort will be continued specially in shifting more and more the construction from the laboratories to industry and more will be known about operational behaviour of such magnets.

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