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Silicon Tracker Design for the ILC*

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The task of tracking charged particles in energy frontier collider experiments has been largely taken over by solid-state detectors. While silicon microstrip trackers offer many advantages in this environment, large silicon trackers are generally much more massive than their gaseous counterparts. Because of the properties of the machine itself, much of the material that comprises a typical silicon microstrip tracker can be eliminated from a design for the ILC. This realization is the inspiration for a tracker design using lightweight, short, mass-producible modules to tile closed, nested cylinders with silicon microstrips. This design relies upon a few key technologies to provide excellent performance with low cost and complexity. The details of this concept are discussed, along with the performance and status of the design effort.

1. INTRODUCTION

1.1. Tracking at the Energy Frontier

With increasing center-of-mass energy and luminosity, a few stubborn problems drive the design of charged-particle tracking systems at collider experiments. First and foremost, precision momentum measurements require similarly precise measurements of curvature that can only be achieved through some combination of large detectors, high fields and precise spacepoint measurements. In addition, high overall occupancies and dense jets require fine readout granularity for pattern recognition. Finally, high data rates often require fast readout, while in some environments, extreme radiation tolerance is also a necessity. The common solution to these constraints in energy frontier collider experiments is the application of silicon microstrip sensors to large tracking systems.

This trend has generally come at the cost of more material. While low-mass silicon detectors with $\approx 0.5\%$ of a radiation length (X_0) per layer have been built for environments where low-momentum tracking is critical (e.g. the B-factories), such detectors are small, highly-optimized, hand-assembled vertexing detectors that are complemented by gaseous detectors at larger radius for tracking. Large-scale silicon trackers, such as those designed for ATLAS and CMS, must be simple, highly modular and mass producible. The widely held view is that such tracking detectors are unsuitable to the physics mission of the ILC.

1.2. Tracking at the ILC

The perception that all-silicon tracking is too massive has led to the abandonment of the concept by many in the ILC community. The alternative TPC-based designs are feasible because of the unique machine characteristics and physics environment of the ILC, but require a much larger tracking volume to achieve acceptable momentum resolution. This increases significantly the size and cost of the calorimeters and solenoid which comprise the most

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expensive components of the detector. These designs also require the development of new types of gaseous tracking detectors in order to meet the performance requirements.

Ironically, the very same machine characteristics that make gaseous tracking possible at the ILC also allow for the design of a silicon tracker with much less material than required for the LHC detectors. First and foremost, the occupancies are relatively low and there is a long quiet period between bunch trains for readout of the detector. As a result, the power-hungry portions of the readout chip need not be continuously operated, eliminating the need for active cooling of the front-end electronics. Lack of digital operation during the bunch crossings also allows for the elimination of material that is traditionally utilized to isolate the chip and other front end electronics from the sensors. Additionally, since the radiation doses are quite small, active cooling of the silicon itself is not needed. Finally, the pattern-recognition power of five pixel layers inside of the tracker greatly mitigates, if not outright eliminates, the need for standalone pattern recognition in the tracker so that fewer layers focused on the precise measurement of momentum will suffice.

2. THE SiD DESIGN CONCEPT

2.1. Mechanical and Electronic Design

The initial impetus for the SiD design concept was to reduce the size and cost of the centerpiece of the detector, the Si-W calorimeter, by using silicon tracking to allow a smaller detector volume. The starting point for this design used five layers of very long ($>$ 1.5 m) ladders of daisy-chained silicon microstrip detectors to reduce material by having only one readout chip per ϕ-wedge at the ends of each barrel. This approach presents some very difficult problems. Most obviously, the readout strips of such ladders have very high capacitances and the low signal-to-noise ratio that results threatens both resolution and efficiency. More significant are the problems of assembly and handing for the elements of a “gossamer tracker”. Such large ladders require many difficult steps to fabricate and tie together many valuable parts: a single mistake at any point means the loss of many components and a great deal of effort. Some steps, such as wirebonding, installation and in-situ replacement are highly problematic. Furthermore, it is not clear from a mechanical perspective how much material can safely be eliminated from such a structure: as the ladders grow in length, the width of each structural beam must increase exponentially in order to provide rigid support. Making such a structure not only rigid but strong and stable (resistant to buckling and vibration) may cost more in material than is a priori obvious.

Taking maximum advantage of the unique attributes of the machine environment provides an alternative: the use of very short modules from which most of the inactive elements of a traditional ladder design have been entirely eliminated. The resulting design shifts the responsibility for rigid and robust support onto an underlying structure of closed, nested carbon-fiber/rohacell cylinders similar to those fabricated for the DØ CFT [1] and the Atlas SCT [2]. The barrel tracking cylinders are closed at the ends with forward tracking disks and nested using annular rings that complete the structure as shown in Figure 1, described in further detail elsewhere [3]. These cylinders and disks are then tiled with small, simple modules; each with its own readout. A drawing of the barrel-module concept is shown in Figure 2. The elements of the mechanical design include a carbon-fiber frame with rohacell cross-bracing that supports single-sided silicon on one or both sides to provide stereo tracking as necessary. These frames clip into mass-producible PEEK (Polyetheretherketone) mounts attached to the support cylinders. The readout chip is Indium bump-bonded directly to the sensor using double metal readout to route signals to the bonding array and eliminates entirely a separate hybrid circuit board. A lightweight Kapton cable carrying power and data also bonds directly to the silicon, and the double-metal layer on the sensor is used to route them to the chip. At only 10 cm × 10 cm, the largest sensor size from a six-inch wafer, these modules are very easily assembled, installed and replaced. They are small enough to be used universally throughout the barrel layers and little is lost when a single module becomes damaged. Finally, should damage occur after installation, such modules can likely be replaced without disassembly of the entire tracker.

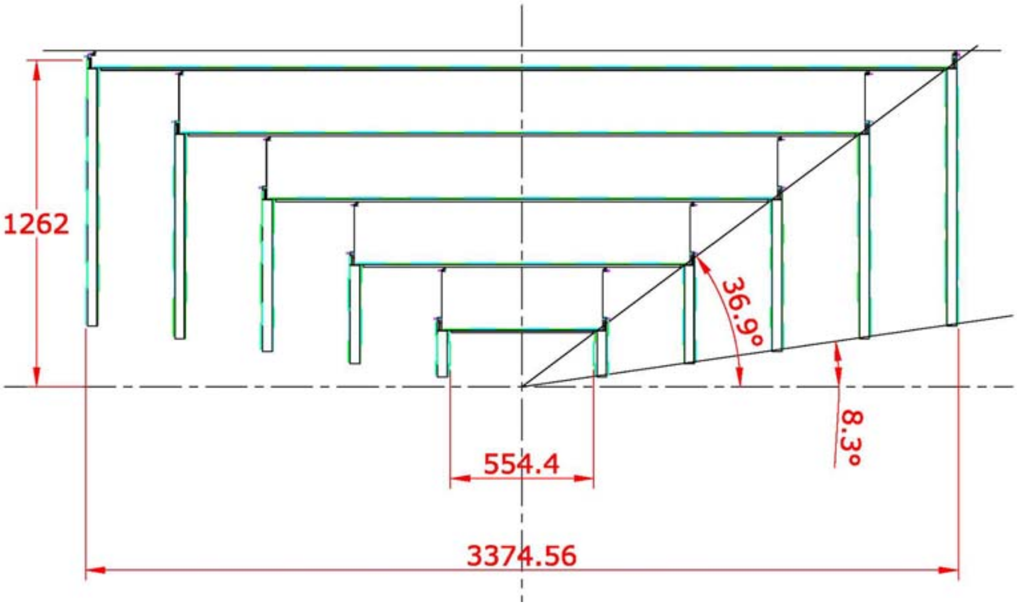

Figure 1: The layout of a proposed all-silicon tracker for the ILC (dimensions are mm). Nested, closed, carbon-fiber/rohacell cylinders are supported via spoked carbon-fiber rings and tiled with small low-mass silicon sensor modules. The material in these three regions (barrel, endcap, support rings) is discussed in Section 2.2.

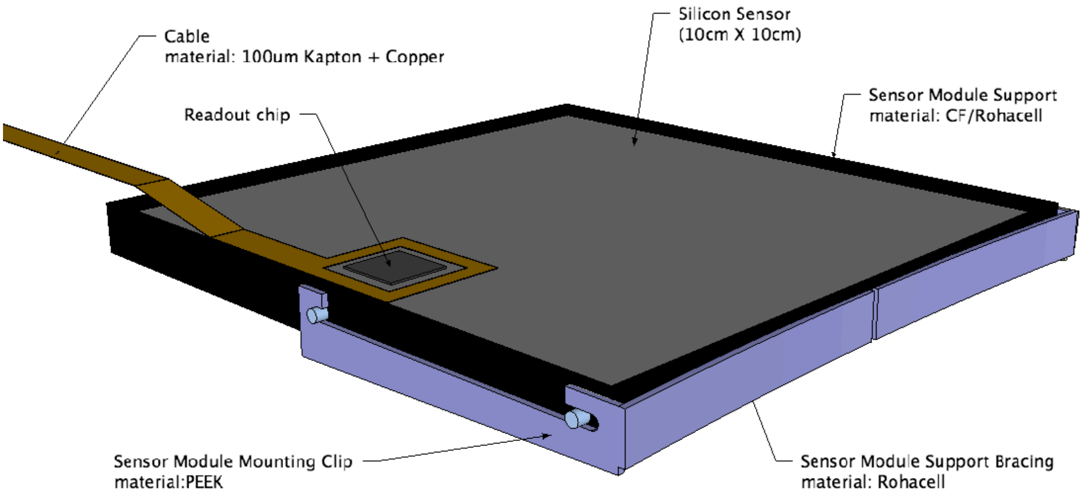

Figure 2: The design of a short sensor module for an ILC tracker. Note the absence of cooling or a hybrid circuit board. The readout chip and power/data cable bond directly to the sensor and all signals are routed using a double-metal layer on the silicon. Modules clip into PEEK mounts that are permanently affixed to the carbon-fiber/rohacell support structure. The small (10cm×10cm) size and simplicity of these modules allow for ease of handling, assembly and mounting.

Of central importance to the success of this design is the readout chip. The chip is a variant of that being developed for the Si-W calorimeter for the SiD concept. [4] This device has its power throttled back during most of the machine cycle to eliminate the need for cooling and create quiet conditions during the passage of the train. A set of four time-stamped buffers for each readout channel stores signals over threshold until the period between trains for digitization and readout. The buffering of raw signals eliminates the need for digital operation during beam

Table I: The material comprising each layer of the barrel tracker. The silicon itself is more than 1/3 of the total material. Slightly more than 1/2 of the remaining material ($0.300\%X_0$) is in the support cylinders. The totals correspond to the total material traversed by a track that passes through all five barrel layers at normal incidence.

Layer	Radius (m)	Half-length (m)	Silicon ($\%X_0$)	Support ($\%X_0$)	Readout ($\%X_0$)	Total ($\%X_0$)
1	0.200	0.267	0.321	0.506	0.045	0.872
2	0.463	0.617	0.321	0.506	0.060	0.887
3	0.725	0.967	0.321	0.506	0.074	0.901
4	0.988	1.317	0.321	0.506	0.088	0.915
5	1.250	1.667	0.321	0.506	0.103	0.930
Total	—	—	1.605	2.530	0.370	4.505

Table II: The material comprising each layer of the endcap tracker. The silicon itself is more than 1/3 of the total material. Roughly 2/3 of the remaining material ($0.500\%X_0$) is in the support disks. The totals correspond to the total material traversed by a track that passes through all five endcap layers at normal incidence.

Layer	$\|z\|$ (m)	Inner radius (m)	Outer radius (m)	Silicon ($\%X_0$)	Support ($\%X_0$)	Readout ($\%X_0$)	Total ($\%X_0$)
1	0.267	0.040	0.250	0.642	0.706	0.090	1.438
2	0.617	0.079	0.513	0.642	0.706	0.120	1.468
3	0.967	0.118	0.775	0.642	0.706	0.148	1.496
4	1.317	0.156	1.038	0.642	0.706	0.176	1.524
5	1.667	0.195	1.300	0.642	0.706	0.206	1.554
Total	—	—	—	3.210	3.530	0.740	7.480

crossings while ensuring that only hits from a single bunch crossing need be considered during pattern recognition and reconstruction of events. This is in stark contrast to much slower gaseous trackers which suffer occupancy from many crossings and thus face a much more difficult pattern recognition task.

2.2. Tracker Material Budget

A critical question for this design remains the material budget. Fortunately, the simplicity of the design and the use of very similar components in existing detectors allows for a realistic estimate of the required material. The material in the single-sided barrel layers is shown in Table I. This model assumes that the power and data cables to the hybrids originate at distribution boards mounted at the ends of the barrels for each layer and uses the estimated power requirements for the chips to define the amount of conductor needed for these cables.

Forward tracking will be a critical task at the ILC, but there are no examples of highly successful forward trackers at energy frontier colliders. Attempts to design forward tracking that overcomes the inherent difficulties have led to the consideration of three different module designs based upon wedge, hexagonal and square geometries. While a detailed design for the forward modules awaits the completion of tracking studies with the various options, it is possible to estimate the material in these modules from the barrel module design with the addition of silicon and readout on both sides. The material in the double-sided forward tracker is shown in Table II. This model assumes power and readout cabling similar to that for the barrels.

The final material that must be included are annular rings that support the end of each nested cylinder from the inside of the next cylinder out and serve as mounting for the power and readout distribution system. The 10 cm×10 cm power distribution boards mounted on these rings use DC-to-DC conversion and are assumed to service as many as 20 readout modules each. The resulting material on these barrel support rings occupies the solid angle in the vicinity of $|\cos\theta| \approx 0.75$ (the region covered by the ends of the barrels) and is summarized in Table III.

Table III: The material of the annular support rings that complete the nested-cylinder support structure and the power/readout distribution system. In the inner four layers, the power and readout distribution are mounted on the support rings: for the outermost layer these components are mounted separately due to space constraints imposed by the electromagnetic calorimeter. Some or all of this material is traversed by particles that pass through the ends of the barrels and the overlap between the barrels and disks.

Layer	$\lvert z\rvert$ (m)	Inner radius (m)	Outer radius (m)	Support ($\%X_0$)	Readout ($\%X_0$)	Total ($\%X_0$)
1	0.277	0.250	0.463	0.620	0.390	1.010
2	0.627	0.513	0.725	0.620	0.770	1.390
3	0.977	0.775	0.988	0.620	0.800	1.420
4	1.327	1.038	1.250	0.620	1.480	2.100
5 support	1.677	1.250	1.270	0.620	—	0.620
5 readout	1.700	1.038	1.250	—	1.910	1.910

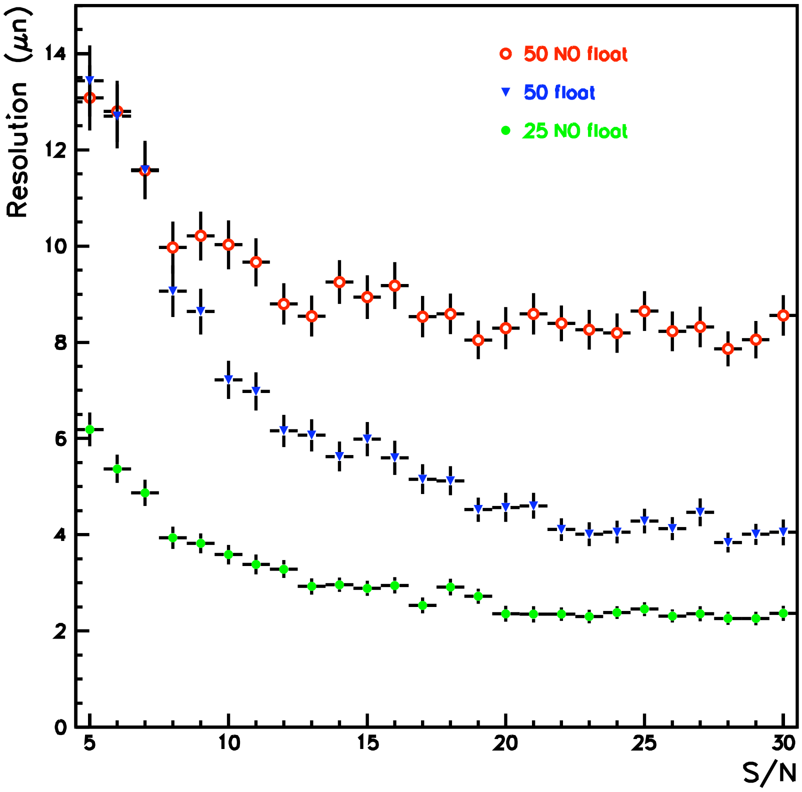

Figure 3: Single hit resolution as a function of signal-to-noise ratio for silicon strip sensors with 50 μm pitch, and 25 μm pitch. For the latter case, the results are shown for the the case where every strip is read out (25 μ readout pitch) and when there is a floating strip between each strip that is read out (50 μm readout pitch). Results are based upon a detailed physical model of charge deposition in silicon that has been tested against a variety of test-beam data and operating detector systems.

2.3. Performance

While material defines the low-momentum resolution via multiple-scattering effects, single-hit resolution determines the precision of momentum measurements for high-momentum tracks. One benefit of such short modules is signal-to-noise ratio in excess of 20:1. Assuming sensors with 50 micron readout pitch, one expects single-hit resolution no worse than 10 μm as shown in Figure 3, calculated using a charge deposition model benchmarked against test beam and physics data from several experiments [5]. However, addition of an intermediate floating strip every 25 microns offers major improvement in this regime, perhaps as good as 5 μm. Using the material model discussed above, the momentum resolution transverse to the beamline can be calculated and approximately parameterized as:

$$\frac{\delta P_T}{P_T^2} = 2.8 \times 10^{-5} \oplus \frac{1.4 \times 10^{-3}}{P_T \sin\theta}(\mathrm{GeV}/c)^{-1}, \text{ for } 10\ \mu\text{m single-hit resolution} \quad (1)$$

$$\frac{\delta P_T}{P_T^2} = 1.4 \times 10^{-5} \oplus \frac{1.4 \times 10^{-3}}{P_T \sin\theta}(\mathrm{GeV}/c)^{-1}, \text{ for } 5\ \mu\text{m single-hit resolution} \quad (2)$$

Studies of benchmark physics measurements have been performed that allow estimates of the physics performance of this design [6] using the above momentum resolutions. In general, these studies appear to support the assertion that this design is light enough that additional reduction in mass for the sake of low-momentum resolution is unnecessary. Those same studies also indicate that the improved single-hit resolution offered by the addition of floating strips to the short modules will offer significant improvement in many benchmark measurements.

Understanding and benchmarking pattern recognition is a more complicated task. Studies are underway that should illuminate the potential advantage of very short modules, the desirability of double-sided modules in the various layers, and the effects of multiple scattering and production of secondaries due to tracker material on efficiency and purity.

In parallel with the simulation effort, the development of the design continues. The main element of this program focuses on the most critical element of the readout chain, the front-end chip. Prototype versions of this device will be submitted alongside those for the Si-W calorimeter and evaluated with existing silicon-strip sensors to provide a realistic test of the design.

3. CONCLUSIONS

The same unique characteristics of the ILC that permit the consideration of a TPC tracker also allow for a large-scale silicon tracker design that uses very little material compared to previous similar trackers for the LHC experiments. This is achieved with existing technologies and construction techniques primarily by the elimination of many components that typically dominate the inactive material in large silicon trackers. The conceptual design for such a tracker uses a large number of small, identical modules to tile carbon fiber cylinders with silicon. This design has the advantage of simplicity and precise single-hit resolution by virtue of low noise and provides excellent momentum resolution for the physics of interest at the ILC. Further work, including the studies necessary to understand pattern recognition issues and prototype the key elements of the design, are currently underway.

Acknowledgments

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