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Physics Procedia 37 (2012) 143 – 150

Physics Procedia

TIPP 2011 - Technology and Instrumentation for Particle Physics 2011

The Silicon Detector Concept

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Abstract

The Silicon Detector (SiD) is a collider detector concept based on all-silicon tracking and a silicon-tungsten sampling calorimeter, complemented by a powerful silicon pixel vertex detector, a hadronic calorimeter contained within the solenoidal magnet and an instrumented flux return functioning as the muon system. Optimized forward detectors are deployed to ensure hermiticity and provide luminosity measurements. In order to meet the International Linear Collider (ILC) physics goals, we have designed a general purpose detector taking full advantage of the silicon technology. The silicon detector is performant, robust against machine-induced background and, by now, a mature concept.

Keywords: Silicon Detector Concept, SiD, International Linear Collider, ILC, Collider Detector

1. The Linear Collider Environment and Detector Requirements

The Silicon Detector [1] has been designed to exploit the physics discovery potential of e^+e^- collisions at center-of-mass energies ranging from $\sqrt{s} \sim 0.5 - 1TeV$. This will allow precision measurements of complex final states with well-defined initial states featuring tunable energy, known and variable beam polarization and a very small interaction region. However, the democracy of physics processes and the lower cross sections for interaction require sensitivity to all decay channels. Precision invariant mass resolution will be required for the higgs recoil measurement, which employs decays of the Z boson to tag higgs bosons irrespective of their decay. Isolating events resulting from $e^+e^- \rightarrow h + Z, Z \rightarrow e^+e^-, \mu^+\mu^-$ will require exceptional momentum resolution in the central tracker. Achieving the goal of $\sigma(1/p_T) = 5 \times 10^{-5}$ (GeV/c)$^{-1}$ for high momentum tracks will require a high magnetic field and a very low-mass precision tracker. Being able to identify and separate W and Z vector bosons via their hadronic decay products will require jet energy resolutions on the order of $\sigma_{E_{jet}}/E_{jet} \sim 3\%$. Studies of the top quark Yukawa coupling or higgs self coupling in the all-hadronic final states will require flavor tagging with high efficiency and purity. Identifying secondary and tertiary decays in jets resulting from b and c quarks places very stringent requirements on the vertex detectors. Achieving an impact parameter resolution of $\sigma_{r\phi} = \sigma_{rz} = 5 \oplus 10/(p \sin^{3/2}\theta)$ [μm] will require the inner radius to be very close to a small beampipe, exquisite intrinsic hit measurement resolution and the ability to time-resolve hits arising from different beam bunches. Searches for non-interacting

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1875-3892 © 2012 Published by Elsevier B.V. Selection and/or peer review under responsibility of the organizing committee for TIPP 11.
doi:10.1016/j.phpro.2012.02.365

beyond-the-Standard Model particles call for a hermetic detector ($\Omega = 4\pi$) to provide the requisite missing energy / mass sensitivity. Last, but not least, the detector has to be affordable, meaning that a cost-constraint needs to be included in the detector optimization process.

2. The Silicon Detector Concept

The Silicon Detector has, since its inception, been envisioned to be the best fully integrated system, not simply a collection of "best" subdetectors. A tightly integrated simulation / reconstruction / analysis software effort provides metrics for physics performance, while an integrated parametric cost model provides cost as a function of performance.

To achieve the requisite dijet invariant-mass resolution, the Particle Flow Algorithm as been employed as the primary design guide. This approach to jet reconstruction recognizes that the momenta of charged particles (contributing roughly two thirds of the average jet energy) is measured exquisitely well in the tracking system, meaning that if one can unambiguously associate clusters in the calorimeter to showers produced by these particles, then one need only measure the energy of neutral particles calorimetrically. Electromagnetic calorimeters can be built to be very efficient with reasonable energy resolution, meaning that only the neutral hadron component of the jet (roughly 10% of the energy) is measured with the resolution normally associated with a hadronic calorimeter.

Being able to distinguish showers from individual particles requires dense, highly segmented calorimeters. For electromagnetic showers, a sampling calorimeter composed of tungsten absorber and silicon readout is preferred. The expense of silicon motivates a small radius for the calorimeter, which places constraints on the tracking system. Achieving excellent momentum resolution requires both a high magnetic field to provide sufficient curvature to measure the track sagitta and very good intrinsic point resolution. This motivates the use of silicon strip detectors for the tracker and silicon pixel technology for the vertex detector. The central hadron calorimeter has to be compact to fit within the bore of an affordable solenoidal magnet. Finally, an instrumented magnetic flux return serves as the muon identification system, tail-catcher for penetrating showers, and makes the detector self-shielding. The key parameters of the SiD design starting point are listed in Table 1. The innermost tracking sub-system is the Vertex Detector (VXD), which comprises 5 cylinders and 4 sets of endcaps, composed of pixelated sensors closely surrounding the beampipe.

SiD BARREL	Technology	Inner radius	Outer radius	Z max
Vertex detector	Pixel	1.4	6.0	± 6.25
Tracker	Silicon strips	21.7	122.1	± 152.2
EM calorimeter	Silicon-W	126.5	140.9	± 176.5
Hadron calorimeter	RPCs	141.7	249.3	± 301.8
Solenoid	5 Tesla	259.1	339.2	± 298.3
Flux return	RPCs	340.2	604.2	± 303.3

SiD FORWARD	Technology	Inner Z	Outer Z	Outer radius
Vertex detector	Pixel	7.3	83.4	16.6
Tracker	Silicon strips	77.0	164.3	125.5
EM calorimeter	Silicon-W	165.7	180.0	125.0
Hadron calorimeter	RPCs	180.5	302.8	140.2
Flux return	RPCs	303.3	567.3	604.2
LumCal	Silicon-W	158.0	173.0	19.0
BeamCal	Silicon-W	295.0	320.0	14.5

Table 1. Key parameters of the baseline SiD design. (All dimension are given in cm.)

The impact parameter resolution will surpass $\sigma_{r\phi} = \sigma_{rz} = 5 \oplus 10/(p \sin^{3/2}\theta)$ [μm]. SiD has chosen a 5 T solenoidal field in part to control the e^+e^- pair background, and the cylinder and disk geometry is chosen to minimize scattering and ensure high performance in the forward direction. The VXD sensor technology

Fig. 1. Illustration of a quadrant of SiD (dimensions in mm).

is not yet chosen because the relatively high luminosity per train at the ILC makes integration through the train undesirable, and optimal technologies for separating the train into small temporal segments, preferably bunches, have not been determined. This is not a problem, since this choice will have almost no effect on the rest of the SiD design, and the VXD can be built and installed after many of the main detector components are complete.

SiD has chosen silicon strip technology, arrayed in 5 cylinders and 4 endcaps for precision tracking and momentum measurement. Particular attention has been given to fabricating the endcaps with minimal material to enhance forward tracking. The sensors are single sided silicon, approximately 10 cm square, with a pitch of 50 μm. With an outer cylinder radius of 1.25 m and a 5 T field, the charged track momentum resolution will be better than $\sigma(1/p_T) = 5 \times 10^{-5}$ (GeV/c)$^{-1}$ for high momentum tracks. The endcaps utilize two sensors bonded together for small angle stereo measurements. Highly efficient track finding has been demonstrated in simulation using the integrated tracking system.

SiD calorimetry is optimized for jet energy measurement based on a Particle Flow strategy. The challenge is identifying the energy which charged particles deposit in the calorimeters, and discriminating it from the energy photons and neutral hadrons deposit, so it can be removed. This requires highly segmented readout, both transversely and longitudinally, and in the ECAL puts a premium on minimizing the spread of electromagnetic showers. SiD calorimetry begins with an exceptionally dense, highly pixelated Silicon – Tungsten electromagnetic section. The ECAL has alternating layers of W and silicon pixel detectors; there are 20 layers of 2.5 mm tungsten followed by 10 layers of 5 mm tungsten. The silicon detector layers are only 1.25 mm thick. This results in a Moliere radius for the thin section of 13.5 mm. Each sensor is divided into 1024 hexagonal pixels, forming an imaging calorimeter with a track resolution of ~1 mm. The ECAL has a total of 26 X_0. The same technology is used in the endcaps. Silicon detector technology is used in the vertex detector, tracker, and ECAL because it is robust against machine backgrounds, only sensitive to backgrounds in a single bunch crossing, and has high intrinsic precision.

The Hadronic Calorimeter (HCAL) is made from 4.5 λ of Stainless Steel, divided into 40 layers of steel and detector. The baseline detectors are RPCs with 1 cm square pixels, inserted into 8 mm gaps between the steel layers. The same technology is used for the endcaps.

The calorimetric coverage is completed in the forward direction by a LumCal and a BeamCal. The LumCal overlaps the endcap ECAL, and is designed to provide a measurement of the luminosity with a precision of ΔL/L of 1×10^{-3}. The Lumcal is Si-W, with the pixelation designed to optimize the luminosity measurement precision. The BeamCal is the smallest angle calorimeter and is mounted to the inboard side of QD0. The BeamCal sensor technology may be diamond or low resistivity silicon. Both calorimeters are designed for a 14 mrad crossing angle.

The SiD 5 T superconducting solenoid is based on the CMS design, but has 6 layers of conductor. The stored energy is ~1.6 GJ. The critical cold mass parameters, such as stored energy/Kg, are similar to CMS.

The flux is returned with an iron structure, configured as a barrel with movable endcaps. The present design limits field leakage to <100 G at 1 m. The flux return is 11 layers of 20 cm iron. The flux return also is the absorber for the muon identifier and is an important component of SiD self shielding. The barrel is composed of full length modules to help keep the structure stable during push pull and to enable full length muon detectors. The endcaps support the final-focus QD0 magnets, with provision for transverse alignment of the quads and vibration isolation. SiD is designed for rapid push pull and rapid recovery after such motion. Precision alignment will utilise a geodetic network of frequency scanning interferometers.

A plan view of one quadrant of the detector is shown in Figure 1.

In the next sections we describe the individual detector subsystems in more detail.

3. Vertex and Tracking System

Within the SiD concept the tracking detectors are regarded as an integrated system. Although individual detector components can be identified in the vertexing and tracking system, the overall design is driven by the combined performance of the pixel detector at small radius, the outer strip detector at large radius and the electromagnetic calorimeter for the identification of minimum ionizing particle (MIP) track stubs. The main elements for the pattern recognition are the highly pixelated vertex detector and the low occupancy outer strip detector.

3.1. Vertex Detector Design

The vertex detector integrates with the outer tracker and remainder of the detector to provide significantly extended physics reach through superb vertex reconstruction – primary, secondary and tertiary. The vertex detector consists of a central barrel section with five silicon pixel layers and forward and backward disk regions, each with four silicon pixel disks. Three silicon pixel disks at larger $|z|$ provide uniform coverage for the transition region between the vertex detector and the outer tracker. Barrel layers and disks are arranged to provide good hermeticity for $\cos\vartheta \leq 0.984$ and to guarantee good pattern recognition capability for charged tracking and excellent impact parameter resolution over the whole solid angle. A side-view of the vertex detector is shown in Fig. 2. To provide very robust track finding performance, the baseline choice is a sensor technology that provides a time stamp on each hit with sufficient precision to assign each hit to a particular bunch crossing, significantly reducing the effective backgrounds. Two technologies are being researched. The first is a CMOS based monolithic pixel sensor called Chronopixel. The main goal for the design is a pixel size of about $10x10\mu m^2$ with 99% charged particle registration efficiency. The second, more challenging technology, is the 3D vertical integrated silicon technology.

3.2. Tracker Design

The ILC experiments demand tracking systems unlike any previously envisioned. In addition to efficient and robust track-finding, the momentum resolution required to enable precision physics at ILC energies must improve significantly upon that of previous trackers. The design must also minimize material in front of the calorimeters that might endanger particle-flow jet reconstruction. Even with the largest feasible magnetic field, the tracking volume is quite large so that tracker components must be relatively inexpensive and easily mass-produced. Finally, the tracker must be robust against beam-related accidents and aging.

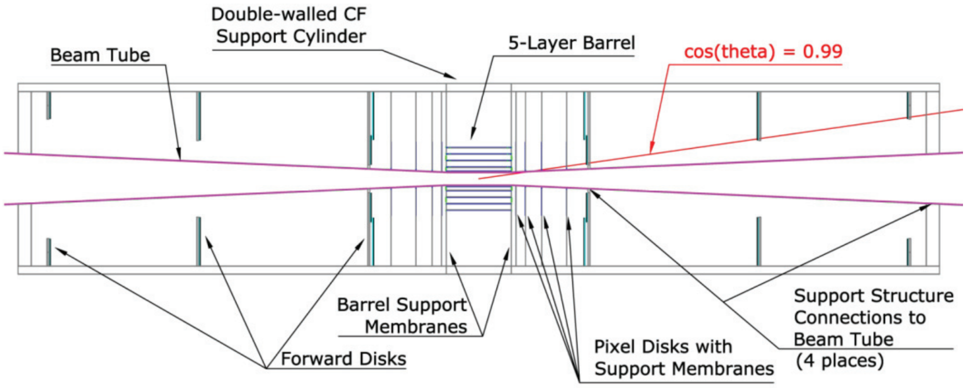

Fig. 2. R-z view of the vertex detector.

These requirements have led to the choice of silicon microstrip detectors for the tracker. The outer silicon tracker design consists of five nested barrels in the central region and four cones in each of the end regions. The sensor modules are overlapped to remove any gaps between sensitive areas of the silicon. Sensors on the disk modules are normal to the beam line. The supports are double-walled carbon fiber structures around a Rohacell core. Fig. 3 shows an elevation view of the tracking system and a 3D cutaway view.

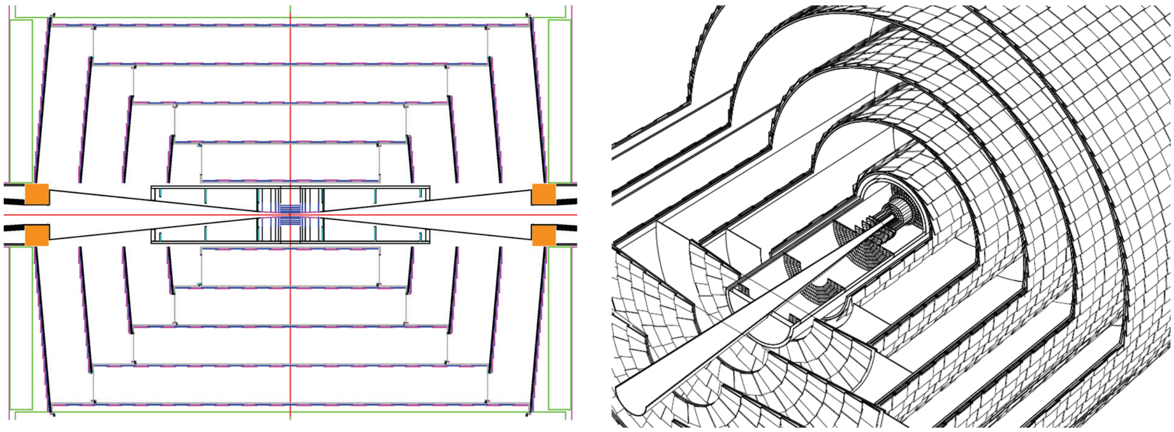

Fig. 3. R-z view of the whole tracking system and a 3D cutaway view.

The number of radiation lengths represented by the tracker and the number of hits deposited by a high momentum track are shown in Fig. 4, demonstrating a material budget less than 20% of a radiation length throughout the tracking volume and uniform coverage of at least ten hits per track down to very low forward angles.

4. Calorimetry

The baseline design for the SiD calorimetry is driven by the Particle Flow Algorithm approach introduced earlier, which imposes a number of basic requirements on the overall system. The entire central calorimeter system must be contained within the solenoid in order to identify all of the energy depositions arising from a particle shower. Both the electromagnetic and hadronic calorimeters must be sufficiently finely segmented, both longitudinally and transversely, to allow efficient tracking of minimum ionizing particles prior to showering, as well as dense enough to contain and isolate the ensuing particle showers. To

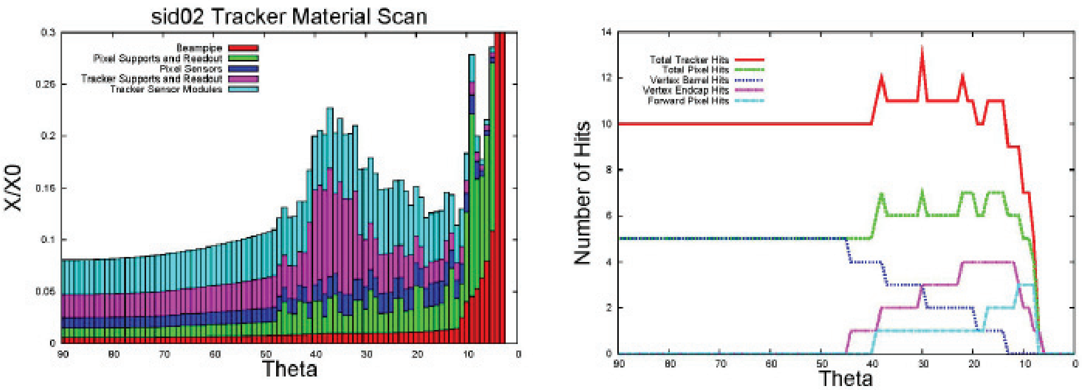

Fig. 4. Material budget of the tracking system (left) and number of hit layers in the tracking system as a function of polar angle (right).

ensure hermiticity the calorimeter system must extend down to small angles with respect to the beam pipe and must be sufficiently deep to prevent significant energy leakage. The mechanical design of the calorimeter must consist of a series of modules of manageable size and weight to ease detector construction and the boundaries between modules must be as small as possible to prevent significant un-instrumented regions. The detectors must have excellent long-term stability and reliability, since access during the data-taking period will be extremely limited, if not impossible. And the technologies chosen must be affordable.

4.1. Electromagnetic Calorimetry

Because SiD is globally optimized and employs the PFA for jet reconstruction, a sampling electromagnetic calorimeter (ECAL) provides sufficient energy resolution for ILC physics. A driving force in our design has been the desire to provide as small an effective shower radius as feasible, along with a transverse segmentation of the readout which is well below this size. Tungsten has been selected as the absorber due to its small radiation length, relatively large interaction length and its mechanical suitability. Since showers will spread in the material between the tungsten layers it is crucial to keep the readout gaps as small as possible. Silicon has been selected for the readout because it can be highly segmented and made very thin. The longitudinal structure has 30 total layers. The first 20 layers each have 2.5 mm tungsten thickness and 1.25 mm readout gap. The last 10 layers each have 5 mm tungsten thickness plus the same 1.25 mm readout gap. This configuration attempts to compromise between cost, shower radius, sampling frequency, and shower containment. The cost is roughly proportional to the silicon area, hence the desire to limit the total number of layers. Finer sampling for the first half of the total depth improves improved energy resolution for showers of typical energy. The total depth is 26 X0, providing reasonable containment for high energy showers. The mechanical design of the ECAL barrel consists of 12 independent wedges arranged as overlapping staves. This eliminates any uninstrumented gaps between the modules pointing to the interaction region and allows the cooling and cables to be located on the exterior of the barrel. In the baseline design, the readout layers are tiled by large, commercially feasible silicon sensors segmented into $13mm^2$ pixels which are individually read out with a wide dynamic range sufficient to record both MIP and Bhabha electron signals. The complete electronics for the pixels is contained in a single chip (the KPiX ASIC) which is bump bonded to the wafer. The low beam-crossing duty cycle allows a reduction of the heat load by power pulsing, which permits passive thermal management within the ECAL modules. The realization of this technology has been the subject of an intensive, ongoing R&D program.

An option to the baseline technology employs Monolithic Active Pixel Sensors to digitally read out $50x50\mu m^2$ silicon pixels. The MAPS option is designed to fit in the same mechanical structure as the baseline option and we foresee a sensor size of 5 x 5 cm (baseline) for a final system.

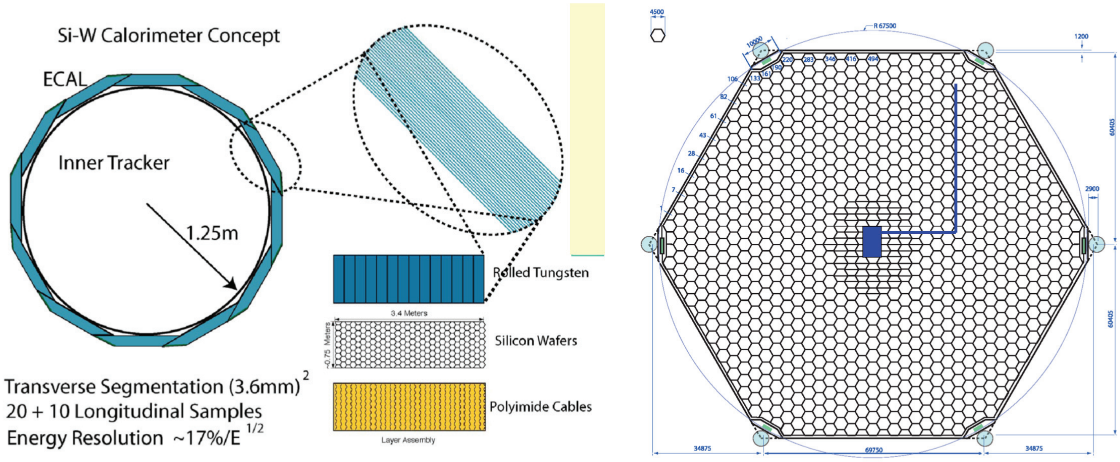

Fig. 5. Overall mechanical layout of the ECAL and layout of one sensor.

4.2. Hadron Calorimeter

The PFA-based hadron calorimeter (HCAL) is again a sampling calorimeter composed of a sandwich of absorber plates and instrumented gaps with active detector elements. The total absorber depth amounts to 4.5λ, composed of stainless steel, divided into 40 layers, separated by 8mm readout gaps. The HCAL barrel is divided into twelve azimuthal modules located inside the magnet and surrounds the electromagnetic calorimeter, the latter being fixed to it. Each endcap forms a plug that is inserted into an end of the barrel calorimeter. The layer structure of the end cap calorimeters is the same as for the barrel.

The baseline readout technology is Resistive Plate Chambers (RPCs), which are gaseous detectors currently employed primarily for the large muon systems of colliding beam detectors. The detectors feature a gas volume defined by two resistive plates, typically Bakelite or glass. The outer surface of the plates is coated with a layer of resistive paint to which a high voltage is applied. Depending on the high voltage setting of the chamber, charged particles crossing the gas gap initiate a streamer or an avalanche. These in turn induce signals on the readout strips or pads located on the outside of the plates. The assembly of the chambers is straightforward and does not require special skills or tools. The materials needed for their construction are readily available and cheap. The readout of the chambers consists of a pad board with $1x1cm^2$ pads, read out individually. In such a digital calorimeter the energy of incident particles is reconstructed as a function of the number of pads with signals above threshold. We have also been developing an option using Gas Electron Multiplier (GEM) as the sensitive gap detector technology. GEM can provide flexible configurations which allow small anode pads for high granularity. It is robust and fast with only a few nanosecond rise time, and has a short recovery time which allows a higher rate capability than other detectors. Another very interesting alternative for the DHCAL active medium is the MICRO MEsh GAseous Structure (MICROMEGAS) based on micro-pattern technology.

5. Magnet

The 5 Tesla superconducting solenoid envisioned for SiD is an expensive and technically challenging component to procure. However, its design is based on the engineering philosophy, experience and details used for the successful 4 Tesla CERN CMS superconducting solenoid, the largest in the world. On the basis of the CMS experience there are no show stoppers for the superconducting solenoid or any other magnet system component. It remains to implement the CMS construction techniques, examine other possible conductor choices, and refine decisions to reduce cost and complexity and improve safety margins.

6. Muon System

The SiD muon system is designed to identify muons from the interaction point with high efficiency and to reject almost all hadrons (primarily pions and kaons). The muon detectors will be installed in the gaps between steel layers of the solenoid flux return. The required position and rate capabilities of the detectors are modest and can be met by several different detector technologies. The baseline design uses double layers of resistive plate chambers(RPC). Also under consideration are extruded scintillator strips read out by silicon photomultipliers (SiPMS). Cost, reliability and physics capabilities will determine the preferred choice.

7. Summary and Future Plans

Clearly a full description of the detector concept and a complete accounting of the tremendous amount of detector research and development completed over the past decade and currently ongoing cannot be accommodated in these conference proceedings. The ILC Letter Of Intent (LOI) exercise [2] was a significant milestone in the evolution of the SiD Concept and provides the most complete description of the detector to-date. Since then we have continued R&D for all subsystems, each on its own timeline. An interim progress report is about to be published detailing the achievements since that time and will be available soon [3]. The current focus and goal for SiD is to complete the design work for the Detailed Baseline Design (DBD) of the detectors which will accompany the ILC Technical Design Report to be delivered in late 2012. The goal is to have a design sufficiently advanced that a detector could be built and ready to take data when the next energy frontier collider facility is realized.

References

[1] http://silicondetector.org
[2] http://arxiv.org/abs/0911.0006
[3] http://www.linearcollider.org/about/Publications