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ATLAS BARREL SUPERCONDUCTING TOROID

CONCEPTUAL DESIGN

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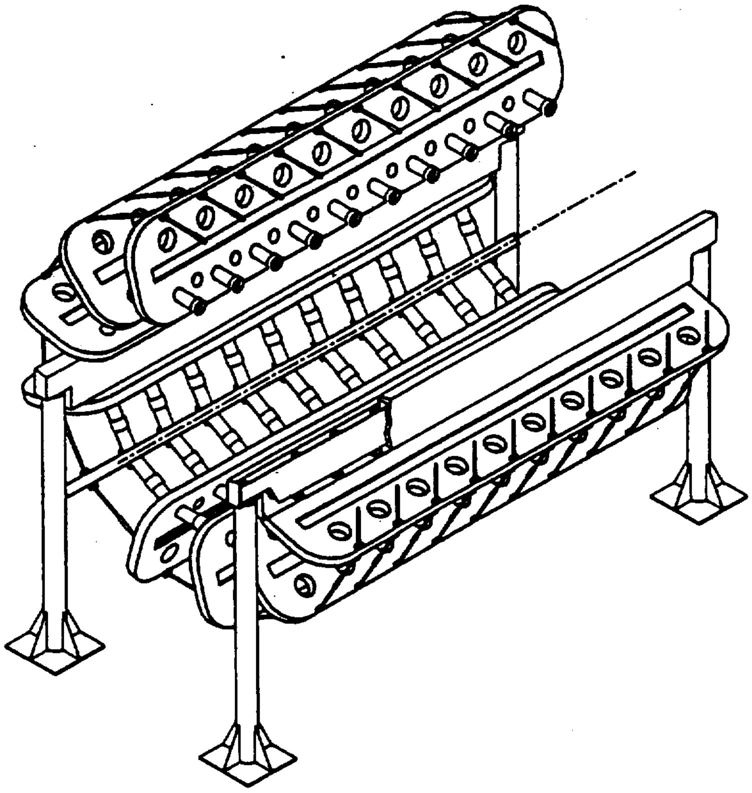

1 - INTRODUCTION

A large air-core superconducting toroidal magnet is proposed for the ATLAS detector at LHC. A conceptual design has been developed in order to satisfy both the Physics requirements and practical feasibility at a reasonable cost. The basic concepts have been chosen according to existing experience and rely on available industrial capabilities.

It must be pointed out that no magnet of that configuration and size has ever been used in High Energy Physics experiments and therefore that special attention is needed in order to demonstrate the feasibility and reliability of such a new device. The only example, on a smaller scale, is an air-core toroid, 5 m in diameter, under construction for CEBAF. Toroidal magnets are also actively developed for Fusion technology and it is worth noting the difference in complexity between these two fields of application : fusion magnets operate at very high fields (10 to 12 T) and under fast field pulses inducing large AC losses. Magnetic forces require huge mechanical structures leaving free the inner bore of the coils for the plasma containment. All these contraints are considerably reduced or even disappear in the case of the present detector magnet which calls for much simpler techniques.

The present report gives an overview of the design of the toroid, of the concepts supporting this design and of the analyses performed in essential areas such as mechanical behaviour, quench protection, stability and cryogenics. The overall configuration, dimensions and field characteristics have resulted from an iterative process of optimization and compromises with regard to the Physics objectives and are not discussed here.

The present design is still at a conceptual stage and outlines the main technical options. Complete engineering and construction details have to be elaborated in connexion with industrial means.

2 - OVERALL DESIGN

The magnet consists of 12 independent coils assembled as an axially symmetrical array around the 10-meter-diameter central region of the detector as shown in Fig.1. The main characteristics of the magnet are shown in Table 1.

Each coil is made of 2 single pancakes wound in a racetrack configuration and clamped rigidly on both sides of a solid plate which acts as a central web to contain internal forces on the straight runs of the winding. The pancakes are epoxy impregnated in their former together with a pure-aluminium sheet which conducts the heat load to a LHe pipe welded at its edge as shown in Fig.2. This mode of indirect cooling will be discussed in the next section.

The magnetic forces, which in a toroidal magnet result in a net radial inward force on each coil, are supported by a series of cold voussoirs tied between adjacent coils and forming all together a set of 10 compression rings distributed along the length of the magnet, as shown in Fig.1.

The coils are individually mounted in their own cryostat, as shown in Fig.3, which consists of the vacuum vessel, made of welded stainless steel panel sheets, and of the usual thermal shields and superinsulation. Internal sliding supports between cold mass and vacuum vessel and distributed stiffeners ensure a compact assembly of the complete coil while accomodating differential thermal contractions. Figure 3 also shows a recess of the vacuum vessel in the central region, allowing a nearly full coverage of the muon chambers located in that region, and a number of distibuted holes, the aim of which is to provide access to the detectors for installation and maintenance and to contribute to the overall stiffness of the vacuum tank by inter-wall sleeving.

The total weight of the magnet, including muon chambers attached to the vacuum vessels, is of the order of 1000 tonnes. In the present scheme, this weight is supported on 4 legs (with cold to warm transitions) at both ends of the magnets. Additional tie rods between vacuum vessels are distributed at the periphery of the coils and at other locations as needed to maintain the symmetrical geometry and to stabilize the overall structure.

3 - COOLING SCHEME

Indirect cooling has been adopted as the most practical, economical and safest scheme.

Alternative methods of cooling would be either pool boiling or force flow in a hollow conductor. Pool boiling is totally inadequate in the present magnet configuration with flat coils oriented in every possible direction. Furthermore the liquid helium vessels necessary to contain the coils, with a flat surface of 130 m^2, would be extremely heavy and expensive. A more general weakness of pool boiling is that, in order to benefit from cryostability, the conductor must be left partly bare in contact with the liquid, which means a weak electrical insulation and therefore a potential risk of failure and eventually of magnet destruction in view of the large amount of stored energy involved.

Force-flow cooling is strongly advocated for fusion magnets and appears necessary for such magnets because of their particular operating contraints. However, to be fully efficient, this technique requires a conductor of the cable-in-conduit type, difficult to manufacture, and a complex cryogenic system, which both would bear heavily on the cost.

For the present magnet, such a forced cooling is unnecessary, as the heat load produced in the winding is small and can be carried away by conduction to a simple cooling loop electrically separated from the conductor. This is the principle of indirect cooling which has been successfully applied to numerous large solenoids. The flat geometry of the coils, with a single pancake structure, lends itself particularly well to this type of cooling as a large heat exchange area is available between the conductor layer and the high conductivity cooling sheet bonded to its surface. The stability issue, which is occasionnally argued against this type of cooling will be discussed later.

4 - CONDUCTOR DESIGN

The type of Alu-stabilized conductor used in a large number of solenoids for physics detectors offers many advantages for the present winding :

- The technique of fabrication has been reliably developed industrially and only requires limited extension in view of the scaling-up in cross-section.

- This technique enables the fabrication of unit lengths of the size necessary to wind a whole pancake without joint. The conductor is made in two steps. The insert Rutherford-type cable using standard superconducting strands is classical and can be made in long lengths since the strands themselves are currently produced in thousands of meters. Both the strands and the cable are carefully controled during fabrication by means of continuous sensitive techniques such as "eddy current", resistive and dimensional methods. Even so, a possible local defect within a strand would not affect the cable performance in view of the large safety factor built in the current rating.

The second step consists in the extrusion of high purity aluminium around the cable. This is also a continuous process which can be applied to long unit lengths provided that adequate toolings are installed for handling and spooling the quantity of material to be processed. The extrusion temperature is kept well below the level which could endanger the performances of the superconductor. The most important factor concerns the quality of the bond between aluminium and the copper coated strands. Experience with all the conductors produced with this technique at different manufacturers has shown that, after correctly setting all the parameters entering into the process, excellent metallurgical bond quality is achieved in a fully continuous and reproducible way. Furthermore, quality control by means of on-line ultrasonic method has proved to be an efficient means of checking the bond integrity.

- Alu-stabilized conductor is a soft material particularly easy to wind into a coil. In previous solenoids, the conductor was bent edge-wise in an inner-winding mode and yet without any difficulty. For the present magnet, the conductor is wound flat in the more classical outer-winding mode and thus in a still easier fashion.

- The Alu-stabilized conductor is also an excellent match with indirect cooling as the high thermal conductivity of pure aluminium contributes efficiently to diffuse the heat produced by local disturbances which might initiate instabilities. It also implies, for thermal contraction compatibility, that the mechanical structure and other components be made of alu-based material, which, again because of good thermal conductivity, compared to stainless-steel, favors the heat conduction process inherent to indirect cooling.

All the above features justify the choice of this type of conductor, which by all means, leads to the most economical solution.

The proposed conductor is shown in Fig. 4. Its characteristics are given in table 2. These are consistent with the magnet design but can be combined differently for manufacturing convenience.

The insert cable is made of 30 strands, 1.25 mm in diameter with a Cu/Sc ratio of 1.4. The main requirement is the critical current, which has been chosen in order to provide an operating temperature margin of 2 K above the steady-state cooling temperature. Standard NbTi conductors reach currently critical current densities above 2500 A/mm^2 at 5 T and 4.2 K. By specifying this value, a cross-section of 15.4 mm^2 of NbTi is needed for the whole cable. With an operating current of 20 000A, the ratio of operating to critical current is of 40% at the peak field of 3.4 T, or 58% along the load line.

For the complete conductor, two other important parameters have to be specified : the amount of aluminium and its RRR (Resistivity ratio between room temperature and 4.2 K). These are essentially chosen in order to fulfill quench protection and stability requirements, which are both crucial issues of any magnet design and will be discussed in further sections.

5 - MECHANICAL ANALYSIS

5-1- Loading conditions :

The magnet structure is submitted to two loading configurations acting in a different way :

- The weight which is unidirectional and unsymmetrical with respect to the axial geometry of the coil arrangement and which affects two structures thermally insulated from each other, the cold mass and the vacuum vessels. Interferences between these two structures must allow freely the differential thermal contraction and preserve their co-axial symmetry.

The cold mass of the 12-coil assembly is of the order of 400 tonnes and the room temperature weight, including cryostats and muon chambers attached to their walls, of 600 tonnes.

- Magnetic forces :

In view of the axial symmetry of the coils, the magnetic forces are contained within the coil plane and are directed radially on the long straight runs of the pancake winding. Internal forces between opposite straight runs are contained by the central plate, which carry the winding, and the resultant inward radial force is transfered by the plate to the bucking cage formed by the voussoir rings.

The symmetrical force distribution is guaranteed in all operating phases by having all the coils electrically connected in series and fed by a single power supply, thus with the same current everywhere. Even in the event of a quench of one coil, the whole magnet is discharged at the same rate by means of a single external dump resistor. Unbalanced azimuthal forces may result from slight geometrical asymmetries due to construction tolerances, but with very small amplitudes easily contained by the stucture.

Larger unbalance of coil currents could only be created by an hypothetical major failure, such as a full shorted coil during operation, which would in any case be detrimental to the magnet and must be totally prevented by safety measures as with any type of magnet. Even in this ultimate event, in order to prevent damage to surrounding equipments and personnel risks, the resulting unbalanced forces must be accounted for in the structure design.

The force distribution in the coils is shown in Fig.5, as computed with a 3-D code. The net radial force per coil is of the order of 670 tonnes with the barrel toroid operated alone. The addition of end cap toroids will increase this force by an amount depending on the type of end cap used, iron-core or air-core. A force of 800 t has been used in the present calculations in order to take into account this effect. With air-core end caps, as designed at RAL, this force could increase to 1200 t.

5-2- Modelling :

All the mechanical computations have been performed by means of CASTEM 2000, a powerful 3-D code developed at SACLAY and based on finite element technique. The type of mesh structure used in the present calculations is illustrated in Fig. 6.

In the modelling, the coil structural plates are represented by thin plates and the other elements (voussoirs, stiffening bars, supports) by simple beams.

Calculations have been performed for the following cases :

- Weight loading alone.
- Magnetic loading alone.
- Both previous loadings together.
- Overall structure stability, under both combined loadings.

5-3- Magnetic loading :

As already explained, the major part of magnetic forces are supported by the cold voussoir structure. With the radial force of 800 t per coil, each voussoir is submitted to a compressive force of 309 tonnes. With a cross section area of 55 000 mm^2, the compressive stress is 5 daN/mm^2, corresponding to a radial shrinking of the structure of 5 mm.

Tensile stresses in the coil plate, due to internal forces in the windings, are also of the order of 5 daN/mm^2.

These stresses are well below the yield strength of current Alu-alloys (17 daN/mm^2 for Al-5083) and represent conservative values. Additional forces created by the end cap toroids remain within acceptable limits and can be accommodated, if necessary, by increasing the cross section area of the voussoirs.

5-4- Weight supporting :

A first approach of the modelling has been to consider the entire weight of the magnet (1000 tonnes) carried by the cold mass and supported at both ends of the magnet. The supports consist of 4 posts connected to the magnet by extended horns attached to the end voussoirs located in the horizontal median plane of the magnet. This location is the best place for stability and for minimizing structure deformations under the weight. It also allows the permanent centering of the cold mass with respect to the vacuum vessel assembly under thermal contraction and magnetic forces. The rigidity of the structure between posts is provided by the stiffness of the large coil plates braced along the length by the solid voussoir arrangement.

Results of the stress analysis show that the maximum deflection of the inner structure is of 9 mm, with maximum Von Mises stresses of 2 daN/mm^2 in the voussoirs. Out of plane bending of the coil plates under the weight is prevented by the warm bracing struts at the periphery of the magnet. Internal sliding pads between coil and vacuum vessel transfer the load to these struts.

Ongoing studies are aimed at defining more precisely the sharing of the weight between cold and warm supporting structures. A possible scheme is to carry the entire weight by the warm structure, with the cold mass being supported internally in the coil cryostats. A comparison of the different schemes will enable the most practical solution to be adopted.

5-5- Stability behaviour :

The overall initial stability of the structure has been calculated in the same configuration of cold supporting and in the elastic range condition.

The same loading cases have been studied. The following overloading factors for the first buckling mode have been determined.

- Weight alone :	6.17
- Magnetic forces :	4.32
- Both together :	4,27

In the case of magnetic forces, in order to achieve the safe factor indicated above it has been found necessary to reinforce the coil structural plates by means of longitudinal stiffeners in line with the voussoir attachments.

Under these conditions, the stability behaviour appears satisfactory.

6 - QUENCH PROTECTION

Quench protection is a major concern of any superconducting magnet. Though a quench is unlikely to happen in an adequately stabilized magnet, safety measures have to be foreseen in view of its hypothetical occurrence.

When a resistive zone is initiated in the winding, following an eventual thermal perturbation, the conductor heats up by Joule effect and in order to prevent overheating upto a damaging temperature the current has to be discharged rapidly in such a way that the stored energy be dumped in a load of adequate thermal capacity.

The classical protection scheme consists in connecting at the onset of a quench a dump resistor at the terminals of the magnet in order to accelerate the current decay and to extract a substantial fraction of the energy in the external resistor.

The complete process involves several mechanisms which have to be taken into account in order to estimate the temperature rise during the dump :

- Thermal diffusion in the winding structure.
- Quench propagation over the coils.
- Build up of the internal resistance and distributed heat generation.
- Eddy currents in the various elements of a coil and occurrence of quench back.

These phenomena are related to the physical properties of the materials, such as electrical resistivity, thermal conductivity, specific heat, which are themselves strongly dependent on temperature.

A detailed analysis of the quench behaviour has been performed for the present magnet, by means of a set of computer codes developed at SACLAY.

First the heat diffusion in the cross-section of the potted coil, after the onset of a quench, has been found to increase the temperature fairly uniformly through the whole structure, showing that a localized hot spot cannot be built inside the coil, and that the velocity of quench propagation in the coil is quite fast, so that after a short time the whole coil is driven normal and will heat up uniformly. Also, the contribution of the structural materials surrounding the conductors is significant in sharing the heat produced in the coil, thus in slowing the temperature rise. The axial velocity of propagation along the conductor has been determined of 4 m/s at the nominal current of 20 kA and the transverse velocity (from turn to turn) of 0.1 m/sec; so after 8 sec. the whole coil is normal.

A particular feature of a toroid is that the coils are split and then weakly coupled thermally and that there is a chance that the quench of one coil may not propagate to the other coils. Such a situation is undesirable for two reasons: first it is advantageous that the entire magnet mass participate in the energy release, thus reducing the peak temperature; second it is still more important that all the coils follow the same temperature rise in order to avoid severe thermal stresses in the structure.

A factor which contributes to speed up naturally the quench in the undisturbed coils, is the "quench back" effect resulting from the eddy curent heating produced by the field decay in the metallic parts of the coils.

The main items submitted to eddy currents are the conductor itself, the structural plate and the aluminium cooling sheets laid on the pancakes. The latter are the most effective as they are made of high conductivity aluminium and intercept a large area of transverse field.

For any of these elements, the eddy current heating power can be expressed in the general form.

$$P = \frac{Po}{\rho(T)} \left(\frac{dI}{dt}\right)^2$$

where I is the magnet current, ρ the resistivity of the element and Po a function of the geometry of the element and of the field distribution on its surface.

Results of the calculation give the following values of P at the initial dump speed dI/dt = 166 A/sec :

- Structural plate :	3 kW/m^3
- Conductor :	0.2 kW/m^3
- Cooling sheet :	12.7 kW/m^3

Introducing these values in the thermal diffusion code shows that the quench back occurs in all the coils 5 sec. after initiation of the dump.

Combining the results of the previous analyses, it is possible to draw the complete evolution of a quench under any dumping condition.

A typical example is shown in Fig.7, corresponding to the actual specified characteristics of the dump circuit. The onset of quench back in clearly illustrated and the temperature difference between the conductor and the structure never exceeds 10 K and even equalize at the end of the quench. The external resistance is set at 0.05 Ω in order to limit the peak voltage at a safe value of 1 kV. With a magnet self-inductance of 6.25 H, the decay time constant at the beginning of the dump is 125 sec. Subsequently, due to the increasing resistance of the coils the current decay is accelerated as shown in Fig.7. The internal resistance reaches 0.09 Ω at the end of the quench, twice the value of the dump resistor. Nearly half of the stored energy is dissipated in the magnet, but this energy is spread out through the entire coils and the peak temperature is less than 50 K, a very low value.

All these results, validated by a comparison of the same analysis with recorded data on the ALEPH solenoid, show that the parameters chosen for the conductor (see table 2) are perfectly adequate.

7 - STABILITY

The stable behaviour of a superconducting coil is characterised by the capacity of the winding to absorb any possible thermal perturbation without driving the conductor to an irreversible transition to the resistive state.

The potential source of disturbances can only be of mechanical origin arising from magnetic induced stresses within the winding. The stress distribution and the associated deformations in the coil cross-section under magnetic forces are shown in Fig.8. The maximum compressive stress within a pancake is 0.75 daN/mm^2. Stress levels are very small and in view of the compaction of the potted coil, motions of individual conductors with respect to each others are practically impossible. The epoxy bond between conductors and the central plate is also submitted to very low shear stresses, well below the usual yield strength of this type of bond, in the range of 2-3 daN/mm^2. The highest bond stress, at the first inner conductor, is of this order of 0.4 daN/mm^2. Assuming that it failed at this point and allowing a conductor motion of 0.05 mm, a higher limit of the possible displacement, the energy by friction would be less than 1 Joule per meter length of conductor.

On the other hand, the heat capacity of the winding is provided by the large amount of aluminium contained in the conductor and by the temperature margin of 2 K taken at the nominal current.

It should be pointed out that the large increase in stored energy compared to previous magnets necessitates to increase the proportion of stabilizing material for quench protection purpose, which results in lower overall current density and enhances the enthalpy margin available in the conductor for stability. For exemple, the ALEPH solenoid operates at a current density of 40 A/mm^2, compared to 26 A/mm^2 for the present magnet.

The enthalpy margin of the conductor alone is of 1.6 J per meter length at the peak field. In reality, in view of the thermal diffusion both along the conductor and through the surrounding elements, the available enthalpy margin is sensibly higher. Simulations of fast heat pulses at the surface of a conductor give values an order of magnitude larger.

From these first estimates, the stability conditions appear well satisfied. Nevertheless, studies of this important issue are still going on and experimental modelling is envisaged in order to qualify more precisely the expected peformances.

8 - CRYOGENIC SYSTEM

8-1- Overall scheme :

The magnetic cryogenic flow chart, shown in Fig.9, consists of 2 parts connected together by a set of cryogenic lines: the external refrigeration power system and the helium circuits associated to the coils.

The overall heat load inventory, given in Table 3, requires a refrigeration capacity in the range of 2 kW at 4.5 K. With such a cryogenic power, the cooling down sequence from room temperature to 4.5 K is estimated at 4 weeks. Recooling down from 80 K will take one week if no external liquid helium supply is provided.

The present scheme is based on an individual refrigerator dedicated to the experiment and installed at ground level. Another way of providing the cooling power would be to use the helium supply from the accelerator main refrigeration system, as applied at HERA. This would bring substantial cost saving both for investment and maintenance.

Anyhow, this does not affect the cooling scheme of the magnet itself, which consists of a network of cooling loops attached to the coils and fed in parallel with a flow of saturated liquid helium circulated by a cold centrifugal pump.

8-2- Coil cooling loops :

Each pancake is bonded to a cooling plate, made of pure aluminium, acting as a heat exchanger and cooled by a single pipe welded along its length. A shown in Fig.10, the cooling circuit of each plate is divided into 2 parallel paths, one per half pancake perimeter, connected at the outlet to a third return branch thermally coupled to a 4.5 K shield covering the coil structural plate.

Such a lay-out, which results for the whole system in 48 parallel helium paths, has been designed with the following purposes :

- The circuit configuration remains the same in the different cooling phases : cooling down, normal operation at 4.5 K, warming up and even quench sequence. No commuting valves are needed. The only change occurs at normal operation where the cold pump is activated.

- During cooldown, temperature gradients must be minimized in order to maintain low thermal stresses in the structure.

8-3- *Cooling down operation* :

The magnet is cooled down with a net helium forced flow of 200 g/s circulated directly from the refrigerator and distributed over the 48 parallel cooling channels. A uniform flow distribution is ensured by means of flow impendances inserted on each tube inlet. The temperature difference between input and output is maintained below 40 K.

In view of the cooling loop configuration indicated above, with all the flow inputs distributed at the same temperature at one end of the magnet and the outputs at the other end, temperature gradients are established uniformly along the length of each plate and are identically distributed in all the coils. In such a way, induced thermal stresses, both within the plates and between coils, are practically negligible.

In case of a quench, all the coils warm up almost uniformly to an average temperature of 50 K. Recooling down can be started again from this temperature, following the same process.

8-4- *Normal operation* :

After the cooling down process has reached the steady state temperature of 4.5 K, the normal operation takes place with the addition of the cold pump for helium circulation.

Boiling helium has been preferred to supercritical helium as the coolant fluid because its temperature is stable and uniform over the cooling path and it has a better heat exchange efficiency. The risk of flow instability which may occur with such a 2-phase fluid can be avoided by imposing the correct flow pattern conditions. The main condition is to ensure an homogeneous dispersed flow pattern which is reliably obtained by the combination of a mass flow rate per unit area above 100 kg/m^2s and a vapour quality below 20%. Also it is recommanded that the flow path be directed upward or horizontally.

For the present magnet, the flow rate per channel is of the order of 8.4 g/s in a cooling pipe of 10 mm in diameter, i.e. 107 kg/m^2s, and the vapour quality does not exced 15%.

The net mass flow rate is 0.4 kg/s with a total head of 0.1 atm. It can be delivered by one or two (for redundancy) centrifugal helium pumps. A liquid helium reservoir in inserted ahead of the helium circuit both for feeding the immersed pump and for collecting the liquid containt of the return flow.

8-5- *Quench behaviour* :

In the case of an eventual quench, which could be initiated by a fast energy dump, the small volume of liquid helium contained in the short cooling circuits of the coils is spontaneously evacuated in a very short time with a small pressure rise. As experienced with the ALEPH solenoid, the pressure rise is limited to 2-3 bars, which does not require venting out helium to the atmosphere.

9 - MAGNET CONSTRUCTION

Since engineering details are still at an early stage, only general comments can be made on the anticipated construction procedures.

Since engineering details are still at an early stage, only general comments can be made on the anticipated construction procedures.

Individual coils, complete with their cryostats, will be entirely manufactured in industrial firms holding the adequate facilities. A selection of 2 firms is envisaged in order to reduce the fabrication time and to get a double assurance of satisfactory completion.

Fabrication of the large structural pieces, such as the coil central plate and cryostat components, is well within industrial capabilities.

For the conductor fabrication, several firms in Europe are known to be fully competent.

The winding operation, in spite of the large coil size, is fairly simple and rely on classical methods, using a horizontal turntable and usual winding fixtures (at the scale of the winding).

The epoxy impregnation can be carried out in different ways, either vacuum impregnation or preimpregnated insulation (as successfully applied for the DELPHI solenoid). The chosen technique will have to be fully qualified on significant mockups before its use in the actual winding.

The assembly of the cryostat will require automatic welding machines and careful testing procedures, which both are currently available.

The completed coils will be transported to the CERN site where they will be individually tested at a temporary test facility. The test will be carried out at the nominal current, thus submitting the coil to roughly the same level of field on the conductor than in the complete toroid.

The assembly of the toroid will be carried in 2 stages. Modules of 2 and 4 coils will be pre-assembled in a surface building. The 4 sub-units will then be lowered down in the underground area for final assembly at the interaction point.

The 12-fold modular nature of the toroid offers several advantages :

- A major part of the fabrication can be carried out in industry where large facilities and the required know-how can be found adequately.

- The type of series production enables the operation sequences, both at the manufacturer's and at the CERN site, to overlap conveniently in a tight schedule.

- The risk, which can never be totally excluded, of a coil defect is minimized. A 13th coil has been included in the production line and in the cost estimate. It must be pointed out that the individual coil test would detect any abnormal behaviour and will guarantee that the coils are safe and sound before their assembly with the detector.

From all the discussions presented in this report, little uncertainties appear in the feasibility of the proposed toroid. The success relies on sound engineering techniques and on strict quality assurance procedures. The next phase of the design work is due to concentrate on these matters. Particular needed developments concern, as already mentioned, the conductor fabrication, the impregnation method and the stability issue.

Table 1

OVERALL MAGNET PARAMETERS

Inner free radius of Toroid :	5 m
Outer radius :	10 m
Number of coils :	12
Overall dimensions of individual coils :	26 x 5 x 0.5 m^3
Total Amp x turns :	24 10^6
Nominal current :	20 kA
Stored energy :	1.25 10^9 J
Peak field at the conductor :	3.4 T
In ward force per coil (without end caps) :	670 t
Coil configuration :	Racetrack
Single pancakes per coil :	2
Turns per pancake :	50
Total weight per coil :	60 t
Refrigeration power at 4.5 K :	2 kW

Table 2

CONDUCTOR PARAMETERS

Operating current (3.4 T) :	20 kA
Critical current at 5 T :	38.5 kA
Operating temperature margin :	2 K
Insert cable	
Number of strands :	30
Strand diameter :	1.25 mm
Cu/Sc ratio :	1.4
Cable dimensions :	19 x 2.3 mm^2
Overall conductor	
Dimensions :	90 x 8.5 mm^2
Alu RRR :	500
Unit length (one pancake) :	2 800 m
Total length :	68 km
Total weight :	140 t

Table 3

CRYOGENIC HEAT LOADS

Cold mass at 4.5 K	400 t
Radiation shield mass	60 t
Radiation shield surface area	4 000 m^2
Static load at 70 K	
Radiation heat load	20 000 W
Supports	500 W
Static load at 4.5 K	
Radiation heat load	800 W
Support system	180 W
Current leads (2.5 g/s LHe)	200 W
Conductor junctions	20 W
Transfer lines (external)	50 W
Total at 4.5 K	**1 250 W**
Transient loads at 4.5. K	
Current ramping (2hrs charging time)	100 W
Helium liquefaction for storage	150 W

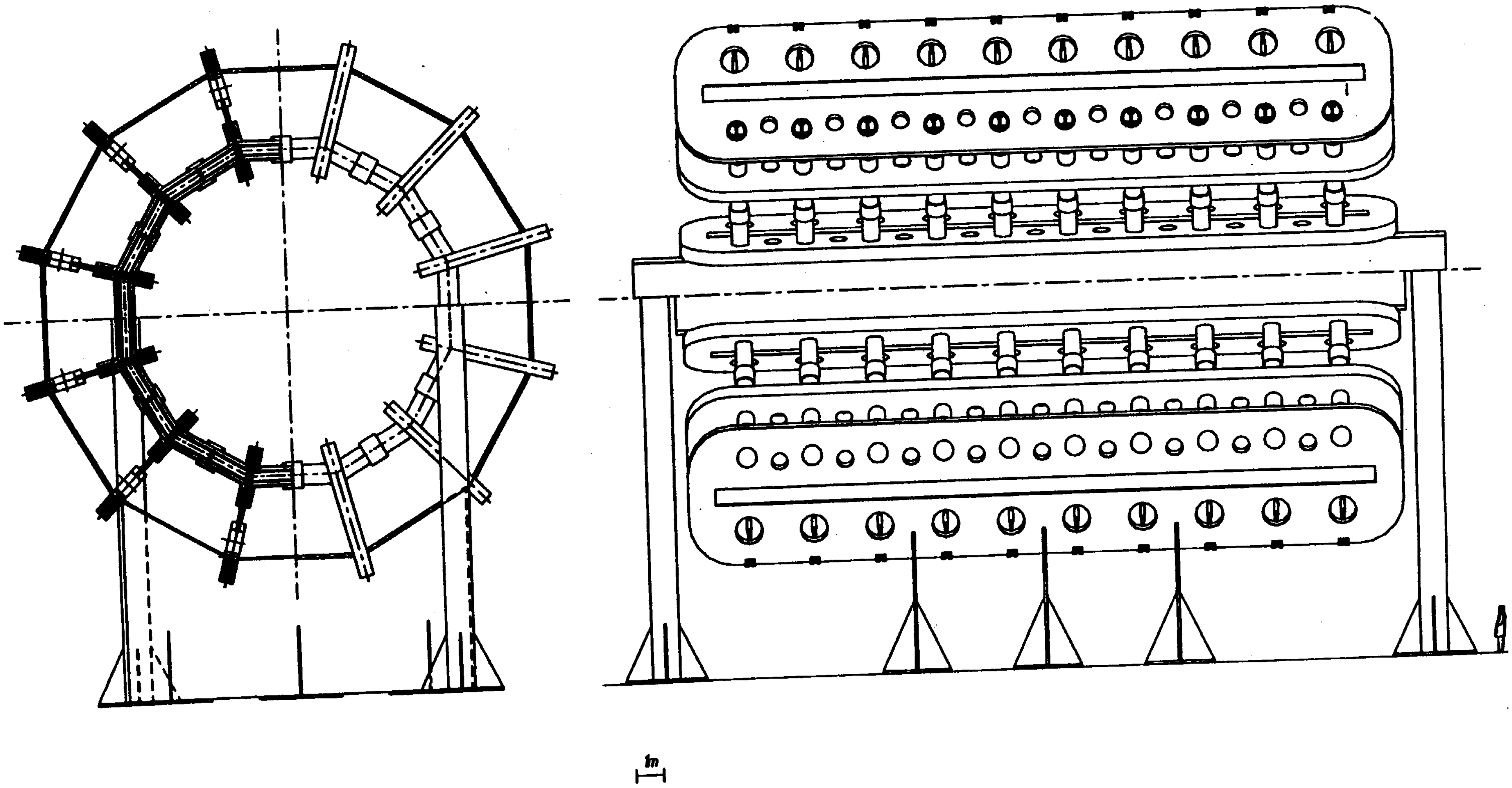

Figure 1 - Overall layout of the toroid.

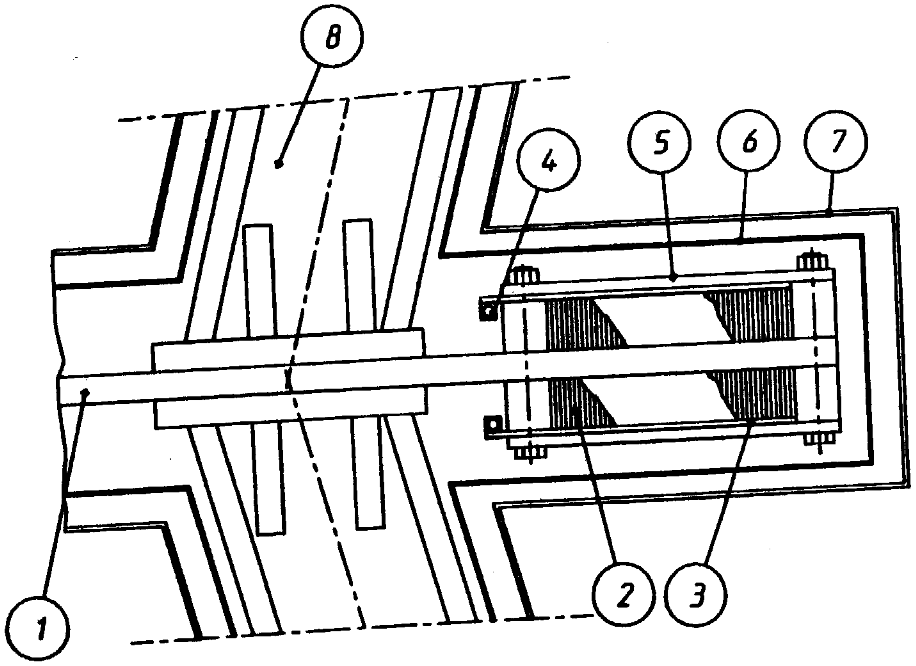

Figure 2 - Winding cross-section.

1 - Central plate
2 - Single pancake (50 turns)
3 - Alu cooling sheet
4 - LHe cooling loop
5 - Clamping pieces
6 - Thermal shield
7 - Vac vessel
8 - Cold voussoir

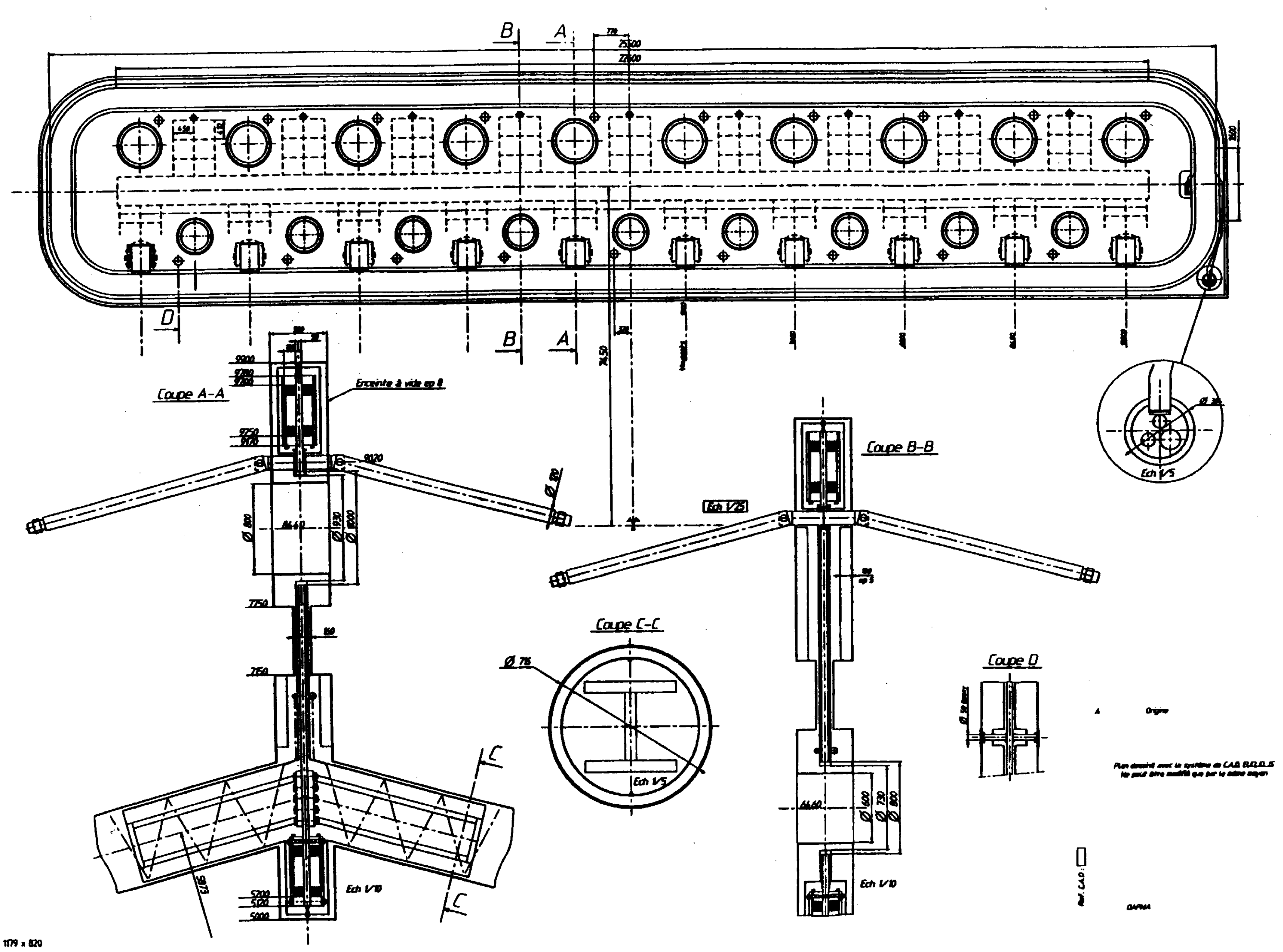

Figure 3 - Complete assembly of individual coils

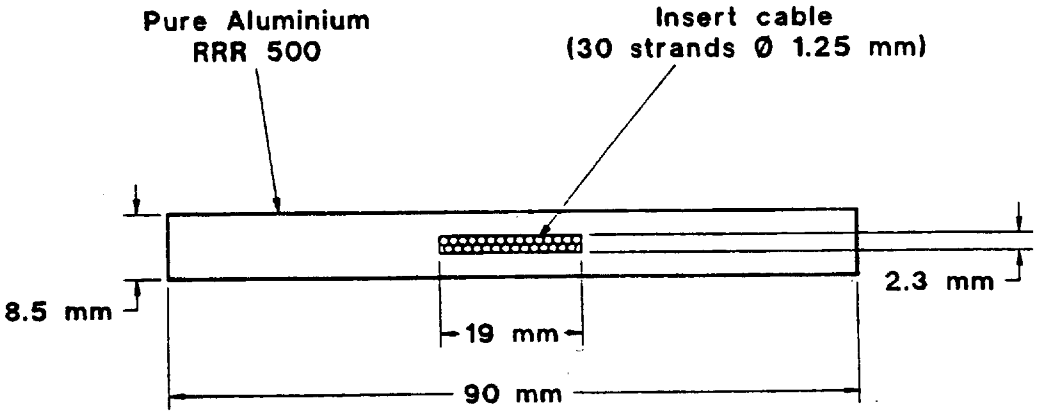

Fig. 4 - Full scale conductor cross section

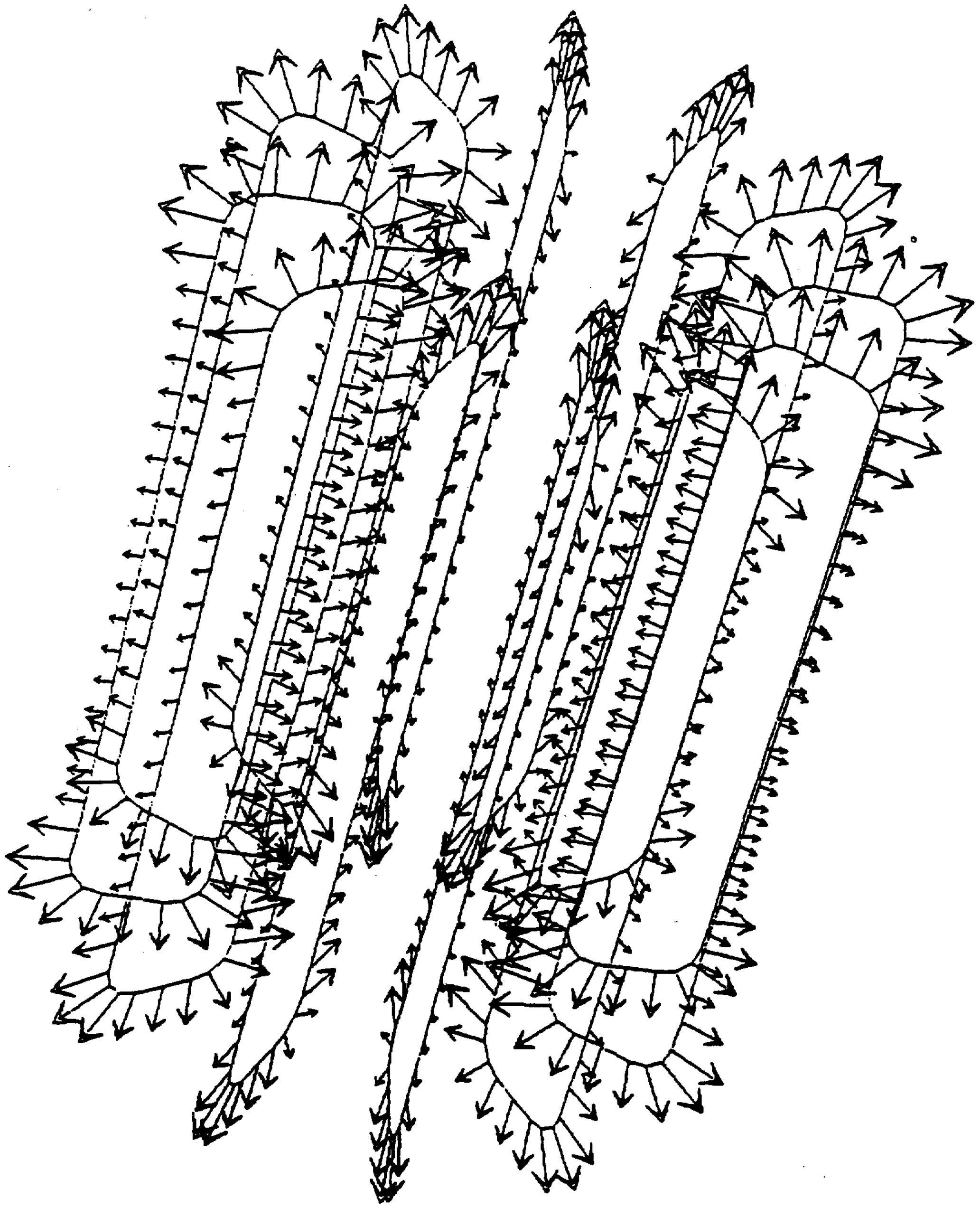

Figure 5

Magnetic force configuration over the coils

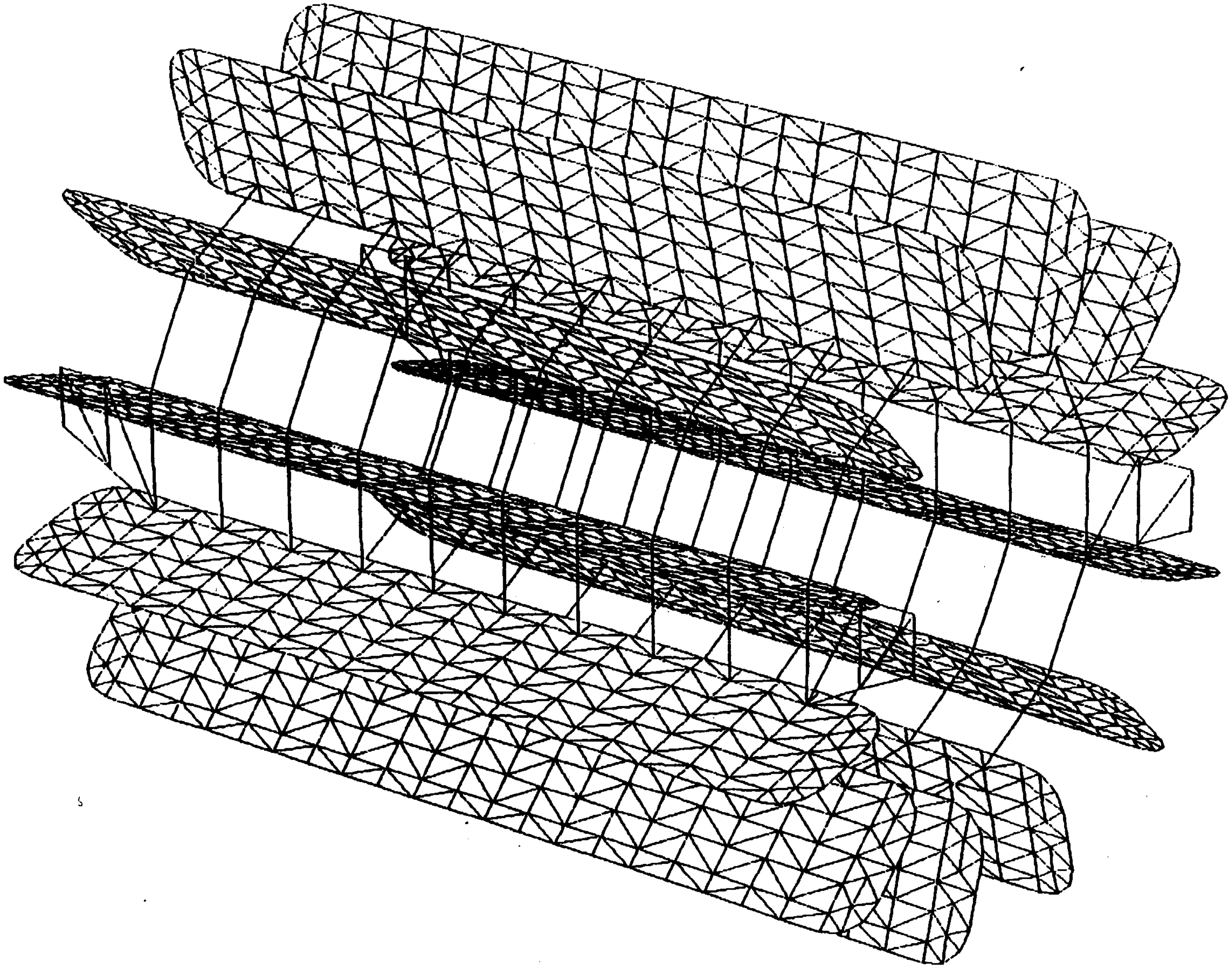

Figure 6

Mesh structure used for 3-D stress analysis

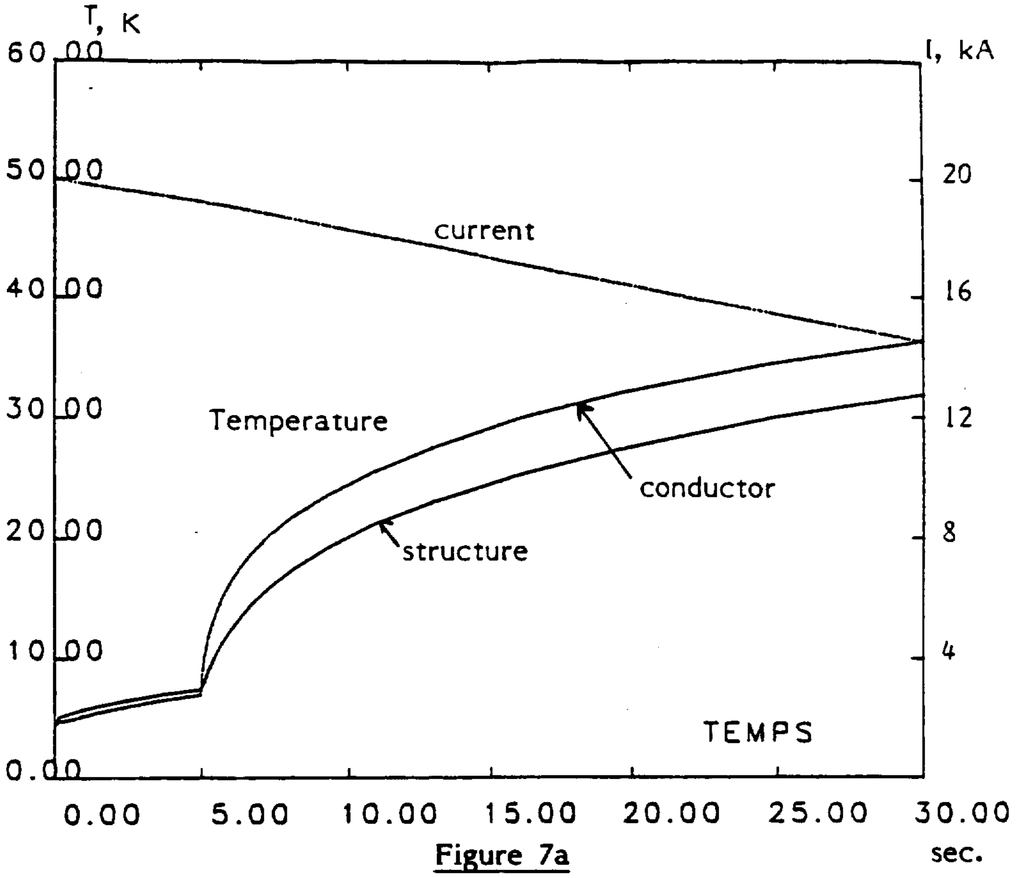

Figure 7a

Start of the dump

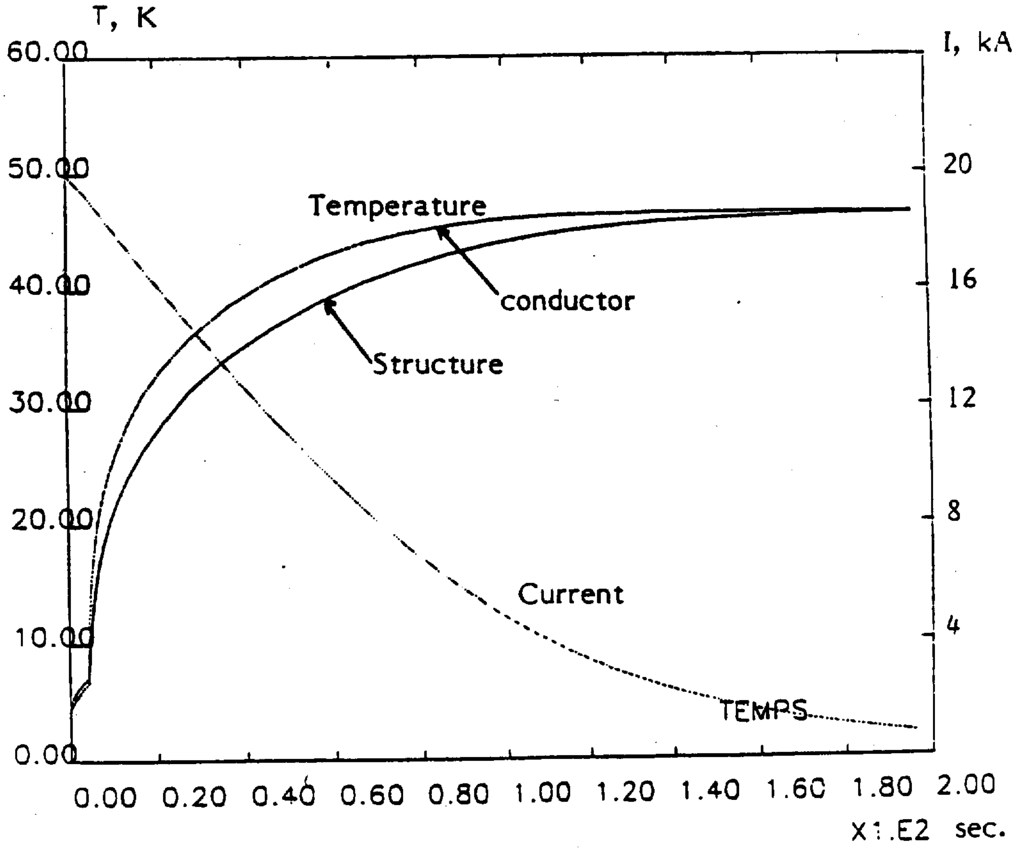

Figure 7b

Complete sequence

Figure 7 - Quench evolution following a dump in an 50 mΩ external resistor, showing the current decay and the temperature rise of the conductor and of the structure.

Figure 8 - Von mises stress distribution in the section of the winding.
Deformations are amplified by a factor of 1000.

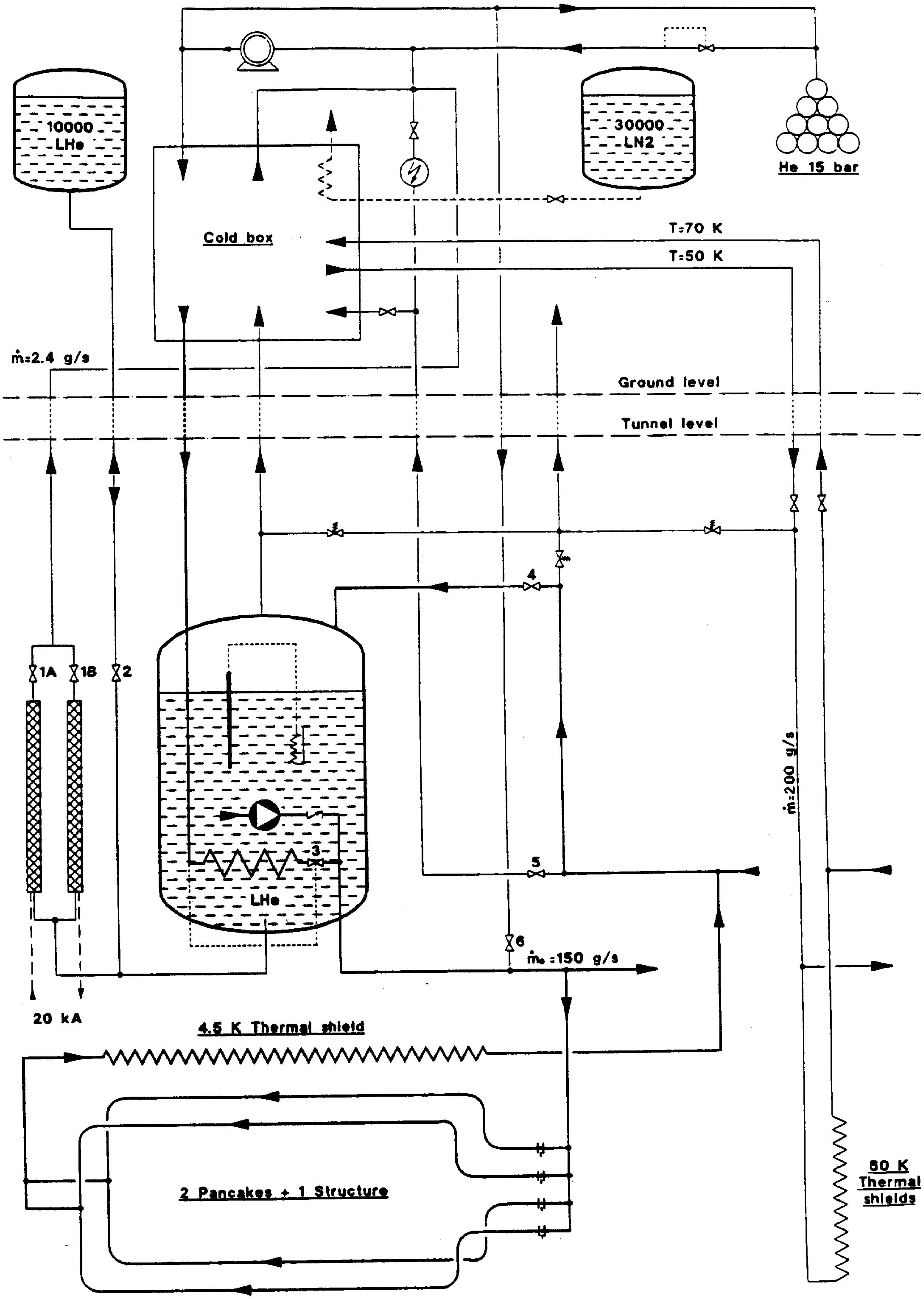

Figure 9 OVERALL CRYOGENIC FLOW CHART WITH LOCAL REFRIGERATOR

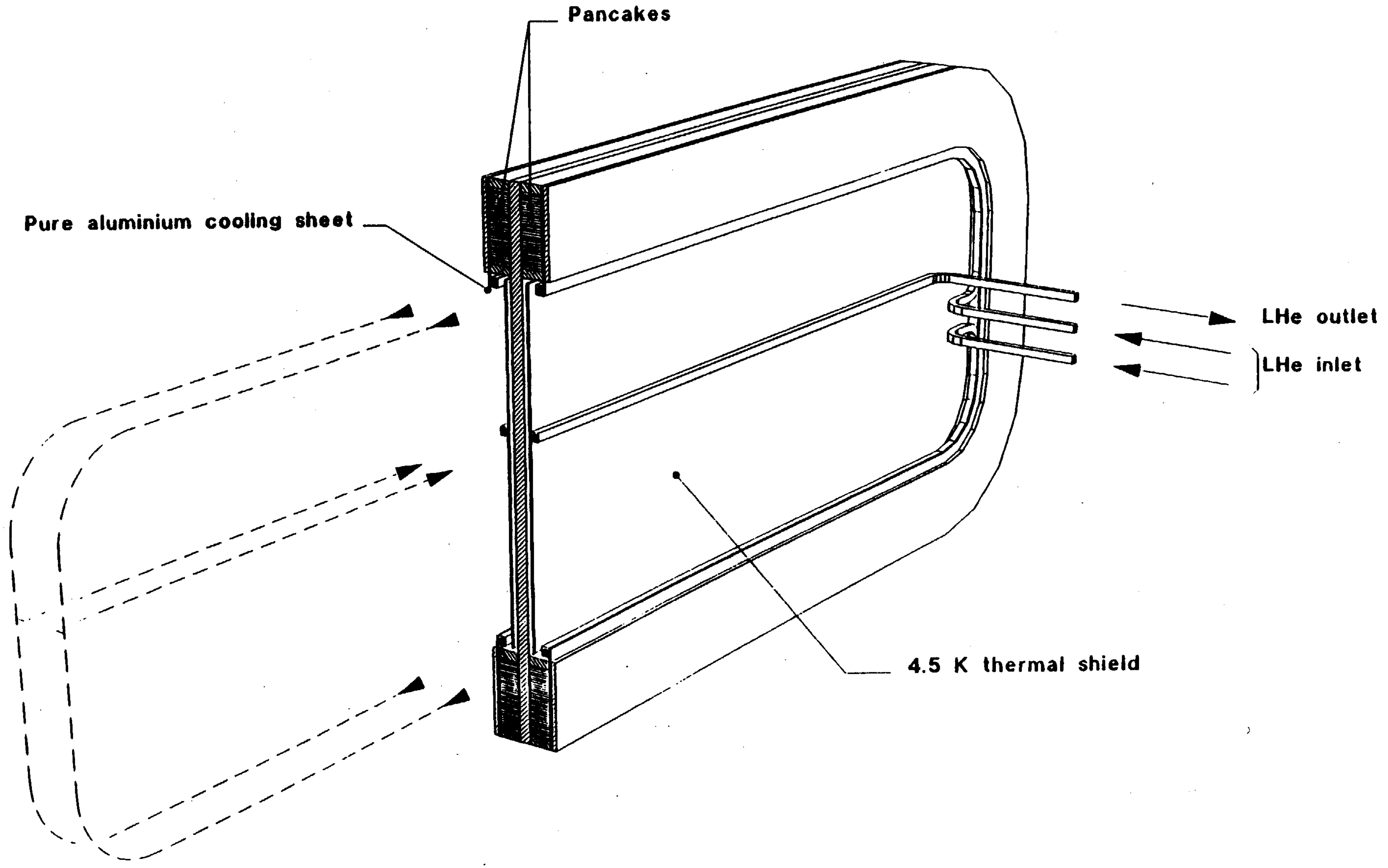

Figure 10 - Schematic pattern of the helium cooling pipes in a coil.