A Reconfigurable Depleted CMOS Active Pixel Sensor for Digital Electromagnetic Calorimetry at Future Colliders

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Digital Calorimetry: The Concept

The number of particles in a high energy shower is proportional to the energy of the incident particle. In a digital Electromagnetic Calorimeter (DECal), the aim is to count the number of particles rather than the total energy which they deposit. The DECal concept is under consideration for future linear colliders [1], the ALICE FoCal [2], and the proposed FCC-hh [3]. The shower density for a 100 GeV electron shower is predicted to be ~100 particles/mm^2 and as such each channel needs to be smaller than 50x50 μm^2. Monolithic Active Pixel Sensors (MAPS) allow such a pixel pitch with low noise and read out electronics on chip in large format sensors. Recent developments in Depleted MAPS (DMAPS) increase the charge collection speed and radiation hardness. The digital version of the ILD and FCC-hh electromagnetic calorimeters have ~10^{12} pixels. The use of commercial CMOS Imaging Sensor technologies should eventually allow significantly reduced costs with respect to other compact high granularity calorimeter concepts e.g CMS HGCAL [4], which also bring the promise of precision particle flow calorimetry.

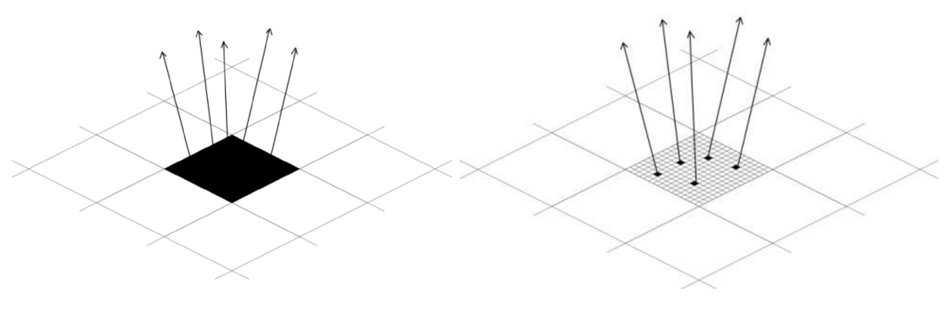

Figure 1: An illustration of a conventional calorimeter (left) where the energy of multiple particles in a cell are summed, and a digital calorimeter (right) where each cell contains a single particle

Reconfigurability

At the proposed FCC-hh the detector must be capable of timestamping all hits every 25 ns. The primary information from DEcal is the number of pixels above threshold. However, the data rate associated with 10^{12} channels every 25 ns is unfeasibly large. To reduce the data rate to manageable levels, the recently delivered prototype DECal sensor uses fast logic to sum the number of pixels over threshold in a 64x64 pixel grid (Pad Mode) and a single 64 pixel strip (Strixel Mode). The Strixel Mode is designed to be suitable for a large radius (short) strip tracker and possibly early layers of a pre-shower, allowing a seamless transition going into the calorimeter.

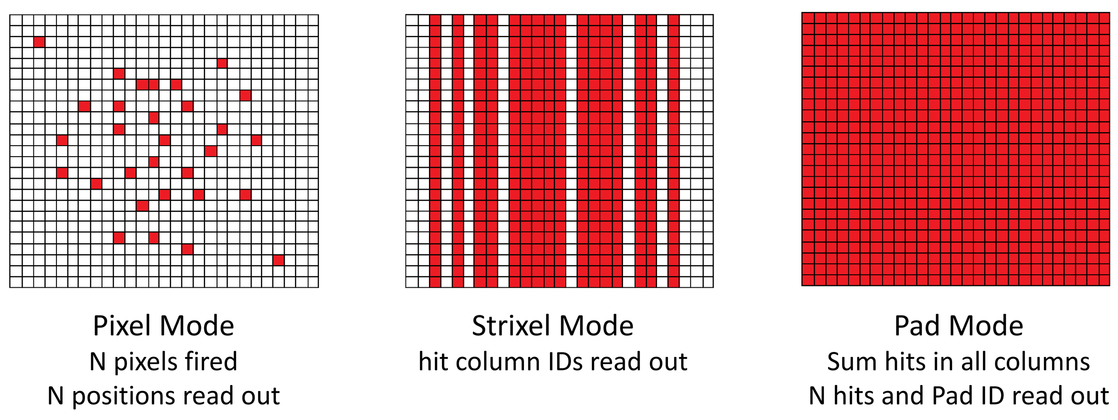

Figure 2: Illustration of differences with summing down columns and across rows for Strixel and Pad readout modes

A prototype sensor has been fabricated in a 180 nm technology and the amount of logic in a pixel is restricted by the pixel pitch. DECal simulations implemented within FCC software [5] demonstrate that the energy resolution (15%/√(E)) is not degraded if we can sum up to 15 hits per column. The pixel pitch was increased to 55x55 μm^2 to allow enough logic for the required pixel functionality.

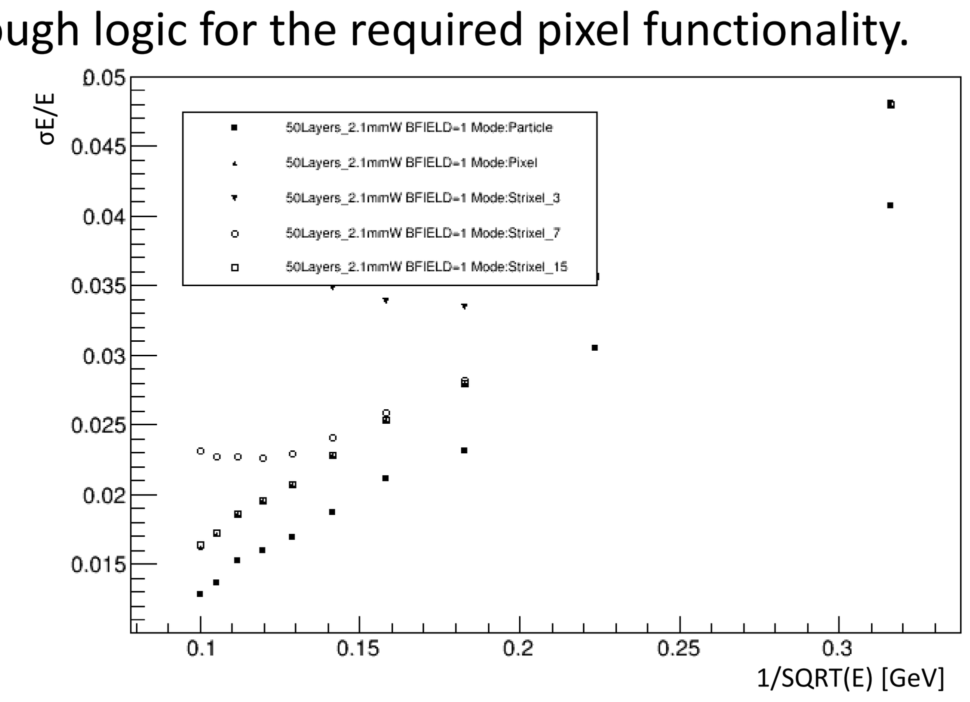

Figure 3: Impact of different upper limits of hit counts per column, for summing down columns using fast logic, on energy resolution for readout in Pad Mode

Dead Time

In order to read each pixel in 25 ns and keep the power low, amplifiers with a slow decay time were chosen. Device simulation illustrates that for this design a pixel can take up to 40 bunch crossings to return to pre-hit levels. Simulations within FCC software of 1 TeV electrons incident upon the exact same region of the DECal, for 200 consecutive bunch crossings demonstrated a negligible effect on the number of struck pixels and energy resolution. This highlights that even in the densest of showers, the same pixels are not struck in consecutive bunch crossings due to the ultra high granularity of the DECal.

First Results

The Sensors, Motherboards, and Daughterboards were delivered from fabrication in November. Figure 4 shows the 64x64 pixel matrix. The sensor uses a high resistivity substrate, and a bias of 1-5 V can be applied to deplete the epitaxial layer under the electronics. Initial measurements are focused on a test pixel which allows the output of the pre-amplifier and shaper to be probed whilst the DAQ is being developed. Figure 5 shows the response of the pre-amplifier and the shaper to a laser with the analogue circuitry biased. The output signal from the shaper increases as it should with laser intensity.

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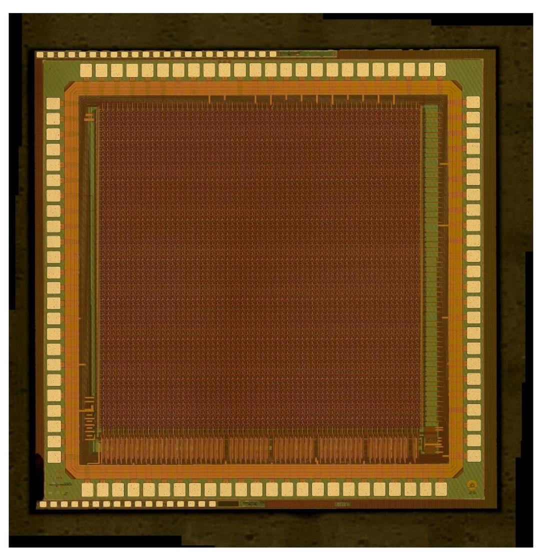

Figure 4: Photograph of the 64x64 pixel matrix

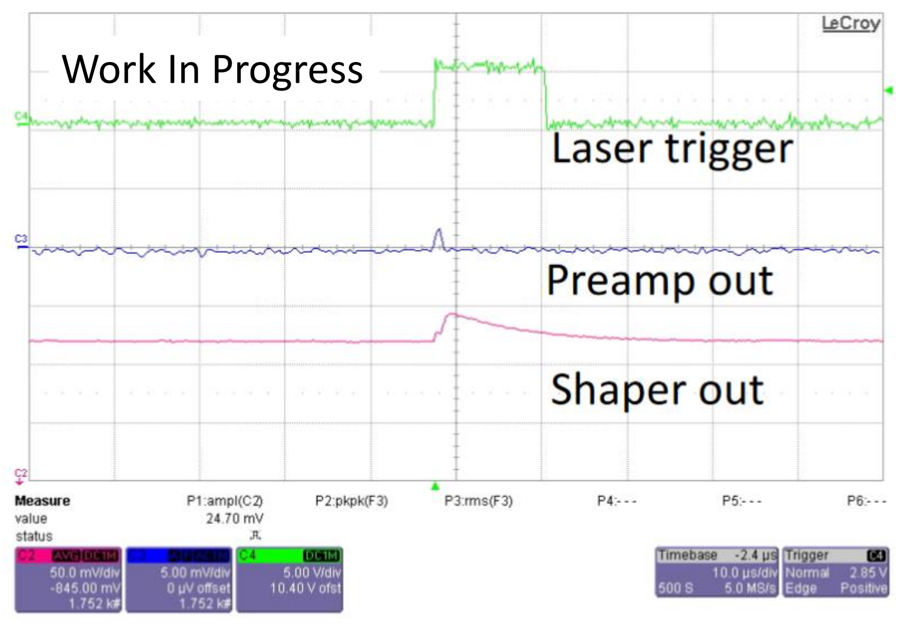

Figure 5: Scope output from the test pixel with incident laser pulse

Future Developments

The motherboard is read out using a Nexys board. Firmware has been written and software currently under development. Once completed there is an extensive list of testing to be completed:

- Evaluate the test pixel response to laser, and radioactive sources
- Perform TCT measurements to evaluate the depletion region as a function of bias voltage
- Calculate pedestals for the digital channels, the signal size, and sensor efficiency to various sources as a function of bias voltage
- Investigate the reconfigurability of the sensor and the effect on noise, pedestal, read out rate, data rate etc.
- Evaluate the radiation hardness using both x-rays at RAL and 28 MeV protons at the University of Birmingham MC40 cyclotron
- Compare the response of test structures in the standard TowerJazz process and the modified-TJ process [6] as a function of radiation.

References

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[2]https://arxiv.org/abs/1708.05164
[3]https://indico.cern.ch/event/556692/contributions/2465167/attachments/1469036/2272313/pricet_decal_fccweek2017.pdf
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