Silicon Photomultipliers in the CMS Upgrade

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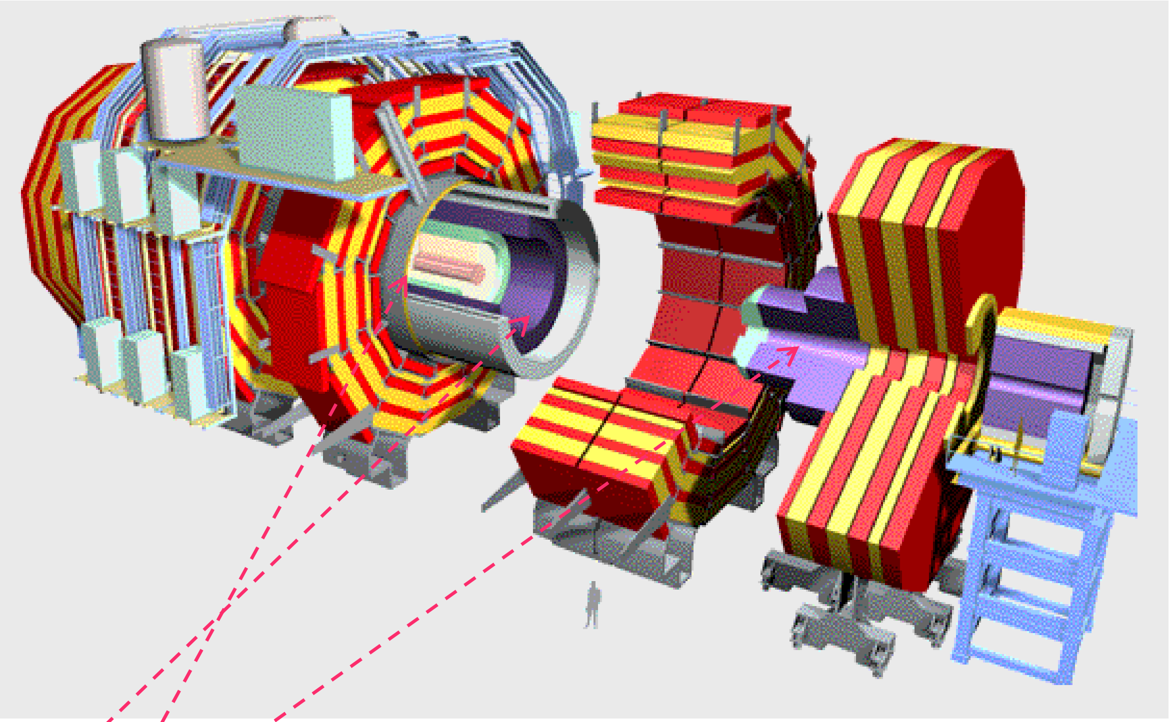
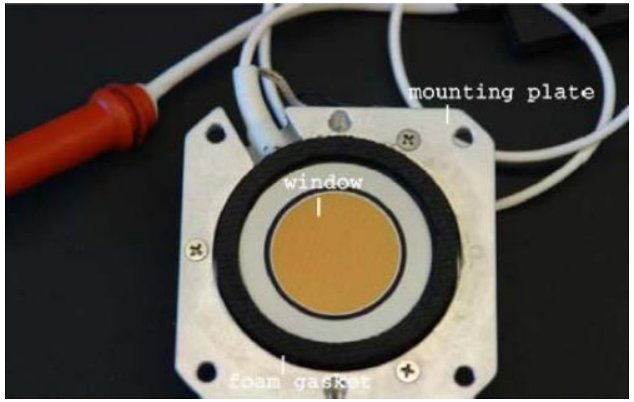
Introduction

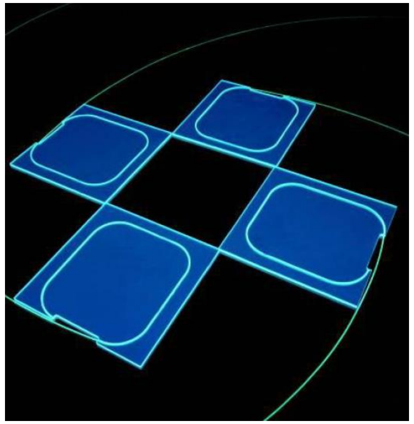
- Over the past decade, the CMS collaboration decided to implement more than 500,000 channels of SiPM as part of the Phase I and Phase II upgrades of the detector. SiPMs are the photon detectors of choice for the following projects:
  - An upgrade of the hadronic calorimeter (HCAL), comprised of three separate detector elements
  - A new, high granularity endcap calorimeter (HGCAL) that is currently under construction
  - A new Barrel Timing Layer (BTL), one part of the MIP Timing Detector (MTD)

The CMS Hadronic Calorimeter



CMS HPD (18 ch.)



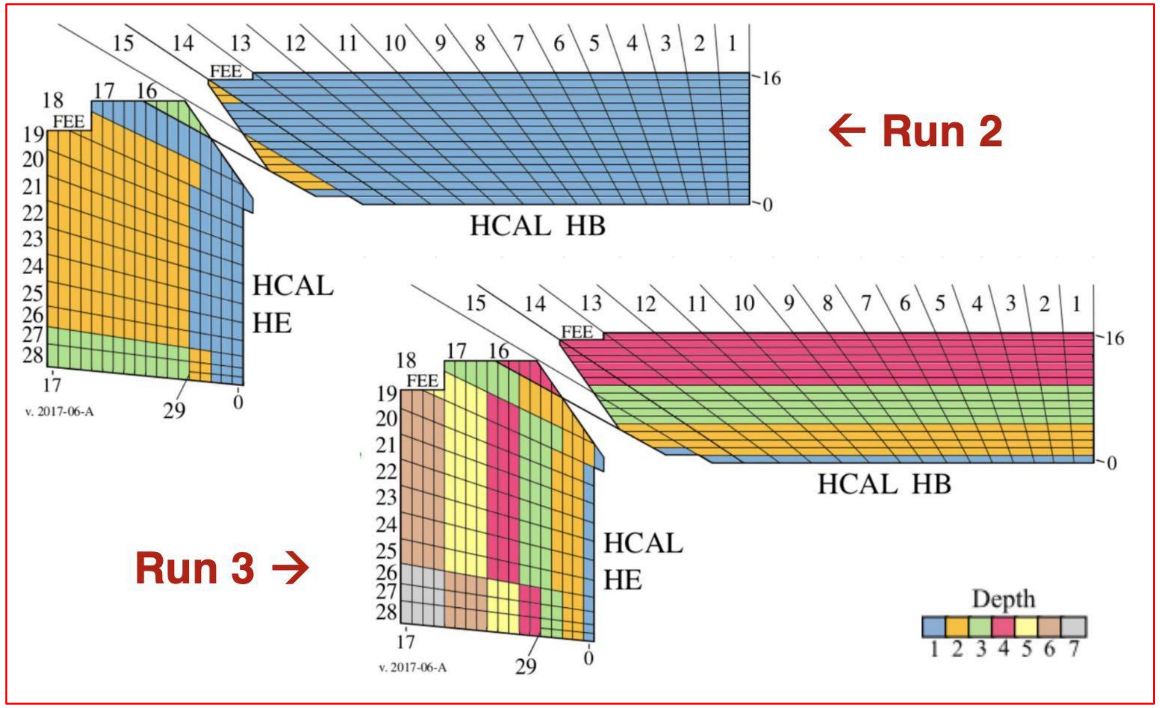


HB, HE, HO similar technology: scintillator tiles with Y11 WLS fiber readout, brass (steel for HO) absorber.
HPD was selected as the CMS HCAL photodetector. All HPDs were replaced with SiPMs after 2020 upgrade

Motivation for replacing HPDs with SiPMs

- Ideal photodetector for calorimetry at the LHC
  - Very fast – minimal impact on pulse shape at high pileup
  - High photon detection efficiency (PDE)
  - High gain (minimize impact of electronics noise)
  - No radiation sensitivity or internal noise sources
  - CMS: 4T magnetic field tolerance and compactness
- HPD was the best option in 2000
  - ☺ PDE of ~12%, gain ~2000, fast, large dynamic range, low radiation sensitivity
  - ☹ Magnetic field tolerance is marginal, internal discharge noise, gain*PDE is too small for thin layers of scintillator
  - ☹ Large device size limits the channel count (depth segmentation)

Phase I Upgrade of the CMS HCAL



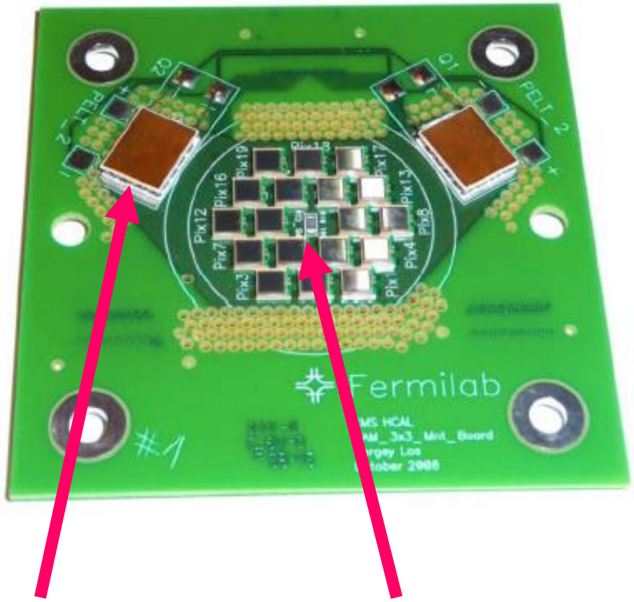
Finer segmentation of HCAL, both HE and HB:

- Better energy resolution
- Improved L1 trigger performance

Optical Decoder Units

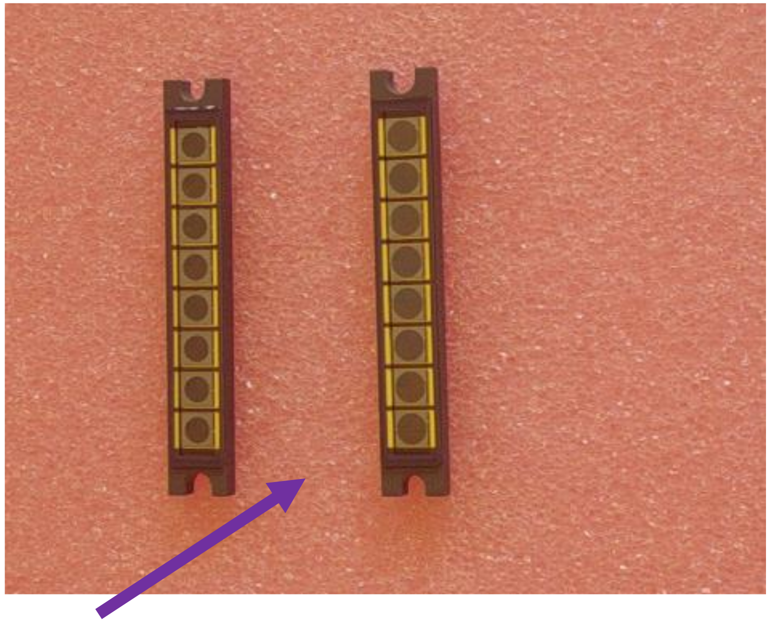
SiPM array

HO (2011) and HB/HE SiPM (2012-2020) arrays



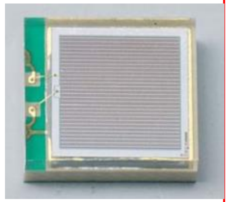
TEC HO SiPM array (18 ch. on PCB board)

HO: 1E11 n/cm^2, ~2000 SiPMs
HE: 3E11 n/cm^2,
HB: 1E12 n/cm^2, ~25 000 SiPMs (HE+HB)



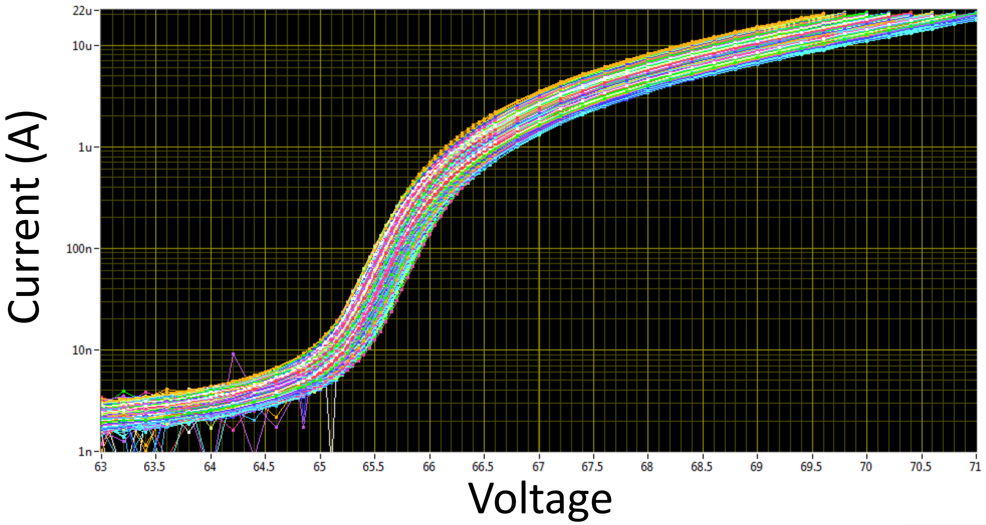
HE/HB SiPM arrays (8 ch. in ceramic package protected by quartz window)

Hamamatsu S10931-050 9 mm^2, 50 um cell pitch):
- PDE(515 nm, dVB=1.5 V) = 30%
- Gain(dVB=1.5 V) = 0.9x10^6
- ENF(dVB= 1.5 V) = 1.3÷1.4 (no trenches)
- Cell recovery time = 13 ns

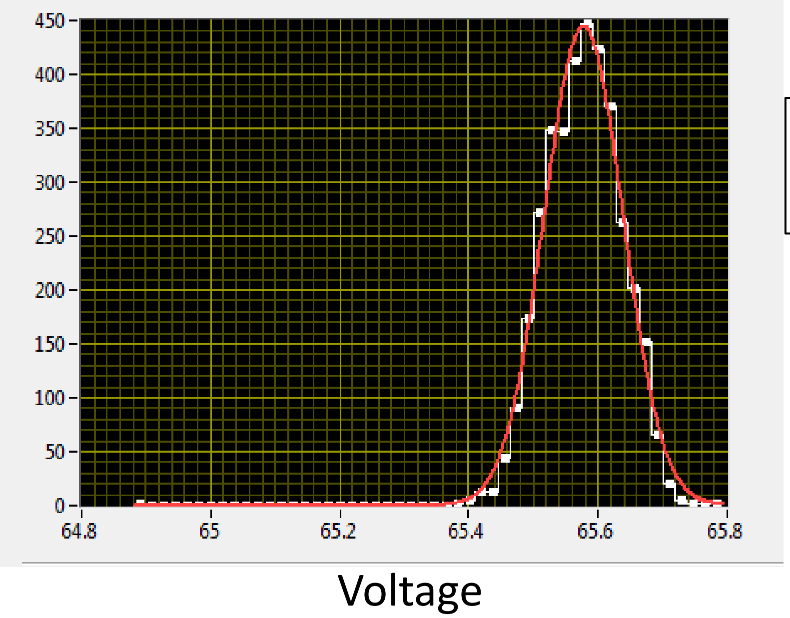


Hamamatsu S12571 SiPM (2.8 mm and 3.3 mm dia., 15 um cell pitch for larger dynamic range):
- PDE(515 nm, dVB=4 V) = 32 %
- Gain(dVB=4 V) = 0.32x10^6
- ENF(dVB= 4V) = 1.3 (no trenches, but lower gain)
- Cell recovery time = 7÷8 ns

CMS HCAL SiPM Performance – 500 arrays/4000 channels

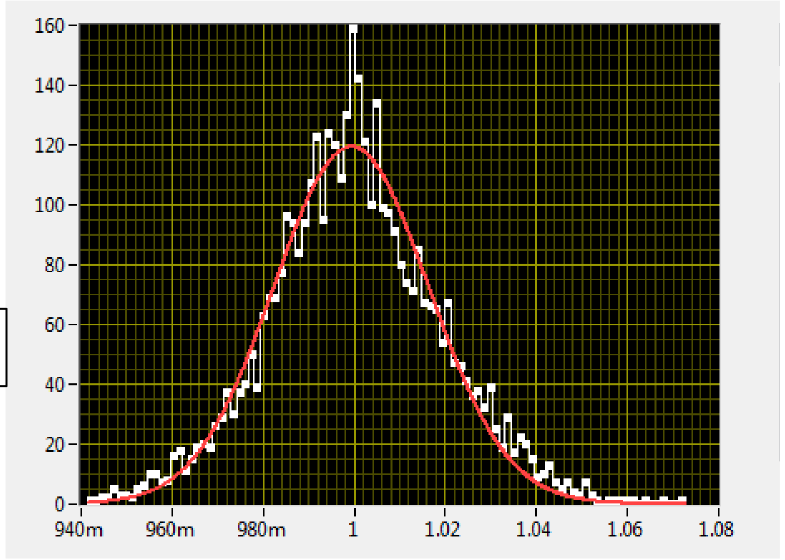


IV curves with LED illumination

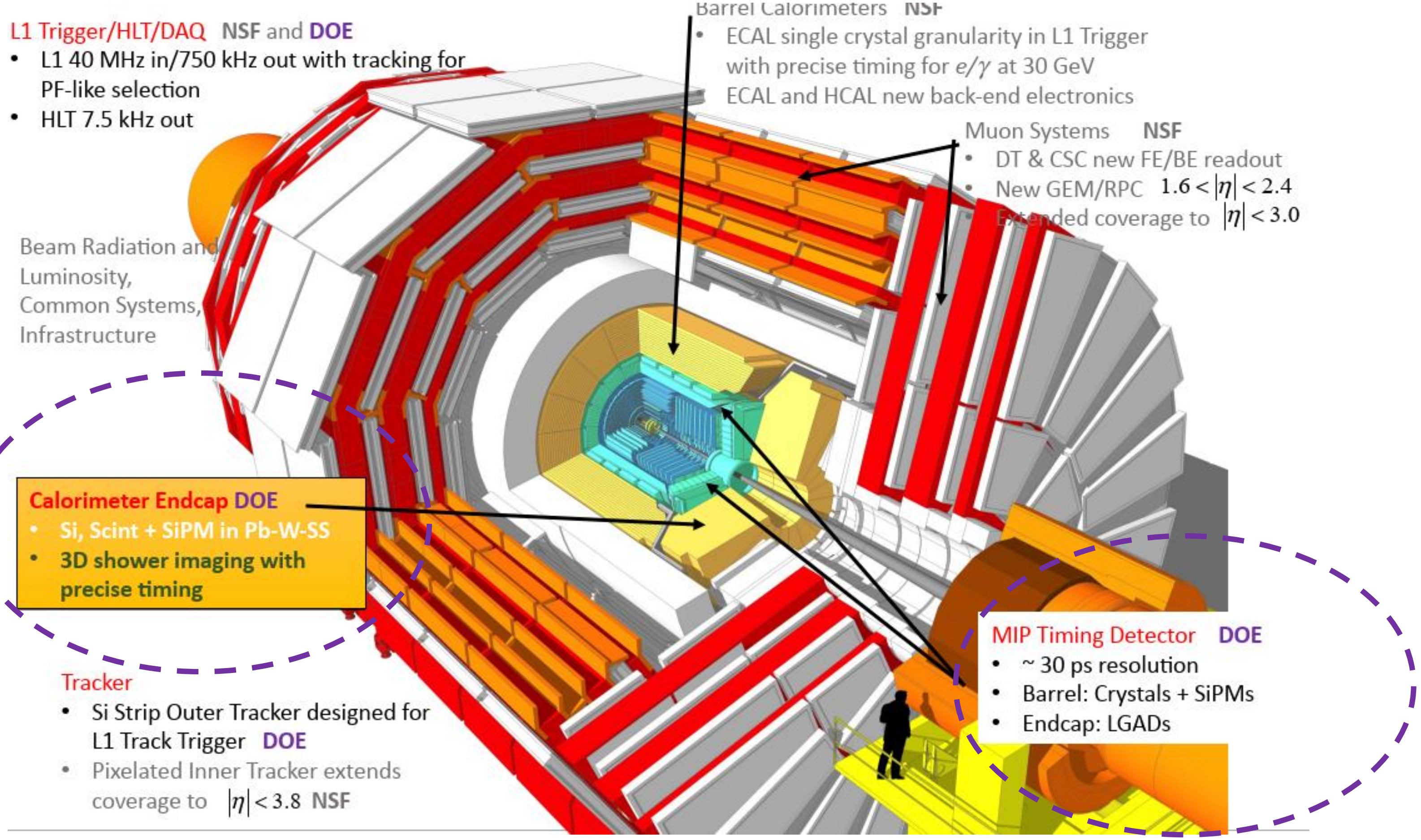


Distribution of breakdown voltages

Gain*PDE*x-talk



SiPMs for the CMS Phase 2 upgrades (HGCAL&BTL): 2017÷2029



L1 Trigger/HLT/DAQ NSF and **DOE**
- L1 40 MHz in/750 kHz out with tracking for PF-like selection
- HLT 7.5 kHz out

Barrel Calorimeters **NSF**
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems **NSF**
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

Beam Radiation an
Luminosity,
Common Systems,
Infrastructure

Calorimeter Endcap DOE
- **Si, Scint + SiPM in Pb-W-SS**
- **3D shower imaging with precise timing**

Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger **DOE**
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$ **NSF**

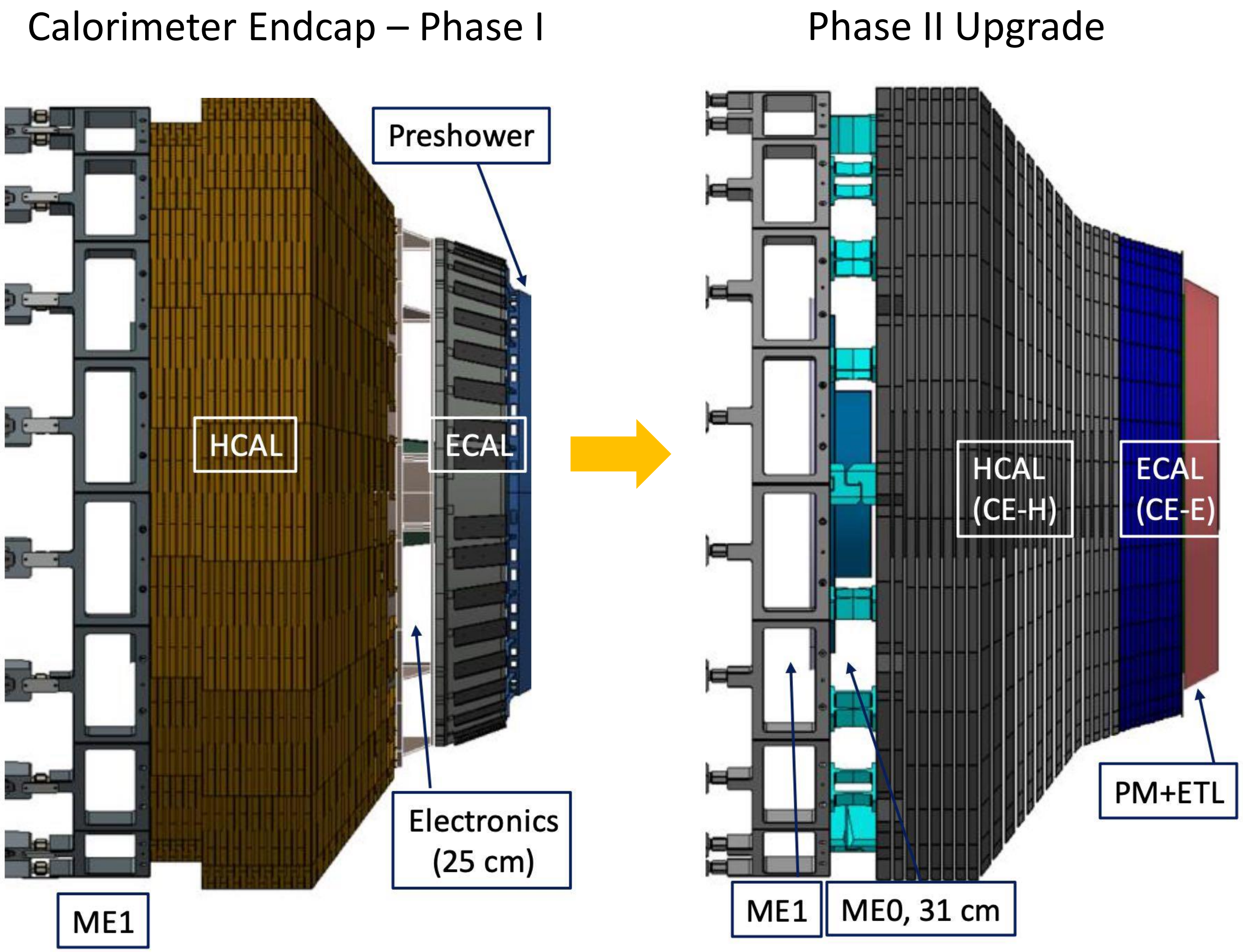
MIP Timing Detector **DOE**
- ~ 30 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

CMS HGCAL will use ~240,000 SiPMs (9 mm^2 SiPMs). MIP Timing Detector (BTL) - ~332 000 SiPMs (9 mm^2 SiPMs)

Phase II upgrade of the CMS Endcap Calorimeter

Requirements:

- Sustain radiation environment and S/N ratio through full HL-LHC operation.
- Highly granular detector for particle flow reconstruction, pileup suppression.
- Fit within the envelope of today's CMS Endcap calorimeters.
- Optimized taking into account: cost, efficiency and radiation tolerance.



Overview of the CMS Endcap Calorimeter (HGCAL) System

Overview

Electromagnetic calorimeter (CE-E):

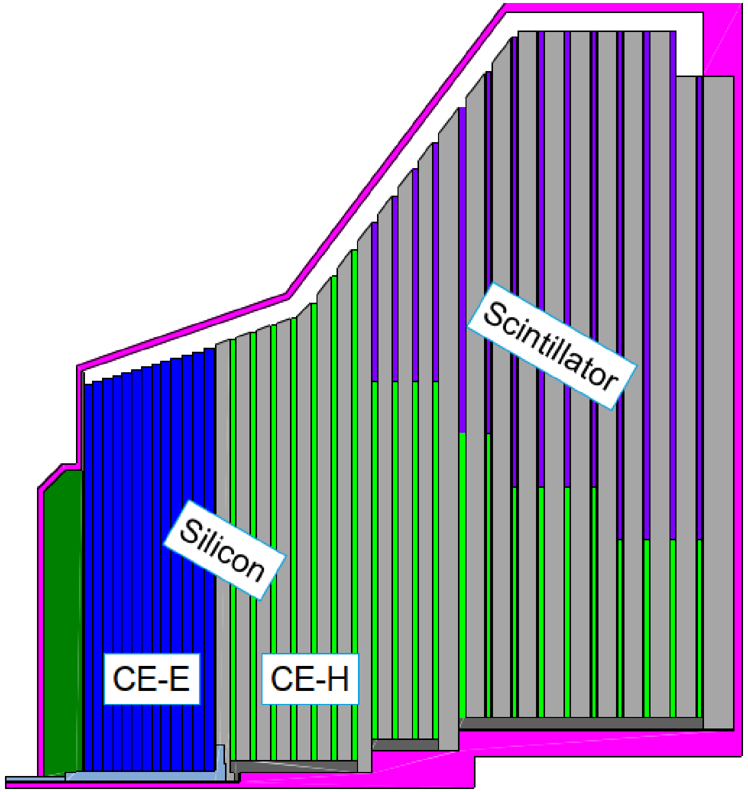
- Active elements: hexagonal silicon modules
- Cu & CuW & Pb absorbers, 26 layers, ~28 X_0

Hadronic calorimeter (CE-H):

- Si (as in CE-E) & **scintillator tiles read by SiPMs**
  - **as radiation levels permit: fluence < 5e13 n/cm^2**
- steel absorbers, 21 layers,10 λ (including CE-E)

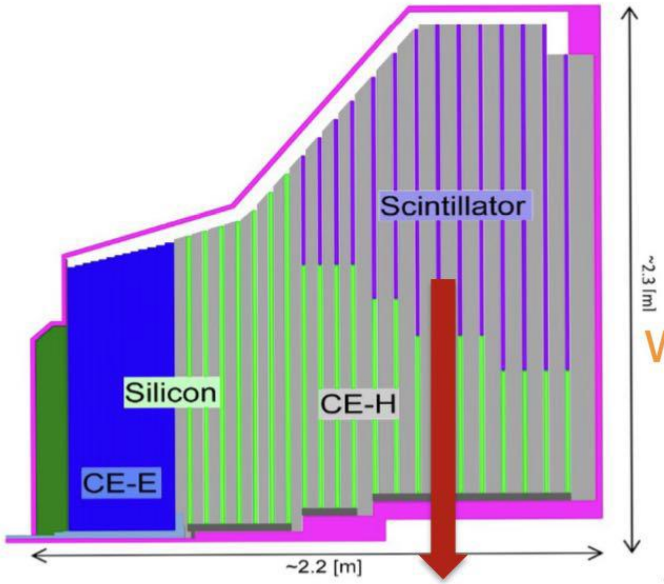
Key Parameters:

- 620m2 Si sensors in ~26000 modules
- 6M Si channels, 0.5 or 1.2cm2 cell size
- **370m2 of scintillators in ~3700 boards**
- **240k SiPM-Scint. channels, 4-30cm2 cell size**
- 220 tonnes per endcap, full system at -30°C
- up to 280kW, two phase CO2 cooling



CMS HGCAL will use ~240 000 SiPMs (9 mm^2 SiPMs, 15 um cell pitch). Neutron fluence up to 5E13 n/cm^2

Overview of the CMS Endcap Calorimeter (HGCAL) System



Lower radiation level than silicon sector

Cell sizes from 4 to 30 cm^2

Tileboard PCB

Hosting the readout chips

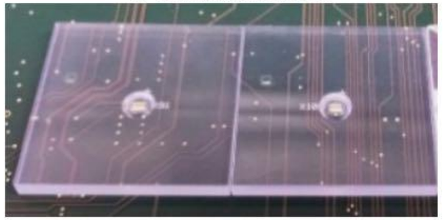
Wrapped Scintillating Tile

Reflective foil

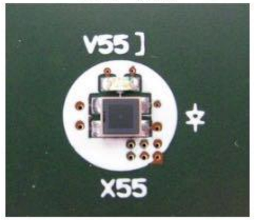
Silicon Photo Multiplier (SiPM)

Calibration with LED

Scintillator



SiPM



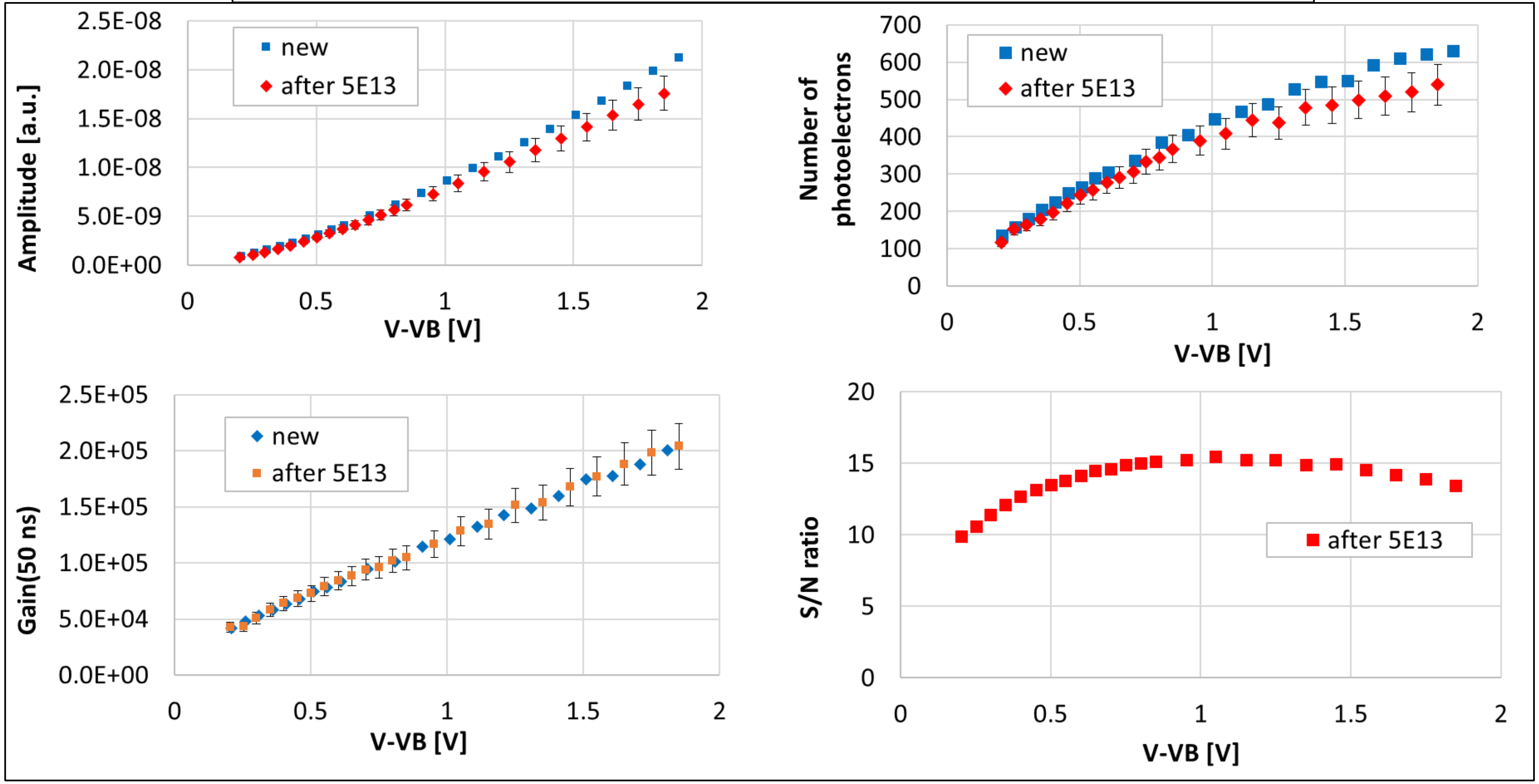
HPK S16713-03
9 mm^2 active area
15 micron pixel size

Endcap Calorimeter SiPM requirements

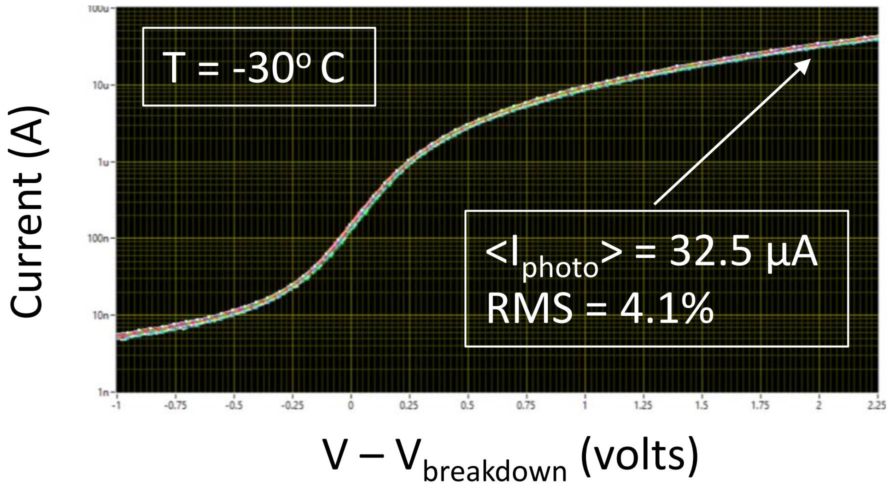
- The requirements for the HGCAL SiPMs are driven by the expected signal-to-noise levels at the end of life of the detector, and by the operating environment. These include:
  - High photon detection efficiency (PDE): > 20% at nominal operating voltage to optimize signal/noise
  - Small pixels (15 micron) for extended linear dynamic range and low occupancy
  - Fast recovery time (< 10 nsec)
  - Insensitivity to magnetic fields
  - Resistance to radiation, both short term (noise) and long term (operation up to 5×10^{13} 1 MeV neutrons/cm^2)
  - Good uniformity over > 200,000 devices
  - Compact size – 9 mm^2 active area

Results of radiation studies

Results for an HGCAL 3x3 mm^2 SiPM after 5E13 neutron/cm^2 equivalent and standard annealing. Illumination with 405 nm light, T = -36°C.



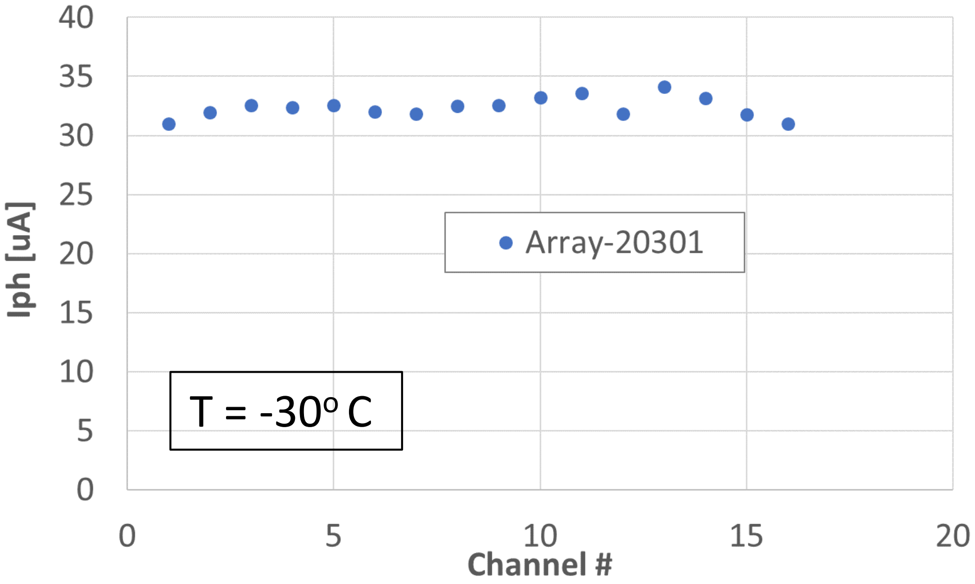
SiPM uniformity after full irradiation



T = -30° C

$\langle I_{photo} \rangle$ = 32.5 µA
RMS = 4.1%

Photocurrent for 16 channels (one array) of SiPM after 5E13 and standard annealing



T = -30° C

Photocurrent for a second 16 channels SiPM after 5E13 and standard annealing

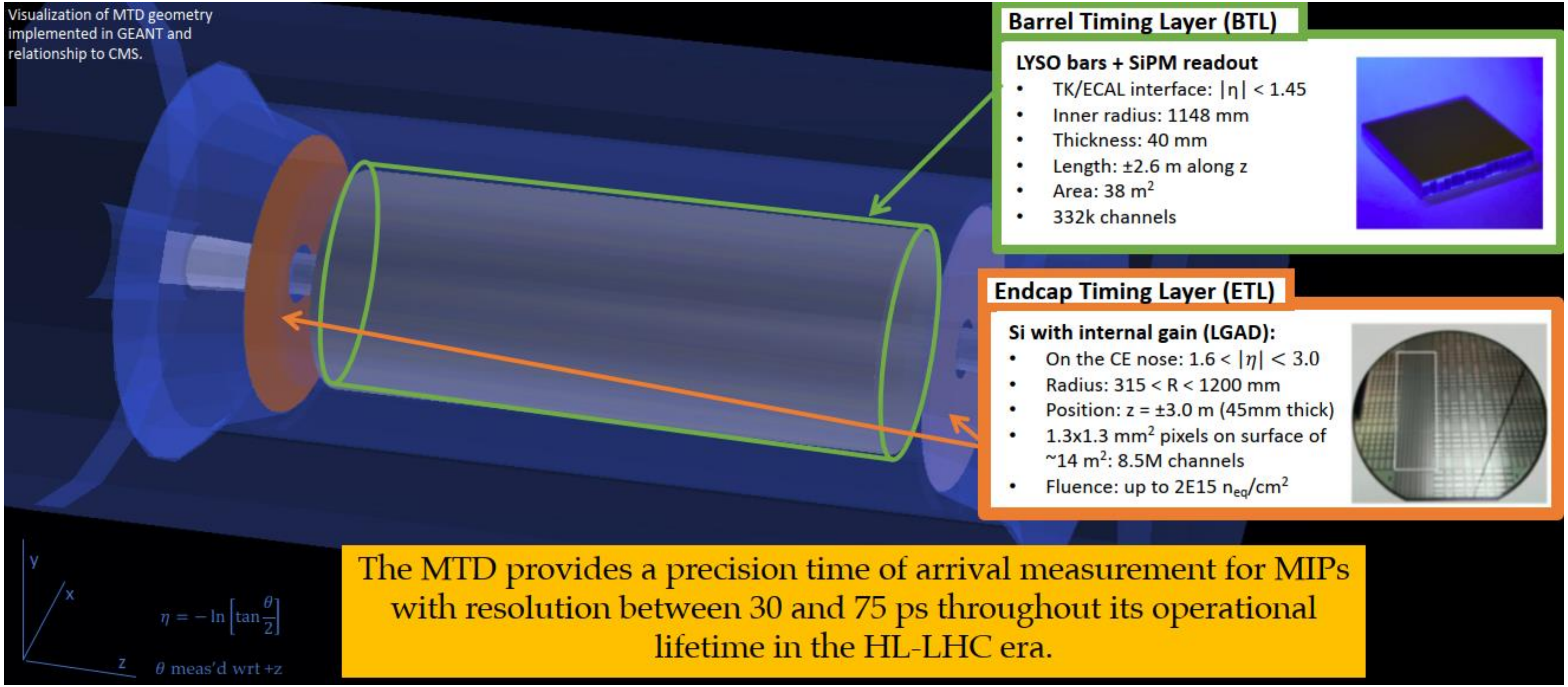
$\langle I_{photo} \rangle$ = 32.4 µA, RMS = 2.7%

Quality control of HGCAL production SiPMs

- The HGCAL SiPMs are delivered on tape reels with 1000 channels, each individual SiPM on its own package. A small sample (≤ 5%) is kept at CERN for quality control and other testing. None of this sample will wind up in the detector.
- For this entire sample (≤ 5% of total)
  - IV curves with and without LED illumination to measure dark current and determine breakdown voltage
  - Signal response = gain * PDE * cross talk
  - Forward resistance to check the quenching resistance
- More detailed measurements are performed on a small subset of the 5%:
  - Photon Detection Efficiency
  - Gain
  - Capacitance
- Destructive testing are done on a small subset of the 5%:
  - Radiation tests
  - Aging studies

HGCAL Adapter boards for QC testing

Design Overview for the CMS MIP Timing Detector (MTD)



Visualization of MTD geometry implemented in GEANT and relationship to CMS.

$\eta = -\ln\left[\tan\frac{\theta}{2}\right]$

θ meas'd wrt +z

Barrel Timing Layer (BTL)

LYSO bars + SiPM readout

- TK/ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm
- Thickness: 40 mm
- Length: ±2.6 m along z
- Area: 38 m^2
- 332k channels

Endcap Timing Layer (ETL)

Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position: z = ±3.0 m (45mm thick)
- 1.3x1.3 mm^2 pixels on surface of ~14 m^2: 8.5M channels
- Fluence: up to 2E15 n_{eq}/cm^2

The MTD provides a precision time of arrival measurement for MIPs with resolution between 30 and 75 ps throughout its operational lifetime in the HL-LHC era.

CMS BTL will use ~332 000 SiPMs (HPK S15408-4125TC, 2.9mm x 3.775 mm active area, 25 micron pixels)

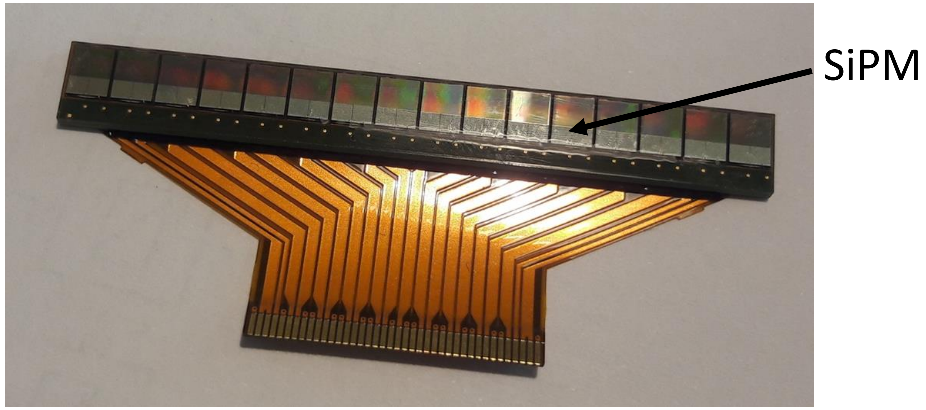
Requirements for the Barrel Timing Layer (BTL) SiPM

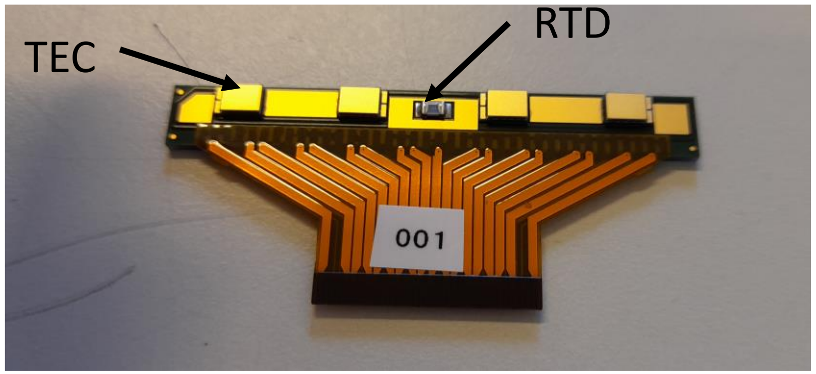
- Silicon Photomultipliers (SiPM) are the photodetectors of choice for the BTL. Features of SiPMs include:
  - Compact size, about 3mm x 3mm for the BTL
  - Small pixels provide extended linear dynamic range and keep dark count manageable
  - High photon detection efficiency (PDE) of > 50%
  - Insensitivity to magnetic fields
  - Low power consumption
  - Good uniformity over large numbers of channels
  - Relative ease of operation
  - Sufficiently radiation resistant for use in the BTL → still performant at end of life of the detector (2E14 1 MeV neutrons/cm^2 equivalent)
- Given the constraints from the detector design and the features listed above, SiPMs are the only reasonable option for the BTL

R&D for the BTL SiPMs

- The R&D program for the MTD SiPMs built on the previous HCAL work and focused on improvements for operation in the new detector. This included:
    - Efforts to increase the photon detection efficiency
    - Developing a SiPM package compatible with the LYSO array structure and detector module design
    - Insuring good uniformity in breakdown voltage, temperature dependence and other parameters across large numbers of channels (more than 350,000)
    - Radiation studies: At end of life (after 3000 fb^{-1}) the BTL SiPMs will experience radiation doses up to 2E14 1-Mev neutrons/cm^2, significantly higher than HCAL
        - Dark currents need to be kept as low as possible to maintain acceptable signal-to-noise after irradiation
        - Effects of radiation on PDE and gain must be kept to a minimum
        - A package with good thermal properties to remove heat is required
    - Annealing studies to determine the expected amount of recovery during the life of the experiment

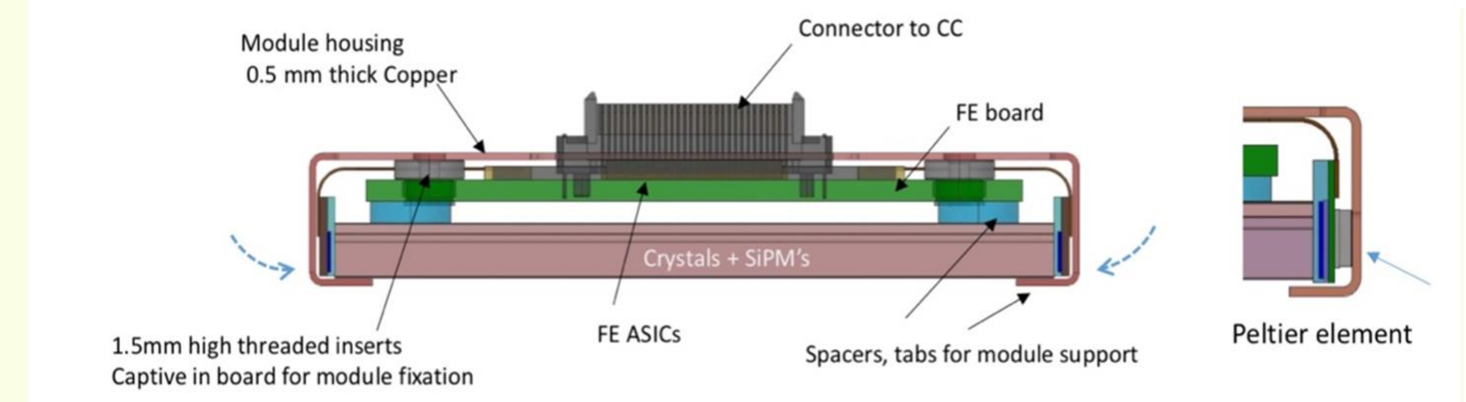
Design features of the BTL SiPM



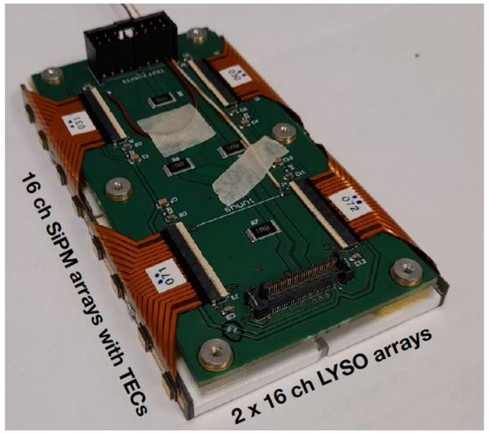


16-channel BTL SiPM Array

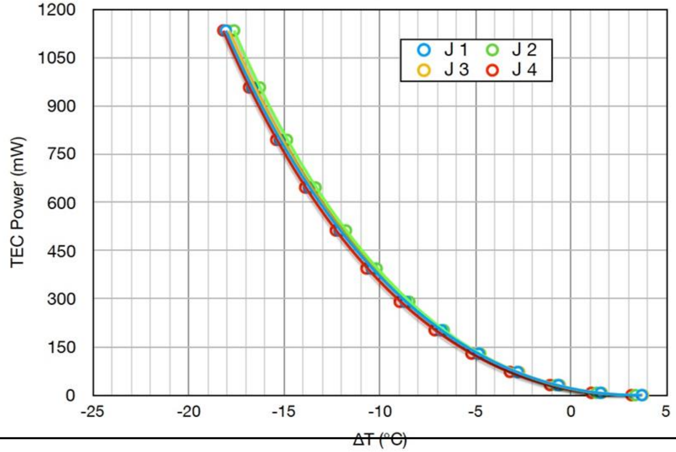
Top View: The 16 individual with 9 mm^2 SiPMs
Bottom View: Four TECs and RTD



BTL dual module with double sided readout



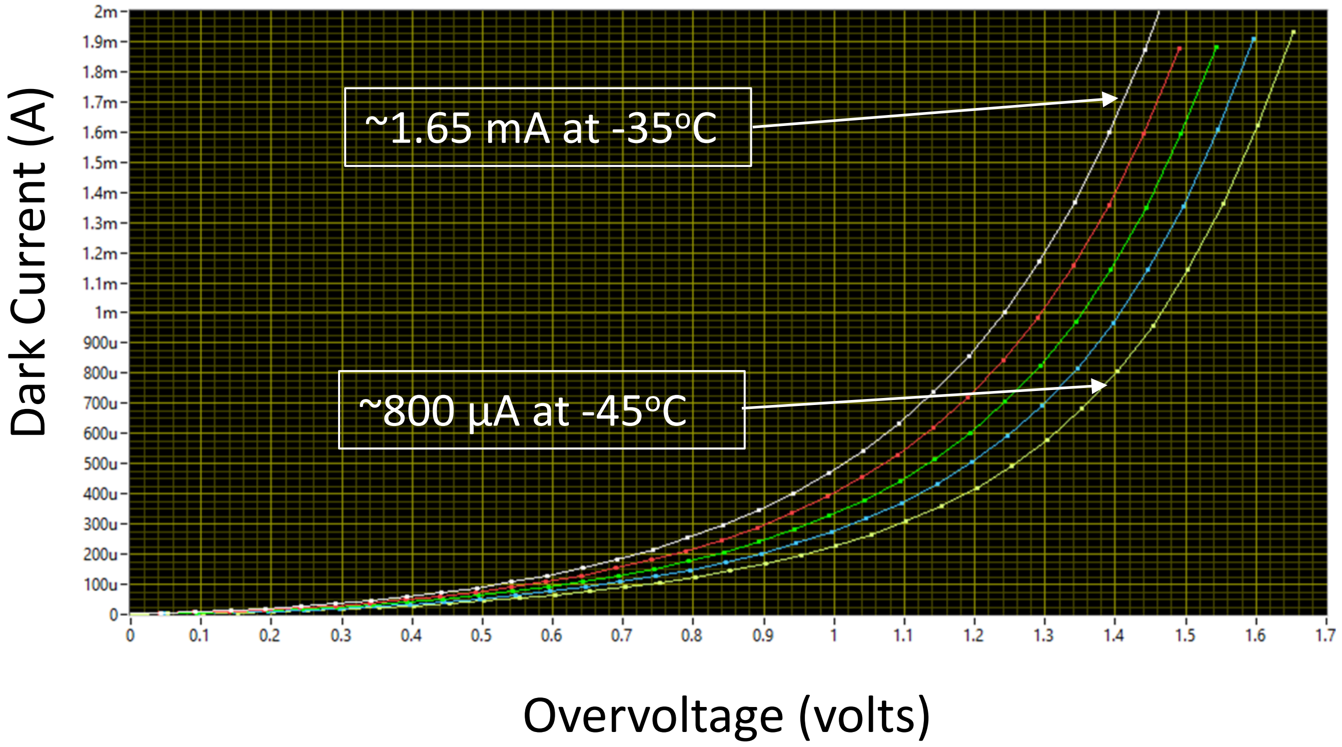
TEC power vs ΔT for the four 16 channel SiPM arrays each running at 420 mW SiPM power (25 mW /SiPM at 38V)



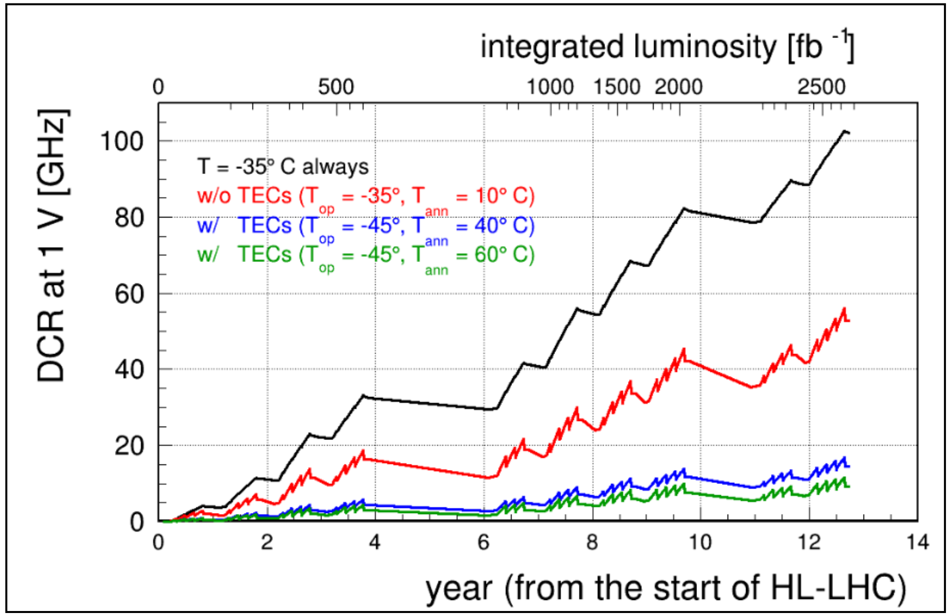
TECs will be used for to reduce SiPM temperature (from -35 °C to -45 °C) and for SiPM annealing during shutdowns. They will allow reduction of SiPM dark currents by a factor of 10.

Benefits of Thermoelectric Coolers (TECs)

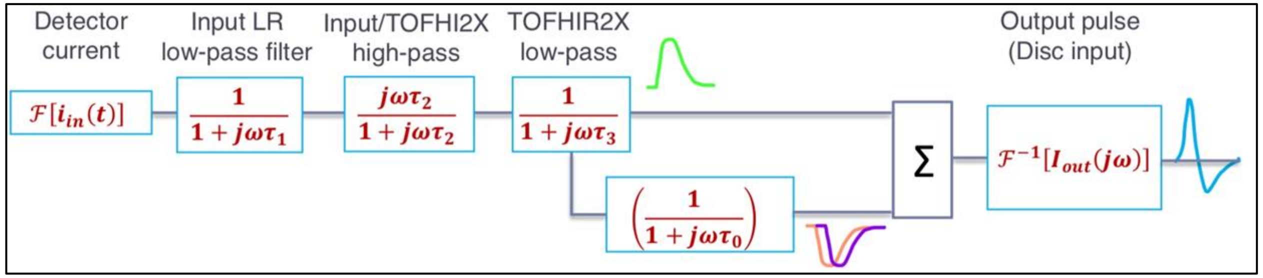
TECs as coolers reduce dark current by factor of two



TECs as heaters provide additional factor of 6 through annealing



Effects of SiPM Pixel Size


Detector current

Input LR low-pass filter

Input/TOFHI2X high-pass

TOFHIR2X low-pass

Output pulse (Disc input)

$\mathcal{F}[i_{in}(t)]$

$\frac{1}{1+j\omega\tau_1}$

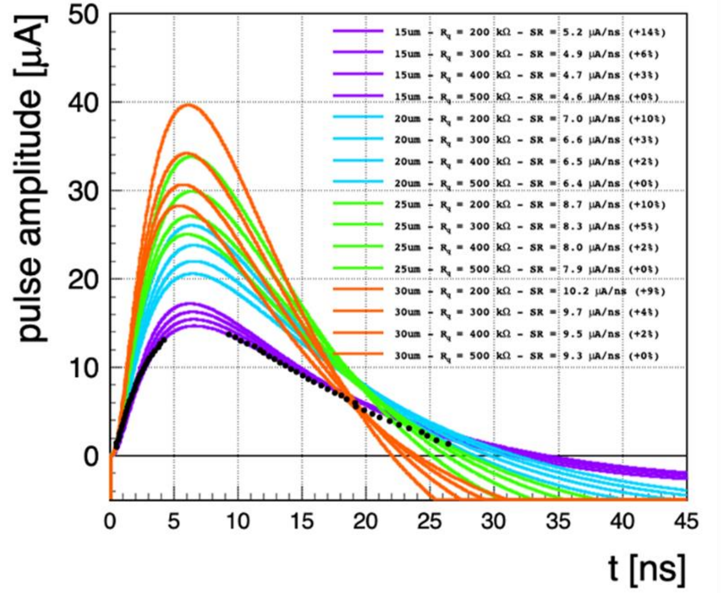
$\frac{j\omega\tau_2}{1+j\omega\tau_2}$

$\frac{1}{1+j\omega\tau_3}$

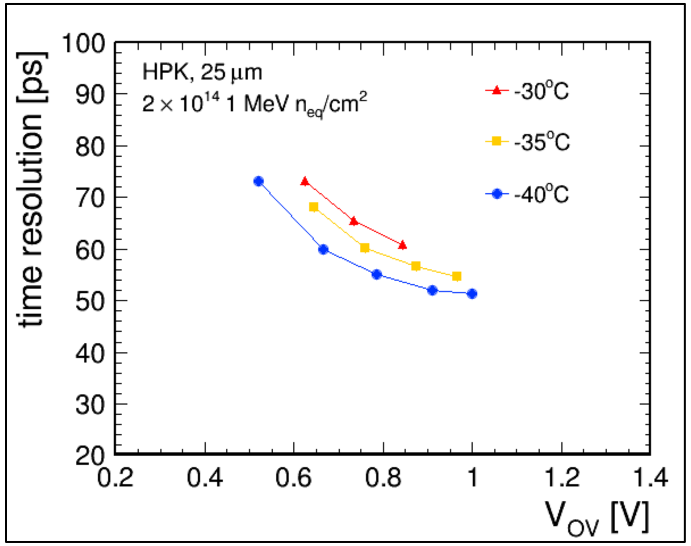
$\left(\frac{1}{1+j\omega\tau_0}\right)$

Σ

$\mathcal{F}^{-1}[I_{out}(j\omega)]$

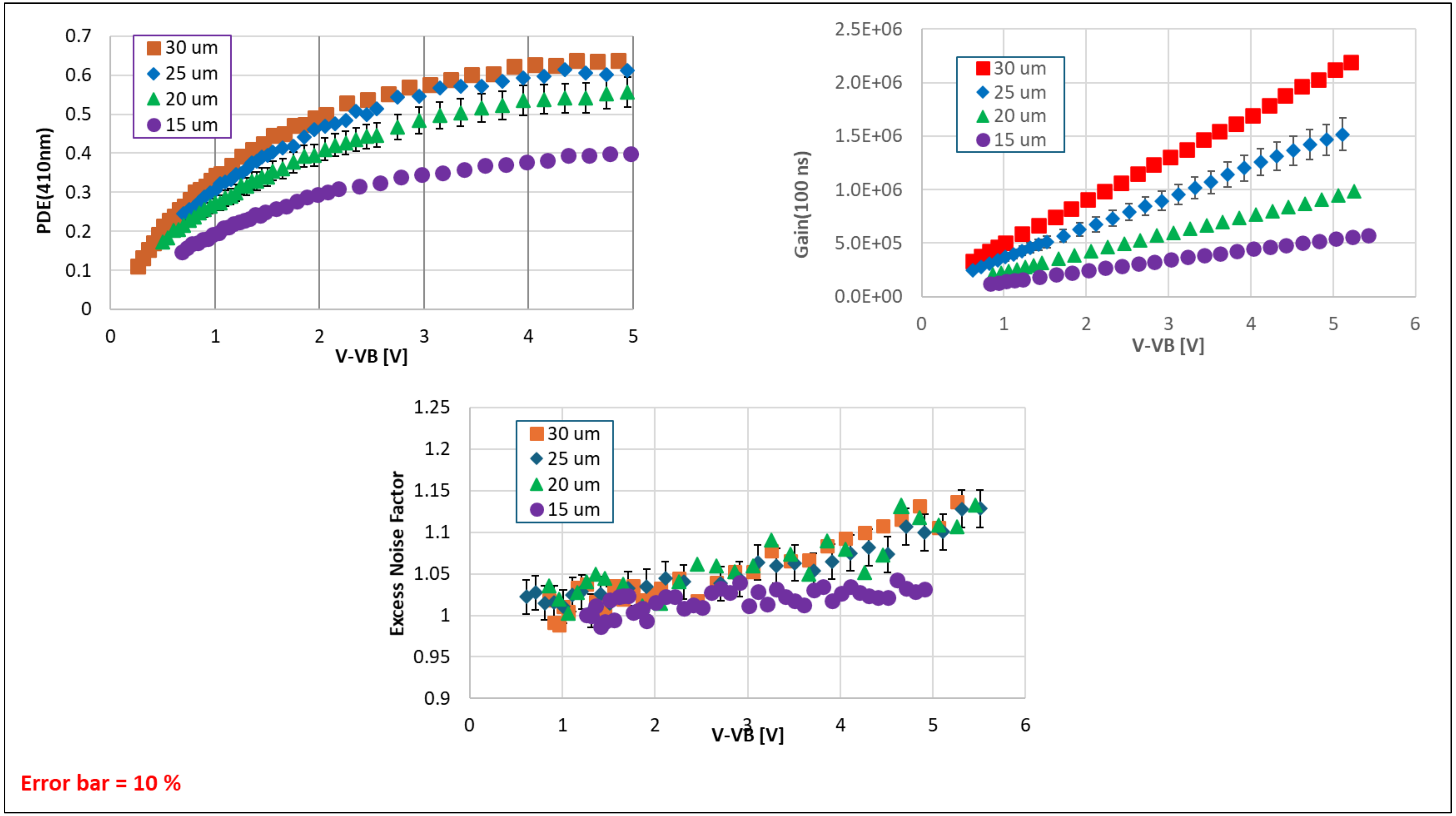

Slew rate increase vs Cell size at Vo=1.5V
(same LY of 3000 p.e from LYSO + SiPM)

Pulse amplitudes for pixel sizes from 15 – 30 microns. Larger pixel size gives higher amplitude and faster signal → improved S/N, timing resolution



Timing resolution from beam test for 25 micron pixel BTL SiPMs

Studies of SiPM Pixel Size



Error bar = 10 %

Quality control of BTL production SiPMs

Measurements of all channels, at room temperature and -30° C:

- IV curves with and without LED illumination to measure dark current and determine breakdown voltage
- Signal response = gain * PDE * cross talk
- Forward resistance to check the quenching resistance
- (Note: 50% done at CERN, 50% at Debrecen, Hungary)

More detailed measurements will be performed on a small subset of channels:

- Photon Detection Efficiency
- Gain
- Capacitance

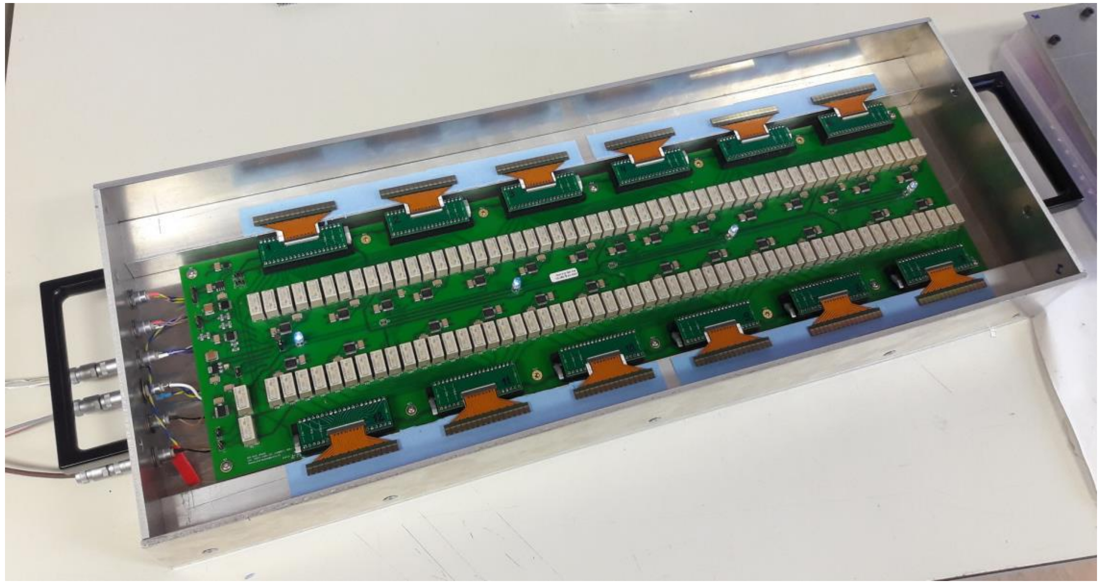
Destructive testing will be done on a small subset of channels:

- Radiation tests
- Aging studies

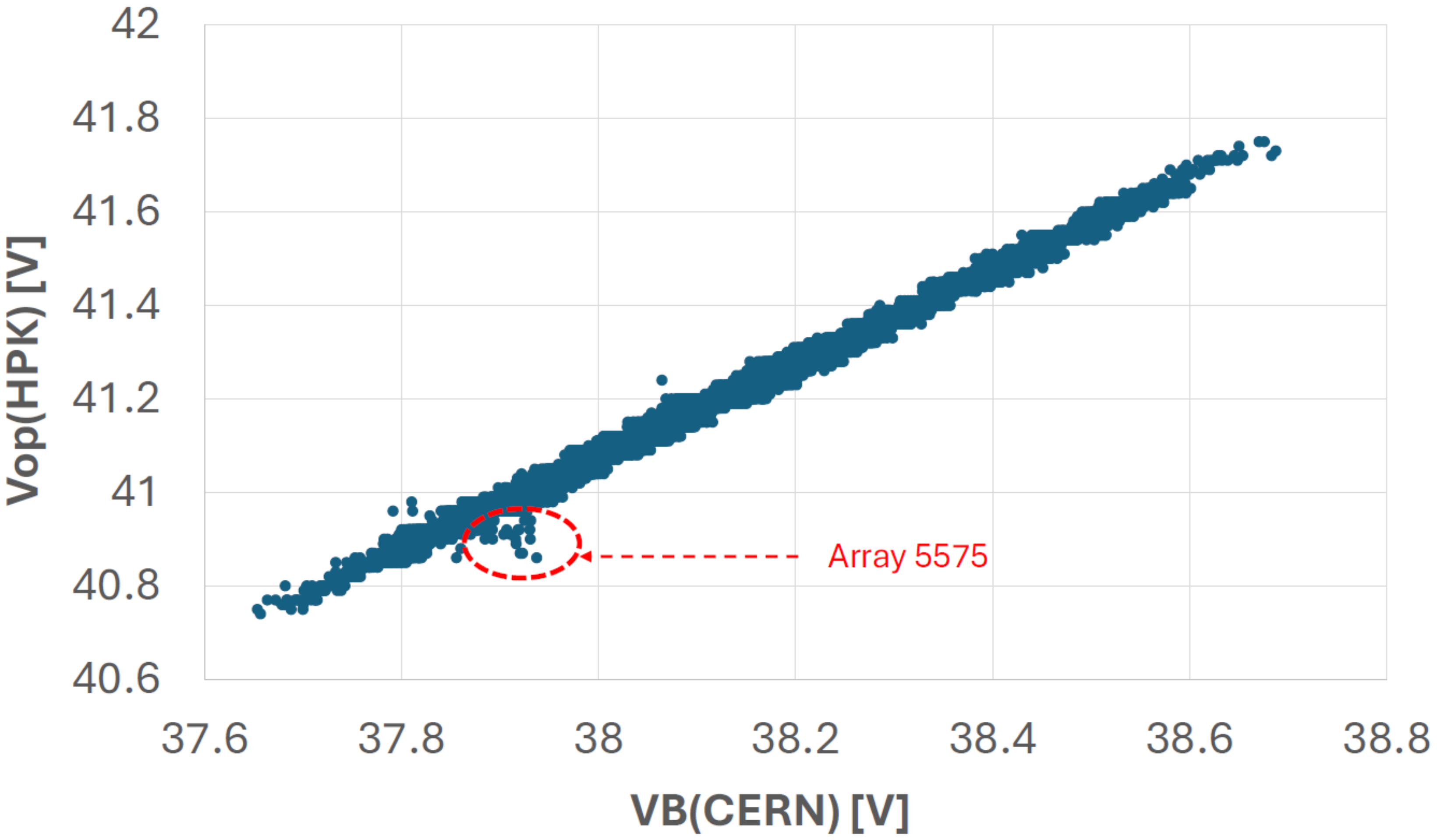
After characterization and qualification, arrays passing our qualification cuts will be sent to assembly centers, with travelers containing array IDs and relevant data

Notre Dame SiPM QC Test Setup

- Measures 12 BTL Arrays (192 channels) at a time
- LED illumination for V_b, PDE*gain
- TEC control
- Also used for HGCAL SiPM QC

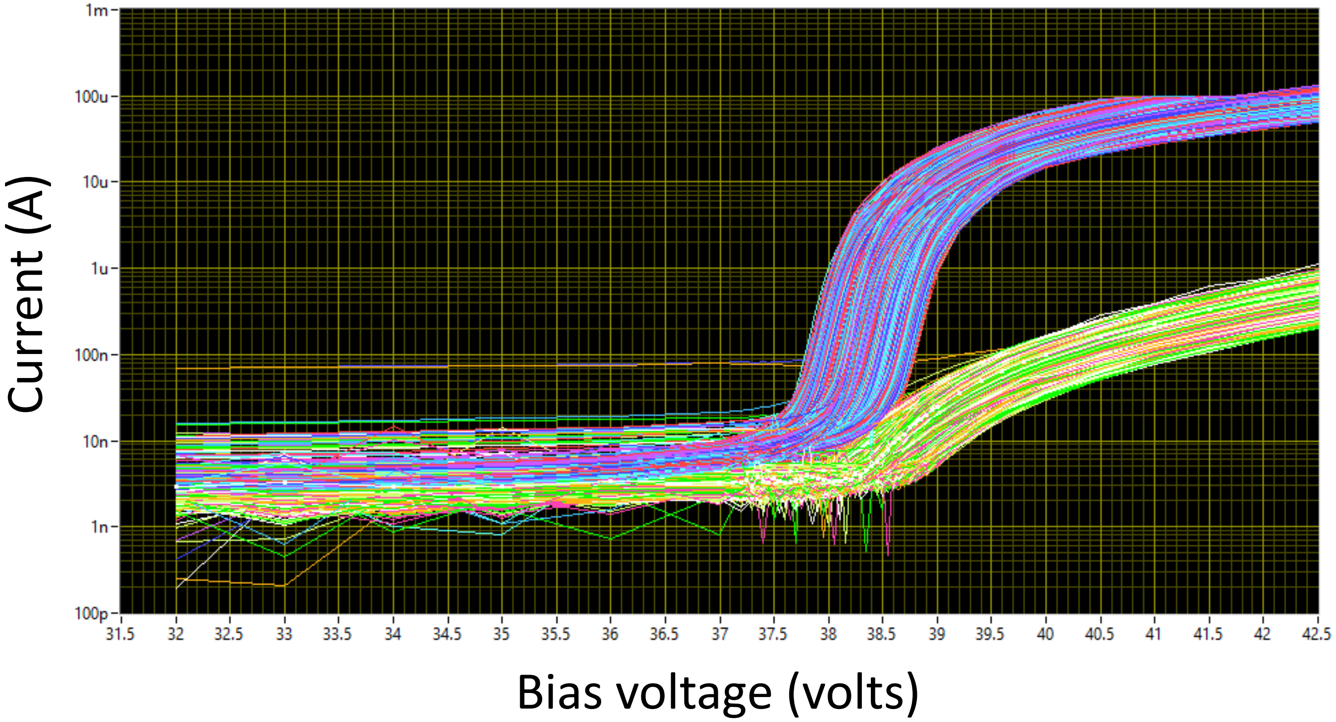


Comparison with HPK measurement

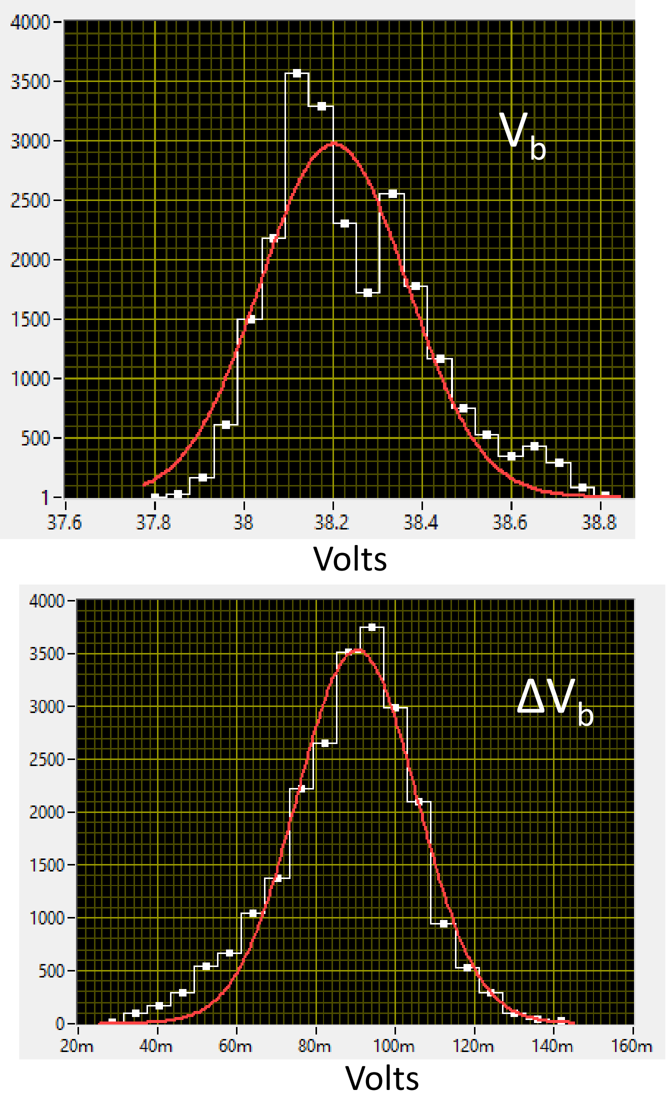


QC results – Production BTL SiPMs 1460 arrays (23,360 channels shown)

Dark current and photon current vs voltage



Breakdown voltage and spread per array



Summary

- Led by the University of Notre Dame group, over the past dozen years CMS committed to the development and implementation of more than 500,000 SiPMs into three upgrade projects – HCAL in Phase I, and HGCAL and BTL in Phase II
- Extensive R&D was carried out with several SiPM companies, including: CPTA, Zecotek, KETEK, FBK and Hamamatsu
- The upgrade of the CMS hadron calorimeter has been completed (~25,000 SiPMs replaced the HPDs). All SiPMs have passed QA/QC testing using special setups developed by our group.
- R&D for the phase II upgrade has also been completed. The developed SiPMs have been shown to be capable of operating in very high neutron fields (5E13 n/cm^2 for the HGCAL and 2E14 n/cm^2 for the CMS BTL). For the BTL, additional SiPM temperature reduction (by ~10°C) and dark current annealing will be provided by TECs.
- Full production of the HGCAL and BTL SiPM is underway. The QA/QC setups for measuring the SiPM parameters (before/after irradiation) have been designed and fabricated. QA/QC measurements of the SiPMs is ongoing. This will include neutron irradiations of SiPMs from different production batches at the JSI reactor.
- To date we have received about 50% of the HGCAL production and 40% of the BTL production at CERN. The yield of SiPMs within specs is nearly 100% and the percentage passing our QC tests is comparably high. We are on schedule to complete the SiPM testing for both projects in the first half of 2025 as planned.