Inner Tracking System for ALICE: Conceptual Design of Mechanics, Cooling and Alignment

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Abstract

We present here the basic ideas for the design of the support and cooling system for the Inner Tracking System of the ALICE experiment at the LHC. The cooling scheme, which must provide 5 kW heat drain from the elelectronics situated inside the tracking volume and stabilise the temperature field for the Si-drift detectors within 0.1 °C, is the starting point of the design. The choice of candidate materials for the mechanics support and integrated cooling structures is done under the general costraint of the total mass minimization. We discuss here some of the ideas for the precise positional alignement and monitoring, and the alternative options which we are considering for the mechanical layout of the Inner Tracker. We also present some first results of prototype tests and of calculations of the gravitational sagging for the ladders.

1 Introduction

The ALICE collaboration has proposed to build a dedicated detector to exploit the exciting physics opportunities of ultra relativistic Heavy-Ion collisions at the LHC [1, 2]. The eperiment will study hadrons, electrons and photons of P_t up to 10 GeV/c in the central rapidity region, in order to detect the expected formation of a new phase of matter, the Quark-Gluon-Plasma.

The ALICE detector will be composed of a central part, consisting of an inner tracking system, a cylindrical TPC, a particle identification array (TOF or RICH) and a single-arm electromagnetic calorimeter, embedded in a weak solenoidal field, complemented by a Zero Degree Calorimeter and a large acceptance multiplicity detector.

Given the very large multiplicities, tracking will be a formidable task; the Inner Tracking System is supposed to ensure the reconstruction of secondary vertices and of the low-momentum particles, for which it will have to provide also idetification capability via dE/dx. Since for the bulk of the interesting tracks the momentum resolution will be limited essentially by multiple scattering, the minimization of the material thickness is an absolute priority for tracking inside ALICE.

Thus the ITS must satisfy very stringent requirements in terms of the high spatial accuracy, momentum resolution, particle type identification, stability and reliability of operation, meeting at the same time the most contradictory demand of matter minimization in the region of interest.

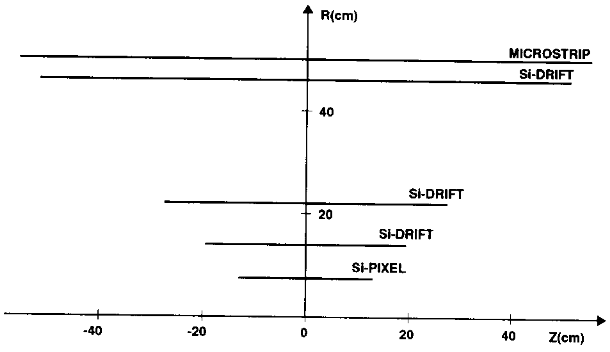

Figure 2.1: Transverse half-section of the Inner Tracking System

2 System Overview

The Inner Tracking System (ITS) will measure charged particles at radii up to 50 cm. Its main purpose is the detection of secondary vertices and the momentum measurement of low-p_t particles, down to a p_t of $\approx$ 20 MeV/c for electrons. It will also improve the momentum resolution at large momenta. In addition, it will perform the identification of the low-momentum particles which do not reach the outer particle identification devices, via dE/dx in the $1/\beta^2$ region.

The system will consist of five cylindrical layers, covering the central rapidity region ($|\eta| \leq 0.9$) for vertices located within the length of the interaction region (2σ), i.e. 10.6 cm along the beam direction (z). A half-section of the system is shown in Fig. 2.1, while the nominal dimensions are summarized in Table 2.1.

Layer	r (cm)	$\pm z$ (cm)	Area (m^2)
(1)	7.5	12.8	0.12
(2)	14	19.3	0.34
(3)	22	27.3	0.75
(4)	46	51.3	2.97
(5)	50	55.3	3.47
Total Area = 7.65 m^2			

Table 2.1: Dimensions for the Inner Tracking System

The criteria which led to the definition of the number and location of layers are the results of the simulated performance and can be found in the Letter of Intent for ALICE [3].

The granularity required for the innermost planes can be achieved only with silicon micropattern detectors with two-dimensional readout, such as Silicon Pixel Detectors (SPDs) and Silicon Drift Detectors (SDDs).

As a baseline design, we consider using SPDs for the innermost plane, the most demanding one in terms of granularity and resolution, and SDDs for the following two. A configuration in which only one of these technologies would be applied might still be considered, if it could be proven to satisfy all the requirements at all radii, and to provide a system which would be simpler to construct and operate.

At larger radii, the requirements in terms of granularity are less stringent, so that for at least one or possibly both planes we foresee the use of a more standard, well-proven and cheaper technique, like double-sided silicon strip detectors [5] or MicroStrip Gas Counters (MSGCs) [6]. The outer layers have large areas, and involve the use of a large number of detectors, so that reliability, ease of operation, and established capability of industrial production become major points in favour of a conservative choice. The MSGCs are cheaper than Si–strips, but have a lower two-track resolution for inclined tracks; also, double-sided silicon microstrips offer the possibility of matching the signals read out from the two sides, to help resolve ambiguities. The final choice will be determined on the basis of simulations using optimized track finding algorithms.

The main parameters of each of the four detector types considered are indicated in Table 2.2: spatial precision, two-track resolution, pixel size, size and number of channels of an individual detector and number of output lines from a detector module.

In Table 2.3 the main parameters of the various layers are summarized, including the number of detecting elements, the number of electronic channels and the dissipated power. The different detector technologies require specific front–ends, and we foresee the unification of electronic standards (type of links, protocols) at the level of optical links, i.e. at the front-end outputs.

3 Materials

As mentioned in the introduction, in the ALICE experiment we are interested mainly in the measurement of low–p_t particles, for which the momentum resolution is dominated by the effects of multiple scattering in the detectors and their support structures. Therefore it is essential that in the design of the ITS only minimal quantities of low - Z , long radiation length materials are used. At the same time those materials must provide the necessary rigidity and mechanical stability of the construction and be radiation hard and thermostabilized. In addition, the coolants must be safe, nonaggresive and satisfy the CERN safety regulations [7].

In accordance to the experience accumulated in

Type	Spatial precision (μm)		Two-track resolution (μm)		Cell size (μm)	Module size (mm)	Channels per module	Output lines
	$r\phi$	z	$r\phi$	z				
Pixel	22	78	150	540	75x270	4.8x69	16384	32
Drift	25	25	500[a]	200[a]	–	57x70	448	448
Si Strip[c]	30[b]	1000	200	7000	100x50000	75x50	2x750	24
MSGC[c]	60	1000	800	12000	200x25000	100x50	2x1000	32

[a] Can be improved with waveform analysis
[b] Can be improved with centroid finding
[c] Layer at $r = 50$ cm

Table 2.2: Parameters of the various detector types

Layer	Type	Detector modules	Electronic channels (k)	Barrel dissipated power (W)	Endplates dissipated power (W)
(1)	Pixel	400	6550	160	
(2)	Drift	96	45	75	430
(3)	Drift	192	90	150	860
(4a)	Drift	765	350	600	3400
(4b)	Si Strip	900	1440	1850	
(5a)	Si Strip	924	1400	1800	
(5b)	MSGC	700	1400	1800	
			$\approx$ 8500 to $\approx$ 9600	$\approx$ 2800 to $\approx$ 4000	$\approx$ 4700

Table 2.3: Physical parameters of layers

various labs in the design and exploitation of vertex detectors [8, 9, 10, 11, 12, 13, 14, 15, 16, 17] the choice of materials that can be used as components of supporting structures, cooling systems, interconnections, etc., is rather limited.

The main parameters of some of the materials that can be applied for the mechanical support and other structures are summarized in Table 3.1.

As can be seen from this table the main candidates can be considered to be Be, BeO and carbon fiber composites.

The use of Be is disfavoured due to the potential health hazards during mechanical processing (although these hazards can be controlled and the protective coating [20] can be used afterwards). In addition, the CTE of Be is rather different from the one of Si, which is a serious disadvantage for a large mechanical structure like the ITS. Therefore we foresee the application of Be only for the central part of the beam pipe and possibly for some micro refrigerators for the heat drain from the front-end electronics.

The BeO is an insulator that has rather high thermoconductivity. Thus it can be used e.g. in some local heat drain devices.

As to the global mechanical structure of the ITS, we foresee the wide implementation of high modulus Carbon Fiber Composites both to the space-frame Si ladders support and to the general support of the Tracker. The use of Carbon Fibers is preferred due to their high mechanical properties and very low CTE that can be matched (if needed) with that of Silicon by using metal additives. Besides, there are quite new materials that possess outstanding properties, like the Super Thermoconductive Graphite fiber THORNEL [18], that has a thermoconductivity 3 times larger than copper. Using such a material one can think about a possible integration of the local heat drain from the front-end electronics and the ladder support structure for Si-strip and MSGC detectors.

Among the materials there is a quite new one which has very interesting properties: the boron carbide foam; it possesses along with high mechanical properties also a CTE that is well matched to that of Si and has the density =0.07 of the solid boron carbide. The radiation length is of the order of 2 m. This material was proposed to be used in a U-form support structures for the CLEO vertex detector [9]. We consider the possibility of implemen-

Material	**Rad** Length cm	**Density** g/cm^3	**CTE** ppm/K	**Elastic** modulus E-GPa	**Thermo-** conductivity W/m/K	**Ref.**
Si	9.37	2.33	2.6-4.2	131	129	[8]
Be	35.43	1.84	11.6	290.0	146.0	[8]
BeO			9		260	[19]
Carbon fiber composites	18	1.9	down to -0.5	>390 (axial)	10-100	[21]
THORNEL graphite K1100X composite		2.15		806 (axial)	1050	[18]
Boron carbide foam	200		5.5			[9]

Table 3.1: Parameters of some materials and substances.

tating such foam (or some other porous materials) for the end-caps.

4 Detector Concept

4.1 Cooling

The design of such a complex detector, involving the use of several different detection techniques, and with very demanding requirements for the temperature stability, the positioning precision and the total material thickness in the sensitive volume, is a task that requires a unified approach.

The cooling scheme ($\approx$ 3–5 kW heat drain in the tracking volume) determines the overall mechanical construction and is in fact a key point to the design of the ITS. Preliminary studies of different cooling schemes (gaseous, liquid, evaporative) have been done [22] for a higher heat load (10 kW) and two options were selected for further development:

– localized, evaporative cooling in a closed system under atmospheric pressure for the Si-drift and Si-strip (or MSGCs) detectors, that is expected to provide uniform temperature fields (within 3–4 °C in the detector volume) and a thermostabilization of the whole ITS of the order of 0.1 °C at ambient temperature. Such an ambient-temperature evaporative cooling scheme, should allow a uniform and stable temperature, with minimal stresses at turn-on and switch-off.

– uniform gas cooling of the first layer of pixel detectors with reasonable air flow.

We will only give here a brief outline of these systems, which are described in detail elsewhere [23].

Evaporative cooling system.

The temperature stability required by the Si-drift detectors (of the order of 0.1°C) is one of the major reasons for the evaporative cooling choice. In addition, it was shown [22] that the use of one of ozon-safe freons as a coolant can optimize the total amount of material compared to the other liquid cooling options. Each of the possible cooling freons has its own temperature vs. pressure working field; in particular C3F7I is suitable ambient temperatures under 1 bar pressure in the system (the boiling temperature is 25-20 °C). Freon C4F10 can be used under 1 bar for temperatures from -2 to +5°C, C4F8 from -10 to 0°C and C3F8 for -30 to -25°C.

The minimum total amount of condensed coolant in the volume of the ITS can be estimated roughly from the total waste of coolant fluid (0.1 kg/s) to be 0.5-1.0 kg. These values were obtained for saturated vapor pressure 1 bar and a total heat drain of 10 kW.

Cooling of the first layer.

In the first layer of sensitive Si-surface, composed of pixel detectors overlayed with the readout electronics, the heat will be produced uniformly with a density of 0.13 - 0.17 W/cm^2. Keeping in mind that the working temperature gradients for pixels are limited only by the requirements of alignement and mechanical stability, we consider gas cooling of this layer possible. The cylinder gap (1.5 cm) between the first layer and the beam pipe can be used as a natural channel for the gas flow

To simplify the system and minimize the material, we would make it an open one; the gas trans-

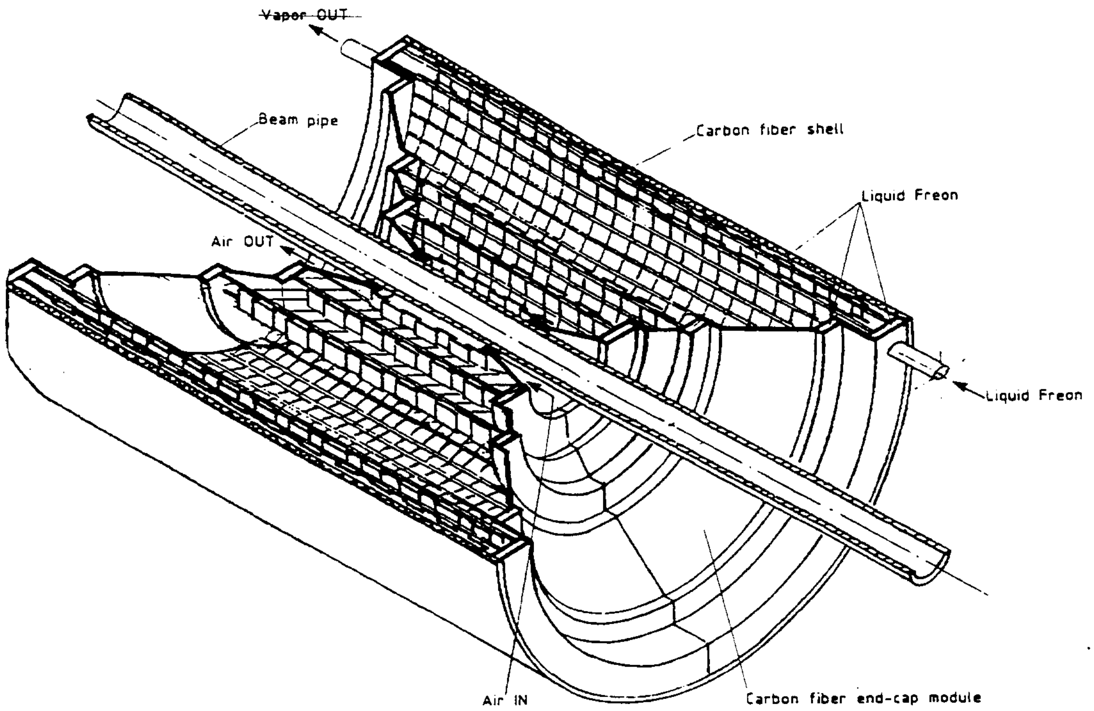

Figure 4.1: General view of one half of the Inner Tracking System

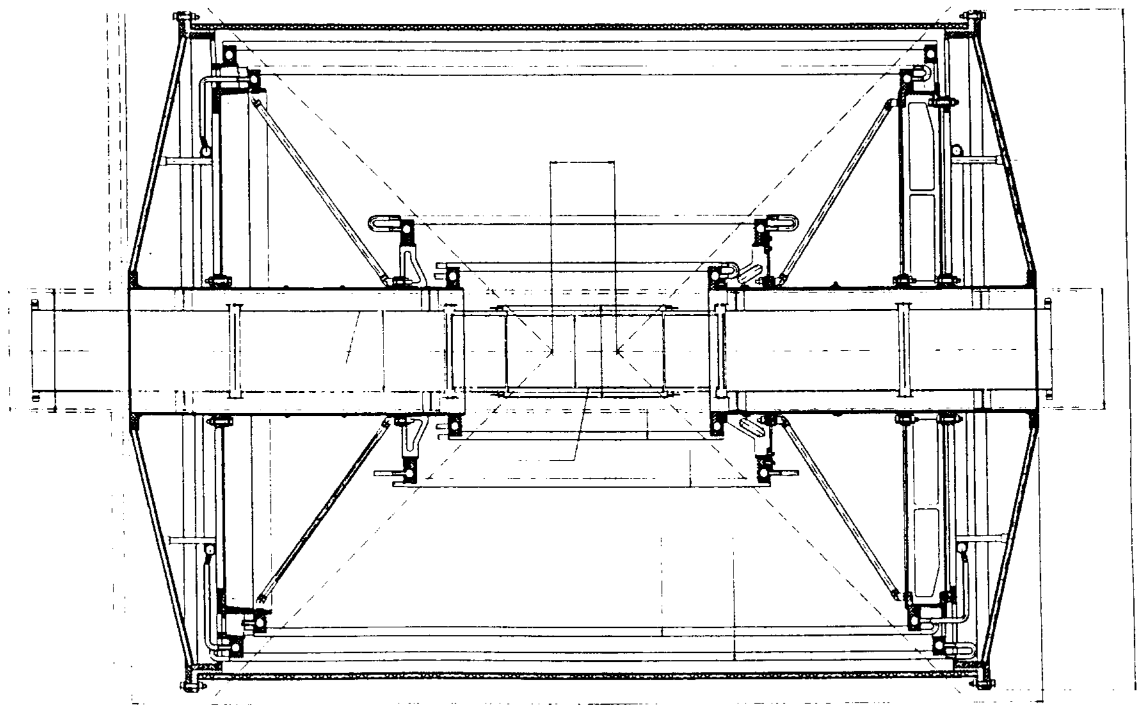

Figure 4.2: General setup of the mechanical support of the ITS. Side view. The independent 1st (pixel) layer is situated directly on the central part of the beam pipe

port may be done under fairly high pressure, i.e 1.5-2 bar, to diminish the volume of gas wastes.

4.2 General Layout

The general layout of the ITS is shown in Fig. 4.1. To ensure a flexible system, we are developing a structure which is mechanically independent from the outer detectors, and can be preassembled and measured accurately before final installation in the experiment.

The general idea is to remove the material of supporting and cooling structures from the central region to the end-caps and to the outer layer to the maximal extent. To this purpose, we are studying a support structure in which the material is concentrated in the conical endplates, covering a minimum solid angle, and the detectors are organized in ladders, parallel to the beam direction and held by linear structures (ribs) that are possibly also used as flow channels for the cooling fluid and possibly as substrate for power distribution. With this design, we plan to keep the total average thickness, including detectors, below 0.6% of X_0 per layer.

The mechanical design for the ITS is not finalised yet and at this stage we are studying three possible options, which arise mainly from different assembly schemes for the ITS:

- rigid end-caps (integrating support, cables to the outer world, connectors, coolant collector) and outer honeycomb carbon fiber cylinder that form a space structure to support Si ladders;
- clamshell design;
- five relatively independent cylinder detectors supported by the cone end-caps and the outer honeycomb carbon fiber cylinder.

The last option is represented in Fig. 4.2 and in Fig. 4.3

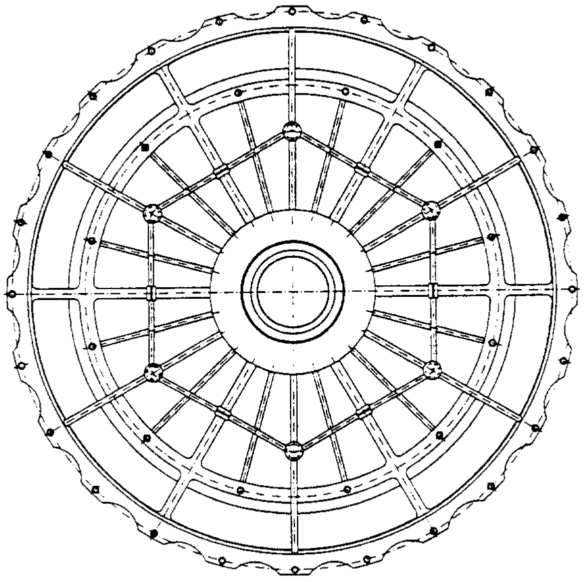

Figure 4.3: General setup of the mechanical support of the ITS. End-cap view.

4.3 The integrated unit for support, cooling, power bus and data bus

The 1st ladder design

The 1st option of the basic linear supporting structure, which must be thermostabilized by the integrated cooling channels, is represented in Fig. 4.4. It is formed by a carbon fiber semicylinder shell (diameter 5 mm,thickness 0.5 mm), which houses the Be (or 100 μm wall Al) pipe of 3 mm in diameter that serve as cooling channel and as a power (or ground) bus.

The thermoconductive Be (or Al) cooling channel is expected to provide a uniform temperature along the line, avoiding the formation of hot spots. The multichannel data bus cables (Be or Al on kap-

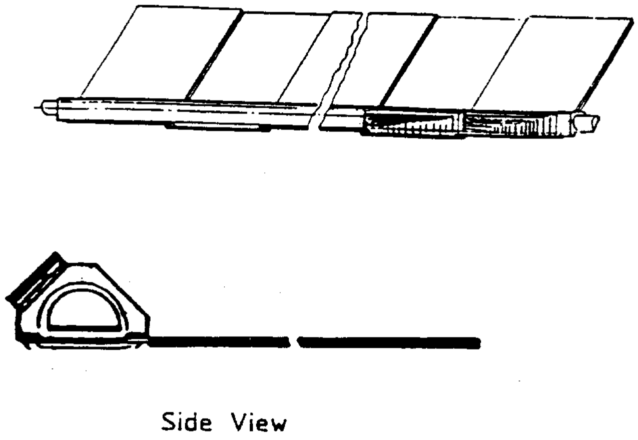

Figure 4.4: Scheme of the ladder, integrated cooling, power and data bus

ton) are embedded into the body of the carbon-fibre support structure.

The cooling channel contains the mixture of gas/vapor and condensed liquid. The amount of the condensed liquid is controlled by the pressure of saturated vapor in the channel and can be kept very low (1-2 mm thick).

The first 0.5 m prototype of the long ladder support was manufactured according to the described geometry, see Fig. 4.5. We got 400 μm wall thickness using three layers of the carbon fiber and a cold process. In fact during mass production one can expect the reduction down to 200 μm.

The first prototype tests were done with 1 meter heat drain prototype of the ladder based on the freon cooling artery of 3 mm in diameter. There were 20 localised heaters that simulated the local heat drain from the front-end electronics. Tests have confirmed our calculations on the evaporative freon cooling up to 25 W power per one ladder providing temperature gradient along the ladder within 0.8 °C.

Calculations of the Gravitational Sagging

The maximal sagging of the uniformely loaded long bar can be evaluated from the formula:

$$f = k\frac{ql^4}{EJ} \tag{4.1}$$

where k is a coefficient that depends on whether the ends of the bar are fixed or free.

We consider here the case in which both ends of the bar are fixed (k=0.0026);

The other parameters in the formula are:

l - the length ($l=1.1 \cdot 10^3$ mm)

q - a uniformly distributed load

E - the module of elasticity of the bar in the direction of its axis

J - the moment of inertia of the transverse cross section of the bar.

The cross–section of the bar is a semicircle with inner diameter d ad outer diameter D. We consider here a bar with D=5.5 mm and d=5mm, with a 0.5 mm wall, made of high modulus carbon fiber composite (E=20000 Kg/mm^2). Our calculations for a 1.1 meter length supporting structure loaded by the Si, the coolant (35 g in this calculation) and its own weight and in the most unfavorable ladder position ("flat horizontal"), give a gravitational sagging of 6.6mm (not including the silicon rigidity), which we consider excessive.

Since the sagging of the rib grows as the fourth power of the length, in the initial stage of the design we foresaw for the outer layers two intermediate annular ladder supporting membranes, made of thin carbon-fibre foil. The same structure supported by a membrane at every 30 cm will provide approximately 40 μm of sagging that already can be considered tolerable.

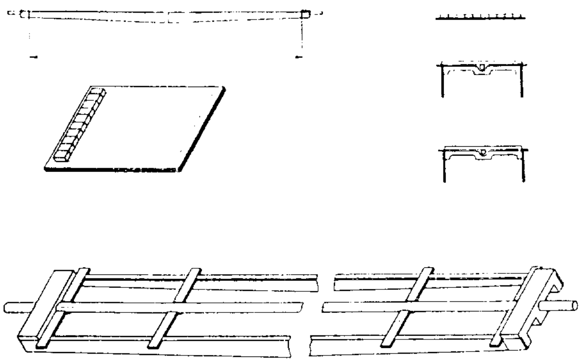

Figure 4.6: Design of the 1.1 m length carbon fiber ladder with the integrated central cooling artery and perpendicular super thermoconductive heat drain bars

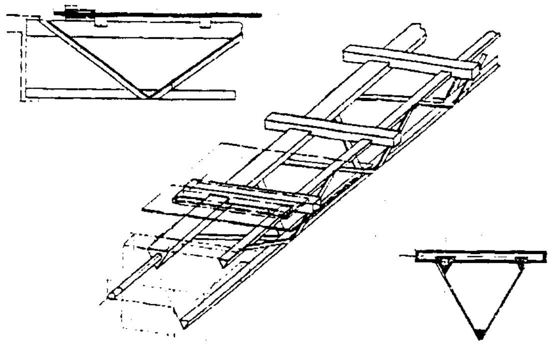

Figure 4.7: Design of the space-frame carbon fiber ladder support

The new ladder design studies

Afterwards, we have investigated several alternative possibilities of ladder design. One of the new designs, shown in Fig. 4.6, is based on lateral blade ribs and a central cooling artery; super thermoconductive graphite fibers are used for the local heat drain from the electronics to the cooling arteries.

The further development of the ladder concept is the transition from the bar-supported ladder to a space-frame carbon-fiber ladder support structure (with the same amount of material as in the previous case). A first concept is represented in Fig.4.7.

The first estimates done for the new structure have shown 20 μm sagging without any additional support. A full scale prototype of this new space-

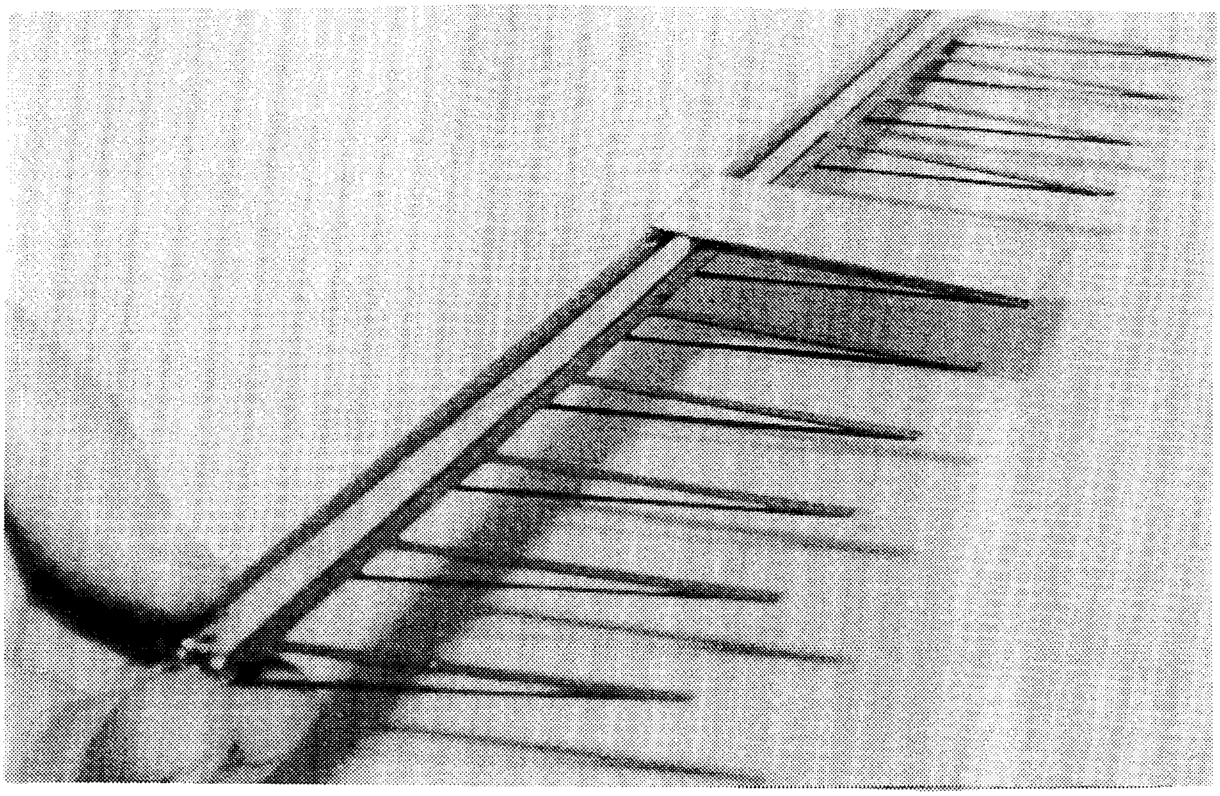

Figure 4.5: Photo of the 1st 0.5 m length 0.4 mm wall carbon fiber ladder prototype with the integrated cooling artery (Al 50 μm foil).

frame 1.1 m ladder support is being manufactured now for the future mechanical tests.

4.4 Estimate of the total amount of material

In the proposed configuration, the material will be distributed non-uniformly in each layer, being concentrated along the ribs. The assembly will be done so that the ribs in the different layers will not be collinear when seen from the vertex point.

The exact amount of material in each layer will be fixed only after the finalization of the design, but we give here the estimate of material for a realistic case, which has been calculated to provide enough mechanical precision and satisfy the cooling requirements. The values, in X_0, averaged over a whole layer, are:

0.03% for the carbon-fibre ribs
0.15% for the coolant fluid.
0.03% for the BeO foil.
0.03% for the Be power bus.
0.03% for the kapton data bus.

The material in the tracker is about 0.27% of X_0 per layer in addition to the detector modules, which are on average 0.33%, giving a total of 3% of X_0 for the ITS with five layers.

4.5 Radiation effects

Thanks to the open geometry of the experiment, we expect the primary particles produced in the interaction to be the major source of radiation damage to the tracking elements, albedo neutrons giving a minor contribution. We estimate a maximum yearly dose of 12 kRad for the innermost plane, not including beam losses; these might ultimately be the main source of radiation, but are at present very hard to evaluate. The above-mentioned levels are not very severe, and should not create a specific problem for the components discussed here, yet care will be taken in avoiding materials and devices known to be sensitive to these radiation levels.

5 Positioning and Assembly

5.1 Assembly of the ladder.

In order to get reliable positioning at the level of 10 μm and to decrease the misalignment errors for the individual Si-wafers in the whole sensitive 1 meter length volume of the Tracking System, the ladder assembly is considered to be done wafer-by-wafer at an optically controlled Working Station -I (WS-I) using fiducial marks located on the Si wafers.

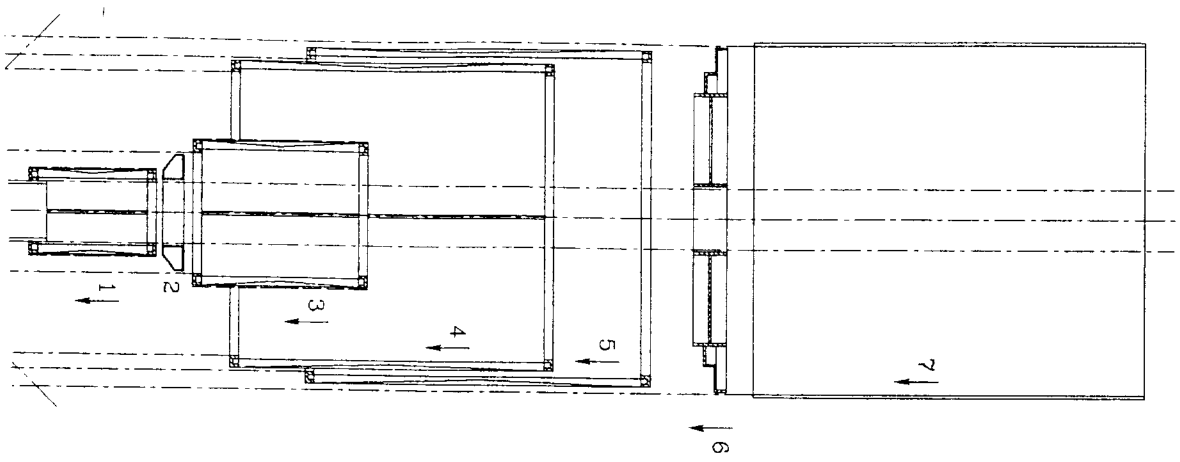

Figure 5.1: Scheme of the module–by–module assembly of the ITS

This station is based on a laser controlled automated movable (photoelectric) microscope that can be adjusted in two coordinates to the prescribed position with the required accuracy by a microdrive. Thus the negative feedback from the laser controlled traditional device is expected to give a rather cheap method of controllable motion along the 1 meter base.

This system will be the analog of the Laser interferometric comparators of National Metrology centers that are used for the length measurements of line scale. For the national primary standards of length unit the international comparison show 0.11 μm for 1 meter [24] For the present task a precision of about 3μm can be achieved in a straightforward way.

The assembled ladder (with integrated cables, buses and cooling channels) should be wirebonded (chips to buses) with the help of Working station - I and one of the modified traditional Bonding Machines. Then operation of the ladder is supposed to be completely tested befor final assembly in the system.

5.2 Assembly of Cylinder Modules and of the ITS.

The overall assembly of the Inner Tracker System is supposed to be done either ladder–by–ladder or module–by–module at a Working Station–II analogous to WS–I, using part of the same fiducial marks. In Fig. 5.1 is shown a possible option for the overall ITS assembly done by separate independent cylinder modules.

5.3 Multichannel Temperature Monitoring of the ITS.

In order to monitor the temperature and thermal gradients inside the ITS it is possible to use an automated multichannel temperature measuring system that can give the necessary information on the operational temperature of any part of the detector. The temperature at a definite point is be monitored by a thin film planar sensors, made of 2 to 5 μm Pt meander directly spread over the Si-plate, on an area of 2x2mm^2. They can provide 0.02- 0.03°C accuracy of measurements in the ± 10°C interval from the working detector temperature in the -10°C to +40°C region.

The number of thermosensors, their place and the way of positioning on the wafer , the points of the ITS that are necessary to monitor, etc. are now under study.

The same multichannel system of temperature measurements can be used for the temperature fields mapping and the temperature control of the working station for the precise alignement of the Tracking System.

Fixation of the wafer on the supporting structure is supposed to be done by traditional epoxy glue.

6 Conclusions

The future R&D for the ITS design will be concentrated mainly on local specific problems that require innovative approaches:

- the heat drain from the front-end electronics to the cooling arteries;
- the thermostabilization and temperature field uniformity of SDD;
- the local liquid freon supply to the ladder cooling arterie.

All the other problems of the design can be solved on the base of existing technologies and experience. A full scale 1.1 m Si ladder prototype is expected to be produced during the next year to test the proposed mechanics, cooling and alignement scheme.

Acknowlegments

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