Development, Characterization and Quality Control of Silicon Photomultipliers for the CMS Barrel Timing Layer

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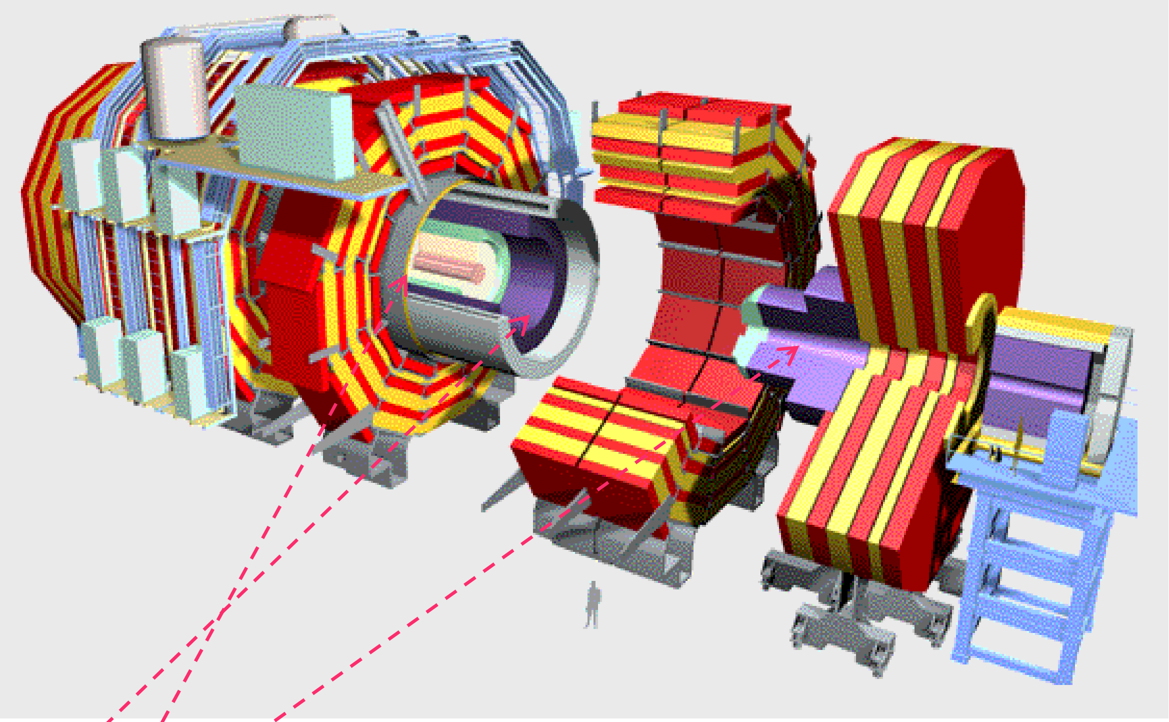
Introduction and background

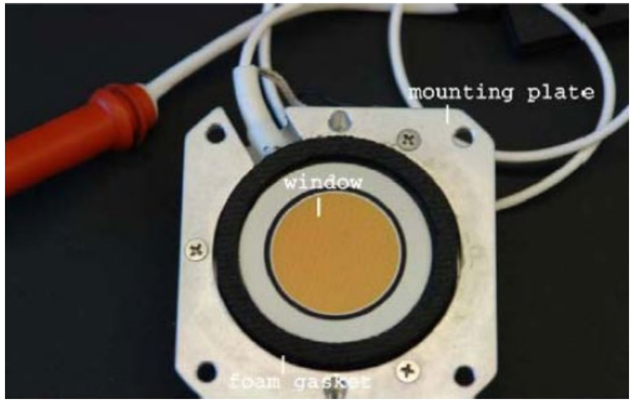
- Over the past decade, the CMS collaboration decided to implement more than 500,000 channels of SiPM as part of the Phase I and Phase II upgrades of the detector.* SiPMs are the photon detectors of choice for the following projects:
  - An upgrade of the hadronic calorimeter (HCAL), comprised of three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

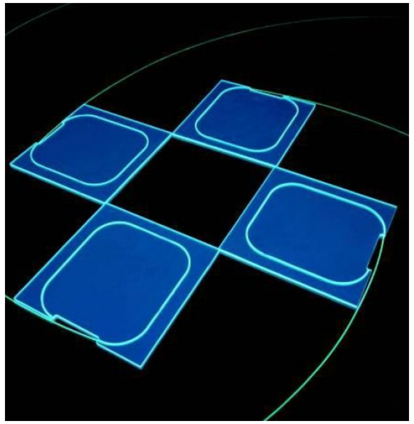
*https://doi.org/10.1088/1748-0221/20/07/P07047

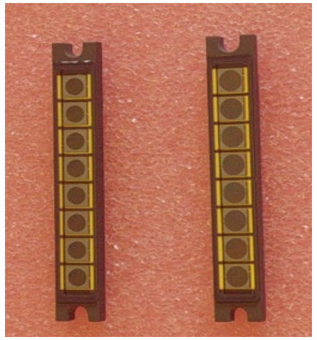
The CMS Hadronic Calorimeter - Phase I Upgrade



CMS HPD (18 ch.)

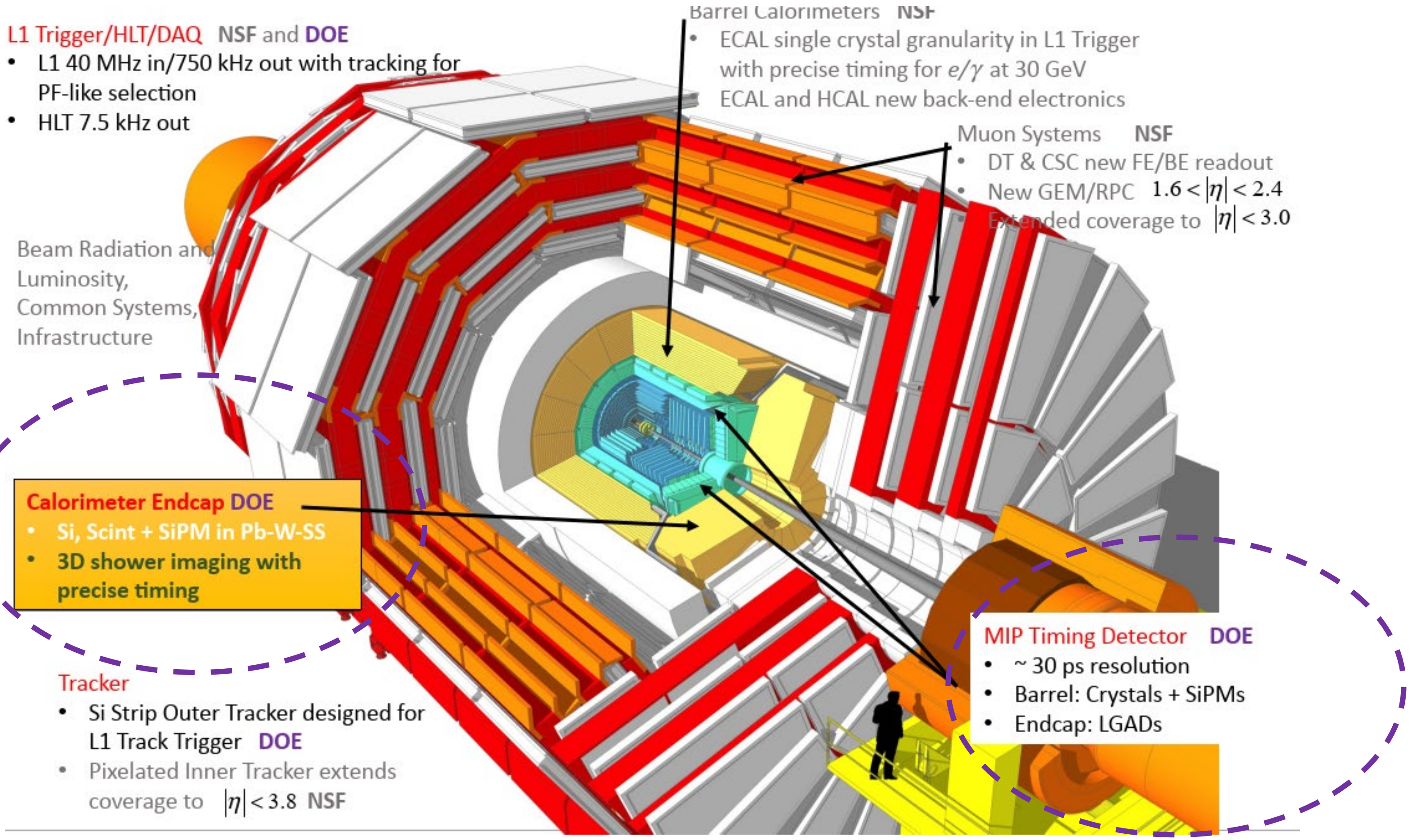






HB, HE, HO similar technology: scintillator tiles with Y11 WLS fiber readout, brass (steel for HO) absorber.
HPD was selected as the CMS HCAL photodetector. All HPDs were replaced with SiPMs after 2020 upgrade

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 and Luminosity, Common Systems, Infrastructure

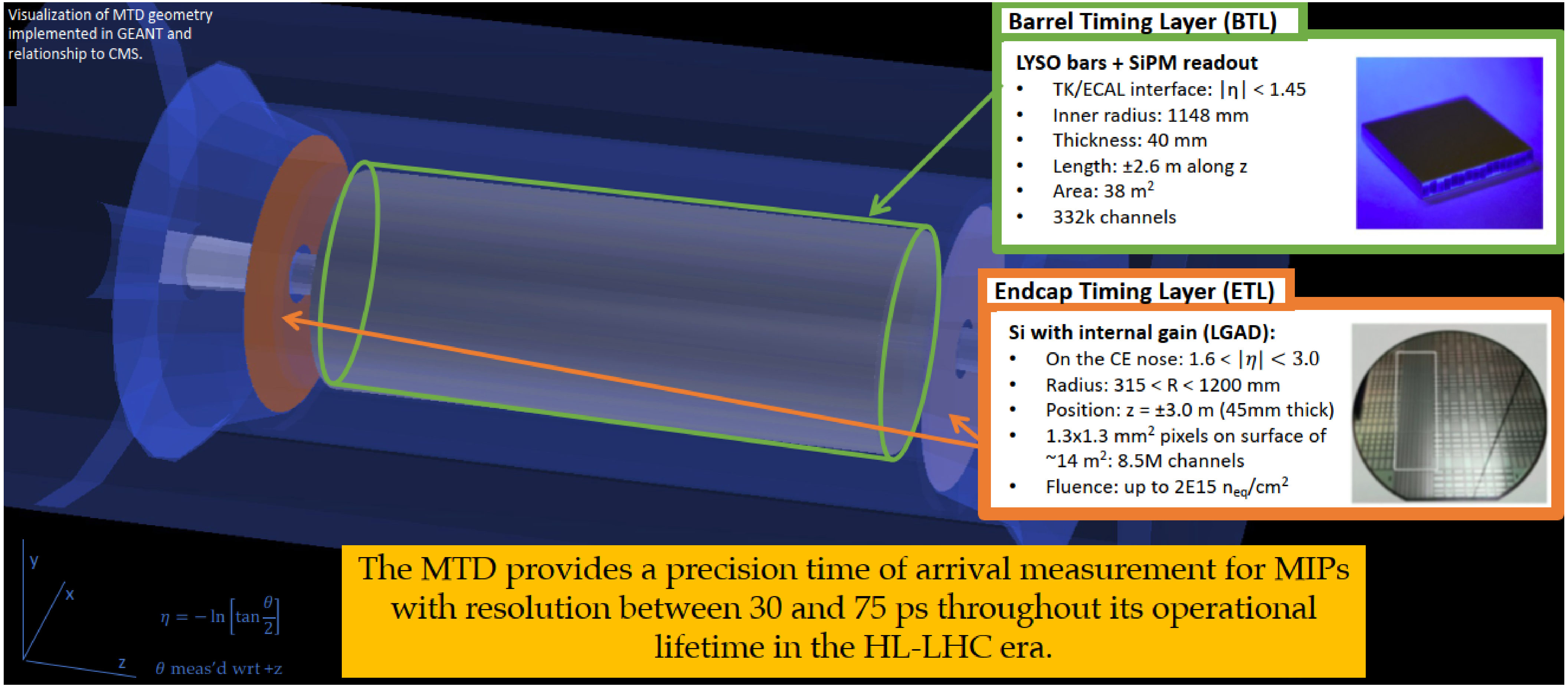
Calorimeter Endcap DOE
- **Si, Scint + SiPM in Pb-W-SS**
- **3D shower imaging with precise timing**

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 (11 mm^2 SiPMs)

Design Overview for the CMS MIP Timing Detector (MTD)



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

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

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

θ meas'd wrt +z

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)

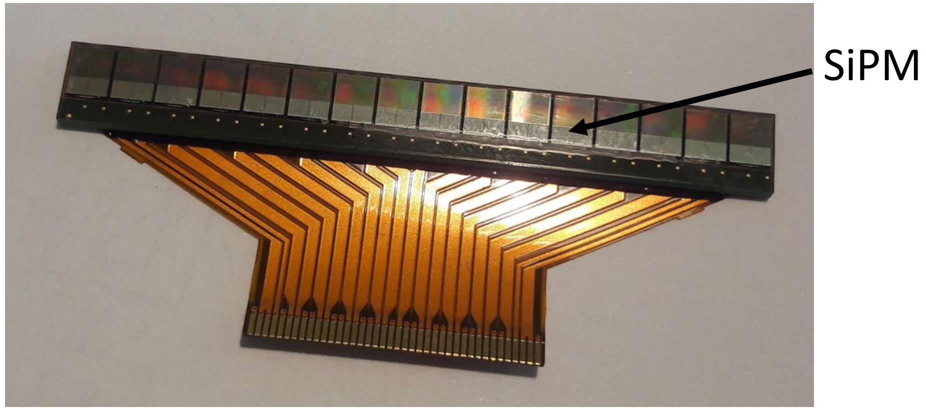
Requirements for the Barrel Timing Layer (BTL) SiPM

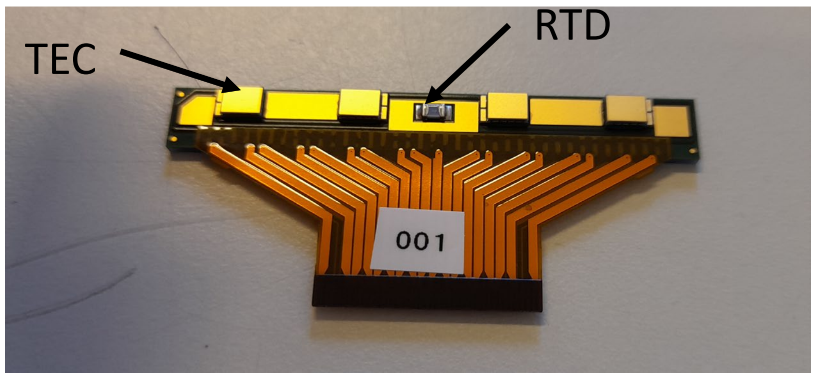
- Silicon Photomultipliers (SiPM) are the photodetectors of choice for the BTL. Features of SiPMs include:
  - Compact size, about 3mm x 3mm for the BTL
  - Small pixels provide extended linear dynamic range and keep dark count manageable
  - High photon detection efficiency (PDE) of > 50%
  - Insensitivity 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

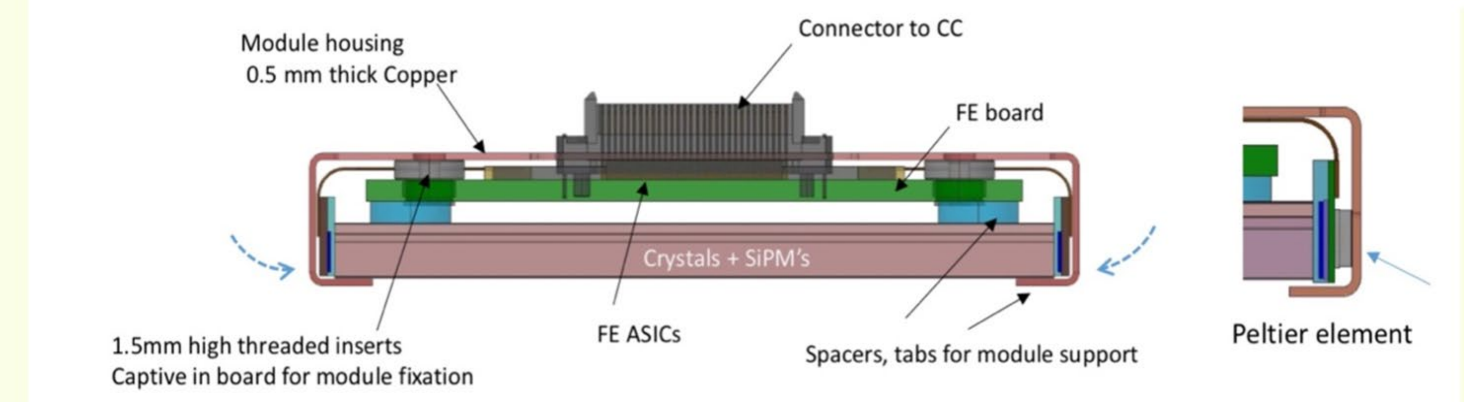
Design features of the BTL SiPM



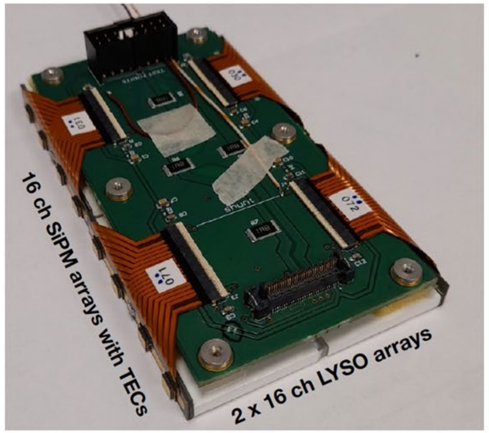


16-channel BTL SiPM Array

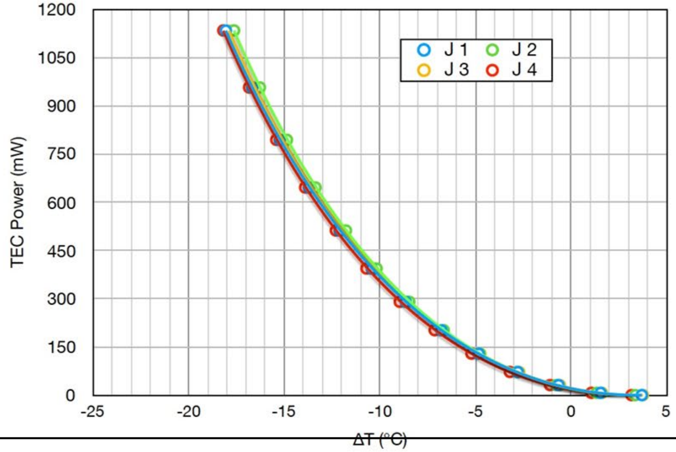
Top View: The 16 individual SiPMs in the array
Bottom View: Four TECs and RTD



BTL dual module with double sided readout



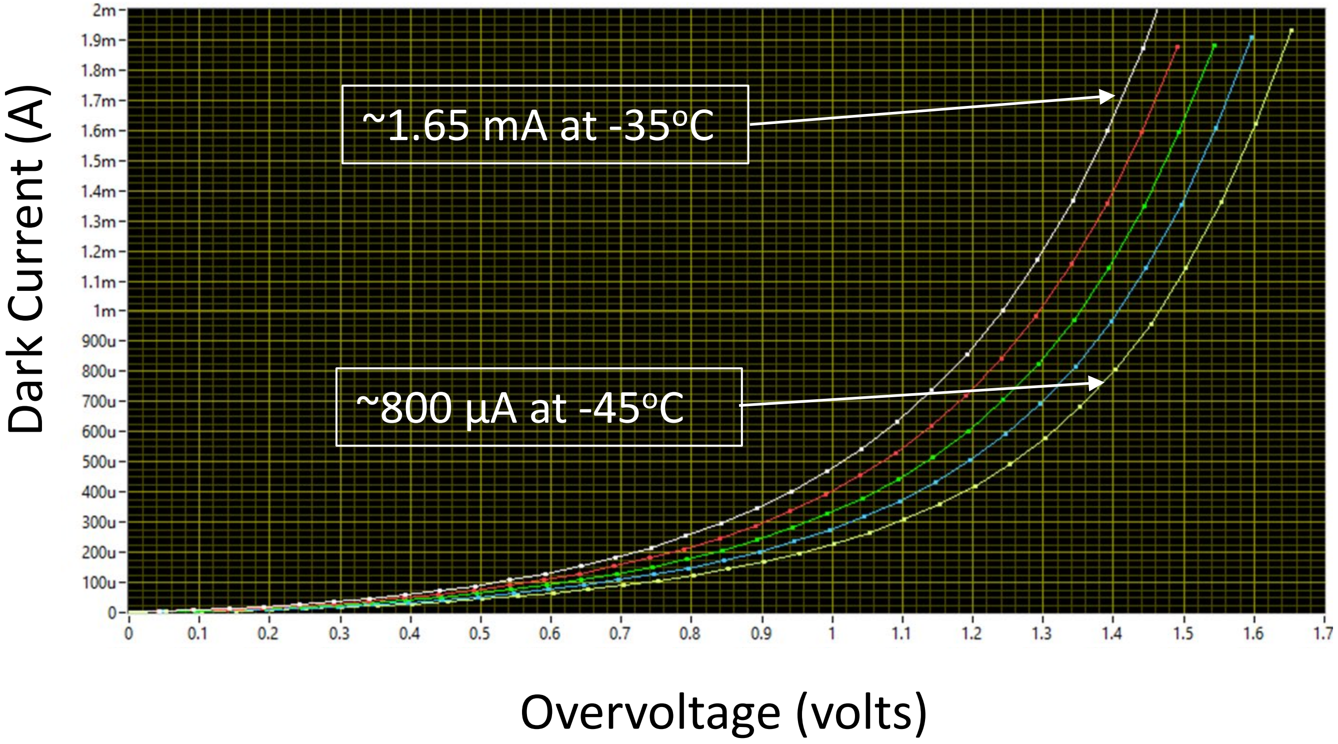
TEC power vs ΔT for the four 16 channel SiPM arrays each running at 420 mW SiPM power (25 mW /SiPM at 38V)



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 or more.

Benefits of Thermoelectric Coolers (TECs)

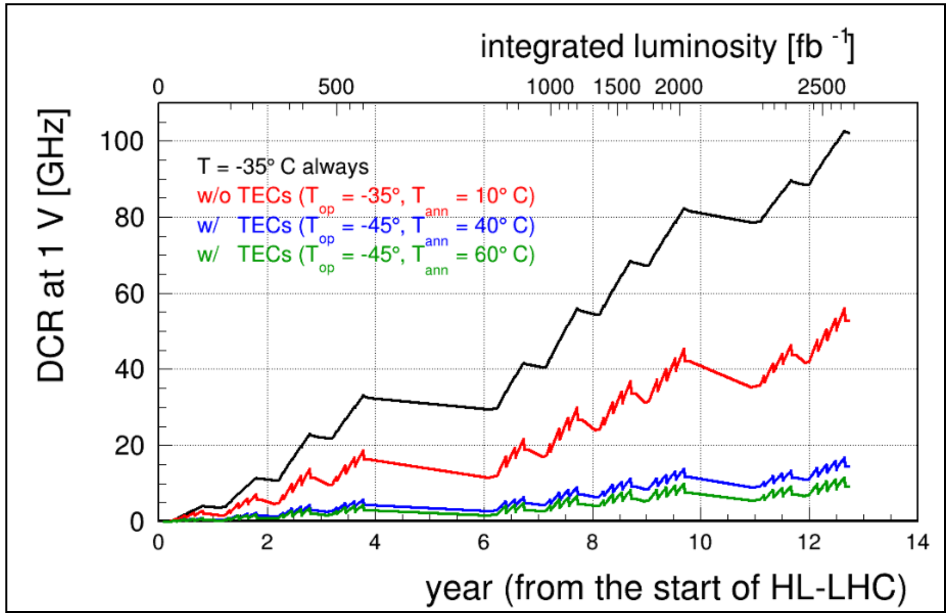
TECs as coolers reduce dark current by factor of two with no additional overall power load



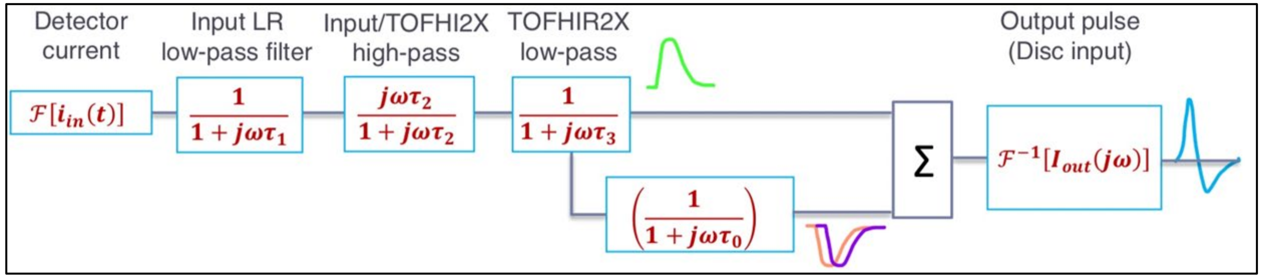
~1.65 mA at -35°C

~800 µA at -45°C

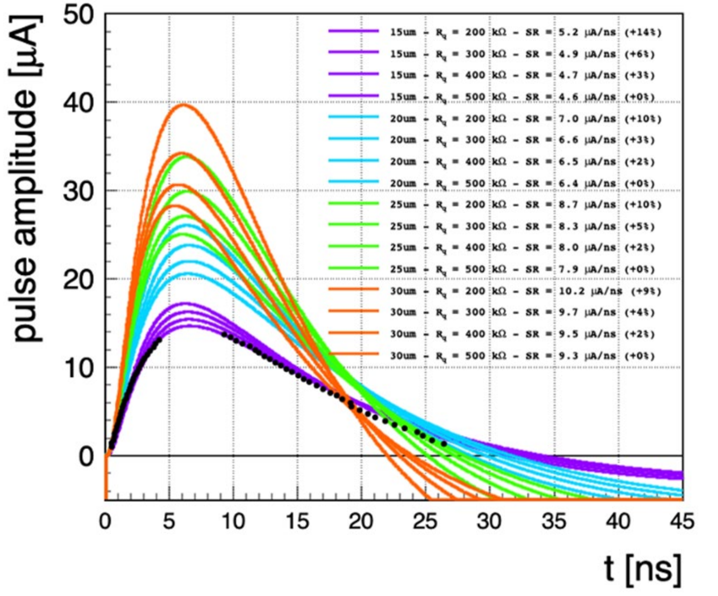
TECs as heaters provide additional factor of 6 through annealing



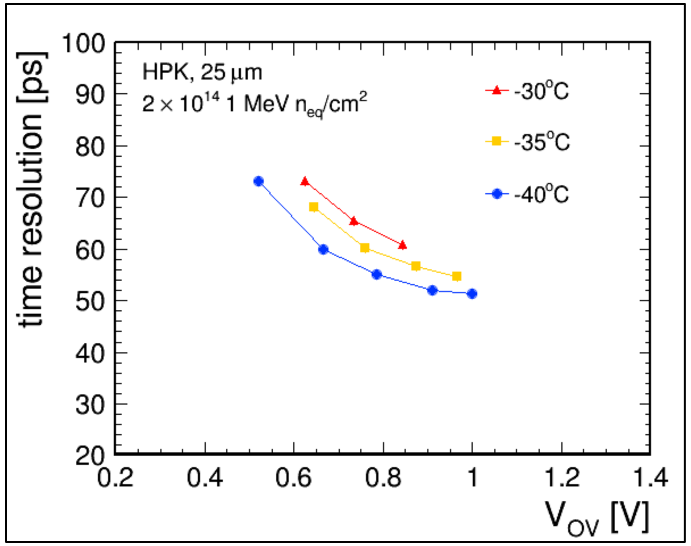
Effects of SiPM Pixel Size



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

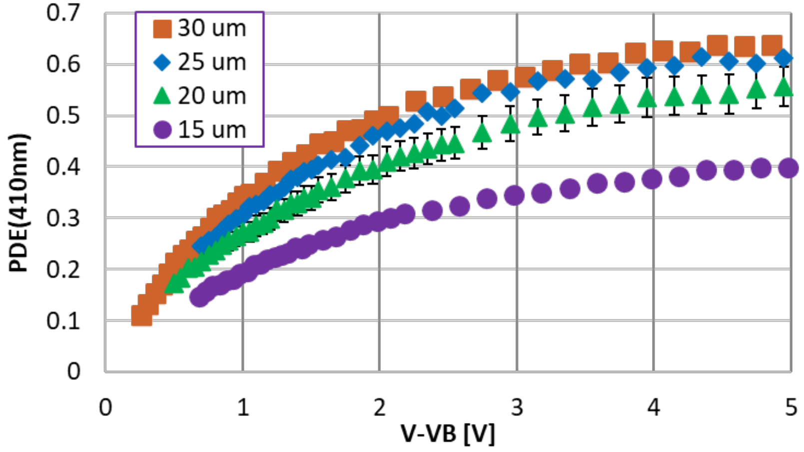


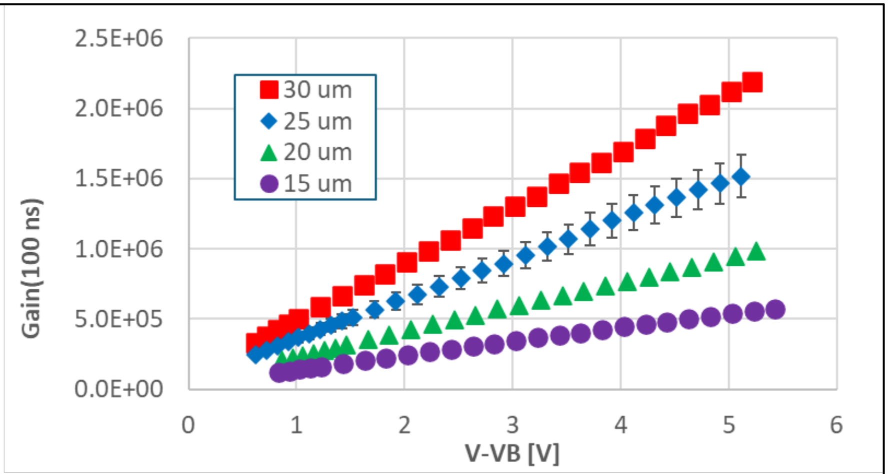
Pulse amplitudes for pixel sizes from 15 – 30 microns. Larger pixel size gives higher amplitude and faster signal → improved S/N, timing resolution

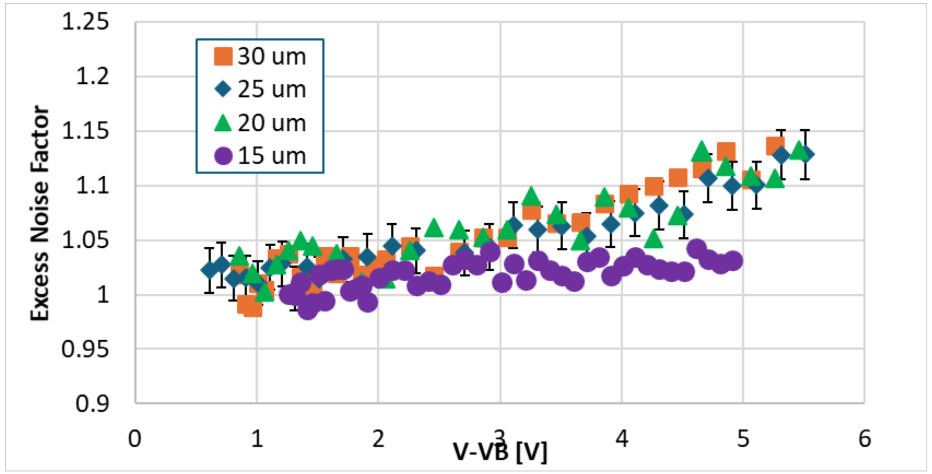


Timing resolution from beam test for 25 micron pixel BTL SiPMs after radiation to $2\text{x}10^{14}$ one MeV neutron/cm^2 equivalent

Studies of SiPM Pixel Size



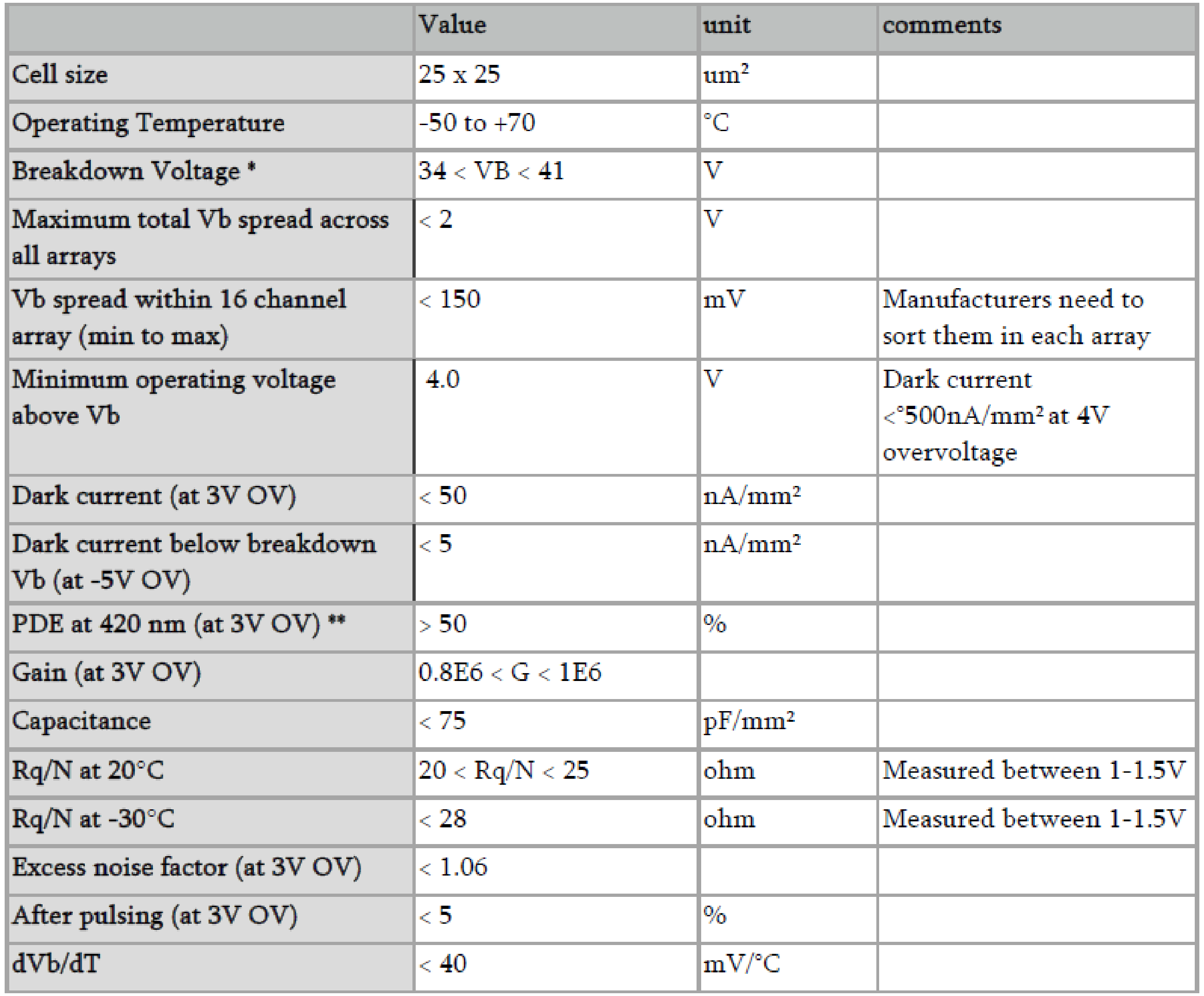




Error bar = 10 %

BTL production SiPM specifications
HPK S15408-4125TC, 2.9mm x 3.775mm active area, 25 micron pixels

→ Denotes a parameter addressed in this talk



		Value	unit	comments
	Cell size	25 x 25	um^{2}	
	Operating Temperature	-50 to +70	°C	
→	Breakdown Voltage *	34 < VB < 41	V	
→	Maximum total Vb spread across all arrays	< 2	V	
→	Vb spread within 16 channel array (min to max)	< 150	mV	Manufacturers need to sort them in each array
	Minimum operating voltage above Vb	4.0	V	Dark current <°500nA/mm^{2} at 4V overvoltage
→	Dark current (at 3V OV)	< 50	nA/mm^{2}	
→	Dark current below breakdown Vb (at -5V OV)	< 5	nA/mm^{2}	
	PDE at 420 nm (at 3V OV) **	> 50	%	
	Gain (at 3V OV)	0.8E6 < G < 1E6		
	Capacitance	< 75	pF/mm^{2}	
→	Rq/N at 20°C	20 < Rq/N < 25	ohm	Measured between 1-1.5V
	Rq/N at -30°C	< 28	ohm	Measured between 1-1.5V
	Excess noise factor (at 3V OV)	< 1.06		
	After pulsing (at 3V OV)	< 5	%	
→	dVb/dT	< 40	mV/°C	

QC of BTL production SiPMs by the ND group at CERN

Measurements of 50% of the production SiPMs, 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

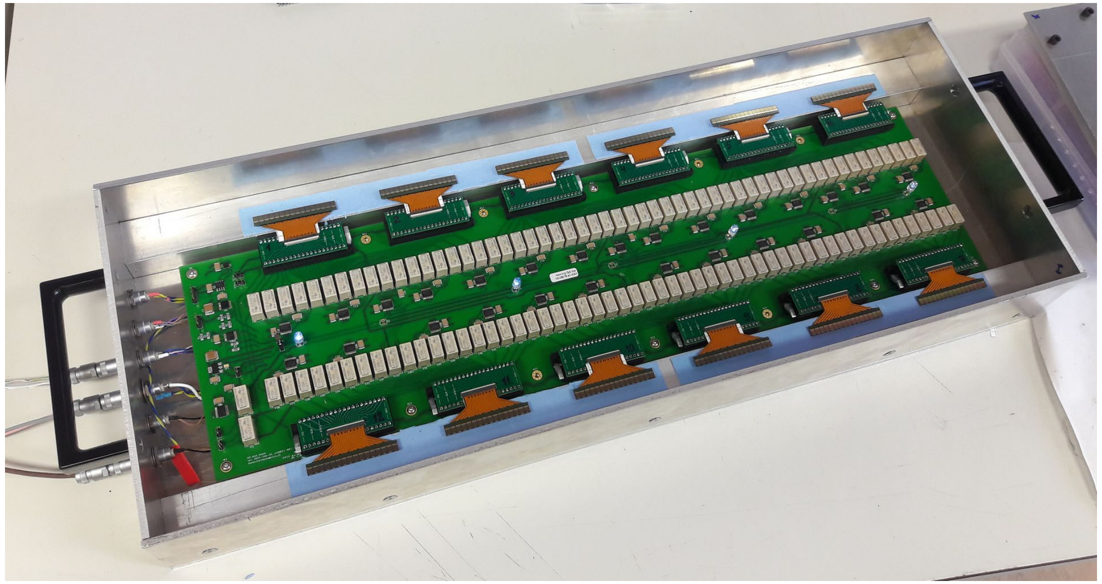
Destructive testing will be done on a small subset of channels:

- 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

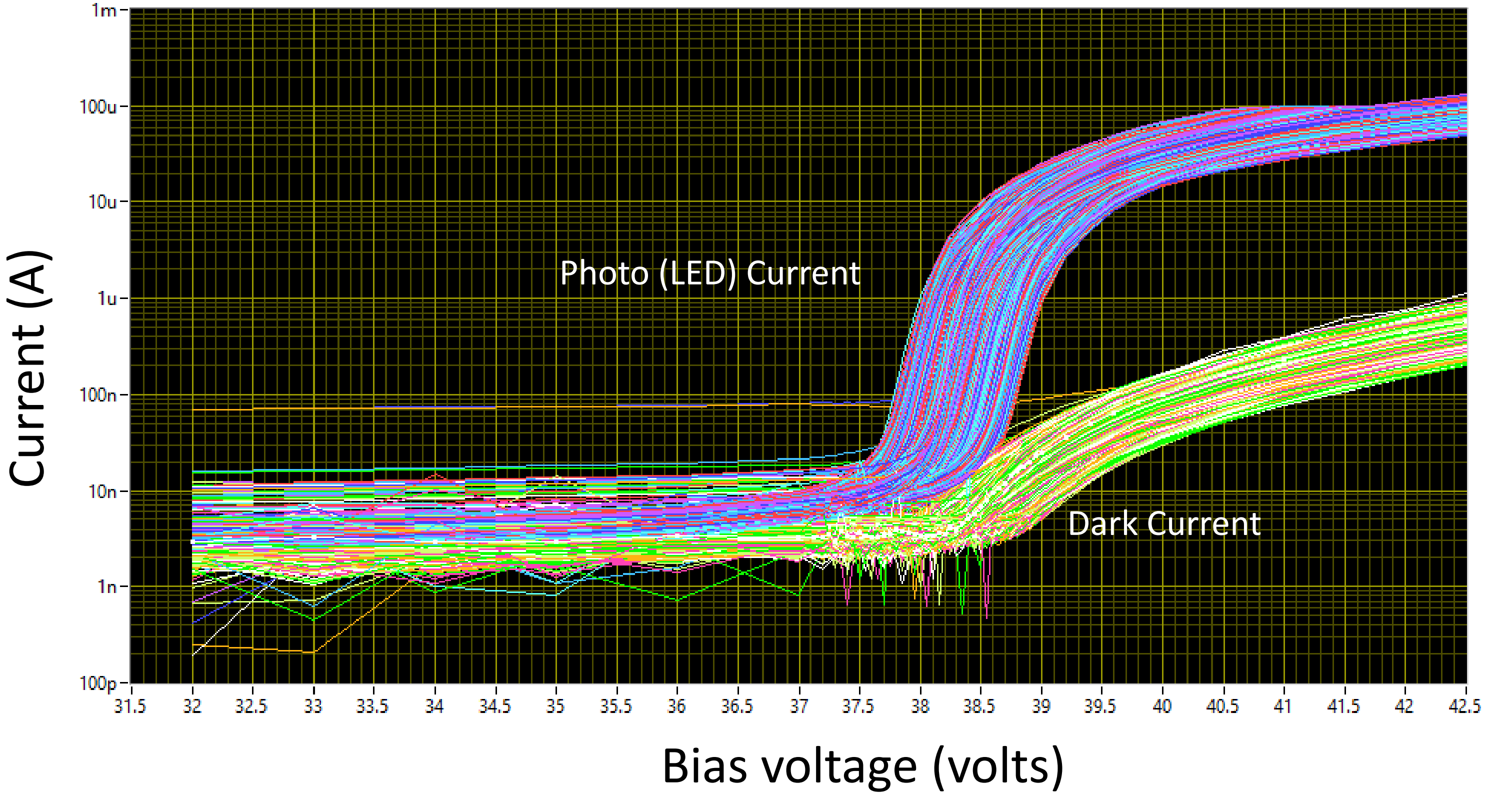
Notre Dame SiPM QC Test Setup

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

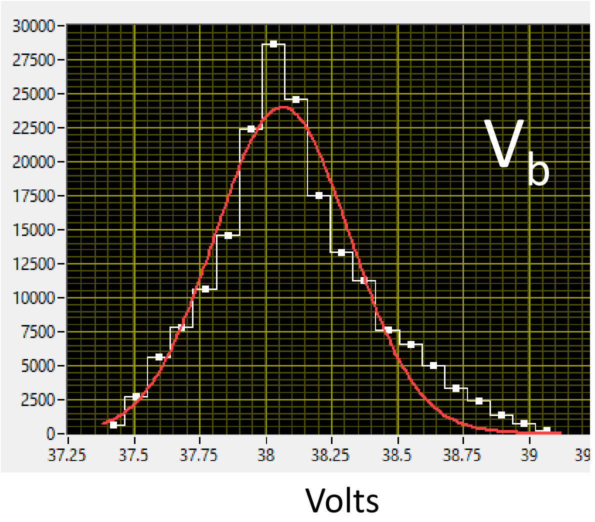


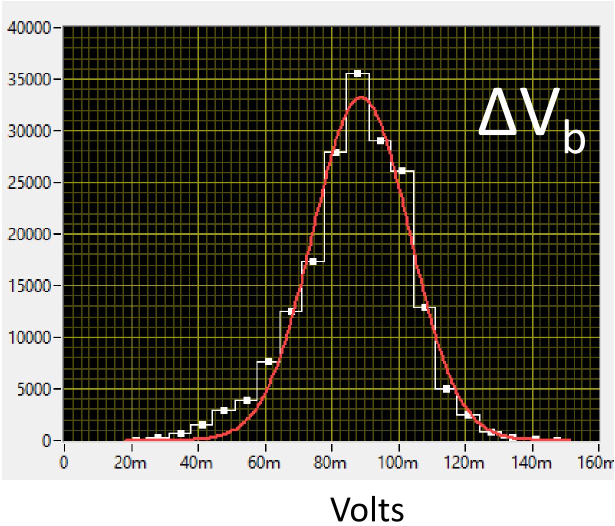
QC results – Production BTL SiPMs
11,689 arrays (187,024 channels shown)

Dark current and photo current vs voltage

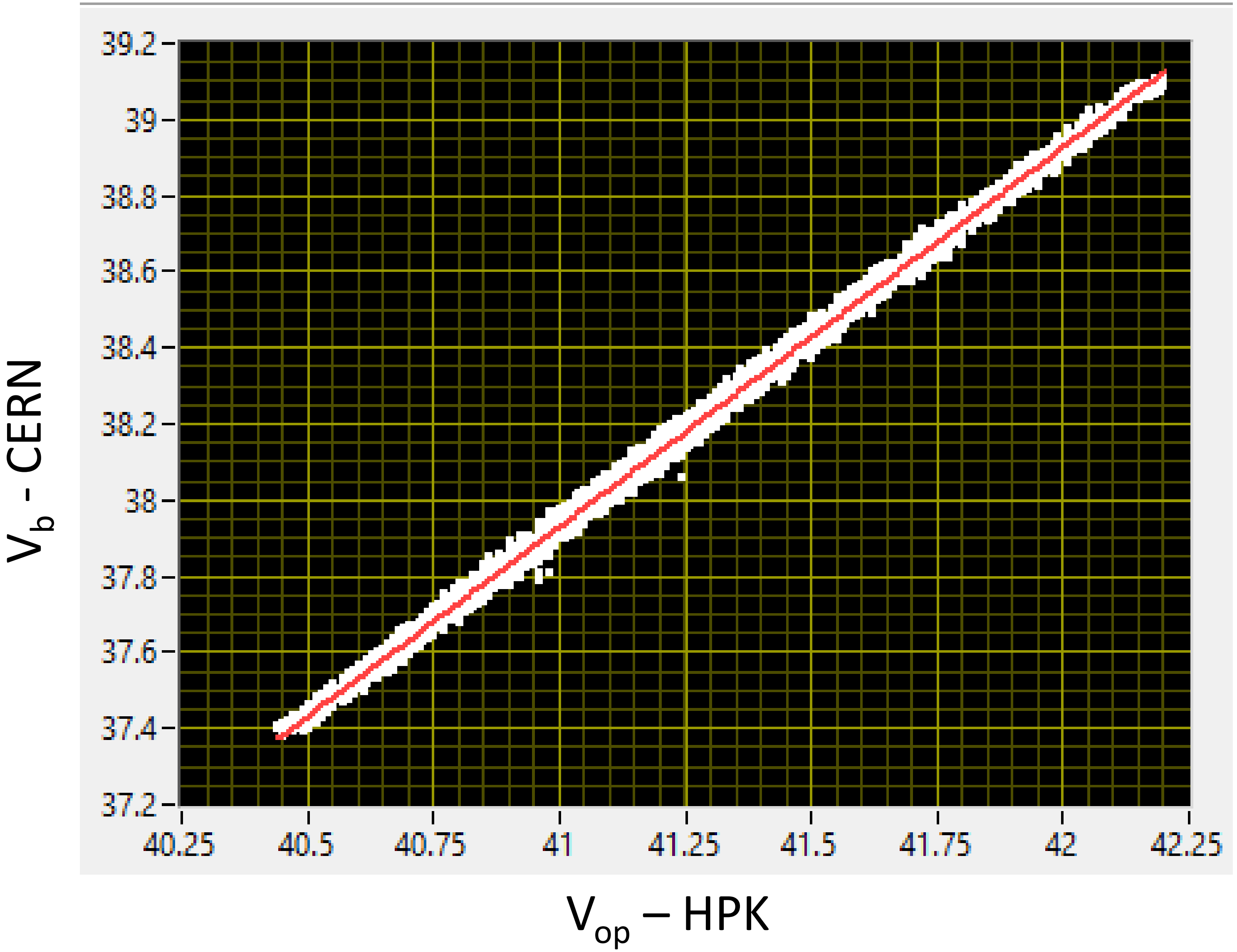


Breakdown voltage and spread per array





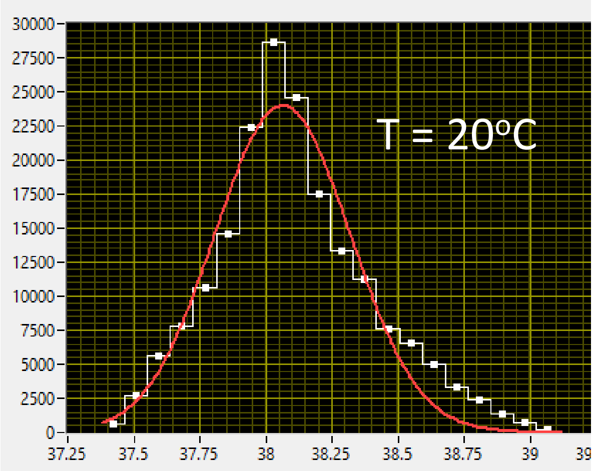
Comparison with HPK measurement



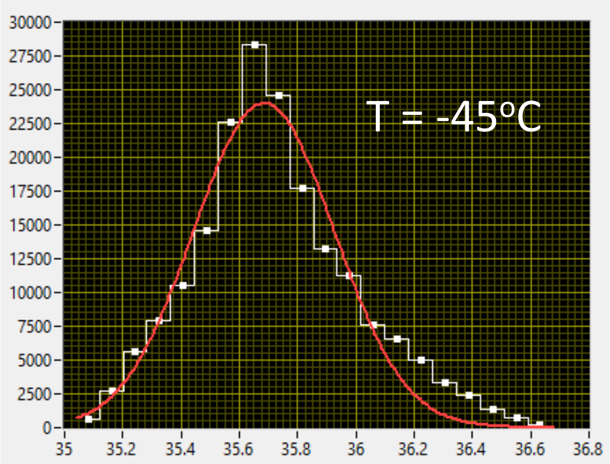
Excellent agreement for more than 187k channels, $\sigma < .5\%$

QC results – Production BTL SiPMs
Change of V_b with temperature

Breakdown voltage



Volts



Volts

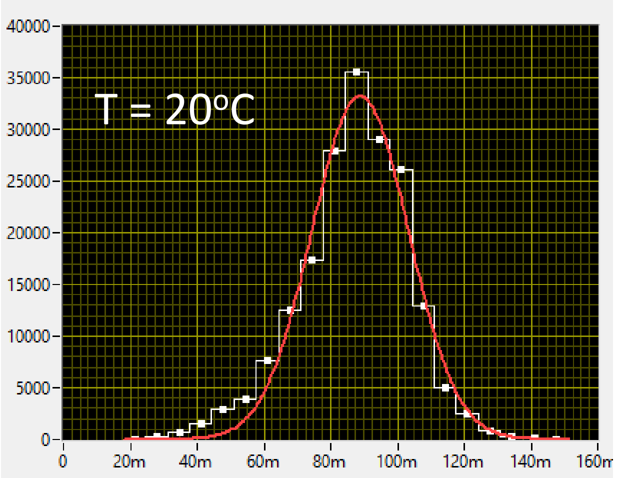
Spread in V_b less than 1.75 volts at room temperature and -45°C

All arrays maintain spread in V_b less than 150 mV at -45°C

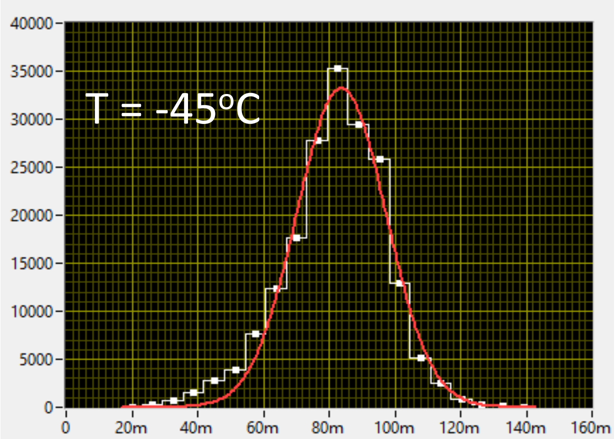
Shift in V_b of 2.38 volts for ΔT = -65°C, uniform to <1% over all channels

Temperature coefficient = 36.6 mV/°C

Breakdown voltage spread per array



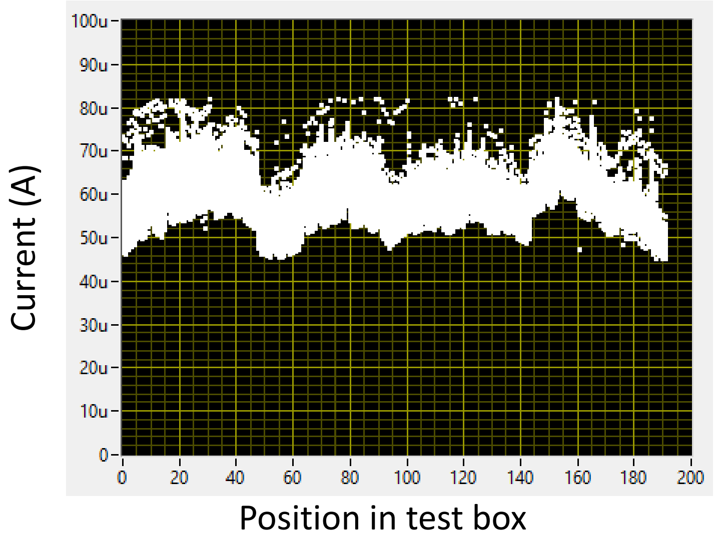
Volts



Volts

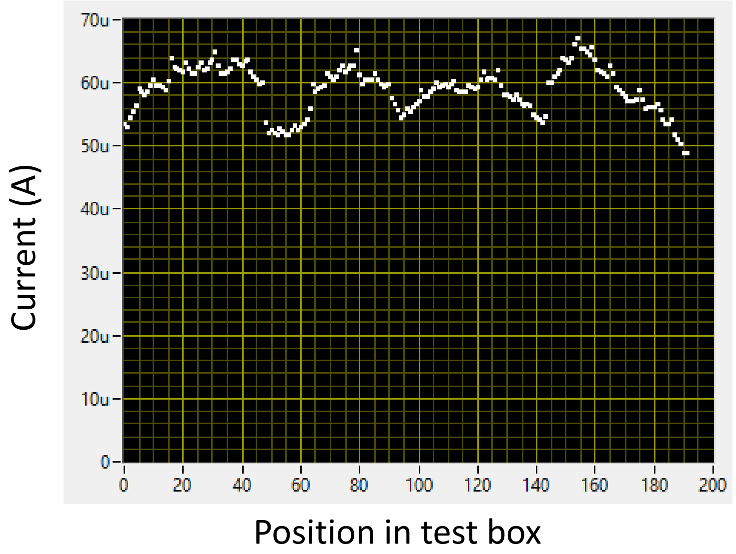
*Measurement of SiPM Gain*PDE*

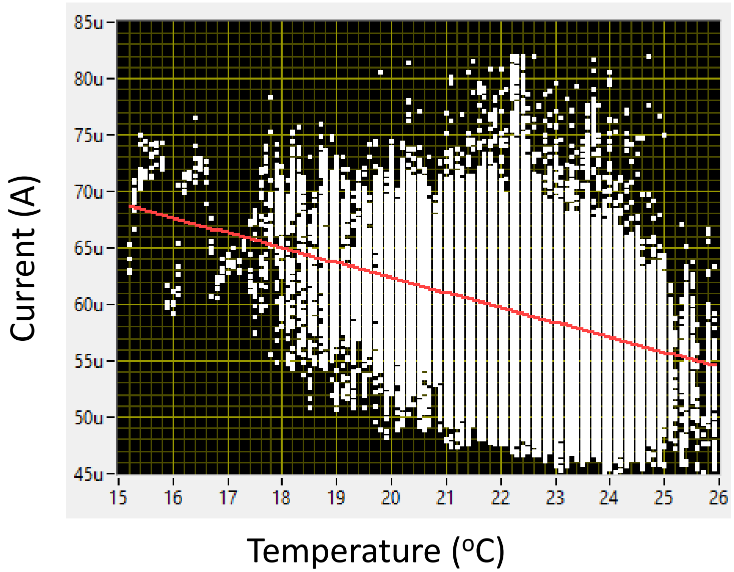
“Raw” response to LED



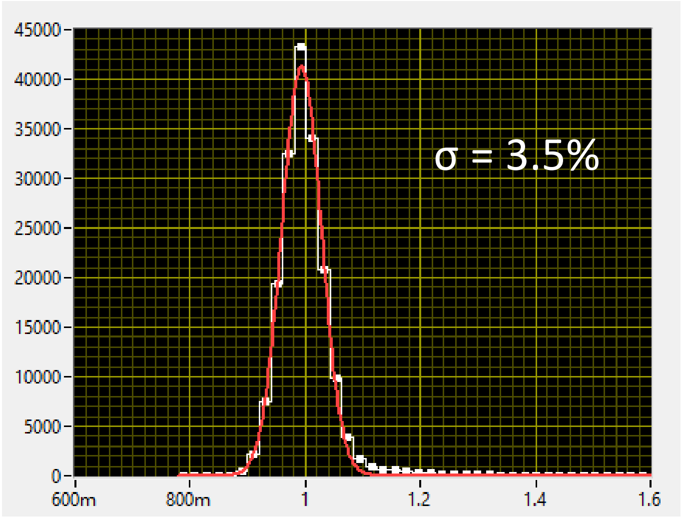
Average over position

Averaged response to LED



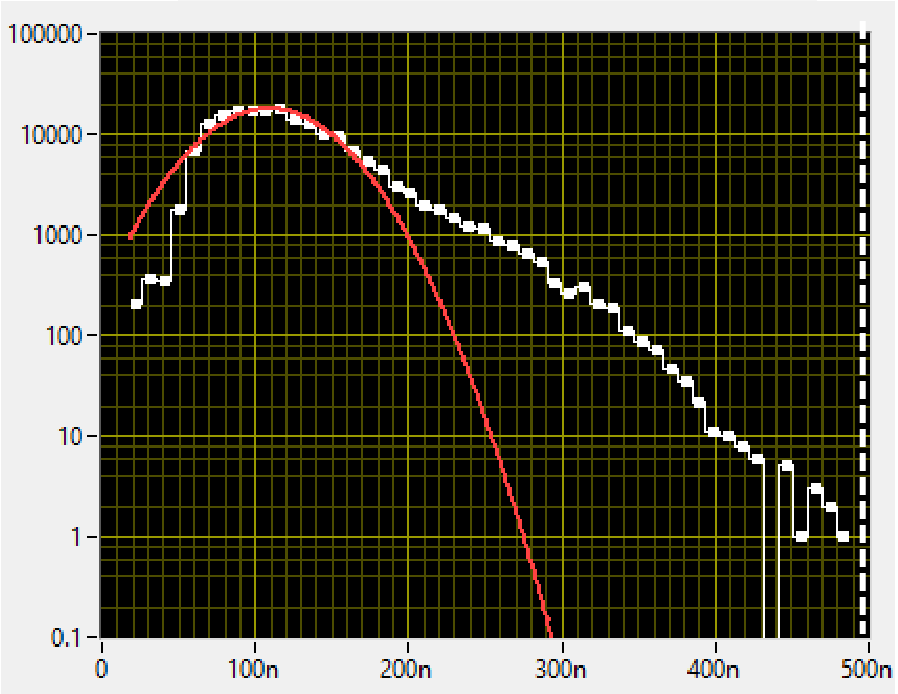


Correct for temperature



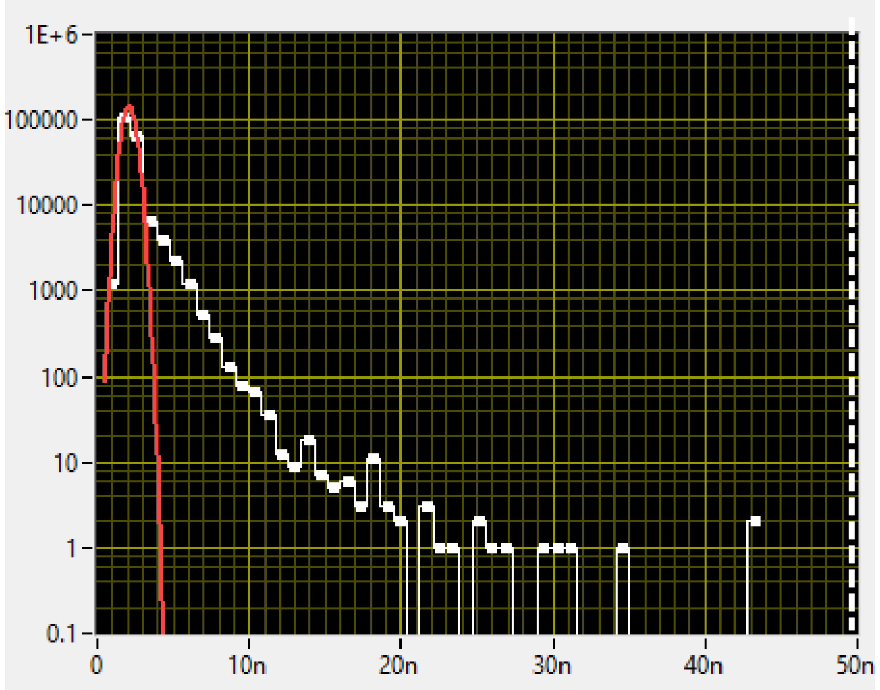
QC results – Production BTL SiPMs
Dark Current

Dark Current at V-V_b = 3 volts



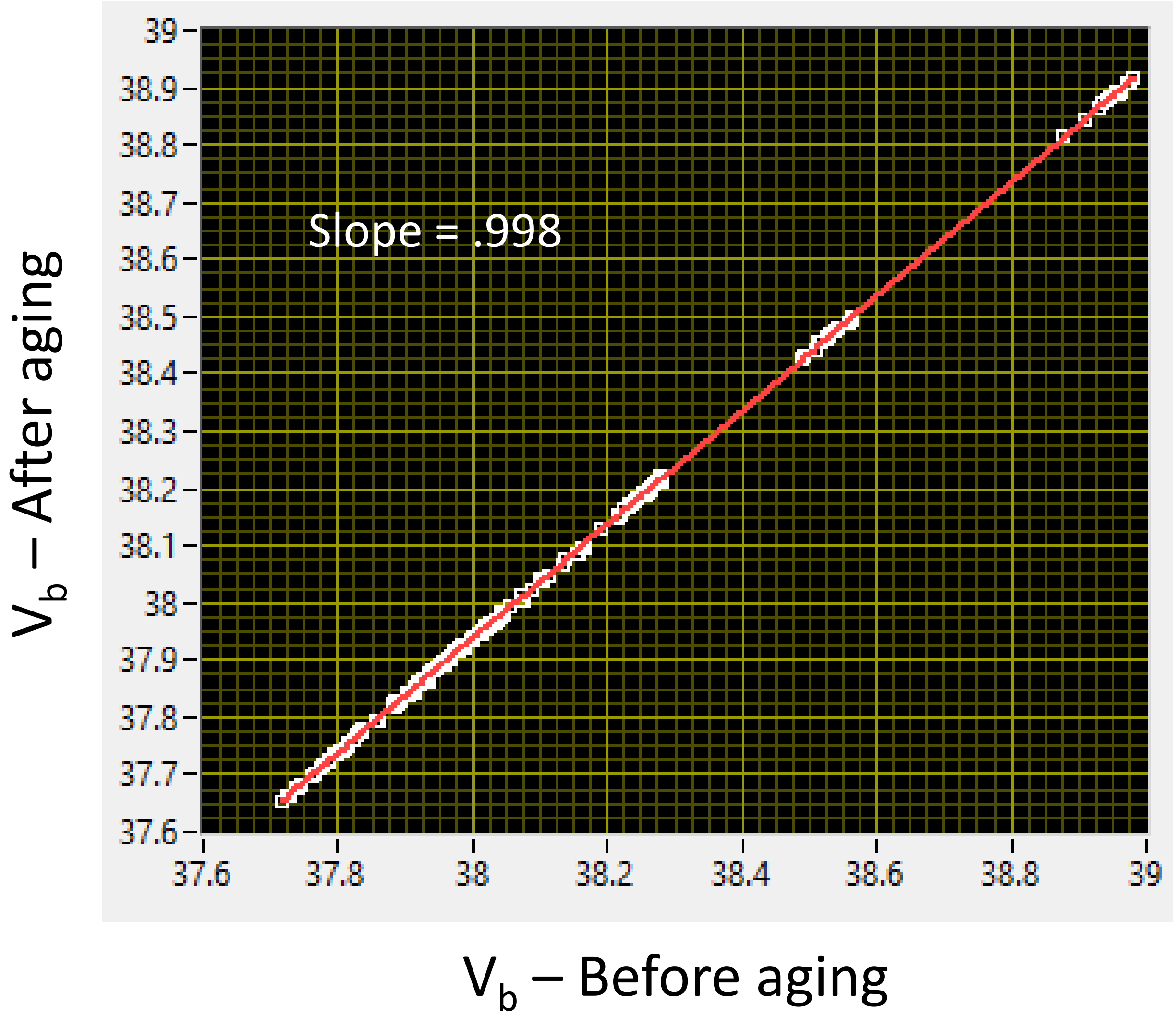
Current (A)

Dark Current at V-V_b = -5 volts



Current (A)

Accelerated aging studies

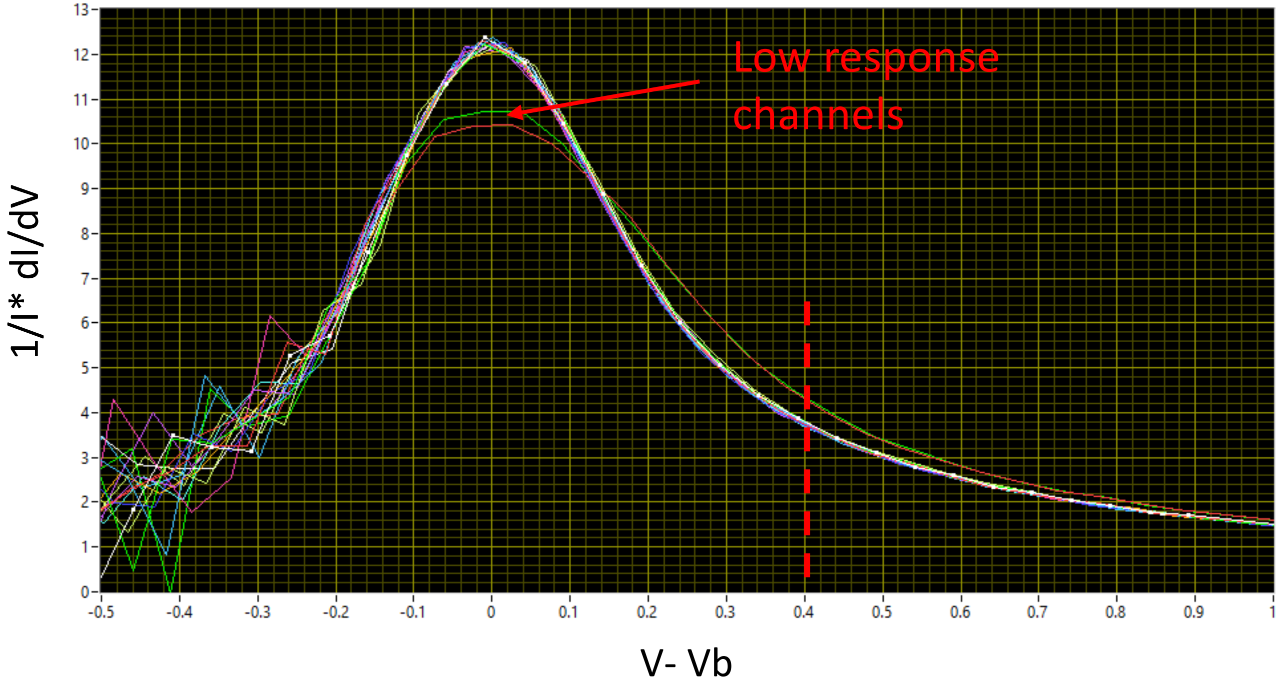


Selected arrays were continuously operated for 50 days at 70°C

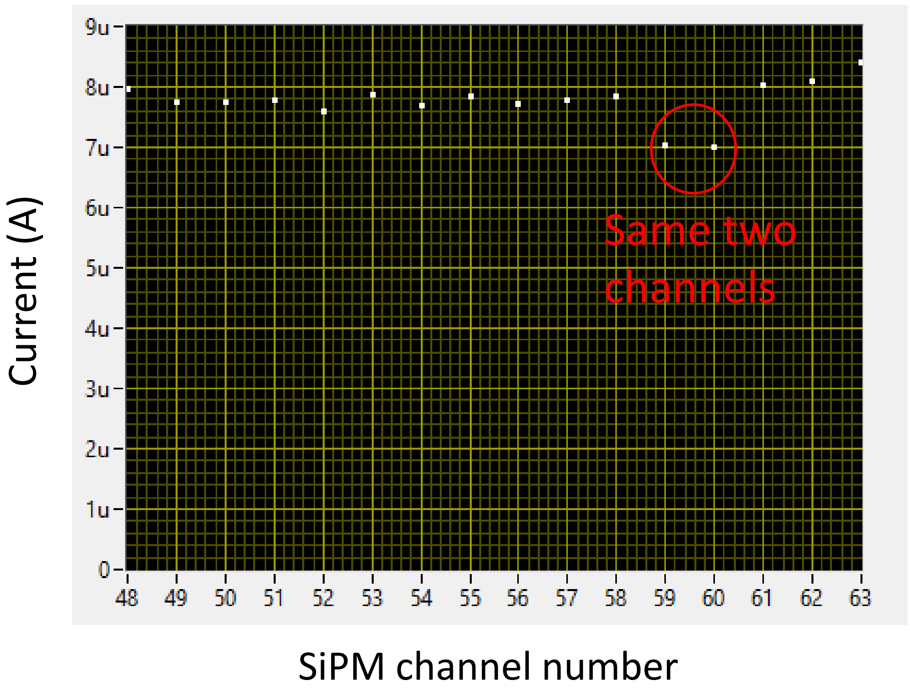
No significant change seen in any parameters: I_{dark}, I_{photo}, R_q/N, R_{Tec}

An unexpected issue

Two channels with a different 1/I*/dI/dV response compared with standard curve



Drop in photocurrent seen for the same two channels before and after irradiation to $2X10^{14}$ and standard annealing. $V-V_b = 0.8$ volts

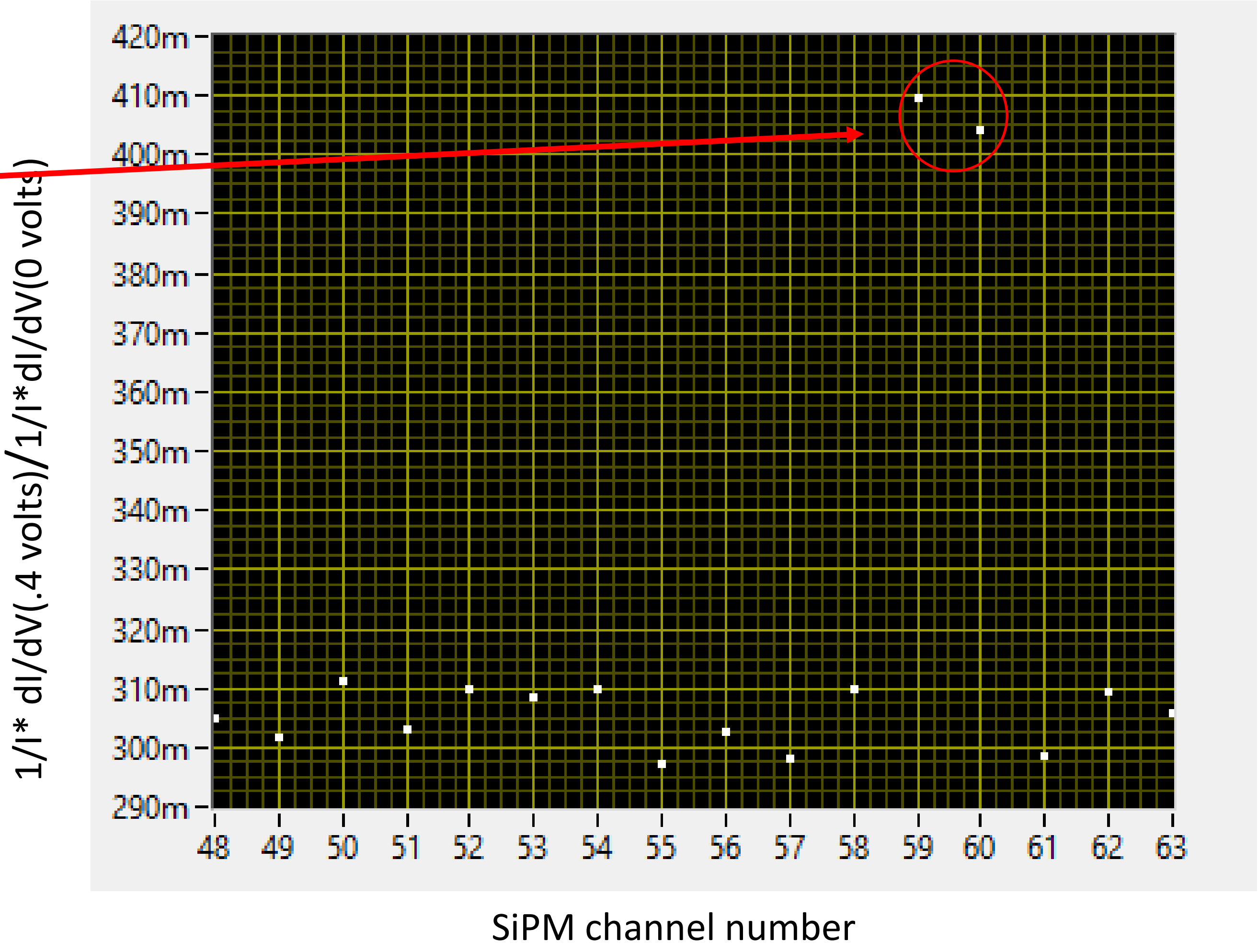


New rejection criterion

By calculating the ratio of 1/I*dI/dV at $V\text{-}V_b$ = .4 volts and at $V\text{-}V_b$ – 0 we can discriminate these channels

~2% of the arrays had one or more channels with this issue, or .1 - .2% on a per channel basis

The vendor (HPK) was able to reproduce our measurement and removed problem arrays from later SiPM delivery batches. They also replaced ~400 arrays.



Summary

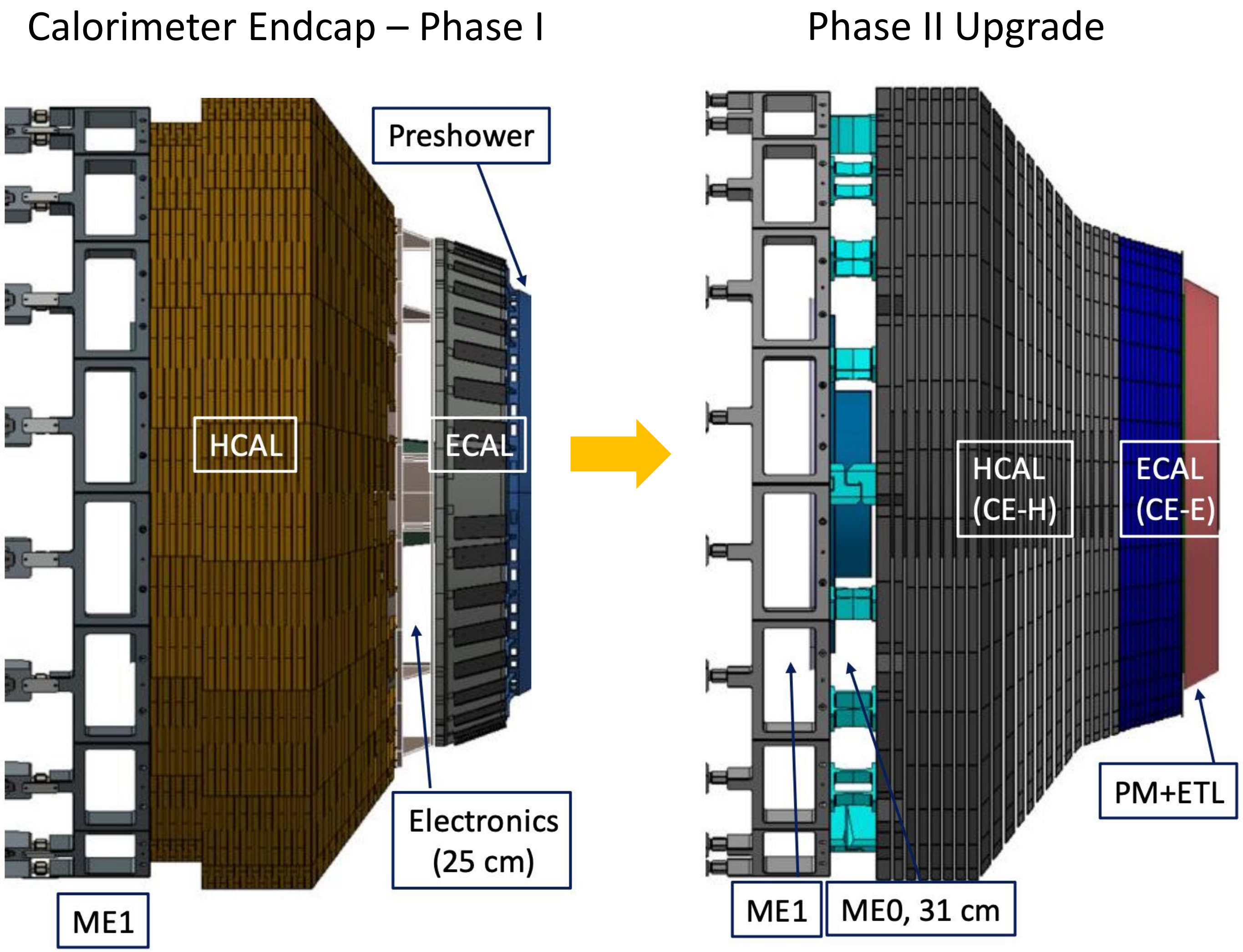
- Led by the University of Notre Dame group, over the past dozen years CMS committed to the development and implementation of more than 500,000 SiPMs into three upgrade projects – HCAL in Phase I, and HGCAL and BTL in Phase II
- The SiPMs developed for the Barrel Timing Layer (BTL) have been shown to be capable of operating in very high neutron fields (2E14 n/cm^2). Additional SiPM temperature reduction (by ~10°C) and dark current annealing is provided by small thermoelectric coolers mounted on the 16-channel SiPM array.
- Setups for measuring the SiPM parameters (before/after irradiation) were designed and fabricated by our group at CERN. These were used to validate prototype and preproduction devices, and for the final quality control.
- We have completed the QA/QC of 50% of the BTL production at CERN – more than 187,000 channels. The yield of SiPMs within specs was nearly 100% and the percentage passing our QC tests was comparably high. Early in the production we were able to identify a subtle problem with a small percentage of channels and working with the vendor (HPK) these were eliminated from the rest of the production.

Backup

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):

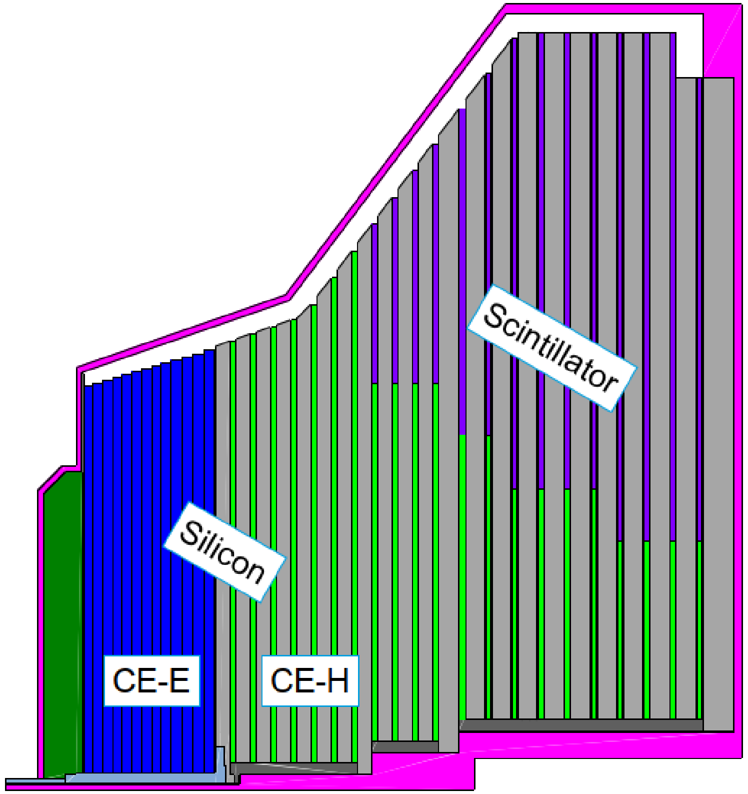
- Active elements: hexagonal silicon modules
- Cu & CuW & Pb absorbers, 26 layers, ~28 X_0

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