11.8 Support Structure

11.8.1 Introduction and Effect of Performance Spec and Environment on Design

The ATLAS Inner Detector occupies a volume of 6.9 metres length and 2.3 metres diameter. The silicon-based precision tracking has a length of 5.6 metres, and an external diameter of 1.12 metres. The mechanical support structure has stringent requirements placed on it by a number of factors. Foremost amongst these is the variation in temperature over the volume (-15°C to +25°C), and the requirement to maintain detector elements at locations known to within a few microns. Other critical environmental factors are the high levels of radiation and the limited accessibility. This last factor implies the need for a high degree of reliability, even though high stability is required while maintaining a low mass.

Although the support structure will be in dry nitrogen in the experiment, it will be assembled in a normal laboratory environment; as a result, a high humidity tolerance is required. These environmental factors dictate a careful choice of materials and an extensive testing programme. In particular modern composite materials are not always well characterised for use at ATLAS.

The performance specification requires the structure to have a minimum material thickness, both in radiation and absorption length. This is qualified by the performance requirement that the material should be preferentially located away from the interaction point and that the distribution of material is uniform. A minimisation of the material impacts the assembly tolerances since overlap to eliminate dead regions adds to the material budget.

To meet the performance specification on position resolution, the support structure must be stable to a level ensuring that the tracking resolution deteriorates by < 20% between successive alignment measurements. There must be no low-frequency vibrational modes and in particular there must be no modes capable of excitation by the movement of cooling fluids.

11.8.2 Specification

The structure of the SCT is described in Section 11.8.3. The function of the support structure is to define the relative module positions in space, and to define the module positions with respect to the beam line or detector axis. Because of the very different geometry of the central barrel and forward disk regions, the module support structures of these regions differ, and consequently the detailed structural specifications also differ.

Only overall tolerances are quoted in this report. The tolerance requirements for individual assembly steps are not yet finalised; however the overall build and long-term stability tolerances are large enough that this is an issue of optimisation rather than a critical item.

Two different stability criteria are relevant to the specification of stability for the ATLAS tracker.

- The first is the long-term structural stability of the detector over the lifetime of the experiment; this is closely connected with the initial assembly precision.
- The second class of stability criteria are short-term and relate to the accuracy with which the alignment is known between successive alignment measurements.

The requirements placed on the assembly precision and subsequent long-term stability are less stringent than those on short-term stability, but still place significant demands on the structure and on assembly procedures. Internal module assembly requirements are discussed in Section 11.5. The primary demand on the support structure is that it holds the module relative positions accurately enough to satisfy the physics and trigger criteria. These require the relative alignment of modules be accurate to a precision of ~0.2 mm in r and r-ϕ, 0.5mm in z, and that the misalignment of module strips with respect to the nominal beam axis should not exceed 1.6 mrads. Stronger r, r-ϕ and z requirements come from other criteria, as discussed below.

The short-term stability requirements are determined by the need to meet the final module alignment requirements which are:.

Table 11-32 Short term alignment requirements.

Barrel region	$\sigma_{r\text{-}\phi}$= 12μm	σ_r = 100μm	σ_z = 50μm
Forward region	$\sigma_{r\text{-}\phi}$= 12μm	σ_r = 50μm	σ_z = 200μm

These are basic constraints on the stability of the structure over a timescale which is sufficient to align the modules with the on-line alignment system and tracks.

11.8.2.1 Module placement

a) Overlaps and clearance

The minimum overlap (geometric overlap) between modules in the same layer is determined by the specification that the detector be hermetic to tracks with p_T > 1 GeV. An additional overlap is required to ensure that the build accuracy does not result in acceptance holes and that sufficient tracks pass through both layers for alignment purposes. To maintain the designed overlaps and clearances between modules on the same support, the following limits are placed on the sum of build error plus long term creep:

- To ensure that the r-ϕ overlap, which is important for alignment with tracks, is not significantly reduced from its design value, the maximum error is 100 μm in this direction;
- To ensure that the 500 μm overlap in the z direction in the barrel (r in forward) is not eliminated by the misplacement of modules it is required that the maximum error is 500 μm in this direction;
- Alternate modules are staggered by 2 mm in r in the barrel and 5 mm in z in the forward regions. This clearance must not be compromised, which implies an assembly accuracy of < 500 μm in the barrel and 1000 μm in forward direction;
- The positioning of whole barrels, of disks relative to each other, or of disks with respect to the nominal beamline can have errors in z of 2 mm before there is any significant effect on the geometric acceptance of the tracker.

b) Trigger

The planned use of tracking to provide a level 2 trigger threshold of a $p_T = 20\pm5$ GeV/c results in the need to calculate the absolute ϕ position of any strip to < 200 μm without using stereo information. A translation of the whole module in the r-ϕ direction can be corrected, but not a rotation, so the build plus creep for rotation must be less than 1.6 mrad within a 12 cm module and its mounting. Furthermore, the transformation from ϕ strip to ϕ value with 200 μm accuracy is only possible in the forward region if the disk is centred on the beam spot to within 500 μm.

c) FSI alignment system

The light beam from a fibre has a useful opening angle of ~0.5 degrees and it must hit the reflector on the next FSI node. This sets a limit on the allowed error in the relative positions of the support structures. The shortest light paths are between barrels (73 mm) which sets the build and creep tolerance to 700 μm (see Chapter 9).

11.8.2.2 Stability

The adopted philosophy is that the support structure is sufficiently stable that the final alignment constants, which must have the accuracies given in Table 11-32, can be derived from the initial survey combined with information from the on-line evaluation of track residuals and the FSI system. An initial alignment survey, repeated at a series of temperatures from -15°C to +25°C, will be used to cross calibrate the FSI network with module motions. The track alignment procedure is not yet precisely defined, but it is anticipated that high energy muon triggers, or tracks from minimum bias events, will be used. Since it is anticipated that the interval between fully understood three dimensional alignments will be a few weeks, the relative movement of modules on the same support should not exceed the final alignment tolerances in r and z during that period.

It is noted that this should be relatively easy to achieve during stable running conditions, but not in the case of significant environmental changes.

The positions of the main support structures (barrels and disks) relative to each other can be measured more frequently with FSI and tracks. In the same time interval it is anticipated that tracks can be used to make small corrections to the alignment constants in the r-ϕ direction. This will bring a medium term r-ϕ error of each module in the global frame from <50 μm to the final r-ϕ error specification of <12 μm. The structure must remain stable to the full required alignment precision for this period.

The primary source of structural distortions are expected to result from localised temperature variations. By choosing low CTE carbon fibre construction these problems will be minimised. However, since the detectors, front-end electronics and cables dissipate up to 41 kW, some fraction of which depends on the nature of the data transmitted, small temperature changes are anticipated even during a fill.

11.8.2.3 Summary of specifications

Table 11-33 summarises the tolerance specifications consistent with meeting the SCT alignment requirements. The quoted numbers are nominally rms units. In order to incorporate a safety margin, the numbers are used as engineering tolerances. The tolerances in Table 11-33 are overall accuracies based on the physics performance required.

11.8.3 Description of Baseline

The choice of support structure for the SCT was motivated by the need to provide a stable structure having known and reproducible dimensional variations following repeated access over the detector lifetime, and following repeated temperature cycling in the range -15°C to +25°C. The chosen structure is the most cost-effective solution satisfying the specifications, and the choice is supported by design and prototype studies.

Table 11-33 Total Accuracy Requirements.

	Dimension	a (μm)	b (μm)	c (μm)	d (μm)
Build Accuracy	r-ϕ	250	50	500	50
	r	250	200	500	250
	z	1000	500	500	250
Maximum Long-term creep allowed, including effect of thermal cycling	r-ϕ	250	50	500	50
	r	250	50	500	500
	z	1000	500	500	250
Maximum motion between full track surveys (a few weeks)	r-ϕ		50		50
	r		50		100
	z		200		50
Stability under normal environment over a period of 2 days	r-ϕ	12	12	12	12
	r	50	50	100	100
	z	200	200	50	50

a/ Forward modules relative to the nominal beamline

b/ Forward modules relative to others on the same wheel

c/ Barrel modules relative to the nominal beamline

d/ Barrel modules relative to others on the same barrel

The general features of the support system are shown in Figure 1-1. The central barrel region and the forward disk regions are mechanically isolated. The regions are suspended independently and are connected via a common final support rail fixed to the cryostat wall. As a result, there are three separate mechanical structures. Each of the assemblies has an outer enclosure, which acts as a gas volume and provides thermal insulation from the TRT.

The support structure in the barrel region consists of four concentric carbon fibre cylinders. Each cylinder has two 0.2 mm thick skins of ultra-high modulus carbon fibre in a cyanate ester resin (CFRP). These are separated by a CFRP honeycomb of 6 mm thickness. The fibres are aligned to achieve a zero-CTE in the z and ϕ directions. The radial CTE is also low. The cylinder ends are terminated in a zero-cte carbon fibre flange, which contributes significantly to the barrel rigidity. The cylinders are rigidly joined using a zero-cte perforated end-plate, which connects to the end-flanges. The connection of the barrels via the end plates provides a further substantial improvement in the mechanical rigidity of the individual cylinders. The end plates are suspended from the inner TRT barrel via four interlink struts. The suspension is via a dynamic load equalisation scheme so that the structure remains unstressed; this has not yet been designed in detail.

In each of the forward regions, the support structure consists of 9 carbon fibre disks. Each disk has the same zero-cte CFRP honeycomb fabrication as the barrel cylinders. A set of four disks and another of five disks are mounted in zero CTE space frames that are joined during final assembly and are connected to the support rails on the walls of the cryostat via four lugs.

In the forward regions, modules are mounted directly onto the disks using precision pins. Aluminium cooling pipes are fixed to the disks, but can expand longitudinally. Between 10 and 33 modules share a cooling pipe. The cooling pipes are manifolded such that one input and one output pipe are required per quadrant of the disk for coolant. In the barrel region, modules are attached to a 'local support'. This structure ties 6 modules that run in a given r-ϕ line as a unit. The local supports are mounted on the barrel cylinders which provide rigidity. The cooling pipes are attached directly to the barrel cylinder, and each pipe contacts 12 modules. The cooling pipes are manifolded at the end of the barrels such that a single input and output pipe services a quadrant of the barrel. Power and the other services are distributed to modules individually in both the forward and barrel regions.

11.8.4 Barrel Local Supports

Individual barrel detector modules as described in Section 11.5 are attached by precision fixations to a rigid CFRP tube, fabricated as for the macroscopic support facings from UHM fibre with cyanate ester resin. To minimise mechanical distortions induced by temperature changes or gradients, modules are fixed with one precise hole and a slot. Details of the local support, showing the module fixations, are shown in Figure 11-81.

In addition to the detector modules, the support will integrate the power and monitoring cables, the opto-electronic readout hybrid, and the optical fibres. The support will be attached to the zero-cte macroscopic support by 4 precision inserts on the barrel, with the modules, opto-electronic board, and cables in good thermal contact to aluminium cooling tubes. The cooling contact will be made using thermally conducting compound [11-83]. A detail of the local support showing the cable layout, attachment to the barrel, and the cooling contact is shown in Figure 11-82.

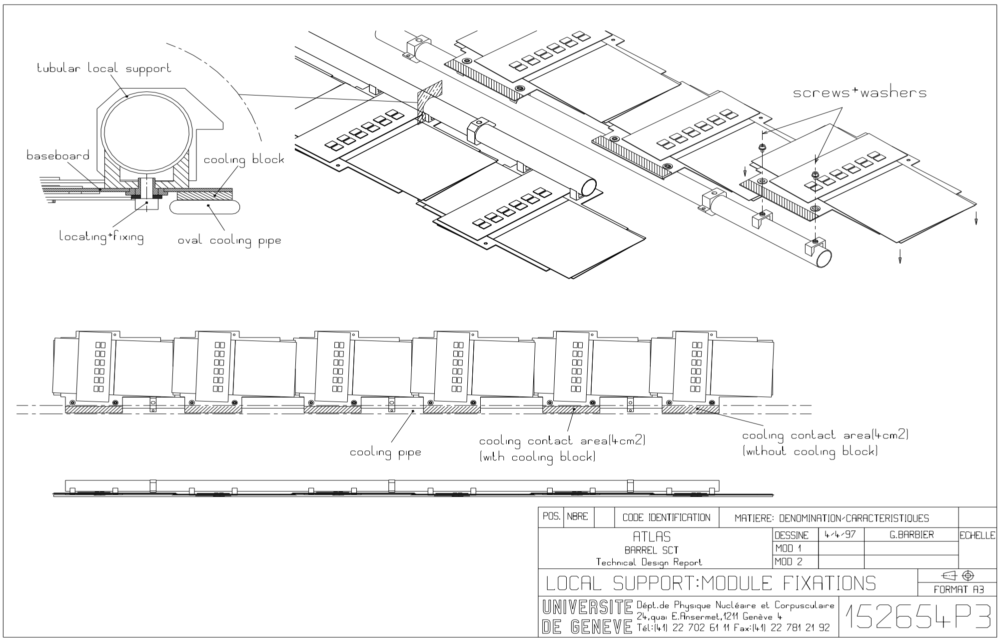


Figure 11-81 Details of local support, showing module fixations.

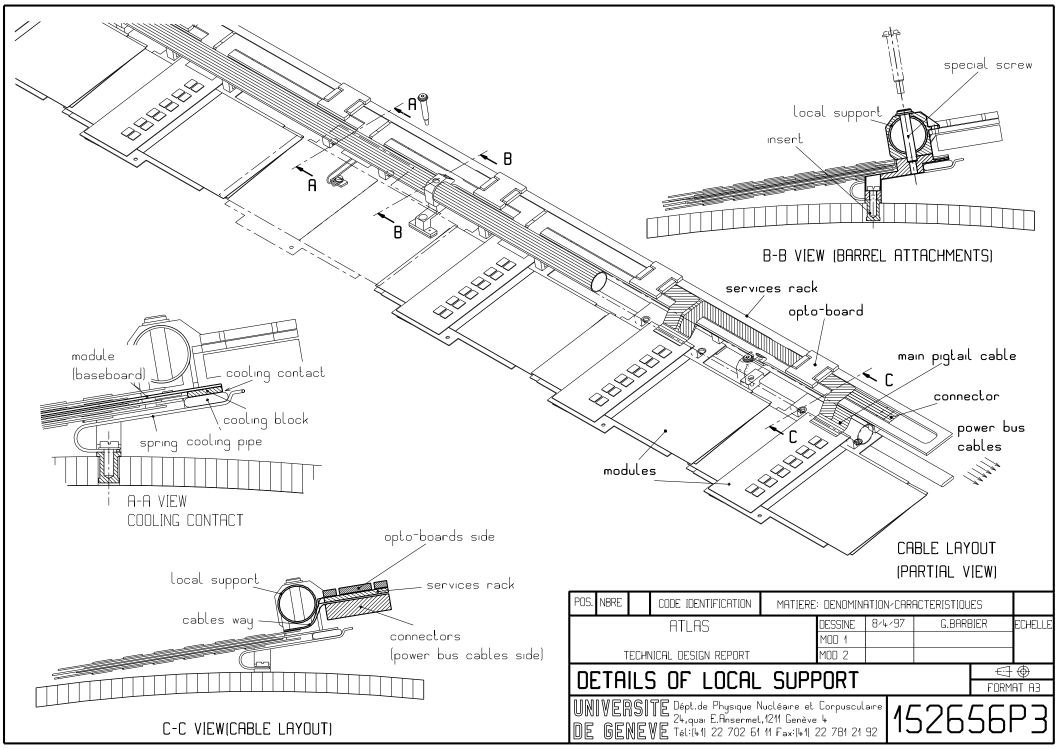


Figure 11-82 Detail of local support showing cable layout, barrel attachments, and cooling contacts.

11.8.5 Barrel and Disk Supports

The general requirements imposed on the structure are outlined in Section 11.8.2. Carbon fibre composites (CFRP) fabricated from ultra high modulus carbon fibres and cyanate ester resins are chosen for the SCT supports. The CTE of such laminates can be tuned to be close to zero in the plane of the laminate.

11.8.5.1 Barrels

The schematic of a partially equipped barrel cylinder of length 1.57 m is shown in Figure 11-83, with detector module local supports, cooling pipes and services attached to the exterior of the barrel. The characteristics of a prototype barrel being constructed are shown in Figure 11-84.

The prototype structure is designed according to the following dimensional stability requirements:

- A CTE of 0 ± 0.5 ppm/°K in the longitudinal and circumferential directions, over the temperature range -20°C to +30°C, is required.
- Under normal operational conditions (-10 ± 1°C and +20 ± 1°C in a dry nitrogen atmosphere), the dimensional changes in all directions excepting the sandwich thickness are required to be <10 µm/m/yr. This condition assumes a 2 point support in the mid plane at each end of the barrel, and a distributed load of 50N/m^2 over the cylinder surface.

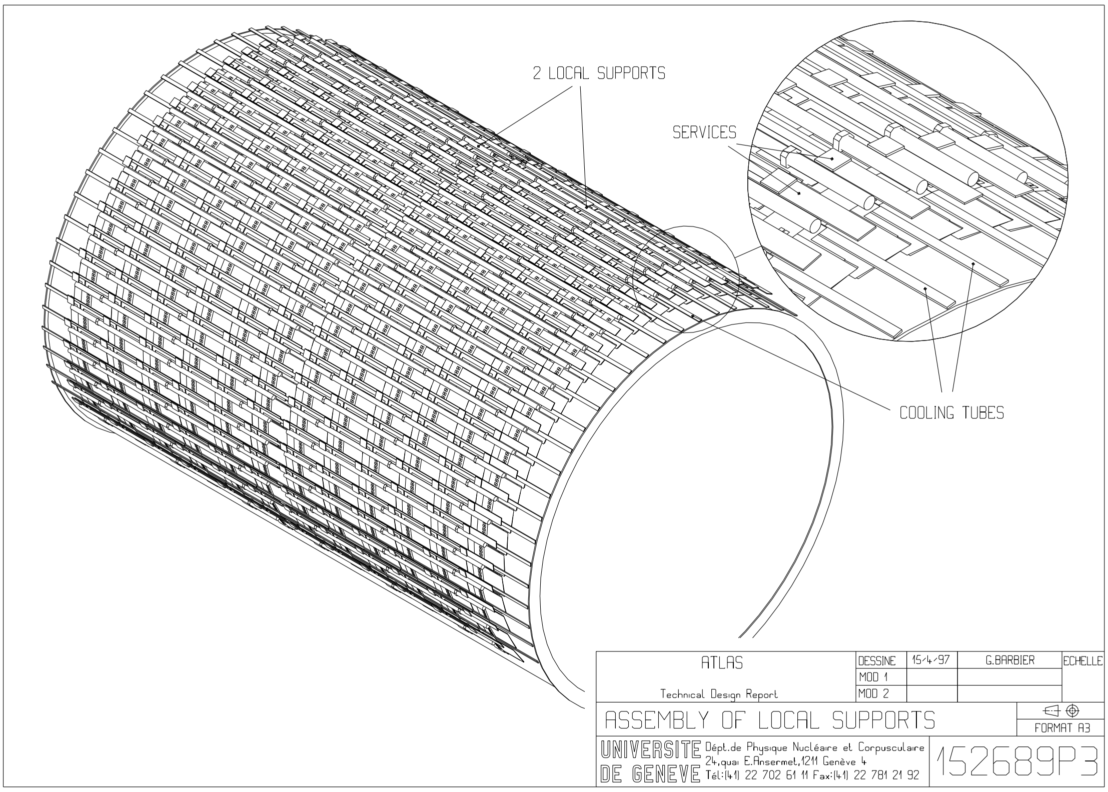


Figure 11-83 Assembly of local supports on a barrel; cylinder.

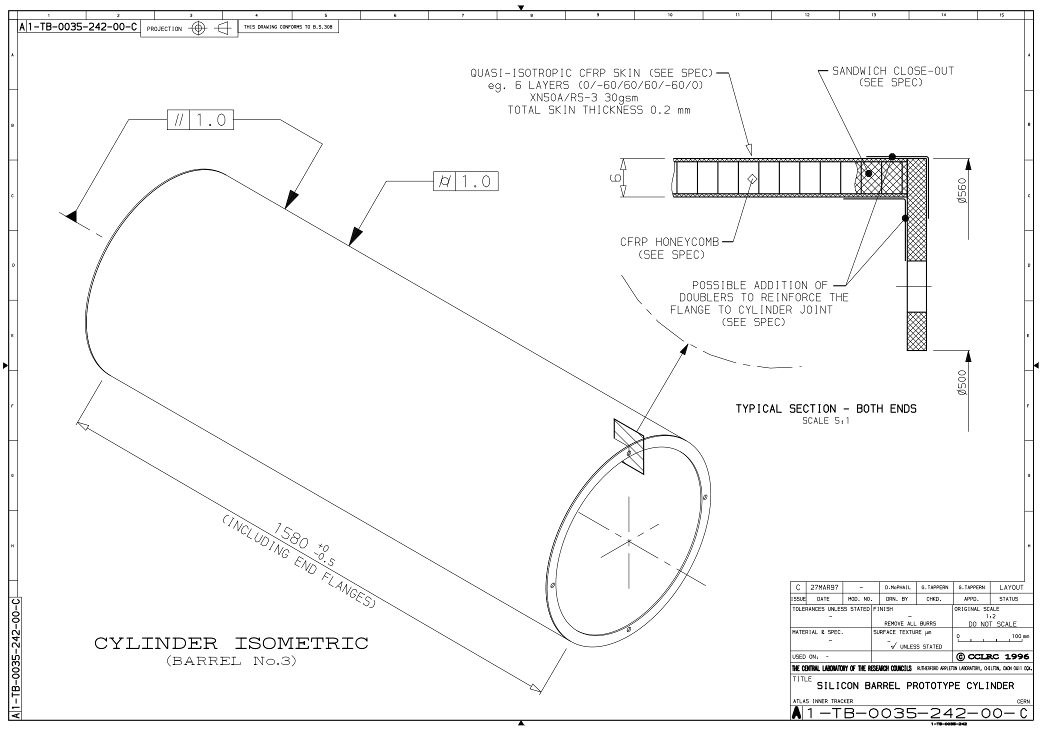


Figure 11-84 Specifications of a barrel prototype cylinder submitted for fabrication.

- A dimensional change of <50 μm/m between assembly (20°C and 20-50% relative humidity) and operating conditions (-10°C, dry nitrogen atmosphere), using a load as above, is required.
- A cylinder stiffness required such that with a load of 280N along the length of the barrel at its highest point, and supported along the length at ±148.5°, the deflection of the horizontal (vertical) directions is less than 1.1 mm and 0.7 mm respectively.

As noted above, the sandwich is fabricated from a carbon fibre/cyanate ester skin with quasi-isotropic lay-ups to ensure the dimensional specifications above. The sandwich has the following properties:

- YLA XN50A/RS-3C carbon fibre skin material [11-84] is fabricated with a pre-preg tape of 30gm/m^2 in a quasi-isotropic layup using YLA RS-4A adhesive [11-84], with an elastic modulus of >100GPa.
- CFRP honeycomb (YLA Ultracor UCF-51-3/8-2.0 [11-85] or Hexcel HFT-G-327-3/8-2.0V) [11-86] of shear modulus of >22MPa, which is heat formed before use, will be used.
- An area weight of <1.2 kg/m^2 is required.
- End flanges are integrated at both ends of the cylinder.

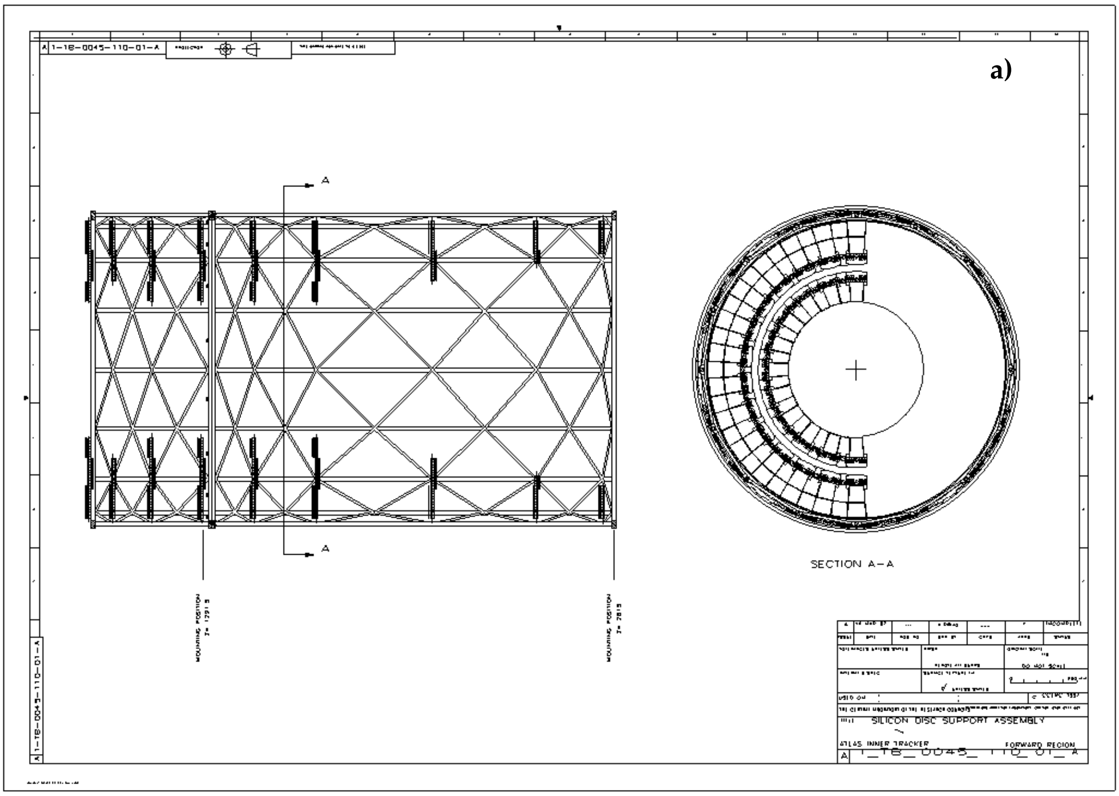
The barrel structure will also serve as an electrical shield. Finite element analysis studies of the barrel stability are described in Section 11.8.7.

11.8.5.2 Forward disks

As described in Section 11.2, the forward modules are mounted on to disks in three distinct rings. Depending on the location of a disk there may be one, two or three rings. There are 52 modules in the outer ring and 40 modules in the middle and inner rings. Figure 11-85a) and Figure 11-85b) show the modules attached to their support frame, and partially populated disks viewed from the front, back and side. For clarity only a few modules are shown. For geometrical and access reasons modules are mounted on both sides of the disk. The outer and inner modules are mounted on the upstream side whilst the middle ring is on the downstream side. This layout minimises the extent of the barrel-forward crack and is maintained for all disks.

The wheel consists of the carbon fibre disk, the cooling and module mounting components, the electro-optical services, the alignment components and the wheel-to-spaceframe mounting points. This construction allows a wheel to be built up from its component parts and thoroughly tested before the mounting of the detector modules is undertaken. Following the mounting of the silicon detectors the completed wheel can then by tested as a system at the construction site. The carbon fibre disk is fabricated as a sandwich of two 0.2 mm thick skins separated by a carbon fibre honeycomb core, as described for the barrel.

The cooling design of the forward disks allows the rigid attachment of modules to cooling blocks that are themselves rigidly attached to the carbon fibre disk. This design requires that the thermally induced differential contraction between the carbon fibre disk and the aluminium cooling pipe is possible between successive mounting points. The cooling circuits for the upstream side of the wheel link together all the modules for both the outer and the inner rings and each cover one octant of the disk. The middle ring, mounted on the downstream side has four circuits.



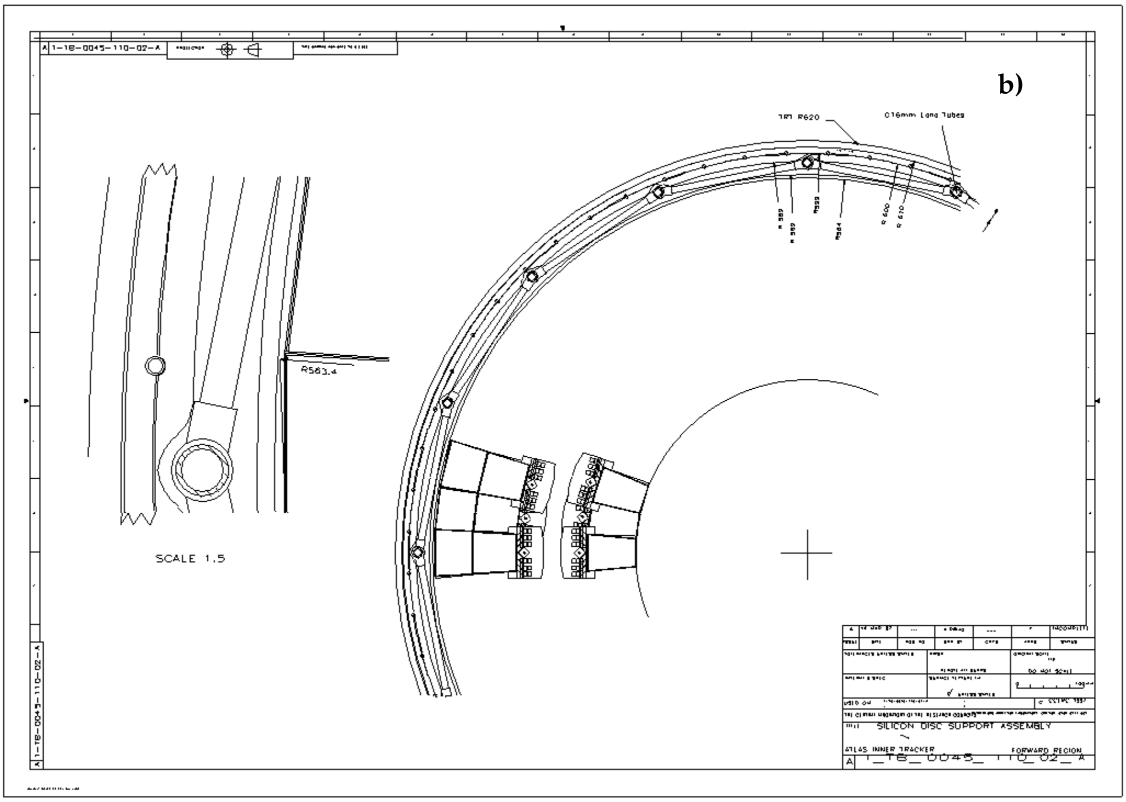


Figure 11-85 Views of the forward disks mounted on the space-frame support, and a detailed view of modules mounted on the disks looking from the beam crossing.

Finite element analysis studies of the induced stresses taken by the carbon fibre disk in such a scheme are shown in Section 11.8.7.

The modules are attached to the cooling structure and the carbon fibre disk via small mounting blocks, shown in Figure 11-86. Two types of block (high and low) accommodate the different z-offsets from the wheel necessitated by the overlapping nature of the modules. The module mounting blocks also serve as local cooling for the opto-electronic interface board.

The cooling blocks are attached to pre-formed cooling rings to an accuracy of 0.2 mm and are then located via an insert positioned to an accuracy of 0.1 mm mounted in the carbon fibre disk. The module mounting hole is then accurately machined into the top of the cooling contact area. The power tapes and fibre-optics run from the periphery of the wheel to a point close to each module, and opto-electronic interface board is mounted close to the module. The power lines and opto-electronic interface lines are terminated by a connector close to the location of a corresponding connector mounted on the read-out hybrid. The connection to the module is made by a small jumper cable.

Six FSI alignment cubes are mounted on each disk. Three cubes are mounted at radius 25.0cm, and the remaining three at radius 50.0 cm.

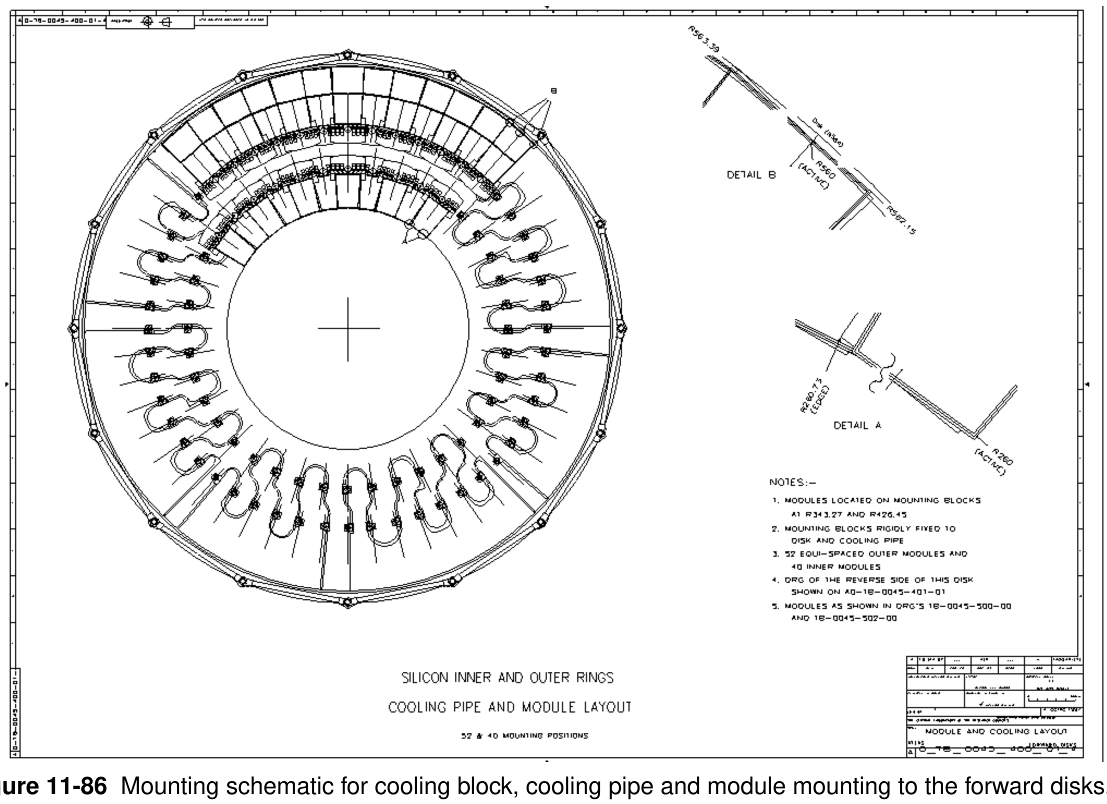


Figure 11-86 Mounting schematic for cooling block, cooling pipe and module mounting to the forward disks.

11.8.6 Overall Supports

11.8.6.1 The forward space frame concept

The layout of the SCT requires that the tracking in the forward direction should be accomplished using planes of detectors supported on annular discs (Section 11.8.3). Nine discs are arranged on each side of the central barrel. The disks require an external support to provide the necessary stability and minimum deformation under load and thermal cycling. The support must have low X_0 and cannot be suspended from the TRT as it is insufficiently strong. Therefore the disks are suspended in the space frame directly from the rails on the inside wall of the cryostat. A space frame affords good accessibility and service distribution to the disks.

The overall support structure must conform to the stability and accuracy requirements described in Section 11.8.2**.**

11.8.6.2 The design of the forward structure

The design of the support structure is shown in Figure 11-87. The spacing between the adjacent disks in z varies from about 0.1m to approximately 0.4 m. This effectively defines the modularity required when the constraints of access are taken into account. The disks at small |z| are the most closely spaced and the wheel at |z| = 83 mm is mounted on the front of the first section in order to minimise the gap between the end of the barrel detectors and the first wheel.

Each section consists of two carbon fibre rings spaced with carbon fibre struts to form a cylindrical section and further strengthened with cross struts. The struts are CFRP tubes. The rings at the end of each section will be a carbon fibre honeycomb with carbon fibre unidirectional skins

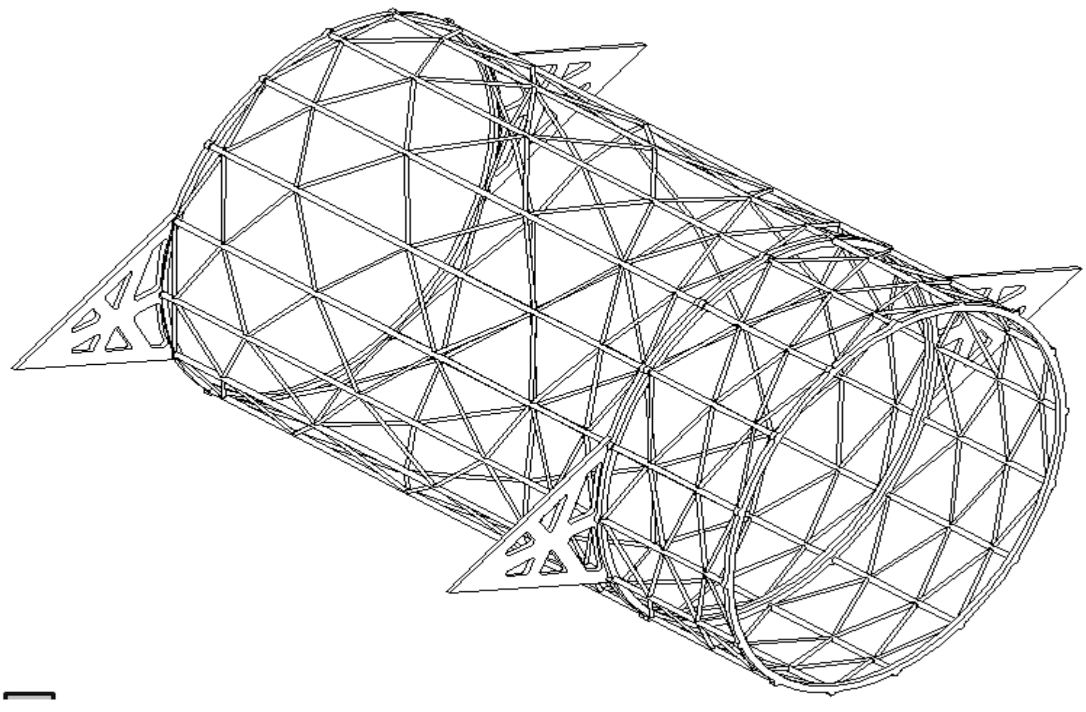


Figure 11-87 Overall Support Structure.

in a balanced layup. The honeycomb will have a radial width of 15 mm and a thickness of 20mm in the z direction. The longitudinal struts have a cylindrical form of diameter 15 mm and the diagonal struts have a diameter of 8 mm, both with a wall thickness of 1.5 mm. The coefficients of thermal expansion of the two types of tubes will be chosen to produce a thermally stable structure. The whole structure is suspended from the cryostat rails by means of the 4 brackets shown in Figure 11-87**.** The main support brackets for the space frame are also constructed from CFRP structures. The main support is 70 mm deep and 20 mm wide with a wall thickness of 3mm, while the diagonal support is 45 mm deep and 20 mm wide with a 2 mm thick wall. The disks are secured to the frame with a 3-point mounting. This is required to help to distribute the load (> 10kg) of each disk on the space frame. A critical part of the design is the kinematic interconnection of the separate sections. This design is still under development.

11.8.6.3 Barrel interlinks

The barrels will have a flange at each end. The interlinking plates, one at each end of the barrels, will be connected to the barrel-flanges at eight positions at each end of the barrels. The services will also go through the disks and for that reason there are holes of radius ~15 mm, (with stiffening collars, also in CFRP) in the position of each local support. The services are supported at the stiffening collars with a clamping arrangement. The interlinking disks have holes close to the outer radius in the median plane for connections to TRT, and close to the inner radius to hang the pixels inside the barrel.

The plates will, like the barrels, be made in CFRP as a sandwich with 0.4mm quasi-isotropic skins, with a 10 mm thick honeycomb-core in the same material. The chosen material is XN50A/RS-3, in order to achieve a CTE of < 0.5 ppm/°C and low moisture absorption. The maximum deformation of the wheel will be less than 5 μm, with all barrels connected and fully equipped with detectors and services.

11.8.7 Expected Performance

The design of the mechanical components is driven by FEA calculations. In this section only the gross mechanical performance is considered. The key issues relate to the deformations that the structures undergo when loaded and their thermal performance. The structures considered in this section are largely built from zero-cte carbon fibre materials, so the principle effect of temperature variations on these components is via any resulting forces.

11.8.7.1 Barrel deformations

A few key parameters have been used to check and motivate the detailed design. These parameters are representative of the stiffness of the structure. A sag in the barrel region translates into r motion at the top and bottom of the barrel and into r-ϕ motion elsewhere. Sag also results in a coupling between ϕ and z. Both effects are undesirable. Figure 11-88 shows the expected deformation for a single barrel fully loaded with modules and supported via a three point kinematic mount The vertical scale is exaggerated and the largest deformation is approximately 15 μm. Figure 11-89 shows the barrel deformation after interlinking. The worst-case deformation is reduced to ~2 μm. Figure 11-90 shows the end plate deformation.

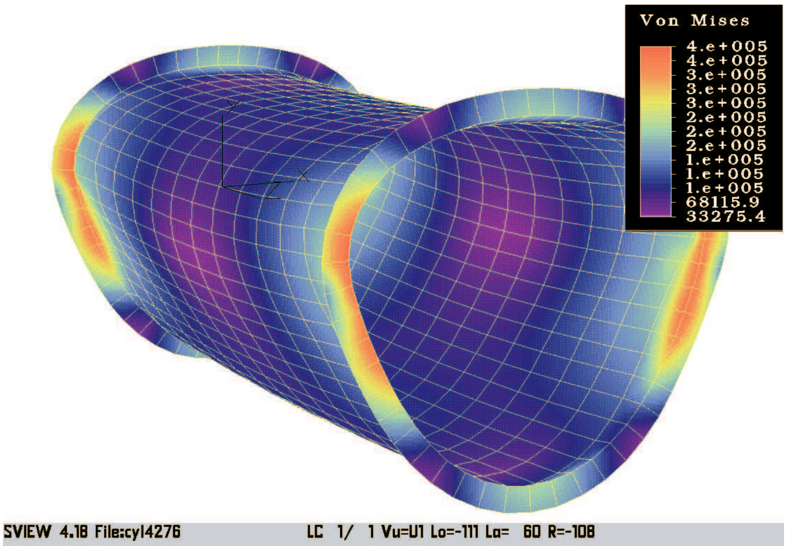


Figure 11-88 Single barrel deformation. The maximum deformation is approximately 15 µm

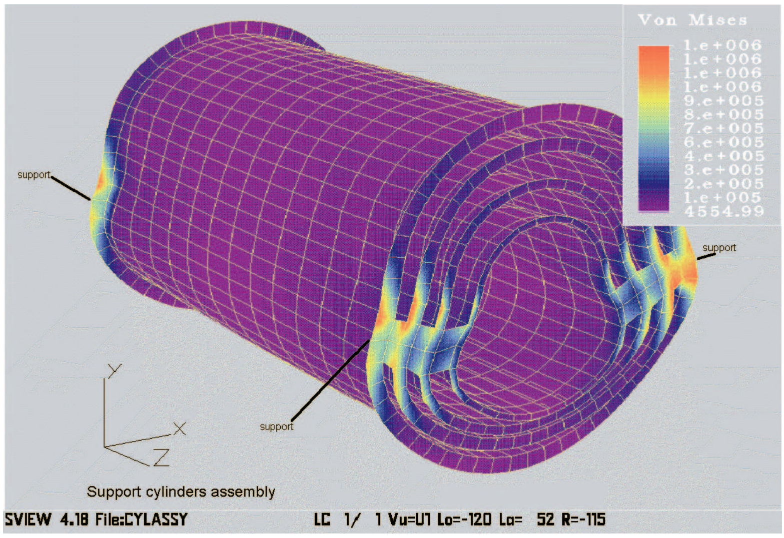


Figure 11-89 Interlinked barrel deformations. The maximum deformation shown is ~ 2µm.

11.8.7.2 Forward disk distortions

Figure 11-91 shows the result of FEA analyses on the forward space frames, with the load from fully equipped disks, but excluding the stresses induced by external service runs. Figure 11-98 shows the movement in y (vertical) and z (along the beam line directed away from the interaction region) of the actual disks. Vertical movements vary from -56 µm, to -172 µm near the beam line. The movement in z is about the median plane, reaching 61 µm at positive y, and -33 µm at negative y.

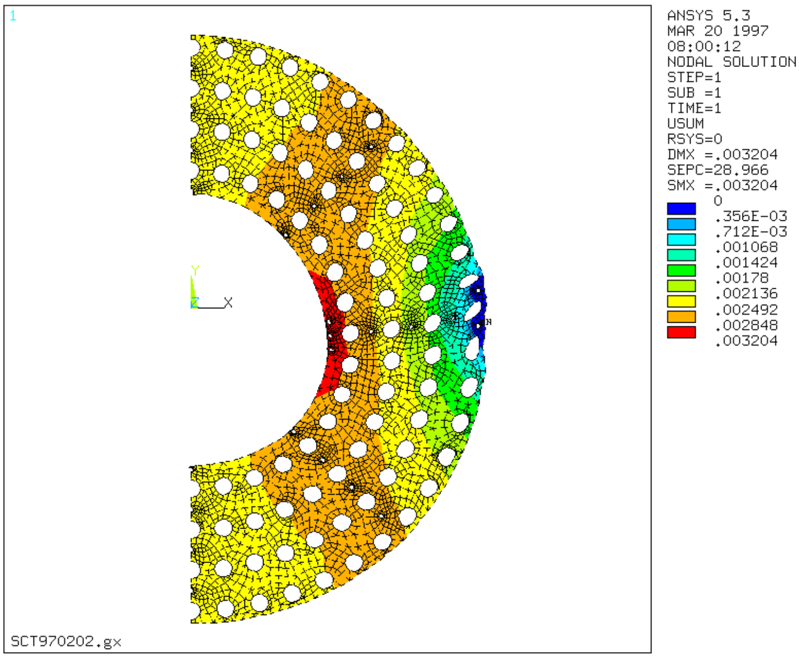


Figure 11-90 End Plate Deformation.

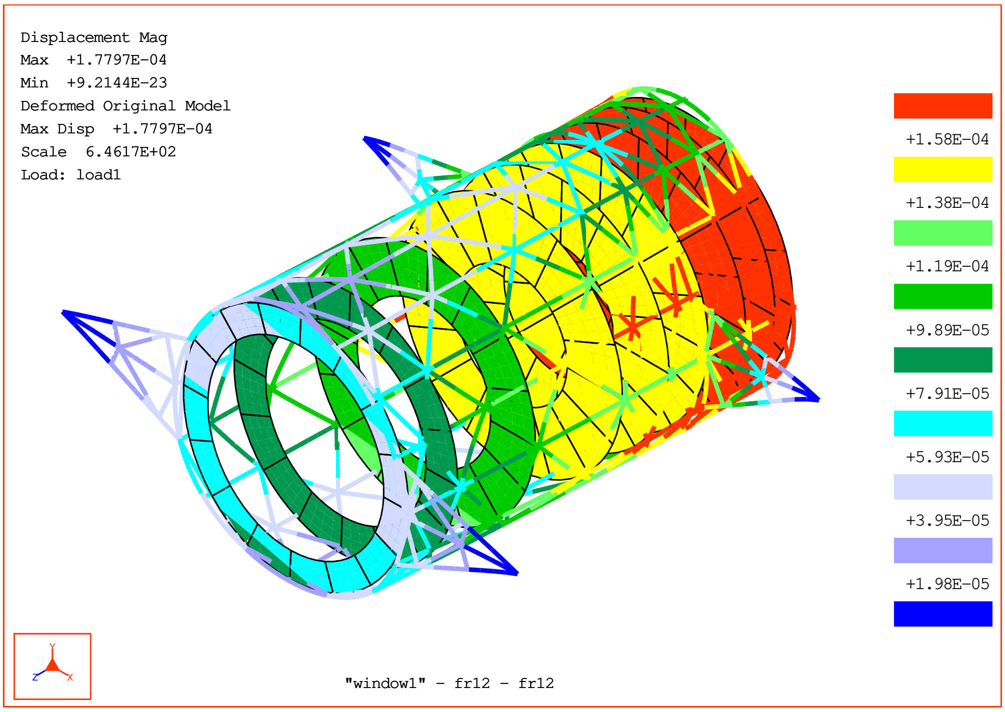


Figure 11-91 FEA calculations of the deformation of the disk and space frame structure after loading with modules, disks and cooling services. The effect of service runs is not included. A maximum deformation of 180µm is expected, in the barrels close to the interaction region.

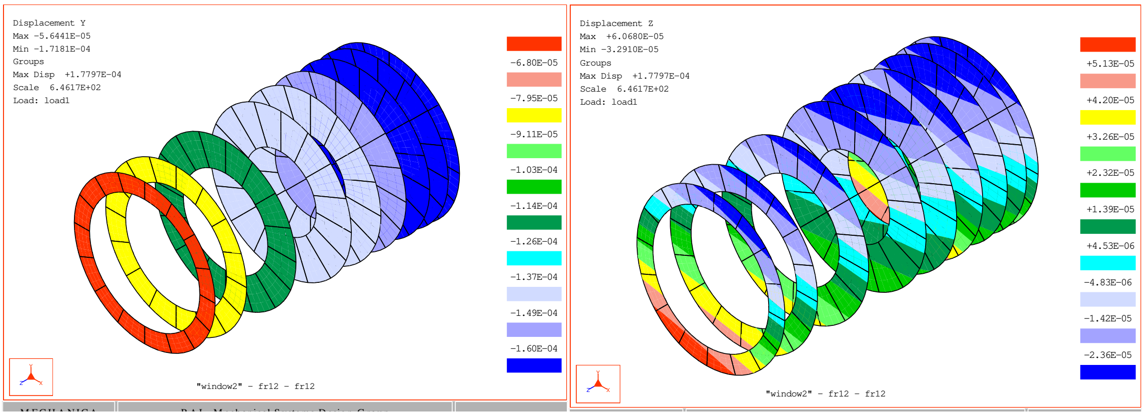


Figure 11-92 FEA calculations of the disk movements in the vertical direction (a), and along the beam line (b). Disk movements in the horizontal (x) direction are < 1µm.

11.8.8 Prototype Results

11.8.8.1 Barrel mechanics

The details of the barrel design have resulted from FEA studies using known material properties, and prototype studies. A number of facing and resin materials have been studied, and as already noted, UHM fibres with cyanate ester matrix [11-84] - [11-86] have been chosen on the basis of these studies (CFRP). This material has approximately zero CTE in the laminate plane, shows almost no humidity effect, and is stable with respect to load. It was intended to use NOMEX [11-87] as the sandwich core, because of its low cost and high torsional stability. Nearly all prototype results were obtained using this core. More recently, because of a small CTE mismatch with the UHM fibre, carbon fibre honeycomb has been chosen, at the expense of cost. Consequently, the quoted experimental studies represent the worst-case scenario.

Table 11-34 Material Properties.

	Elastic modulus E (N/mm^2)	Density (gm/cm^3)	CTE (ppm/K)	Radiation Length X0 (cm)	Relative specific stiffness (E'/ρ')
Beryllium	$2.9\ 10^5$	1.85	11.6	35.4	6.0
Quasi-isotropic C-fibre/Epoxy UHM	$9.6\ 10^4$	1.76	0.2	25	7.8

Table 11-34 shows the properties of several facing and sandwich materials studied, compared with the benchmark of beryllium. Small test cuts have been fabricated by industry, with the aim of reducing the mass per unit area of the sandwich by the use of different fibre lay-ups and less adhesive between skins and honeycomb. These were subjected to test:

- The CTE of a 70 cm-long panel with quasi-isotropic RS3/XN50A facing over a NOMEX core was measured at ~0.5 ppm/m/°C. The panel, used as a support plate for thermal and mechanical tests of silicon modules, was measured using an electronic speckle interferometer. It was heated by halogen projector and the temperature distribution of the plate was measured using an infra-red scanner. The total in-plane distortion of the plate, following a homogeneous temperature change of 7º C, was 2.5 μm, corresponding to a CTE of a= 0.5±0.2 ±0.1 ppm/m/°C. This was attributed to the non-zero CTE of the core.

- On several sandwich plates using different materials, four point bending tests (see Figure 11-93) were carried out to ASTM specification C393, to determine the flexural properties. Data were in good agreement with calculations from an FEA simulation. These measurements give confidence in the specifications of a prototype barrel (see Figure 11-94)
- To within a measurement accuracy of <10 μm, a sandwich panel of the same material, 300x120 mm^2, was unaffected by humidity cycling between 55% to 0%; controlled moisture absorption measurements on several plates according to ASTM specification C272 gave (with open sandwich) the results of Table 11-35.

Table 11-35 Typical dimension changes due to humidity on a sandwich sample.

Core	Skin	Dimensional change in μm over 70 mm length
Rohacell 31	EP104 2 ply 0/90	25
Nomex 3.2-48	UHM 3501 4 ply	5
Hexcel HFTG	EP104 2 ply 0/90	15
Hexcel HFTG	UHM 3501 4 ply	5
Hexcel HFTG	YLA RS-3 XN-70A	<4

After humidity cycling, the 300 x 120 mm^2 plate was measured for creep, after loading in excess of tracker expectations over a 1 year period; as shown in Figure 11-95, no creep was measured to within the previously quoted 10 μm precision.

The order of a prototype cylinder satisfying ATLAS specifications is imminent. Details are given in Section 11.8.5. A series of distortion measurements are planned for this barrel, using the EPSI technique, as a function of load and environmental conditions (temperature, humidity). The barrel will then be used to prototype the mounting, cooling and cable fixtures.

11.8.8.2 Barrel module attachment

To mount detector modules on the support, the detector modules are first assembled on a local support which is a rigid zero CTE structure. The prototype tests described below are relevant to this and the other options that were considered.

- Precision attachment points are required to attach modules to a precision of ~10μm, while maintaining some longitudinal freedom of movement. This has been demonstrated by the use of moulded (for prototype purposes aluminium was used) inserts fabricated by numerical tooling.
- Post-fabrication machining to the required ATLAS specifications has been ascertained experimentally.

Several design studies have been completed and prototypes made to mount silicon modules to local supports with high precision and subsequently to cool them.The aluminium cooling pipes (again with longitudinal movement freedom) are mounted on the cylinder. Modules attached to

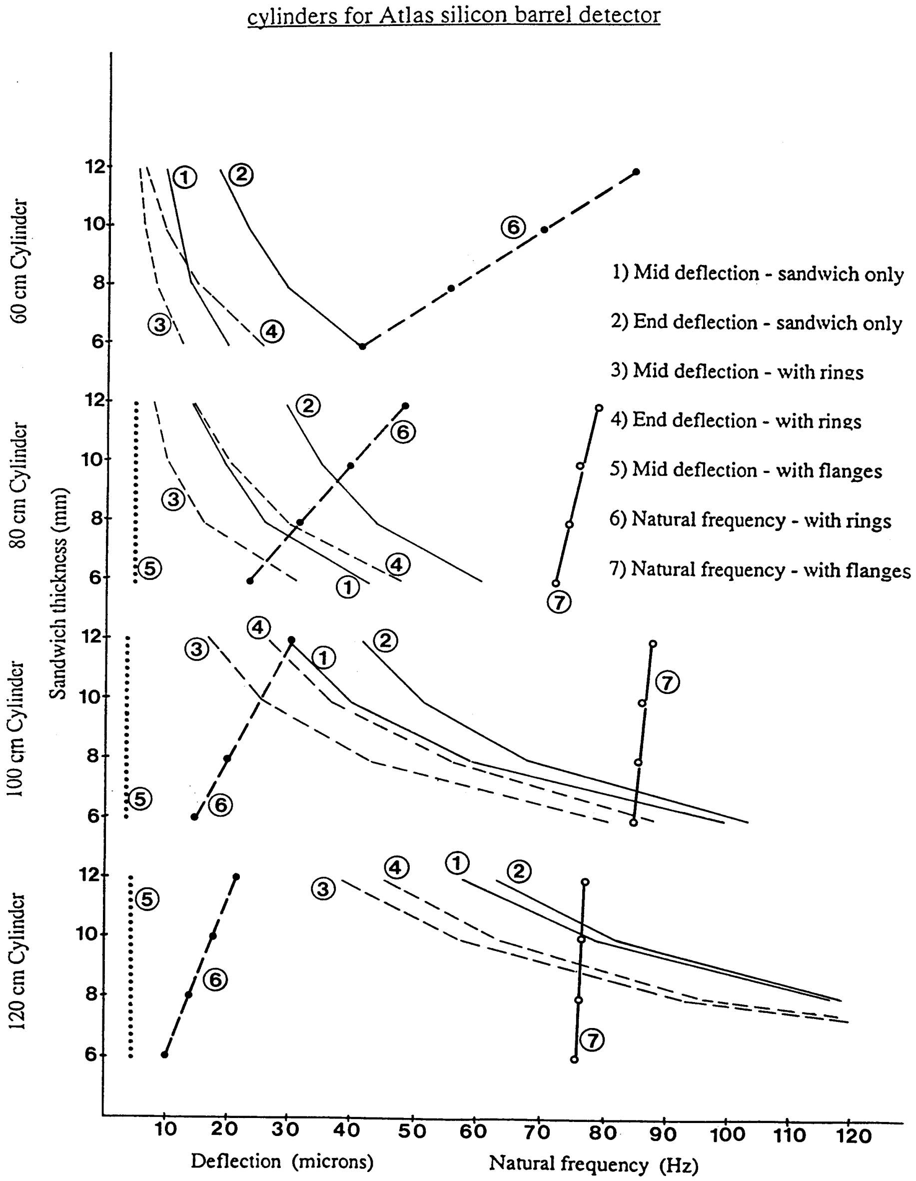


Figure 11-93 Deflection and natural frequency, for some composite cylinders of the ATLAS silicon barrel detector, assuming XN50A/RS-3 skin and Nomex ECA3.2/48 core, and flanges of CFRP.

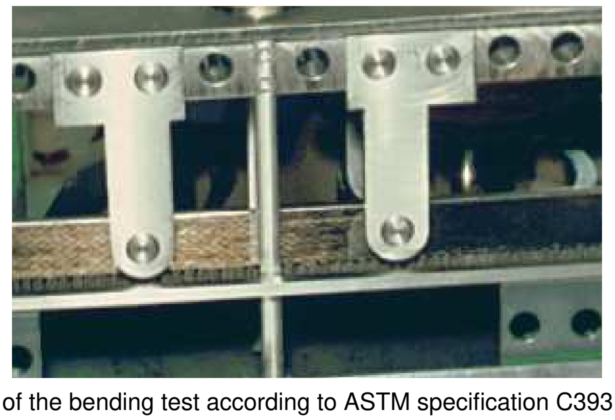


Figure 11-94 Photograph of the bending test according to ASTM specification C393.

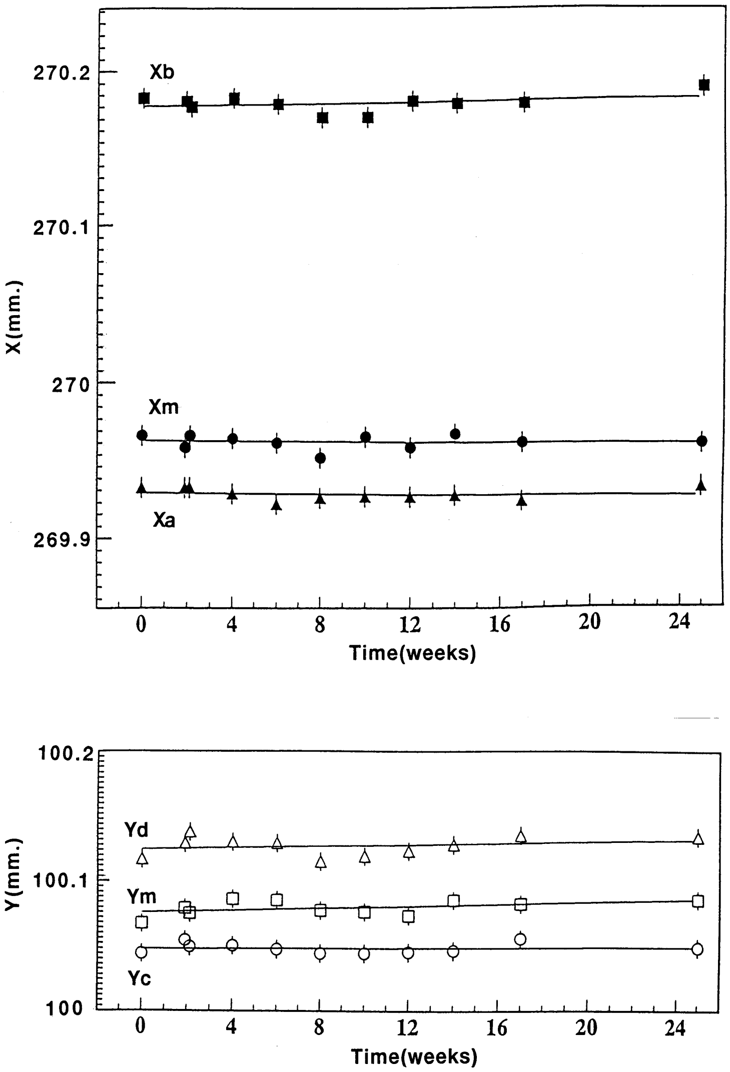


Figure 11-95 Measurements of dimensional stability between 3 fiducial points in each of the x -and y- directions, for a rectangular slab of CFRP sandwich placed in a dry nitrogen environment.

the local support must then be placed in thermal contact with the cooling tubes. As described in Section 4.8.5, an accurate mounting for the baseline module design is possible.

Work on the optimisation of the heat path from modules to coolant has resulted in the concept of a thin aluminium oval cooling pipe, offering a large flat area of heat transfer with the module and a low temperature gradient in the coolant itself. Using the prototype ATLAS Z-module as a working model with 8.75 x 1.5mm^2 Al coolant pipes, design and prototype studies have been made of the mechanical and thermal contact of the cooling pipe with the module. Figure 11-96 shows pipes attached kinematically to precision mounting points. Heat spreader plates provide a significant heat contact between the hybrid and pipe. Modules are screwed to the precision attachment points shown, and contact is assured with light pressure and a thin layer of thermal grease between the pipe and thermal plate.

A test program was carried out using a full length barrel segment (see Figure 11-97) [11-89]. The thermal model consists of a flat carbon fibre plate with NOMEX core, the full cooling pipe work, and Z-module thermal and mechanical prototypes. A total of 13 thermal Z-modules, with alu-

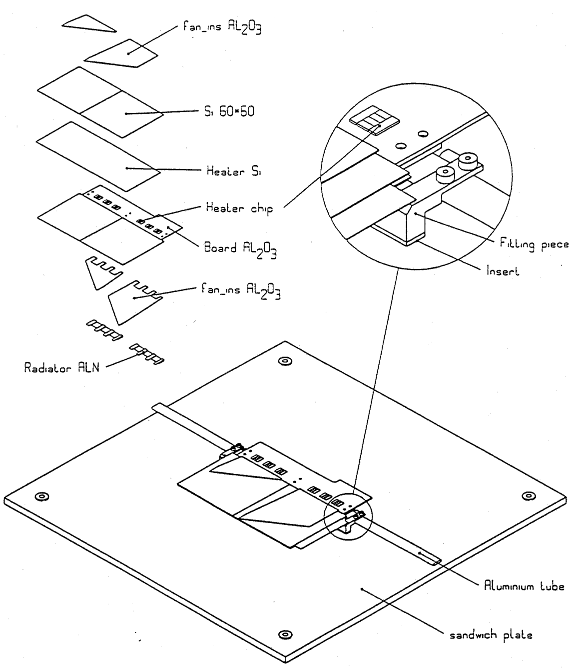


Figure 11-96 Prototype showing cooling pipe and modules on a support.

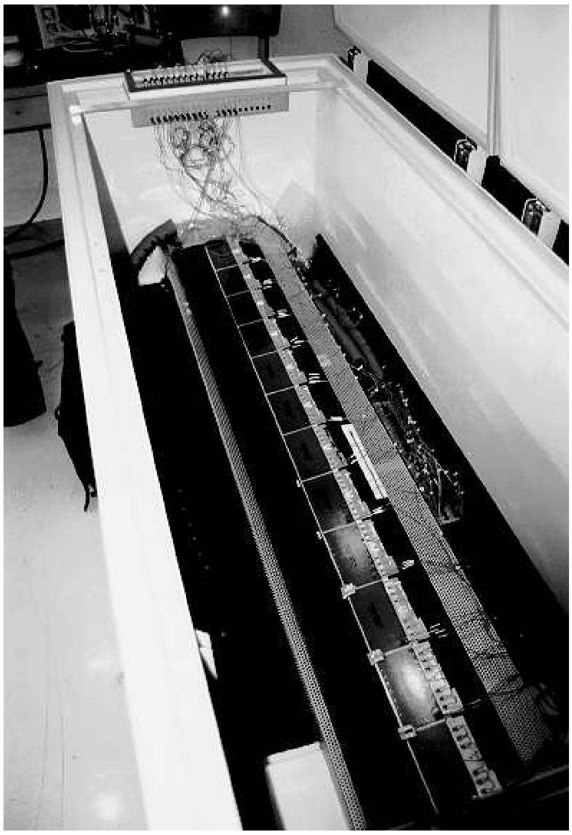


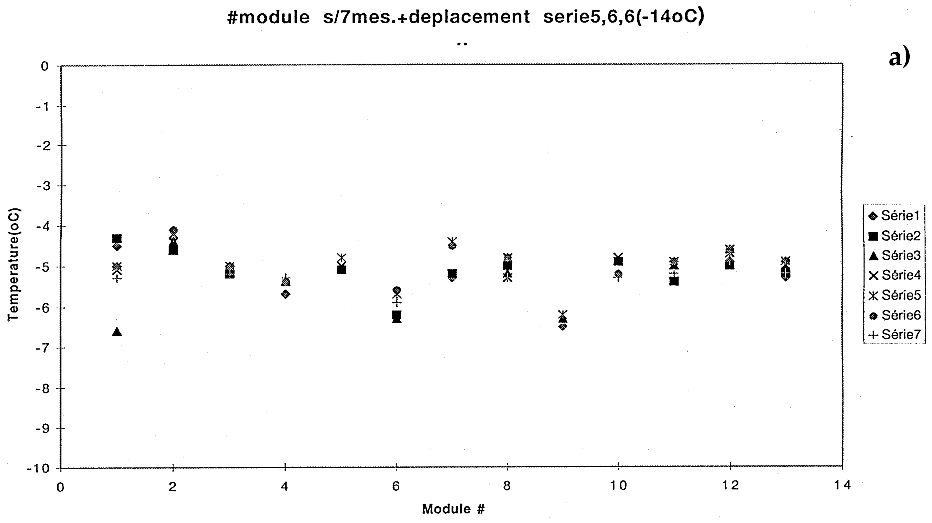
Figure 11-97 Photograph of the full length prototype.

minium plates tuned in thickness to simulate the thermal properties of silicon were constructed and mounted on the base plate. Each module was fitted with a heating resistor to simulate the silicon power dissipation, and a temperature sensor. A second smaller model was used to study the heat transfer for thermal models of other module types, for example Z-type thermal modules using silicon wafers and either ceramic or aluminium nitride thermal hybrids, and a thermal r-ϕ module. These modules were each fitted with several temperature sensors. The cooling contact and its reproducibility were demonstrated using both the full-length prototype, and the individual modules.

Data for the cooling reproducibility of the full length module are shown in Figure 11-98. The reproducibility was tested 3 times, removing the modules and replacing the ~50 μm grease joint each time. In some cases the module was replaced at a different position. Module-to-module variations of up to 1°C were recorded; these were module-associated, since the temperature variation of repeated runs for a given module was <0.4°C. The input coolant was -10°C, with one run at -14°C. This result demonstrates the mechanical feasibility of module and detector cooling.

A thermal model of the centre-tap module was also constructed, based on a TPG high conductivity plate [11-88],[11-89]. Between the average fluid temperature, and the hottest point on the TPG module, there is only a 5.4°C temperature difference, meaning that the full detector can be maintained within ATLAS operational specifications.

Measurements of the mechanical movements after temperature cycling are at present under way. The main concerns remain the risk of corrosion, and to a lesser extent the long-term reliability of the grease in a high radiation environment. Concerning the latter point, no change in mechanical properties were measured in the grease, following a radiation dose of 6 x 10^{13} protons cm^{-2}. A more extensive test of heat conductivity following a proton irradiation of > 2 x 10^{14} cm^{-2} is being prepared. First results prior to radiation indicated a thermal conductivity of ~0.9 W/mK. The radiation induced corrosion of the aluminium pipe will also be studied this year.



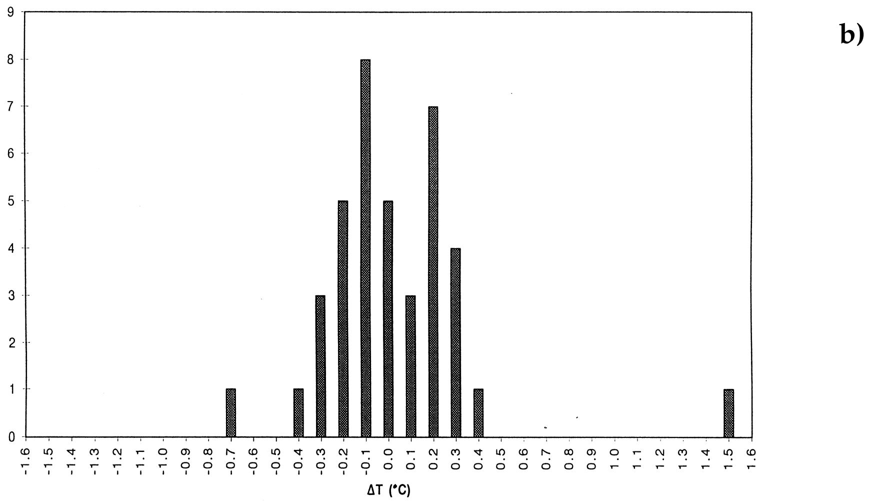


Figure 11-98 Reproducibility of module contact to the cooling tube a) following 3 separate module manipulations (including removal of the module and heat sink followed by replacement, and replacement in different positions on the local support), and b) shown statistically. In b) the data are averaged for each module, and deviations are shown about the mean. Except for 2 values at -0.7°C and 1.5°C caused by poor tube guiding, all points were reproduced to within 0.4°C, with an rms of ~0.2°C.

11.8.9 Component List and Material

11.8.9.1 Barrel support structure

The modules will be supported on local supports, mounted on 4 concentric carbon fibre cylinders each 158 cm long, numbered B3 through B6. Each cylinder will be composed of a 6 mm thick carbon fibre honeycomb with 0.20 mm thick skins on the inner and outer surfaces. The mean radii of the cylinders are 27.5 cm, 34.8cm, 42.2 cm and 49.5 cm respectively. Each cylinder will incorporate 6 rings of local assembly attachment points, and solid carbon fibre end rings. The cylinders will be supported from the barrel TRT.

Table 11-36 Barrel material at normal incidence.

ITEM	X_0 (%)
Carbon Fibre Cylinder	0.265
Local Support	0.110
Local Support Fasteners	0.016
Inserts	0.013
Cooling Blocks	0.023
Cooling Tubes	0.096
Coolant	0.060
Cable Guides and Support	0.020
Fasteners	0.047
Total Support Structure	0.651

11.8.9.2 Forward support structure

The forward modules will be mounted directly onto carbon fibre disks, nine at each end of the barrel structure. The disks will be supported in a carbon fibre space frame, which in turn will be supported at four locations through the forward TRT from the rails mounted on the inside of the coil cryostat.

Table 11-37 Material of barrel end flanges.

R min (cm)	R max (cm)	X_0 (%)
25.5	28.0	0.90
32.3	35.3	0.90
38.7	42.7	0.90
46.0	50.0	0.90

11.8.9.3 Material in barrel support structure

Table 11-36 and Table 11-37 list the barrel components and their associated radiation lengths. The Tables explicitly exclude the silicon modules themselves (see Section 11.5), and the electrical services (see Section 11.4). The radiation lengths given in Table 11-36 are for normal incidence to the cylinder surface, and are smeared over the surface. The components are uniform in η, but are lumped in ϕ, there being respectively 32, 40, 48, and 56 local support structures around barrels 3 through 6. The mean radius of each barrel is listed in Table 11-37, and the components are at 10mm larger radius.

The cooling pipes running along the barrels will be fed from, and feed into manifolds at each end of the barrel. There will be 4 manifolds at each end of each barrel, each feeding or collecting from the cooling tubes for one quarter of the barrel.

The solid carbon fibre flanges of the cylinders are at a $|z|$ position of 780, the ends of the cylinders, and have radial extent as given in Table 11-37. The radiation length given in Table 11-37 is along the axial direction.

The barrels are interconnected and supported from the TRT by interlinking wheels. The radiation length of these, smeared over η, is 0.498%. The interlinking wheels have holes in them to allow passage of the services. These holes will be lined with carbon fibre, 1 mm thick. The material of these linings almost exactly compensates for the material which would have been in the hole.

11.8.9.4 Material in forward support structure

Table 11-38 lists the components and percentage radiation lengths of the forward structures (see Section 11.2.2). The tables explicitly exclude the silicon modules themselves and the electrical services, which are discussed elsewhere. The radiation lengths given in Table 11-38 are for normal incidence to the disk surface, and are smeared over the surface.

Table 11-38 Material in disks assuming normal Incidence (% X_0)

Disk number	1, 3, 4, 5, 6,	2, 7	8	9
Carbon Fibre Disk	0.527	0.527	0.527	0.527
Mounting Block	0.119	0.101	0.133	0.095
Mounting Insert	0.012	0.011	0.014	0.010
Fasteners	0.008	0.007	0.009	0.006
Cooling Pipes	0.137	0.159	0.169	0.095
Coolant	0.095	0.107	0.140	0.100
Total per wheel	0.898	0.912	0.992	0.833

The total radiation length in the radial direction of the two space frame modules is an additional 1.049%. To obtain this number, the material of the space frame including the square section end rings has been smeared over the surface of the cylinder.

The forward space frame will be supported from the rails on the inner surface of the cryostat by four approximately triangular carbon fibre honeycomb lugs described above. Two lugs exist on each side of the space frame at $|z|$ positions of 128.0 cm and 281.5 cm. The base of the triangle of these support pieces will be attached to the space frame, over approximately half the circumference. The apex of the support will mount to the rails. The radiation length of this support will be 0.56% X_0. Since these are very localised in both ϕ and η they have not been smeared.

11.8.10 References

11-83 DC340 Silicone Heat Sink Compound, Dow-Corning Company.

11-84 YLA Inc. advanced composite materials, Bay Vista Court, Benicia, California.

11-85 YLA Cellular Products Company, Sierra Court, Dublin, California.

11-86 Hexcel International, Dublin Blvd., Dublin, California.

11-87 Composite Company, DuPONT Company, Magnolia Run, Wilmington, Delaware.

11-88 TPG97, Advanced Ceramics Corporation, Cleveland, Ohio.

11-89 G. Barbier et al., Status Report on Module Cooling and Mechanics, ATLAS Note ATLAS-INDET-NO-166 (1997).