The Silicon Detector Concept

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What is SiD?

- A detector concept based on Si/W calorimeter and Si tracker.
- Silicon detector is
  - fast,
  - robust against background,
  - fine in segmentation, and by now
  - mature.
Time Structure and Event Rates

There are five trains of 2820 bunches per second (nominal).

- bunch separation is 307.7 ns
- \( \mathcal{L} = 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-2} \) (at \( \sqrt{s} = 1000 \text{ GeV} \))

Event rates

- At a luminosity of \( 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  - \( e^+e^- \rightarrow qq, WW, t\bar{t}, HX \): 0.1 event / train
  - \( e^+e^- \rightarrow \gamma\gamma \rightarrow X \): ~200 / train

Background from beamstrahlung

- \( 6 \times 10^{10} \gamma/ BX \)
- 140,000 \( e^+e^- / BX \) + secondary particles (n,\( \mu \))

Must have a Silicon device (either the tracker or Ecal) to identify the right bunch crossing. True for any of concept studies!!
SiD

- Pixel Vertex detector
- Si trackder
- Si/W is for the ECAL and digital calorimetry for HCAL
- All within 5T magnet
- plus instrumented flux return as a muon detector
- Results in the smallest of the three detector concepts

~ 12m x 12m x 12m
Tracker

Impact parameter resolution: \( \sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10 / (p \sin^{3/2} \theta) \ \mu m \)

Momentum resolution: \( \sigma_{P_T} / P_T^2 \approx 5 \times 10^{-5} \text{(GeV}^{-1}) \)
**Vertex Detector**

- 5-layer / 4-disk detector covering $R_{\text{in}} = 14$ mm to $R_{\text{out}} = 60$ mm
  - To tag b- and c- jets and tau-leptons with high efficiency reducing background
  - To efficiently perform heavy quark sign selection, via the vertex charge

- **Barrels**
  - Five barrels
  - 24-fold phi segmentation
  - Two sensors covering 6.25 cm each
  - All barrel layers same length

- **Disks**
  - Four disks per end
  - Inner radius increases with Z

- **Support**
  - Supported from beampipe
Generic option employs CCD readout:
- 15 – 20 µm pixel size
- 10^9 pixels for barrel detector
- \( R_{in} = 14 \text{ mm} \) (cf. 25 mm SLD, 15mm Belle)
- Layer thickness of 0.1% \( X_0 \) per layer!
  - 20 µm of Si is 0.02% \( X_0 \)

Disadvantage of CCD readout is that it is slow
- 20% occupancy in inner layer if integrated over a train
- Significant concern regarding EMI (SLD experience)

Many different alternative technologies (CMOS) being pursued
- DEPFET
- MAPS
- HAPS
- FAPS
- ISIS
- Sol
- ...

Barrel Design Vertex Detector
Beampipe radius a critical parameter, which is determined by the background from $e^+e^-$-pairs

- Five barrel layers
  - $r = 1.4, 2.6, 3.7, 4.8, 6.0\text{cm}$
  - $z = +/- 6.25\text{ cm}$
- Four endcap layers
  - $z = 7.0, 9.5, 12.0, 17\text{ cm}$

500GeV nominal in 5 Tesla and 20 mrad Xing

Layer#1
Beam pipe at $r = 1.2\text{ cm}$

Z (cm)
Average and RMS of VXD hits over 20 bunches

• ~10% more hits in 20 mrad crossing angle
• But the difference is small compared to the bunch-to-bunch fluctuation.
• ~30% more hits if no lowz.
• 300 hits/BX (layer #1)
  0.027 hits/mm^2/BX
  77 hits/mm^2/Train
Silicon Outer Tracker

- 5-Layer silicon strip outer tracker, covering $R_{\text{in}} = 20$ cm to $R_{\text{out}} = 125$ cm, to accurately measure the momentum of charged particles

- Support
  - Double-walled CF cylinders
  - Allows full azimuthal and longitudinal coverage

- Barrels
  - Five barrels, measure Phi only
  - Eighty-fold phi segmentation
  - 10 cm z segmentation
  - Barrel lengths increase with radius

- Disks
  - Five double-disks per end
  - Measure R and Phi
  - Varying R segmentation
  - Disk radii increase with Z
Material Budget

With current design, possible to stay within 0.8% \( X_0 \) per layer at normal incidence.
Pattern recognition in SiD

$tt\rightarrow$jets

Ecm=500GeV

-$\approx$100 hits/cm$^2$ in VXD Layer 1

over ~150 beam crossings

- Tracker sees only physics event

Time stamped even for 150 ns bunch spacing
• Begin with all combinations of 3D VXD hits.
• Attach hits in tracker in 2D space to find tracks.
Preliminary study of performance based on GEANT4
(single track study)

Momentum resolution

Impact parameter resolution

$\sigma_{\text{intrinsic}} \approx 7 \mu m/\text{point}$

Multiple scattering included
Jet energy resolution: $\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E(\text{GeV})}}$
Particle Flow Algorithm

- Measure energies of individual particles, not energy deposition in cal modules.

- Pattern recognize to perform the neutral-charged particle separation in the calorimeter, followed by a substitution of the charged energy with the corresponding measurement from the tracker
  - **Step I: Track – Calorimeter cluster matching**
    - Identify calorimeter cells belonging to shower from charged track
    - Algorithm based on ‘tubes’
    - Use track momentum and eliminate calorimeter cells
  - **Step II: Photon Identifier**
    - Identify photons in ECAL
    - Use longitudinal and lateral shower profile
  - **Step III: Measure neutral hadron energy**
    - Excluding charged and em neutrals, apply cone jet algorithm
    - Identify remaining cells as energy from neutral hadrons

Requires fine lateral and longitudinal segmentation and large BR$^2$
Proof of Principle

- Particle Flow Algorithm applied with the CDF detector
  - Use Photon + Jet data
  - Apply PFA
  - Plot balancing jet energy resolution as function of photon $p_T$
- Jet energy resolution improved:
  \[
  \sigma_E/E = 83\% / \sqrt{E} \quad \text{(old)}
  \]
  \[
  \sigma_E/E = 64\% / \sqrt{E} \quad \text{(new)}
  \]
- However, it is not clear if a resolution of $30\% / \sqrt{E}$ is achievable
P-Flow requires high transverse and longitudinal segmentation and dense medium

Choice: Si-W can provide $5 \times 5 \, \text{mm}^2$ segmentation and minimal effective Molière radius

<table>
<thead>
<tr>
<th>Absorber</th>
<th>$X_0$ [cm]</th>
<th>$R_M$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>9.05</td>
<td>4.7</td>
</tr>
<tr>
<td>Copper</td>
<td>1.44</td>
<td>1.6</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.35</td>
<td>0.9</td>
</tr>
<tr>
<td>Lead</td>
<td>0.58</td>
<td>1.6</td>
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</tbody>
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transverse segmentation ~5mm
30 longitudinal samples
energy resolution ~15%/$E^{1/2}$

hexagonal SI wafers
EM Calorimeter Configuration

- Silicon from 6” wafers
  - p-on-n silicon
  - 300 µm thick
  - ~ 2000 m² of silicon
- Transverse segmentation
  - 5 mm hexagonal pixels
  - 1mm gaps for Si and readout:
    \[ R_m \text{ (effective)} = 14 \text{ mm} \]
- Longitudinal segmentation
  - 30 Layers, 0.25cm thick W, 5/7 \( X_0 \) / layer
- Readout through one ASIC per wafer
  - 1024 channels per wafer

SLAC – Oregon – BNL Collaboration
EM Readout

- ASIC bump bonded to silicon wafer
  - Double metal layer in silicon
- Performance requirements
  - Dynamic range: 0.1 to 2500 MIPs
    - Two ranges
  - S/N > 20
  - Capacitance
    - Pixels: 5.7 pF
    - Traces: ~0.8 pF per pixel crossing
    - Load up to \( C_L = 40 \text{ pF} \) on input amplifier
- Output
  - Fully digitized, zero suppressed
  - Pulse height + time buffered 4-deep to accommodate multiple hits along train
- Power
  - < 40 mW/wafer \( \Rightarrow \) power cycling
    (An important LC feature!)
  - ENC = 200 + 30*C_L

Rows of bumpbonds
Bonus Tracking Calorimeter

- Can track particles from “the outside-in”, starting in the calorimeter
  - Track from outside in: $K^0_s$ and $\Lambda$ or long-lived SUSY!
Digital sampling HCAL

- Digital calorimetry works due to:
  - Low density of hadronic showers
  - Linear response to single hadrons
  - Single particle resolution preserved
  - Landau tail reduced

Based on Geant4 simulations, digital readout, 1cm² readout pads

**Single Particle Resolution**

<table>
<thead>
<tr>
<th>E_{rec} (GeV)</th>
<th>Analog</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
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<table>
<thead>
<tr>
<th>#Hits</th>
<th>Digital readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
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<tr>
<td>20</td>
<td>25</td>
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<td>30</td>
<td>35</td>
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**5 GeV π⁺, 1 cm² pads**

- **Analog**
  - $\sigma/\mu \sim 22\%$

- **Digital**
  - $\sigma/\mu \sim 19\%$

$E_{true}$ (GeV) vs $E_{rec}$ (GeV)
Resistive Plate Chambers

- DHCAL with RPC’s are the baseline technology for the SiD
  - Glass as resistive plates; Freon-Isobutane-SF6 as active medium
  - Transverse segmentation 1cm x 1cm

Current parameters:
- Inside the coil
  - $R_i = 139 \text{ cm}$, $R_o = 237 \text{ cm}$
- Thickness of 4$\lambda$
  - 34 layers of 2.0cm steel
  - One cm gap for active medium
- Transverse segmentation
  - $1 \times 1 \text{ cm}^2$

RPC
- EM showers narrow in RPC’s
- Had. showers narrow in RPC’s
  - Density of gas too low for sizeable neutron cross section
  - Energy deposition has no slow component
To retain BR^2, solenoid with B(0,0) = 5T (not done previously)

- Clear Bore Ø~ 5m; L = 6 m: Stored Energy ~ 1.4 GJ
- For comparison, CMS: 4 T, Ø = 6m, L = 13m: 2.7 GJ
Solenoid

- Initial feasibility completed by Fermilab, preconceptual design based on CMS
  - Credible approach to conductor/winding design
  - Credible engineering approach for industrial fabrication and cost estimates
- More conservative design than CMS: go from 4 winding layers to 6
  - $I_{CMS} = 19500 \text{ A}$, $I_{SiD} = 18000 \text{ A}$
Solenoid

- ANSYS modeling of solenoid (2d, 3d)

R_{out} = 3098 \text{ mm}
R_{in} = 2645 \text{ mm}
Z = 2847 \text{ mm}

23 Layers Barrel Steel
Si Tracker Boundary

23 Layers End Steel

Outer Portions of Steel Omitted from Figure

Z = 0
Z = 2847 \text{ mm}
Z = 6247 \text{ mm}
Detector Optimization needs Detector Costs

Some Critical Unit Costs

- Si Detector (trkr and Ecal): $2.00/cm²
- Ecal W: $75/kg
- Hcal, Muon Detectors: $2000/m²
- Electronics: ($100+100 install)/Chip
- Solenoid: $0.81(MJ)^{0.662} M
- Flux return Fe: $3.48/kg

Cost drivers

- Muon: 10%
- Si_tracker: 2%
- EM Cal: 30%
- H Cal: 24%
- Solenoid: 34%

R_{trkr} = 1.25m is optimum.
Current SiD organization

Design Study Coordinators
J. Jaros and H. Weerts
Asian and European Contact Persons H. Aihara and Y. Karyotakis

SiD Executive Committee
Design Study Coordinators
SiD R&D Coordinator A. White
Godfathers M. Breidenbach and J. Brau

SiD Advisory Group
SiD Executive Committee
Working Group Leaders

SiD Working Groups
Benchmarking (T. Barklow), Calorimetry (R. Frey, J. Repond), Costs (M. Breidenbach), Magnet/Flux Return (R. Smith), Muons (soon!), Simulation (N. Graf), Tracking (M. Demarteau, R. Partridge), Vertexing (D. Su), MDI (P. Burrows, T. Tauchi)
Conclusion

• The (almost) all silicon SiD concept is an aggressive approach to a compact ILC detector.
• Fast and robust.
• Cost control in place.