A digital ECAL based on MAPS

First Sensor Results and Physics Expectations

On behalf of the CALICE-UK MAPS group
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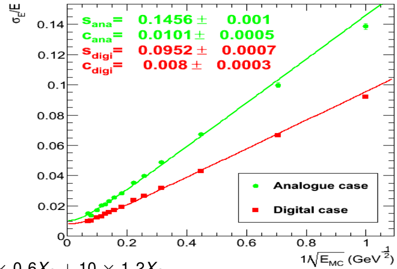
Digital vs Analogue: motivations

	Analogue	Digital
Measure	$E_{deposited} \propto N_{Charged\ particles} \propto E_{incident}$	$N_{Charged\ particles} \propto E_{incident}$
Fluctuations	statistical, angle of incidence, velocity and Landau spread	statistical
Ideal resolution	$\simeq \frac{0.15}{\sqrt{E}}$ for ILC-like ECAL	$\simeq \frac{0.10}{\sqrt{E}}$ for ILC-like ECAL
Realistic effects	noise, dead areas	Charge diffusion, noise, dead areas, counting particle
Impact	Expected small	under study/never measured

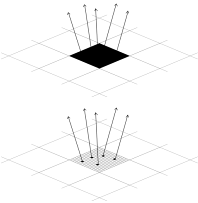
- Can we measure the number of charged particles directly?
- Can we get anywhere near the ideal resolution for the digital case?

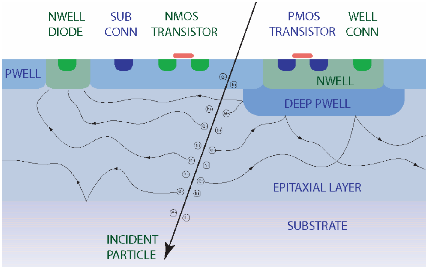


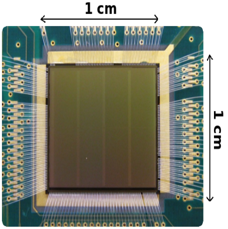
$20 \times 0.6X_o + 10 \times 1.2X_o$

A digital ECAL based on MAPS

- EM shower density $\simeq$ 100 mm^{-2} in core $\Rightarrow$ need pixels $\simeq 50\mu$m with binary readout = hit/no hit
- Very high granularity should help with PFA too
- Real ECAL: $\simeq 10^{12}$ pixels $\Rightarrow$ need readout integrated into pixel
- Implement as CMOS MAPS sensor, including deep p-well INMAPS process to shield PMOS circuit transistors and increase charge collection efficiency.
- First version: TPAC 1.0 (Tera Pixel Active Calorimeter)



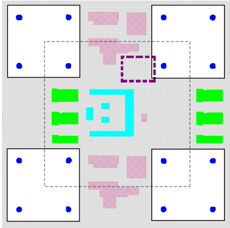


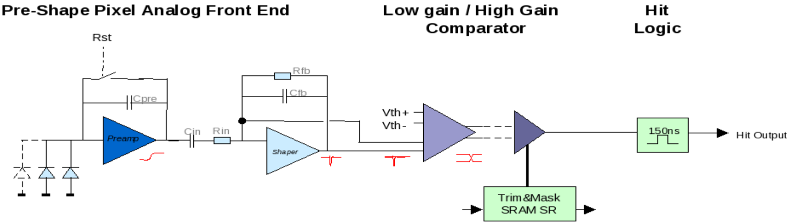


TPAC 1.0

TPAC 1.0 : pixel design

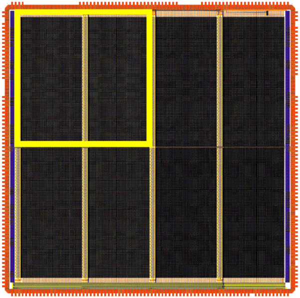
- $50 \times 50 \mu m^2$ pixel, with two variants: "preshapers" and "presamplers". Preshapers perform better and are described here.
- 0.18 μm CMOS process with INMAPS deep p-well implant
- Every pixel has 4 diodes, charge preamplifier and shaper, mask and 4-bit pedestal trim, asynchronous comparator and monostable to give hit/no hit response
- Pixel hits stored with 13-bit timestamp on-sensor until end of bunch train.

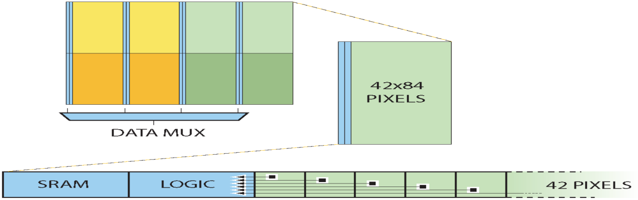




TPAC 1.0 : 1 $\times$ 1 cm^2 array

- 168 $\times$ 168 pixels = 28k total.
- Two major pixel variants, each in two capacitor combinations. One quadrant performs better and is described here.
- Memory needed for data storage : 11% dead area in 5-pixels wide columns, every 42 active pixels.



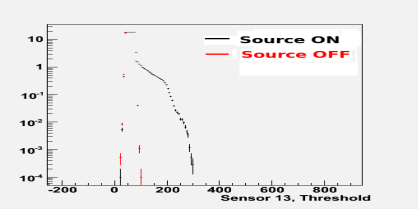


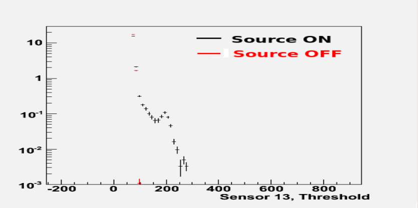
General method

- Binary readout $\Rightarrow$ threshold scan, in “Threshold Unit” (TU)
- Measure pedestal and noise
- Signal:
  - Measure real physical deposit, with ^{55}Fe source: γ at 5.9 keV, depositing all energy $\simeq$ 1620 electrons within 1μm^3 of silicon $\Rightarrow$ Absolute Calibration
  - Characterise gain uniformity : relative calibration with laser, single pixel enabled, scan of the whole array.
  - Measure charge spread with laser : localised deposit, scan of 3 $\times$ 3 array $\Rightarrow$ Comparison with simulation predictions
  - Measure tracking efficiency and behaviour in showers : beam test
- Noise-only runs systematically for comparison

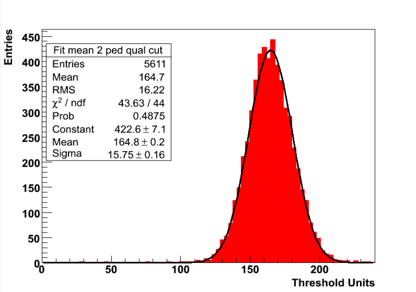
Absolute calibration with ^{55}Fe source

Threshold scan and derivative





Gain for all pixels studied

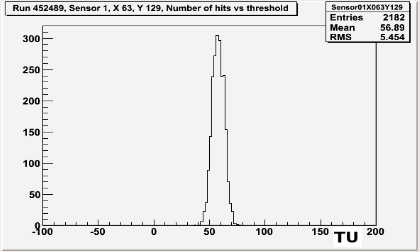


Signal peak is 165 TU above pedestal with $\simeq$ 10% spread.

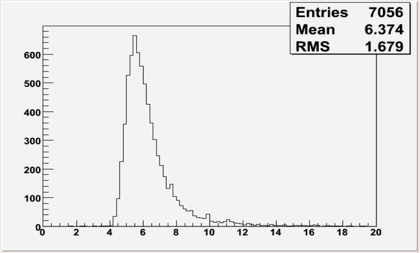
$\Rightarrow$ 1 TU $\simeq$ 10 e^- $\simeq$ 36 eV.

Noise measurement

Single pixel response : mean=pedestal, RMS=noise



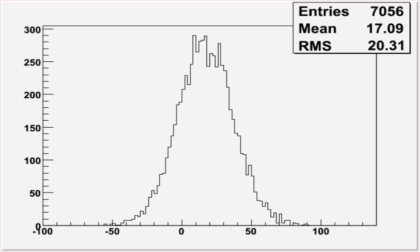
Noise for all pixels studied



- Noise is about 6 TU $\simeq$ 60 e^- $\simeq$ 220 eV.
- Minimum noise is 4 TU $\simeq$ 40 e^- $\simeq$ 140 eV.
- No correlation with position on sensor.

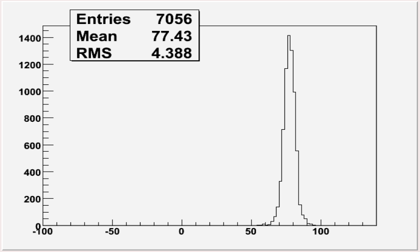
Pedestal measurement

Pedestal for all pixels studied without trimming



⇒ pedestal spread $\simeq$ 4 times single pixel noise

Pedestal for all pixels studied with trimming

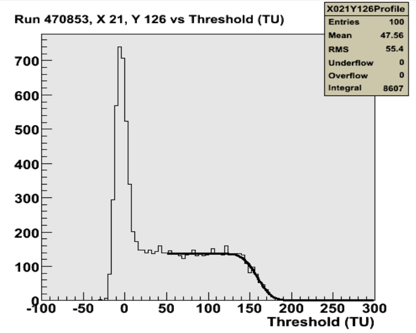


⇒ 4 trim bits gives pedestal spread $\simeq$ single pixel noise: more trim bits would be better.

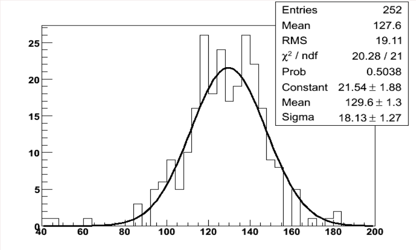
Relative calibration with Laser

Single pixel gain with laser

Si transparent to 1064 nm light: illuminate from back side, focus on epitaxial layer. Spot size $\simeq 2\mu$m.



Gain for all pixels studied

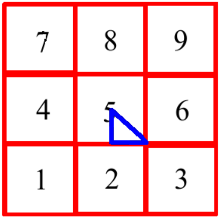


- Gain uniform to 14%.
- Consistent with absolute calibration $\Rightarrow$ laser can be used to measure charge spread.

Charge diffusion measurement and simulation

- Charge diffuses to neighbouring pixels:
  - Reduces signal in “hit” pixel
  - Causes hits in neighbouring pixels
  - Need to make sure this is correctly modelled
- Simulation using Sentaurus package
  - Full 3D finite element model
  - 3×3 pixel array = $150 \times 150 \mu m^2$ area
  - Thickness of silicon to 32 μm depth; covers epitaxial layer of 12 μm plus some of substrate

- Use laser to fire at different points within pixel
  - Scan bottom-right corner.
  - Laser spot size < 2 μm, step size 5 μm.
  - Assuming symmetry means these cover whole pixel surface
- Measure signal using threshold scan in centre pixel and all eight neighbours

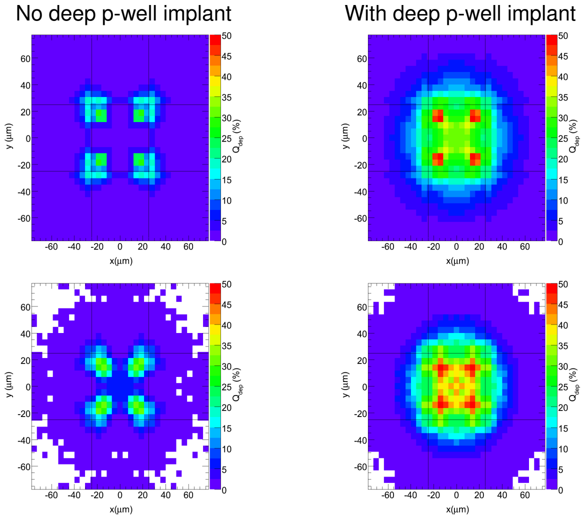


Charge diffusion results
Validation of the INMAPS process

No deep p-well implant — With deep p-well implant

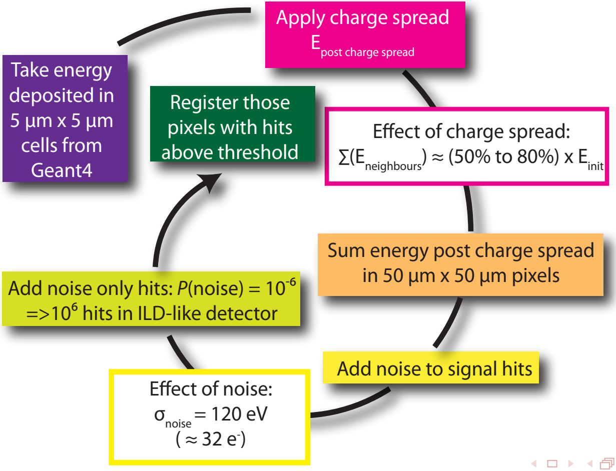
Sentaurus Simulation

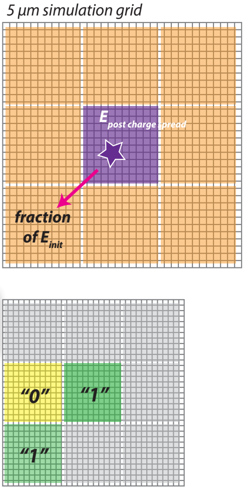
Real Data with Laser



The digitisation chain

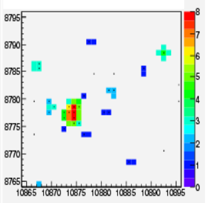
From ideal to real conditions

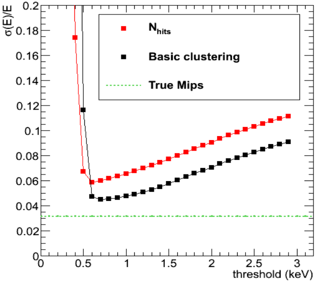




MIP clustering
Dominant effect: hit confusion

- Basic property of an EM shower
  - How dense are hits in the core?
  - GEANT4 not verified at this granularity
- Clustering helps but it is not clear where the limit is
  - Which algorithm to use depends on effects which may not be modelled well
  - Dominant effect in degrading the resolution
  - Major study of clustering algorithms still to be done
  - Essential to get experimental data on fine structure of showers to know realistic resolution

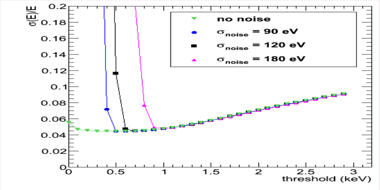




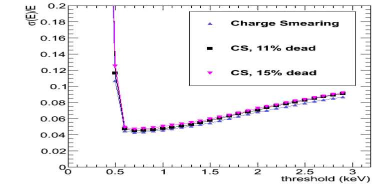
10 GeV electrons

Impact of each step with 10 GeV electrons

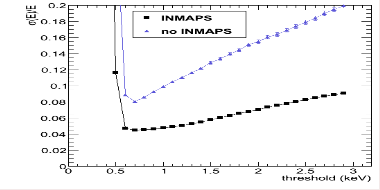
Effect of noise



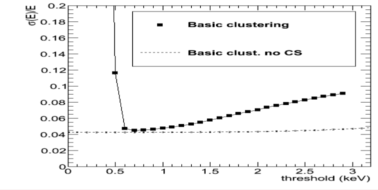
Effect of dead area



Effect of INMAPS process

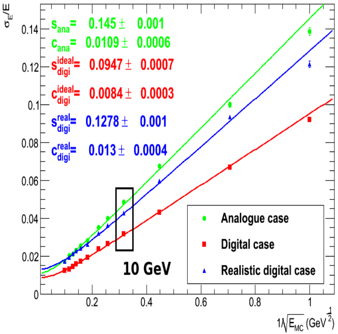


Effect of charge diffusion



Resolution vs Energy

- Now have concrete noise values and measured charge diffusion
- Current extrapolation to “real” detector shows significant degradation of ideal DECAL resolution, but still less than ideal analogue resolution.
- 35% increase in error.
- Number of pixels hit not trivially related to number of charged tracks



Degradation arises from

- Noise hits : $\simeq$ 5% degradation when increasing noise by factor 2.
- Dead area : $\simeq$ 6% degradation + $\simeq$ 2% if adding sensor edges effect.
- Charge diffusion to neighbouring pixels : after clustering, $\simeq$ 5% degradation.
- Particles crossing pixels boundaries and sharing pixels : $\simeq$ 20% degradation.

Conclusion

First version of the sensor fully characterised:

- INMAPS process fundamental to charge collection efficiency.
- Studied pixels uniform to within $\simeq$ 10% in gain.
- Good agreement between simulation and real data for charge spread.
- 1 MIP $\simeq$ 1300 e^-: on average only $\simeq$ 35% collected by the hit pixel.
- Signal/noise for a MIP deposit on average $\simeq$ 7.6.
- From ideal to real conditions: about 35% degradation in energy resolution, due mainly to hit confusion.
- Energy resolution after digitisation still lower than analogue case.

Critical missing measurement: behaviour in a shower.

- Need real data samples of showers at various depths in tungsten
- Compare with Geant4 simulation at 50 μm granularity
- Check critical issues of charged particle separation and keV photon flux

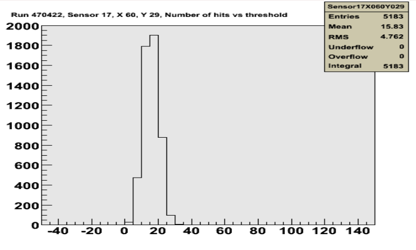
"Debugged" version, TPAC1.1 received this autumn

- All pixels uniform. Trim setting changed to 6 bits to allow finer trim adjustment.
- Will check sensor performance fully over next year including beam test at DESY.
- Still 1×1 cm^2: will not be able to verify full performance of a DECAL yet...

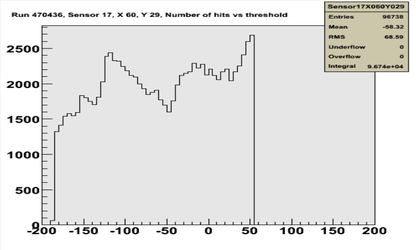
Thank you for your attention!

Crosstalk measurement

Single pixel response : only one enabled



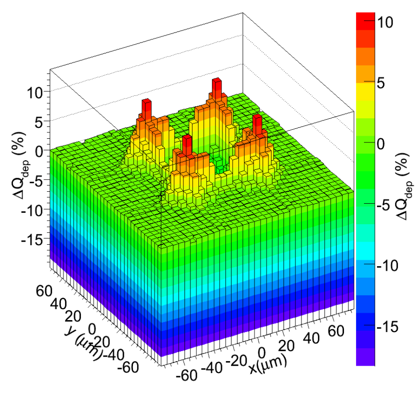
Single pixel response : all enabled



- Effect discovered after Dec 2007 beam test: data unusable.
- Probably due to shared power mesh for comparators and monostables: if more than 100 pixels fire comparators at same time, power droops and fires other monostables.
- Not an major issue for normal use (once understood), but render sensor useless in beam test.

Comparison bewteen data and simulation

No deep p-well implant Q_{dep}^{Simu}-Q_{dep}^{data}



With deep p-well implant Q_{dep}^{Simu}-Q_{dep}^{data}