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END CAP TOROID DESIGN REPORT

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THIS DESIGN REPORT PRESENTS THE PRELIMINARY DESIGN OF A SUPERCONDUCTING END CAP TOROID FOR THE ATLAS EXPERIMENT PROPOSAL FOR LHC.

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SUPERCONDUCTING END CAP TOROID - DESIGN REPORT

1 GENERAL

The Atlas Experiment proposed for the LHC machine will use toroidal magnet systems to achieve high muon momentum resolutions. One of the options under consideration is an air cored superconducting toroidal magnet system consisting of a long barrel toroid with small end cap toroids inserted in it to provide high resolution at high pseudorapidity. The overall toroid system is shown in Figure 1.

The design of the barrel toroid has been studied over the past two years and the design outline is given in a Saclay Report.

More recently consideration has been given to an end cap toroid system which is based on air cored superconducting coils. This report presents the basic engineering design of such a system, the proposals for fabrication, assembly and installation, and an outline cost estimate for one end cap is presented in Appendix 1.

2 SCOPE OF THE DESIGN

The major parameters of the end cap toroid are given in Table 1.

2.1 Design Concepts

The design presented in the report embodies a distributed winding and a single large cryostat, concepts which were shown to achieve the most efficient superconducting coil design while satisfying the physics requirement to achieve high muon resolution at high rapidity.

2.1.1 Coil Design - Distributed Windings

The design is based on a system of 12 superconducting coil units, each of which is fabricated as a pair of single layer pancakes.

In a simple air cored toroid winding the magnetic field will decrease with radius as 1/r. For a simple coil with a large ratio of outer/inner radius it is therefore difficult to achieve a realistic bending power at the large radii without incurring prohibitively large fields at small radii. In the present design this is avoided by distributing the inner windings as shown in Figure 2.1. In this way the overall performance of the end cap toroid for muon resolution has been improved without incurring excessive fields at the inner radii.

2.1.2 Single Cryostat

The barrel toroid for ATLAS will be fabricated as 12 individual super-conducting coils each mounted in its own cryostat. It is not considered feasible to mount the barrel toroid system in a single cryostat. Similar design concepts for the end cap toroids have been considered.

The design presented here is based on a single large cryostat with the 12 coil units mounted as a common cold mass as shown in Figure 2.2. This concept offers a number of design advantages.

(i) It is mechanically possible to design for a rapidity, η in excess of 3, compared to a maximum of 2.6 for individually insulated coils. This is due to the space required at small radii for vacuum vessels and thermal barriers.

(ii) The magnetic forces are all reacted at 4.5k in a single structural cold mass.
- this gives design simplicity and minimises thermal loads on refrigeration.

(iii) The single large cryostat needs only a single current and cryogenic connection which simplifies coil inter-connections and makes reliability easier to guarantee.

Set against those advantages the single cryostat concept has some disadvantages.

(i) The cryostat must be fabricated off site in sections and assembled at CERN.

(ii) The cryostat is more than 10m diameter which is large and requires specialist fabrication techniques.

(iii) A special test cryostat will be required to test the coils individually.

The merits/demerits of these two design concepts are discussed in detail in this design report.

3 MAGNETIC DESIGN

A full 3-d analysis of the end cap toroid magnetic design has been made using the TOSCA Code. The magnetic design includes the barrel toroid in order to model correctly the interactions between toroids and the bending power as a function of rapidity.

Magnetic design parameters are given in Table 1. The detailed magnet design layout is given in Figure 3.1.

3.1 ∫Bdl vs. Pseudorapidity

Figure 3.2 illustrates the performance of the superconducting air cored end cap in terms of ∫Bdl vs η. Data is presented for four azimuthal positions (ϕ=0, 3.75, 7.5 and 15°) in order to illustrate the variation of ∫Bdl in planes which do not include the superconducting coils.

The design offers the possibility of excellent resolution up to rapidity η = 2.9 with decreasing but useful resolution almost out to η = 3. The resolution at the intersection between barrel and end cap is shown to have good continuity.

3.2 Forces

Symmetric magnetic forces on the superconducting coils are presented in Table 3.1 for the case where the full system is powered ie barrel and end cap and also with only the barrel and the one endcap powered.

This analysis shows the substantial reduction in force on the outer end cap coil section due to the barrel. Similar reactive forces will be present for the barrel system where the forces are increased and these should be included in the mechanical analysis.

A simplified, 2-d analysis has been made to ascertain the offset forces which can arise from a number of different assembly errors.

(i) Non symmetrical assembly of the end cap structure alone.

(ii) Non symmetrical mounting of the end cap in the barrel geometry.

Computation of these offset forces is required in order to define support criteria and dimensional/assembly tolerance effects.

Table 3.1 indicates that for reasonable assembly and mounting tolerances of around 10mm, the offset forces of around 50t overall, are relatively easy to contain.

3.3 Stored Energy

The stored energy of the end cap toroid has been computed to be 210MJ. This is approximately a factor of 2 larger than the largest detector solenoids fabricated to date eg DELPHI, ALEPH, H1.

3.4 Peak Fields

The peak field has been estimated from 2-dimensional analysis to be 3.2 Tesla. Since the estimated self field of the superconducting cable is 0.8 Tesla, the total magnetic field intensity at the conductor is 4.0T.

4 CONDUCTOR DESIGN

4.1 Conductor Design

Conductor design parameters are given in Table 4.1. The conductor is based on the concept developed for large solenoid fabrication and consists of a Rutherford cable protected and stabilised by a high purity aluminium substrate. See Figure 4.1. An operating current of 20kA is chosen to achieve a realistic aspect ratio for a single layer winding.

The aluminium cross-section is defined by quench protection requirements and the present design is based on the conservative adiabatic design criterion

$$J^2 = \frac{G(\theta)IV}{E}$$

with Tmax ~ 100k, $G(\theta) \sim 6 \times 10^{16} A^4 m^{-2} sec^{-4}$

Vmax = 750V
I = 20kA
E = 210MJ

The design of the superconducting cable is chosen to give an operating point at 60% along the peak field load line, see Figure 4.2. This operating point will allow adequate operating temperature margin for the indirectly cooled conductor ie approximately 2k between the operating temperature of 4.5k and the current sharing temperature 6.5k.

4.2 Conductor Fabrication

The conductor will be fabricated by extrusion cladding a basic Rutherford Cable with high purity aluminium.

4.2.1 Cable Fabrication

For the chosen operating current of 20kA the required cable is 30 strand by ~ 1.4mm diameter. This cable is somewhat larger than the cables for LHC dipoles, 26 x 1.29mm diameter, but within fabrication capability.

4.2.2 Aluminium Cladding

Fabrication of a conductor with the specified dimensions 6.25 x 50mm has been discussed with manufacturers. This represents an increase in scale from previous conductors such as DELPHI, 4.5 x 25mm^2, and some special tooling will be required but technical feasibility is confirmed.

Piece lengths of 1Km are achievable with simple pancake spooling. This readily meets the requirement for winding a half coil pancake, ~ 0.75Km, which is the basic unit.

4.2.3 Quality Control

Production techniques for cable manufacture are well established with extensive quality control. Fabrication of extrusion clad cables for DELPHI, ALEPH, H1, have demonstrated that the extrusion technique is capable of producing high quality product with well established techniques for post-fabrication QA ie mechanical bond testing, electrical bond testing. The conductor would be delivered to the coil winding facility in a fully cleaned state ready for winding.

5 COIL DESIGN

5.1 Design Principles

A detail of the winding support structure is shown in Figure 5.1. The coil unit is made up in a sandwich type construction and consists of:-

(i) A central plate of aluminium alloy which forms the basic element for coil winding. This control plate will be insulated with approx. 1mm of GF epoxy laminate prior to delivery to give the required ground plane isolation.

(ii) A single layer pancake winding on each side of the central plate. The pancake winding will be formed by winding the insulated conductor around formers mounted on the central plate to give the required coil distribution.

The winding will be carried out with the plate in the horizontal plane - details are described in Section (5.2.1).

(iii) Two outer closing plates. Two outer plates of aluminium alloy will be used to close the sandwich type construction. These plates will be pre-insulated with 1mm of ground plane insulation and cooling tubes which will carry the liquid helium coolant will be welded to them.

(iv) Force containment strips. The outer edges of each coil will be closed by thick strips secured by bolting through the total sandwich structure for force containment.

5.2 Coil Fabrication

5.2.1 Coil Winding

The central plate will be mounted on a winding machine with a horizontal table. The first insulated former will be mounted on the plate and the coil will be wound as a single layer. The conductor will be insulated in the winding process as shown in Figure 5.2.

As winding proceeds additional formers will be added to create the desired winding distribution.

When a single pancake is complete the winding will be closed with a closing plate and a force containment strip.

The coil will be turned over and the second pancake wound and contained in identical fashion.

5.2.2 Bonding

A fully bonded coil structure is proposed. Since each single coil is of relatively simple geometry and a total of 24 coils is required, it is proposed to vacuum impregnate and cure the coils in a specially designed bonding facility.

Vacuum impregnation offers the highest quality bond and structural integrity. With the proposed design of coil a relatively simple 'flood' impregnation technique is proposed.

5.2.3 Alternative Mechanical Structure/Force Constraint

The fully bonded coil structure will present a robust self contained unit. The magnetic forces can in principle be contained within the structure and transmitted from the coil blocks to the central and outer plates through the resin bond. Initial analysis shows that the stress levels at the coil/plate interface will not exceed 1-2MPa, which is more than an order of magnitude below the expected bond strengths.

Further investigation, including possible deterioration due to radiation exposure, is being carried out on this possibility. Pending the results the previously mentioned force containment strips have been included to show the alternative design feasibility.

6 COLD MASS STRUCTURE

6.1 Cold Mass Assembly

The twelve coil units will be assembled as a single cold mass structure. The proposed assembly is shown in Figure 6.1. Coil component masses are given in Table 5.3.

Coils will be mounted and supported by azimuthal structural plates. These plates will serve to give accurate location of the coils and will also be used to react the net inward magnet forces on the coil units. They will also be used to transfer the cold mass weight to the vacuum vessel of the cryostat.

The estimated total weight of the cold mass is 168 tonnes.

6.2 Cold Mass Support

The cold mass will be supported at four points, two at each end on the horizontal centre plane. The supports will be short compression columns fabricated in G10 laminate using the same principle as that for the H1 Solenoid. Supporting the cold mass at the central plane in this way means that the toroid cold mass will remain essentially on the central horizontal plane during cooldown with minimal compensation. The cold mass support is shown in Figure 6.2. Each support will have 80k intercepts. Transverse and longitudinal constraints will also be provided.

The estimated conduction heat loads for cold mass support are:

Conduction Heat Load at 4k	10 watts
Conduction Heat Load at 80k	50 watts

7 CRYOSTAT DESIGN

7.1 Vacuum Vessel

The design is based on a single large cryostat vacuum vessel for each end cap. The proposed vacuum vessel design is shown in Figures 7.1 and 7.2.

7.1.1 Outer Vessel

In order to insert the end cap toroid into the barrel structure and achieve maximum field overlap the design is based on a castellated vessel as seen in Figure 2.2. The vessel will be assembled from 12 pre-fabricated shell units, shown in Figure 7.1. The basic units will be fabricated from 40mm thick aluminium alloy plate using a break/pressing technique. This has been discussed with manufacturers and the fabrication technology exists to press half length units from plate as a single operation. These will be welded together to produce the full lengths required.

Because of the size of the vessel (>10m diameter) it is not possible to transport significant assembled sections to CERN. It is therefore proposed to transport single units and assemble the outer vessel on site. The vessel will be assembled by coupling units through a specially designed channel extrusion. The vessel will be structurally formed and sealed by welding along the channel section.

Assembly of the vessel has been discussed with the manufacturers and technical feasibility has been confirmed. The vessel will be assembled using the end plates as the basic jig with additional jigs for specific operations.

7.1.2 End Plates

The vessel end plate design is shown in Figure 2.2 The plates will be fabricated from 110mm thick plate with thick local strengthening in the form of turned collars at the centres.

Sealing of the centres will be by 'O' rings, the grooves for which can be included in the overall machining. Connection to the castellated outer vessel will be by bolting for structural integrity and the vacuum seal will be made by welding of a sealing strip across the joint. The cold mass will be supported by connection to the end plates which, in turn, will be supported to ground.

7.1.3 Inner Vessel

The inner vessel will be fabricated from 20mm aluminium alloy plate with large end flanges.

7.1.4 Vacuum Vessel Stress Analysis

A model of the entire vacuum vessel has been subjected to finite element stress analysis. The main results are:-

1. The atmospheric load on the outer vessel is transmitted to the end plates rather than being taken as a hoop stress as would be the case if the vessel were circular rather than castellated. This occurs because the castellated sections function as beams.

2. The atmospheric load on the end plates results in a significant build up of stress at the centre holes requiring significant reinforcement to be included in these areas.

7.2 Radiation Shields

The outer radiation shields will be fabricated on the same principle as the outer vacuum vessel. Basic shield components will be formed by pressing. They will be joined structurally using the same channel principle.

The shields will be fabricated from 20mm thick aluminium alloy plates and will have sufficient structural stiffness to be self supporting.

Cooling pipes will be welded to the individual shield units prior to delivery. Manifolding together the total shield cooling circuit will be completed after assembly on site.

Shield end plates will be fabricated from 20mm plate sectors to form a full structural plate.

The inner shield will be a 10mm aluminium alloy cylinder.

Radiation shields will be mounted as a single unit and supported from the outer vessel with low heat leak supports.

7.3 Superinsulation

Superinsulation will be prefabricated into blankets of 15 layers. The technology to produce blankets 6 metres in length and 2.3m width exists.

For the outer shield, the blankets will be mounted on the outer surface with longitudinal joints. A double layer of blankets will be installed with overlaps to achieve an overall cover of 30 layers of insulation.

End plate shield will be installed with prefabricated blankets.

Inner vessel superinsulation will be installed directly on the inner vacuum vessel.

7.4 Services Turret

Cryogenic feeds for helium at 4k and 80k and electrical connections will be connected through a single port. The precise location of this port is not yet decided. Instrumentation feeds will be through the main services turret.

8 FABRICATION AND ASSEMBLY PROPOSALS

Because of the large scale of the end cap toroid system, >10m diameter, final assembly on site is essential.

The design has taken this requirement into account and is based on the fabrication off-site of defined structural units which can be transported easily and can be assembled rapidly on site.

Coil units and cold mass support structure will be fabricated off site. A trial assembly of the 12 coils to form a single structural unit will be made at the coil manufacturers premises.

Superconducting coils will be cooled down and powered in a test cryostat at the manufacturers.

Vacuum vessel and radiation shield components will be fabricated off site.

Assembly on site will be made with the toroid axis horizontal. The proposed assembly sequence is as follows:-

(i) Assemble outer vessel and end caps on site and mount with inner vessel for initial vacuum test of basic vessel. Mount outer vessel on trolley.

(ii) Assemble outer radiation shield and mount on centre lever bracket. Install manifold pipework and superinsulation. Transfer inside outer vessel and transfer weight.

(iii) Assemble coil cold mass on cantilever bracket - transfer to outer vessel and support.

(iv) Assemble inner vessel, inner superinsulation and inner radiation shield on cantilever.

(v) Move outer vessel over inner vessel and mechanically connect.

(vi) Fit end radiation shields supports etc and end plates.

9 TEST

After complete assembly a full test of the toroid above ground is proposed.

10 INSTALLATION

It is assumed that the endcaps will be installed after the barrel has been installed and tested in position and that the barrel toroid is maintained at 4.2K after such testing.

It is proposed that, after ground level testing, each complete endcap be lowered into position onto the rails which also carry the central calorimeter and possibly other components. They will then be driven along the rails and locked in their final positions along the axis of the detector.

These actions will be part of a sequence which also includes other components in such an order that all the components, including the endcap toroids, are finally placed in correct sequence along the detector axis.

As each endcap is so located and before other components which would obscure the assembly space are introduced:

1. Its' position in space will be finely adjusted by survey, using jacks placed in each of the four wheel carriages

2. Vacuum, cryogenic and electrical connections will be made.

3. Full cooldown and power tests will be performed firstly with the barrel toroid field OFF and then with it ON.

After testing, the endcap toroids will be maintained at 4.2K during subsequent assembly of other components.

After installation of the second endcap, the complete toroid system will be power tested.

TABLE 1

Radius inside cryostat	0.457 - 1.016	m
Outer radius	4.9 and 5.872	m
Number of coils	12	
Individual coil dimensions		
a. Parallel to axis	5.040	m
b. Radially	4.934 - 4.471	m
Total ampere turns	11.10^6	
Stored energy	210.10^6	J
Peak field at the conductor	4.0	T
Net inward force/coil		
a. Barrel toroid ON	273	t
b. Barrel toroid OFF	620	t
Total weight of one coil	11	t
Cold mass	168	t
Refrigeration power at 4.5K	200	W

TABLE 3.1

FORCES RESUME

1.	Net inward force with all coils powered:		
	a.	On one barrel coil	1610 tonnes
	b.	On one endcap coil	273 tonnes
2.	Endcap coils only powered		
	a.	On one endcap coil	620 tonnes
3.	Barrel coils only powered		
	a.	On one barrel coil	627 tonnes
4.	Forces due to relative displacement of endcap to barrel toroids		
	a.	Translation of endcap axis along a barrel radial plane.	5.1 tonne/mm
	b.	Rotation of endcap	1380 tonne.m/deg
		(equivalent to 3.2t/mm at 5m radius)	

CONDUCTOR PARAMETERS

TABLE 4.1

Operating Current	3T 4.5k	20kA
Design Current	6T 4.5k	40kA
Cable		
Rutherford Type		
Strand No.		30
Strand Diameter		1.4 mm
Cable Dimensions (approx)		20 x 2.6 mm^2
Superconducting Composite		
Cu:Sc		1.35
Aluminium Stabiliser		
Section Width		50.00
Thickness		6.25
RRR (Zero field)		1000
Conductor Length/Coil		1.5Km
Conductor Weight/Coil		1.2t
Piece Length/Half coil		0.75Km

END CAP TOROID MAGNET MASSES

TABLE 5.3

Vac. Vessel

1 off shell fabrication 2336 kg.	12 off	28032 kgs.
1 off end plate 30 deg. sector 1471 kgs.	24 off	35304 kgs.
1 off centre tube		3000 kgs.
	Total	66336 kgs.

Cold Mass

1 off coil mounting assembly 11123 kgs.	12 off	133476 kgs.
1 off structural plates 1700 kgs.	12 off	20400 kgs.
1 off rad. shield 30 deg. sector 1140 kgs.	12 off	13680 kgs.
	Total	167556 kgs.

Total Overall Mass. Vac. Vessel + Cold Mass = 233892 kgs.

Force Support			
Conduction Heat Loads			
80K to 4K			
Materials Data			
Intk.dt	w/m	Int(k.dt) 4-80K GF lam	18
Force	t	Force Trans to 80K	230
Sig2	N/m^2	Design stress in support	5.00E+07
Xsas1	m^2	Support X section	0.05
ls1	m	Length of support	0.1
Intk.dt	w/m	Int(k.dt) for support	18
300K to 4K			
Materials Data			
Intk.dt	w/m	Int(k.dt) 80-300K GF lam	100
Force	t	Force Trans to 300K	230
Sig3	N/m^2	Design stress in support	5.00E+07
Xsas2	m^2	Support X section	0.05
ls2	m	Length of support	0.1
Intk.dt	w/m	Int(k.dt) for support	100
Conduction Head Loads			
Qcon4K	w	Con Heat load 4K	8
Qcon80K	w	Con Heat load 80K	46.00
Radiation Heat Loads			
grad4K	w/m^2	Spec Heat load 4K	0.2
Area4K	m^2	Cold Mass area	250
QRAD4K	w	Rad Heat load to 4K/coil	50.0
grad80K	w/m^2	Spec Heat load 80K	2.0
Area80K	m^2	Shield Surface Area	300
QRAD80K	w	Rad Heat load to 80K/coil	600.0
Coil Heat Loads			
Q4K	w	4K Heat load/coil	58
Q80K	w	80K Heat load/coil	646

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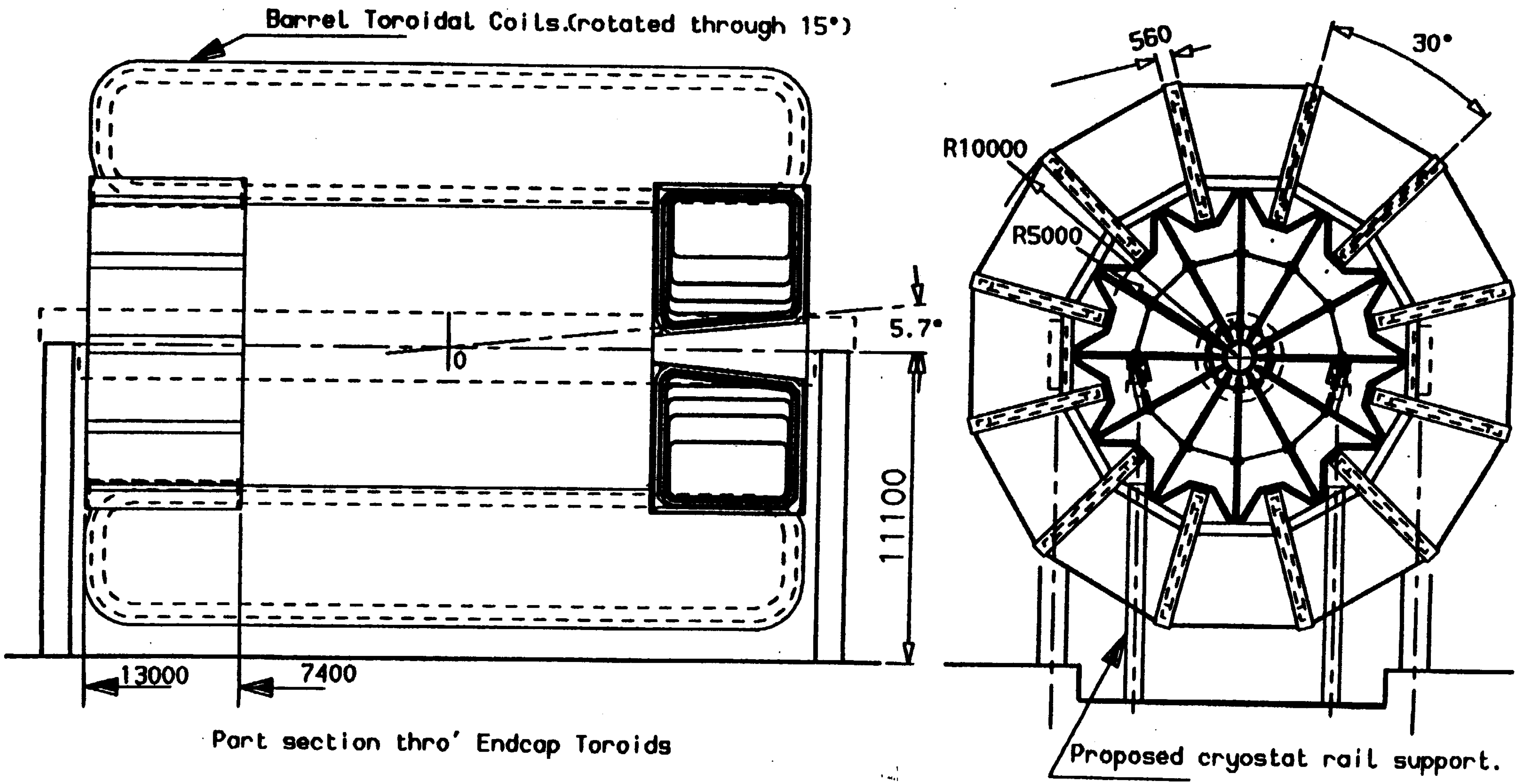
Fig.1 Atlas Toroidal Magnet System.



Scale 1/200

Fig.2.1 Atlas Endcap winding distribution.

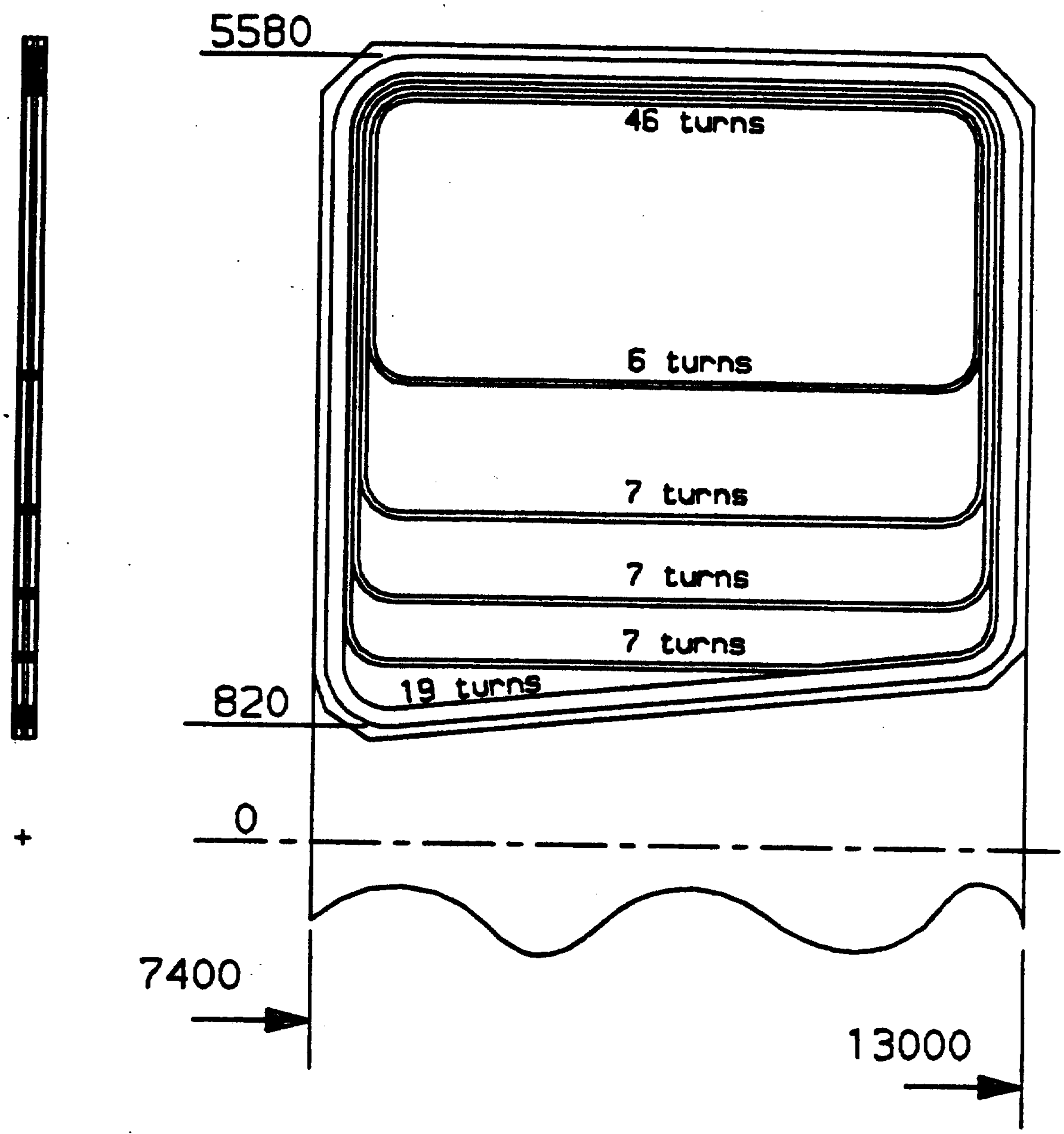


Fig.2.2 Atlas Endcap configuration.

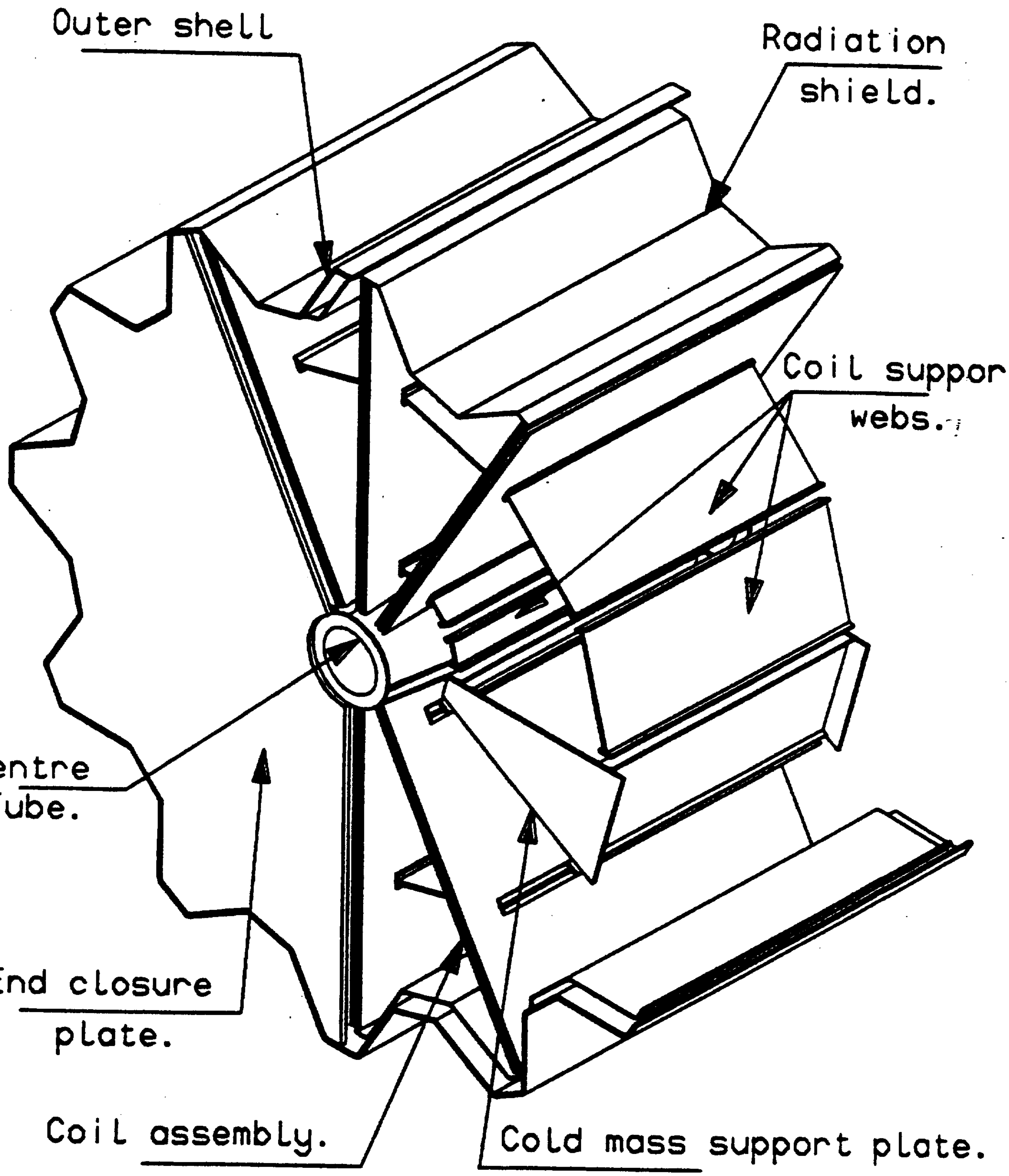


Fig.3.1 Detailed Magnet design Layout.

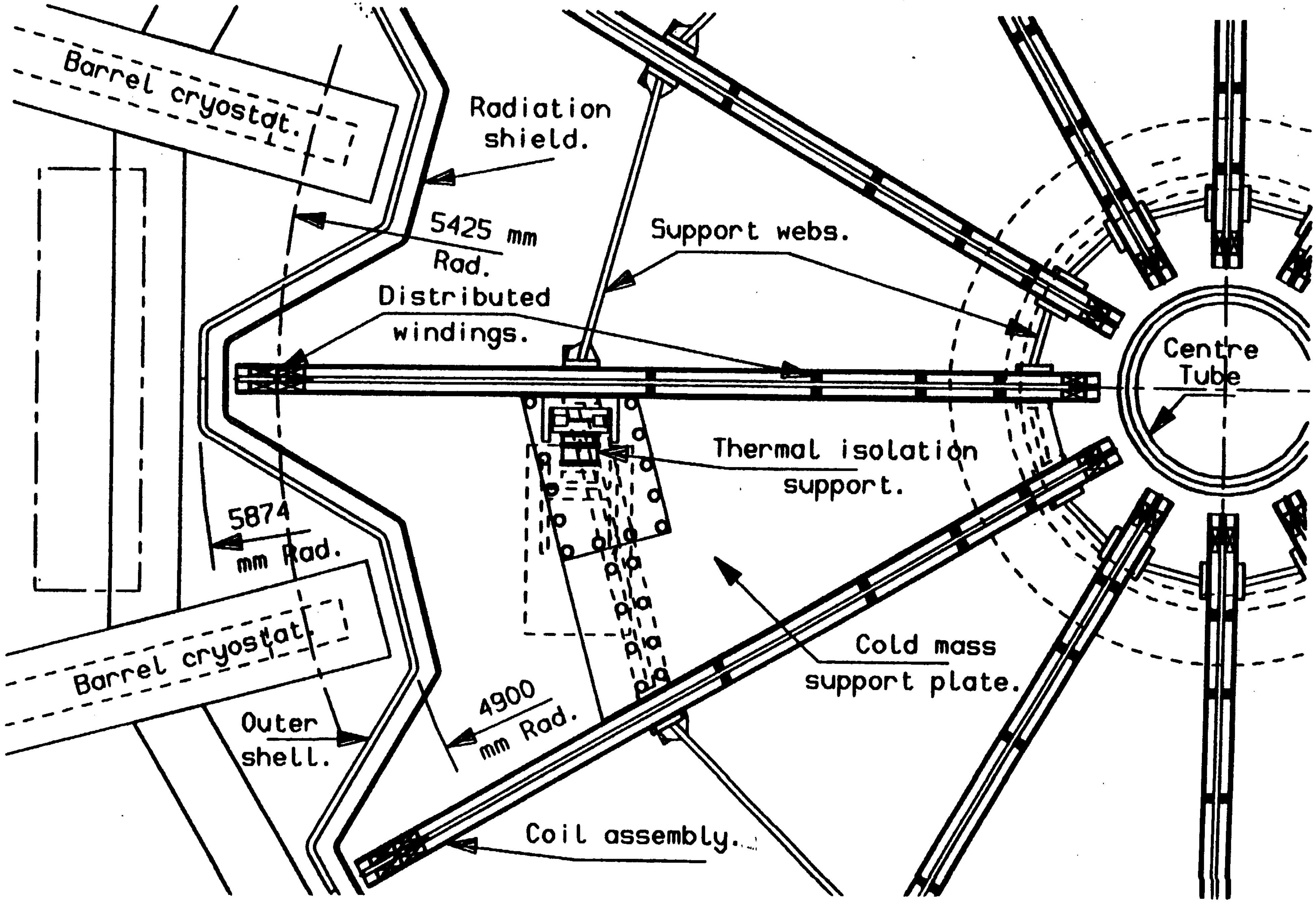


FIGURE 3.2

AIR-CORED TOROID FIELD INTEGRAL At 0, 7.5, 15 deg. to ENDCAP COIL

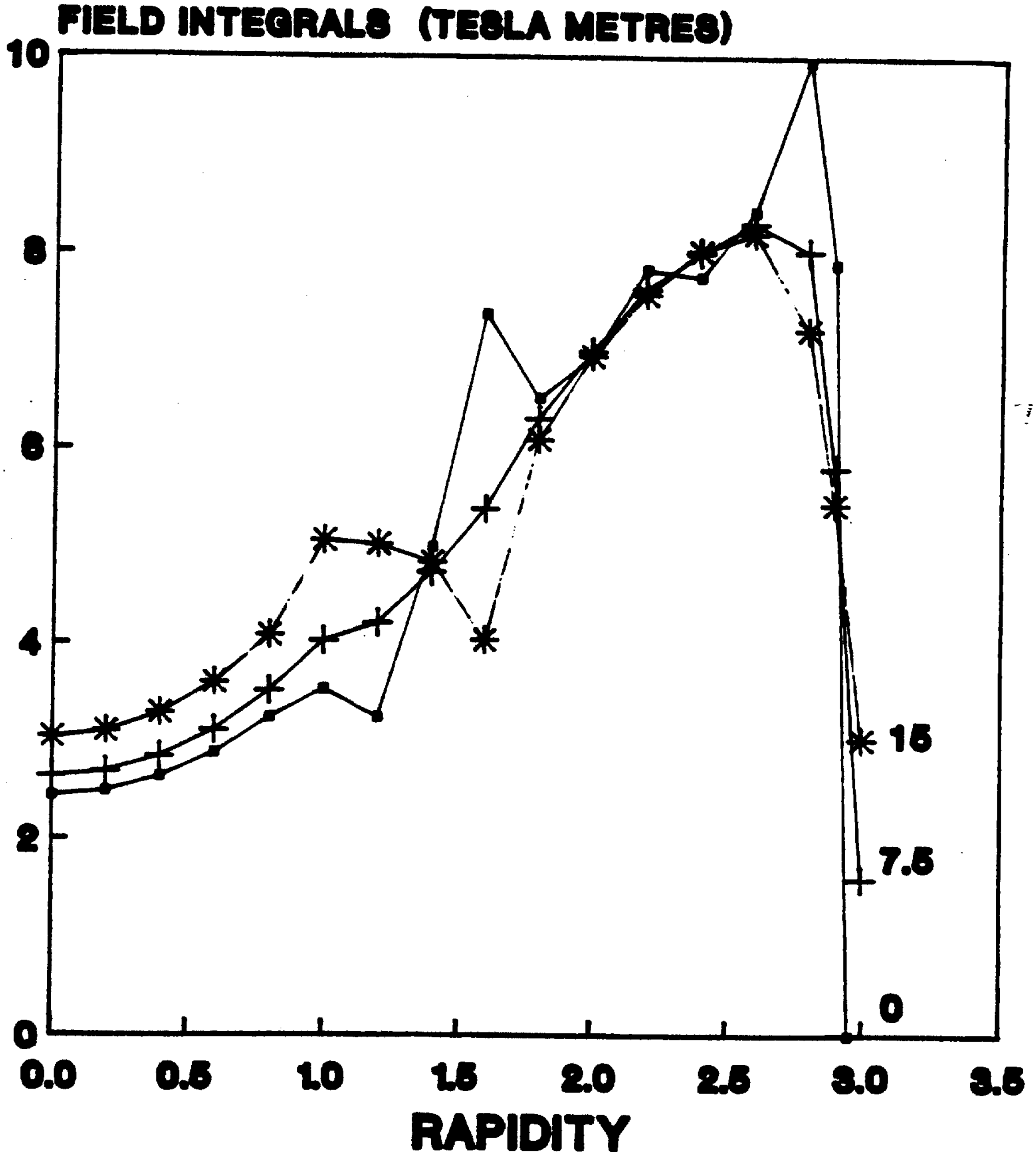
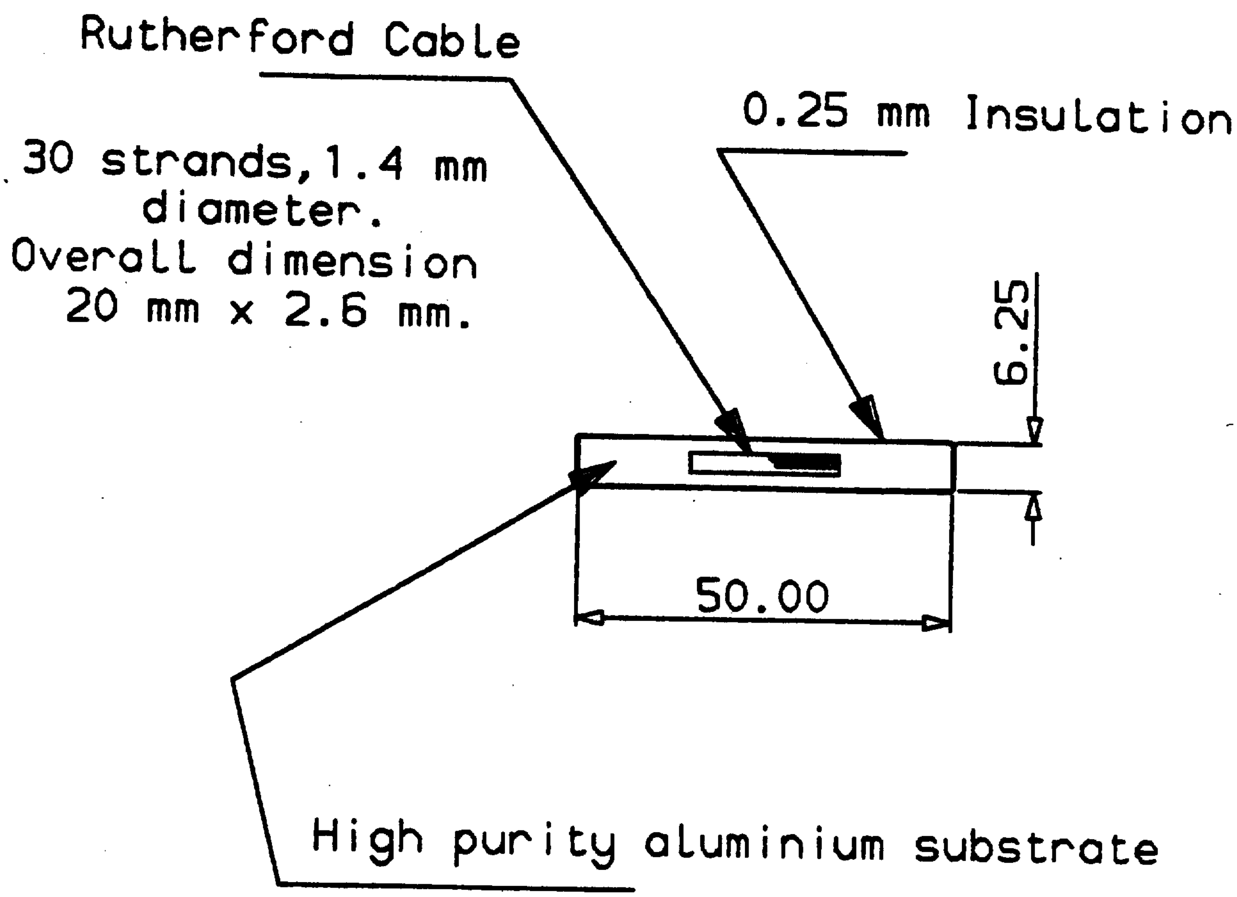


Fig.4.1 Conductor detail.



scale 1/1

FIG.4.2 Conductor Specification

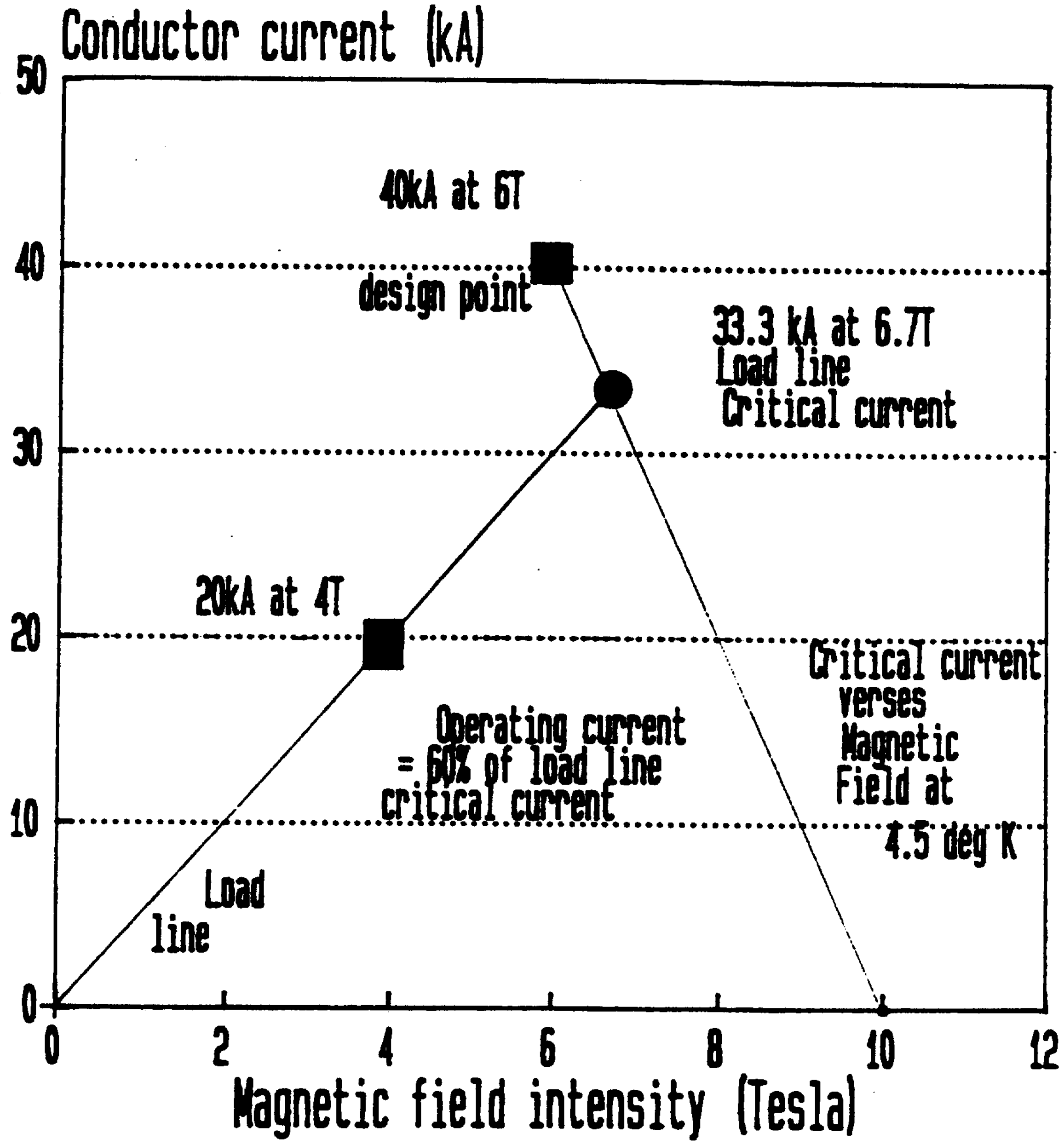


Fig.3.1 Winding support structure detail.

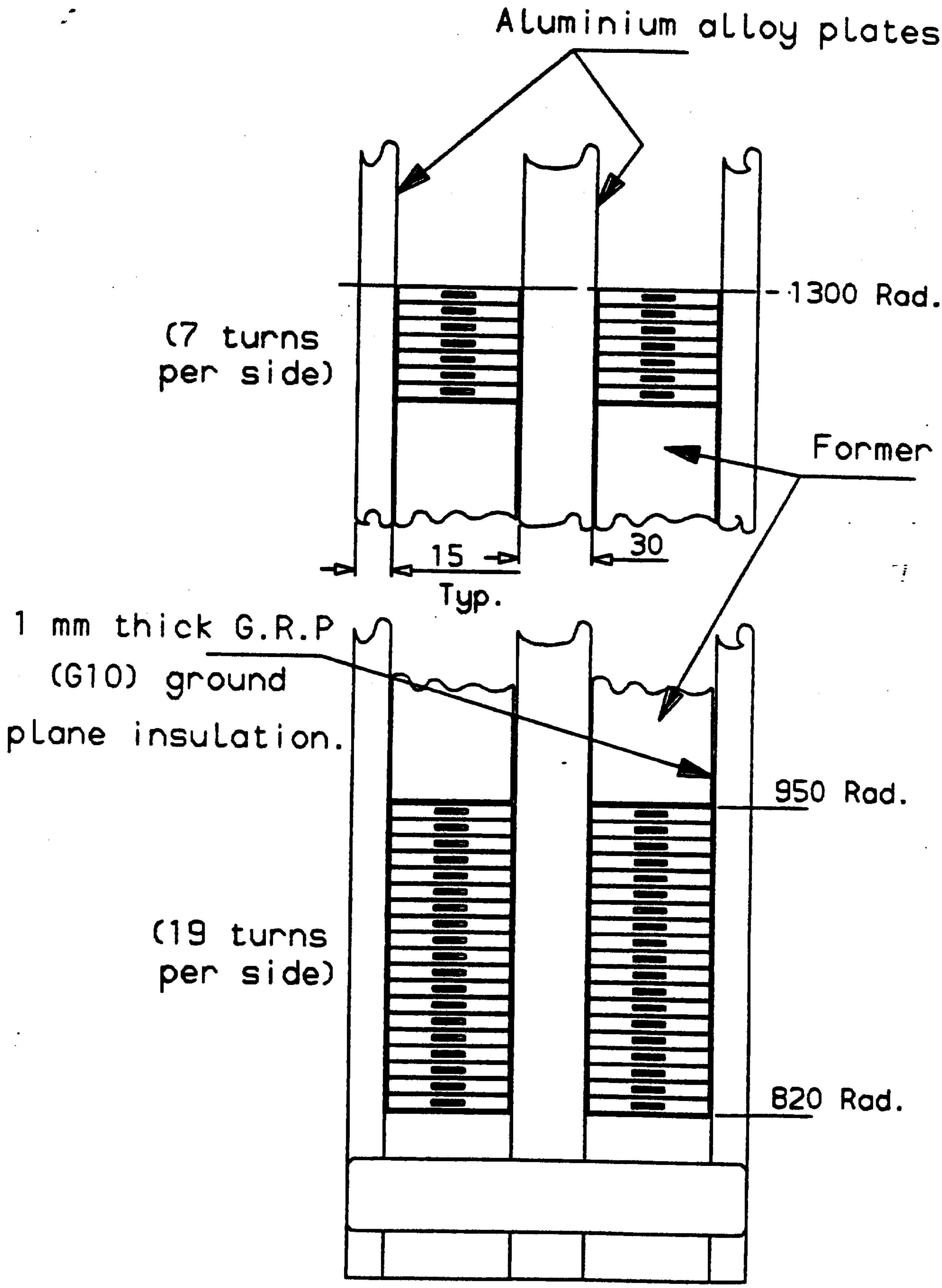


Fig.5.2 Toroid coil winding process.

(winding speed 3m/min.)

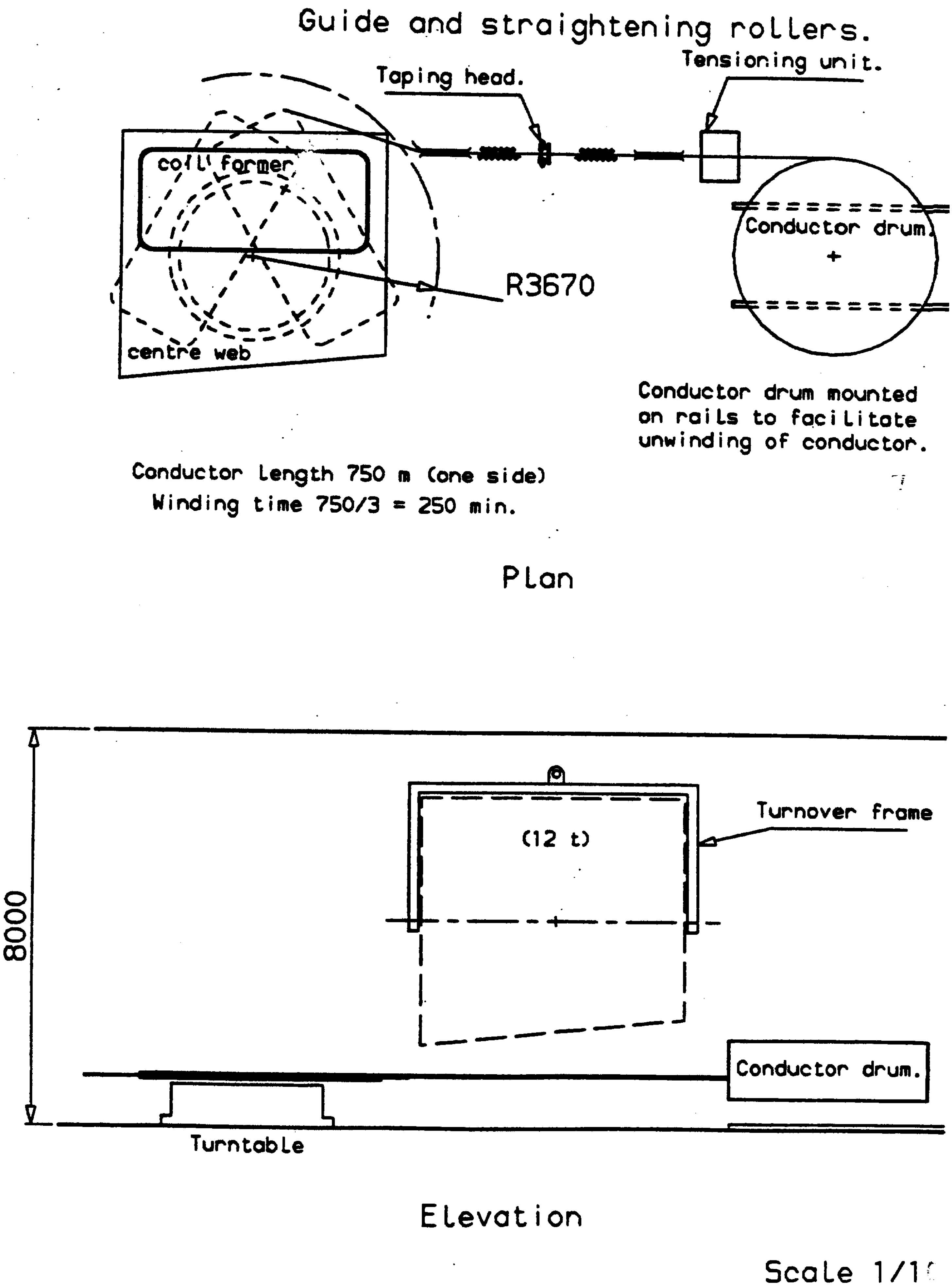


Fig.6.1 Atlas Endcap Coil Assembly.

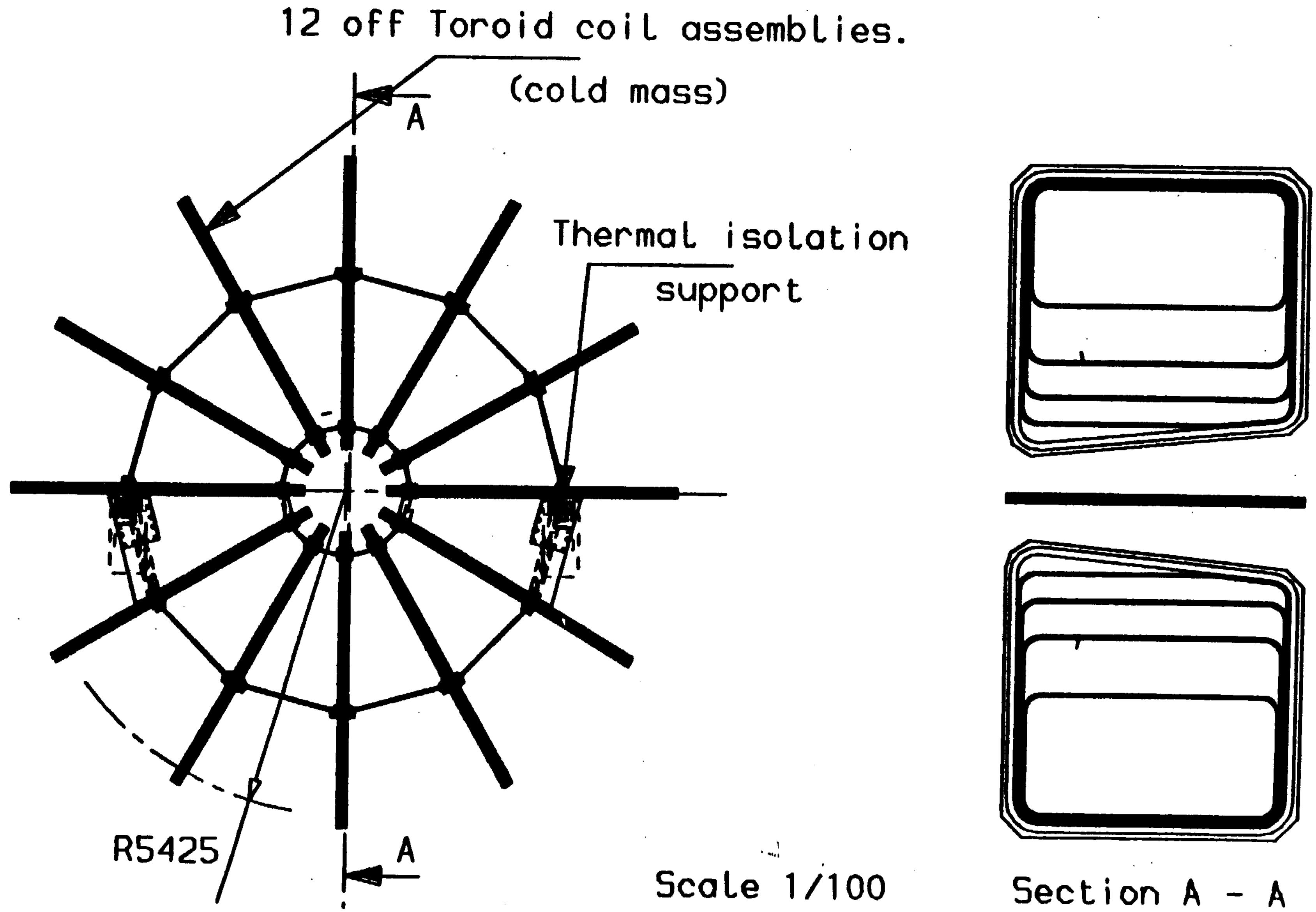


Fig.6.2 Cold mass support.
(part section thro' support and upper coil assembly)

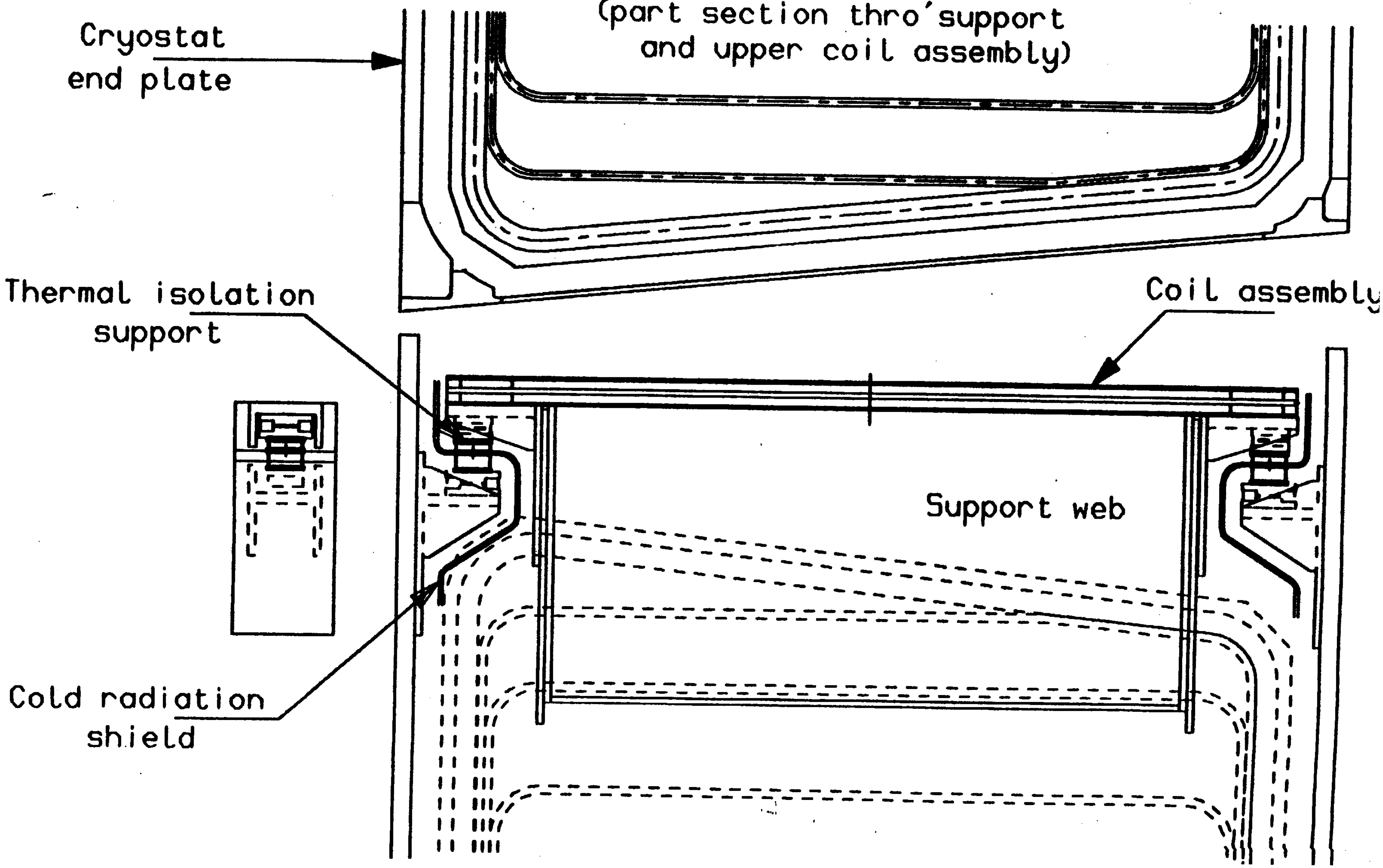
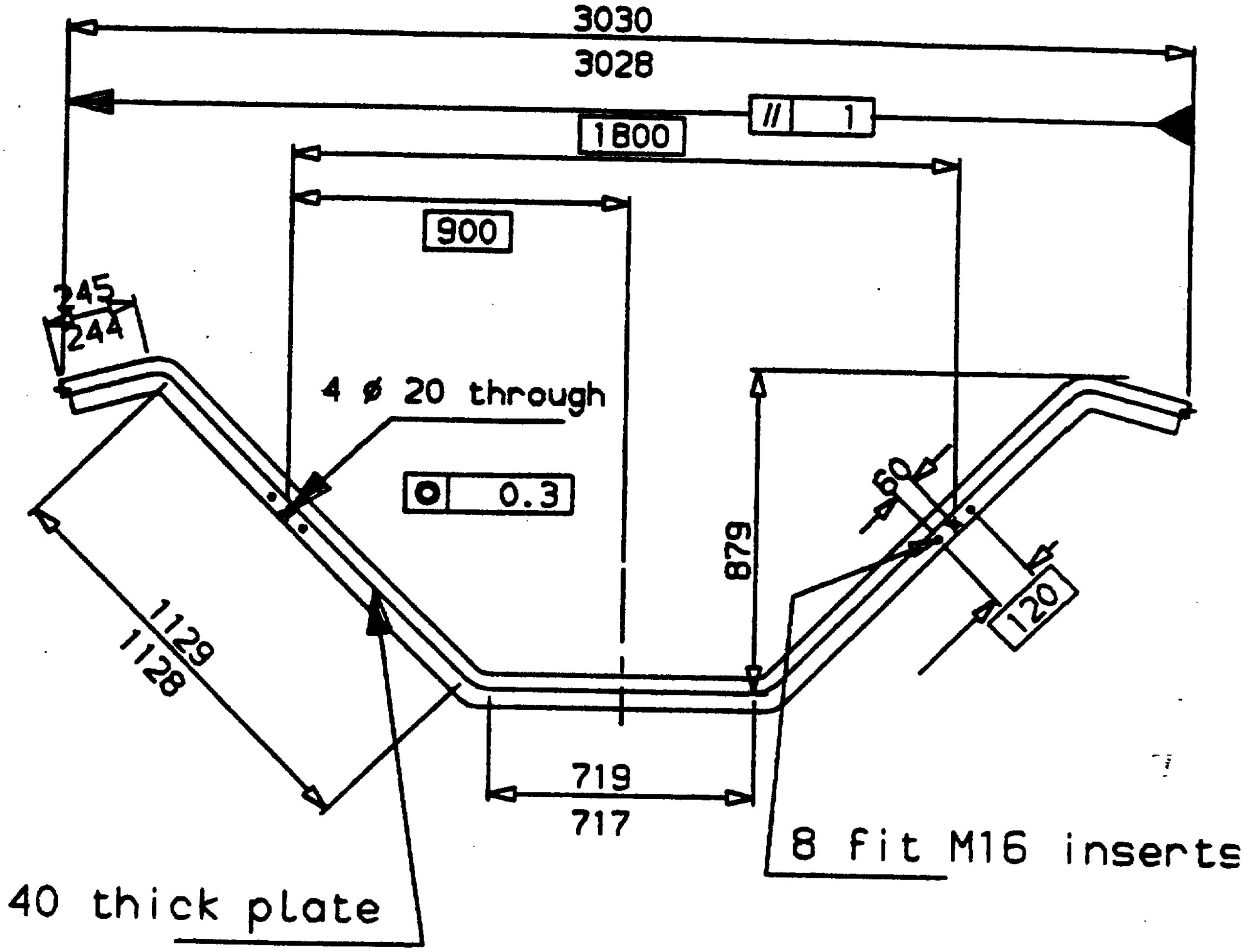
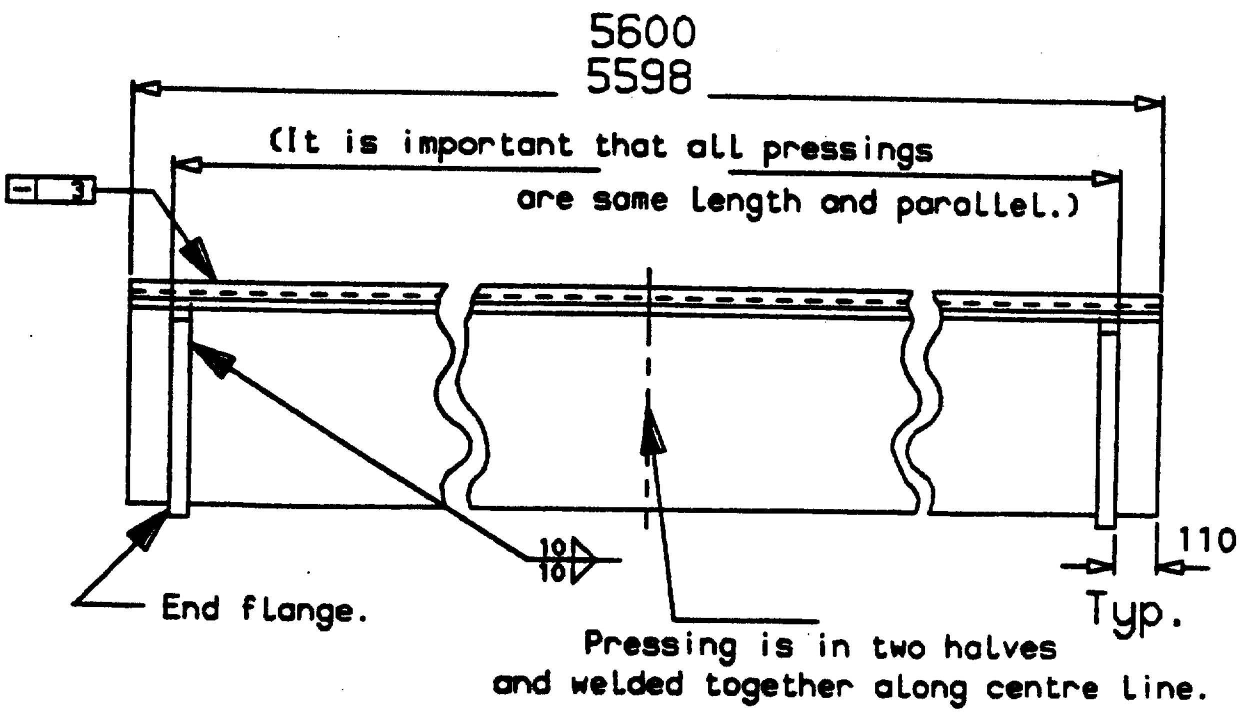


Fig.7.1 Shell Pressing

Material AL. Alloy. 5083-0



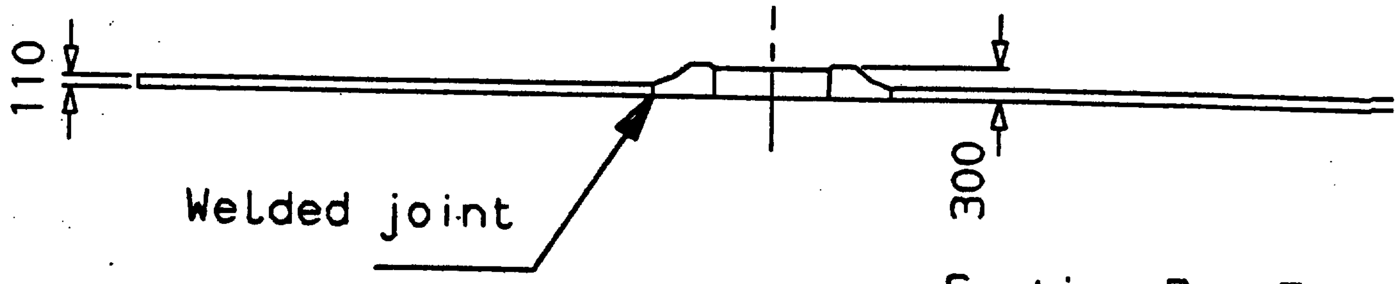
End elelvation

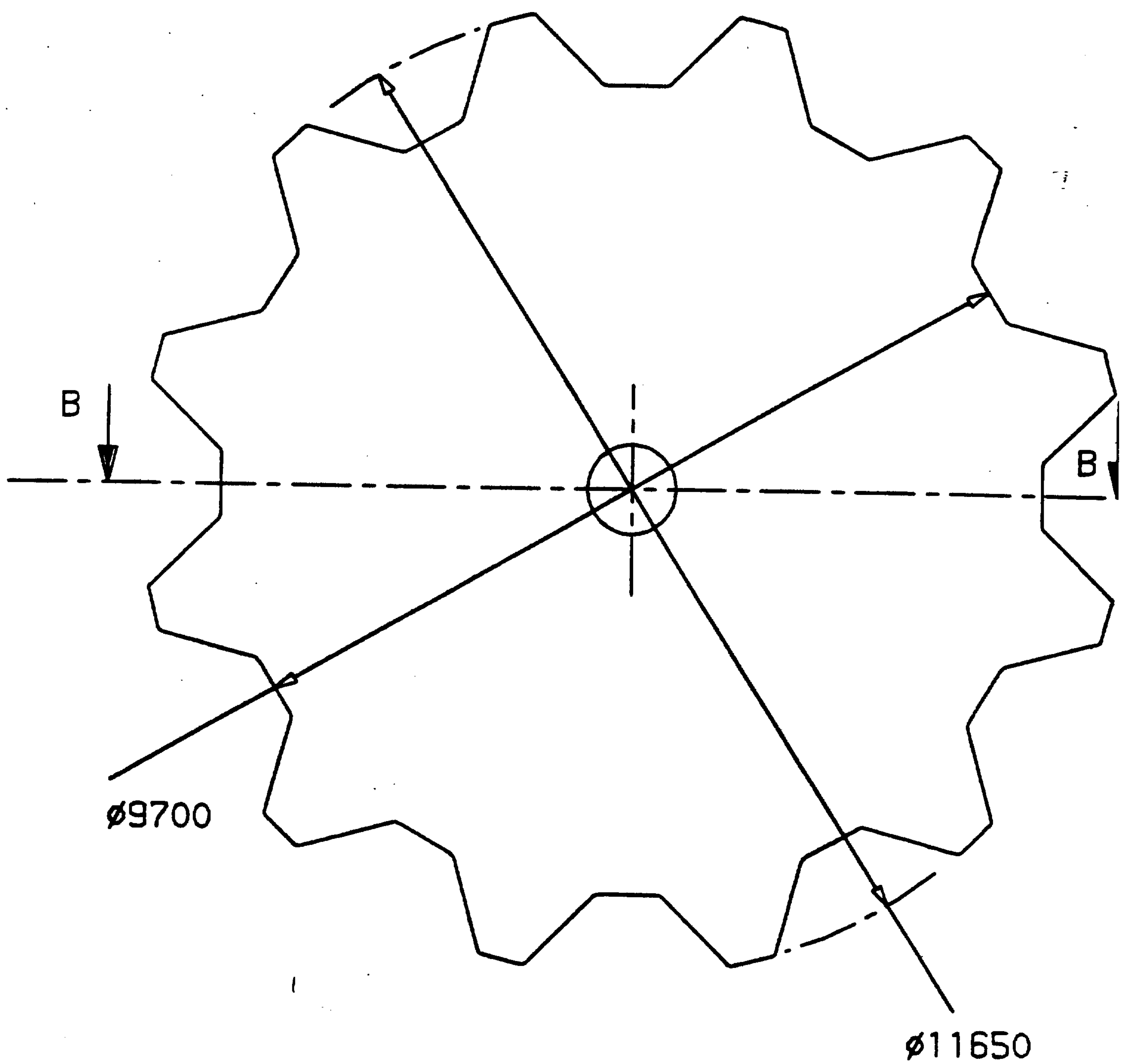


Side elevation

Fig.7.2 Cryostat end plate.

Material Aluminium alloy 5083-0





(to suit small dia. of centre tube)

APPENDIX 1

COST RESUME FOR ONE END CAP

COST RESUME MSF/ENDCAP AT 2.45 SF/£

COILS		
Conductor	3.67	
Winding Structure	3.23	
	****	6.9
CRYOSTAT		
Vacuum Vessel	1.22	
Radiation Shield	0.61	
Superinsulation	0.24	
Supports	0.49	
	****	2.57
MANPOWER – 42 MY	****	4.04
OTHER		
Vacuum System	0.49	
Electrical	1.10	
Infrastructure	0.73	
Refrigeration Interface	0.61	
Transport	0.59	
Travel & Subsistence	0.49	
	****	4.01
TOTAL		**17.52**