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Applied superconductivity conference.
Santa Fe, NM, USA, September 29 - October 2, 1980.
CEA - CONF 5462

FR8002672

SUPERCONDUCTING MAGNET FOR EHS

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A 55 Mjoules Magnet has been installed and commissioned at CERN for the Rapid Cycling Bubble Chamber of the EHS experiment (European Hybrid Spectrometer). The magnet consists of two separate circular coils, assembled with their axis horizontal into a massive iron structure, and provides a central field of 3 T in a useful volume of 1.4 m in diameter and 0.82 m gap with a completely azimuthally free acceptance of ±18° from the central plane. Special features of the magnet, which is otherwise of a classical pancake-type, bath-cooled design, are a relatively high average current density (2500 Amp/cm^2) and an elaborate support structure required by the particular force configuration within the iron structure.

Main characteristics

The EHS experiment is being set up at CERN by a joint collaboration of European Laboratories[1]. The central part of this device is a Rapid Cycling Bubble Chamber constructed at Rutherford Laboratory. This bubble chamber is equipped with a large superconducting magnet which was contracted by CERN to the CEN/Saclay[2].

The general configuration of the system is shown schematically on Fig.1. The cylindrical Bubble Chamber has its axis horizontal and is actuated axially through a circular plastic bellow-piston assembly driven by a hydraulic expansion system which is tied to an 120-ton iron frame. This frame serves also as a yoke for the magnet, though contributing little to the central field, and for reasons of symmetry is split into two thick vertical plates braced by 4 massive cylindrical columns.

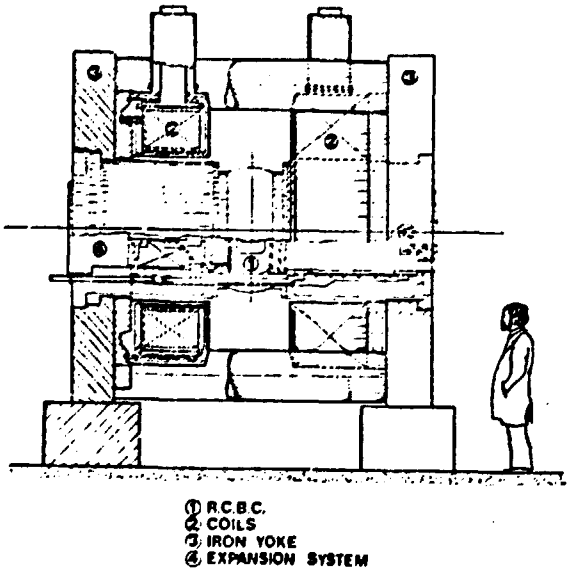

Fig.1 - Schematic view of RCBC and superconducting magnet.

The two circular coils are coaxial with the chamber and generate a horizontal field of 3 T in the center. They are built as two separate units and are rigidly supported onto the respective backing plates of the iron frame. In such a way, the space between the coils is completely free for beam access and detector location and the geometry can be easily changed for further eventual use. The main parameters of the coils are given in Table I.

Manuscript received September 29, 1980.

TABLE I

Room temperature bore	1.4 m
Room temperature gap between coils	0.82 m
Acceptance angle from central plane	±18°
Overall O.D. of cryostats	2.8 m
Winding I.D.	1.65 m
Winding O.D.	2.4 m
Axial length of each coil winding	0.46 m
Distance between windings	1.13 m
Number of double pancakes per coil	13
Number of turns per double pancake	84
Conductor dimensions	14.8 x 8.6 mm^2
Spacing between pancakes	3 mm
Nominal current	4000 Amps
Central field	3 T
Peak field on the conductor	5.8 T
Total Amp x turns	8.74 10^6
Stored energy	55 MJ
Conductor weight	8 tonnes
Total weight per coil (at 4.2 K)	12 tonnes

Coil construction

The coil design follows a classical scheme similar to existing large DC magnets. Each coil is made of 13 double pancakes separated by spacers and immersed in liquid helium as shown in Fig.2.

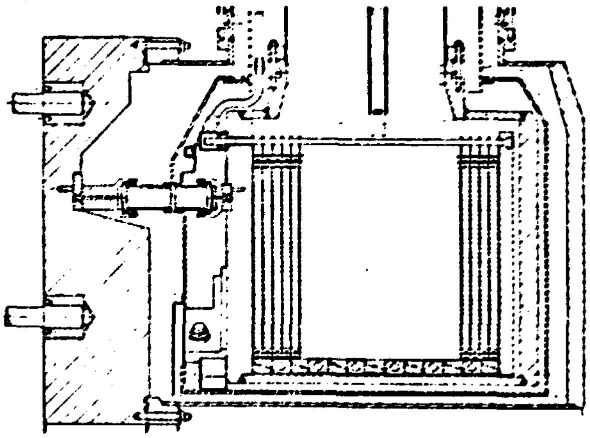

Fig.2 - Cross-section of one coil with main parts of the cryostat and supporting columns.

The conductor is made of a rectangular copper strip (14.8 x 8.6 mm^2 cross-section) with a rectangular longitudinal groove in which is laid and soft-soldered a Cu-NbTi multifilamentary composite of dimensions 3.45 x 5.7 mm^2. This composite contains 823 filaments of NbTi of 96μ twisted along a pitch of 100 mm with a Cu/Sc ratio of 2/1. The rated current for this conductor is 4500 A at 6.5 T and 4.5 K and the resistivity ratio of the copper between 300 K and 4.2 K is above 300 at zero field.

Each double pancake was wound separately using one single length of the above conductor, 560 meter long, so that no electrical joint is required on the inside of the coil. The winding line includes a roller head for straightening up and gauging the conductor both ways, a constant tension device (400 kg winding tension) and a horizontal turntable. In order to wind double pancakes, half of the conductor length was first wound on an auxiliary spool which was lifted above the turntable. Then both single pancakes were wound successively in opposite directions starting from the middle point. Electrical insulation was laid between turns during the winding by means of a mylar tape of the width of the conductor and 350μ thick, leaving the small edge of the conductor bare for cooling purpose. On the last turn of individual pancakes a single turn of a 1.5 mm thick stainless steel tape was added and short welded in order to prevent the outer turn from slipping or loosening. Detail of this part of the winding is shown in Fig.3. No other reinforcement or bandage were included as the hoop stresses in the conductor do not exceed 7 kg/mm^2 at full field without bandage.

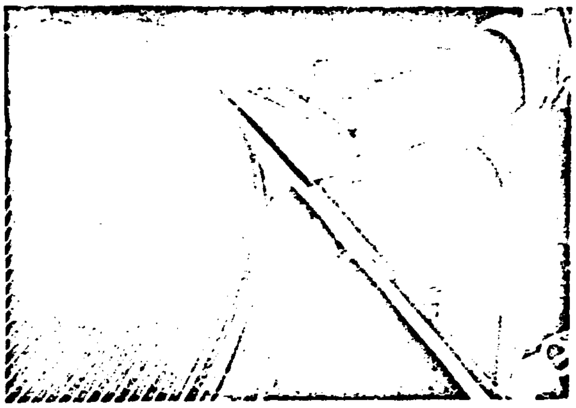

Fig.3 - Detail of winding showing the introduction of the SST bandage at the last turn.

After being wound, the double pancakes were stacked together with glass epoxy interleaving spacers on the 5 cm thick bottom plate of the helium cryostat (see Fig.4) and axially clamped onto this plate by means of a counterplate and two coaxial rows of aluminium tie rods. A precompression of the whole coil of 100 tonnes was achieved during assembly, which guaranties a minimum of 50 tonnes to be maintened permanently after cooling down and after further compaction induced by the high magnetic load cycling, so that the coil will never become loose.

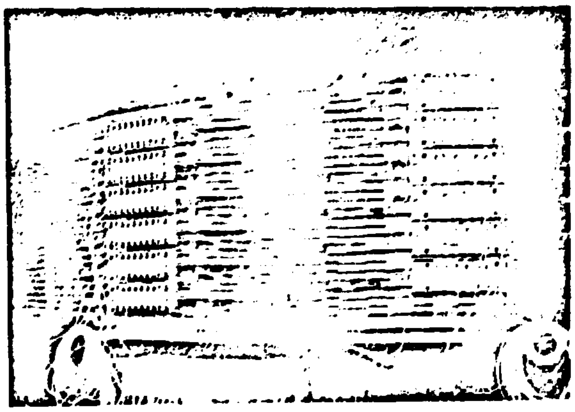

Fig.4 - Stacking of the pancakes on the cryostat base plate, with interpancake electrical connections.

The fiber glass spacers between individual pancakes are 3 mm thick and are cut for leaving radial cooling channels of 40 mm width. Approximately 62% of the conductor edge surface is exposed to liquid helium at the inner turns (where the field is maximum) and 43% at the outer turns.

Electrical connections between double pancakes were made by indium soldering of the two conductor ends together and heavy clamping with copper and stainless steel plates, as can be seen on Fig.4.

After these joints and all the various sensors were secured into place, the helium can was closed and shut-welded, except for the dome part, after which the coil was ready for complete assembly of the support structure and of the remaining components of the cryostat.

Support structure

The coil is completely supported onto a 20 cm thick iron annular vertical plate, which both serves as the vacuum tank wall and as an integral member of the massive iron frame previously mentioned.

The support structure has to fulfill a number of simultaneous requirements : 1) Support the axial force between the coil and the iron yoke (250 tonnes full field-horizontal magnetic load. 2) Hold the weight of the coil (12 tonnes vertical) and other transverse forces due to asymmetric loads such as close-by shielding for aerogel counters. 3) Stand for vibrationnal pulses transmitted by the RCBC expansion system to the iron structure (fundamental frequency of 20 to 30 Hz), which can be applied either with or without the field. 4) Accommodate the thermal contraction difference between the coil and the warm iron. 5) Keep a centering tolerance of the magnetic axis with respect to RCBC within 0.5 mm under all the above effects. 6) And, minimize the heat load to the cold sink.

The adopted scheme features two sets of supports. The first set takes care of axial static and dynamic components. It consists of a ring of 24 fiberglass/epoxy columns tied between the helium can base plate and the warm iron plate through spherical bronze bearings at both ends of each column, as shown in Fig.2. Each glass column, 45 mm in diameter, is made of high strength high modulus uniaxial fiber glass and is able to withstand a a compress force of more than 70 tonnes with a Young's modulus of about 3800 da N/mm^2. Heat intercepts are provided at one position of each column by means of aluminium collars cooled by helium gas evaporated from the cryostat. In this way, the heat input at the 4.2 K end is only 0.175 Watt per column. Fig.5 shows the columns partially assembled. In addition, 10 peripheral titanium rods, also parallel to the axis and tied under prestress between the He can and the iron, maintain a permanent compressive load on the glass columns of 50 tonnes when the magnet is not energized, which enables the expansion system to be operated with or without field.

The second set of supports is aimed at carrying the weight and transverse loads in any azimuthal direction. It consists of an array of titanium rods disposed in a vertical plane according to the pattern shown in Fig.6. The rods are 16 mm in diameter, are tied through spherical bearings to the He can base plate and to the iron plate and are equipped with heat intercepts connected to the thermal shield. They are prestressed during assembly with a force about 4 tonnes per rod in such a way as to center the coil properly and to maintain the required centering tolerance during operation.

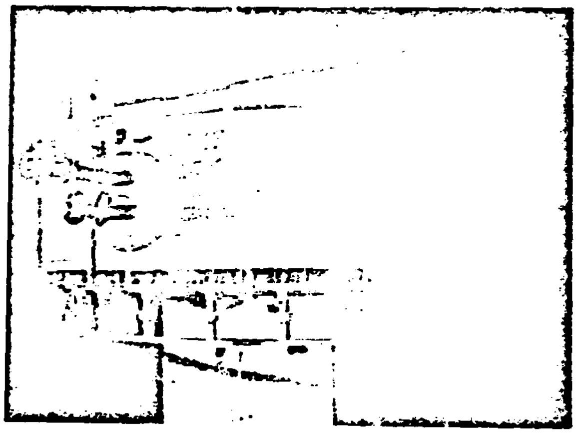

Fig.5 - All-welded helium tank with the ring of glass-fiber columns attached to the bottom plate.

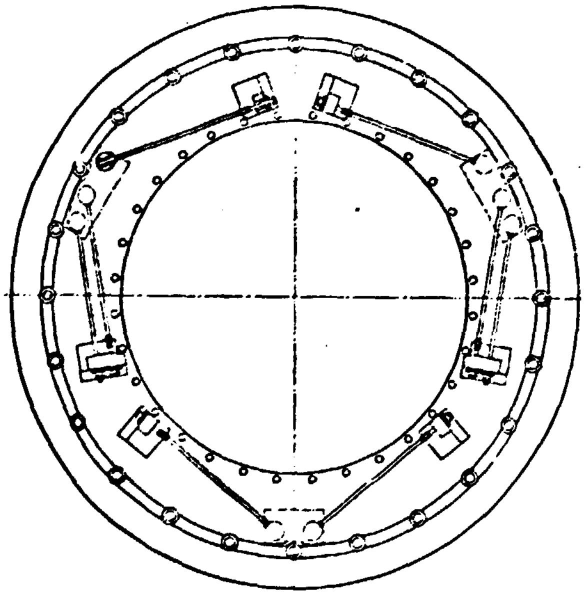

Fig.6 - Configuration of suspension rods and glass columns (outer ring).

Cryostat

The shut-welded helium can was completely surrounded by an aluminium thermal shield covered with super-insulation. The shield is cooled by cold vapour from the cryostat circulating in a welded aluminium pipe. The cooling loops are all in series, starting with the heat intercepts of the columns, at the lowest temperature ($\sim$20 K), and running along the various sectors of the shield, to come out at a temperature of about 50 K which is still usable for cooling a shield on the Bubble chamber or for returning to the refrigerator heat exchanger line. This avoids the use of liquid nitrogen and leads to optimum cooling efficiency.

The vacuum tank is a bell-shape stainless-steel can which was sealed onto the iron plate cover by means of double O-ring gaskets with inter vacuum pumping.

Next came the assembly of the upper dome including power leads and cryogenic lines. The power leads are made of massive copper rods with cut-out fins and are inserted in close-fit stainless steel pipes. They are cooled by a counter flow of cold helium gas and have enough thermal capacity to carry the full current for a period of 400 sec. without any cooling, which enables the current to be safety discharged in case of failure of the helium flow. All parts of the dome were shut-welded and thermal insulation was provided in the same way as for the main part of the cryostat. Figure 7 shows an intermediate stage of the dome assembly.

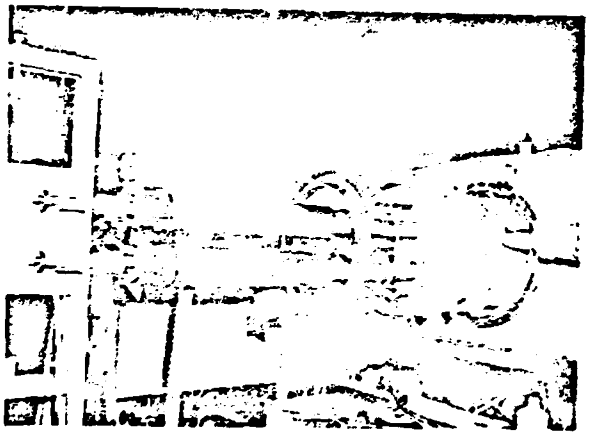

Fig.7 - Dome being assembled, showing the current leads

The last element of the cryostat is the pumping line, which is mounted on the outside shell of the cryostat at 90° from the dome. A double sleeve, with separate vacuum, enables instrumentation wires to be fed through the vacuum port. Figure 8 shows the completed coil with its upper dome and vacuum port assemblies.

Tests and performances

The two coils were first tested separately at Saclay. A major part of the electrical testing equipment was supplied by CERN, including a 10 V DC power supply, the dump resistance, connecting cables and a microcomputer-based data acquisition system for recording the many sensors installed in the magnet. About 120 measuring points were monitored in each coil, 32 for temperatures, 43 for strain gauges, 30 for voltage taps, etc. Cooling down was carried out using an in-house refrigerator, followed by direct transfer from storage dewars.

All specified tests were carried out successfully, including a number of charges at nominal current, followed by repeated discharges on a 25mΩ dump resistor, and an ultimate test at 4200 Amps and 4.5 K (5% above specification). No quench was experienced during these tests.

Following these tests, the coils were transported and mounted on the iron structure at CERN, where all the peripherical equipment was provided and installed by CERN. These include a 100 l/h liquefier and storage dewar, cryogenic and safety circuits, vacuum pump, computer control and monitoring.

The complete test of the magnet was carried out in April 1980 following the same procedure and leading to the same performance as during individual tests. Subsequently, the magnet was operated consistently for a period of two weeks for field mapping. It is at present shut down for installation of the Bubble Chamber, which is scheduled for first testing in November 1980. Figure 9 shows the magnet assembly at CERN.

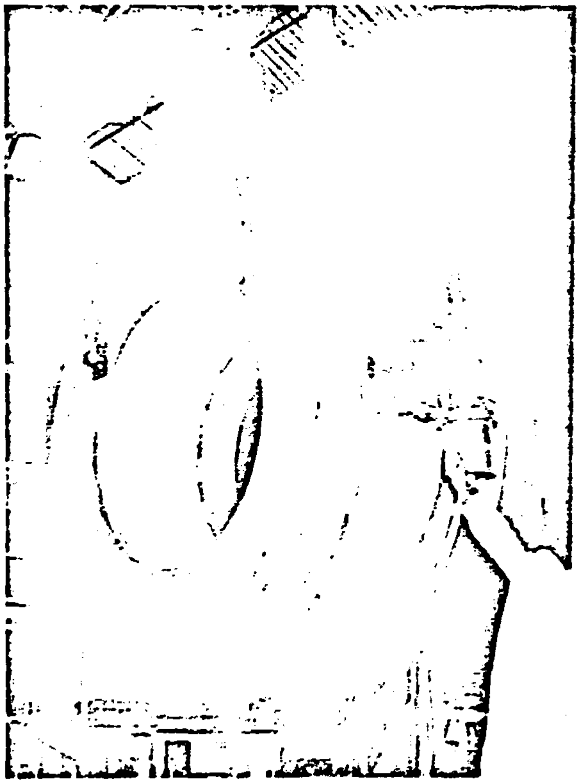

Fig.8 - Completed coil.

The performances obtained during the above tests deserve a few comments :

- With respect to actual short sample measurements at 4.5 K, the maximum operating current of 4200 A achieved in the magnet represents 93% of the critical current along the peak field load line. This leaves a temperature margin of less than 1 K for intrinsic stability.

- The overall stability of the magnet was clearly demonstrated since no quench was experienced up to this maximum current, in spite of the fact that full cryostability (according to the so called "Steckly" criterion) was not accounted for in the design. In order to fulfill such a criterion, a heat exchange coefficient of nearly [illegible].5 W/cm^2 would be needed in the peak field region, which is about twice what can be reasonably expected in steady state. This last statement was effectively confirmed on tests of a small solenoid made of the same conductor with similar cooling channel configuration, for which a recovery current of 2800 A was measured after inducing artificially a normal transition, whilst the minimum propagating current was of the order of 3500 A.

- The actual stability of the magnet can be explained by the fact that in a magnet of this structure there is no source of instability large enough to exceed locally the thermal enthalpy offered by the conductor and by the helium bath within the allowed temperature excursion. The major effect generally recognized for instabilities is mechanical motion within the coil, generating heat by friction. With the high compaction built in the coil both axially and radially during the construction, such possibility of motion is practically eliminated and the whole coil behaves as a solid body which is free to expand or to contract homogeneously and elastically. On the other hand, the volume of helium in direct contact with the conductor provides, by the heat of vaporisation alone, a heat sink of 0.5 joule per cm length of conductor which could still allow local displacements as high as 100 μ. In conclusion, the relatively high current density achieved in this magnet, compared to other large magnets, is safe and could probably be further increased in similar applications.

- A slightly different behaviour has been observed when discharging the magnet in the dump resistance. During separate tests, the first coil dissipated roughly the amount of energy which was expected from eddy and coupling currents in the conductor, but the second coil dissipated about 3 times more. Furthermore, during the complete test, it was found that the dissipated energy increased if the discharge time constant was increased, which showed evidence of a local normal transition when the initial current is above 3500 Amps, transition which did not propagate over a large area and even recovered during the current decay. Though no satisfactory explanation has been found for this behavior, it could be due to a length of untwisted conductor which may have occurred accidentally during conductor fabrication.

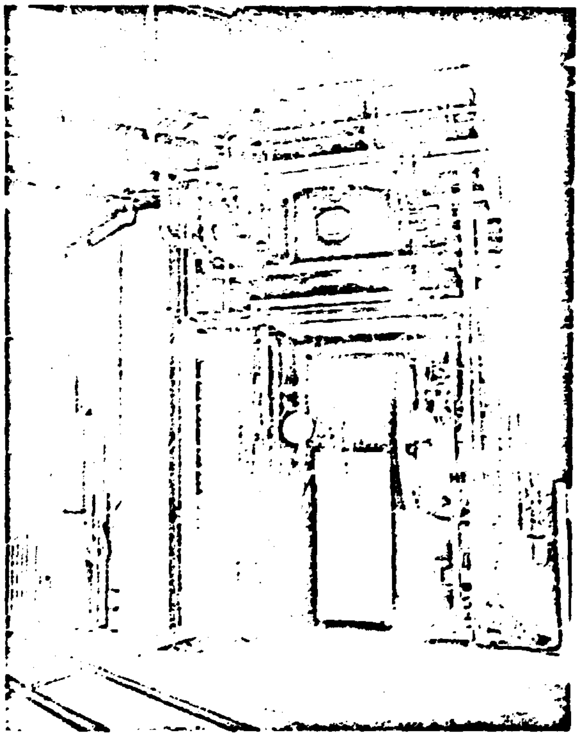

Fig.9 - Completed magnet installed at CERN;

Aknowledgement

The authors are most thankful to MM. Cusewell, Hervé and Wittgenstein of CERN for their active interest and help during the construction and for their contribution to the tests.

References

1. Proposal CERN/SPSC/75-15/P42.
2. CERN contract n° 590 176/FF.