KERNFORSCHUNGSZENTRUM

KARLSRUHE

Dezember 1972

KFK 1720

Institut für Experimentelle Kernphysik

Studies for a European Superconducting Synchrotron
a GESSS report

W. Heinz

GESELLSCHAFT
FÜR
KERNFORSCHUNG M.B.H.

KARLSRUHE

GESELLSCHAFT FÜR KERNFORSCHUNG M.B.H.
KARLSRUHE

KERNFORSCHUNGSZENTRUM KARLSRUHE

KFK 1720

Institut für Experimentelle Kernphysik

STUDIES FOR A EUROPEAN SUPERCONDUCTING SYNCHROTRON

A GESSS REPORT

W. Heinz

Gesellschaft für Kernforschung m.b.H. Karlsruhe

Abstract

A group of three European laboratories - IEKP Karlsruhe, Germany; RHEL Chilton, England; and CEN Saclay, France - is studying the feasibility of pulsed superconducting magnets for use in high energy synchrotrons, especially in the European 300 GeV proton synchrotron CERN, Geneva.
The progress achieved in developing a pulsed superconducting magnet system including design considerations, conductor studies, magnets and cryogenic equipment is reported. Test results give confidence that most of the physical and engineering problems are reasonably well understood. The investigation concentrates now on fully engineered preprototype synchrotron magnets which cover most of the parameters for a full scale prototype.

Eine Gruppe von drei europäischen Laboratorien - IEKP Karlsruhe, Deutschland; RHEL Chilton, England und CEN Saclay, Frankreich - untersucht die Verwendbarheit von gepulsten supraleitenden Magneten in einem Hochenergiesynchrotron speziell im europäischen 300 GeV Protonensynchrotron CERN, Genf. Es wird der bei der Entwicklung eines gepulsten supraleitenden Magnetsystems erzielte Fortschritt berichtet, einschließlich der Überlegungen zum Entwurf, den Leiterstudien, den Magneten selbst und dem Kryozubehör. Die Versuchsergebnisse zeigen, daß die meisten physikalischen und ingenieurmäßigen Probleme gut verstanden sind. Die Untersuchungen konzentrieren sich jetzt auf ingenieurmäßig ausgeführte Synchrotronmagnete, die die meisten Parameter für einen Prototypmagneten voller Größe überdecken.

Studies for a European Superconducting Synchrotron
A GESSS Report

W. Heinz
Institut für Experimentelle Kernphysik
Kernforschungszentrum Karlsruhe

September 1972

1. Introduction

The highest centre-of-mass energy ever obtained by a man-made accelerator is the energy of the CERN intersecting storage rings (ISR), with beam momenta of 31.4 GeV/c in each ring equivalent to over 2000 GeV of a conventional accelerator-beam striking a stationary target. The accelerator with the highest energy of the particles in the accelerated beam itself is now the American proton synchrotron at NAL, Batavia, which has reached 300 GeV and is expected to reach 400 GeV this year. An equally powerful machine will be the European proton synchrotron now under construction at CERN, Geneva, which is scheduled to reach the first beam at a 200 GeV level in 1976 and have full energy of 300 or 400 GeV two years later.

The conversion of any of these accelerators into a superconducting synchrotron would equip the high physics community not only with a powerful research instrument but also with the biggest liquid helium temperature cryogenic plant. Together with plasma physics the requirements of high energy physics have been and will continue to be a challenge to physicists and engineers to develop new technologies. A superconducting magnet system for high energy accelerators or superconducting beam lines would have a great impetus on the development of superconducting and cryogenic components.

This might help to establish superconducting and cryogenic technology on a full industrial scale and possibly open new resources of support for fundamental research.

2. Superconducting high energy accelerators

The energy available from accelerated beams has steadily increased from several hundred keV of the first cascade of Cockroft and Walton in 1932 to several hundred GeV of the Batavia synchrotron in 1972. Whenever the existing technique hit their inherent limits a new acceleration principle was invented. In a nuclear reaction the available energy is the centre-of-mass energy of the hitting particles, which at high energies is proportional to the square root of the peak energy of the particles in the accelerated beam. Total energy is available if two particles of equal but opposite momentum hit. Consequently the latest new principle now successfully in operation is the colliding beam technique where two particle beams circulating in opposite directions cross at definite collision points to enable head-on collisions of the particles in the two beams.

A survey of the development of the maximum energy of accelerators is given in Fig. 1. For storage rings the equivalent energy is given which would be necessary to obtain equal centre-of-mass energy with a target at rest. In looking at this diagram one has to keep in mind that the usefulness of an accelerator is determined by a number of parameters. Energy is only one of them, other important ones are intensity, duty cycle, and the kind of available particles. So the development of accelerators goes into different directions and a superconducting synchrotron may well be the next step.

The magnets in a conventional synchrotron accelerator operate at a maximum field of 1.5 to 2 T. If these magnets could be replaced by superconducting magnets of 4 to 6 T, the energy of the accelerator could be increased by a factor of three or four. Pulsed superconducting magnets have been built in a number of laboratories since 1967. By 1971 model dipole magnets representative in many respects of those required for a superconducting synchrotron had been built and tested. In Europe this work got a great impetus by the decision to build the 300 GeV machine in Geneva. This machine will be built as a so called missing magnet machine: half of the bending magnets will be left out in the first stage. The gaps can be filled with additional conventional iron magnets to give the "design" energy of 300 GeV. With the full set of bending magnets in position and powered to 1.8 T the energy will be 400 GeV. An energy of 1000 GeV could be reached by replacing the iron magnets by superconducting ones operating at a maximum field of 4.5 T [1,2]. The missing magnet scheme allows superconducting magnets to be installed during the completion of the accelerator if they are found technically feasible and economically reasonable. This can be done in several ways. After reaching 200 GeV (stage A) a set of superconducting magnets could be installed in the lattice rather than another set of conventional magnets. This "missing magnet solution" will give a final energy of 500 GeV with the superconducting bending magnets powered only. The iron quadrupoles are designed to focus an accelerated beam up to this energy, possibly with some additional correcting devices. In a later stage all the conventional magnets could be replaced by superconducting magnets to give 1000 GeV or more depending on the field level. The missing magnet solution requires the matching of the apertures and lattice to the existing part of the machine. It allows the use of all the facility already in place: RF accelerating system, control system, part of the vacuum system, etc.

Another solution could be to place the superconducting magnets above the main ring magnet system in the same tunnel. The 200 GeV of stage A would be used as an injector into the superconducting ring. This "separate ring solution" could be advantageous in several respects. Compared to the missing magnet solution there are less restrictions in the design of the cryogenic system and in choosing the lattice, the aperture is small because of the higher injection energy. But additional facilities for injection, acceleration and control of the beam are needed.

Appropriate lattices for the missing magnet and separate ring solutions were found to be compatible with the lattice chosen for the conventional machine. At 200 GeV the beam may be transferred from the conventional to the superconducting ring on top using the long and medium straight sections of stage A. Reasonable ejection schemes at a 1000 GeV level were found [2].

A variant of these solutions utilises an extra tunnel to accommodate the superconducting ring, concentric to the first one but several meters away. This last solution would allow the maximum degree of freedom in designing the lattice for the superconducting synchrotron and might in part compensate the extra cost. Another attractive feature of this solution is minimum interference of running experiments during construction time. In separate ring solutions distortion problems due to remanent fields are less severe because of the relatively high injection field.

In 1970 a group of three national laboratories (RHEL, Chilton, England; CEN, Saclay, France; IEKP, Karlsruhe, Germany) formed the GESSS collaboration - Group for European Superconducting Synchrotron Studies. The objective is the coordination of their work, directed towards pulsed superconducting magnets and their application in future accelerators, especially in a possible completion of the European 300 GeV machine with superconducting magnets or a conversion of this machine to a fully superconducting one. This collaboration is closely linked to the CERN laboratories. Each of its laboratories cooperats with national industry. A number of working groups exists to cover special subjects.

3. Superconducting magnet development

3.1 Preliminary remark

The parameters of pulsed superconducting magnets are determined by the requirements of superconducting and low temperature techniques and by those of the accelerator builders and users. The final choice of parameters will be a balance between physical, technological and economical requirements. Dipole magnets built and unter study have central fields ranging between 4 and 6 T, useful aperture diameters of 5 to 12 cm and effective lengths of 0.4 to 3.0 m, ultimately the effective length will be 5 to 7 m depending on the lattice. Field rise times reached are above 5 T/sec in dipoles, thus allowing a cycle time of several seconds. Dipoles have been tested with and without cold iron.

Superconducting d.c. magnets have been studied, built, and used since the discovery of "hard" superconductors in 1961. The biggest representatives of this type are the bubble chamber magnets built at Argonne and Geneva. Operation of a superconducting magnet in a pulsed mode was not possible until the development of low loss superconductors by the Rutherford laboratory in 1968, that is intrinsically stable multifilamentary composites of NbTi filaments embedded in a copper or cupro-nickel matrix.

Dynamic losses in the superconducting composite are mainly due to hysteretic losses in the superconductor itself, eddy current losses, and coupling effects. Other contributions (self field losses etc.) may be neglected [3]. The dynamic losses depend on the size and mutual coupling of the individual superconducting filaments in the composite and on the rate of change of the magnetic field. For example, in a dipole with a composite conductor of 10 μ filaments the a.c. losses are about 11 W/m at a rise time of 1.5 T/sec allowing for a 10 sec cycle with a flat top of 4 sec at 4.5 T.

Additional losses are due to eddy currents in the iron, to the heat leak of the cryostat and losses down the current leads. The total loss of a dipole magnet system is expected to be between 10 and 20 W/m. Measurements are in agreement with calculations. The power consumption of the refrigerator at room temperature is 300 to 500 times this value. This has to be compared with the ohmic losses of conventional pulsed iron magnets, e.g. 5.7 kW/m in the case of the 400 GeV CERN II synchrotron. That means, a superconducting synchrotron has roughly the same losses as a conventional one but with a considerable gain in energy.

3.2 Conductor development

The key to the reliable performance of a pulsed superconducting magnet is the development and use of a suitable composite conductor. Superconducting magnets will be operated at currents of several thousand amperes to restrict the inductance of the coil and charging voltages to reasonable levels, so the use of braids or cables is required. The conductor parameters should be optimized with respect to its mechanical, thermal, and electrical performance in the final magnet. Some vital items are intact filaments of constant thickness, an appropriate ratio of copper to superconductor, low a.c. losses, and a good insulation between filaments and strands. A.c. loss behaviour of superconducting composites is reasonably well understood [3,4]. Degradation and training effects are under study in several laboratories.

Current superconducting wires for use in pulsed magnets are based on niobium titanium with a critical temperature of 9.5 K and a critical field of about 12 T. The critical current density at 5 T is about $2 \cdot 10^5$ A/cm^2. Superconductors with higher critical parameters are known and may well be used in the future. Materials of particular interest are Nb_3Sn and V_3Ga.

They show high critical current densities at high fields. One of their attractive features is high critical temperature: Nb_3Sn - 18.25 K, V_3Ga - 15 K, thus allowing higher operation temperatures at reduced cooling costs. Because of their brittleness they are difficult to produce in form of multifilament wires. Encouraging results, however, have been obtained at Brookhaven [5].

Type II superconductors like NbTi are dissipative in a changing field. The generated heat can make the superconductor normally conducting. This has to be prevented by stabilization of the conductor. From d.c. applications the principle of "static stabilization" is well known: The heat generated in the superconductor has to be removed to its surroundings faster than it is generated. This is achieved by cladding the superconductor with copper (e.g. in big bubble chamber coils). In a.c. applications this copper would cause additional losses and hamper stable operation. In this case dynamic stabilization can be achieved by limiting the rate of energy release in the superconductor to become commensurate with the thermal diffusivity of the composite. Some copper is required because of its thermal properties, but the ratio of copper to superconductor can be as low as about 1 : 1. The heat release is limited by very thin filaments of superconductor down to several microns, by twisting these filaments with a pitch of several millimeters and by embedding the superconducting filaments in a matrix with highly resistive barriers. Niobium titanium multifilament wires now available at several firms have typical filament diameters of down to 5 μ, strand diameters between 0.2 and 1 mm with several hundred to several thousand filaments in a single strand. These filaments are embedded in a pure copper or copper/cupro-nickel matrix. Cupro-nickel provides the resistive barriers to interfilament current flow, copper is included to provide stable operation. The superconducting wire is twisted with a pitch of typically 0.2 to 1 cm.

The required number of strands to deliver the design current is woven into braids or fully transposed cables and finally compacted to the correct cross section used in the coil. Braids or cables are now available from different firms with currents of several thousand amperes at 5 T. They have about 10 to 30 strands which are combined by twisting and full transposition. Twisting of strands without full transposition can cause self field effects, leading to a nonuniform current distribution, conductor degradation and additional losses. A nonuniform current distribution, even a negative current in the central strand has indeed been observed [6]. A fully transposed cable or braid has a low filling factor and a large number of cross-over points between strands which may cause strand or filament breakage when compacted to desired dimensions. These dimensions have to be maintained during and after the winding procedure to get the required field homogeneity in the useful aperture of the final dipole ($\Delta B/B$ less than 10^{-3}). This can best be achieved by using a highly compacted braid or cable were single strands are fixed by some means.

A first possibility could be the return to a single strand conductor. This development is under way at Rutherford laboratory and IMI, Birmingham, England. At a field of 5 T a single 5 μ filament of NbTi will only carry about 30 mA. 10^5 filaments have to be connected in parallel to get a typical current of 3000 A. There are limits in the number of filaments in the composite due to filament coupling effects which will limit the ultimate size of composites in pulsed magnets. The present limit with a three component conductor seems to be about 20 000 [7] due to losses in the matrix. If these losses can be reduced by a more effective and sophisticated arrangement of filaments and resistive barriers the upper limit is to be expected as high as 10^5 filaments of 5 μ diameter. A 1 mm diameter composite conductor containing 13,255 NbTi filaments 5 μ thick in a copper and cupro-nickel matrix was manufactured by IMI. It carries 470 A at 5 T [1].

Another way to maintain cable shape during coil manufacturing is to fix the single strands by soldering with a high resistivity solder. One of the Karlsruhe dipoles has been built with such a cable, another one is under construction. The advantage of such an approach is a performance predictable from short sample values with respect to the maximum attainable field and the field quality because of tight mechanical tolerances of the conductor. The drawback is the relatively high heat release in pulsed operation thus introducing a lower limit for the maximum rate of change of the magnetic field. Soldered cables could well be used with long cycle times (above 10 sec).

The Brookhaven group [8)] has developed a promising metal composite and metallurgical processing of decoupling single strands in the braid or cable. Finally organic insulated strands and cables are developed by industry. They are highly compacted (above 0.7 filling factor) and mechanically stable during winding.

It is important to design superconducting magnets in such a way that their performance is predictable and reproducible in many specimens. Improved prediction of performance leads to reduced safety margins for reliable operation and a more economic design. So a lot of quality tests of the conductor and of potted and unpotted test coils were taken in all GESSS laboratories to study the effects of training and degradation.

An example for short sample measurements of individual multifilament NbTi wires down to 4 µ filament diameter is shown in Fig. 2. From U-I-curves measured, a resitivity ρ is determined and plotted against current density J in a logarithmic scale showing slope and take-off currents. The curve shown in the left part was obtained from a conductor which was known to contain many broken filaments. Obviously, the slope of these curves is a sensitive measure of the integrity of filaments.

3.3 Coil structure and magnet design

Synchrotron magnets are pulsed dipoles and quadrupoles of high field quality. In classical magnets field accuracy is guarenteed by the correct shape of the iron surface and the reproducible performance of the normal conducting field coils. Superconducting magnets go to fields where iron saturates. The iron surface can no longer act as an equipotential plane and can therefore no longer be used to shape the field properly during the whole cycle. A superconducting coil has to produce the required field distribution by an appropriate distribution of the currents in the coil.

There are two idealised theoretical coil cross sections which would produce a uniform dipole field: the intersecting-ellipses configuration with a homogeneous distribution of current outside their overlapping parts and a distribution with concentric boundaries and therefore circular aperture with a cosine variation of current density. Practical designs approximate these configurations in various ways. Different ways are used in the three GESSS laboratories: concentric layers at RHEL (Fig. 3a), shaped blocks of horizontal layers at CEN (Fig. 3b), and spaced sectors wound of several layers at IEKP (Fig. 3c). The correct position of conductors is determined by computer calculations. The thickness of layers, their azimuthal position and extension and the space between layers for impregnation and heat drains or cooling channels give enough degrees of freedom to get rid of or minimize the contributions of higher order multipoles. From this point of view all designs are equally well suited to give the required field accuracy. So, design concepts are determined by engineering approaches.

The coils will be surrounded by an iron shield in the form of a laminated steel cylinder. It will reduce stray fields and stored energy by enhancing the central dipole field without enhancing the current. To maintain the field accuracy during the whole cycle iron saturation has to be avoided or carefully controlled. The iron shield will be an integral part of the design and act as part of the magnet structure to withstand electromagnetic forces during operation and keep the coils in their correct position.

The conductor has to be fixed and stay in place during cycling. Conductor movement would not only introduce field distortions but cause additional heat release. Therefore the winding is potted in a suitable material, mostly epoxy resins, and bandaged and supported by a glass fibre or stainless steel structure.

A rather compact coil package will result preventing free access of the cooling medium to the conductor if no precautions are taken. The heat generated in a coil package has to be carried away through the coil and transferred to the helium. Cooling channels or heat drains have to be provided in order to prevent local overheating. The maximum thickness of a coil package, a layer or double layer is limited by the allowable temperature rise within the layer.

Little experience has been gained so far in tackling the problem of differential thermal contraction of different parts of the dipole (coil, coil bandages, iron shell, cryostate, etc.). It is particularly important to maintain the symmetry of the magnet and thus avoid harmful coupling terms in the field. Components could be matched thermally and prestressed during assembly which might partly compensate for differential contraction.

3.4 Superconducting pulsed dipoles completed and under construction

This report will present the current status of the development and in particular the progress obtained since the GESSS report [1)] at the spring ECFA-meeting in Geneva. Several completed magnets were presented at that time among them an iron core magnet DT (IEKP) and an air core magnet AC3 (RHEL).

The dipole DT [9] is a 0.4 m long dipole (Fig. 4) wound from a 10 strand cable with a central copper strand, the cable being InSn-soldered to ensure mechanical rigidity. The iron yoke is of the window frame type with a rectangular window. It is laminated and hyperbolically shaped towards the ends to linearize field decrease. It is immersed in liquid helium. The coil is an unpotted flat racetrack coil with cooling channels between every two layers.

During the first period of operation the magnet has been tested for almost 10 000 cycles with triangular pulses down to 2 sec pulse duration. At a slow field rise of about 0.1 T/sec a central field of 4.5 T and a peak field of 5.2 T on the winding surface were obtained. This corresponds to short sample values, neither training nor degradation were observed. Degradation occured at faster rise (Table). The peak field values given represent the maximum fields attainable during half an hour pulsing ("permanent pulse mode"). They are considerably reduced with decreasing rise times. This is most likely due to the high losses of the low resistivity solder of the cable and the eddy currents in the copper strand and iron sheets. The losses per cycle are approximately proportional to the frequency and the square of the field.

Table: Losses in dipole DT at peak field

Rise Time (s)	Peak Central Field ("Permanent Pulse Mode") (T)	Losses (J/cycle)
45	4.5	<8
31	3.5	14
5	3.2	130
2.5	3.0	107
1	2.4	90

In the same iron yoke a high purity aluminum coil (resistivity ratio 9200) has been tested. A peak field of more than 4 T was reached with a power consumption of 60 to 70 W at helium temperature when triangular pulses of 3 to 10 sec pulse duration were applied.

AC3 is a magnet of approximately the right size and shape for a synchrotron operating at realistic values of field, current, and rise time [10]. It is 0.4 m long without an iron yoke and has a circular aperture of 10 cm diameter. In a first version 4 T central field were reached at 5200 A. In a second version two additional pancake coils reducing the aperture to 7.5 cm diameter were used to give a central field of 4.6 T at a current of 4500 A. Like DT it is operated vertically. A schematic drawing of the coil geometry is given in Fig.5. The ends are bent up vertically to give minimum field disturbance. Cooling is provided by laminated copper heat drains placed between layers. The dipole is vacuum impregnated with a semiflexible resin which has good crack resistance at low temperature. The fully assembled magnet is shown in Fig. 6.

Measured a.c. losses are in good agreement with calculations. At a rise time of 3 sec considered for a superconduction version of the European synchrotron the decrease of quench current is negligible compared to d.c. operation. At 0.25 sec rise time the quench current is decreased by about 25 %.

In the meantime the successor of AC3 has been succesfully tested. AC4 has two double layers per pole [6] and uses a 25 strand cable of 2035 filament superconducting wire rated at 5400 A. The coil aperture is 9 cm in diameter. AC4 has a split iron yoke with laminated iron of 0.5 mm thickness. Each pancake coil is separately vacuum impregnated with a filled epoxy resin. The dipole is operated horizontally. Cooling channels between each layer of windings are used instead of the heat drains in AC3. They allow vertical passage of the helium from below the coil by natural convection. Fig. 7 shows the dipole fully assembled. During the first run it was pulsed to over 4.5 T corresponding to a current of 5300 A with 2 sec rise time and a few percent less with 1 sec rise time. All losses are as predicted. Field measurements are under way. A field uniformity of $4 \cdot 10^{-4}$ over a "good field" region of 6 cm diameter is expected.

The next dipole to be build at RHEL (AC5) will be based on the design of AC4. It will be about 1.5 m long with a specified pulsed field of 4.5 T and field rise time of 3 sec. The conductor has yet to be finally selected. Completion of AC5 is expected in mid 1973.

GESSS laboratories try to cover all the relevant parameters for the final design of a prototype synchrotron dipole to be used in the big European machine. The experience with different physical and engineering parameters and techniques in these laboratories is complementary. So MOBY [11], the dipole magnet under construction at CEN-Saclay, is the highest field pulsed magnet presently considered in the GESSS laboratories being designed for a central field of 6 T.

MOBY has a coil aperture diameter of 10 cm and a magnetic length of 0.5 m. It is designed for a rise time of 5 sec and an operating current of 1500 A. The coil is a block of a parallelogramme shape with layers of conductors parallel to the horizontal plane. A circular iron shielding is provided very close to the coil. The coil is totally epoxy impregnated and cooled by means of copper heat drains. Fig. 8 shows the coil and iron shielding configuration. The type of winding is unique. It makes use of a technique of going a constant turn perimeter per layer (Fig. 9) and produces a stable mechanical location of turns without any stretching forces. It is possible to build a whole pole with only one piece of conductor. The influence of this configuration on the end fields has to be measured. Some experience with this winding technique has been gained from two d.c. quadrupoles (OGA) built formerly.

The conductor is a 24-strand compacted braid. The braid was chosen to get the desired rectangular cross section. Many broken strands and filaments due to the braiding and compaction procedure were observed. This was also found at other places.

A difficult problem with this design is the positioning of the coil inside the shielding because of the different thermal contractions of the coil and iron shield. All the coil support is from outside, the inner part serves for cooling only. The helium circulation on the inner coil surface where the heat drains protrude is made by natural convection in chimneys through the stacking.

The winding of MOBY is in progress, the iron shielding is completed. The main parts of the cryostat are also completed, (Fig.17); Low temperature tests are in progress. First test runs are planned for the end of this year.

Another magnet based largely on MOBY design is ALEC. It is of greater aperture (11 cm) and length (1.5 m) than MOBY, but with slightly reduced central field (5.5 T). Winding, impregnating and cooling techniques are the same as used with MOBY. It is tried to design both magnets as close as possible to an engineering version. Industry will be involved in the construction to ease technology transfer to the manufacturer.

The design philosophy for a superconducting magnet is depending on a lot of parameters. The Karlsruhe programme is designed for a set of longer magnets of 4.5 T central field with a small circular aperture of 8 cm in diameter.

Dipole D2 of 1.5 m length will actually exist in two versions with different conductors: D2a which is presently being wound employs a soldered rectangular cable while D2b will be wound from a flat cable with fully organic insulated strands. Dipole D3 will be based on the design of D2b but with a length of 3 m. For all magnets a modified cos Θ current distribution is chosen because of its symmetry (Fig. 10a) which is relevant to the problems associated with differential thermal contraction during cooldown. As the field will be uniform independent of the position of the iron shell, two approaches for D2 are under investigation. The first one with an inner diameter of the iron shell of 17.2 cm becomes saturated as the magnet goes to high induction; the other one with an inner diameter of 21.6 cm, remains unsaturated throughout the cycle. The coils for D2a and D2b may be used in either iron shell or with no iron at all.

The number of layers chosen depends on the cable or braid which is available. We have decided to use fully transposed cables (no central strands) instead of braids, because cross over points are eliminated as potential shorts and higher packing factors are obtained (~ 70 % vs. 50 %). Like a braid, a fully transposed cable gives good cooling conditions in an impregnated coil because all strands are periodically carried to the coil surface to allow contact with the liquid helium. While a braid can easily be compacted to a rectangular shape, this is difficult with a fully transposed cable. If the strands are soldered, however, the cable may be shaped as required. The drawback are the high losses in a metallically insulated cable which allow only reduced rise times.

For D2a a superconducting soldered cable with 2.1 × 2.6 mm cross section was chosen. It is wrapped with a terylene-glass braid insulation 0.2 mm thick. A current of 2000 A at 5 T and 4.2 K is guarenteed by the manufacturer (IMI).

The peak field at the conductor surface is designed to be only a few percents above the central field. Due to the losses in the solder shortest rise times will be between 10 and 20 sec. The cable has to be wound into double layers because of the winding technique. They will be mounted together to form a magnet pole. Since the number of double layers does not essentially influence the field accuracy, from this point of view a low number is desirable in order to simplify winding and impregnation of the individual double layers. On the other hand, ease of shaping the three-dimensional ends limits the height of the flat cable. This leads to a design with 2 or 3 double layers for D2b as shown in Fig. 11. Double layers are separately vacuum impregnated and mounted to a glass fibre coil structure with spaces for the coolant between each of them.

The end regions of the coil were designed very carefully in order to avoid a variation of $\int B\,dl$ over the coil aperture and field enhancement at the coil ends. In contrast to conventional iron magnets, the latter effect has to be considered because the current carrying capacity of a superconductor decreases with increasing local field. By lengthening the inner layers and shortening the outer ones, a negligible field enhancement in the ends is achieved. Fig. 10b shows the end region of D2a which also gives constant integrated field within 0.1 %, and no substantial eddy currents in the iron.

The iron yoke of the final version D3 will be chosen according to the results obtained with the saturated and unsaturated iron yokes of D2. The effects of iron saturation on a.c. losses, peak field, and field uniformity will be measured. The expected field as a function of current for a saturated, unsaturated and no iron shell is shown in Fig. 12 together with the critical current characteristics at different operating temperatures and the iron enhancement factor of the field. The iron is laminated and coated with a 10 μm phosphate layer.

Magnetic forces will be supported by stainless steel rings. Liquid helium will flow between the coil and the iron and through the cooling channels between each of the double layers which allow natural convection cooling through holes drilled into the top and bottom of the iron shell. The cooling channels will also permit forced cooling in axial direction.

The coils of D2a are presently being wound. Fig. 13 shows a trial coil winding of a double layer pancake of this dipole. Completion is expected in January 73. An axiometric view of the magnet is given in Fig. 14.

3.5 Low temperature properties of materials

The current density in a superconducting composite is more than an order of magnitude higher than in normal conducting material, the fields applied are 2 to 4 times higher. Thus the forces on the conductor are increased by one or two orders of magnitude compared to room temperature magnets. Though the material strength is increased at low temperatures, the gain is not nearly sufficient to compensate the increased strain by Lorentz forces. The development of heat at low temperatures due to eddy currents in metallic structure material has to be avoided as far as possible because of the bad overal efficiency of a refrigerator. Therefore non-metallic materials, e.g. glass fibre or epoxy resins are widely used.

No comprehensive data on the low temperature mechanical, thermal and electrical properties are available for the materials of interest. Extensive test programmes have been started in different GESSS laboratories. The main interest is directed to understand the behaviour of the epoxy resins used to impregnate the coils. Degradation effects observed in most of the coils and magnets built are partly due to the misbehaviour of the impregnation material. Mechanical release of energy within the coil may raise the temperature locally and thus initiate degradation. Frictional energy can be generated by conductor movement, mechanical strain energy can be stored during fabrication and cooldown due to differential thermal contraction and subsequently released when the magnet is pulsed. This is especially dangerous if it happens in the impregnated coil near the conductor itself as would be the case with a badly matched impregnation material. Otherwise, a reasonably well matched impregnant should ensure satisfactory coil performance at nearly critical current.

The objective in selecting the epoxy resin should be twofold: minimum differential thermal contraction between conductor and resin to avoid cracks during cooldown and minimum irreversible deformation and crack energy per unit volume to reduce temperature rise in case of a crack. The force developed by differential thermal contraction is proportional to the product of Young's modulus E(T) and relative thermal contraction $\Delta L/L(T)$, which has to be minimized. Unfilled or filled resins and resins which are flexible or rigid at room temperature can be chosen, since they behave similar when cooled down. Flexible resins have smaller Young's moduli but the contraction is greater, rigid resins behave vice versa (Fig. 15).

The filler increases Young's modulus approximately as much as it decreases thermal contraction. The higher curing temperature of rigid resins gives an additional contraction and therefore enhanced forces. So, flexible and filled epoxy resins with relativly low curing temperatures seem to be favorable.

Investigations of the influence of fillers and different epoxies on crack energy are under way.

4. Magnet power supplies

Stored energy and field rise time determine the size of the power supply. Stored energy can be minimized by minimizing the magnet aperture, and this on the other hand depends on the requirement of an effective injection and ejection. A high injection energy (separate ring on top of the conventional injecting machine) and an effective ejection scheme (high β insertions) may limit total stored energy to less than 500 MJ. Three types of power supplies may be considered: a motor generator set as used in most big machines; a static power supply, where power is directly drawn off the electric grid, as is used at NAL, Batavia; and a superconducting energy storage system as proposed by Smith [12)]. The first two may be well adopted to a 1000 GeV superconducting version of the CERN machine.

5. Magnet cryostat and refrigeration system

5.1 Cryostat

The superconducting magnet is put into a cryostat and maintained at helium temperature. It has to give a rigid support to the magnet with a total weight of several tons (1 to 1.5 t/m) and on the other hand to minimize the flow of heat to the helium vessel to reduce static heat losses. Heat leaks will occur by radiation, by thermal conduction down the support system, the supply necks and electric leads. By superinsulation the heat input can be reduced to between 0.3 and 1 W/m^2 and by an additional nitrogen shield by another factor of 3 to 4. Heat input down the electrical leads is about 10 W/1000 A of current per pair. Therefore, magnets and cryostats will be interconnected at low temperature level. A design chosen for D2 is shown in Fig. 16. Parts of the cryostat for MOBY are shown in Fig. 17.

The cryostat of a prototype dipole should be an integral part of the magnet design, possibly even including helium transfer lines. Several magnets may be contained in one cryostat, up to half a period in the separate ring solution (Fig. 18).

5.2 Refrigeration system

Estimates have been made of the total heat load of a 1000 GeV synchrotron at helium temperature. Including dynamic losses in the superconductor, hysteretic losses in the iron shield, and static heat losses of the magnet cryostat and in distribution pipes, a total of between 10 and 20 W/m is obtained. The heat load at the refrigerator is thus 50 to 100 kW at liquid helium temperature. Large accelerators are subdivided into superperiods, e.g. 6 in the case of the 300 GeV accelerator. The same might apply to the refrigeration system.

A preliminary design study was completed [13]. It was found advantageous to subdivide the system and operate it economically at the average energy loss rate, storing refrigeration during low loss time intervals. Interconnecting all the refrigerators by a common supply ring might offer a high degree of redundancy in case of a fault. A common compressor or 6 compressors interconnected by supply lines could be used.

Serious consideration has to be given to the operating temperature of the cryosystem. Current superconducting wires for use in pulsed magnets are made of NbTi composites with a critical temperature of 9.5 K. Its critical current density at 4.2 K is about $2 \cdot 10^5$ A/cm^2 at 5 T and changes rapidly with temperature: about 35 % per degree K. Thus a lot of superconducting material can be saved by lowering the temperature in the coil, but more refrigeration has to be spent. Overall economics seem to favor operating temperatures below 4.2 K. Parameters of the refrigerator are going to be worked out by the cryogenic subgroup of GESSS. A technical and economical study by national industries will be based on these data.

6. Outlook and summary

The development of superconducting pulsed magnets has made rapid progress in both Europe and the United States. A lot of dipoles has been finished. Test results give confidence that most of the physical and engineering problems are reasonably well understood. We are now in a state of investigating fully engineered preprototype synchrotron magnets which cover most of the relevant parameters for a full scale prototype: apertures ranging from 8 to 11 cm, central fields from 4 to 6 T and lengths of magnets between 0.5 and 3 m. Different winding configurations, impregnation techniques and cooling measures are applied in different laboratories. The conductors used include braids and cables, soldered and fully insulated versions with current carrying capacities ranging between 1000 and 6000 A at 5 T. Field rise times are as low as 1 sec without significant degradation.

One of the most important features of the magnet development is the conductor available. Magnet design and development reflects the development of the conductor and will further do so. If in the future, superconducting materials with higher current densities and higher critical parameters will become available in form of appropriate conductors improved design parameters will be used. The higher current densities will allow more compact coil designs with smaller amounts of superconducting material. Higher magnet operation temperatures, e.g. typically 10 K rather than 4 K, will greatly reduce refrigeration requirements. The higher critical magnetic fields of these superconductors could point a way to even higher energy accelerators.

After having completed the dipoles now under consideration by the end of 1973 enough information should be available to select parameters for a pre-production prototype synchrotron magnet to be manufactured by or in close cooperation with industry. Different dipole magnets then available should be assembled to a series of magnets operated simultaneously thus simulating a magnet system in a closed refrigeration loop.

The work of GESSS will be relevant to all types of pulsed magnets (dipoles, quadrupoles etc.) as considered in various laboratories. It will be equally relevant to d.c. operated magnet rings and d.c. beam handling elements which are counterparts of their pulsed equivalents.

Acknowledgement

The author is grateful for many discussions with colleagues of the GESSS collaboration. Especially the exchange of latest results and relevant photographs is greatly appreciated. He thanks F. Arendt for critically reading the manuscript.

References

1) GESS-collaboration, Towards a European Superconducting Synchrotron, GESSS-1, May 1972

2) F. Arendt et al., Proc. 8th Int. Conf. High En.Acc., CERN 1971, p. 171

3) G. Ries and H. Brechna, KFK Rep. 1372 (1972)

4) P.F. Smith, J.D. Lewin, C.R. Walters, M.N. Wilson and A.H. Spurway, RHEL, preprint RPP/A-13, 1969 (unpublished); J. Phys. D3, 1517 (1970)

5) M. Suenaga and W.B. Sampson, Appl. Phys. Letters, 18, 584, (1971); Appl. Phys. Letters, 20, 443, (1972) and BNL - 16415

6) P.F. Smith, Proc. 8th Int. Conf. High En. Acc., CERN 1971, p.35

7) M.N. Wilson, RHEL, preprint RPP/A89

8) A.D. McInturff, Proc. Appl. Supercond. Conf., Maryland, May 1972 (to be published)

9) P. Turowski et al. (to be published)

10) D.B. Thomas, Proc. 8th Int. Conf. High En. Acc., CERN 1971, p. 190 and M.N. Wilson et al. (RHEL), Proc. Appl. Supercond. Conf., Maryland, May 1972 (to be published)

11) A. Berruyer et al. (CEN/Saclay), Proc. 4th Int. Magn. Conf., Brookhaven 1972 (to be published)

12) P.F. Smith, Proc. 8th Int. Conf. High En. Acc., CERN 1971, p. 213

13) J.W. Dean, Rutherford Laboratory Memorandum, RHEL/M/A22 (December 1971)

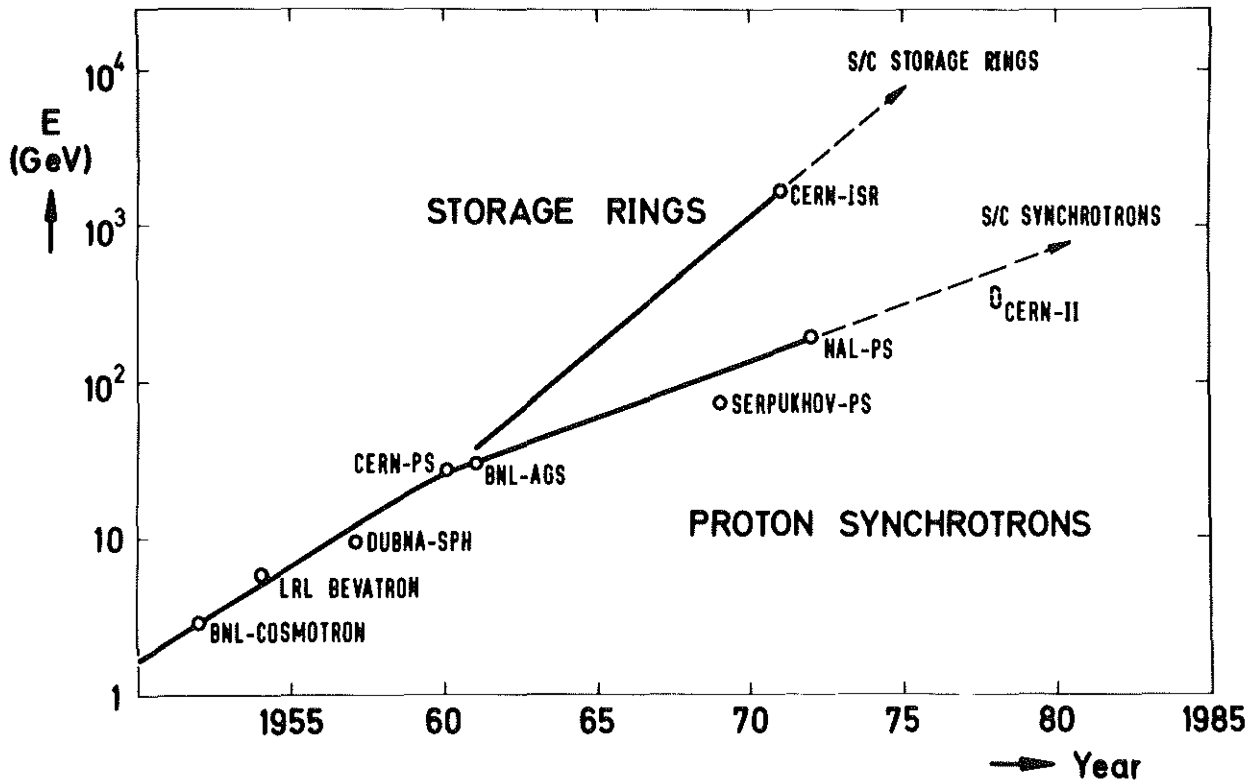


Fig. 1: Maximum energy of various accelerators versus date of first beam obtained

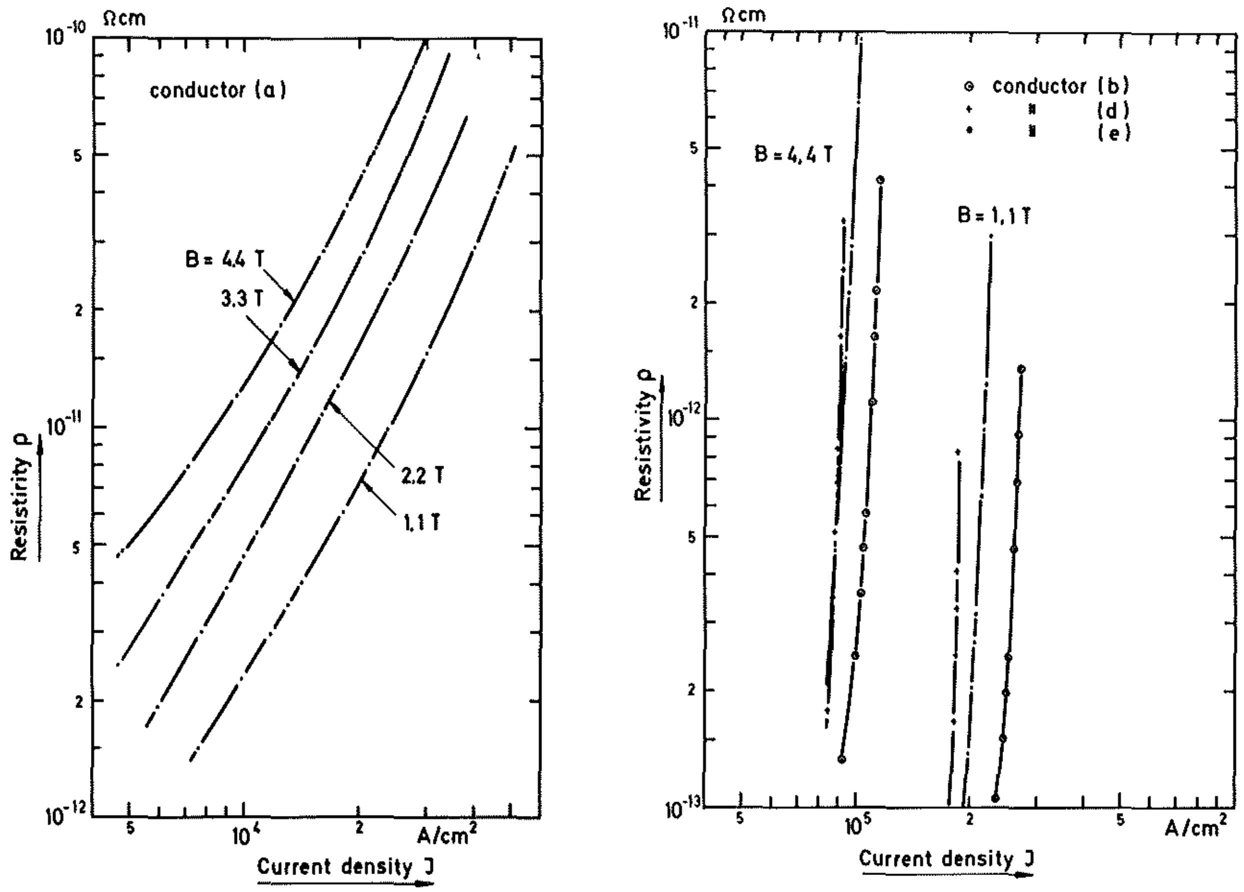
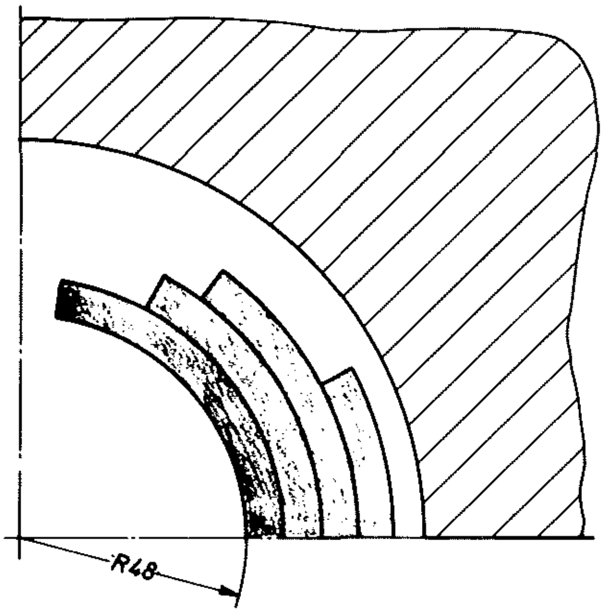
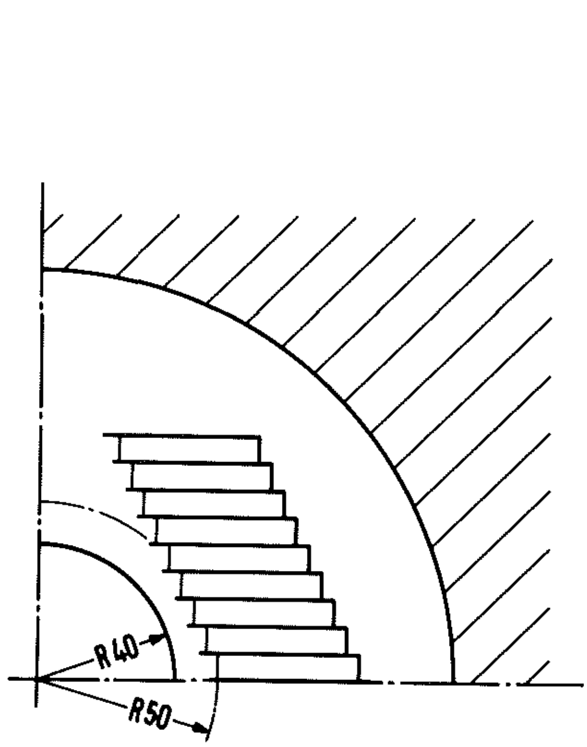


Fig. 2: Short sample characteristics: Resistivity versus current density for some selected conductors

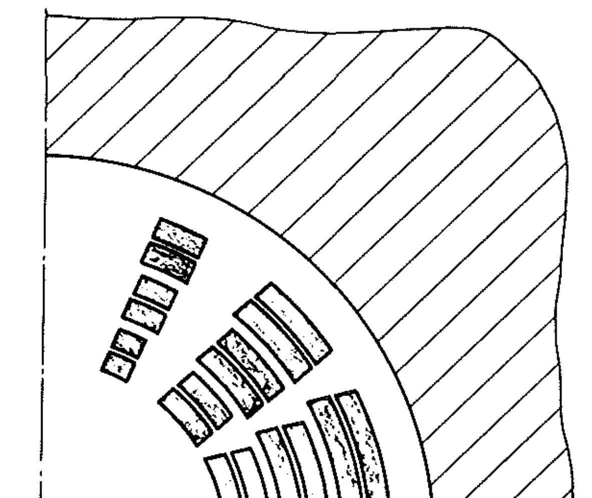
Conductor	Wire Diameter (mm)	Filament Diameter (μm)	Number of Filaments	Cu:Sc Ratio
(a)	0.4	10	300	3.8 : 1
(b)	0.4	24	130	1.2 : 1
(c)	0.28	10	361	1.25: 1
(d)	0.38	8.5	1000	1 : 1
(e)	0.2	7.5	400	1 : 1



a) concentric layers (RHEL)



b) shaped block of parallel layers (CEN)



c) spaced sectors with 3 double layers (IEKP)

Fig. 3: Conductor configurations

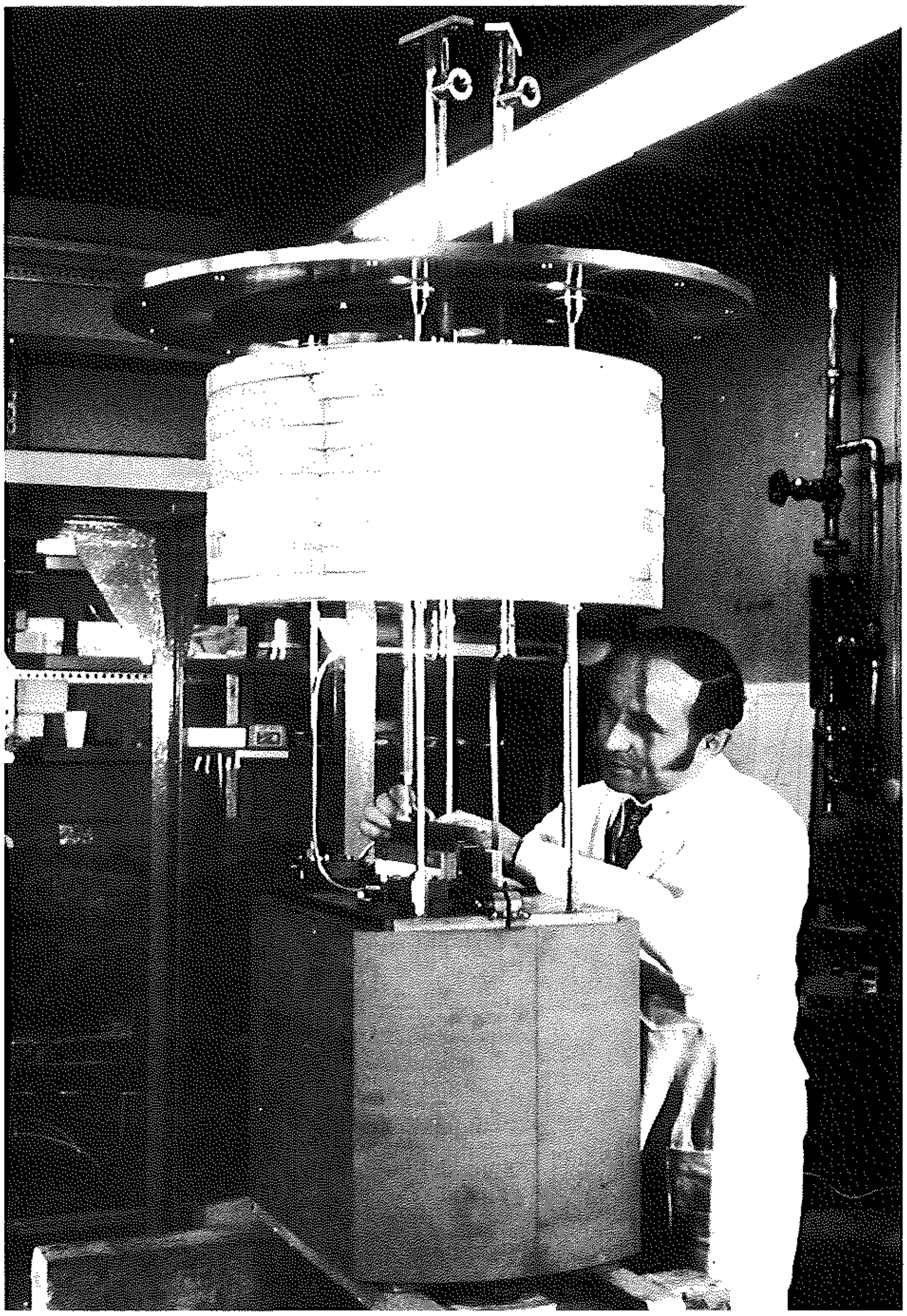


Fig. 4: DT dipole magnet (IEKP)

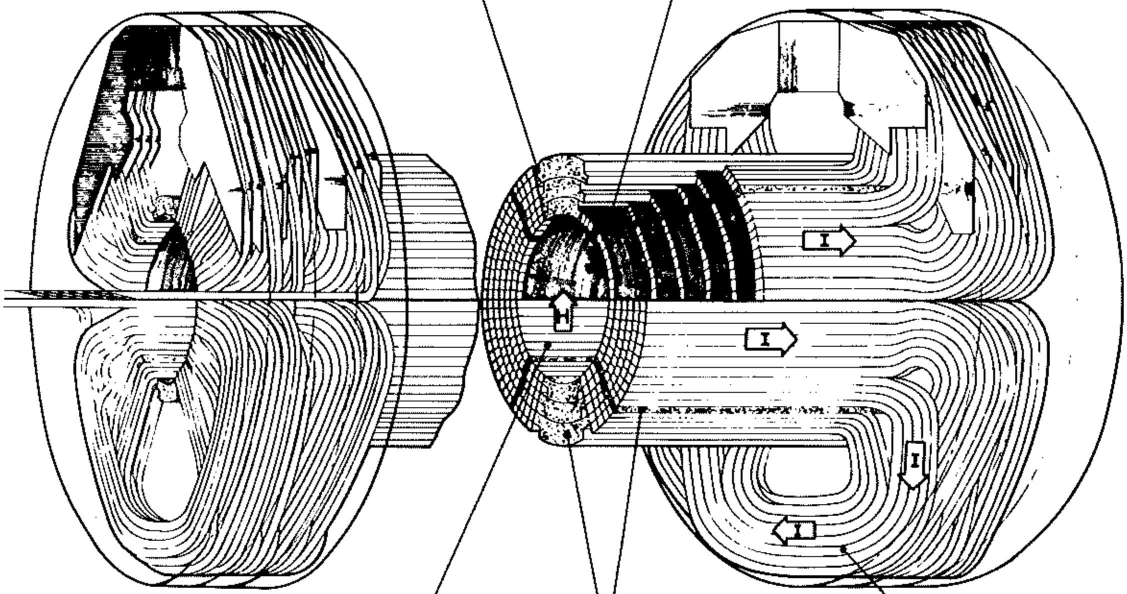


Fig. 5: Schematic view of coil geometry of dipole AC3 (RHEL)

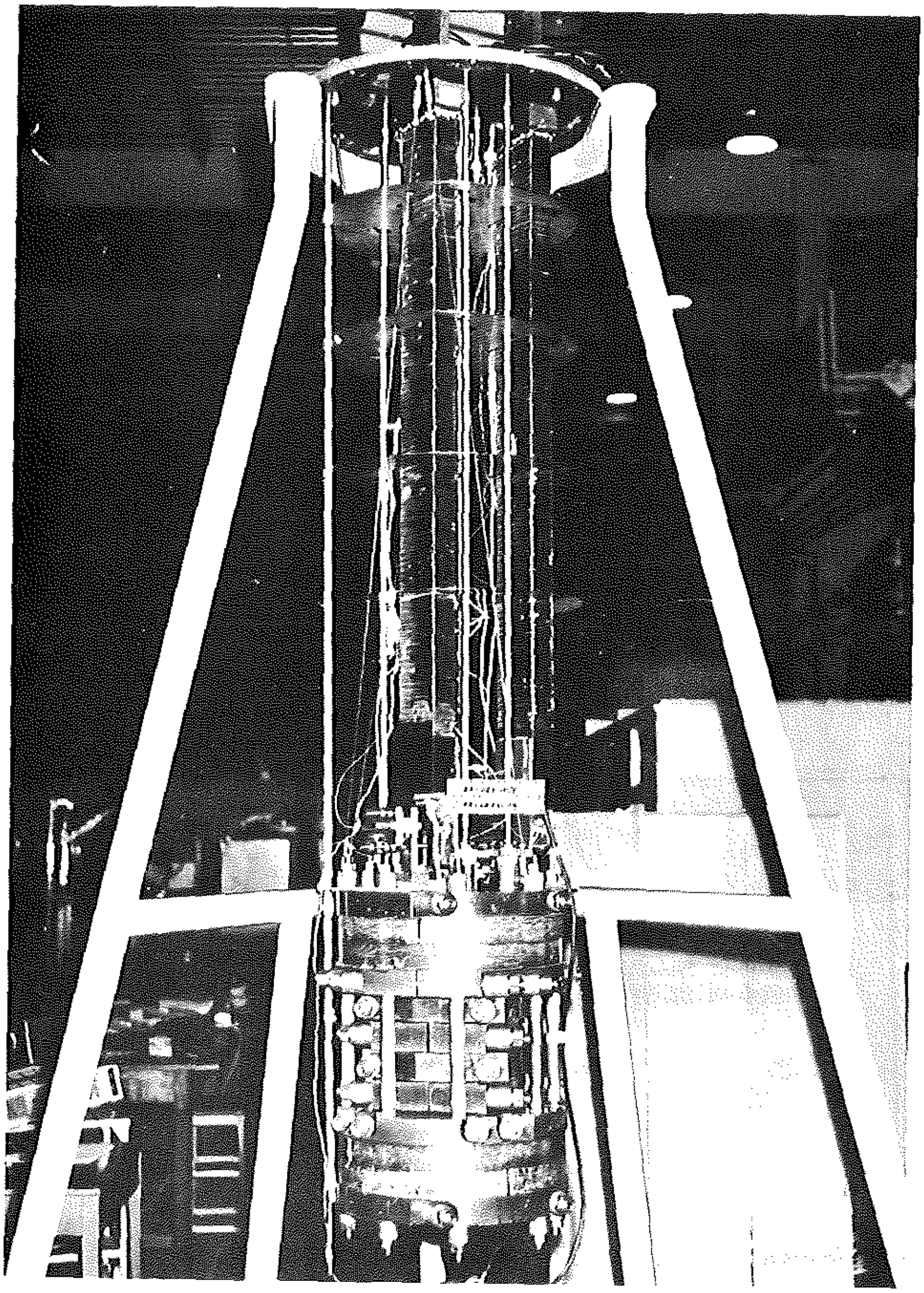


Fig. 6: AC3 fully assembled

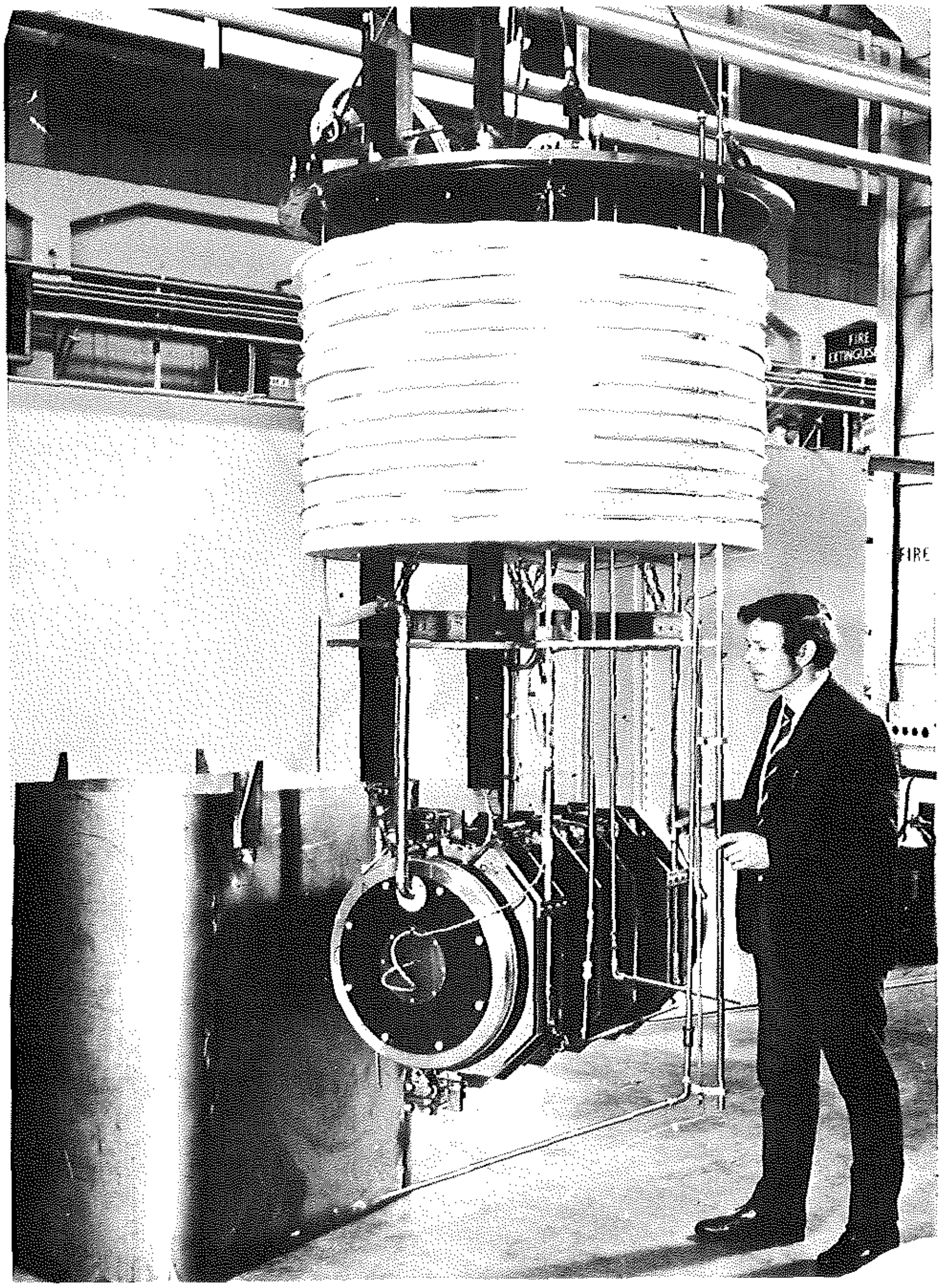


Fig. 7: AC4 fully assembled

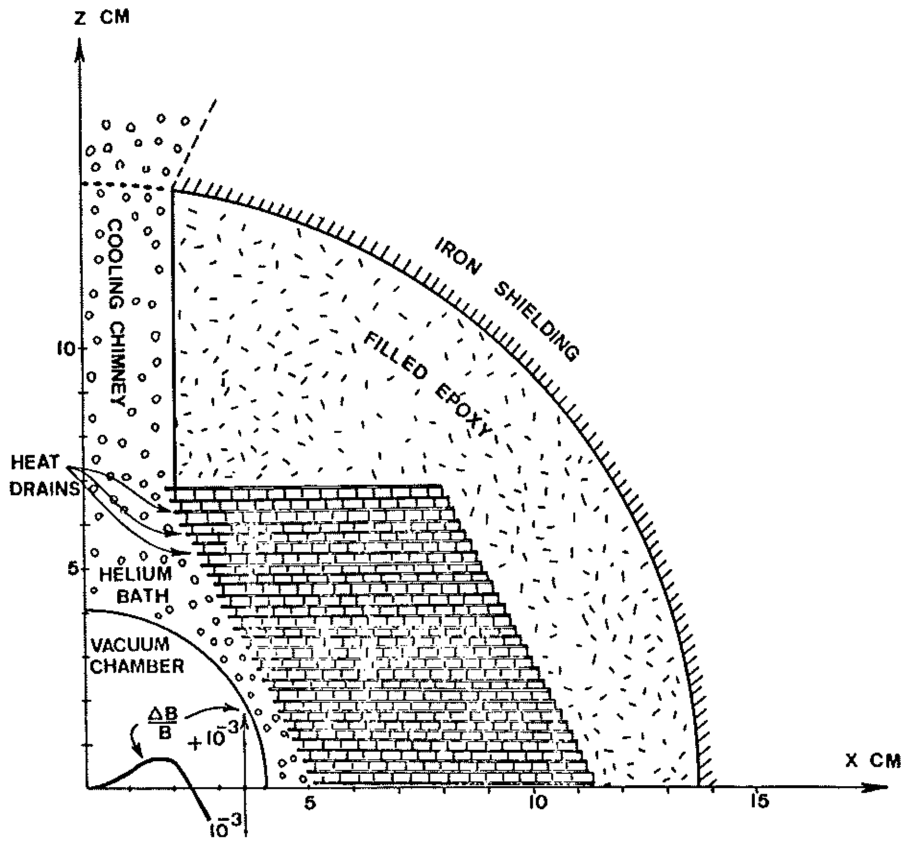


Fig. 8: Coil and iron shielding configuration of MOBY (CEN)

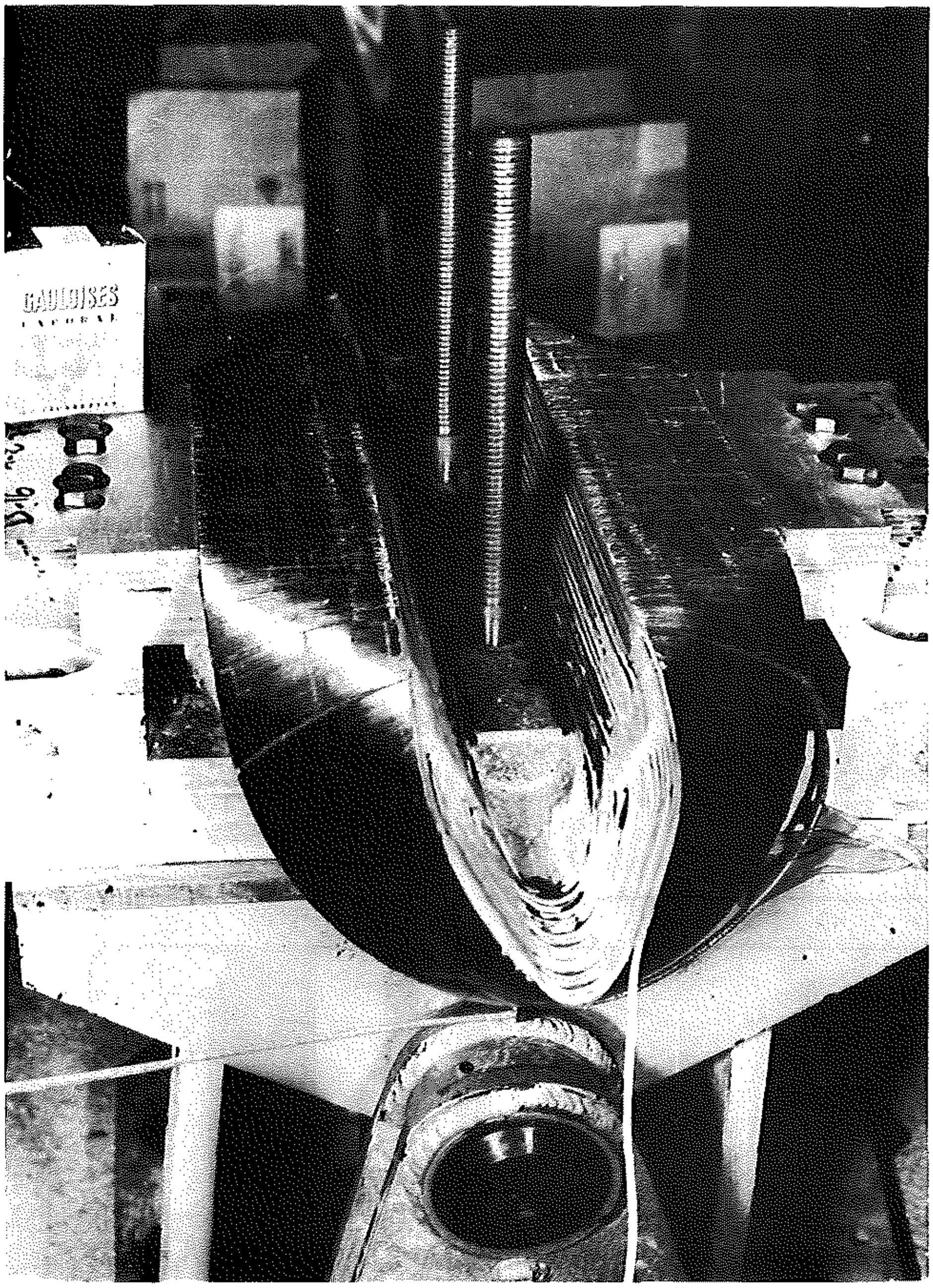
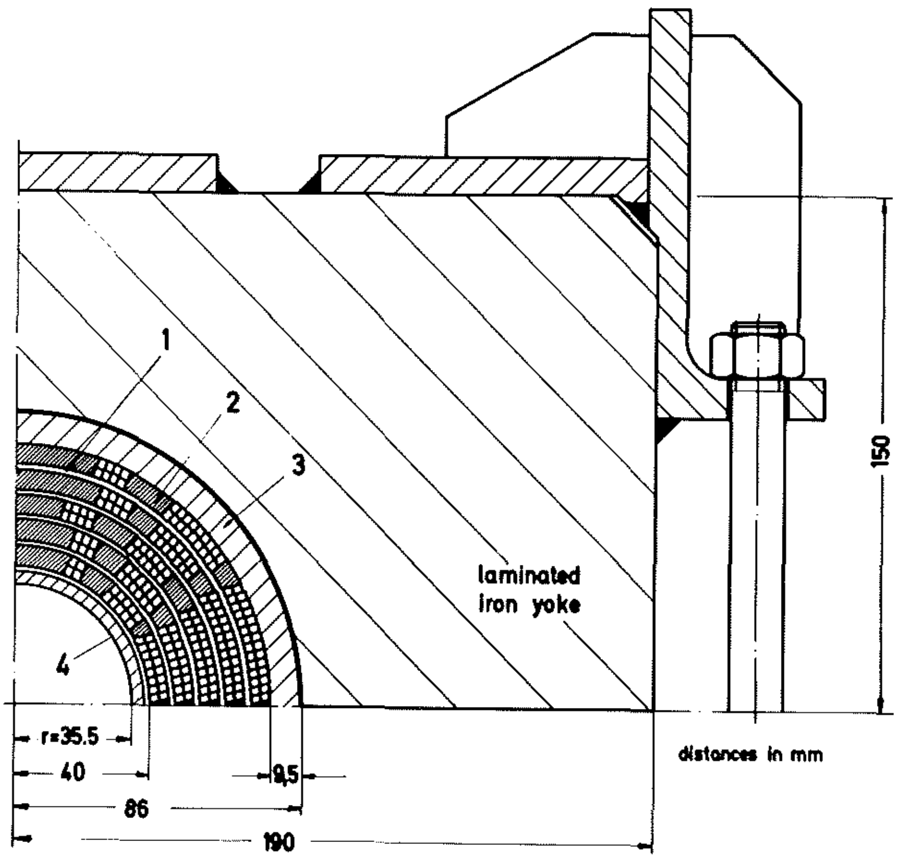


Fig. 9: Completed bruss model showing winding technique of MOBY



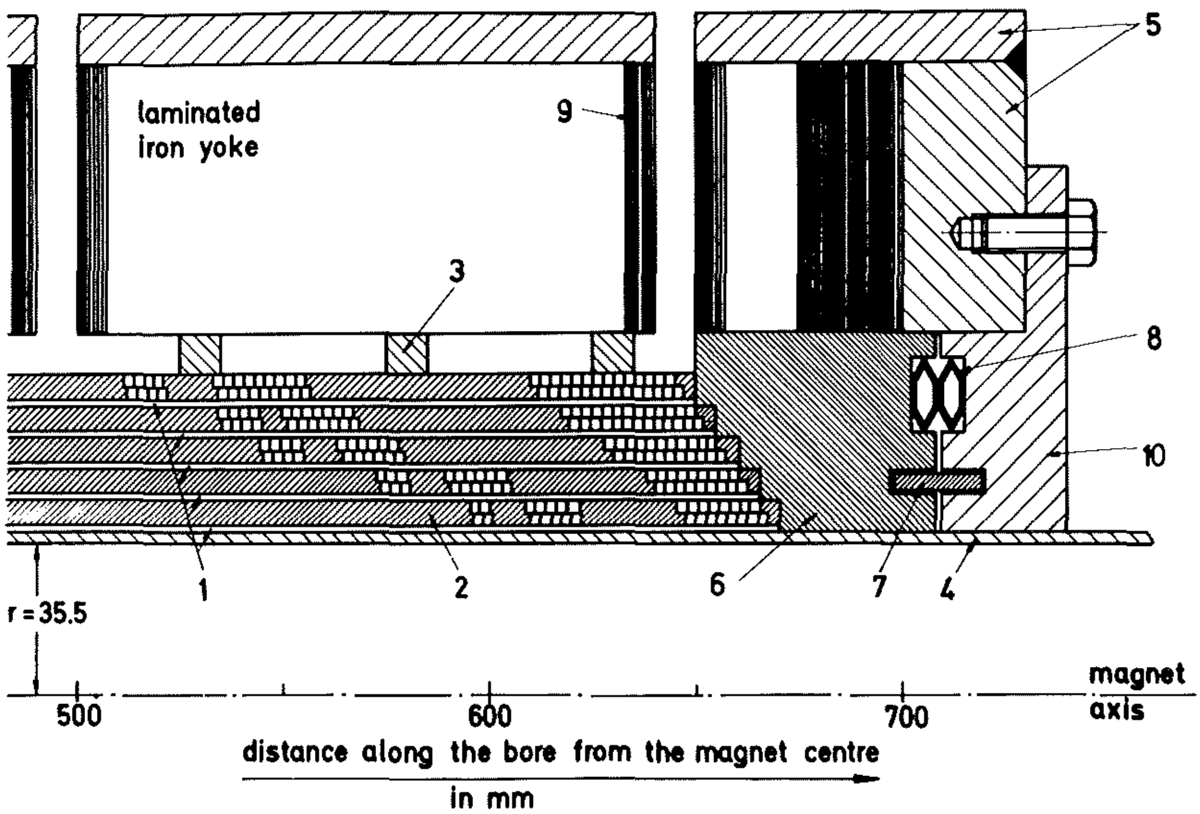
Dipole D2a cross section with conductor configuration (left) and longitudinal section with conductor end configuration (below):

1. Cooling channels, 1.5 mm in width,
2. spacers, glass fibre reinforced epoxy;
3. support rings, stainl. steel;
4. tube, stainl. steel;
5. yoke top and end plate, stainl. steel;
6. sleeve, glass fibre reinforced epoxy;
7. guide pin;
8. Belleville springs;
9. Cooling hole;
10. front panel, stainl. steel.

Fig. 10:

Dipole D2a (IEKP)

a) Radial cross section



b) Axial section of the end region

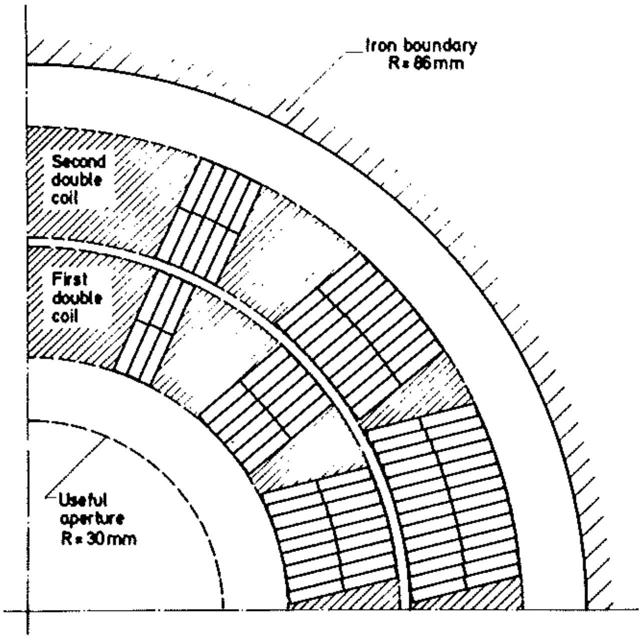
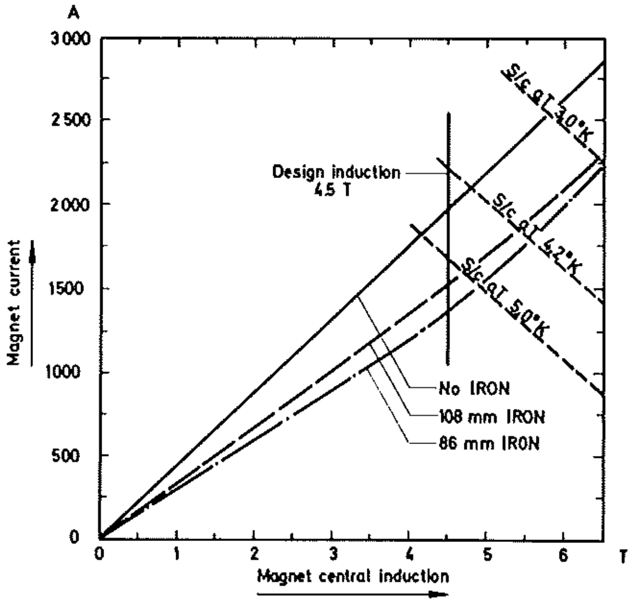


Fig. 11: Cross sections of a two double layer dipole using a flat cable

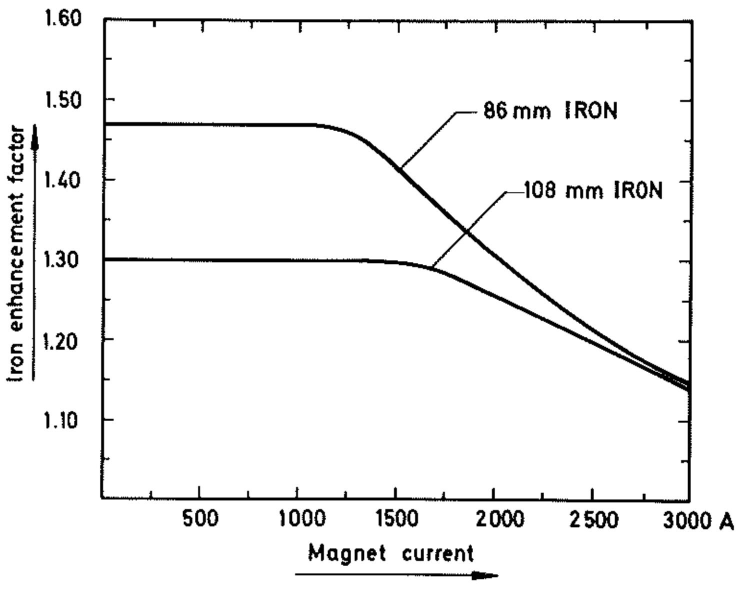
Bo = 4.5 T
I = 3190 A
N = 95 turns/pole

Fig. 12:

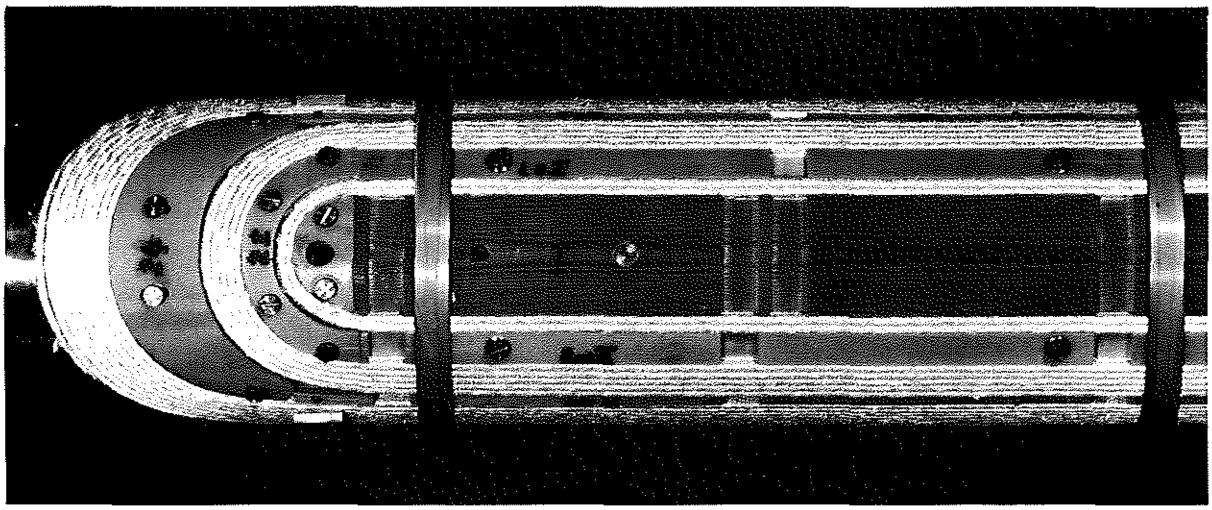
a) Dipole D2a operating current vs central induction and short sample characteristics of the cable used



b) Field enhancement factor for saturated (86 mm) and unsaturated (108 mm) iron version



A N 2992-2102



A N 2993-2102

Fig. 13: Trial coil winding of D2a (IEKP).
Overall view and detail

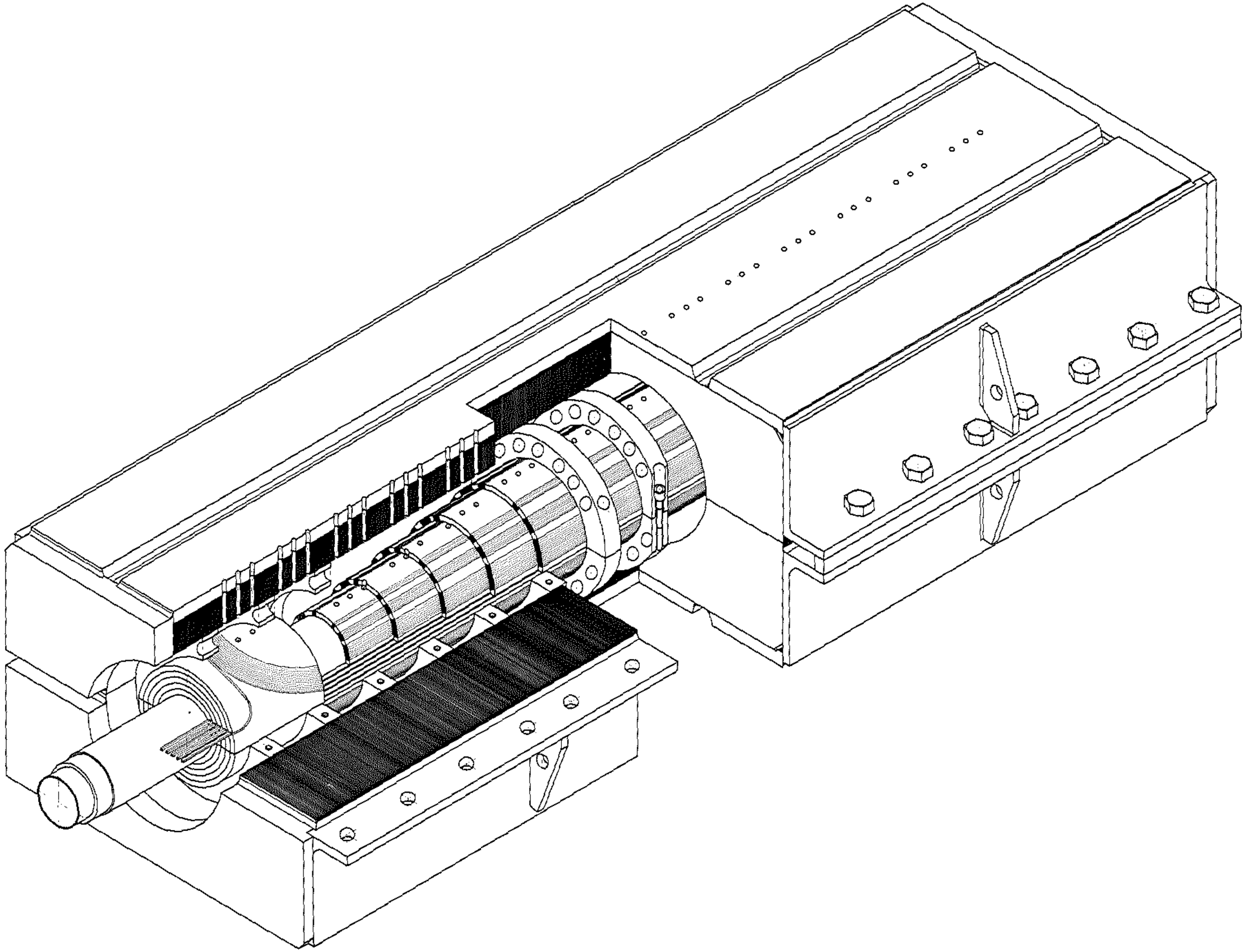
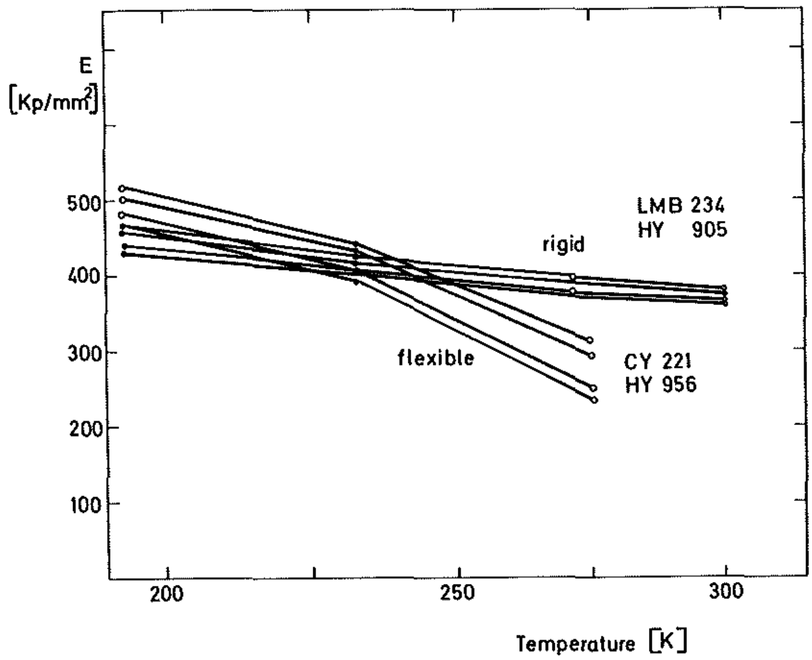


Fig. 14: Axiometric view of D2a (IEKP)
Explanation of details should be taken from Fig. 10



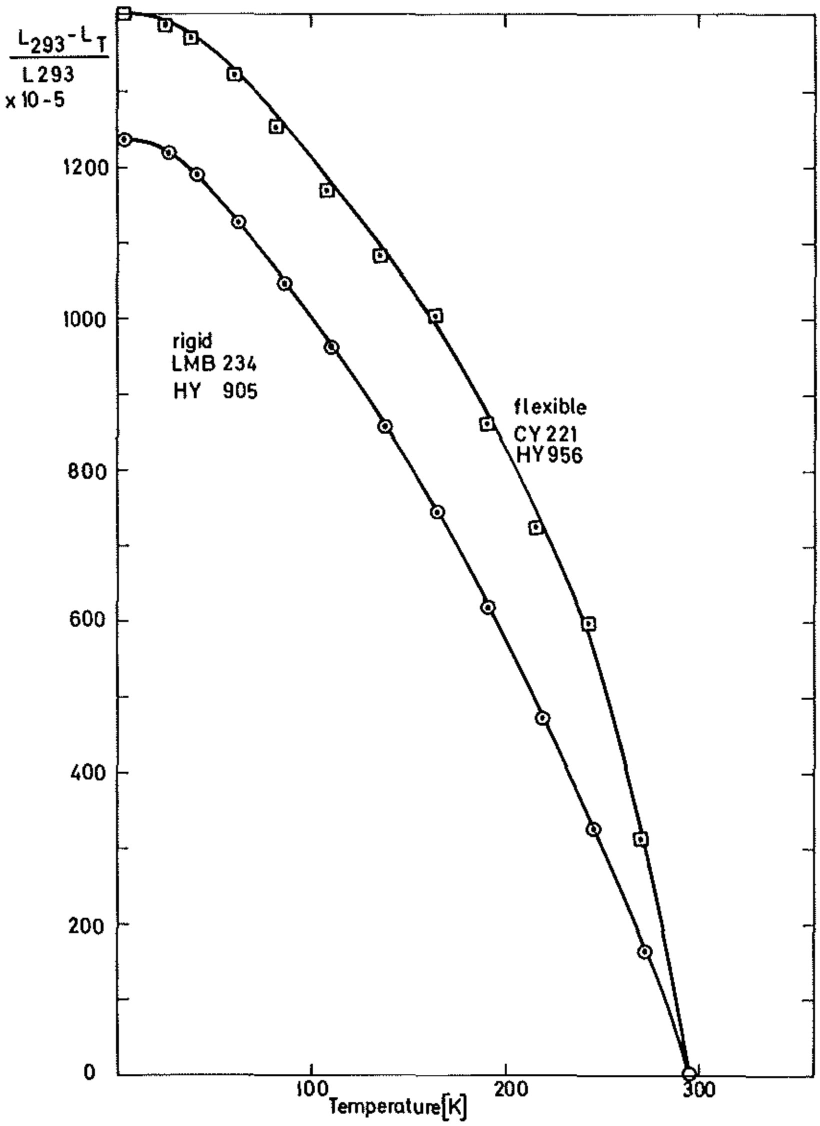


Fig. 15:

Young's modulus and relative thermal contraction vs temperature of unfilled epoxies. Flexible or rigid refers to their behaviour at room temperature.

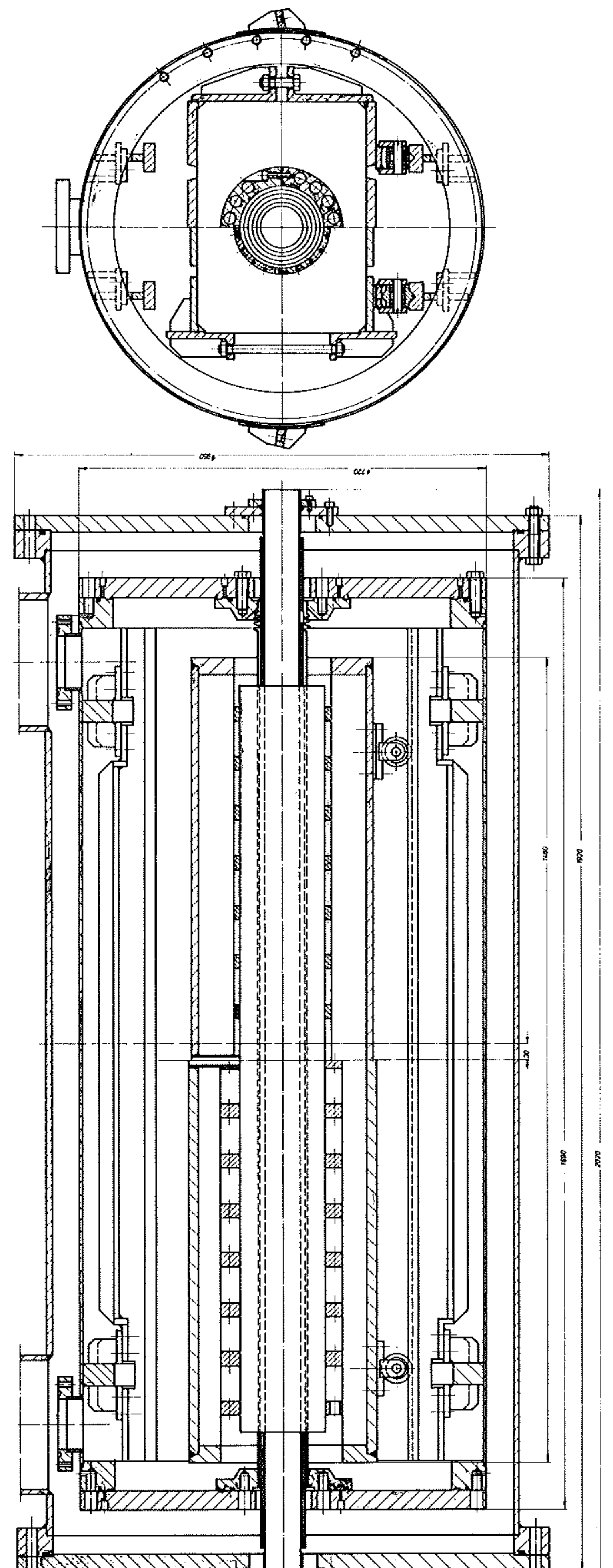
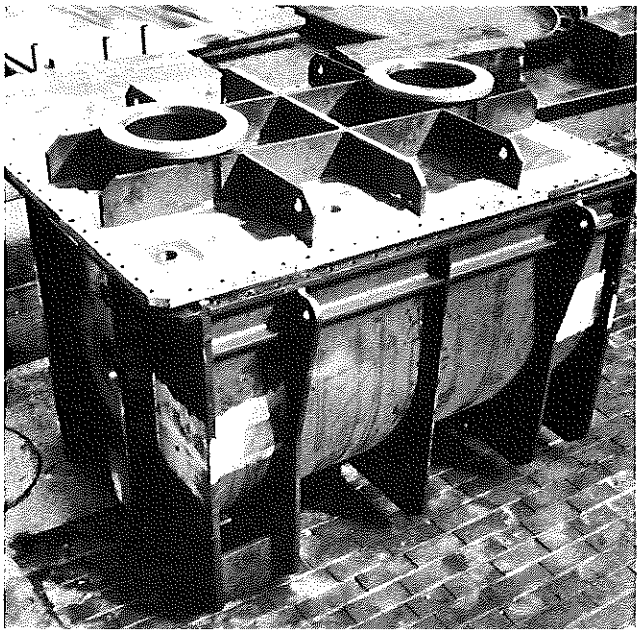


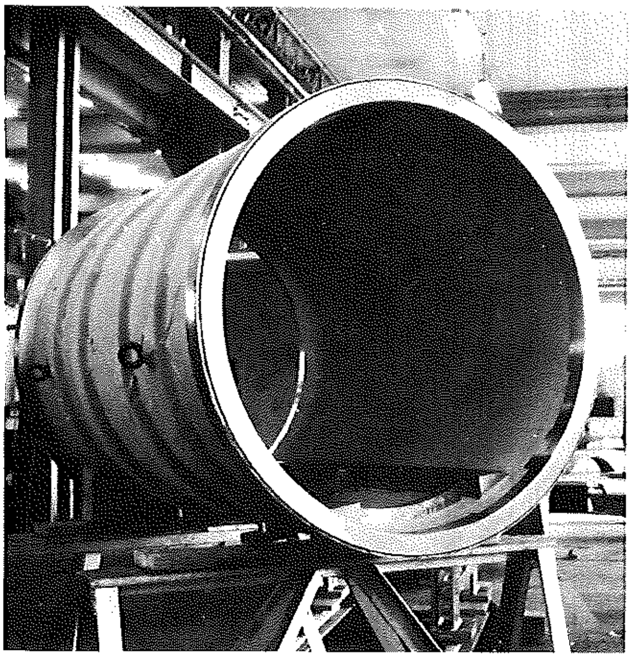
Fig. 16: Axial and radial views of cryostat for D2 (IEKP)



a) vacuum tank

Fig. 17:

Cryostat for MOBY (CEN)



b) helium tank

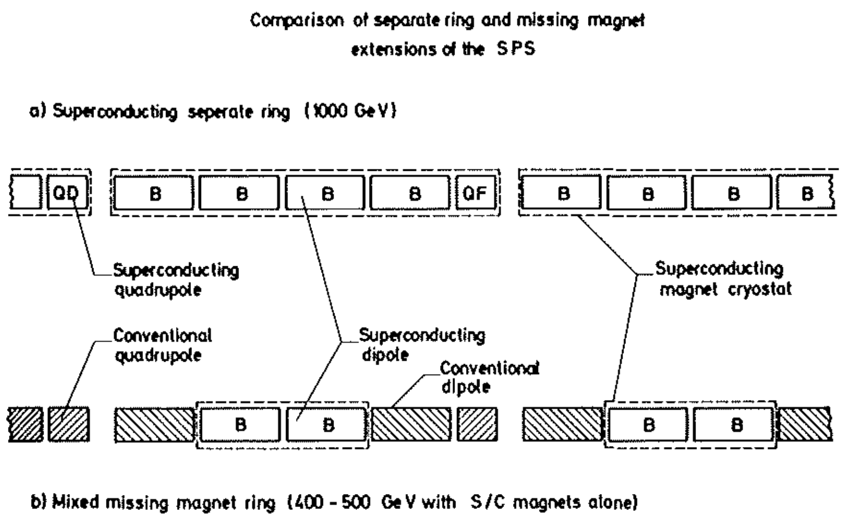


Fig. 18: Possible arrangements of cryostats in a missing magnet and separate ring solution