UNIVERSITY OF BIRMINGHAM

SPiDeR

Digital Calorimetry at Future Linear Colliders

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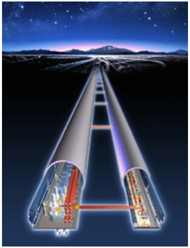
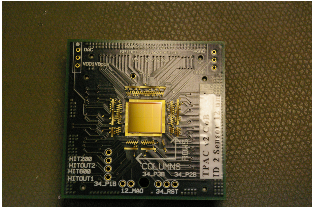
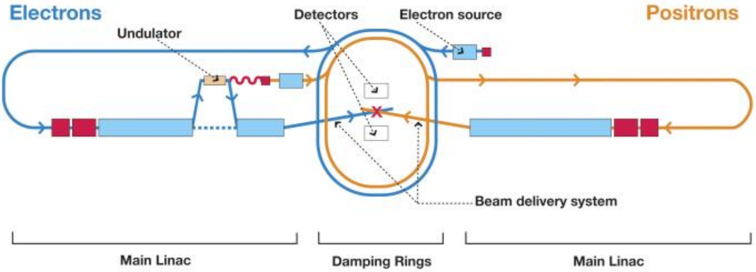
Overview




DAC
HIT200
HITOUT2
HIT600
HITOUT1
COLUMNS
ROWS
TPAC v2 C4B
ID 2 Sensor 12

ILC Overview

- The International Linear Collider (ILC) is a proposed e^+e^- linear collider
- Initial $\sqrt{s} \leq 500$ GeV rising to 1 TeV after upgrade
- ILC will be largely complementary to LHC physics
- ILC initial state much cleaner so measurements will be much more precise
  - H-boson properties
  - W-boson measured with precision of 7 MeV with threshold scan
  - ttbar threshold scans allowing $\Delta M_t \sim$34 MeV



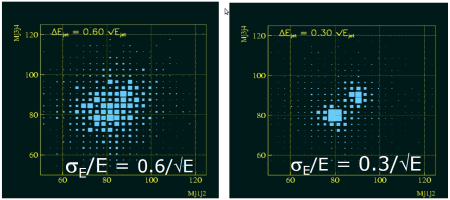
ILC Overview

Benchmark Processes

- Final states will include multiple t, Z, W, H leading to 6-8 jet final states
- Benchmark processes
    - $e^+e^- \rightarrow t\bar{t}H$
    - $e^+e^- \rightarrow \nu\nu H$
    - $e^+e^- \rightarrow W^+W^-$
- All have small cross sections compared to $e^+e^- \rightarrow t\bar{t}$ so need high luminosity
- Detectors must be optimised for final states with multiple jets

ILC Detector Requirements

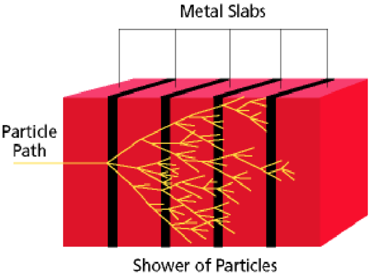
- ILC design goal for jets $\frac{\sigma_E}{E} = \frac{0.3}{\sqrt{E[GeV]}}$
- Required to separate W→qq and Z→qq in final states



- Generally accepted way is Particle Flow
  - Required high granularity (cell size $\sim R_{Moliere}$)
  - Full containment
  - Excellent calorimeter systems
- Use tungsten as showering material

Electromagnetic Calorimetry

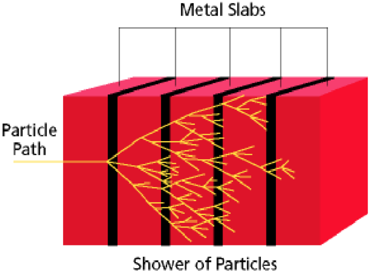
The Concept



- Incident particle interacts within the metal slabs causing a particle shower to develop
- Shower particles deposit energy in the sensitive regions
    - Si sensors, scintillators, liquid argon, etc..
- Sum energy deposits and scale to incident particle using scale factor determined in design and commisioning

Electromagnetic Calorimetry

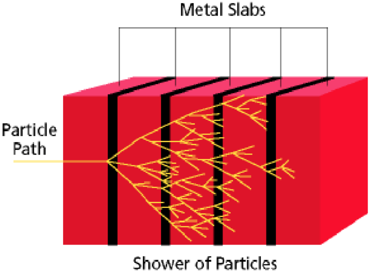
Sources of Uncertainty



- Average number of charged particles in em shower $\propto$ incident energy
  - Statistical fluctuations in the number of shower particles
- Energy deposited in sensitive layer $\propto$ number of particles
  - Fluctuations from incident angle,
  - Particle velocity,
  - Landau energy deposition spread

Electromagnetic Calorimetry

Sources of Uncertainty



- Average number of charged particles in em shower $\propto$ incident energy
  - Statistical fluctuations in the number of shower particles
- ~~Energy deposited in sensitive layer $\propto$ number of particles~~
  - ~~Fluctuations from incident angle,~~
  - ~~Particle velocity,~~
  - ~~Landau energy deposition spread~~
- Counting particles removes these sources of error!!!

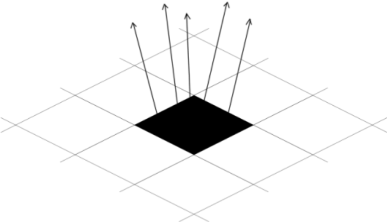
Digital ECAL

The Concept

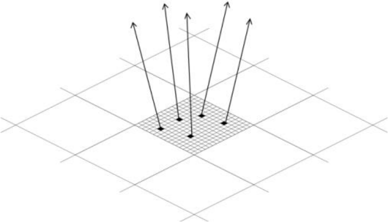
- Make a pixellated calorimeter to count the particles
- Digital readout i.e hit/no hit
- Ensure the pixels are small enough to avoid multiple particles passing through a single pixel
  - Avoid undercounting and non-linearity in higher particle density environments
- Max density of 100 $particles/mm^2$ leads to pixel sizes of 50 μm^2
- Digital variant of ILD ECAL would need 10^{12} channels!!
- Dead area and power consumption per channel must be kept to a minimum

Digital ECAL

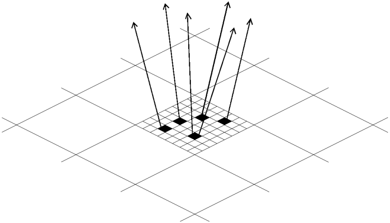
The Concept



Analogue ECAL



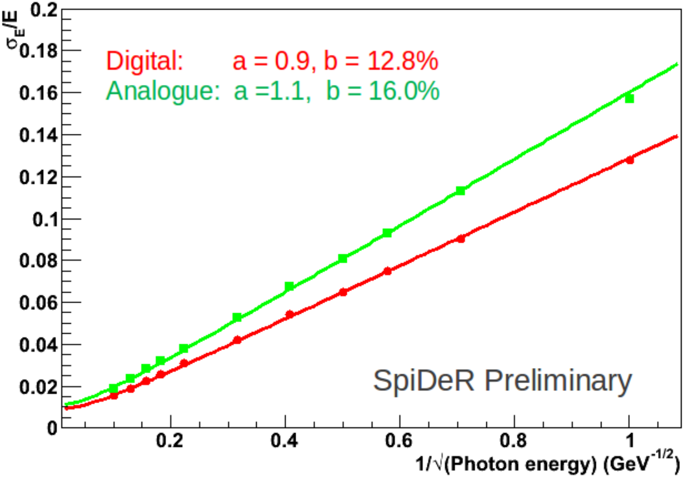
DECAL $N_{pixels} = N_{particles}$



DECAL $N_{pixels} \leq N_{particles}$

Digital ECAL

Energy Resolution Vs analogue ECAL



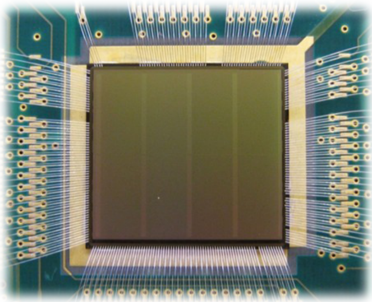
20 layers 0.6 X_0 & 10 layers 1.2 X_0

TPAC Sensor

TeraPixel Active Calorimeter Sensor

CMOS sensor designed with the DECAL requirements in mind

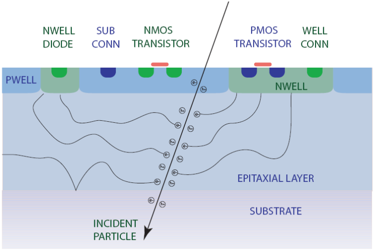
- 168×168 pixel grid
- $50 \times 50\ \mu m^2$ pixel size
- Digital readout
- Low noise
- Utilise INMAPS process
- 42 pixels served by one strip of SRAM and logic
- Charge collected by diffusion to signal diodes

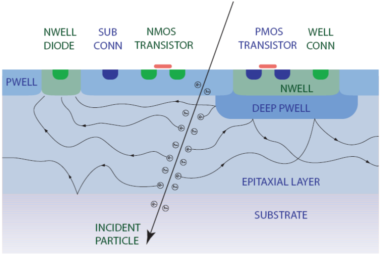


TPAC Sensor

TPAC Sensor

INMAPS Process





CMOS architecture causes parasitic charge collection at the N-wells reducing the pixel efficiency. INMAPS technology uses a deep P-well which inhibits the parasitic collection increasing the signal at the diodes. Allows use of standard full CMOS

- lower cost
- allows fabrication at multiple foundaries
- allows different resitivity epitaxial layers

TPAC Testing

Test Beam Overview

Beam tests of TPAC sensors conducted at

- CERN 20-120 GeV pions
- DESY 1-5 GeV electrons

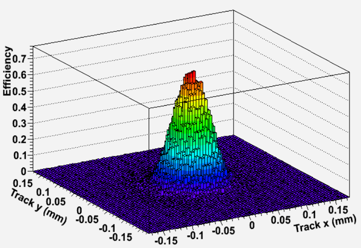
to study the sensor response to MIPs and particle showers

TPAC Testing

Pixel Efficiencies to MIPS

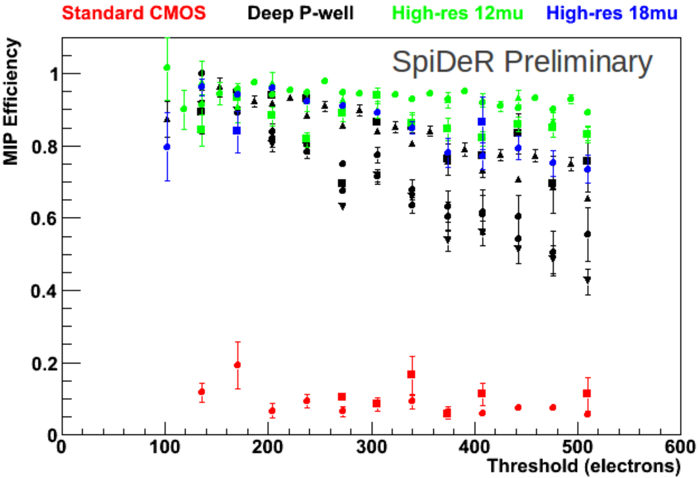
Studies conducted for both pions and electrons at CERN and DESY

- Formed a track in the event
- Project the track into sensor
- Look for hits around the projection and look for hit probability
- Fit the resulting distribution (right) to extract efficiency



TPAC Testing

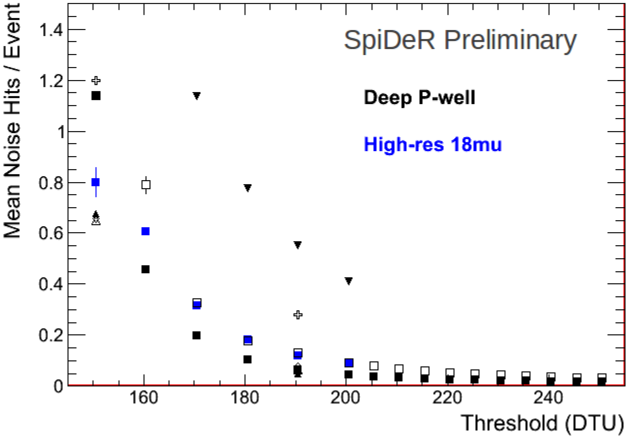
Pixel Efficiencies to MIPS



Efficiency vastly increased using the INMAPS process over standard CMOS

TPAC Testing

Noise Studies



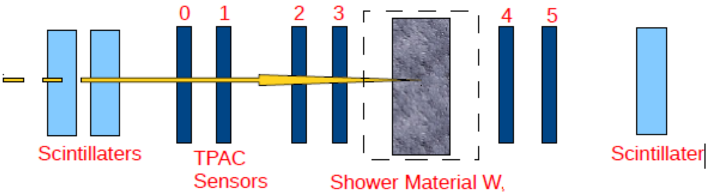
1.2 noise hits out of 28224 pixels / event at lowest threshold so low noise requirement achieved

Changing the epitaxial layer does not affect noise rate

TPAC Testing

Shower Multiplicities

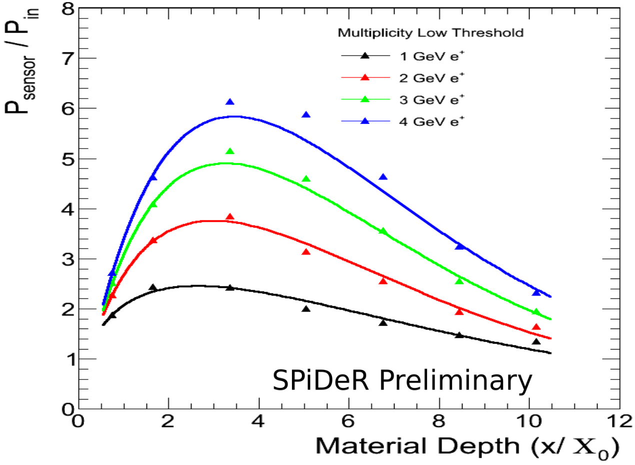
At the DESY testbeam the electrons were showered through various amounts of tungsten to look at the sensor response to em showers at various positions within a DECAL without the need of a prototype



layers 0-3 used for tracking
layers 4-5 used to detect shower

TPAC Testing

Shower Multiplicities



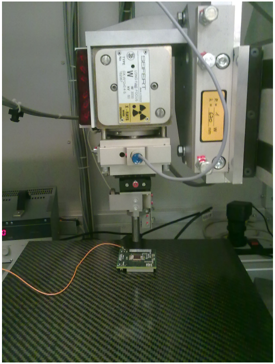
Multiplicity increases with energy as required for DECAL

TPAC Testing

Radiation Testing

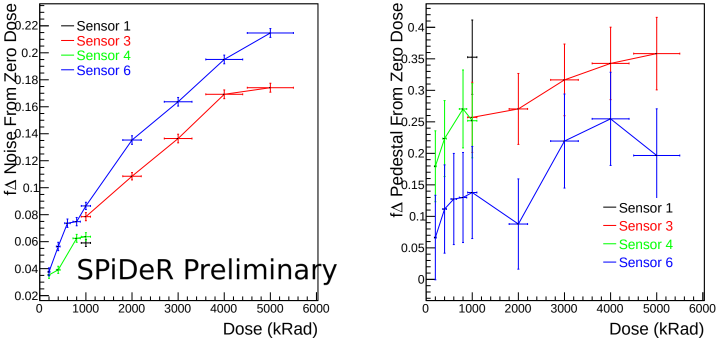
Potential use of TPAC sensor technology in high radiation environments such as tracking and vertex systems. Need to know the sensor response to radiation!

- Multiple sensors irradiated with 50 KV X-rays
- Sensors held at 0 Volts and operating voltage
- Sensors exposed to various doses between 200 kRad and 5 MRad
- Mean noise and pedestal of the pixels tested after each dose



TPAC Testing

Radiation Testing - Unpowered



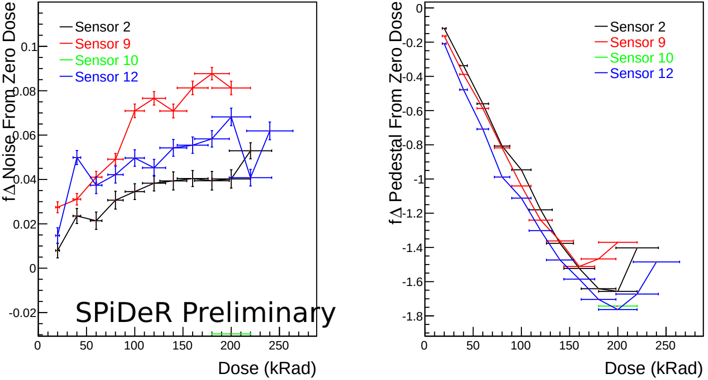
At 1 MRad noise increase ∼8 % rising to ∼20 % at 5 MRad

Pedestal increases by ∼30 %

Non-linear increases in pedestal at higher doses accredited to annealing

TPAC Testing

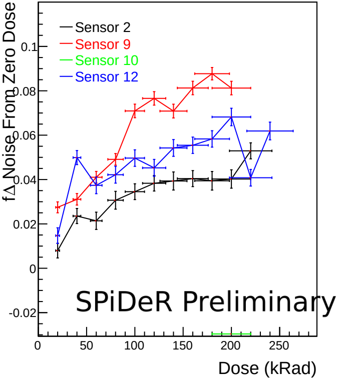
Radiation Testing - Powered

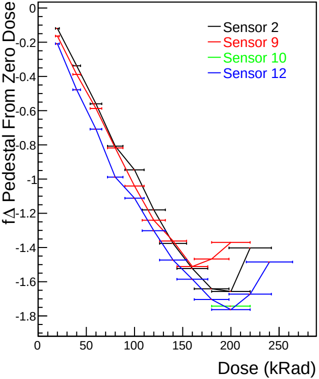


Much lower doses achieved due to sensor readout problems above 200 kRad when powered

TPAC Testing

Radiation Testing - Powered





Powered noise increase at 200 kRad ≈ Unpowered noise increase at 1 MRad

Pedestal rapidly decreases showing different behaviour to unpowered sensor

Summary

- Simple DECAL simulation shows an improved resolution over a conventional ECAL with significantly lower costs expected
- INMAPS process demonstrates an improved efficiency over standard CMOS
- Noise rate of 1.2 pixels per event
- Noise rate shows exponential decrease with theshold
- Tests have demonstrated the the DECAL idea is feasible
- Showers detected using TPAC sensors show an increased multiplicity with energy - Essential for a DECAL
- Interest in the INMAPS process from outside the ILC community
- Small noise increase during radiation testing