LA-UR--92-692

DE92 008477

**TITLE SILICON-BASED TRACKING SYSTEM:
 MECHANICAL ENGINEERING AND DESIGN**

**AUTHOR(S) W.O. Miller, M.T. Gamble, T.C. Thompson, K.A. Woloshun, R.S. Reid,
 J.A. Hanlon, F.D. Michaud, G.D. Dransfield, H.-J. Zloek, and
 A.P. Palounek**

**SUBMITTED TO Fourth International Industrial Symposium on the
 Super Collider**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The publisher acknowledges that the U.S. Government retains a certain degree of ownership in the copyright in this report, and that the publisher is authorized to reproduce and distribute reprints for government purposes.

The publisher also acknowledges that the publisher is authorized to reproduce and distribute reprints for government purposes.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

SILICON-BASED TRACKING SYSTEM: MECHANICAL ENGINEERING AND DESIGN

W. O. Miller, M. T. Gamble, T. C. Thompson, K. A. Woloshun, R. S. Reid,
J. A. Hanlon, F. D. Michaud, G. D. Dransfield, H.-J. Ziock, and A. P. Palounek

Los Alamos National Laboratory
Los Alamos, NM 87545

SILICON TRACKING SYSTEM MECHANICAL DESIGN

The Silicon Tracking System (STS) is composed of silicon strip detectors arranged both in a cylindrical array and an array of flat panels about the interaction region. The cylindrical array is denoted the central region and the flat panel arrays, which are normal to the beam axis, are denoted the forward regions. The overall length of the silicon array is 5.16 m and the maximum diameter is 0.93 m. The Silicon Tracking System Conceptual Design Report,¹ should be consulted for the body of analysis performed to quantify the present design concept. For the STS to achieve its physics goals, the mechanical structures and services must

- support 17 m² of silicon detectors and stabilize their positions to within 5 μ m,
- uniformly cool the detector system to 0° C and at the same time potentially remove up to 1.3 kW of waste heat generated by the detector electronics,
- provide up to 3400 A of current to supply the 6.5 million electronics channels, and
- supply all control and data transmission lines for those channels.

These objectives must be achieved in a high ionizing radiation environment, using virtually no structural mass and only low-Z materials. The system must be maintainable during its 10 year operating life. Tables 1 and 2 enumerate the silicon detector modules and STS performance specifications, while Figure 1, a cutaway view of the STS identifies its major components.

The method for supporting the individual central region silicon layers combines adjacent layers into superlayers. The four superlayers in the central region are supported pairwise by two composite support cylinders made of graphite/cyanate-ester resin (G/C-E) to minimize structural materials. The maximum silicon detector module length in the central region is 24 cm and correspondingly the maximum shell length is 24 cm. Three silicon shell assemblies, two 24-cm and one 12-cm long, comprise a 60-cm-long central region superlayer. The three shell combination is staggered in the z-coordinate as a function of r, to disperse the structural support mass, while the edge-to-edge overlap of each silicon layer provides circumferential particle hermeticity.

Electronics for powering the strips and data readouts are mounted at each end of the module assembly. Ten electronic read-out chips (128 channels each), 5 per side of the double sided strip detector, are required for each detector module. The silicon module is stiffened by edge-bonding two ultra thin G/C-E strips along the length of the detector edges. The silicon modules are bonded to the structural rings made from G/C-E to form the silicon shell assembly. These rings, hereafter denoted cooling rings, in addition to providing structural support, provide a passage for an internal heat pipe wick artery structure. Since the detectors in the central region are canted at an angle of 7.4° (Table 1) the top and bottom surfaces of the cooling ring take on a serrated appearance. Butane working fluid is wicked to this area. Heat from the electronics flows through

Table 1. Silicon Detector Module Specifications

	Central Region	Forward Region
Shape:	Rectangular	Trapezoidal
Active detector width:	3.2 cm	~6.4 cm
Number of channels:	1280	2560
Heat dissipation:	2 mW/channel	2 mW/channel
Module heat load:	2.56 W	5.12 W
Thermal conductive area: (@ cooling ring surface)	8 cm x 3.3 cm	~8 cm x 6.5 cm
Module heat flux: (@ cooling ring surface)	1.0 W/cm ²	1.0 W/cm ²
Cant angle:	7.4°	0°

Table 2. STS Performance Specifications

Positional stability:	r, r ϕ , z-80, 5, 250 μ m
Mounting precision:	r, r ϕ , z-80, 25, 250 μ m
Radiation exposure:	10 Mrad over 10 year service life. No measurable stability effects >5 μ m.
Material radiation length budget:	Structure and related service connections < 3% (excepting transition from central to forward and high rapidity regions).

the thin-walled composite cooling ring surface, onto which the module is mounted, and evaporates the cooling fluid medium.

The two forward regions are each composed of thirteen silicon annular disks. The detector modules in the forward region are not canted, which significantly simplifies the cooling ring design. Large separations between individual silicon layers make the prospect of combining adjacent layers into superlayers unattractive. Indeed, only for silicon layers near the central region are layers in sufficient proximity for this arrangement to be feasible. Individual modules are arranged circumferentially around the beam axis and are approximately twice as wide as those in the central region. The forward modules are trapezoidal-shaped to fit as individual arc sectors. Circumferential hermeticity is preserved by overlapping adjacent trapezoidal modules. Further simplification of the cooling and structural ring construction is provided by having adjacent modules in one disk on alternating sides of the cooling ring.

The space frame provides structural support for the cylindrical arrays of the central region and the flat, planar arrays of the forward regions. The design of this structure is intended to satisfy the STS performance specifications set forth in Table 2. The dimensional stability requirements motivated the use of MMC construction materials. Their ultrahigh elastic modulus is supplemented by their immunity to moisture induced distortions and the capability to tailor their longitudinal CTE to approach zero. This materials

Figure 1. STS detector view

selection also facilitates the use of adhesives in the demountable joints as a design option. The frame features an inner hexagonal geometry rotated about its longitudinal axis to avoid aligning with the outer hexagonally arranged members. This diminishes the radiation length experienced by any particle. Finally, the MMC space frame readily satisfies the requirement for butane compatibility in a high radiation environment.

The enclosure, in addition to containing the evaporated butane coolant, provides the primary conduit for transferring the mechanical loads on the silicon tracker space frame to the outer tracker space frame. The outer structure and the kinematic mounts prevent extraneous loads from being directly imposed on the delicate silicon structures while maintaining precision alignment. Hence, the outer shell structure is a key member in maintaining STS stability. An ultralightweight G/C-E sandwich construction has been chosen for the outer shell and two end cover plates. A 0.5 mm-thin beryllium shell will be used for the inner liner. This combination will provide a stiff low-mass structure.

Materials Investigations

The materials selection for the STS is motivated by three primary factors: (1) $5 \mu\text{m}$ stability in $r\phi$, (2) 3% radiation length restriction, and (3) radiation resistance in the presence of hydrocarbon fluids. The large scale of the detector dictates that linear expansion effects be minimized, whether from thermal or moisture effects. During the conceptual design effort, materials choices were narrowed to MMCs, whose CTEs can be tailored to be approximately zero, and hydrophobic cyanate-ester resin systems for the G/C-E composite candidate. Although the cyanate ester resins possess low moisture saturation levels, typically 1% (producing an overall laminate CME that is 1/50 that of a G/E laminate), there are still uncertainties in overall stability in a radiation and butane environment. The CTEs of G/C-E composites are also tailorable as well as having long radiation lengths. Experimental verification of the CTE and CME of the G/C-E system is in progress; Table 3 lists the experimental results of mechanical properties verification of this materials system.

Radiation Length Considerations

Throughout the design process, the need for ultralightweight, low-Z, radiation resistant materials will be stressed. Structures are configured to have minimum material thicknesses along the particle trajectories. The design requirement is expressed in terms of the number of equivalent radiation lengths. The design is restricted to using no more than 3% of a radiation length at normal incidence for all materials exclusive of the silicon detectors. Figure 2 illustrates the radiation length associated with silicon and the silicon detector support material, detector electronics, cabling, cooling, etc., expressed as a function of rapidity. It is clear that the baseline design nominally meets the requirement at zero rapidity ($< 3\%$), but as expected, its contribution increases slightly with increasing rapidity. This is an area of concern, and the preliminary design effort must address how further reductions in support materials may be attained.

COOLING RING DEVELOPMENT

Mold Development

A 30° cooling ring arc segment mold was fabricated to produce partial cooling ring prototype components for compression molding evaluation. Small components present similar technology issues as their larger counterparts. When an attempt to use an epoxy-based molding compound proved unsuccessful,

Table 3. Mechanical Test Results of P75054-3

Test	Neat Resin	Longitudinal	Transverse	Quasi-isotropic
Tensile Modulus	3.8 GPa	323.8 GPa	6.4 GPa	96.5 GPa
Tensile Strength	58.6 MPa	1 GPa	23.4 MPa	293.8 MPa
Poisson Ratio	0.39	0.32	0.0063	0.33
Comp. Modulus	3.4 GPa	268.7 GPa	6.2 GPa	77.2 GPa
Comp. Strength	6.9 MPa	337 MPa	41.3 MPa	131 MPa
Shear Modulus	0.96 GPa	4 GPa	1.6 GPa	
Shear Strength	27.6 MPa	40 MPa	19.3 MPa	

MX4925, a phenolic-based compound, was attempted because of its ease of fabrication. Both compounds were composed of approximately 63% graphite fibers and 37% resin. The cooling ring wall thickness of 0.4 mm is substantially thinner than typical compression molded components and proved troublesome. Poor material flow, quick curing, and difficult uniform charge deposition complicate fabrication. Ultimately, molding success was achieved using MX 4925 molding compound and the desire to use an epoxy resin was replaced by plans to use an advanced hydrophobic resin system.

Cooling rings composed of a very high elastic modulus graphite fiber and hydrophobic cyanate-ester resin are the ultimate objective of this program. Hence, a molding compound composed of P75 graphite fibers that were ball milled to approximately 100 μ m lengths and mixed with 954-3 resin was produced. These were significantly shorter than the 2.5-mm-long fibers used with the phenolic resin. The mold was again used to produce 30° arc segments from this compound. This resin system exhibited much more flow than the phenolic but failed to evenly distribute the fibers in the process. The segments also tended to adhere to the mold tenaciously. These problems were overcome by carefully shaping the partially cured, or advanced, charge in the mold which had been teflon coated. Uniform arc segments with well filled walls were produced by this process.

A larger mold, spanning 120° of arc, was fabricated to further this compression molding evaluation. Problems have been encountered because the larger mold requires more time for filling, hence allowing resin hardening during charge deposition. Resin flow and fiber uniformity issues are difficult to control using this new mold. High quality components are being produced with the mold but the rejection rate must be minimized. Once this is accomplished, material qualification and thermal conductivity enhancement will be undertaken using this mold. A photograph of high quality 30° and 120° arcs produced appears as Figure 3. Ultimately, a 360° cooling ring mold will be fabricated and rings will be produced for prototype testing, manufacturing optimization, and deployment into the STS.

Thermal Conductivity Enhancement

Chopped fiber/resin compression molded products are quasi-isotropic. The fibers tend to align with the mold wall yielding much higher in-plane physical properties than those transverse to the wall. Figure 4 depicts an ultrasonically obtained image of the distribution of fibers in the plane of a compression molded arc segment. More specifically, both mechanical as well as thermal properties are higher in the wall plane. Material physical properties transverse to the wall are fixed largely by the matrix physical properties. Since both the resin and the transverse fiber thermal conductivity are low, the transverse wall thermal conductivity is typically quite low. This situation is of significant concern for the STS. It is important to minimize the thermal gradient from the electronic readout chips to the cooling system evaporative wick structure. If not, the silicon strip detectors will operate above the 0°C base temperature chosen to maximize performance amid a radiation environment. Enhancement of the transverse thermal conductivity, while concurrently placing emphasis on obtaining uniform cooling ring properties is in progress.

Figure 2. Average fraction of a radiation length in the silicon detectors alone expressed as a function of rapidity: a) Silicon detectors alone; b) Add the gas inside enclosure vessel; c) Add the beam pipe; d) Add the outer enclosure vessel wall, cooling rings and wicks, support cylinders, and the space frame averaged over phi; e) Add the electronics packages, cabling and inner enclosure vessel wall.

Figure 3. 30° and 120° partial cooling ring arc segments

We have studied the thermal gradient through the cooling ring for conditions simulating the polystyrene wick conditions. Analytical FEM predictions were made as a function of transverse thermal conductivity (K_t) for a constant heat flux. This solution isolated the fin effect of the cooling ring sidewall. For low K_t , e.g., $0.5 \text{ W/m}^\circ\text{C}$, characteristic of the MX-4952 carbon/phenolic system, heat flows down the sidewall as well as through the top surface of the ring. In this situation, the peak temperature gradient is ameliorated through the sidewall fin effect. For higher assumed K_t values, the gradient directly across the ring top surface diminishes significantly. Since the temperature gradient is reduced noticeably, the sidewall fin effect similarly diminishes. In short, as we improve the transverse wall thermal conductivity of the molded ring, a significant reduction in the temperature gradient across the wall is achieved. The temperature gradient in the cooling ring sidewall becomes insignificant as the fin effect diminishes to zero. The results of this study clearly identified the benefit of achieving a K_t of roughly $4 \text{ W/m}^\circ\text{C}$. For this case the temperature gradient becomes the temperature drop across the wick, 2.5°C for the effective wick convective film chosen.

Numerous ring segments and material specimens have been fabricated and their thermal conductivities measured during the initial phase of this investigation. We studied the effects of high conductivity additives in the resin and the potential benefit of using shorter fiber lengths. To date, we have achieved a seven-fold increase in K_t ($3.6 \text{ W/m}^\circ\text{C}$). The results of this program are quite encouraging, however, they are preliminary. Noticeable improvements to this particular aspect of the ring design have been achieved and a factor of 10 increase over the earlier development ring models is ultimately expected. The final results of this investigation will be reported in the STS FY92 research and development report.

Thermal Stability Studies (Cooling Ring)

An analytical assessment of the ability of the silicon substructures to resist thermally induced

Figure 4. Ultrasonic image of graphite fiber distribution in a compression molded component

distortions is in progress. Precise measurement of the charged-particle momentum requires an ultrastable platform. It is important to note that the STS cooling system under development is intended to maintain a high degree of thermal stability. The evaporative cooling system should preclude any significant thermal gradient within the support structures. An understanding of the structures' sensitivity to thermally-induced distortions, will alleviate concerns regarding structural stability. An FE model of the central region silicon shell module has been developed and will aid in the design and construction of a prototype to be used in stability tests. As the STS design progresses this analytical effort will be expanded.

An FE model of a typical central region structure was developed representing a structure that has outer and inner diameters of 420 mm and 360 mm respectively and a length of 240 mm. Thirty-six silicon strips are attached to each diameter. The cooling ring cross section is 8 mm wide by 30 mm high with a wall thickness of 0.40 mm. The cooling ring will ultimately be a compression molded G/C-E resin composite component, possessing 60-64% fiber by volume. This analysis was performed assuming mechanical properties characteristic of IM7 graphite fibers embedded in an epoxy matrix. This combination yields an elastic modulus of approximately 78.3 GPa. Verification of the final compression molded cooling ring properties will be undertaken. A larger modulus of elasticity is anticipated for the final product than used in this analysis. Boundary conditions applied to the model simulate kinematic restraints at three equally spaced locations on each end. Figure 5 depicts the distortion that occurs when the temperature of the outer layer of silicon is allowed to rise uniformly. For small temperature changes, the distortion of the structure is linear with temperature.

For the size module studied, a 6° C to 8° C temperature difference between the upper and lower silicon layers composing a silicon superlayer could be tolerated because of the small, 2.5 μ m radial and 0.94 μ m axial, displacements that are induced. The larger silicon shell modules will be more flexible and are likely to exhibit more distortion under this temperature variation.

EVAPORATIVE COOLING SYSTEM WICK DEVELOPMENT

The dimensional stability requirements of the SSC silicon detector array dictate precise thermal control of the entire array to a nominal operating temperature with minimal thermal gradient within the array. The cooling system developed to achieve this thermal stability is by the free-surface evaporation of a cooling liquid in near-equilibrium with its vapor.¹ Thus, the entire detector containment vessel is filled with the coolant vapor and liquid is distributed to the cooling rings by a combination of hydrostatic and capillary forces. Based on the desire to maintain a nominal pressure of 1 atm. while operating near 0° C, butane was chosen as the coolant.

The critical research and development component of this system is the distribution wick. The wick must have sufficient capillary pumping capability to overcome the hydrostatic head in the system, up to 93 cm for the largest disks in the forward region, plus overcome the flow impedance through the wick itself. The gravity contribution dictates a maximum pore size of 5.4 μ m. The flow impedance is minimized by providing a low impedance artery circumferentially around the cooling ring. However, even a short flow path through the wick can contribute a substantial pressure drop if the wick permeability is low. The actual pressure drop contribution due to flow impedance is a function of wick thickness, which must be minimized, proximity of the heated surfaces to the circumferential artery, and the wick permeability, which is coupled to the pore size.

Based on these requirements, the wick development approach has been to examine candidate wick structures that have a maximum pore size of 4 μ m or less, have a feasible means of integrating a distribution artery and integrating with the complex geometry of the cooling rings in the central region, and are likely to have a high enough permeability to keep the wick thickness to an acceptable value.

The baseline wick material is a polystyrene foam which can be molded to the desired shape and incorporate the distribution artery in the molded form. The foam is produced by mixing water with a monomer with a ratio of 90/10. An emulsifying liquid and an initiator is added to the mixture. The emulsion is polymerized at 60° C and then dried. The resulting foam has densities of less than 0.1 g/cm³ and 95% porosity. A scanning electron micrograph of a typical foam wick cross section is shown in Figure 6. The structure consists of a honeycomb pattern of large pores connected by smaller pores that govern the effective capillary pore size. This structure has the potential of offering a relatively high permeability for a given capillary pore size.

The desired pore size has not yet been achieved, but it has been bounded. A 30 μ m pore radius sample has been machined from bulk material. Micrographs of this material show pore sizes less than 10 μ m, which suggests that the large pore size is a result of damage to that structure due to machining. Geometrically simple

Figure 5. FE model of a typical central region structure, deformed configuration.

Figure 6. Electron micrograph of the polystyrene wick structure demonstrating pores of 6–10 μm diam.

molded wick samples are currently being produced that have a capillary pore size less than 1 μm . The permeability of these molded samples is unacceptably low. Research and development efforts are focusing on tailoring the pore size and increasing the permeability by altering the foam mixing process.

Temperature drop was measured as a function of power density at the cooling ring surface, across a cooling ring/wick assembly. The test apparatus was a 30° arc segment on a 40 cm radius with electronic resistive heaters on each of 6 flats. A photograph of a 30° arc segment bearing a minimized polystyrene wick can be seen as Figure 7. The measured temperature drop was through the aluminum plate (negligible), cooling ring, wetted wick, and wick-vapor interface. For 1 W/cm², the measured temperature drop is approximately 4.5° C.

Further experiments were conducted to estimate the effective thermal conductance across the wick only. A resistance heater is mounted on a thin aluminum plate. The wick is attached to the opposite side of that aluminum plate. The measured temperature drop is from the center of the aluminum plate to the wick-vapor interface. Wick thicknesses of 0.25, 0.50, and 1.25 mm were tested. An effective conductance of about 0.3 W/cm² °C was calculated from the temperature measurements. This conductance was independent of wick thickness and power density in the range of 0.4 W/cm² to 1.3 W/cm².

These results, together with the assumption that wick pore size can be tailored to the desired value, indicate that the polystyrene wicks will meet the system design requirements. These wicks will be molded to the cooling ring shape in machined delrin molds thereafter bonded in place. Delrin has good machinability for cost effective mold production and good wettability to assure foam pore configurations at the foam-mold interface are essentially the same as in the bulk material.

Figure 7. 30° arc segment bearing a minimized polystyrene wick

ALIGNMENT AND ASSEMBLY CONSIDERATIONS

The overall alignment and assembly concept must be integrated with the mechanical structure in many important ways. The concept must provide a method for positioning silicon ladders to micron accuracies while they are being attached to the cooling rings and provide a method to integrate the structural shells and forward region planar arrays onto the detector space frame. The concept must also include alignment considerations for the completed detector including alignment shifts in shipping, reassembling, and positioning the detector onto the SSC beam line, in situ alignment, verification, calibration, and maintaining knowledge of alignment changes over the detector operating life. These alignment and assembly tasks are in addition to component and subassembly testing, structural verification, and correlation of test data with FE models which are important components of the overall alignment and assembly process.

One of the most important and challenging alignment tasks is developing a time-saving alignment maintenance system for the calibrated detector. With a recently developed fiber optic system, it will be possible to continuously monitor the relative 3-dimensional position of one subassembly relative to another and the position of the detector to the outside world using a compact, nonintrusive fiber optic motion sensor that functions by observing variations in light intensity. For this to be possible, the integrity and stability of the subassemblies must be assured so that the subassemblies can be treated as rigid bodies. This is another important reason for careful subassembly testing.

Detector Stability

The stability of silicon ladders, barrel, and planar subsystems will be tested using TV holography which provides quantitative and qualitative information about object shape changes in the presence of heat or mechanical forces. The results will be used to optimize subassembly designs, aid in the choice of appropriate adhesives, benchmark FE models, and provide experimentally tested analytical models for predicting many other detector mechanical performance features or structural performance characteristics under unusual operating conditions. TV holography offers sub-micron shape change resolution and hundreds of microns of dynamic range over a 1-m field of view using 30 mw He-Ne lasers. The system operates like an optical interferometer for objects that are not interferometric quality by comparing the shape of the object under load with its unloaded shape. Fringe patterns provide the information about shape change. Recent TV holography advances provide a way to interpret the fringe patterns and obtain quantitative information about the test object. As an example of the technique, a silicon ladder glue joint was tested using TV holography. Two silicon pieces, each 30 mm $\times$ 60 mm $\times$ 0.3 mm, were glued together along the 30 mm $\times$ 0.3 mm sides with Epoxy Technology H70S adhesive. The assembly was secured and loaded by deflecting its free end. The arrow of Figure 8 indicates the position of the butt joint, while continuity of the fringes across the joint indicate that the bonding is mechanically equivalent to a single piece of silicon.

Figure 8. Continuous fringe pattern across silicon detector butt joint.