DESIGN AND DEVELOPMENT OF A DENSE, FINE GRAINED SILICON TUNGSTEN CALORIMETER WITH INTEGRATED ELECTRONICS

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A fine grained silicon-tungsten calorimeter is ideal for use as the electromagnetic calorimeter in a linear collider detector that is optimized for particle-flow reconstruction. Our design is based on readout chips which are bump bonded to the silicon wafers that serve as the active medium in the calorimeter. By using integrated electronics we plan to demonstrate that fine granularity can be achieved at a reasonable price. Our design minimizes the gap between tungsten layers leading to a small Molière radius. The size of the Molière radius is an important figure of merit for energy-flow detectors.

1. Calorimetry for the SiD Detector

The Silicon Detector (SiD) is a conceptual design for a linear collider detector that is being developed as part of international efforts to explore

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detector options for future linear colliders. The SiD design is based on the much discussed concept of "particle flow" in which events with hadronic jets from electron-positron collisions are reconstructed using combined measurements from the tracker, the electromagnetic calorimeter and the hadronic calorimeter. In order to obtain the highest resolution for angular and energy measurements, it is important to have high enough granularity in the calorimeters to separate energy deposited by charged particles (which has already been measured in the tracker) from that of the neutral particles. The role of the granularity of the electromagnetic calorimeter is especially important in the SiD concept because the SiD detector is more compact that other detectors which have been proposed of the linear collider such as TESLA[1,2].

In addition to particle-flow measurements, important for hadronic final states, a linear collider detector must be able reconstruct high momentum leptons or photons in events such as $e^+e^- \rightarrow hZ \rightarrow \mu^+\mu^-X$ where the $\mu^+\mu^-$ results from the Z boson. The momentum resolution for this process scales as BR^2 where B is the field and R is the tracker radius. In the SiD design, the B field is chosen to be large, 5T, to confine low energy e^+e^- pairs produced as the bunches cross in the detector to the beam pipe. To give the required momentum resolution, the radius of the tracker is then taken as 1.25 m.

Another important consideration for the detector is the ability to reconstruct τ lepton final states that result from a wide range of new physics scenarios. The τ lepton include closely spaced charged and neutral pions which must be resolved in the electromagnetic calorimeter.

In the SiD design both the electromagnetic and hadron calorimeters are placed inside of the coil (see Fig. 1). This gives the best possible resolution for neutral hadrons and allows for efficient tracking of charged tracks that penetrate the electromagnetic calorimeter and interact in the hadron calorimeter.

In addition to high granularity, it is also important that the electromagnetic calorimeter have reasonable energy resolution. Simulations show that the resolution of a sampling calorimeter with 30 longitudinal samplings is approximately $15\%/\sqrt{E}$. This exceeds the requirements for particle flow algorithms and for most physics processes of interest[3].

Silicon-tungsten is a reasonable technology for a high granularity sampling electromagnetic calorimeter in an LC detector[4]. Silicon can be segmented finely and tungsten has a small Molière radius. The concept for the silicon-tungsten electromagnetic design is shown in Figure 2.

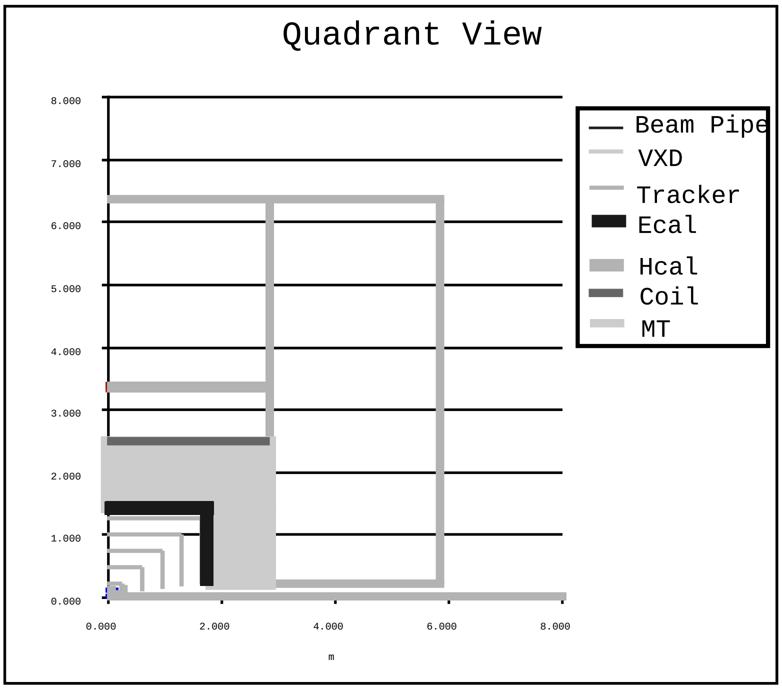

Figure 1. Quadrant view of SiD detector.

1.1. *Calorimeter Optimization*

Most of our effort has been devoted to designing a calorimeter with highest granularity possible. A reasonable figure of merit for the granularity is

$$f_E = \frac{R_M}{R_{cal}}$$

where R_M is the Molière radius of the calorimeter and R_{cal} is the inner radius of the calorimeter. Here it is assumed that granularity of the individual pixels can be made smaller than R_M. Cost optimization calculation[5], in which the radius of the calorimeter (and tracker) R_{cal} is increased, while keeping BR_{cal}^2 constant, favor small values of radius and the largest practical value of B, in this case 5 T. Given that R_{cal} is effectively fixed by cost constraints, the SiD design attempts to make R_M as small as possible.

The value of R_M depends on the sampling material in the calorimeter and the size of the gap between layers. There are no materials widely available with a significant better value of R_M then tungsten, so most of

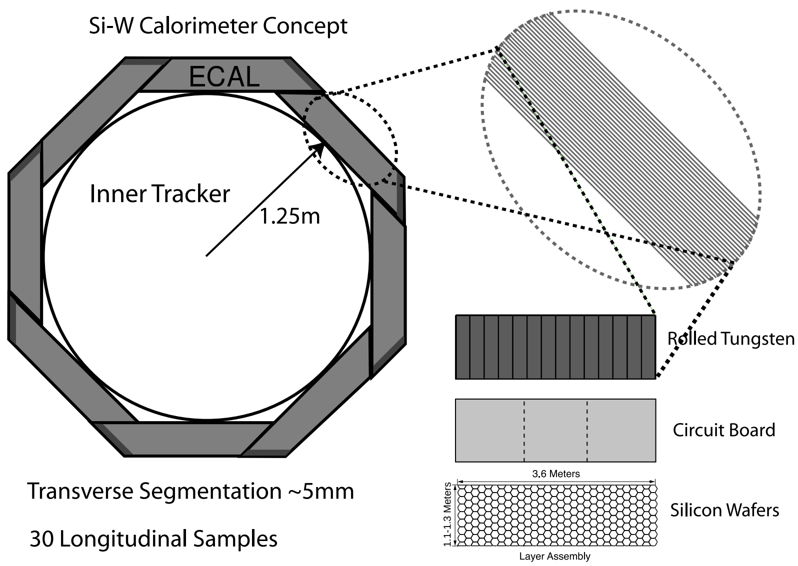

Figure 2. The concept for the electromagnetic calorimeter.

our effort has been aimed at a design with a narrow gap between tungsten layers.

The size of the gap is closely connected to the design of the electronics. We plan to use electronics which are directly bump bonded to the silicon sensors. This avoids having a large number of connections routed to the outside of the detector and makes the cost of the detector nearly independent of the number of channels on each wafer. A major concern is producing electronics which have low enough *average* power to allow the heat to be brought out of the detector via the tungsten alloy plates.

It the following we briefly give some details of how competing demands on the detector design are balanced. In section 2 we describe the silicon sensors. In section 3 our plans for electronics as well the expected timing performance of the calorimeter are discussed. In section 4 we give our first thoughts about the mechanical design of the detector.

2. Silicon Sensor

The design of the 300 μm thick silicon sensors is illustrated in Figure3. The signals are DC coupled to electronics via 6 micron wide traces which bring the signals to the front-end chip at the center of the wafer. The capacitance associated with each of the 1024 pixels is expected to be approximately 6 pF. The capacitance of the longest traces is expected to be somewhat larger, approximately 15pF. Each trace will cross over several pixels on its way to the front-end chip potentially introducing crosstalk. Our simulations show that for the planned electronics, the resulting crosstalk will be 1% or smaller.

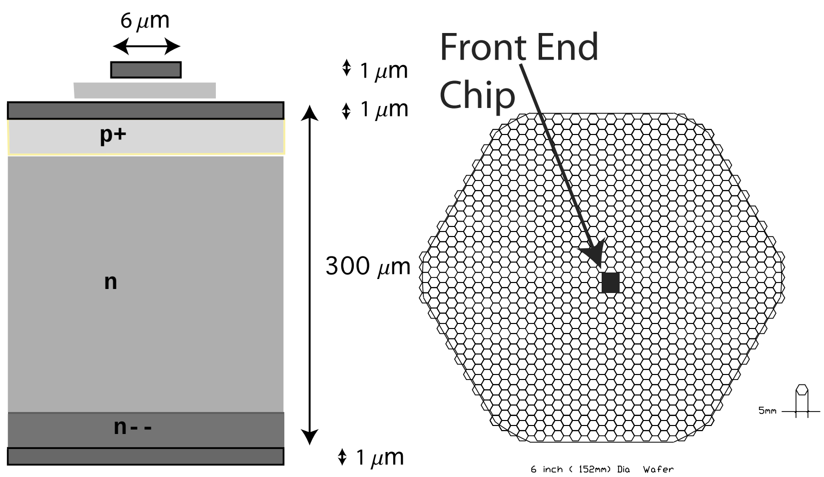

Figure 3. Left: silicon cross section. Right: wafer layout showing 1024 pixels. The traces connecting the individual pixels to the front end chip are not shown.

3. Electronics

The front-end electronics are required to measure time and charge. The electronics have been designed specifically for use with X-band technology with 192 bunches spaced by 1.4 ns. With this time structure we integrate over the entire bunch train for charge measurements, but tag the time arrival of each pulse.

The upper end of the dynamic range for the charge measurement is set by 500 GeV Bhabhas that give signals equivalent to 2000 minimum ionizing particles (MIP). The lower end is set by the MIP sensitivity. MIP sensitivity is needed to track charge particles through to the hadron calorimeter. This requires a total dynamic range corresponding to almost 16 bits. This is a challenge in sub-micron semiconductor processes where the operating voltage is 3 V limiting maximum signals to about 1 V.

The novel design shown in Figure 4 has a feedback capacitor which can be dynamically switched to accommodate large signals, but provides reasonable gain for more common MIP sized signals. MIP signals produce voltages of $\sim 8\,\mathrm{mV}$, well above the noise floor in the chip. The charge circuit has a relatively long time constant $\sim 200\,\mathrm{ns}$ whereas the signals for the timing circuit will have a rise time of 40 ns or better. The output of the charge circuit is sampled approximately $1\,\mu\mathrm{s}$ after the bunches cross, giving the signals time to settle in those cases that the larger feedback capacitor was switched in. An important feature of the electronics is that the digital portion of the chip is not active during the beam crossing. This will minimize any noise in the timing circuit.

After the beams cross, the charge measurement is digitized by comparing the voltage at the output of charge signal with a common voltage ramp. When the ramp crosses voltage at the charge output or a given channel, a common clock is latched as the charge reading for that channel.

The front-end chip is designed so that the current through the charge amplifier and shaper portions of the circuit is only pulsed on when the beams cross in the detector. Simulations show that at an X-band machine the duty cyle of the on-time of the charge amplifier is less than 1/1000 allowing for large($\sim$ mA) peak currents in the input FET to the charge amplifier. This improves noise for both timing and charge measurements.

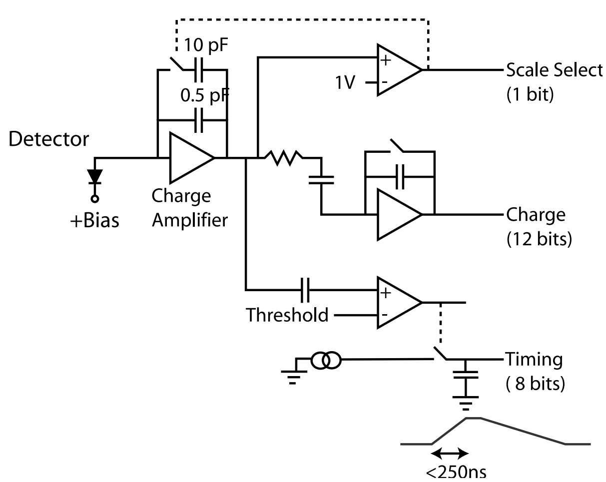

Figure 4. Schematic design for the electronics.

The timing circuit uses the time expansion technique to produce an 8-bit digitized time signal with a granularity of 1 ns. This timing signal can be used to help separate background tracks and energy from "two-photon" events that occur in other beam crossings from tracks and energy from the signal event of interest. Since each MIP will cross 30 layers of the calorimeter we need to aim for a resolution of order 5 ns/layer. In order to explore the possible timing resolution we have used a "toy" Monte Carlo simulations which incorporates the distribution of trace lengths on the wafers to simulate effects of trace resistance and capacitance from tracks crossing the calorimeter. In addition to expected noise from the input FET, "excess" noise, equal to the amount expected from the FET was assumed. The expected distribution of Landau fluctuations was used and a corrections to the timing signal based on the pulse height measurement was performed. The results for a typical set of parameters are given in Table 1.

Table 1. Electronics parameters used in the simulation and the resulting timing results.

Parameter	Value
Input FET	1.5 mS
FET capacitance	10 pF
Time constant of timing signal	50 ns
Threshold value	8000 electrons
Threshold variation	5%
Uncertainty in time-walk correction param.	5%
RMS for each layer	5.3 ns
RMS for truncated mean of 30 layers	0.7 ns

4. Mechanical Design

The mechanical design of the detector is under development. The main goal is to minimize the gap between the layers of tungsten to keep the effective Molière radius smaller. Figure 5 shows a calculation of the effective Molière as a function of the gap between layers. The upper line corresponds to a gap that includes a 1 mm thick copper layer to conduct heat from the electronics. This will be unnecessary if the average power used by the electronics can be kept below 40 mW/wafer. If a 1 mm gap is possible the angle subtended by the Molière radius is approximately 11 mrad. For comparison, a 3 mm gap would require a calorimeter radius of almost 2 m to subtend the same angle.

A possible design, which allows for a 1 mm gap, is shown in Figure 6. The main challenge is finding space for the capacitors. They must large enough to maintain the low voltage when the beam cross, but should have a low profile. Presently available $\sim 10\,\mu$F capactiors are at least 1.2 mm thick, requiring that a dimple be machined in the tungsten to allow sufficient clearance. Compact capacitor technology seems to be rapidly evolving, opening the possibility that lower profile capacitors will be available when the detector is built.

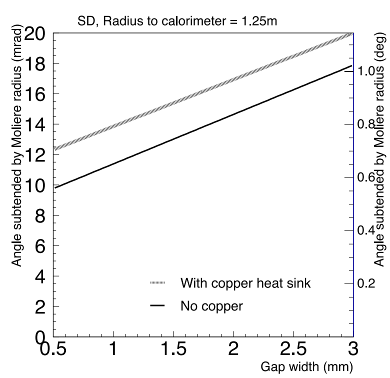

Figure 5. Effective Molière radius as a function of gap width.

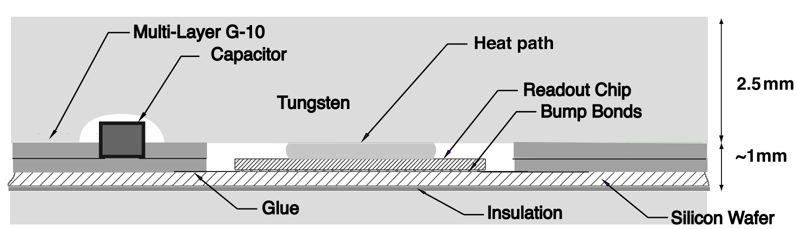

Figure 6. Schematic design for the gap between layers.

An important aspect of the mechanical design is the use of rolled tungsten for the absorber. By using rolled tungsten, it should be possible to produce plates with a 1% tolerance but avoid wasting large amounts of tungsten in the grinding step. Using a nonmagnetic tungsten alloy which is 92.5% pure, it should be possible to produce pieces up to 1.2 m meters long, long enough to span the short dimension of the barrel. The effective Molière radius shown in Figure 5 includes a correction for the materials used in the 92.5% tungsten alloy.

5. Conculsion

We have developed a conceptual design for a highly granular silicon tungsten electromagnetic calorimeter that is able to meet the requirements imposed by the expected physics processes at a linear electron-positron collider. Our design includes a small gap between tungsten layers and integrated electronics that perform both charge and time measurements.

Acknowledgments

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References

1. J. A. Aguilar-Saavedra *et al.* "TESLA Technical Design Report Part III: Physics at an e^+e^- Linear Collider," arXiv:hep-ph/0106315.
2. H. Videau and J. C. Brient, "A Si-W calorimeter for linear collider physics," *Prepared for 10th International Conference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California, 25-30 Mar 2002*
3. G. Wilson, "ECal Design Studies, Si/Scint/W Hybrid", ALCPG 2004 Winter Workshop, SLAC.
4. J. Brau, A. Arodzero, D. Strom, "Calorimetry for the NLC Detector," in Proceedings of the 1996 DPF/DPB Summer Study on New Directions in High-energy Physics, SLAC-PUB-7693.
5. M. Briedenbach, "SD, an Introduction," ALCPG 2003 Summer Workshop, Cornell.