The work on accelerator superconducting magnets of the GESSS collaboration

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I. Introduction

This paper is a review of the new results and projects obtained in Europe on superconducting magnets by the three laboratories belonging to the GESSS (Group for European Superconducting Systems Studies).

The group was formed in 1970 with participants from Rutherford High Energy Laboratory, Chilton (England), Institut fur Experimentelle Kernphysik, Karlsruhe (W. Germany) and Centre d'Etudes Nucleaires, Saclay (France).

At the beginning, the aim of this group was to coordinate the work of the three laboratories towards the design and the construction of a superconducting accelerator in Europe, in the range 500 - 1000 Gev[1,2]. It quickly appeared that the pulsed dipoles would be the main problems; so several dipoles were made in different ways and tested in each laboratory between 1970 and now.

Unfortunately, such a project was delayed but the experience acquired enables the group to be asked to make several D.C. superconducting magnets either for use on high energy beam lines or for special applications (ion sources, polarized targets ···).

Obviously, the realization and successful test of such magnets are possible thanks to general studies which are also done in the three laboratories.

The results given here are the new ones obtained since the beginning of the year ; the projects are those which are now under construction or which have been or almost financially approved.

More details will be found in the " Proceedings of the 5th International Conference on Magnet Technology " held in Frascati (Italy) by the end of April 1975; the reader will be often referred to these proceedings.

II. General studies

II. 1 Magnetic calculations

The most important work is made by the Rutherford Lab. with the development of a new three-dimensional computer program GFUN[3,4]. This program can calculate the field produced by different conductor geometries in two and three dimensions, taking into account an iron shielding with variable permeability.

II. 2 Multifilamentary conductors stability

Developments in the theory of self-field effects in a composite have been recently carried out at Saclay[5,6].

The theory takes into account a current distribution not so simple as the one which is generally taken. Also the boundary conditions (helium bath or resin) are taken into account to study the thermal behaviour of the composite.

The main results are to give the maximum composite size to avoid magnetic instabilities in magnet structure. Good agreement has been found between the theory and experimental results for short samples ; the agreement was not so good for larger coils where the experimental results are better than expected ; a possible explanation has been recently given[7].

II. 3 Conductors development

Developments on superconducting wires and cables are made in close relation with the manufacturers : IMI (England), Harwell (England), Vacuum-schmelze (W. Germany) and till a recent time Thomson - Houston (France) which is now changing its organization.

A large study of oxide insulation has been carried out for the development of the pulsed dipole ALEC ; the results are an increase of losses due to circulating currents less than 20 % of the magnetization losses at 5 T with a rise time of 1 T/ sec (Thomson-Houston, IMI).

Among the new A 15 materials, filamentary Nb_3Sn is specially studied by Harwell and the Rutherford Lab. Several small solenoids have been wound and tested[8], giving interesting results. However, the state of the art must be still improved for the winding of long accelerator magnets with small curvature radius in the ends.

II. 4 Properties of materials at low temperature

The measurements made by the three laboratories on metallic and non-metallic materials were summed up last year[9]. This kind of measurements continues, according to the asking.

II. 5 Training and quenching processes

Some systematical studies have been made about the training process[10,11,12]; general results can be carried out :

- the less of resin, the less of training.
- filled resins reduce the training.

- a magnet under compression and well-supported shows less training.

For example, the magnet D2A which showed a large training when using fiber glass epoxy rings wound around the coils as reinforcements and a random behaviour, reached its designed field quite quickly when aluminium rings were used (Fig 1).

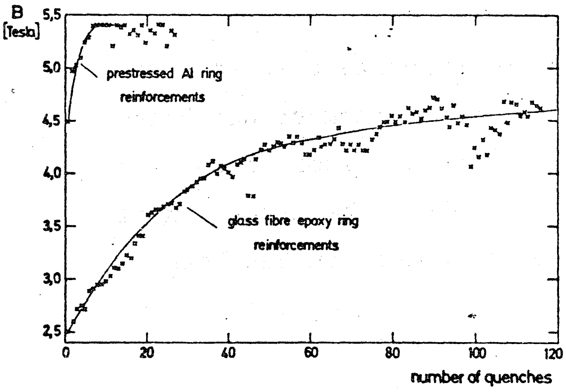


Fig 1 : D2A training

New results about the quenching phenomena show that in large resin impregnated coils, the quench propagation velocity varies according to the square of the current[12,13].

III. Magnets tested since the beginning of the year

III. 1 PT55 (Rutherford Laboratory)

This magnet has been designed to be used in a polarized target experiment at Rutherford Lab.[14].

The main requirements are :

- central field : $\hat{B} = 2.5$ T
- field homogeneity : $\leq 2.10^{-4}$ over a length of 5 cm and a diameter of 3 cm.
- field stability $\leq 5.10^{-5}$ over 8 hours.
- access in a cone of ± 60°
- use of a refrigerator.

The magnet is designed with two main coils and two inner coils (Fig 2) Other parameters of the magnet are listed in Table I.

Central field	:	2.5 T
Peak field	:	5.6 T
Current	:	104 A (72 % Ic)
Current density	:	100 A/mm^2
Inductance	:	98 H
Stored energy	:	500 KJ

S.C. Wire : IMI C361
Conductor diameter : 1 mm
Cu/Nb-Ti : 2 : 1
Bath temperature : 4.4 K

Table I : P.T. 55 main parameters

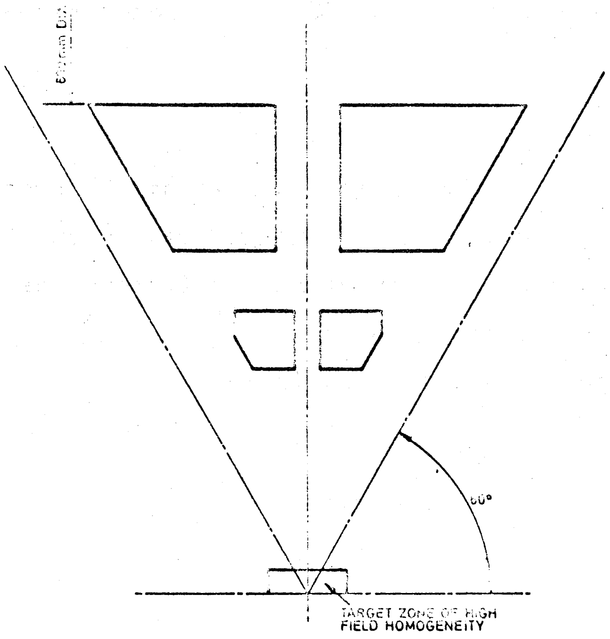


Fig 2 : Geometry of PT55 magnet coils

The coils were vacuum impregnated after winding, mounted on an aluminium back bone them clamped.

The coils were energized to 2.62 T after two quenches and then the helium bath temperature was raised to 4.5° K without problems. The energizing time is around 50 minutes.

Field measurements made with a small coil have shown that the requested homogeneity has been reached.

III. 2 SOLO (CEN SACLAY)

This long solenoid has been wound as a prototype for a Donetz type heavy ions source.

Its main characteristics are listed in Table II.

Length : 85 cm
Aperture diameter : 15 cm
Nominal current : 600 A(88 % Ic)
Winding : 18 layers, 400 turns/layer
Central Field : 6 T
Self inductance : 1.3 H
Stored energy : 234 KJ

Table II : SOLO main characteristics

The winding is very simple : no impregnation, no special cooling, no force holder.

The solenoid was tested in MOBY's cryostat[15]. The field of 6T was reached after a few quenches, the rise time being about 3 mm.

The results obtained with this kind of magnet seem good enough to think of a larger solenoid with its own low consumption cryostat to be used on a heavy ion source at the accelerator SATURNE, now under renovation.

III. 3 AC5 (Rutherford Laboratory)

The basic design concept of this prototype pulsed dipole synchrotron magnet follows that for AC4[16,17] ; however, major changes have been made in the constructional aspects to reduce training and to improve the field homogeneity through greater constructional accuracy[18].

The main parameters of this magnet are listed in Table III.

Design central field	: 4.5 T
Cold bore diameter	: 100 mm
Magnetic length	: 0.78 m
Stored energy	: 110 KJ
Peak field at conductor	: 4.75 T
Conductor	: 3 components 0.40 Nb-Ti, 0.15 Cu-Ni, 0.45 Cu 8.917 × 7.1 μ filaments per strand, 15 × 1.08 mm strands with organic insulation, compacted 8.28 × 1.86 mm^2; 0.15 mm cotton braid insulation overall.
Current	: 3300 A (~ 75 % Ic)
Manufacturer	: IMI limited
Mean current density	: 13900 A/cm^2

Table III : AC5 main parameters

A sectional view of the magnet is shown on Fig 3. Main improvements are :

- cooling channels incorporated in the impregnated coil structure.
- warn stainless steel bands strunk onto the pre-cooled coil before put it inside the one piece iron shielding.

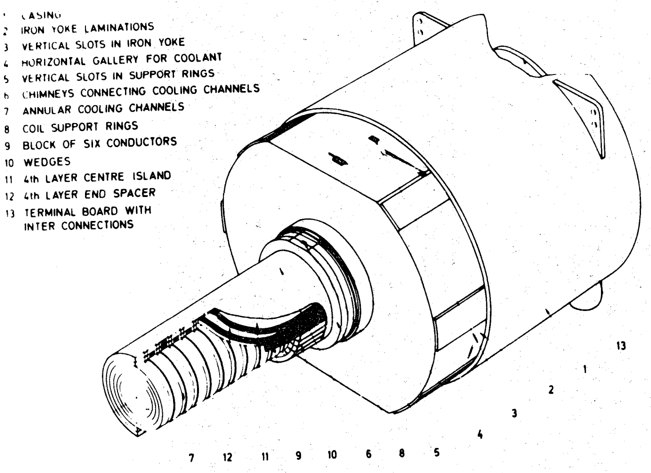


Fig. 3 : AC5 sectional view

The first test of the coil was made in March in horizontal position (Fig.4)

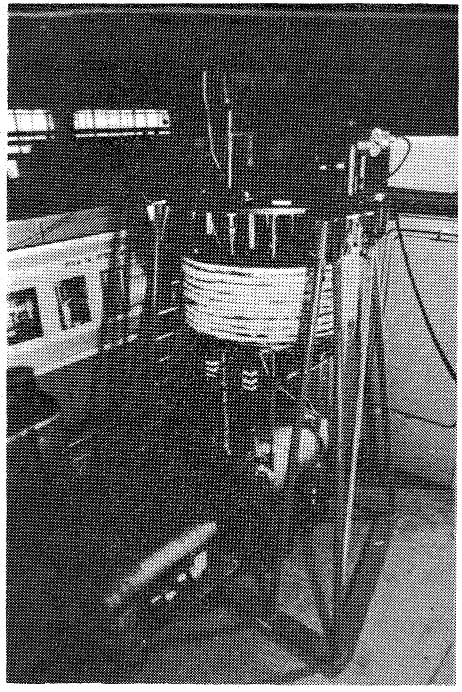


Fig. 4 : AC 5 assembly

A central field of 5.2 T was reached after several quenches. On the second cool-down, training began at 4.0 T. Loss and magnetic field measurements were made during this run.

Loss measurements are made with an electrical method ; the total losses per cycle for different currents and different rise times are shown on Fig. 5.

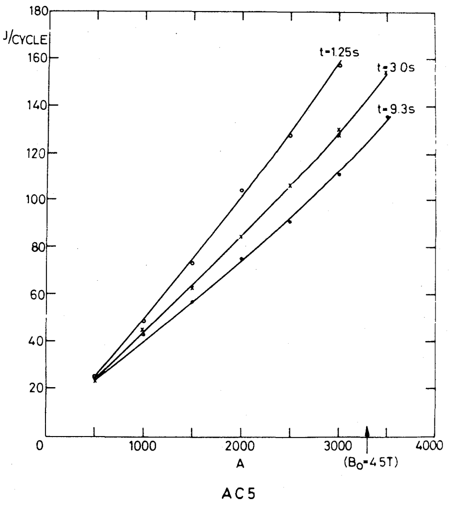
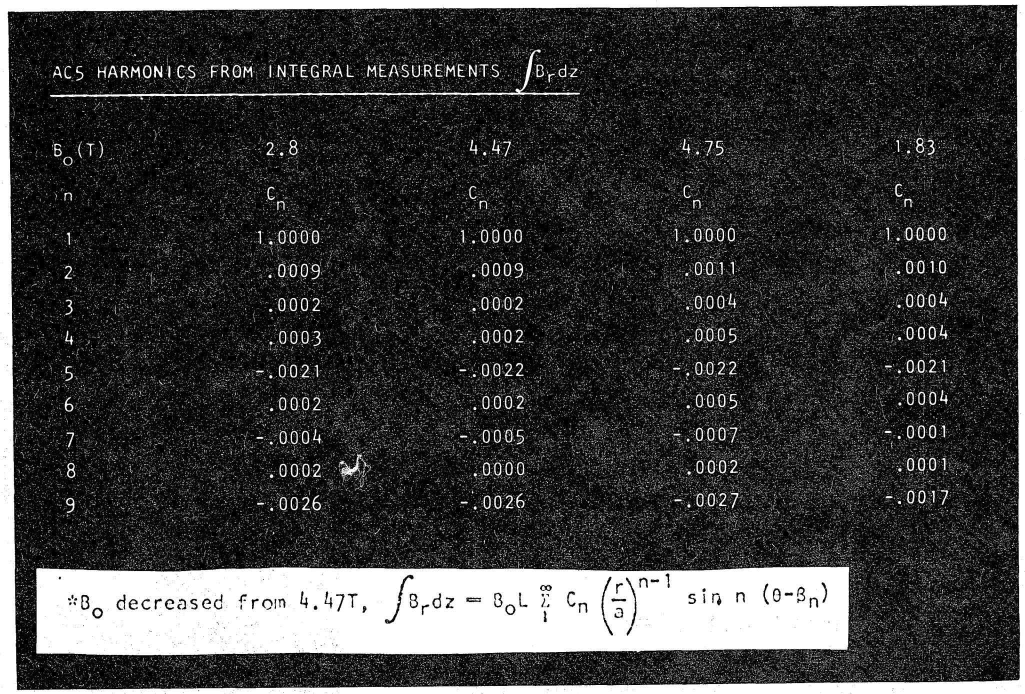


Fig.5 : AC5 loss measurement
(t is the rising time)

Magnetic measurements are made with a small coil in the central part of the magnet or with a long integrating coil for the integrated field. The values obtained for the integrated field are shown in Table IV.

One can see that the values of the harmonic coefficients are quite small, except for the quadrupolar term.

Recently, this magnet reached a central field of 5.6 T with a very slow rise time[19].



AC5 HARMONICS FROM INTEGRAL MEASUREMENTS $\int B_r dz$

B_o(T)	2.8	4.47	4.75	1.83
n	C_n	C_n	C_n	C_n
1	1.0000	1.0000	1.0000	1.0000
2	.0009	.0009	.0011	.0010
3	.0002	.0002	.0004	.0004
4	.0003	.0002	.0005	.0004
5	-.0021	-.0022	-.0022	-.0021
6	.0002	.0002	.0005	.0004
7	-.0004	-.0005	-.0007	-.0001
8	.0002	.0000	.0002	.0001
9	-.0026	-.0026	-.0027	-.0017

*B_o decreased from 4.47T, $\int B_r dz = B_o L \sum_1^\infty C_n \left(\frac{r}{a}\right)^{n-1} \sin n\,(\theta-\beta_n)$

Table IV : AC5 integral Field measurements

III. 4 ALEC (CEN SACLAY)

This other prototype of a pulsed dipole magnet has been designed by CEN Saclay in closed collaboration with industry : ALSTHOM (Belfort) and CGE (Marcoussis)[20]. So, all the mechanical parts of the magnet (coil, iron shielding, cryostat) were built in the ALSTHOM factory.

The general design of this magnet is quite similar to MOBY's, tested in 1973[15].

The main characteristics of the magnet are listed in Table V.

Design central field : 5 T
Coil aperture diameter : 110 mm
Magnetic length : 1.5 m
Stored energy : 340 KJ
Peak field at conductor : 5.25 T
Cycle : 20 sec (5 + 5 + 10)
Superconducting cable
  Composite : 1045 fil. × 10 μ
    0.52 mm diameter
    Cu/Sc = 1.6
    Oxide insulated
  First stage : 6 composites + 1 copper wire
    Oxide insulated

Second stage : 6 (6 + 1)
Oxide insulated
Rectangular shape : 4.65 × 2.20mm^2
0.1 mm fiberglass tape insulation
Manufacture : THOMSON-HOUSTON
Operating current : 2000 A (72 % Ic)
Overall current density: 12000 A/cm^2

Table V : ALEC main characteristics

The coil is impregrated in two stages (after each layer and when one pole is finished); cooling is made by copper heat drain mats put between each layer.

The iron shielding is in one piece; the coil is put inside by bending it thanks to a belt put around the coil and a jack introduced to stretch the belt (Fig.6)

A special cryostat has been constructed for this magnet : the helium tank and the nitrogen screen are circular whereas the vacuum tank is bell-shaped (Fig.7).

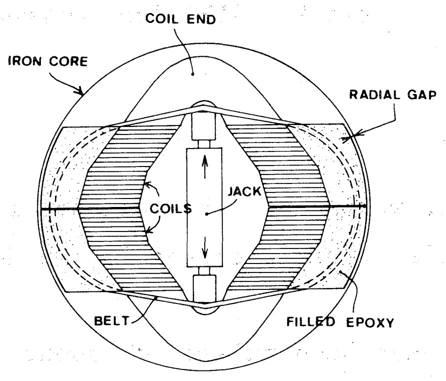


Fig.6: ALEC structure and assembly

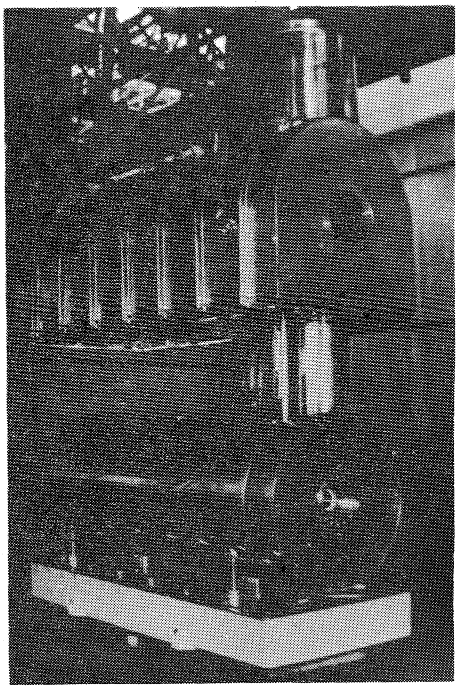


Fig.7 : ALEC cryostat

The first test of the magnet was made by the end of March in vertical position (Fig.8). The nominal field of 5 T was reached after 45 quenches, most of them with fast pulsing (1 T/sec). Loss measurements were made at this time and are reported on Fig.9.

The second test of the magnet was made in its own cryostat ; the first quench occured at 4.9 T. The magnetic measurements were made during this test, showing also a large quadrupolar

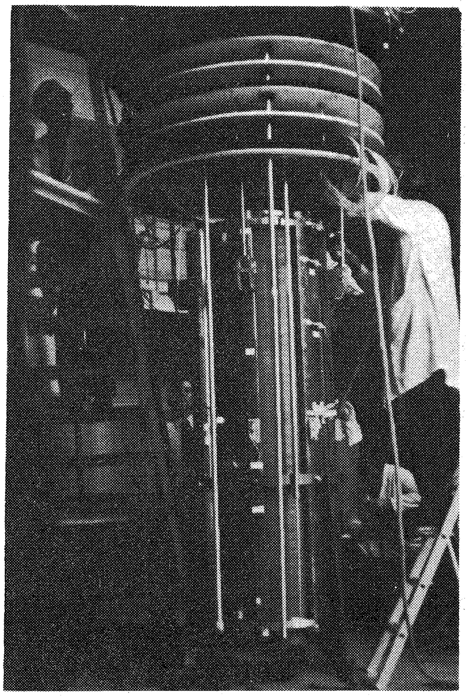


Fig.8 : ALEC in vertical position before the first test

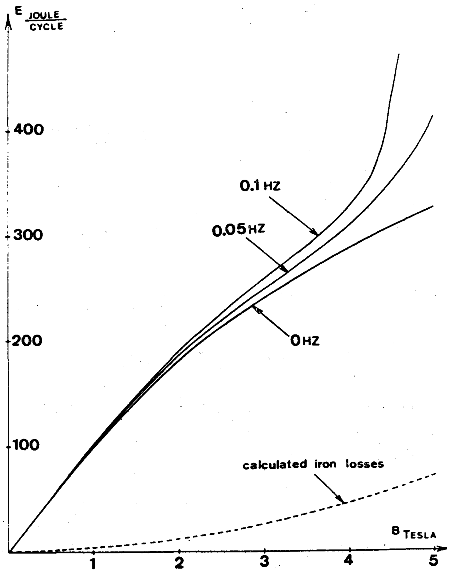


Fig.9 : ALEC loss measurements

term.

At the end of this run, the magnet was pulsed at a central field of 5.41 T at 1 T/sec, (78 % of short sample critical current) ; we decided to stop the test here.

During these two runs, the magnet has been pulsed for about 50 h at 1 T/sec without problems, including 10 h at 4.5 T and 2 h at 5.2 T.

In conclusion of these two tests, one can say that :

- the phenomenon of training has been reduced thanks to mechanical improvements but some are still necesary.
- the designed integrated field can be reached except for the quadrupolar term, due to mechanical tolerances.

IV. New projects

IV. 1 New projects at the Rutheford Laboratory

* I.C. Dipole

This D.C. dipole will be used for optical spectrometry work at Imperial College (England). Its main characteristics are a diameter of 140 mm, a magnetic length of 1.1 m and a designed field of 5 T for a current of 700 A (~ 80 % Ic)[21].

This magnet will be impregnated at a pressure of about 35 MN/m^2. The designer is hoping so to reduce the training.

The first test of this magnet has been delayed due to problems with the double layer enamel insulation.

* Prototype of a quadrupole for the I.S.R.

It has been suggested to insert superconducting quadrupoles in the Intersecting Storage Rings at CERN to increase their luminosity. A prototype is now under design at the Rutherford Lab. in collaboration with the I.S.R. magnet team .

Main designed parameters are a gradient of 40 T/m in a useful aperture of 150 mm in diameter (the internal diameter of the coil being 250 mm) and a magnetic length of 1.25 m. A sextupolar winding will be inserted between the helium tank and the main coil.

* Superconducting sextupole

This sextupole is required for neutron beam experiments. Main characteristics are a inner coil diameter of 50 mm, a magnetic length of 0.8 m and an operating field of 4 T on the inner coil diameter. One thinks now of using multifilamentary Nb_3Sn for the winding of this magnet.

IV.2 New projects at Karlsruhe

* Quadrupoles for a S.C. linac

Eight pairs of quadrupoles are now under construction to be used in a S.C. linac at Karlsruhe. The main characteristics are a length of 110 mm, an aperture diameter of 80 mm and a gradient of 37 T/m. The current will be 85 A, carried by a 1.0×0.4 mm^2; Cu/Sc = 2, F 130 type Vacuumschmelze conductor.

These quadrupoles are required to be run in a persistent current mode.

* Quadrupoles for a hyperon beam line

Two S.C. quadrupoles will be used on a hyperon beam line at CERN SPS to reduce the length of the beam line. The design is made in collaboration with CERN Lab. II.

The characteristics of the two quadrupoles are the same, except for the magnetic length :

- usefull aperture : 30 mm in diameter

- coil internal diameter : 46 mm
- magnetic length : 1.15 m for Q1, 0.83 m for Q2,
- gradient : 156 T/m

The conductor chosen is the F 160 type of Vacuumschmelze : 1.2 × 0.75 mm^2 without insulation, Cu/Sc = 2, operating current : 450 A (80 % Ic).

The external diameter of the quadrupole tank must be smaller or equal to 24 cm.

IV. 3 New projects at Saclay

* ECO

The aim of this project is to replace the copper coil of a conventional magnet (shown of Fig.10)by a superconducting coil in order to reduce the electrical power consumption by a factor of 5 to 10.

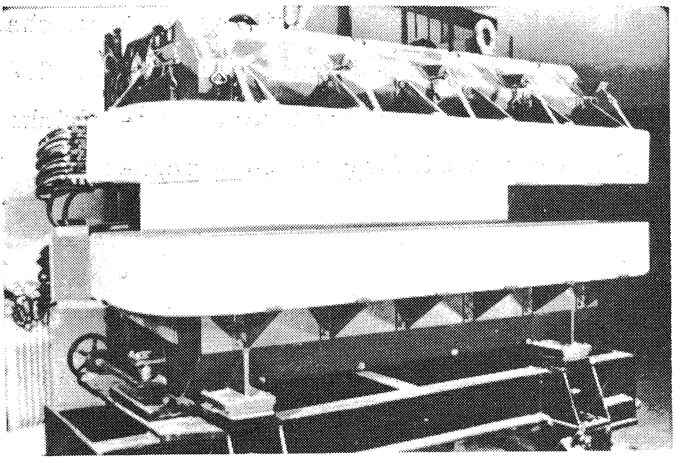


Fig.10 : ECO magnet

Main parameters of this coil are a length of 3 m, a central field of 2 T, an inductance of 32 H.
The stored energy is 640 KJ for a current of 200 A.
The conductor is a 0.8 × 0.4 mm^2 , Cu/Sc = 5, one, ordered to Vacuumschmelze.

This magnet is planned to work with its own 6 W refrigerator.

* ORSAC

These two D.C. quadrupoles will be used at CERN SPS, just behind the target on a bispectrometer beam line to increase its acceptance.

Their characteristics are a gradient of 35 T/m, a coil internal diameter of 185mm and a magnetic length of 0.95 m. Due to the lack of space, the cryostat will be elliptical (Fig.11)

The nominal current of 600 A (75 % Ic) will be carried by a rectangular conductor (361 fil.× 50μ , Cu/Sc = 2, 2 × 1 mm^2)

This project is made in collaboration with a team of physicists from ORSAY working on this experiment.

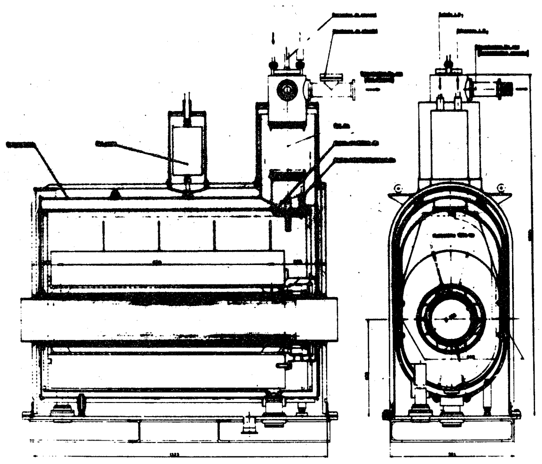


Fig.11: ORSAC design

* CESAR

This project consists of two D.C. dipoles to be used on the experimental areas of the CERN Lab II, either as bending magnets or as spectrometer magnets ; the project is made in close collaboration with CERN II Experimental Areas staff.

The design of each magnet is such as to have the same bending power as a conventional magnet but in a length twice shorter :

- central field : 4.57 T
- magnetic length : 2.12 m
- overall length : 2.83 m
- coil internal diameter : 150 mm

The nominal current will be 860 A and we expect a rectangular conductor (1.3×2.2 mm^2 without insulation, Cu/Sc = 2, 361 fil. of 50μ); the current corresponds to 85 % of the critical current.

Due to the high field homogeneity requested for spectrometer use ($\frac{\Delta B}{B} = 10^{-4}$ in a rectangle ± 4 cm × ± 2 cm), supplied correcting coils will be put inside the main coil aperture (Fig.12) : the quadrupolar and the sextupolar harmonics will be cancelled.

These magnets are expected to be tested by the beginning of 1977.

V. Conclusions

The work done by the GESSS collaboration since 1970 has been quite successfull. Most of the work till now has been made on fast pulsed dipoles with good results ; a large experience, also useful for D.C.

magnets, has been obtained.

New projects are essentially D.C. magnets, most of them to be used on the experimental areas of the SPS. It is encouraging that the staff of CERN, generally very particular in his choices has approved and financed the construction of superconducting magnets ; these magnets which are now interesting for 400 GeV beam lines[22], will be a must when 1000 GeV accelerators will be running.

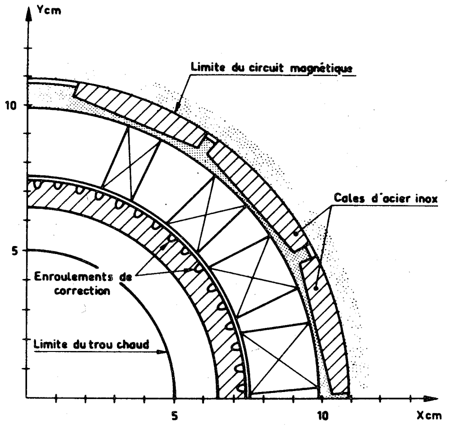


FIG.6 MONTAGE TRANSVERSAL DES DIFFERENTS ELEMENTS

(SOLUTION FER NON COUPE)

Fig.12 : CESAR design

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