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Mechanics and cooling of pixel detectors

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Abstract

A review of the design choices for the mechanical support of the new generation pixel detectors (ALICE, ATLAS, CMS, BTeV) is presented. Material selection and specific cooling solutions versus requirements are discussed © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Pixel detector; Mechanics; Cooling; ALICE; ATLAS; BTeV; CMS

1. Introduction

The vertex detectors to be operated at new hadronic accelerators are requested to have higher resolution and to survive higher collision rate.

They imply an increase of the amount of electronics close to the detector elements (to speed up the acquisition process), a much larger radiation resistance and more severe alignment and stability requirements.

The pixel technology is the preferred solution, which allows delivering true space point information with high resolution.

There are currently four pixel vertex detectors under development for four new high-energy physics experiments: three at CERN (ATLAS [1], ALICE [2] and CMS [3]) and one at Fermilab (BTeV [4]).

Similar problems are being encountered in the design of the mechanical support structure and the cooling system of the pixel detector.

Different specific solutions are being adopted, but the same approach has been used.

The major design rules, basic choices and common approaches will be discussed and an overview on the peculiar design features will be given as well.

2. Pixel sensitive elements

The core unit of the pixel detectors is the module (see Fig. 1). Different geometries have been designed, but the basic concept is always the same.

A module is a highly integrated electromechanical unit including:

- Silicon pixel sensor
- Readout chips bump-bonded on the pixel sensor
- Hybrid circuit wire-bonded to the readout chips, housing the module control chip and providing the interfaces to the optical, signal and power cables.

High electronics density produces a relevant amount of heat, which has to be efficiently

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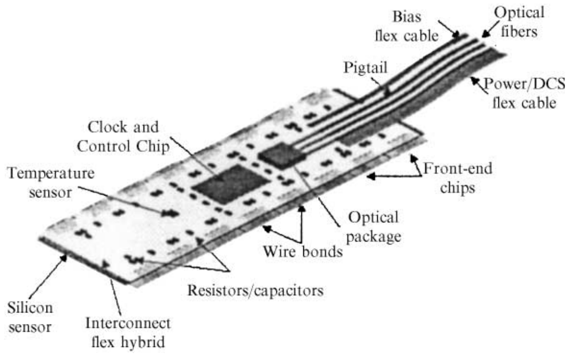

Fig. 1. Typical pixel detector module assembly.

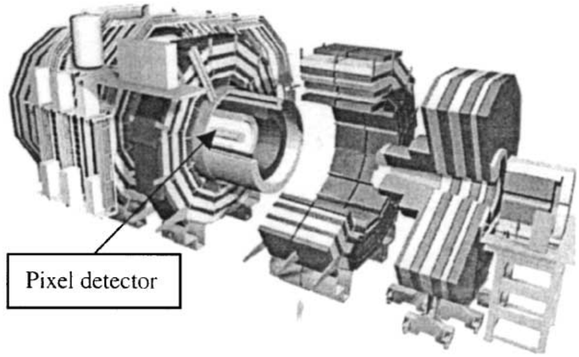

Fig. 2. CMS cut view: pixel detector is shown.

dissipated in order to keep the silicon volume at a temperature typically below 0°C to minimise the radiation damage of the sensor.

3. Requirements and constraints

Physics requirements as well as operating environment and integration constraints drive the design of the support structure of the pixel detector.

The physics requirements are relatively simple to state, but very hard to meet.

The detector has to be:

- Hermetic within the given coverage range
- As transparent as possible to particles (a "material budget" equivalent in term of thickness to less 1% of the radiation length of the material is a common requirement)
- Stable to a few microns

The last two statements are conflicting and require to pass a compromise.

The operating environment of the pixel detector imposes additional constraints:

- high radiation area,
- detector kept in dry atmosphere to avoid condensation on cool parts.

In addition the vertex detectors, being the innermost structure of particle detectors, are the most difficult to be accessed (see Fig. 2). Therefore both the installation and removal for maintenance are critical operations to be carried out and they must be foreseen with the lowest possible frequency, since:

- long shut down periods are required
- warm up time of sensors after irradiation must be minimised to limit the effect of reverse annealing.

The design has to be reliable enough to minimise maintenance interventions.

The integration requirements are another critical constraint for the vertex detectors.

Particularly the services (cables and cooling pipes) layout, routing and break points location are always very complex tasks as they have to:

- pass through all other detectors, minimising the space occupancy and material while maximising the modularity
- cope with the installation and maintenance requirements.

All these constraints could be translated in a basic set of specifications on the mechanical structure of pixel vertex detectors:

- lightweight: low mass, materials with high radiation length (X_0)
- stiff: small natural deflections, less supports, higher natural frequencies
- stable: materials with small coefficients of thermal (CTE) and moisture (CME) expansion
- radiation hard

and on the cooling system:

- efficient: liquid systems either mono-phase or even two-phase (boiling) in case of high heat fluxes (gas cooling is not sufficient)
- coolant properties: stable, non flammable, non toxic, electrical insulator, low viscosity and low density.

4. Topology and basic geometry

The pixel vertex detectors occupy typically a cylindrical volume around the interaction point.

The layout of the detector modules is driven by physics requirements like granularity and coverage.

The module elements are usually arranged in two basic geometries: disk, barrel layers and a combination of the two (see Fig. 3).

If required, the hermeticity of each basic geometry down to given minimum momentum particles is improved by different strategies: module overlapping combined or not with tilting.

5. Support structures: fundamentals

In general the pixel vertex detector support structure can be functionally split into local and global supports.

The local support structures are multifunctional, actually the core of the detector.

In fact they combine essentially two functions: keeping the module in place and cooling the module keeping the temperature on the sensor element within the given range.

The design choices and material selection for the local supports are vital issues affecting the performances of the whole detector.

They will be discussed in detail later.

The global support structures are basically passive structural elements providing:

- support to disk and barrel local supports
- interface to other detectors
- support and strain relief for services

The global support structures are lightweight frames typically made out of Carbon Fibres Reinforced Polymers (CFRP).

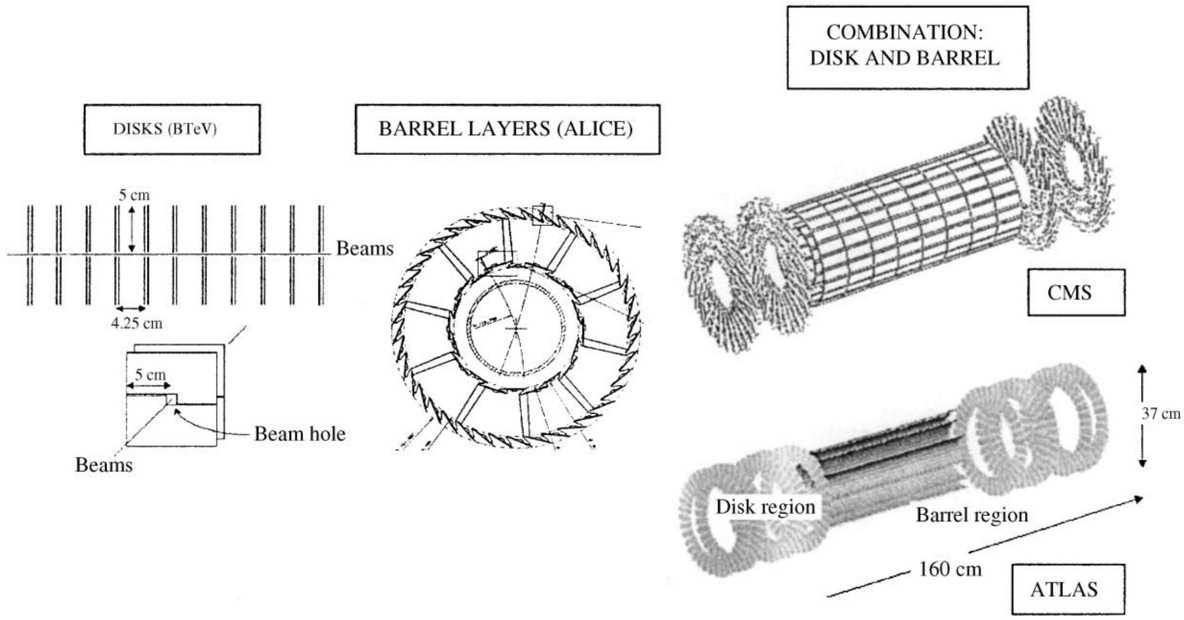

Fig. 3. Layout of the sensitive elements of ALICE, ATLAS, BTeV and CMS detectors.

The most advanced raw materials, the same adopted in aerospace industry, are widely used: Ultra High Modulus carbon fibres with low moisture adsorption cyanate ester resin matrix to minimise swelling due to change in moisture content.

A typical weight of a well designed global support structure ranges from 10% to 15% of the total weight of the detector.

6. Thermal management

The problem to be solved, common to all detectors, is shown schematically in Fig. 4.

The heat is produced quasi-uniformly over the relatively wide module area and has to be efficiently transferred to the coolant flowing inside a small cooling pipe, which must minimise the material.

The thermal design of the local support has to achieve:

- a good temperature uniformity over the module
- a good heat transfer efficiency to minimise the module-to-coolant temperature difference.

To accomplish the temperature uniformity goal the local support structure material has to have a good in plane as well as transverse thermal conductivity.

High X_0 metallic materials, typically beryllium or aluminium, are in principle good options for the module thermal management.

However the metallic materials make the thermal stability issue more critical due to their relatively high CTE, limiting the application range to small structural parts.

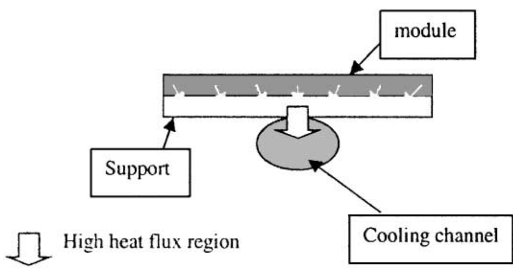

Fig. 4. Module thermal management fundamentals.

Moreover the Al is usually not adopted as stand alone structural material due to its poor mechanical properties.

Attractive alternatives to metals are the carbon-based materials. Standard CFRP are difficult to be adopted in an efficient thermal design due to their poor transverse thermal conductivity.

Carbon–Carbon materials are in principle the best option combining good thermal properties even in transverse direction to fibres (thermal conductivity 1 or 2 order of magnitude better then standard CFRP) with excellent mechanical properties, stability and transparency to particles. The C–C materials have essentially two technological drawbacks limiting the application range: porosity and difficulty to achieve complex and accurate geometry due to the high temperature manufacturing process.

The selection of the material for the cooling channel and of the coupling method to the module support is a critical issue for the local support thermal efficiency and stability.

There are three possible options:

1. pipe material with the same CTE of the support: hard and reliable thermal joint is possible
2. pipe material with different CTE: elastic joint is necessary, but reliability becomes an issue
3. cooling fluid in direct contact with the module support (integrated cooling channel)

Solution 1 is the safest design but possible just in very limited cases.

Solution 2 is the most widely adopted, because it leaves the maximum freedom in the design choices.

Solution 3 minimises the material, but is difficult to be implemented.

Additional stability constraints as well as specific design solutions will be discussed in the following sections.

7. Cooling options

The minimisation of the material of the cooling circuit (pipes, connections) and the need of a good heat transfer efficiency to meet the temperature requirements on the module, restricts the choice to a liquid cooling systems (either monophase or two phase).

Moreover fluorocarbon fluids have been proven to be the best coolant choice for the pixel detectors.

They feature:

- excellent stability,
- good thermal properties,
- relatively low viscosity at low temperature,
- high electrical resistance.

However the adoption of fluorocarbons rises two important issues which have to be carefully taken into account:

- material compatibility: the fluorocarbons have a small diluting action on resins and glues, and they become relatively aggressive under irradiation,
- coolant purification: moisture contamination has to be absolutely prevented.

ALICE and CMS pixel detectors have adopted so far C_6F_{14} monophase liquid cooling systems as baseline.

BTeV pixel detector is currently making the first preliminary studies on water based leakless systems, but they are now looking more favourably at the safer C_6F_{14} coolant option.

ATLAS pixel detector, compared to all other three detectors, has to dissipate a quite larger amount of power (up to 20 kW) in a relatively small volume (0.3 m^3).

Therefore a custom evaporative cooling system with C_3F_8 has been developed [5]. Liquid C_3F_8 will be injected in the local support cooling channels where boiling conditions will be established by controlling the fluid pressure.

8. Stability

There are basically two actions affecting the stability of the pixel detectors:

- long term effects: swelling due to moisture release from resin-based structures and/or coolant absorption, creep of plastics due to loading conditions and to irradiation
- short term effects: detector cool down (from fabrication to operating temperature), local temperature changes due to power on/off transients, pressure and temperature transients of the cooling system.

The long-term effects have to be minimised, but they can be accounted for by the periodic realignments of the detector.

Short term effects (those that could occur between two sequential alignment steps) are the most critical ones.

The thermal stability is the most relevant effect to be controlled. The goal consists in minimising the bi-metallic distortions induced by the temperature change of the structural elements.

There are two possible approaches to improve the stability:

- minimise both CTE mismatches at the interfaces of different materials and the absolute values of the CTEs
- introduce flexible joints at the interfaces

There are three relevant interfaces affecting the thermal stability as shown in Fig. 5.

Interface A is critical not only from the stability point of view, but also because it has to hold the module in place providing a reliable thermal coupling and minimising the mechanical actions on the module itself due to the unavoidable CTE mismatches module-to-support.

The selected adhesive has to be:

- flexible to minimise the thermal distortions and actions on module

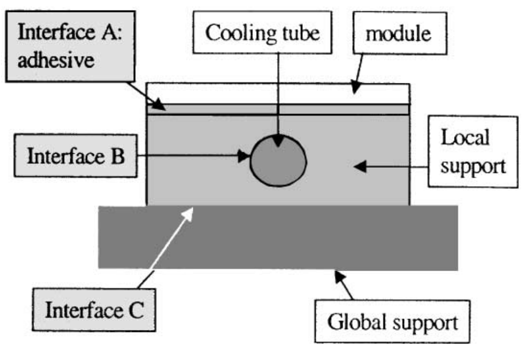

Fig. 5. Thermal stability: relevant interfaces.

- thermally conductive
- electrically insulator
- radiation hard
- room temperature curing
- guarantee a reliable heat contact

It is very difficult to find a candidate meeting all these requirements.

Generally speaking the reliability of the adhesive bonding is proportional to the stiffness.

Fig. 6 shows a typical plot of the induced thermal distortions as function of the adhesive Young Modulus.

The modulus threshold (in the range 1–10 MPa in Fig. 6) depends upon the stiffness of the support structure and the allowable stresses on module.

The ideal adhesive is the one with a stiffness close to the threshold.

Common thermally conductive epoxies are too stiff.

There are essentially two families of potential candidates:

- thermal pastes
- silicon conductive adhesives

Thermal pastes rise the problem of reliability of thermal contact and they require additional rigid adhesive tasks to keep the module position.

Silicon adhesives are in principle the best solution but they usually get harder after irradiation.

A long-term test program is always required to select and qualify the proper adhesive for a given application.

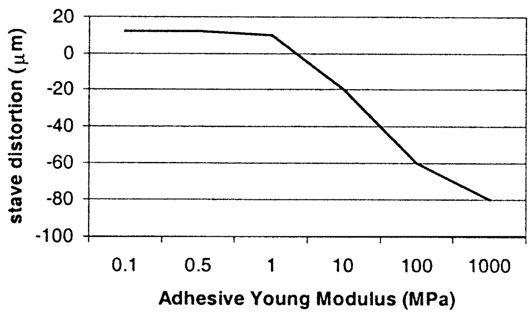

Fig. 6. Cool down distortions vs. adhesive Young Modulus for ATLAS pixel stave.

Interface B has to guarantee an efficient and reliable heat transfer and to minimise distortions.

In case of materials with same CTE then a rigid bond is possible.

In case of materials with different CTEs, then a flexible joint is needed: thermal greases are more widely used, BTeV adopts a proprietary carbon fibre joint, which will be discussed later.

Interface C is just a structural interface: in case the relative displacements are not negligible kinematic fixations have to be implemented.

9. Specific design solutions

Hereafter the major design features of the ALICE, ATLAS, BTeV and CMS pixel detectors are presented.

9.1. ALICE pixel detector

ALICE pixel detector is the only one of the four here discussed which can be operated at room temperature (lower radiation dose, less degradation of sensitive elements due to reverse annealing).

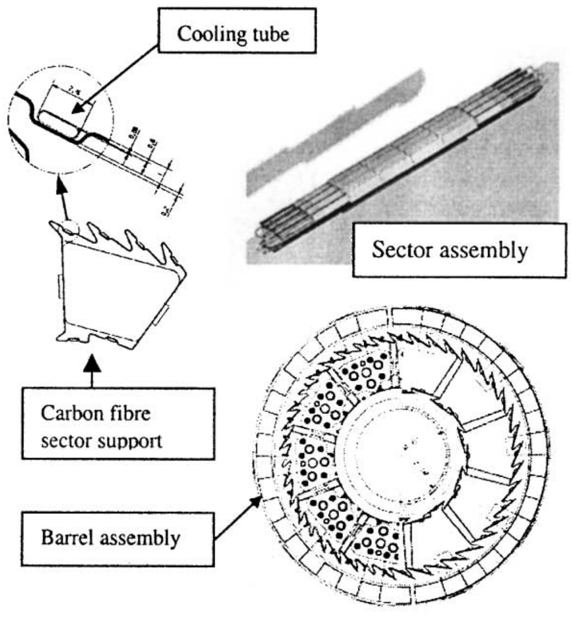

Fig. 7. ALICE pixel detector: barrel layout, sector assembly, sector structure and detail of module cooling pipe is shown.

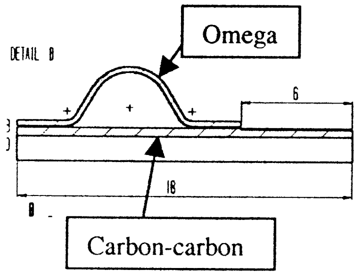

Fig. 8. ATLAS pixel detector barrel stave (transverse view).

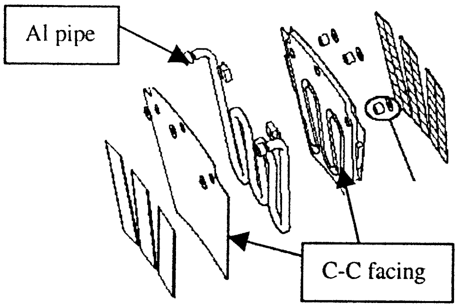

Fig. 9. ATLAS pixel detector: exploded view of the disk sector.

Pixel modules are glued on a carbon fibre support sector and cooled by very small flattened stainless steel cooling tubes, hosted in grooves and in direct contact, via a thermal grease, with the modules (see Fig. 7).

Ten support sectors are assembled onto an external frame to form two barrel layers.

9.2. *ATLAS pixel detector*

ATLAS pixel detector is made of one barrel section with three coaxial layers of staves and two disk sections with 5 disks each.

Each barrel layer consists of a cylindrical sequence of staves assembled on shell structures.

A stave is an 800 mm long structure supporting 13 modules.

Due to a relatively high power density ($\sim$140 W per stave) an ultra light zero thermal impedance design has been adopted. The cooling channel is an integral part of a monolithic carbon-based support structure made out of a CFRP omega piece glued onto a C–C tile (see Fig. 8).

The fluid is in direct contact with the C–C tile supporting the modules.

The disks are made of an assembly of disk sectors mounted on one support ring.

Each disk sector supports 6 modules 3 on each side.

A disk sector is a sandwich structure made of two C–C facings embedding a wiggle shaped

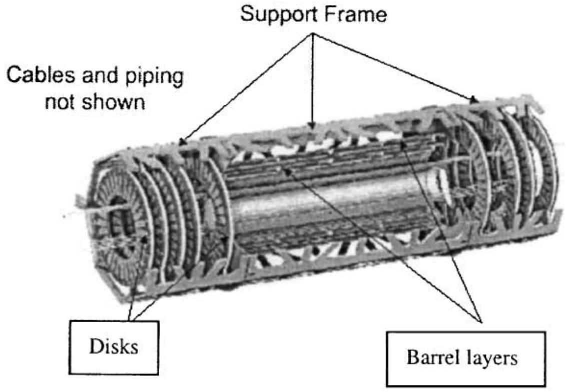

Fig. 10. ATLAS pixel detector overall assembly.

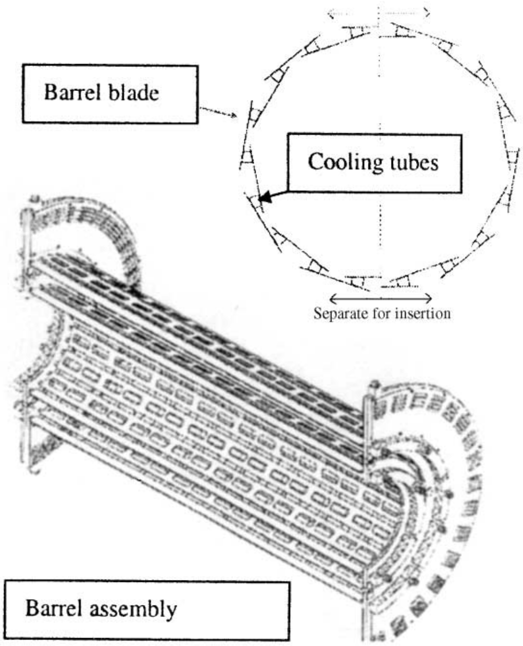

Fig. 11. CMS pixel detector barrel design.

flattened A1 pipe connected to the facing by means of a thermal grease (see Fig. 9).

Barrel layers and disks are fixed on an external support frame (see Fig. 10).

9.3. CMS pixel detector

CMS pixel detector is made of one barrel section with two layers and two disk sections with 3 disks each.

The barrel design consists of a very compact geometry with A1 pipes structurally active glued onto CFRP blades supporting the modules (see Fig. 11).

This self-supporting structure is intrinsically balancing the CTE mismatches A1-CFRP and is connected to end flanges to form the barrel assembly.

The disks are turbine-like design consisting of a sequence of tilted blades (see Fig. 12), the disk mechanical structure is all made of beryllium.

A blade consists of a U shaped pipe rigidly bonded onto two panels, which support the modules.

9.4. BTeV pixel detector

BTeV pixel detector philosophy differs quite significantly from other detectors previously described.

There is no vacuum pipe in the detector region as the pixel detector itself is fully enclosed in a vacuum vessel connected to the vacuum pipe at the two ends.

This unusual design allows to place the sensitive elements as close as possible to the

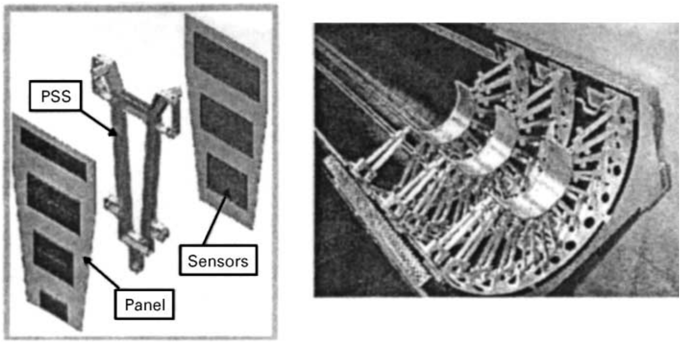

Fig. 12. CMS pixel detector disk blade exploded view and disk assembly.

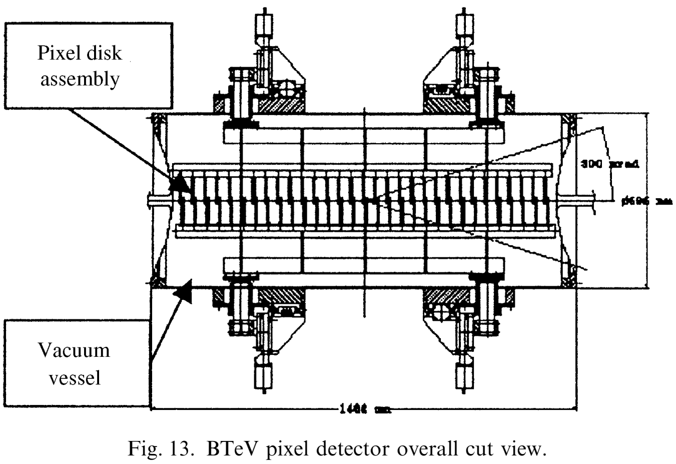

Fig. 13. BTeV pixel detector overall cut view.

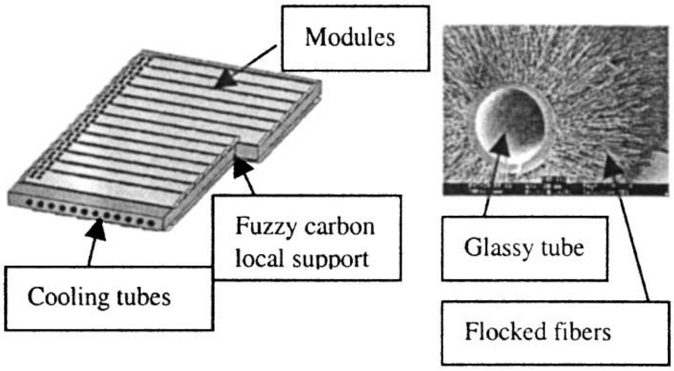

Fig. 14. BTeV pixel detector support plane with detail of cooling structure.

beam, thus improving the vertex reconstruction resolution.

The pixel detector consists of a regular axial array of 31 disk planar stations distributed along the interaction point (see Fig. 13).

Each half station is made of two L-shaped half planes supporting the modules.

Each half plane consists of a fuzzy carbon composite structure (made of flocked fibres CVD densified), which includes integrated glassy carbon cooling channels (see Fig. 14).

The carbon support and cooling planes are held in position by structural cooling manifolds, whose position is controlled by motors located just outside the vacuum vessel.

10. Conclusions

Mechanics and cooling design of new generation pixel detectors are state of the art technologies and push some of them a bit further.

A careful material selection and cooling strategies allow meeting the precision, thermal and stability requirements.

The design is at the same level of aerospace standards: very hostile environment vs. ultra light structures.

The assessment of long term performances and the implementation of high-level quality assurance standards during the manufacturing and assembling are crucial issues for the success of these very demanding designs.

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