	Research and Development - Local Supports for Pixel Detector Upgrades		
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Abstract

This proposal describes a multi-year research and development program for local mechanical supports with integrated cooling for upgrades to the pixel detector system. Local supports provide the mechanical support and integrated cooling for pixel modules.

Design studies to reduce the material budget and simplify production of the local supports would be completed.

Prototypes would be fabricated and tested for their mechanical and thermal properties.

Different concepts for the local supports would be evaluated through design studies and prototype fabrication and testing.

The design studies and prototype fabrication/testing would include aspects related to the principal interfaces to the local supports – support structures, module attachment, services routing and cooling.

The primary emphasis of the research and development described in this proposal is for the SLHC but aspects of the work are anticipated to be applicable to the more immediate upgrade of the B-layer of the current ATLAS pixel detector system.

Contact Person: (with e-mail address)

Prepared by:	*Checked by:*	*Approved by:*
J. Albert, G. Darbo ,P. Delebecque, M. Gilchriese*, D. Giugni, H. Kagan, H. Lubatti, P. Mättig*, M. Oriunno , A. Rozanov, P. Schwemling, E. Vigeolas *** Contacts**	**ATLAS High Luminosity Upgrade Steering Group**	

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1 Introduction

The local supports are mechanical structures with integrated cooling that provide support and thermal management of pixel modules. The local supports also have direct interfaces with power and signal cabling and connections for the pixel modules, with global mechanical support structures and, in some regions, possibly the beam pipe structure. Future upgrades to ATLAS are anticipated to require a pixel detector with a total area three or more times larger than the current pixel system. Material reduction in the future detector is a critical goal to improve tracking efficiency and reduce tracing confusion. In addition, operation of pixel modules at colder temperatures (eg. by using CO_2 or other coolants) than in the current pixel detector system is likely to be required. These conditions, and others, impose requirements on the local supports for upgrades that are briefly summarized here.

The local supports must satisfy layout and hermeticity requirements. Coverage by a combination of barrel and disk elements for a pseudorapidity range $|\eta| \leq 2.5$ is required.

The lifetime radiation dose exposure of the local supports in an upgraded SLHC pixel detector depends strongly on radius and weakly on z (the direction along the detector axis). The maximum integrated dose could be up to about 10^7 Gy, which is approximately 20 times more than the requirement for the current pixel detector since detection elements, and thereby local supports, will be closer to the collision point in the SLHC detector.

The thermal performance requirements for the local supports are determined by a combination of the expected power from integrated circuits, local power distribution, local data transmission and detector self-heating. The power from integrated circuits and power distribution is expected to be no more than 0.5 W/cm^2 and the current best estimate for nominal power is 0.3 W/cm^2. Silicon detector self-heating, from leakage currents that increase with radiation, can lead to thermal runaway. The design of the local support and the cooling is required to provide a conservative margin against thermal runaway. This requirement to prevent thermal runaway, and the need to minimize radiation damage, leads, in general, to colder operation at the SLHC compared to the current pixel system. Thus cooling with CO_2 or combinations of C_xF_y fluids is also under active development. Careful attention to the cooling requirements and future capabilities is an essential aspect of the local support research and development.

Material reduction, whilst meeting other requirements, is also a critical goal for future developments. Material reduction may be achieved by a combination of new techniques and very careful design and prototype development to minimize all aspects of the local support design.

The SLHC pixel detector will be significantly larger than the current pixel system. Yet the construction time is expected to be about the same or less. Thus it is essential that the new designs of local supports take into account the need to cover larger areas and to increase the rate of module placement on the local supports. The sensors for the innermost region of the upgraded pixel detector and the outer regions of the detector are likely to be different. The local support designs must allow for these differences but at the same time aim for maximum commonality to minimize the design and prototype effort.

Reliability, particularly of the cooling and thermal aspects, of the local supports is perhaps the most important requirement for any future pixel system. Reliability can only be confidently achieved through both extensive design studies, including anticipating fault conditions, and a rigorous program of prototype fabrication and test.

Finally, the mechanical requirements of the SLHC pixel system are anticipated to be similar to the existing pixel system. Stability (under operating conditions) at the level of a few microns in ϕ and a few 10's of microns in z or R is required. In addition, placement and survey of pixel modules to high accuracy (better than 5 microns in the most demanding coordinate) is a requirement for the local support design and fabrication.

This proposal describes a program of work lasting about two years that covers all aspects of the design and prototype fabrication of local supports. A number of options for the local supports are described. It is only through the combination of design studies and prototype fabrication and testing that the best local support design can be achieved. Although self – consistent, this proposal is closely related to other R&D efforts for the SLHC pixel detector – module development, on – detector services and cooling. The developments in these areas will be considered, as this R&D proposal will lead to constraints on these related issues.

2 Participating Institutions

The participating institutions and an initial list of participants at each institution is given in Table 1.

Institution	***Participants***	***Area of Interest***
University of Victoria	*J. Albert*	*Design for use of diamond and diamond detectors*
Centre de Physique des Particules de Marseille (CPPM)	*J.-C. Clemens, G. Hallewell, M. Niclas, A. Rozanov and E. Vigeolas*	*Cooling services design (connectors and tubes)* *Thermal tests and calculations with various cooling liquids (C3F8, C2F6, CO2)Structure design and prototype with metal tube option* *Module attachment interface and placement robot*
Laboratoire d'Annecy-le-vieux de Physique des Particules (LAPP)	*P. Delebecque* *T. Todorov*	*Thermal simulation of local structures and comparison with thermal measurements*
Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE)	*P. Schwemling* *G. Daubard*	*Local support design* *Material calculation tools for CAD* *Thermal qualification of materials and prototypes*
Bergische Universität Wuppertal	*K. H. Glitza, G. Lenzen, P. Mättig and B. Sanny*	*Carbon fiber tube development* *Structure design and prototype* *Test of materials* *Thermal and mechanical qualification* *Support structure design interface*
INFN Genoa	*G. Darbo, G. Gariano, A Rovani and E. Ruscino*	*Module attachment interface*

INFN Milano	*S. Coelli, D. Giugni, C. Meroni and M. Monti*	*Carbon fiber tube development* *Structure design and prototype*
Lawrence Berkeley National Laboratory (LBNL)	*E. Anderssen, S. Dardin, M. Garcia-Sciveres, M. Gilchriese and N. Hartman*	*Thermally conducting foam development* *Structure design and prototypes* *Thermal performance measurements and calculations* *Support structure design interface* *Module attachment interface*
Ohio State University	*H. Kagan and S. Smith*	*Design for use of diamond and diamond detectors*
Stanford Linear Accelerator Center (SLAC)	*M. Oriunno and D. Su*	*Cooling system, piping* *CO_2 development and testing*
University of Washington	*C. Daly, H. Lubatti and T. Zhao*	*Thermally conducting foam development* *Structure design and prototype development*

Table 1 Participating institutions, preliminary list of participants and a summary of areas of interest.

In addition, there will be strong participation from partner technical institutions and a few companies with particular expertise in fabrication of carbon composite structures. These are listed in Table 2.

Affiliated members	***Contribution***
IVW : Institut für Verbundwerkstoffe GmbH Kaiserslautern	*Carbon fiber tube development and local and global support structures*
IFB :Institut für Flugzeugbau Universität Stuttgart	*Carbon fiber tube development*
BERCELLA Carbon Fiber	*Carbon fiber structures*
Allcomp, Inc	*Carbon foam development and prototype development*

Table 2 Affiliated technical institutions and companies.

3 Topics and goals of the R&D proposal

In this section we describe the principal R&D topics and the goals for this proposal. In general, the topics may be divided into general concepts for barrel or disk local supports that integrate different R&D components and R&D on specific components that may be applicable to a number of concepts. We start with an overview of the concepts currently being explored for silicon detectors and briefly describe design and prototype studies (eg. thermal performance) that are underway. We also outline measurements of the thermal and mechanical properties that must be done on components of the local supports for silicon detectors. This is followed by a short discussion of the principal interfaces to the local supports, emphasizing those that are most important in determining the design of the local supports. Research and development related to the local supports for diamond detectors, which have significantly different thermal requirements than silicon detectors, are described briefly at the end of this section.

The overall layout of the pixel system for the SLHC remains to be finalized in detail. We show in Figure 1a simplified candidate layout for the SLHC pixel system. Currently, all candidate layouts consist of an outer pixel system with barrel and disk layers that is permanently attached to the silicon strip system at a larger radius and an inner pixel system that is replaceable. It is assumed that the inner pixel system consists of only barrel layers. The design of the local supports must meet the requirements of the layout.

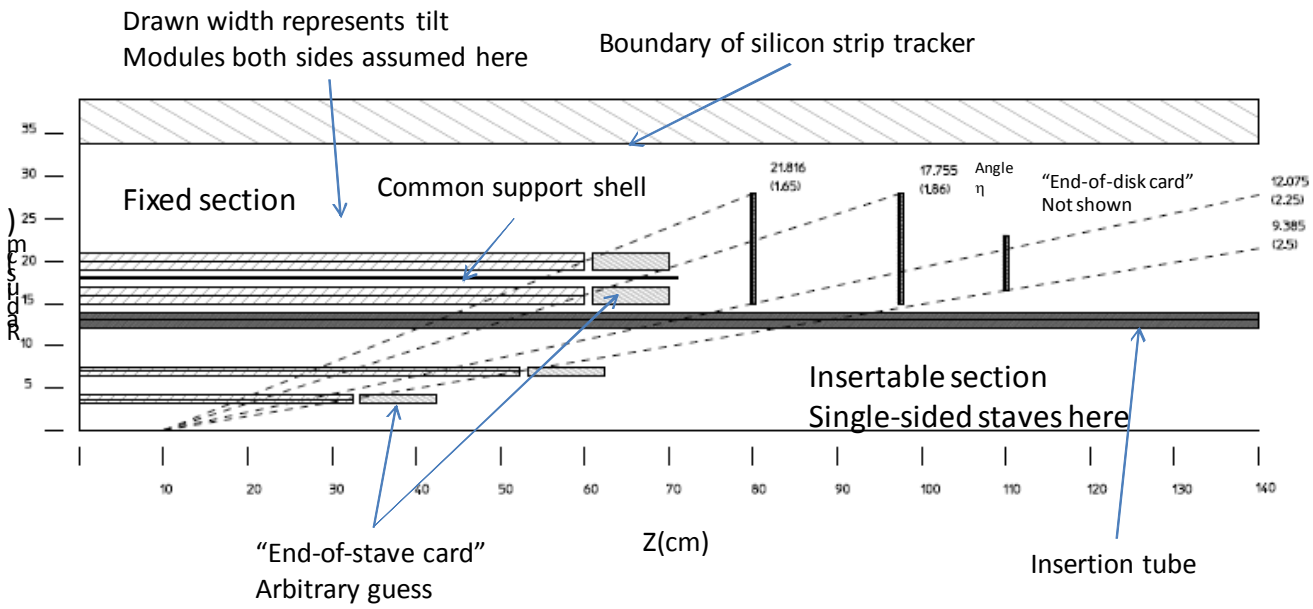

Figure 1 Generic layout of the pixel system for the SLHC.

3.1 Barrel stave concepts and prototypes

In this section we present the status and plans for different concepts for outer and inner barrel regions.

3.1.1 The Concept of an All – Carbon Stave

Significant progress has been made during the last year towards an "*all carbon stave*" consisting of three main elements:

- carbon foam as bulk material;
- CF (Carbon Fiber) laminate for the structure ;
- CF pipe for the boiling channel.

Whereas the first two are commercially available, substantial R&D had to go in the development of a small, light but leak tight carbon pipe that withstands high pressure. The aim is to reduce the radiation length of the local supports preserving, at the same time, a high geometrical stability and good thermal properties. The aim of the stave is to provide mechanical support in parallel to remove the heat load generated in the front-end electronics and in the sensor. The default cooling system is based on evaporative cooling, where the coolant is boiled off in channels thermally coupled to the surrounding local structures.

Whereas most stave concepts use hybrid solutions of carbon together with a metal pipe, the all-carbon stave has several advantages:

a) Since carbon is a low Z – material, a CF pipe allow a significant reduction of the total radiation length of the piping while withstanding the MDP (maximum design pressure) required by some coolant[1]
   Given the MDP and their large Z, metal pipes contribute typically a three times higher X/X_0 than carbon pipes, contradicting one of the basic aims for the design of the local support.
b) The CTE of the carbon based materials is around zero, ranging from negative to positive value within few ppm/°C. Vice versa the light metal materials, suitable for producing piping, have CTE values above 10 ppm/°C. During the cool down of the structures, the CTE mismatch may generate undesired deformations or high stress levels.

[1] CO_2 cooling systems require an MDP of 100bar

c) Some of the metals commonly used previously for the piping, like the aluminium and its alloys, are in the galvanic series very far from carbon. Since aluminium behaves as an anode it turns out to be the "sacrificial" electrode in case of galvanic corrosion and it can suffer irreversible damages.

The above mentioned issues are successfully addressed by the use of CF pipe in the homogeneous stave.

Design and qualification of the carbon pipe

The development of the carbon pipe has been pursued successfully during the last years.

The pipe is obtained by the impregnation of carbon fiber braid via poltrusion[2] or RTM[3] (Resin Injection Moulding). The produced CF (Carbon Fiber) pipes are required to meet the stringent requirements currently foreseen by the cooling system and detector constraints as well as the physics requirements of minimizing material.

a) CTE: The apparent longitudinal CTE of the pipe matches the ones of the surrounding parts.
b) Tightness: The overall pipe tightness is better than 10^{-7} atmm.cc/s. (He test)
c) Thickness: 250μm wall thickness can be achieved to minimize the thermal impedance across the pipe.
d) Strength: Structural SF (safety factor) of 4 (or more) on the Tsai-Hill failure criteria for MDP of 100bar are easily reached.

To achieve these goals, an important parameter is the fiber angle, which can be controlled with high accuracy. Analytical calculations for various angles have been performed and are listed together with the mechanical properties of the resulting pipe. Table 3 summarizes the mechanical parameters of the pipe as function of several possible lay-ups for a 3mm outer diameter CF pipe with a wall thickness of 300um.

Pipe OD [mm]	Wall Th [μm]	MDP [bar]	Proof Pressure [bar]	Lay-up		V_f %	Safety Factor on MDP	Strains % @150bar ε_T	CTE [ppm/C] (Matrix 70) estimate
3	300	100	150	[+30/-30]		30%	1.4	0.701%	-1.1
						60%	1.5	0.458%	-6.5
				[+45/-45]		30%	4.2	0.124%	8.9
						60%	4.7	0.067%	1.9
				[+55/-55]		30%	7.7	0.091%	42.3
						60%	9.9	0.053%	16.1
				[+55/$0_{.1}$/-55]	0 ply	30%	5.5	0.192%	18.3
					±55 plies		7.7	0.082%	
					0 ply	60%	7.7	0.101%	5.4
					±55 plies		10.1	0.045%	
				[±45/±55]	± 45ply	30%	8.4	0.100%	23
					±55 plies		9.8	0.080%	
					± 45ply	60%	11.3	0.050%	7.4
					±55 plies		11.6	0.040%	
				[±40/±55]	± 40ply	60%	9.6	0.060%	1.8
					±55 plies		10.1	0.040%	

Table 3 Table summarizing the main mechanical properties of the CF pipe as function of the lay-ups.

One can note that there are two lay-ups fulfilling all the requirements: [±45] and [±40/±55].
These pipes have in fact:

- a safety factor (Tsai-Hill failure criteria) at the MDP above 4,
- transversal strain <0.1%

[2] Technique has been worked out at IVW [Institut für Verbundwerkstoffe, Kaiserslautern, (DE)] in collaboration with the Bergische Universität Wuppertal.
[3] Technique has been worked out at IFB [Institut für Flugzeugbau –Stuttgart, (DE)]

– CTE around 2 ppm/°K .

So far several samples of 800mm long pipes (see Figure 2) have been produced that meet the specifications. These pipes went through a qualification process at the Wuppertal University:

– He leak rate before and after the pressurization at 1.5xMDP (150bar) proven tight at 10^{-7} scale;
– Measurement of the apparent longitudinal CTE and comparison with the calculated value;
– Multiple thermal cycling (+20 -> -40°C) to verify that the tightness is not affected by the thermal transients.

Figure 2 Prototypes of CF pipes.

A prototype stave

A prototype of the homogenous stave has been assembled at the IVW lab with the CF pipes described above – see Figure 3(a). The assembly has two cooling pipes sandwiched between a carbon foam[4] material and a 300µm quasi-isotropic laminate[5]. The thermal contact is provided by an aluminum oxide loaded epoxy.

The stave has been tested in order to measure the thermal figure of merit (defined as the ΔT/P [°K.cm^2/W]) that characterizes its thermal performance. The measurement has been carried out running a monophase water-based coolant into the pipes loading the stave with a known heat flux. The obtained results give a figure of merit FM=7.33 [°K.cm^2/W] in good and conservative agreement with value obtained with the thermal simulation: FM_{sim}= 8.4 °K.cm^2/W [2].

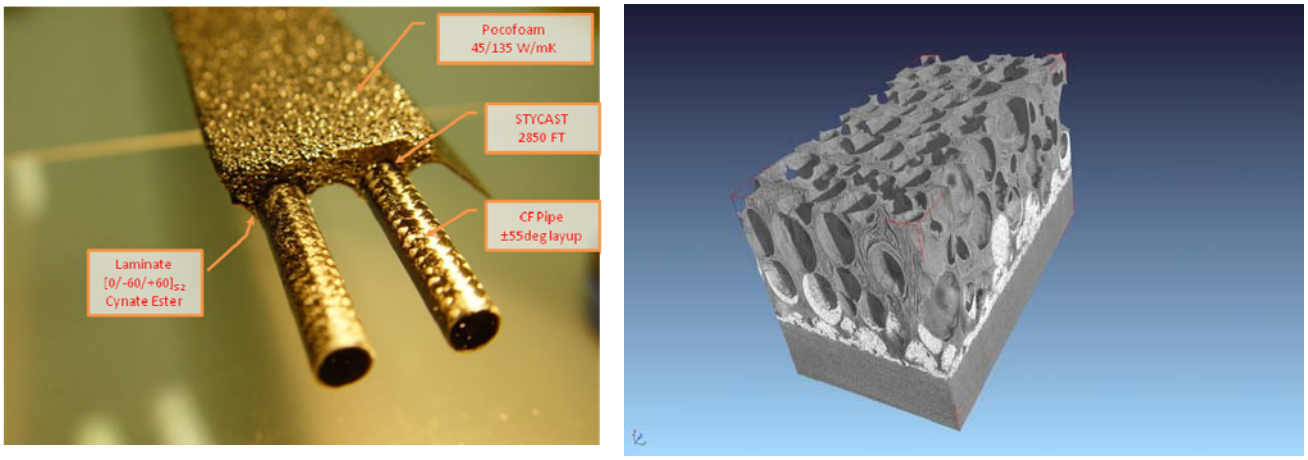

Figure 3 (a) Prototype of the homogeneous stave and (b) X-Ray tomography of the bond between the CF pipe laminate and the carbon foam. The thermal compound enters into the foam pores minimizing the effective thermal impedance.

Since the pipes have to be bonded to the foam, dedicated studies were performed to investigate the characteristic of the interface. Figure 3(b) shows the result of an X – ray tomography taken at IVW. Adhesive leaks into the foam pores reducing the effective thermal impedance of the interface. The bond gap is driven by geometrical accuracy of the bonding parts and it is about ~20µm,

The prototype of the stave weighs 34.4 grams, half of it due to the carbon composite laminate. It appears doable to decrease further its contribution reducing by a factor two the thickness of the laminate. As a result the weight can be reduced by more than a factor two compared to the existing pixel stave and even more in terms of radiation lengths.

Further investigation has shown that such a stave can deal with the thermal run-away effect up to the power generated in the planar sensors at the maximum SLHC expected integrated luminosity (6000 fb^{-1}).

[4] POCO foam ρ=0.55g/cm^3

[5] Fiber YS-80A; resin EX-1515; lay-up $(0/60/-60)_{S4}$

R&D Plan

The qualification of and improvements to the design requires additional R&D efforts.

Micro-cracking resistance

The micro-cracking resistance has to be proven for irradiated materials. Matrix toughness is generally affected by the radiation that might reduce the minimum acceptable ply transversal strain at which the matrix cracking phenomena takes place. Cracks constitute a potential path through which the coolant confined in the boiling channel can go through and generate leaks.

The measurement can be carried out by means of pull tests on irradiated 0/90/0 cross-ply laminates for the different resin systems (epoxy and cyanate ester). The cracks formation is inspected optically on the section of the specimen and the number of cracks (per unit of length) can be plotted as function of the transversal strain.

Pipe connections

The carbon fiber pipe of the homogenous stave needs to be connected to the external cooling piping. This can be done via permanent bonding technique that allows connection of the CF pipe to most of the common metal pipes made of stainless steel or titanium. The design and the qualification of the bond are critical due to the high pressure.

Thermal performances

The thermal overall performances of the homogeneous stave are driven by the transversal coefficient of thermal conduction of the laminate constituting the wall of the pipe. The value depends, mainly, by the $K_{\perp}$ of the fiber and the K_m of the matrix. The calculated value must be experimentally verified both on the $K_{\perp}$ of the pipe laminate and, globally, on the stave where it is possible to take into account the contribution from all the thermal interfaces. New techniques to improve the thermal conductivity should be explored.

Effect of the pipe surface on the HTC (Heat Transfer Coefficient) and on the CHF (Critical Heat Flux)

The CF pipe is the boiling chamber of the stave and the thermal performances depends upon the HTC of the coolant. The coefficient, that sets the thermal gap between the bulk of the fluid and the temperature of the inner side of the pipe wall, is heavily affected by the characteristics of the surface. Since the thermal performance is critical, the value of the HTC and the evaluation of the flow-pattern must be measured on an evaporative pilot plant for the CF pipe with all the considered coolants.

Furthermore, the CHF is essential to exclude the dry-out. This effect would lead to a rapid increase of the temperature gap between the fluid and pipe wall. The power generated in the sensor has an exponential relation with its absolute temperature and the dry-out effect might lead to instabilities of the sensor temperature.

Optimization of the design

The design of the homogeneous stave needs to be optimized both for the IBL[6] and ATLAS SLHC Upgrade. The working conditions in the two detectors are significantly different especially for the power load and maximum sensor temperature. The design parameters like the weight, thermal performances, stability etc, must be optimized in a tradeoff process to come to the optimum solution. Development of new carbon materials will be closely watched and eventually used in a new design.

Interfaces and the global support

The design of the global support is fundamental to benefit from the advantages offered by the homogeneous stave. Stability, service routing and integration issues of the overall mechanics will constitute the natural field of interest next to the design of the stave.

[6] ATLAS Inserted B-Layer

3.1.2 Staves Based on Low-Density Carbon Foam

Concepts for staves for the inner and outer pixel system based on the use of thermally conducting, low-density carbon foam are described here. First, we summarize the development of this new type of foam. Second, we describe concepts for outer staves and options for inner staves. Third, we summarize the fabrication and test of critical prototypes that have been made. Finally, we outline a plan for additional R&D and prototype fabrication and test of future stave structures.

We are developing staves concepts in which low-density, thermally conducting carbon foam is an integral aspect of the mechanical structure – see Figure 4 for an example of an outer stave concept.

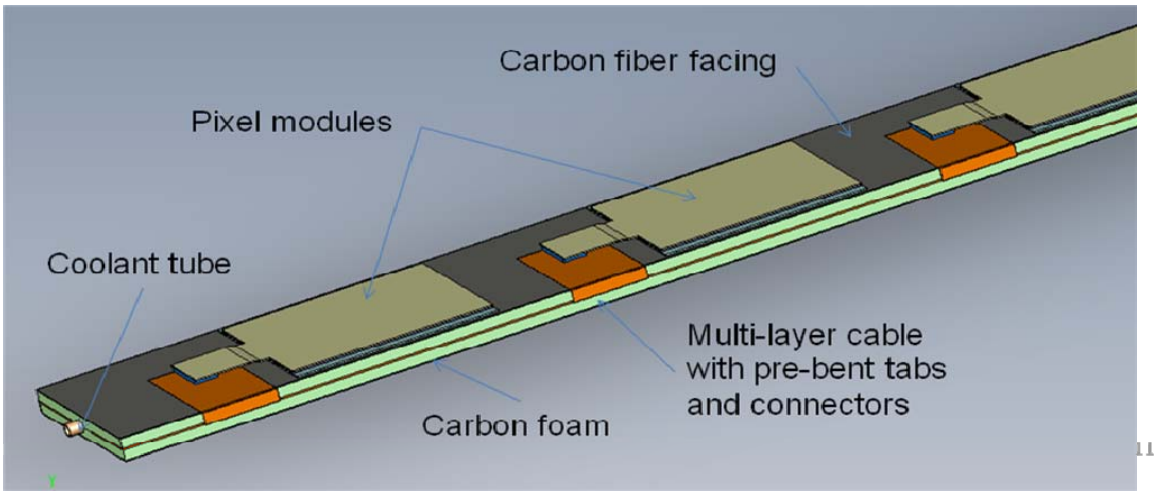

Figure 4 Example of an outer stave concept.

Two types of carbon foams are under investigation – so-called graphitic foams and a foam based on a reticulated vitreous carbon (RVC) precursor to which highly thermally conducting material is added by chemical vapour deposition and heat treated. A blow-up of the RVC-based foam is shown in Figure 5(a) and a typical block(the dimensions are in inches) is shown in Figure 5(b). The RVC-based foam is produced with a typical porosity of about 100 pores per inch (ppi). Graphitic foams (low density versions of the foam described in section 3.1.1) are also under investigation.

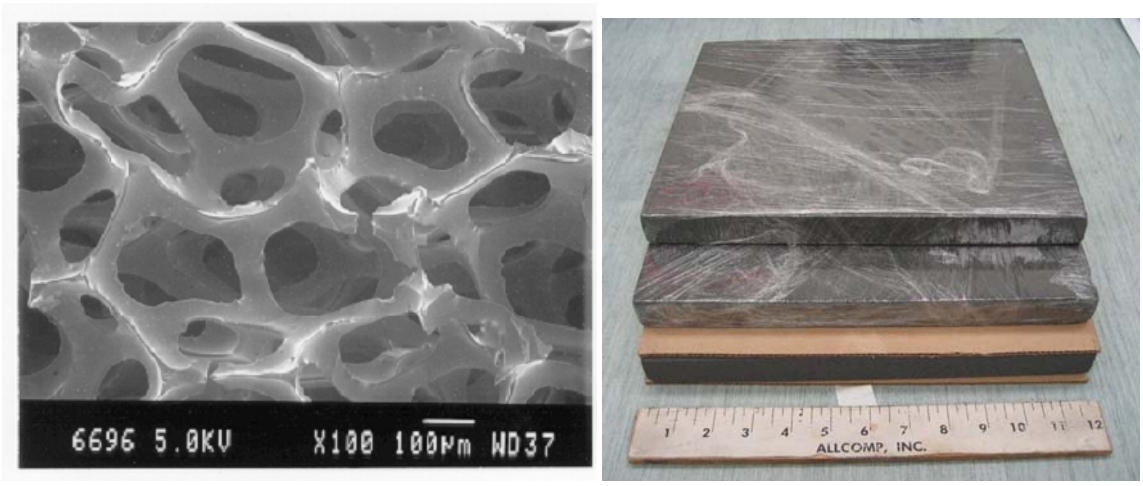

Figure 5 (a) Microphotograph of RVC-based foam and (b) typical foam blocks produced.

The thermal conductivity of these foams is approximately proportional to the density of the high conductivity material in the foam as shown in Figure 6 for a subset of the foams under consideration. Graphitic foams have higher thermal conductivity in the "foaming" direction (nominal because the conducting path length is shorter in this direction) whereas the thermal conductivity of RVC-based foams is isotropic.

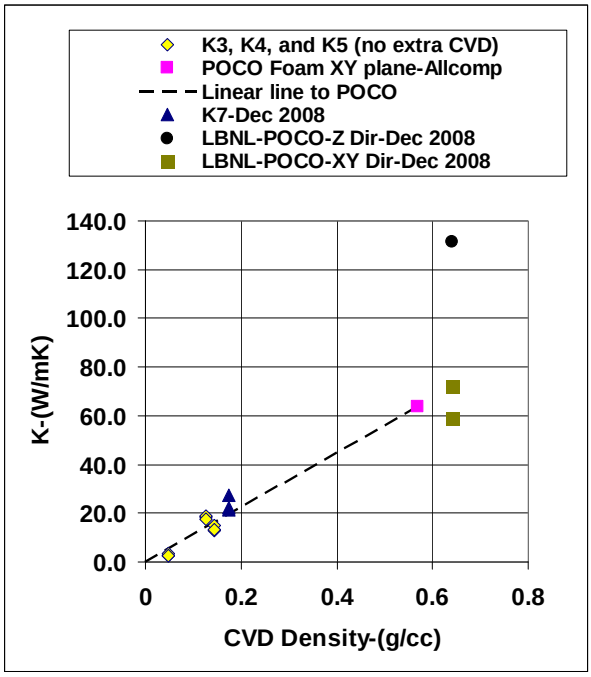

Figure 6 Thermal conductivity of different foams vs the CVD density – the density of highly conducting material.

Both types of foams can be machined, although the RVC-based foams are easier to form into complex shapes by machining. More than a dozen, mostly short, prototypes have been constructed with these low-density foams and the results are briefly summarized in a later paragraph.

The outer stave concept using the low-density foam, as shown in Figure 4, consists of thin (about 0.2mm thick) carbon fiber facings (of high strength and thermal conductivity material eg. K13D2U) about 4cm wide and 1.2m long surrounding the low-density carbon foam. A single cooling tube is embedded in the foam. We are pursuing two options to fix the tube in the foam and make good thermal contact: a very low-shear strength thermal compound and rigid epoxy loaded with boron nitride. Two approaches are understudy since there is a significant mismatch between the foam (CTE 2-3 ppm)/carbon fiber (CTE about 0) and a metallic tube (stainless steel or titanium). This mismatch can cause stresses in the materials in the case of the epoxy bonding of the tube to the foam. Conversely reliability of the joint between tube and foam with a low-shear strength material after hundreds of thermal cycles is a potential issue. Both must be understood through prototype construction and test and finite-element simulation.

A significant number of prototypes have been made and tested using low density foams. There have been three types of prototypes constructed to date:

- About ½ dozen small (6-20cm long, 2.5 cm wide) prototypes to evaluate the thermal performance of foam candidates, both graphitic and RVC-based, as these foams were developed;

- Also about ½ dozen short (6-13 cm long, 4cm wide) prototypes to measure the thermal performance of stave segments using recently produced RVC-based foams with K=16-22 W/m-K; and

- 1m long, 4cm wide staves (see Figure 7) to evaluate production techniques for the outer staves, and also to measure thermal performance on a section of such an object.

Figure 7 A 1m long, 4 cm wide outer stave prototype using RVC-based foam.

The lessons from measurements of the prototypes constructed and tested to date may be summarized as follows:

- The thermal performance of the design using foams with K ~ 20 W/m-K can meet the requirements with bulk fluid temperatures around -35C (see the discussion of thermal runaway below);
- Thermal performance does not degrade after dozens of thermal cycles for both types of attachment (low shear strength material and rigid epoxy) of a metallic tube to the foam;
- RVC-based foam is preferred for practical reasons (easier to machine and obtain); and
- Long, precision staves can be readily manufactured with well understood properties, both thermal and mechanical, that are in reasonable agreement with analytic and finite-element calculations.

Extensive studies have been done to estimate the thermal performance, including thermal runaway, of the outer staves and also potential inner staves. Representative calculations are shown in Figure 8. These calculations were done assuming $C0_2$ coolant with a temperature of -34C and a heat transfer coefficient h=10,000 W/m^2-K and assuming an electronics heat load of 0.5 W/cm^2.. The maximum sensor power (at -25C) is expected to be less than 0.05 W/cm^2 (for an integrated luminosity of 6000 fb^{-1}) and a design concept may be found that provides adequate3 margin. These results are for a foam of K=16 W/m-K and additional margin would be obtained with higher conductivity foams.

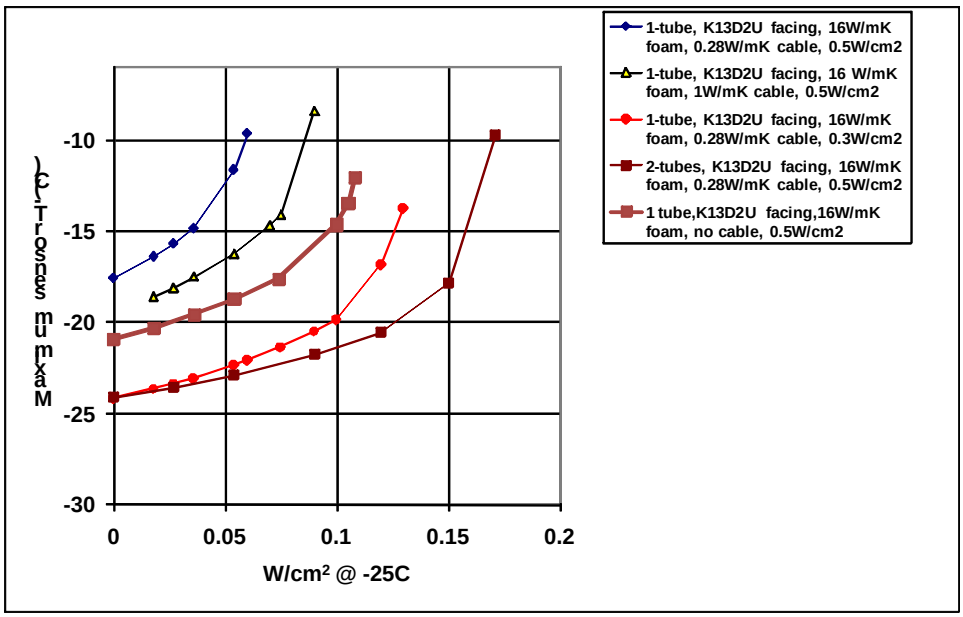

Figure 8 Thermal runaway calculations for different stave configurations using assumptions described in the text.

Multiple concepts are under investigation for the staves or equivalent structures for the inner pixel region. Our investigations include exploring the option of "coupled-layer" structures, examples of which are shown in Figure 9. In this type of structure, carbon fiber is formed to create a rigid structure providing room for 4cm-wide modules at the outer radius (L1) and 2cm wide modules at the inner radius (L0). Carbon foam is used to couple the cooling tube to the relevant carbon fiber facings (and cabling is attached to the sides of the structures). Thermal runaway calculations have been done to evaluate these structures. It is possible to meet easily meet thermal requirements for planar or 3D sensors on L1 (for 3000 fb^{-1}) and similarly for L0 (the 2cm width overcomes the higher radiation levels). More conventional stave structures, supported on barrel shells, are also under investigation but would have about the same thermal properties.

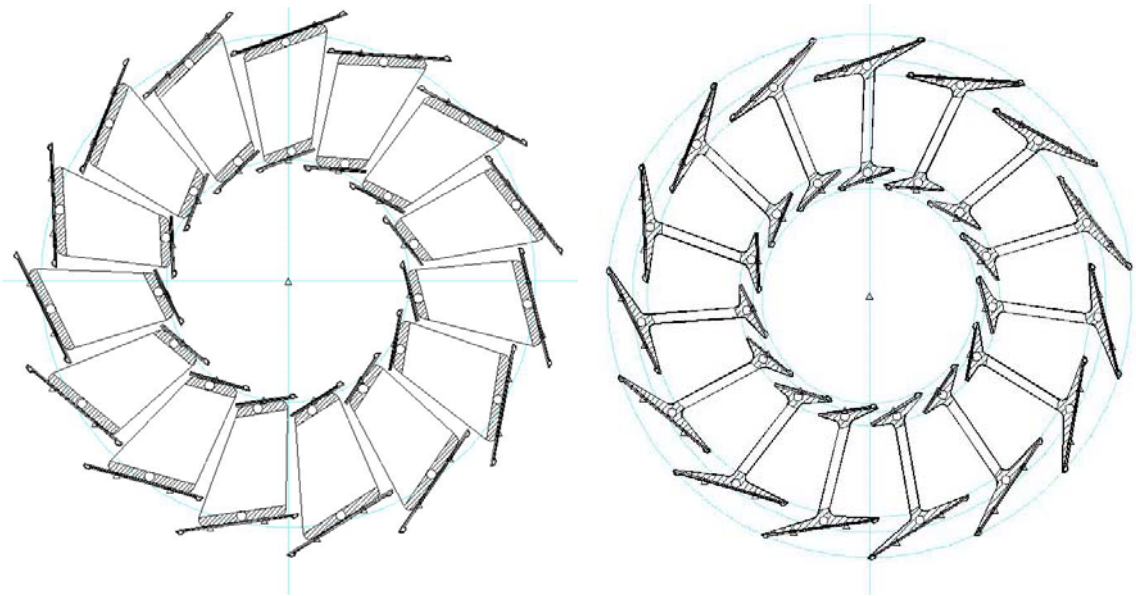

Figure 9 Example of coupled layers structures for the inner pixel system.

The proposed work plan for these stave concepts has two principal components – continued design studies both to optimize the designs for different radial regions but also to take into account critical interfaces (supports, cabling, etc) and the fabrication and test of additional prototypes. The prototype testing will first focus on the reliability of the thermal performance after extensive thermal cycling (hundreds of cycles from 20C to at least -35C) and thermal shock. This will be done first for prototypes using epoxy bonding of the tube to the foam. This is clearly preferred, if the reliability requirements can be met. If not, we would turn the focus to additional tests of prototypes with a low-shear strength coupling of the tube to the foam. A parallel program of finite-element calculations will be performed based on measured foam and other properties (including non-linear behaviour). Additional full-length (1m-scale) prototypes will be made to understand manufacturing tolerances as well as thermal and mechanical performance. Prototypes of coupled-layer structures or other stave designs for the inner layers will be constructed and tested. In addition, we will instrument a 1m stave prototype completely with dummy platinum-on-silicon heaters. This object will be first tested with water coolant at LBNL and then with CO_2 at SLAC. Prototypes will also be constructed and tested using thin-wall (100- 130 microns) titanium pipes, which offer the possibility to maintain good thermal performance but attain both lower radiation length and a reduction of the CTE mismatch between pipe and foam compared to stainless steel pipes. R&D on connections (fittings or welding) to the titanium pipes will also occur (see section 3.4.2).

3.2 Disk concepts

Work on disk concepts for the outer system is at a very early stage. A current concept utilizes the low-density carbon foam and machined carbon fiber facings with an embedded cooling tube to form disk segments to make a full disk. Modules identical in size to those used for the outer barrel staves are mounted on both sides of the segment to maintain 100% coverage as shown in Figure 10. Four rings of modules are shown in Figure 10 but fewer rings may be needed in the final design.

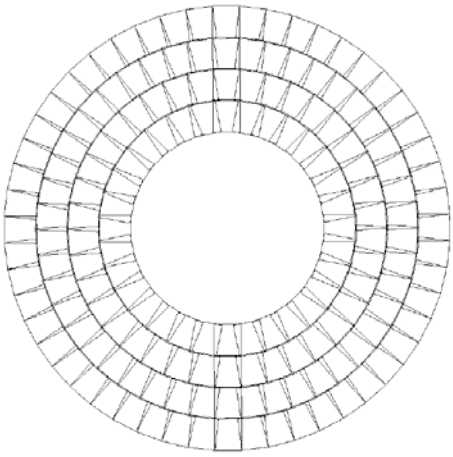

Figure 10 Overlap of disk modules on the front and back of a disk. Only the active area of a module is shown.

A basic concept for a disk segment is shown in Figure 11. Complete radial coverage is achieved by having a step in the foam/carbon fiber such that the middle row of modules is displaced by about 1mm in z from the outer and inner ring of modules. Our work scope includes creating CAD models of the disks, including preliminary definition of the interface to local cabling and readout boards that are close to the disks. A prototype of a disk segment will be made and the thermal performance measured in a manner similar to that described above in section 3.1.2. At least one generation of prototypes will be needed, possibly two to arrive at a sound basis for a conceptual design.

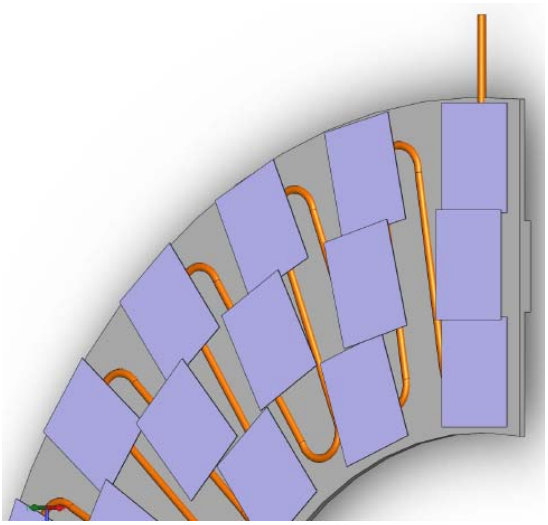

Figure 11 Concept for a basic disk segment showing buried tube.

3.3 Properties of the local support components and material estimates

We have initiated a program of work to systematically measure the thermal and mechanical properties of components that may be used in the local supports. We described here only the general directions of the proposed work and do not summarize the existing results since this effort is just starting. We also include a brief description of the need for an irradiation program that is primarily done at the component level. Finally, tools to automatically estimate the radiation length (or interaction length) from CAD models are under development. Since material reduction is a key goal of the R&D program, this capability is highly useful.

3.3.1 Thermal Properties

Correct understanding of the thermal behaviour of the detector in real conditions requires measurements of the thermal properties (thermal capacity and thermal conduction coefficient) of the individual materials used to build the detector. Some of the materials may show anisotropic thermal properties, and this anisotropy has to be taken into account.

The thermal parameters are best measured with a test bench allowing to set well defined and uniform (i.e., constant temperature on a given surface) boundary conditions on the material to study, to ease comparison with thermal FEA simulations. Typical temperature measurement techniques can be resistive thermal sensors (PT-100) that provide precise measurements at specific places, and can be placed in the bulk of the material under study, or thermal cameras, that yield the temperature field of the surface of the material imaged. Analysis of the temperature profile as a function of time and of position within the material under study allows to measure thermal capacity and thermal conduction coefficient.

In addition to the thermal properties of the materials used to build it, the thermal behaviour of the detector also depends upon the thermal resistivity of the contact between two materials. This thermal resistivity is often not well known, since it depends upon many parameters, like surface roughness, chemical composition of the surface, assembly procedure. By studying the thermal behaviour of assemblies of materials whose individual thermal characteristics are well known and comparing the measurements with simulations, it will be possible to measure the contact thermal resistivities and to establish precisely upon which parameter they depend.

3.3.2 Mechanical Properties

The measurement of mechanical properties of components of the local supports – carbon fiber materials, foam, pipes, adhesives and others – is part of the work scope of this proposal. Basic understanding of the stress-strain relationship, CTE and CME are needed to accurately model the mechanical performance of the local supports. Measurements at the component level will be supplemented by measurements on prototype assemblies to understand the impact of interfaces and adhesives.

3.3.3 Irradiation Program

Our work scope includes measurements of critical material thermal and mechanical properties after irradiation. Typically this has been done to understand the changes in adhesive performance after irradiation. However, the peak radiation dose for the SLHC upgrade (innermost layer) is about 10^7 Gy, which implies that the effects on all but metallic components should be measured.

3.3.4 Material Estimates

Optimisation of the performance of the detector depends crucially upon the understanding of the matter distribution as a function of position. To take into account all the materials present in the detector, including the ones having a complicated and non-uniform distribution among the detector, like services and support structures, it is useful to use as much as possible the information from the 3D CAD files. Analysing regularly spaced in phi two dimensional cuts of the detector, it is possible to automatically produce 2D and 3D maps of the x0 distribution of the detector as a function of eta and phi. This technique allows also one to spot local densities of matter in the detector and to study the effect of these structures on the physics performance.

3.4 Principal Interfaces

We briefly summarize here the connection of the work on local supports to the principal interfaces to the local supports: module attachment, the cooling system (pipes and coolant) and integration of the local supports (support structures and services). Groups involved in this proposal are working in these areas or have prior experience from the current pixel detector project.

3.4.1 Module Attachment

This section defines the requirements for module assembly on the SLHC local support structures. This activity has been covered in different ways by many groups during the ATLAS pixel detector R&D and assembly phase. Different options have been chosen giving good results. Based on this experience a proposal is made for the main engineering requirements and tasks needed to cover this activity.

The module attachment process on the local support structures must meet the following requirements:

1. <u>Module integrity → 100% yield aim.</u> From module reception to work at an assembly site to module assembly on local structures, many operations need to be performed. All these processes and tools need to be clearly defined and controlled to provide a high quality level of the assembly process. An example of the process used in the current pixel detector is shown in Figure 12.

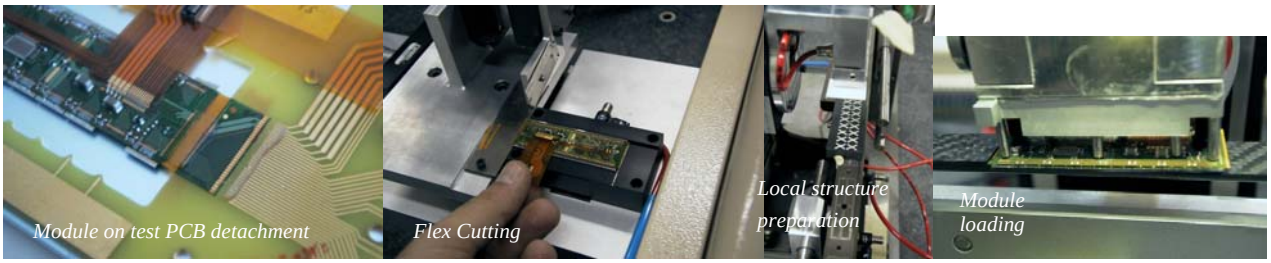

Figure 12 Task sequence of module assembly on ATLAS pixel detector.

2. Repeatability → e.g. good uniformity of the thermal coupling between modules and structures. An example of glue coverage measured in prototypes for the current pixel detector is shown in Figure 13.

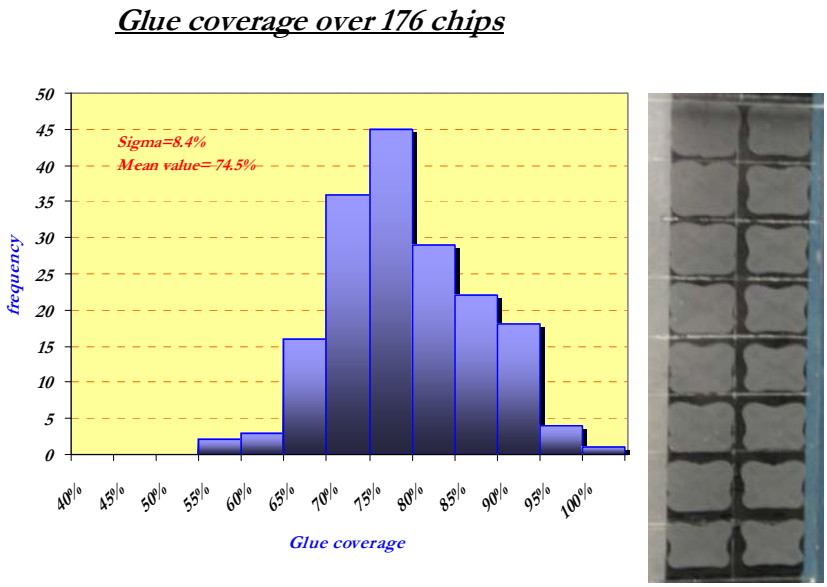

Figure 13 Glue deposition control on ATLAS pixel detector.

3. Accuracy →e.g. for detector alignment, for good module overlap with precision of the order of 50 microns.

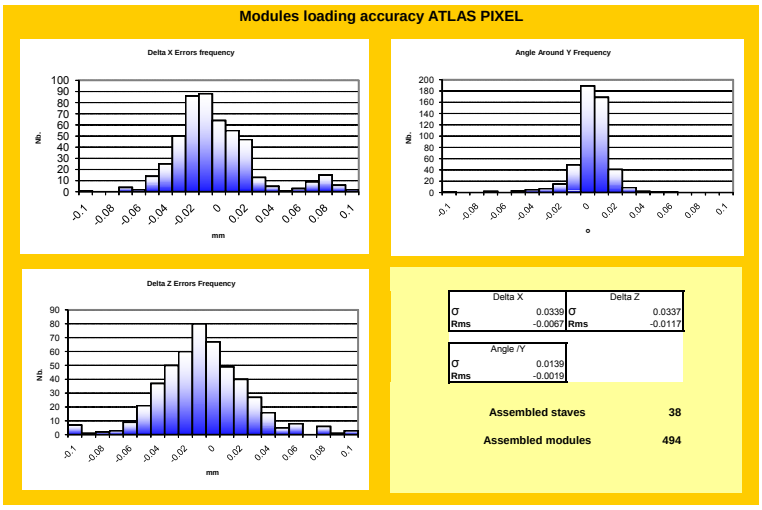

Figure 14 ATLAS pixel module loading accuracy overview.

4. Processes and tools easily deployable from one assembly site to another, since multiple module loading sites will be needed to meet future project schedules.

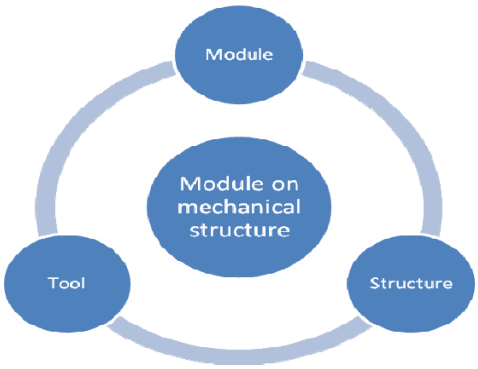

Figure 15 Schematic view of the interface of the local support to module attachment.

The interface between module loading and the local support is shown schematically in Figure 15. Our primary concerns are the interfaces between each element.

Module/Local Support interface:

- Need to design attachment techniques or to foresee structure designs that permit module replacement during assembly. This operation depends strongly upon the attachment method chosen and the local support design
- Need good thermal coupling (glue choice, glue deposition procedure, repeatability of module deposition)
- Need radiation hardness (mainly the glue choice)
- Need a process that is safe for flip-chip bonding (loads applied on modules need to be controlled and limited to reduce stress on bumps)
- Need a process which does not pollute the chip/detector interface (glue deposition procedure which guaranties high chip coverage and no glue between adjacent chips)

Local support/tool interface:

- Need to locate precisely the module placement tool relative to the local support (assembly accuracy).
- Tool needs to be flexible enough to be usable on various structure design types.

Tool/module interface:

- Design of module handling technology, which will require a coordination with the module design and flex design groups to allocate interface surfaces
- Fiducials (minimum three) visible on a module to align them on mechanical structures
- Flexibility needed to be usable for various modules sizes

3.4.2 Cooling System

The choice of coolant has a major impact on the design of the SLHC local supports. Studies done to date have, for the most part, assumed CO_2 cooling with a bulk fluid temperature near -35C. Carbon dioxide is a Green gas which offers a high Heat Transfer Coefficient with low pressure drops, provided it is operated at higher hydraulic pressure compared to standard refrigerants. The availability of experimental cooling test stands is crucial to carry on systematic studies on the heat transfer coefficient and the pressure drop in small diameter tubes with the goal to optimize the thermal performance and the material budget. Tubing material must be also characterized at high pressure to achieve a performing a reliable thermal design of the local support. In a preliminary phase, a basic cooling test stand where CO2 is metered from a bottle and vented in the atmosphere is required. This quickly allows the preliminary definition of the main cooling parameters for the thermomechanical design of the local

supports. A more refined system in closed loop recirculation, is then required for systematic measurement campaign and the qualification of the prototypes. Additional studies will be done in close communication with the Thermal Management group to determine the overall cooling requirements.

The second type of major interfaces of the cooling to the local supports are the pipes and connections (fittings or welding). Some pixel developments eg. for carbon-fiber tubes require a close connection of the tube design and fittings and this work is underway. Titanium pipes are an attractive option for the pixel system if they can be obtained readily with the appropriate length, wall thickness and diameter. Special fittings or connection methods are likely to be required for titanium piping (as opposed to stainless steel). A close connection with the Thermal Management activities to qualify pipe candidates, fittings and connection methods will be maintained.

3.4.3 Services and Integration

It is not the purpose of this proposal to provide complete designs for the pixel global supports and services. Nevertheless these are critical interfaces for the local supports and cannot be ignored. We will work closely with the ID Upgrade Integration working group on these issues. The goal is to make the local support designs compatible with concepts for the global supports and local services routing.

3.5 Diamond Detectors

Diamond sensors provide a variety of potentially advantageous features for a pixel detector for the ATLAS SLHC upgrade. In addition to a vast improvement in radiation hardness, diamond pixels provide the opportunity for a variety of simplifying and material-reducing features to the present ATLAS pixel support. Most importantly, the fact that diamond pixels can run at a large range of temperatures, including room temperature, rather than the silicon pixel requirement to run at temperatures below freezing, significantly reduces the need for cooling fluid and the resulting size of cooling pipes. The extremely high thermal conductivity of diamond, the highest of any non-superconducting material, reduces the amount of required cooling fluid further still. Additionally, diamond pixels are stiffer than silicon, reducing the necessary amount of material to avoid gravitational sag and vibrations.

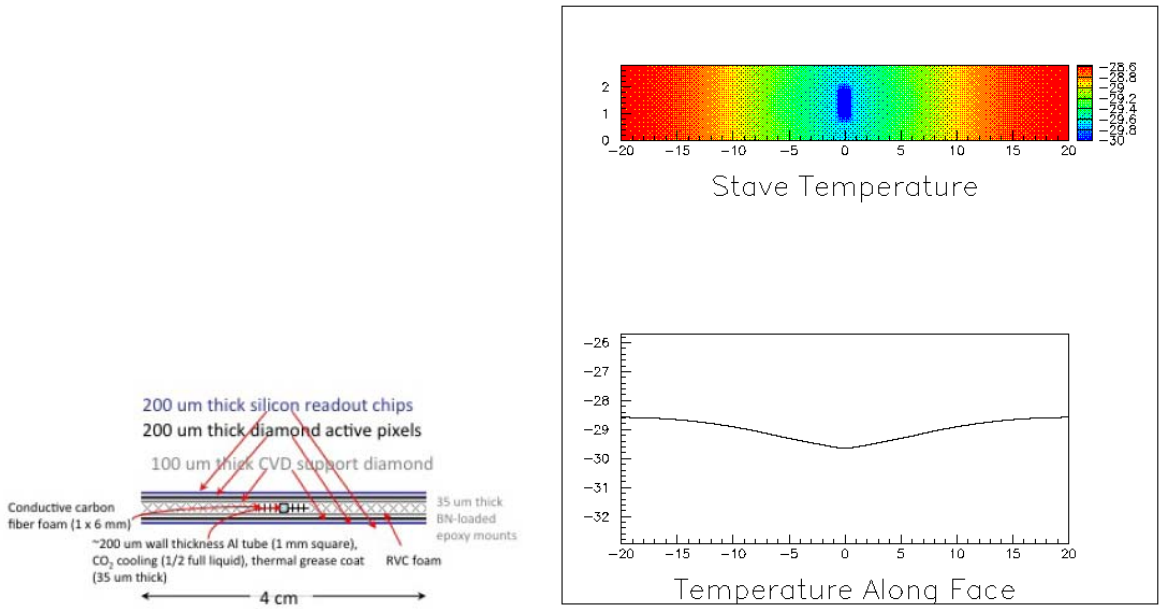

Figure 16 A baseline concept for a pixel barrel stave using diamond sensors(end-on views). Sensor, readout chip, structure, and cooling components are shown in the diagram on the left. The plots on the right show the steady-state temperatures in the stave, for 0.5 W/cm2 power consumption by the readout chips on each side of the stave, as determined by a simulation program. Dimensions are in mm, and temperatures are in C; note the difference in scale between the x- and y-axes in the upper right-hand plot.

Below we illustrate the present concepts for local support of diamond sensors, as well as the use of diamond's advantages as a structural and interface material regardless of whether diamond is chosen as the sensor technology, and briefly outline current R&D work as well as future plans.

In Figure 13, we illustrate a rudimentary baseline concept for the end-on view of a pixel barrel stave using diamond sensors. This is a double-sided stave, with sensors on both sides to maximize the ratio of hit information to total material. We use finite difference grid-based calculation program to simulate the steady-state temperatures in the stave and on the upper and lower surfaces of the stave. The material budget for this concept is given in Table 4. We have considered several variations on this baseline as well, including direct chemical vapor deposition of diamond on the silicon readout chips, without the need for glue or thermal grease.

Material	Avg. thickness (mm)	X_0 (%)
Silicon	0.4	0.427
Diamond	0.6	0.494
RVC foam	1.7	0.020
CCF foam	0.9	0.114
Aluminum	0.02	0.022
CO_2 liquid	0.07	0.029
Epoxy glue	0.14	0.115
Thermal grease	0.21	0.017
Copper traces	0.02	0.139
Total		1.37

Table 4 Material and radiation length as described in the text.

Diamond's advantages in thermal conductivity and stiffness make it a “perfect" structural material. Diamond would provide superior performance as a support and heat spreading material within the detector structure, independent of its advantages as a sensor material. Diamond could be used structurally in either of two ways: 1) as heat-spreading and stiffness-providing support sheets adjacent to the sensors, and/or 2) within glues and/or thermal greases as an additive to increase thermal conductivity. Several companies now provide diamond-loaded glues and thermal greases as their highest- performance thermally conductive compounds, and multiple manufacturers of chemical vapor deposited (CVD) diamond sheets and coatings exist.CVD structural diamond and diamond-loaded thermal grease have been ordered for testing.

In CY 2009, we will begin by testing the thermal conductivity of a CVD structural diamond sample, and the performance of diamond-loaded thermal greases and glues, that we have presently ordered. Thermal measurement will be performed using an IR980 infrared thermography camera from Cantronics Systems (Coquitlam, B.C.) in our laboratory. Following tests of the individual material properties, we will create a mock stave composed of a heating unit (graphite sheet, heated with an electric current) and a diamond sheet, with thermal grease between to provide the thermal contact. Following these tests, we will investigate cooling the heated diamond sheet with a cooling pipe as well as easily-adjustable Peltier thermoelectric chips. In addition to hardware studies, we will continue to computationally simulate both test-bench and realistic stave designs which use diamond materials.

4 Relation to existing efforts

The work on local supports for the SLHC is connected to similar activities for the Inner B-Layer (IBL) project. A subset of the participants in this proposal are responsible for the design of the local supports for the IBL and for important interfaces to the IBL local supports. Some of the R&D done under the auspices of this proposal may be applied on the much earlier timescale of the IBL project. However, we recognize that the IBL developments must occur on a faster timescale than for the SLHC. This will inevitably limit the time for new developments that will be needed for the SLHC. In addition, the scale and number of the local supports for the SLHC is much greater than for the IBL, and many of the requirements are different.

The requirements for the local supports for the SLHC are determined in part by the type of sensor used for pixel modules. We will maintain the necessary connection with development of planar, 3D and diamond sensors to update the thermal and other requirements as needed. A similar connection will be maintained with the front-end electronics development that is the principal driver of the heat load on the local supports. In addition, a connection with the global engineering design of the SLHC Inner Detector upgrade, including layout and services routing, will continue with regular exchange of information. Similarly, we have a close connection with the group developing thermal requirements and implementation. The goal is to reach common solutions to the type of coolant and the components of the cooling system to the greatest extent possible.

5 Schedule

The required schedule of work is determined by the critical milestones for the overall development of concepts to be documented in ATLAS SLHC Letters of Intent and Technical Design documents. We anticipate that our work will be reviewed before the submission of these documents. In addition, the design of the local supports depends critically on the type of coolant selected for the SLHC.A summary of these significant milestones is given in Table 5. A more detailed technical schedule to meet these milestones must be developed and reviewed by October 2009.

Milestone	Date
Initial Review of Design Concepts and R&D Plan	October 2009
Selection of Baseline Coolant	November 2009
ATLAS SLHC Letter of Intent	March 2010
Review of Designs and Prototype Results	September 2010
ATLAS SLHC Technical Proposal	March 2011

Table 5 Major milestones leading to documentation of concepts and prototype results in an ATLAS SLHC Technical Proposal.

6 Resources

The anticipated capabilities of each institution are described briefly below. The affiliation with technical institutions or companies is also described in conjunction with the applicable ATLAS institution.

6.1 University of Victoria

The University of Victoria is pursuing thermal and structural testing of both a diamond pixel option and diamond-containing high-thermal-conductivity interface compounds (glues & thermal greases). Our human resources presently include a faculty member, 1 undergraduate (full-time) and 1 graduate student (part time on this project), with more potentially to come next year. Our equipment resources presently include a Fluke TiR2 thermal imager, CGR7019 diamond-loaded and CGR7018 Al-nitride loaded thermal greases from AI Technologies, and a 2 cm x 6 cm CVD diamond sheet from Diamond Detectors Ltd.

6.2 Centre de Physique des Particules de Marseille (CPPM)

CPPM was the birthplace of evaporative fluorocarbon cooling for the ATLAS pixel detector and subsequently the ATLAS SCT detector. Initial studies started with C4F10 and moved to C3F8, the present coolant. In addition, CPPM designed the variant of the ATLAS pixel barrel stave with Al cooling pipe, which was finally adopted. CPPM designed the module placement robot which was used for 40% of barrel modules at Marseille and was duplicated for module placement in Genova. All replacements of defective modules of ATLAS barrel staves were done at Marseille. CPPM performed thermal measurements of the pixel barrel staves with Si heaters and real pixel modules both on evaporative C3F8 and classical liquid cooling systems. For this R&D CPPM will provide engineering and technical personnel for the design and test of Ti tubes, connectors, prototype staves with Ti tubes and module placement robot. The existing facilities include two 3D CMM machines, placement robot in the clean

room, a evaporative C3F8 cooling plant (also adaptable to other fluorocarbon coolants including C3F8/C2F6 mixtures) with thermal box and PVSS DAQ system, one liquid cooling facility with thermal box, climate-controlled chamber, and CAD systems with simulation software.

6.3 Laboratoire d'Annecy-le-vieux de Physique des Particules (LAPP)

LAPP generally contributes to the thermo-mechanical simulation of pixel local supports, in particular to the pixel IBL. This task is closely linked to CPPM stave prototype activities. Based on the current design, new developments are performed on fittings. The major change is the use of titanium alloy instead of aluminum. Other parameters such as the cone angle, the thread and the amount of material are being optimized to improve the physics performance. We use FEA codes that include optimization tools. A significant effort is made to take into account the quality assurance to increase the reliability of the solution. The validation procedures will have to be precisely defined. Contacts have been established with companies to have alternative industrial solutions. The manufacturing of the custom prototypes and the main part of the tests are performed at LAPP (except tests with C3F8 or CO2). These developments made for pixels could be a possible solution for strips as it provides a dismountable connection with a rather low amount of material.

6.4 Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE)

LPNHE has been involved in the design, construction and installation of several subdetectors for HEP experiments at LEP and LHC. For ATLAS, the contributions have been mainly on the Liquid Argon calorimeters up to now. For the ATLAS upgrade, LPNHE will provide 1.2 FTE experienced engineers for the design and simulation of mechanical structures, working with Catia and SAMCEF. Help will also be available from technicians for prototyping and construction of mechanical or thermal test benches. The workshop is equipped with a 3D measurement machine, a CNC mill, and several conventional machines (milling machines and lathe)

6.5 Bergische Universität Wuppertal

The University of Wuppertal has delivered major parts of the mechanical support for the barrel part of the current pixel detector. It has a mechanical workshop with special facilities to also mill carbon structures. At this workshop the basic structures for the pixel staves, the TMTs, were produced and high precision tools for stave and global support production machined. Module loading on the stave was another major mechanical responsibility of Wuppertal. Wuppertal has also a leading role in the development of an all – carbon stave with substantial experience in the machining of foam and R&D on a leak tight carbon pipe. Substantial equipment exists to qualify materials, pipes and staves. There is a close collaboration with the Institut für Verbundwerkstoffe (IVW) and other companies, particularly some specializing in carbon materials and composites.

6.6 INFN Genova

Genova has extensive experience in many aspect of stave design, qualification and module loading from built pixel detector. Genova will work in this project developing interfaces to modules, to flex hybrid and to global supports. Genova is interested to develop jigs or assembling and reworking staves with modules and flex hybrid. Also qualification of loaded and bare staves is a planned activity. Finally Genova wants to contribute to specific design issues needed for IBL staves.

6.7 INFN Milano

INFN Milano has been extensively involved in the design and production of several parts of the actual ATLAS Pixel detector and leaded the engineering of its integration. At present the lab is playing a relevant role in the design and in the prototyping of the mechanics of the IBL (Inserted B-Layer) developing the homogeneous stave concept. INFN Milano can provide personnel and engineering know how for thermal and thermo-mechanics simulation and, more generally, for the engineering issues related to the TMG (Thermal Management) and cooling.

6.8 Lawrence Berkeley National Laboratory (LBNL)

LBNL has extensive experience and capability for the design and fabrication of composite structures. LBNL designed and fabricated the local supports for the disk region of the current ATLAS pixel detector. LBNL is currently leading the effort to develop local support concepts based on low-density, thermally conducting carbon foam for all regions of the SLHC pixel detector. LBNL will provide engineering design and technical support personnel for the design, fabrication and test of prototype structures.

Allcomp, Inc is an industrial affiliate with LBNL. Allcomp, Inc is leader in the development of carbon foams and custom composite structures. We anticipate that Allcomp, Inc will continue the development of carbon foams and explore the feasibility of industrial production of staves and disk segments.

6.9 Ohio State University

OSU has experience in mechanical design, testing and extensive capabilities for fabrication of mechanical structures with access to the Physics Department Mechanical shop. This shop is staffed with six experienced machinists and tool & die makers and includes 2 CNC largebed mills and 2 CNC lathes. Together with the University of Victoria and the University of Toronto, OSU is pursuing designs using diamond as an active thermal material for primary heat transfer, thermal and structural testing of both a diamond pixel option and diamond-containing high-thermal-conductivity interface compounds (glues & thermal greases). OSU will provide machining and technical personnel for design, fabrication and testing.

6.10 SLAC National Accelerator Laboratory (SLAC)

SLAC has hosted many major HEP and astrophysics projects, including several silicon detectors, with a broad range of experience in design, testing and integration. Experimental and analytical studies on cooling system for ATLAS upgrade are in progress, in particular on the effective use of Carbon Dioxide as coolant. SLAC will provide engineering and technical personnel as for the design, fabrication and test of prototype structures and experimental cooling facilities. SLAC also has user support infrastructure to host university groups interested in jointly exploiting the lab facilities for ATLAS Upgrade.

6.11 University of Washington

Since 1990, the University of Washington group (a collaboration of the Physics and Mechanical Engineering Departments) has been involved in the design and fabrication of several particle detector subsystems. These have included the muon subsystems for the SDC detector at the SSC, the end cap muon subsystem for ATLAS at the LHC and the Run2b upgrade to the innermost two layers of the silicon detector system at D0. The latter was de-scoped to be just the addition of a new layer0 to the Run2a system and this device has been completed, installed in D0 and is now running successfully. All of the D0 work has involved the design, FEA analysis and fabrication of very lightweight, stiff and precise carbon fiber/epoxy structures. As a result, the UW group has developed a major core competence in this area. Another new major resource is the FAA Centre for Excellence for Advanced Materials in Transport Aircraft Structures that has been established at the University. The major thrust of this center is R&D on advanced composite structures. The University of Washington Physics Department machine shop is one of the largest physics department machine shops in the United States. We have high performance PC workstations with the required CAD/CAM (Unigraphics) and FEA (Ansys) software and personnel with long experience with these systems.

References

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[2] Thermo-mechanical simulation of the homogeneous stave ATL-IP-EA-0002