CMS Endcap Calorimeter Upgrade, HGCal



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Challenges at HL-LHC

Dose [Gy]

• HL-LHC plans 5e34/cm²/s instantaneous luminosity and 3000/fb integrated

- High pile-up conditions (200 PU)
- High radiation dose (150Mrad, 10¹⁶n/cm²)
- Resolution of current endcap EE increases to O(10%)



Endcap Calorimeter needs replacement

The HGCal Endcap Design

Construction:

- Modules built from W/Cu baseplate, hexagonal sensors and readout PCB
- Cassettes built from modules and Cu cooling plate

In 2015 CMS chose a silicon based calorimeter

20 years of experience from tracker and pixel

- Radiation effects are well understood and manageable with -30C temperature operations
- High granularity and fast timing capability help mitigate pile-up
- Electronics in 130/65nm allows low noise and low power readout even for large dynamic range

• Key parameters:

- 600 m² of silicon
- 6M readout channels, 0.5-1 cm² area cells
- 21660 modules (8" or 2x6" sensors)
- Cassettes inserted into absorber
 115kW power at end of life

Expected Performance

minimize thickness in design

Silicon Sensor R&D

Hexagonal sensors from 6" vs 8" wafers

8" wafers offer lower costs

Inter cell distance (20um - 80um)

- The larger the distance the smaller the inter-cell capacitance
- The smaller the distance the larger the break down voltage

p-type vs n-type

 n-type are cheaper but at highest fluences less radiation tolerant

Active layer thickness (100um - 300um)

 at high fluences thinner ~100um sensors give more absolute collected charge than 200 or 300um ones

Comparison of performance of sensors from various vendors

- HPK: 6" n-type fabricated and tested, p-type to be ordered
- Infineon and HPK: 8" p-type are being fabricated
- Novati: half of 6" p-type from 8" wafer being tested

HPK Sensor Testing at Fermilab

Prototype 6" n-type sensors from HPK

- Testing with custom probe card, contacting all channels with spring loaded pins
- 50 tested sensors showed expected performance and excellent quality: no breakdown till 900V

Irradiation Studies of Si Diodes

Types of diodes

- Silicon growth technique: dd-FZ: float zone deep diffusion Epi: epitaxial layer
- n-on-p (p type), p-on-n (n-type)
- Active thickness: 50um 320um
- Size: 5mm x 5mm

• Goal: investigate performance CMS FLUKA geometry v.3.720 after neutron irradiation up to 1.5e16 n/cm²

List of sensors and status:

Fluence n/cm2	Float zone			Epitaxial	
	320	200	120	100	50
4.00E+014	1 n-on-p, 1 p-on-n				
6.00E+014	2 n-on-p, 2 p-on-n				
9.00E+014	1 n-on-p, 1 p-on-n				
1.50E+015		1 n-on-p, 1 p-on-n			
2.50E+015		2 n-on-p, 2 p-on-n			
4.00E+015		1 n-on-p, 1 p-on-n			
6.25E+015			2 n-on-p, 2 p-on-n	2 n-on-p	
1.00E+016			1 n-on-p, 1 p-on-n	2 n-on-p	2 n-on-p, 2 p-o
1 60E+016			1 n.on.n 1 n.on.n		2 n-on-n 2 n-o

Thickness (um)

Radiation Hardness Results

Signal injected with IR laser, confirmed with ⁹⁰Sr

- Leakage current normalized by the volume of the diode is proportional to the fluence, even at high fluences
- The alpha measured at 800V is equal to the value measured during the CMS tracker upgrade with proton irradiation, 5.3x10-17 A/ cm3 in both cases (scaled to +20C) and consistent with Moll's thesis alpha value
- P type dd-FZ diodes of 320um thickness showed significantly lower signals than N type diodes (under investigation), while similar for other thicknesses
- Signals from Epi (100um) diodes are larger after radiation than from dd-FZ (120um) diodes

Timing Studies of Diodes at CERN

- Goal: to measure intrinsic timing capabilities of silicon detectors for EM showers
- Study time resolution as a function of signal amplitude, active thickness and fluence
- Used Cividec amplifiers and Caen V1742 fast (5GHz) digitizer with >500MHz bandwidth

Cold box (-25°C)

Timing Results

 Time resolution is measured by comparing time of signal arrival from two Si diodes, event by event

Time resolution is determined by S/N

- Dependence on sensor thickness is via S/N
- Dependence on fluence is also via S/N
- Timing resolution is < 20ps for S/N > 50
- Application of timing capabilities of silicon sensors may resolve showers in time and help mitigate pile-up at HL-LHC
- ~10ps resolution for EM shower with 50ps cell resolution

Module Design and Construction

- The electromagnetic part of HGCal requires compact construction to keep shower size small
- Module design is being optimized
 - to obtain low profile
 - requires as thin as possible electronics design
 - wire-bonding sensor cells to PCB requires
 - meeting tight gluing tolerances to ensure the PCB is flat, horizontal (~100um) and well supported by the glue
 - good alignment (~100um) of sensor and PCB layers
 - may require deep access wire-bonding machine (~1mm deep)

Module Assembly

Wire Bonding

~ 700 wire bonds on a single module!

Double-layer Module Prototype

- In parallel, a double-layer module structure has been explored
 - bottom layer is a passive PCB connecting silicon pads to a connector
 - top layer carries all electronics, SKIROC chips, etc...
 - allows replacement of electronics and reuse of the sensors during R&D
 - Successfully operated in test beams

Automated Assembly of Modules

- Setting up Gantry machine for automated assembly of modules
- Reproducible results
- High rate and volume of assembly
- Will be tested for the production of the test beam prototype calorimeter

Clamping tool Sensor holding tray Baseplate on carrier tray Assembled module cures under clamping tool

Overview of Beam Tests

Goals				
 verify functionality of design with a full depth but 	Laboratory	Layers	Rad length	Date
narrow calorimeter prototype	FNAL	1	6	March 2016
 performance studies: signal to noise, timing, energy and position resolutions 	FNAL	4	12	May 2016
Several beam tests at FNAL and CERN	FNAL	16	15	July 2016
 FNAL: 120GeV protons, 4-32GeV electrons/pions CERN: 125GeV pions, 20-250 GeV electrons 	CERN	8	27	Aug 2016
Each layer contains 1 sensor mounted				
on a copper cooling plate		Electronics Cra for carrier car	nte ds	
 6", 200um active thickness, p-on-n, 1.1cm2 cell size 		with FMC-IO, a ZedBoard		
Hanging file design for mechanical structure				

Cooling wate

manifold

 Flexible insertion of absorbers and modules on cooling plates

Cern Test Beam (27 X₀ with 8 Layers)

Calibration and Event Displays

Muon beam used to calibrate sensors

- After pedestal and coherent noise subtraction distribution of ADC counts is fit with a Landau distribution convoluted with a Gaussian
- 1 MIP ~ 17.9 ADC

Detailed analyses of data ongoing

L1:5.1X L2:8.5X L3:11.9X₀ L4:14.7X₀ L5:17.2X₀ L6:18.7X₀ L7:21.1X₀ L8:27.07X₀ MPV = 17.859284

~ 7.4

Fermilab Test Beam (15 X₀ with 16 Layers)

Zoltan Gecse

Energy Depositions and MC Comparisons

- All layers have been calibrated
- Pedestals and noise subtracted
- Top plot shows energy deposited in each layer
 - Shower max moves to higher depth with increasing electron beam energy, as expected
- Bottom plot shows total energy deposited in all layers as a function of e⁻ beam energy
 - Dependence is linear
 - Compared to Geant 4 simulation
 - Good agreement (~5%) observed

Summary

- CMS is preparing for a High Granularity Endcap calorimeter largely based on silicon sensors, (600m² and 6M channels)
- First prototype HGCal sensors have been fabricated and show excellent quality and expected performance
 - comprehensive suite of studies is planned and well underway
- Radiation studies of silicon diodes show good radiation hardness for entire lifetime of HL-LHC (3000fb-1)
- Good intrinsic timing resolution (<20ps at high enough S/N) of silicon diodes has been measured. This can help mitigate the effect of pileup and in localizing the primary vertex of the event of interest.
- Construction of prototype modules has been successfully demonstrated and work started on automated assembly
- Successfully constructed and operated a 16 layer EE prototype in the test beam

Additional Material

Front-end Electronics

Very stringent requirements for Front-End Electronics

- Large dynamic range 0.4 fC 10 pC (15 bits) noise < 2000 e- to keep MIP visibility for low thickness sensors after 3000 fb-1
- Leakage current compensation
- Low power budget < 10 mW/channel
- Timing information 50 ps accuracy
- System on chip (digitization, processing), high speed readout (>Gb/s), large buffers to accommodate 12.5µs latency of L1 trigger
- Preferably compatibility for positive and negative inputs.
- High radiation resistance (150 MRad, 10¹⁶ n/cm²)

Strategy for FE Electronics

 Modify existing CALICE chip to include most of the required functionalities Exercise functionalities such as ToT, cross calibration ADC-ToT, fast timing... Allows study of FE printed circuit board and module assembly Test beams 2016-2017

> SKIROC2 -> SKIROC2-CMS 0.35 µm AMS (non radhard) faster shaper 25ns instead of 200 ns sampling @ 40 MHz, depth 300 ns ToT TDC for ToA 20 ns binning 50 ns jitter

TDC for ToA, 20 ps binning, 50 ps jitter Received late June, under test (see next presentation)

2) Submit Test Vehicles in 130 nm

TV1 received mid-September: analogue architecture, baseline + variants TV2 to be submitted before end 2016: 8 channels, analogue+ADC+ToT+ Trigger sums

3) Submit first "complete" ASIC June 2017

(some digital functionalities may still be incomplete)

4) Two more iterations foreseen in the overall planning

Test Beam DAQ

