SiPM Gain Studies for
daptive Power Supply

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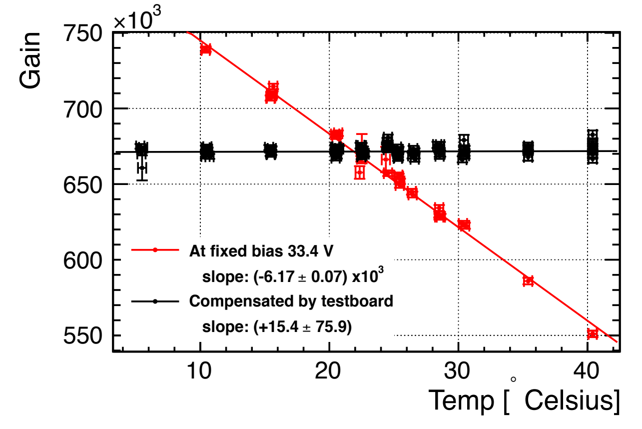
Outline

- Measurement methodology
- Studies and gain stabilization of Hamamatsu MPPC B2 (1 mm x 1 mm, pixel size 20 μm)
- Studies and Gain stabilization of Hamamatsu MPPCs with trenches LCT4#6 and LCT4#9 (1 mm x 1 mm, pixel size 50 μm)
- Studies of KETEK SiPM W12 (3 mm x 3 mm, pixel size 20 μm)
- Studies of afterpulsing
- Conclusions and outlook

Principle of Gain Stabilization

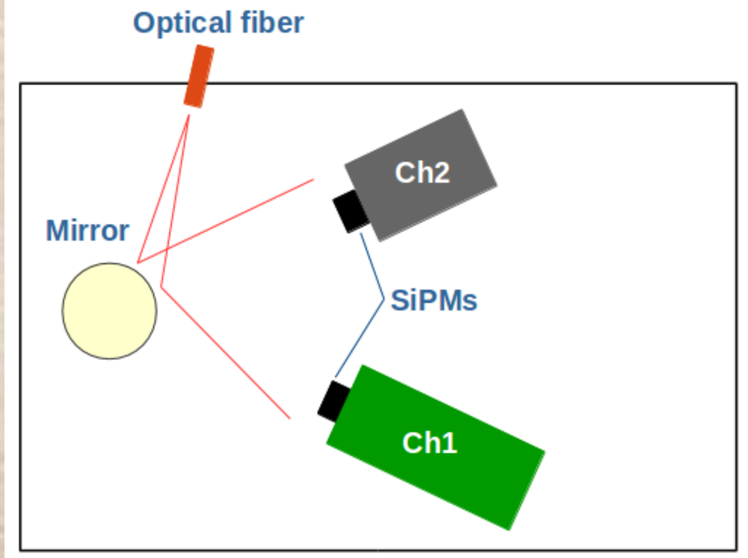
- The gain of SiPMs increases with V_{bias} and decreases with T
- For stable operation, the gain needs to be kept constant, especially in large detectors such as an ILC/CLIC analog hadron calorimeter with 10^6 channels
- The method is to adjust V_{bias} when T changes
  ➔ this requires knowledge of dV/dT that can be determined from measurements of dG/dV & dG/dT

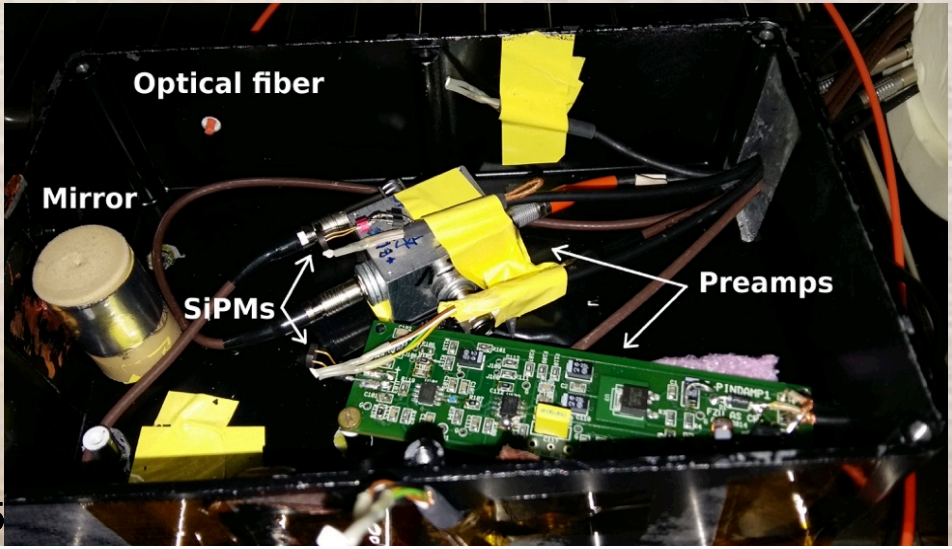


- We measured dG/dV and dG/dT for 17 SiPMs from 3 manufacturers in 3 test periods in a climate chamber at CERN
  ➔improved readout in last test (August 2015)
- We built a V_{bias} regulator test board to show proof of principle by testing the gain stability for 7 (12) individual SiPMs
- Goal is to show gain stabilization in a system test with 10-20 SiPMs
- Implement this into the power distribution of the analog hadron calorimeter

Gain Stabilation Test Setup

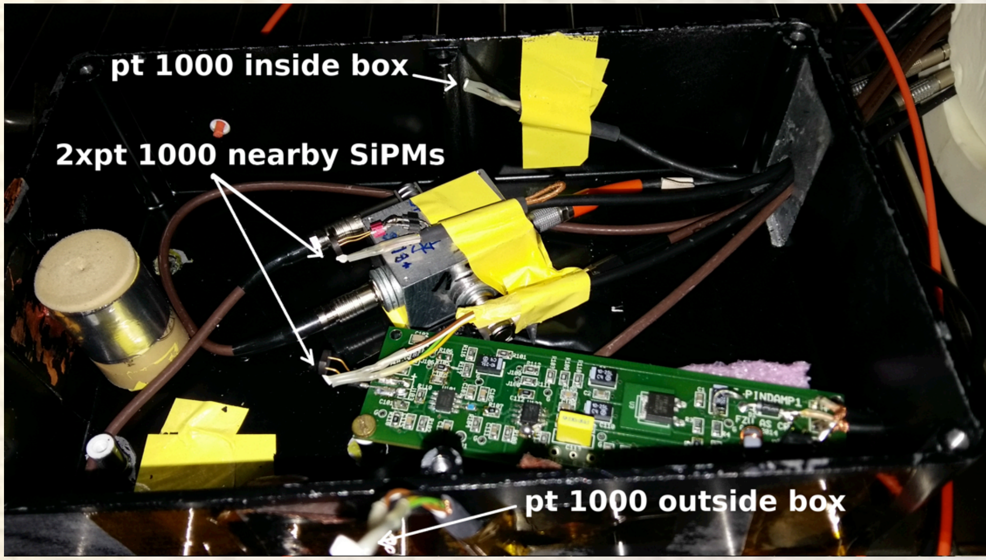
- Work in climate chamber at CERN, stability ~0.2°C
- Readout 2 channels/preamps simultaneously with digital LeCroy oscilloscope (12 bit ADC, 2.5 GS/s)
- Low voltage, bias voltage and scope is controlled by LabView program
- Shine light from blue LED via optical fiber and mirror onto two SiPMs simultaneously



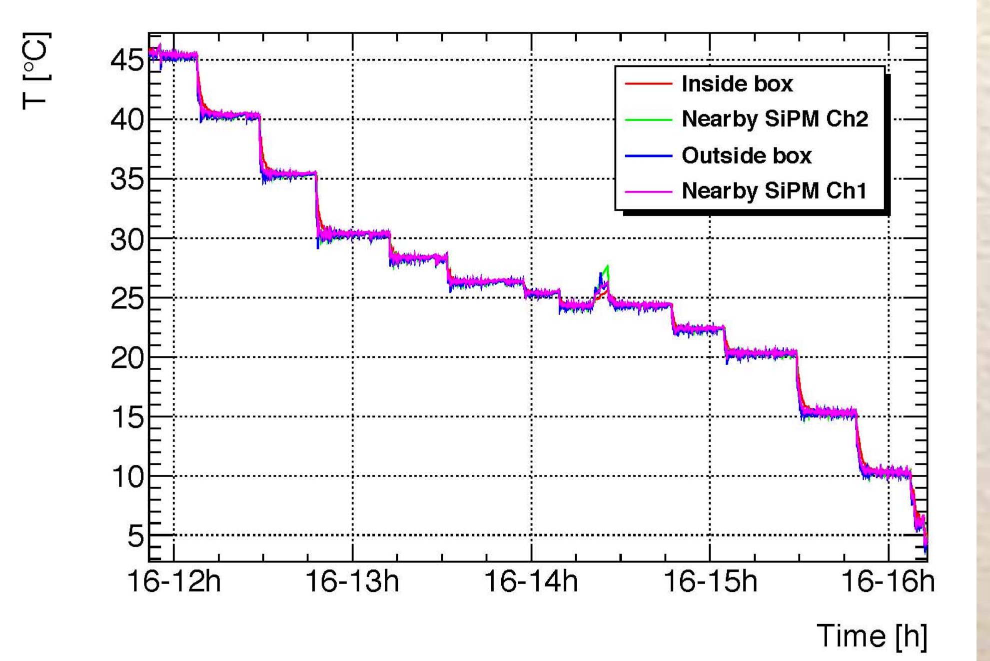


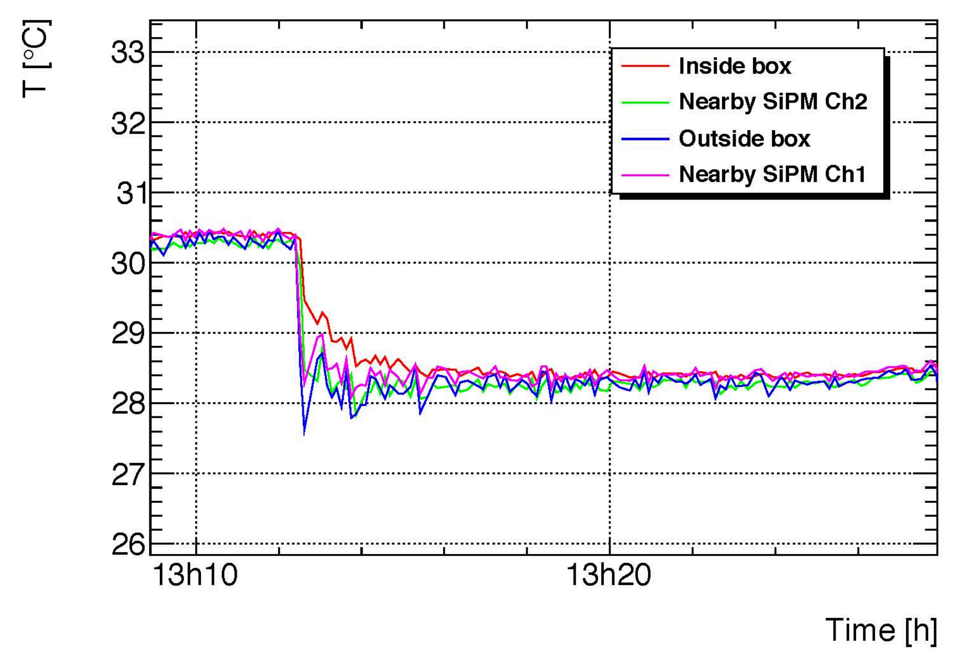
Gain Stabilation Test Setup

- Use 4 pt1000 sensors
  - 2 near SiPM,
  - 1 inside black box
  - 1 outside black box



- We varied T from 2° to 50°C in 5°C steps reducing steps to 2°C in 20°-30°C
  - $T_{SiPM}=T_{set}$ +0.4°C
  - Offset remained constant over entire T range





Gain Determination

- We measure waveforms of SiPMs with a 12-bit digital oscilloscope
- We subtract a DC offset & integrate all 50k waveforms over Δt=74 ns time window to determine charge ➔ spectrum of pe
- We fit pe spectra with likelihood function

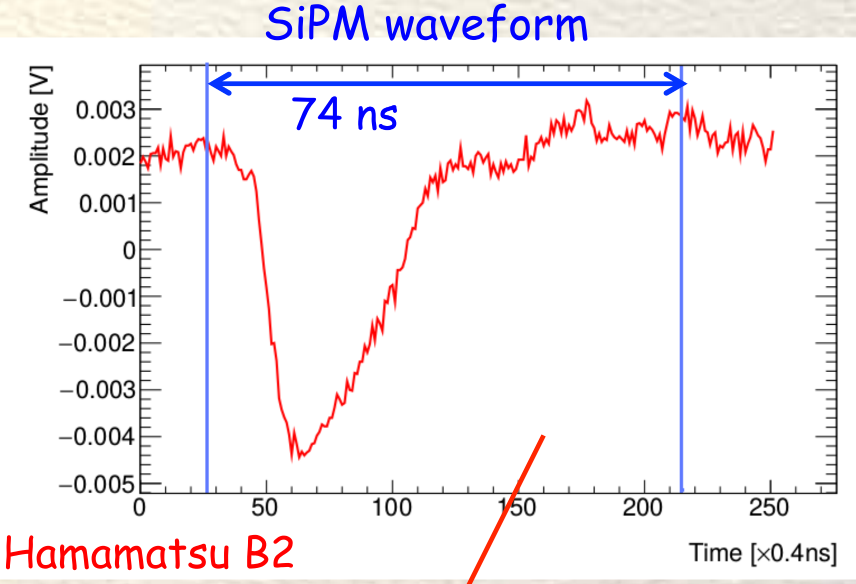
$$L = \prod_{i=1}^{50000} \left[f_s F_{sig}\left(w^i\right) + \left(1 - f_s\right) F_{bkg}\left(w^i\right) \right]$$

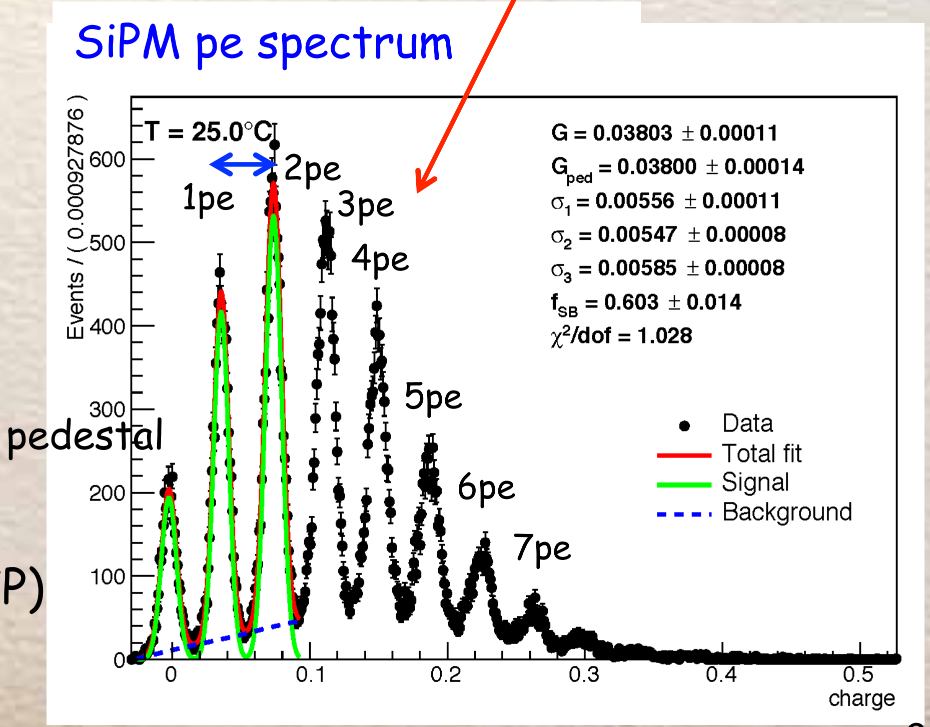
f_s: signal fraction

- Determine pe peak position by fitting Gaussian functions G_{ped}, $G_{1,2}$ to pedestal, 1pe and 2pe peaks

$$F_{sig} = f_{ped} G_{ped} + f_1 G_1 + \left(1 - f_1 - f_2\right) G_3$$

- We parameterize the background F_{bkg} by sensitive iterative clipping algorithm (SNIP) implemented in ROOT T spectrum class



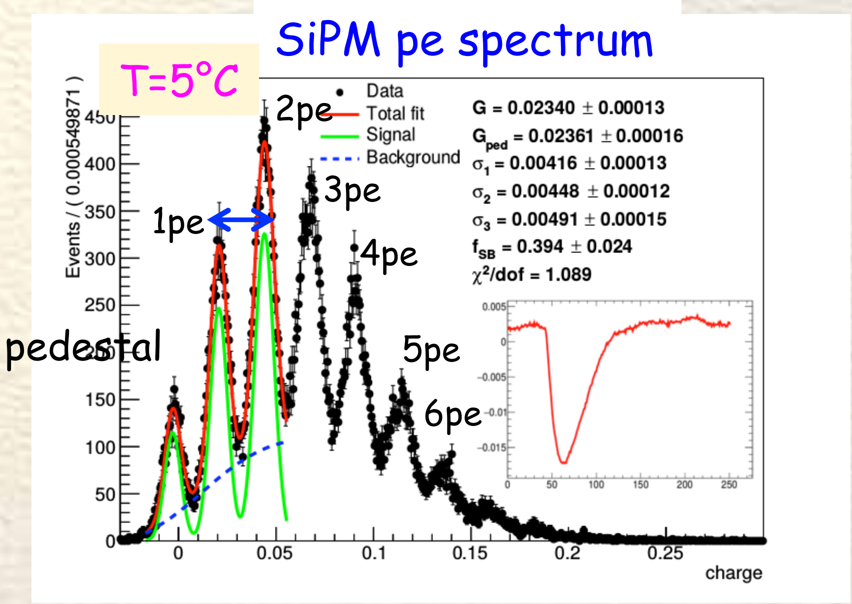


Gain Determination

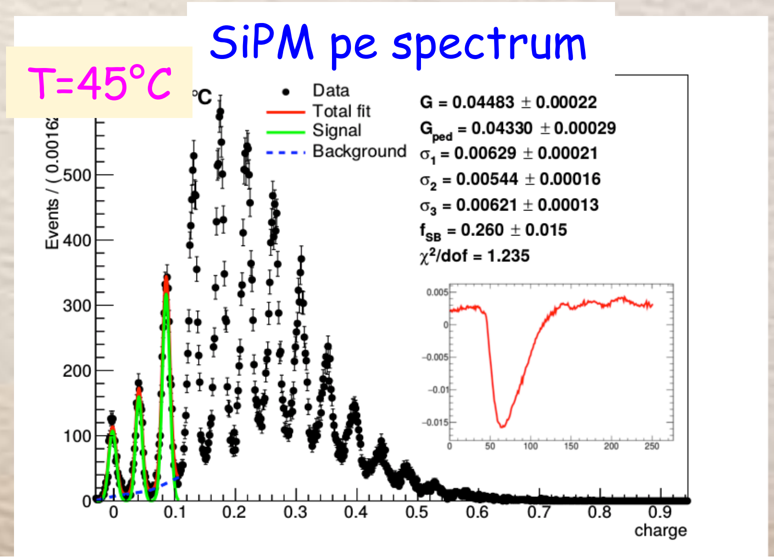
- We perform binned fits on spectra with at least 2 pe peaks
- The gain is determined from the distance between 1pe and 2pe peaks G_2-G_1
- This is more reliable than distance G_1-G_{ped}
- $G_{1,2}$ and G_{ped} are not constrained in the fit
- The error on the gain is obtained from the uncertainties of the peak positions G_1, G_2

$$\sigma_{gain} = \sqrt{\sigma_{\mu_1}^2 + \sigma_{\mu_2}^2}$$

Hamamatsu B2

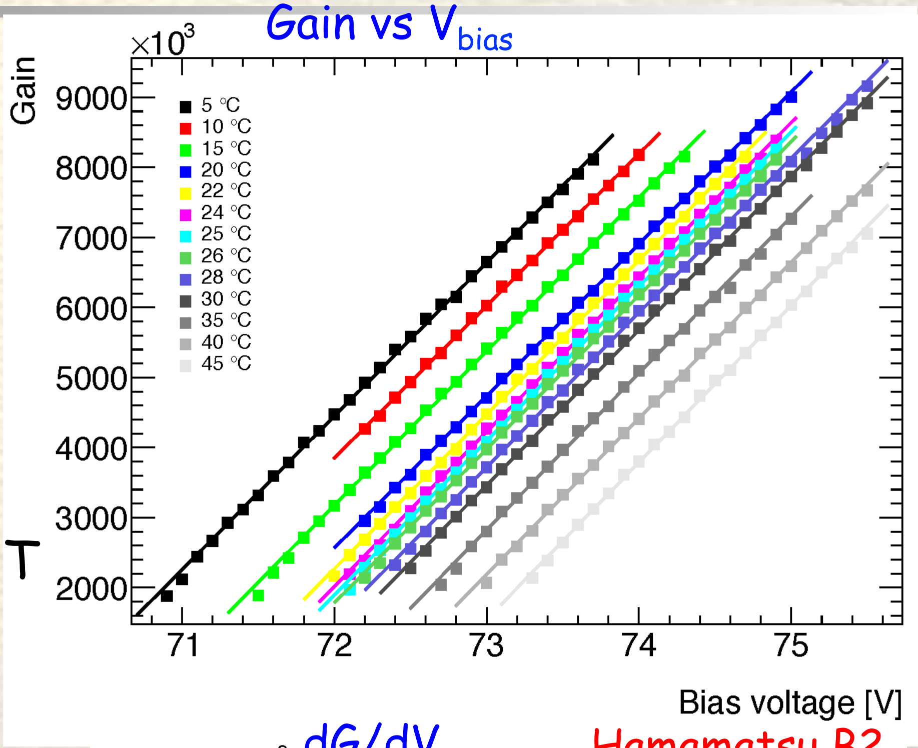


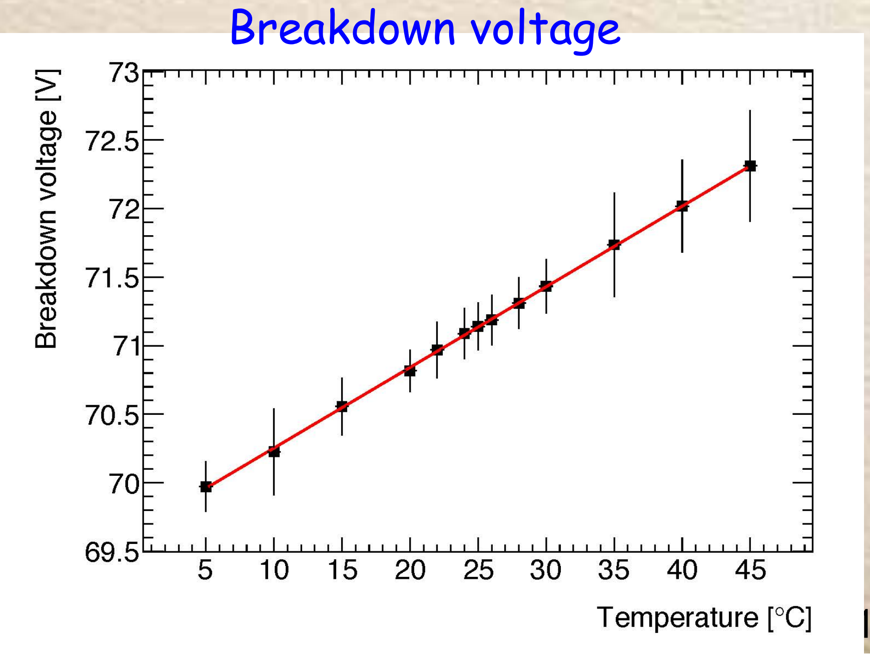
Hamamatsu B2

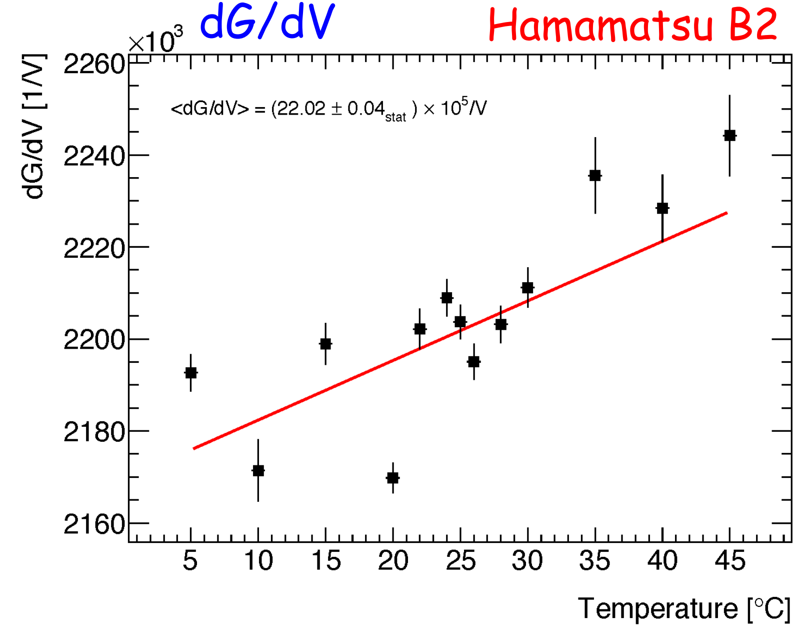


dG/dV Measurements

- We explore temperature range 5°C-45°C
- At fixed temperature, we vary V_{bias}
  ➔ at each point we take 50k waveforms
- For each temperature point, we perform a linear fit for G vs V_{bias} to extract
  - Breakdown voltage
  - dG/dV
- Breakdown voltage increases linearly with T
- dG/dV~C increases with T (use linear fit)
  2% effect in 5°C-45°C T range



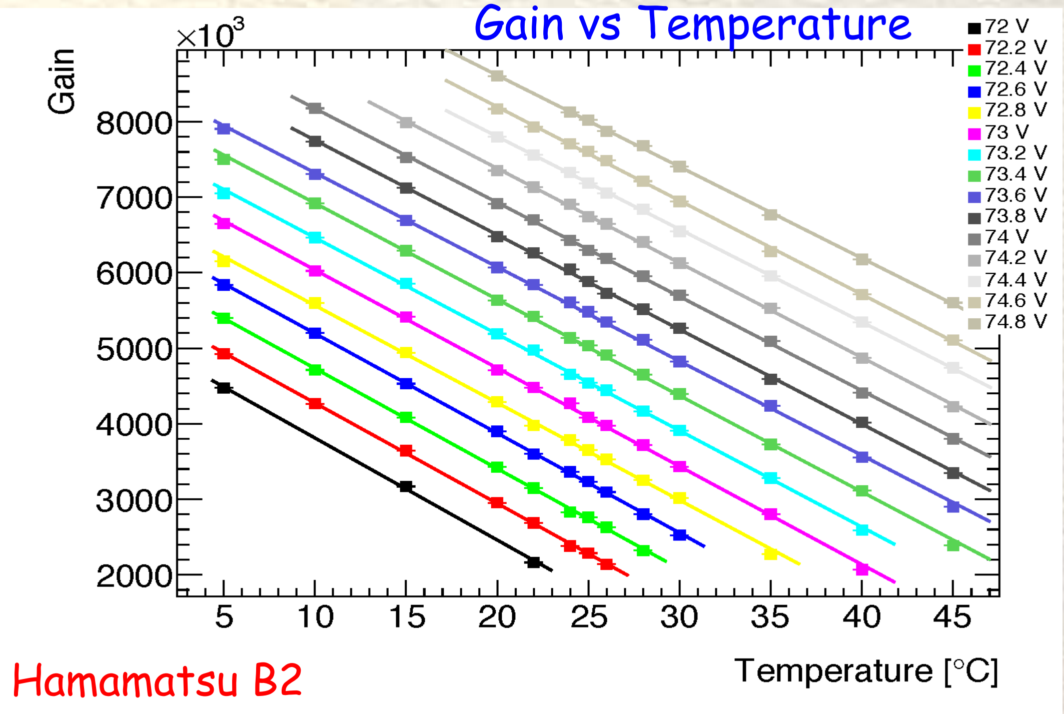




$<dG/dV>=(2.202\pm0.004_{stat})\times10^{6}/V$

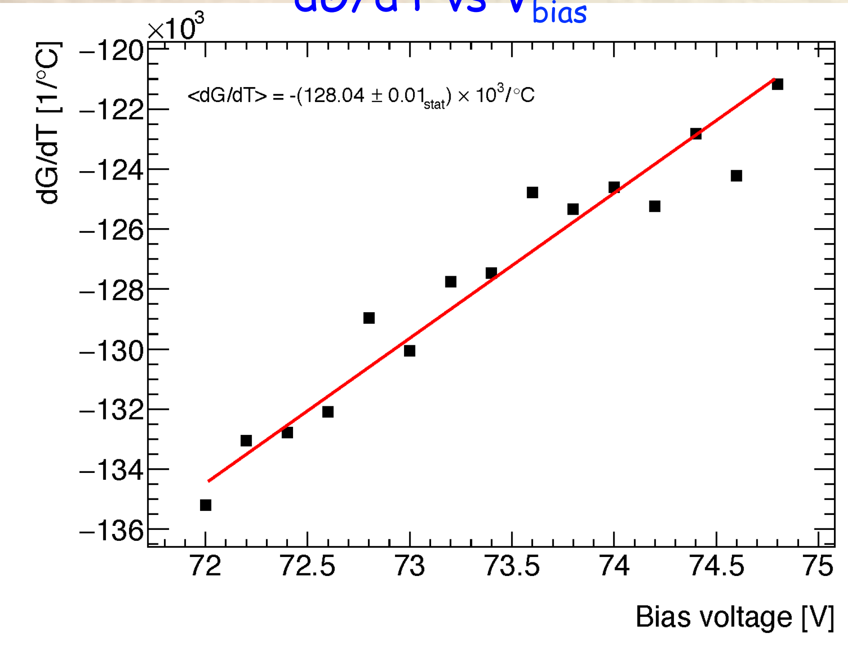
dG/dT Measurements

- For fixed V_{bias} plot gain versus T
- Gain decreases with temperature
  ➔ perform linear fit to extract dG/dT
- dG/dT increases linearly with T (11% variation from 5°C to 45°C)
  ➔ perform linear fit


Gain vs Temperature

Hamamatsu B2

dG/dT vs V_{bias}



- From the fit at T=25°C, we measure $\langle dG/dT\rangle = -(0.12804 \pm 0.00001) \times 10^6/°C$
- With the result for dG/dV we get $\langle dT/dV\rangle = -\langle (dG/dV)\rangle / \langle (dG/dT)\rangle$

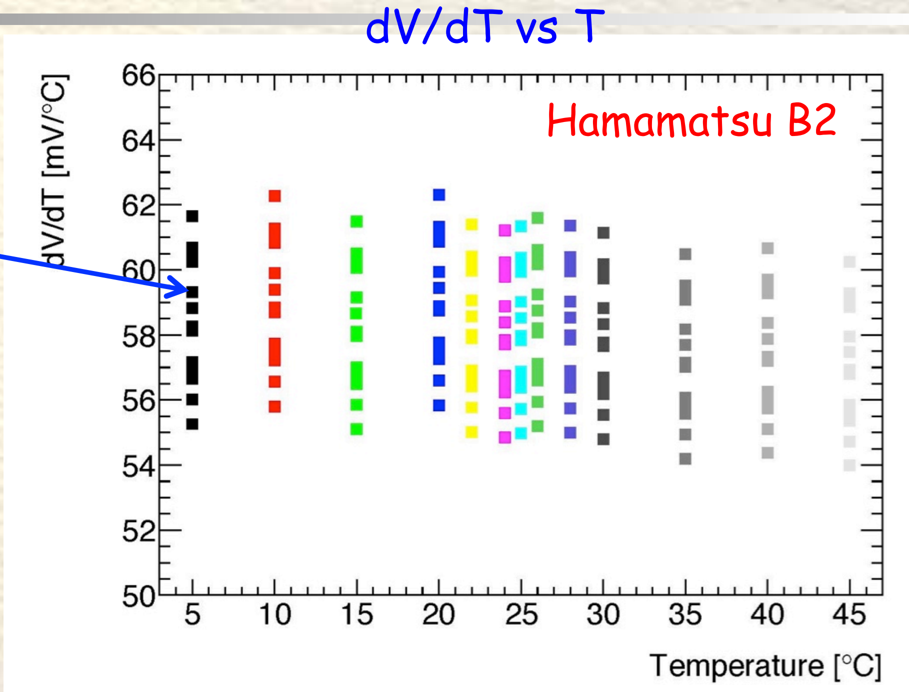
  $= (58.15 \pm 0.1)$ mV/°C
- Hamamatsu quotes 60mV/°C

Systematic Error determination for dV/dT

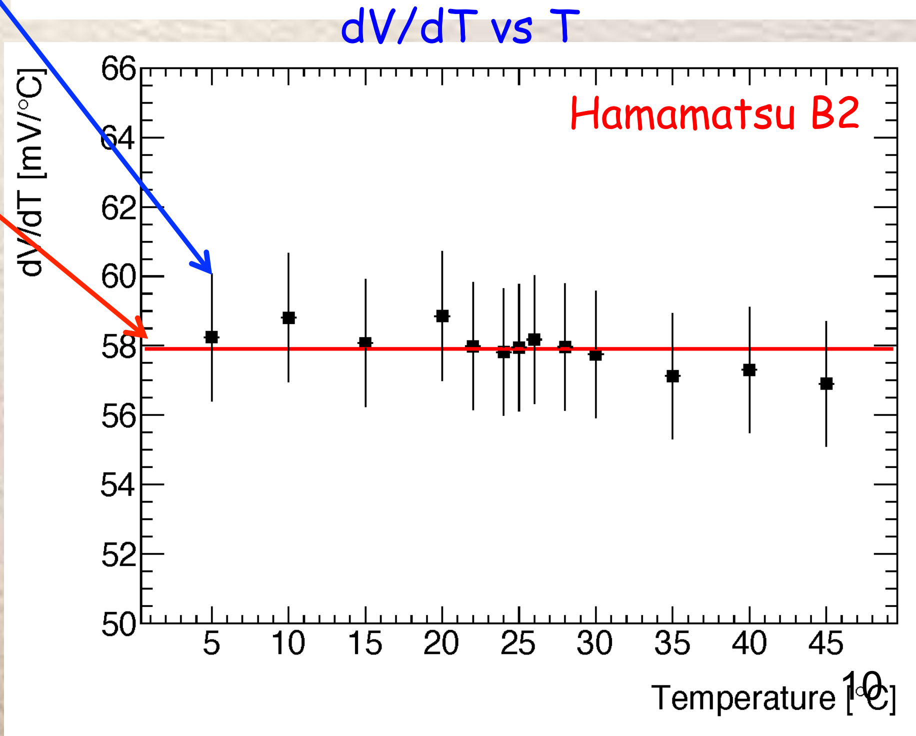
- At each T point, determine dV/dT distribution by dividing all dG/dT measurements by dG/dV
- At each T point, average dV/dT values and compute standard deviation
- Fit the resulting distribution with a uniform distribution
  ➔ estimate of systematic error by taking the fit parameter uncertainty
- $dV/dT=(58.15\pm0.10_{stat}\pm0.51_{sys})\ mV/°C$
- We estimate a gain stability of

$$\frac{\Delta T}{G}\frac{dG}{dV}\sigma\left(dV/dT\right)=0.01\%$$

dV/dT vs T



dV/dT vs T



Exact dV/dT Relation

- For stable gain, extract ➔ $$\frac{dV}{dT} = -\frac{\left(\partial G(V,T)/\partial T\right)}{\left(\partial G(V,T)/\partial V\right)}$$
- We observed linear dependence

$$\frac{\partial G(V,T)}{\partial T} = a + bT \quad \text{and} \quad \frac{\partial G(V,T)}{\partial V} = c + dV$$

- The analytic solution is

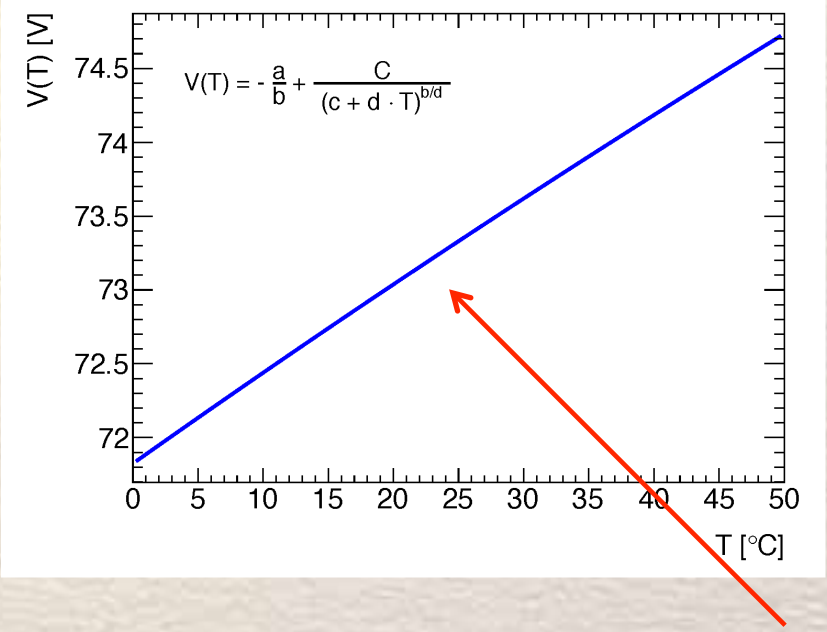
$$V(T) = -\frac{a}{b} + \frac{K}{\left(c + dT\right)^{b/d}}$$

K: integration constant

for b≠0, d≠0

V(T)

Hamamatsu B2

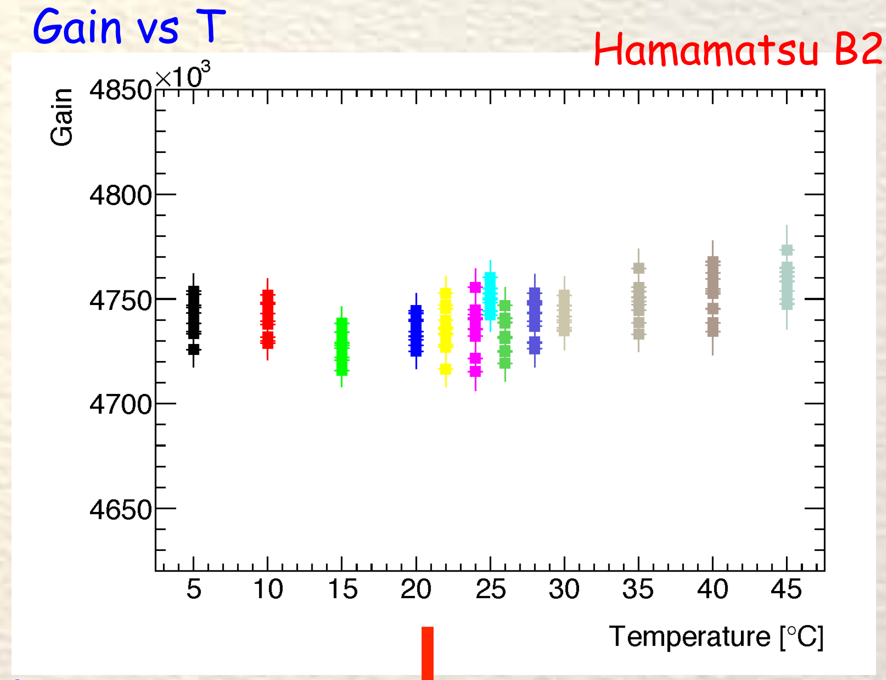


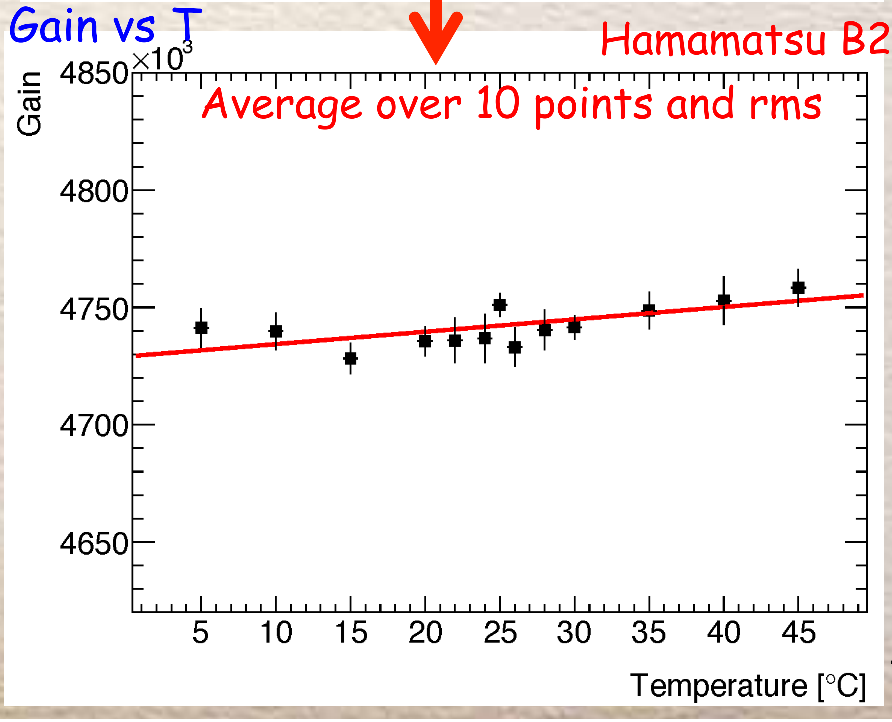
- By plugging the values for a,b,c,d for Hamamatsu B2 yields V(T) dependence ➔ in the 2°-50°C range this yields an excellent linear approximation

$a=(-0.48266\pm0.0002)\times10^{6}$; $b=4835.9\pm0.3$; $c=(2.17\pm0.003)\times10^{6}$; $d=1295\pm152$

Test of Gain Stabilization

- Adjust V_{bias} with regulator board using compensation of 58 mV/°C
- Test gain stability in 5-45°C T range
  ➔use 5°C steps reduced to 2°C steps in T=20°C-30°C
- At each T point take 10 samples with 50k waveforms each
- Fit distribution with linear function
  offset=$(4.73\pm0.01)\times10^6$
  slope =527±209
- Gain is uniform in 5°C-45°C T range
  ➔non-uniformity is ±0.1%

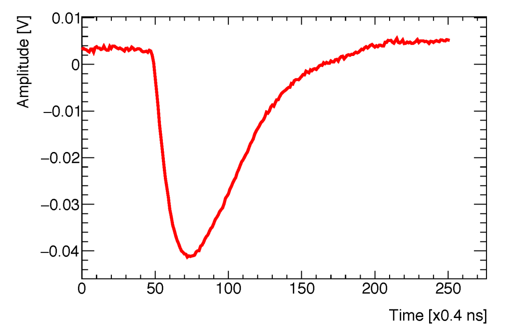


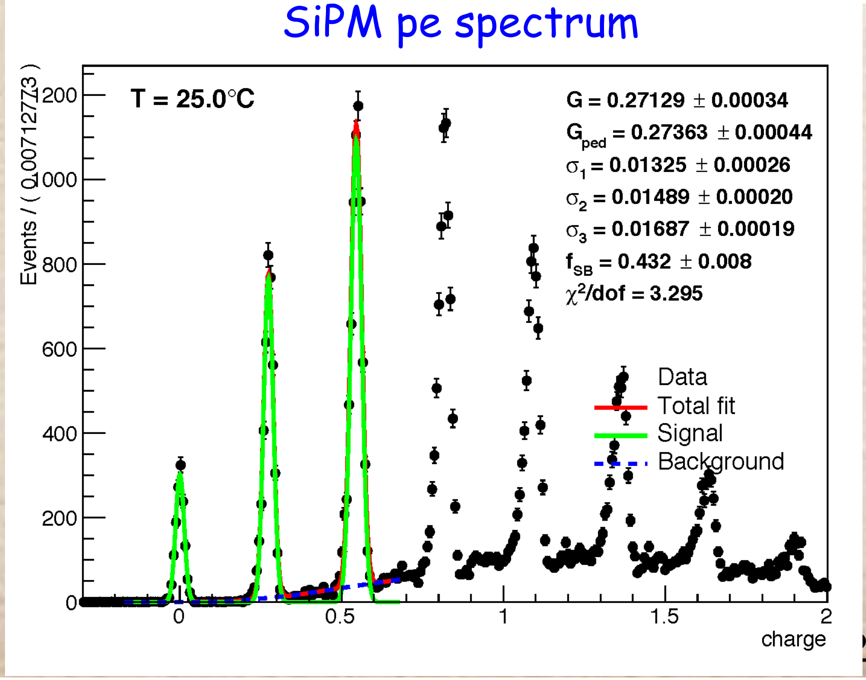


Study of Hamamatsu MPPCs with Trenches

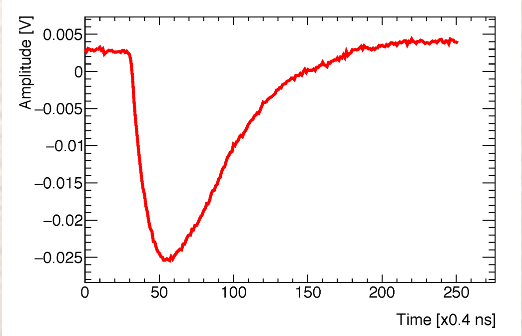
- New Hamamatsu 1 mm ×1 mm detectors with 50 µm pitch and trenches (LCT4)
  ➔ trenches suppress cross talk
  ➔ see perfect waveforms, not much noise
  ➔distinctive pe peaks and low background

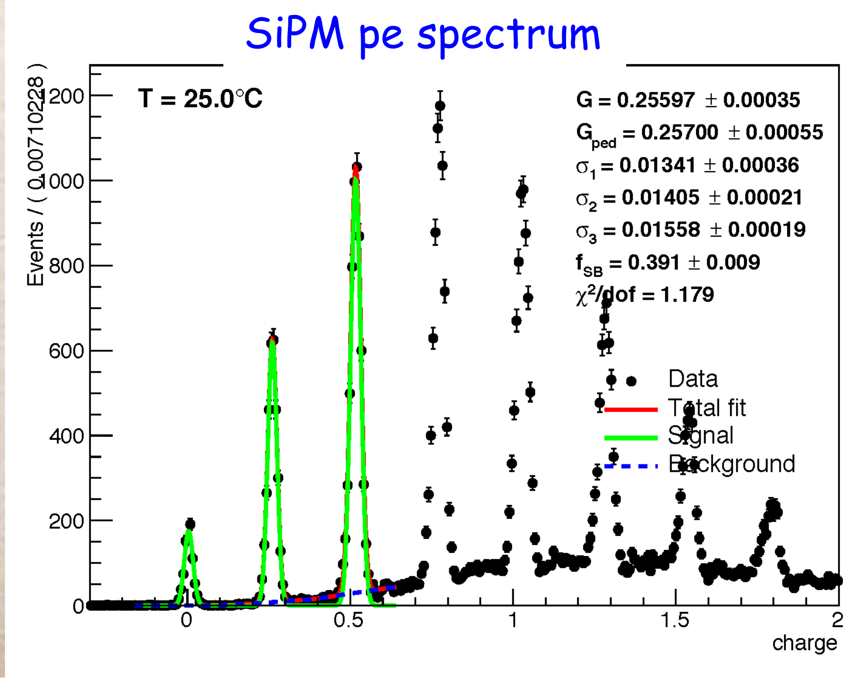
- LCT4#6





LCT4#9





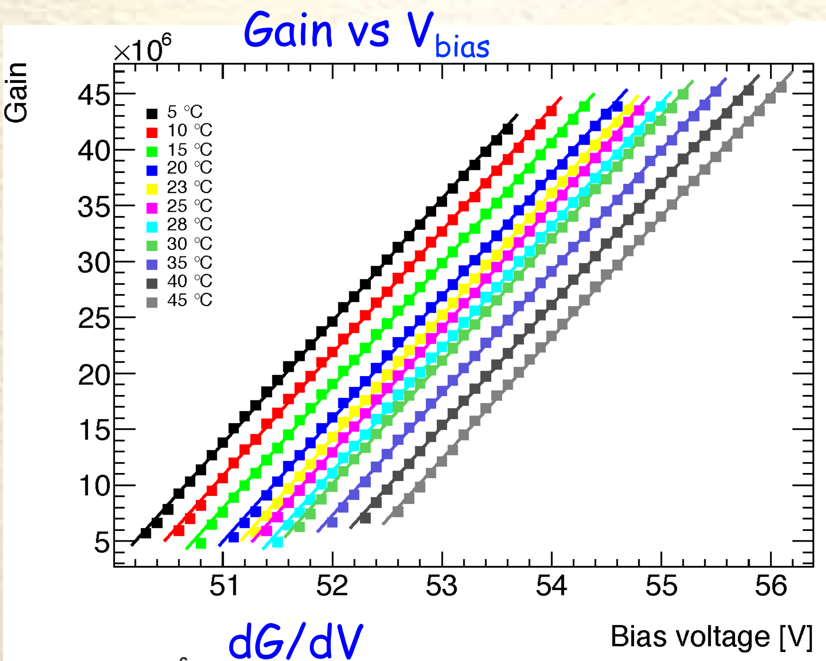
dG/dV and dG/dT Dependence

- We perform the same analysis as for the B2 MPPC

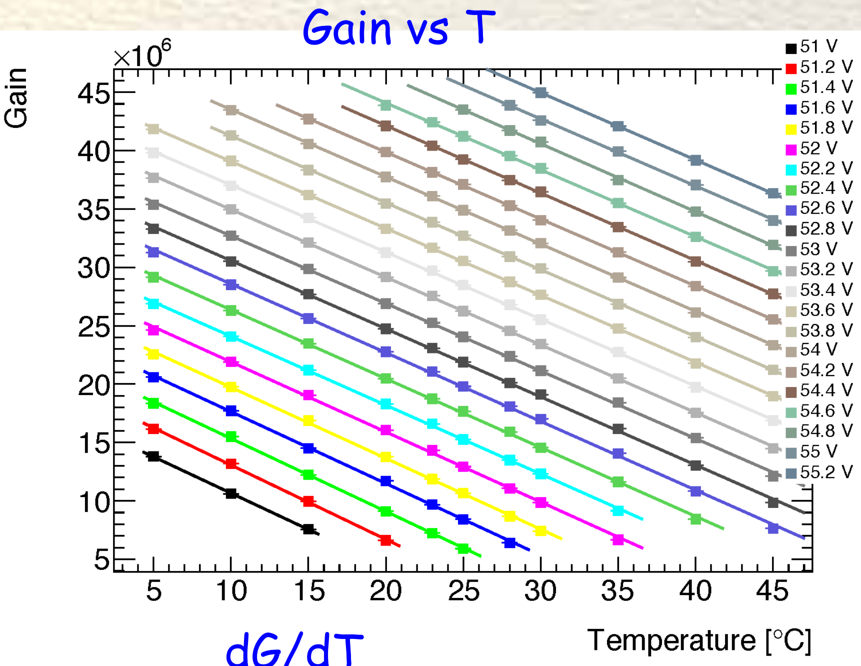
LCT4#6

- Results for LCT4#9 look very similar
- At low T, capacitance seems to be constant, maximum deviation between low and high T is ~1%

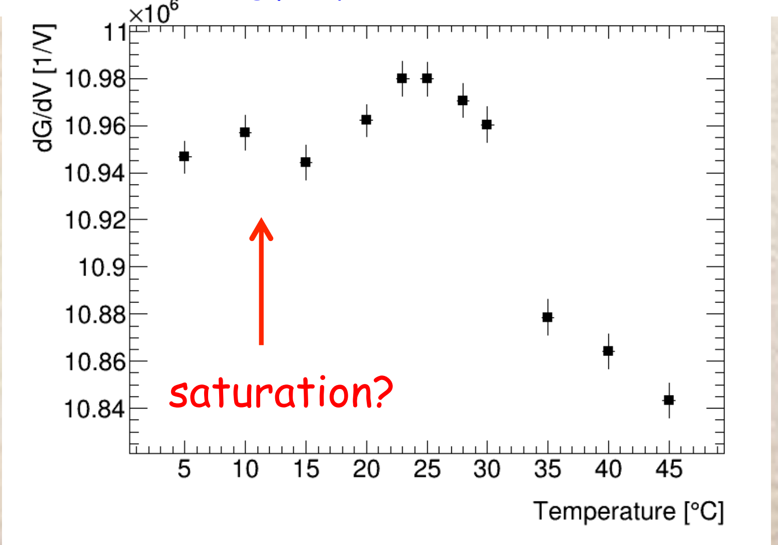
Gain vs V_{bias}



Gain vs T

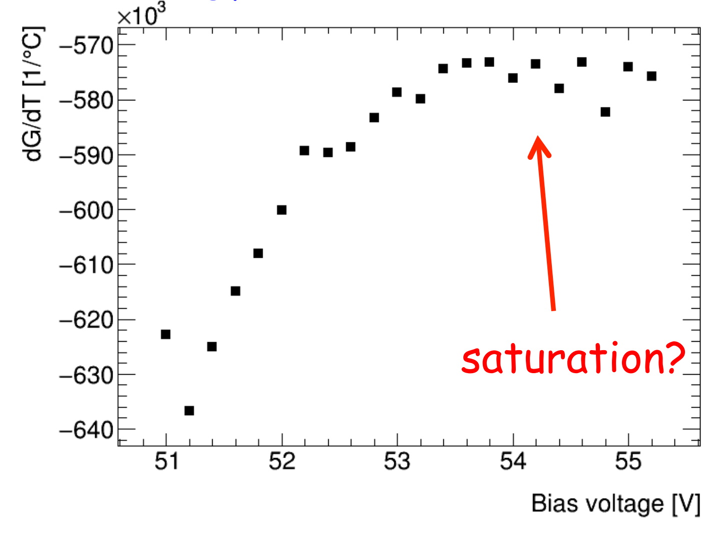


dG/dV



saturation?

dG/dT



saturation?

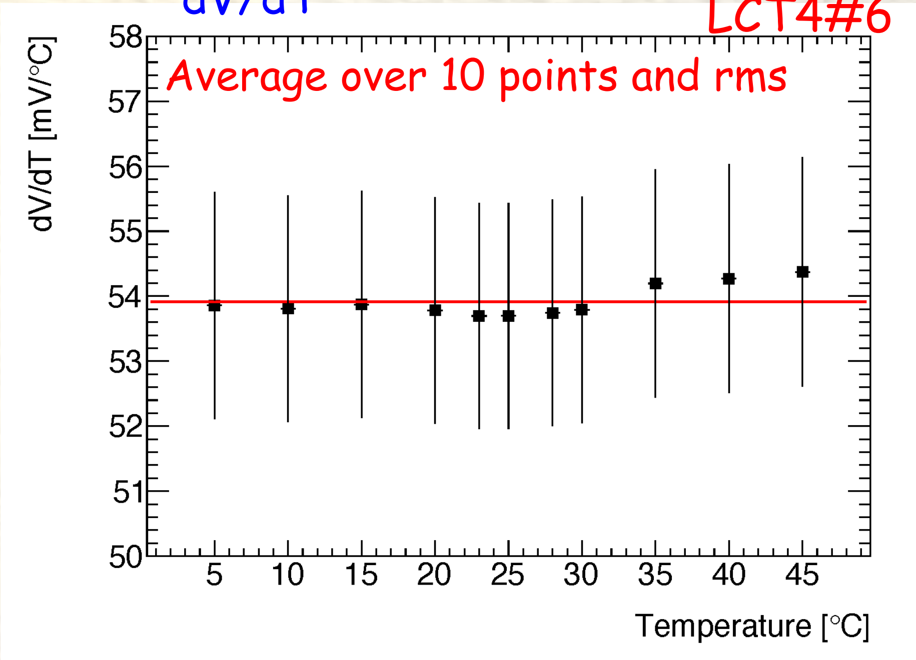
Gain Stabilization for LCT4#6

- We measure
  $\langle dG/dV\rangle = (11.004\pm0.005)\times10^{6}/V$
  $\langle dG/dT\rangle = -(1.5265\pm0.0009)\times10^{6}/°C$
- We extract from these values
  dV/dT=53.9±0.5 mV/°C
- This is ~10% lower than the manufacturer specification of 60 mV/°C
- The analytical solution for results in a linear V(T) dependence

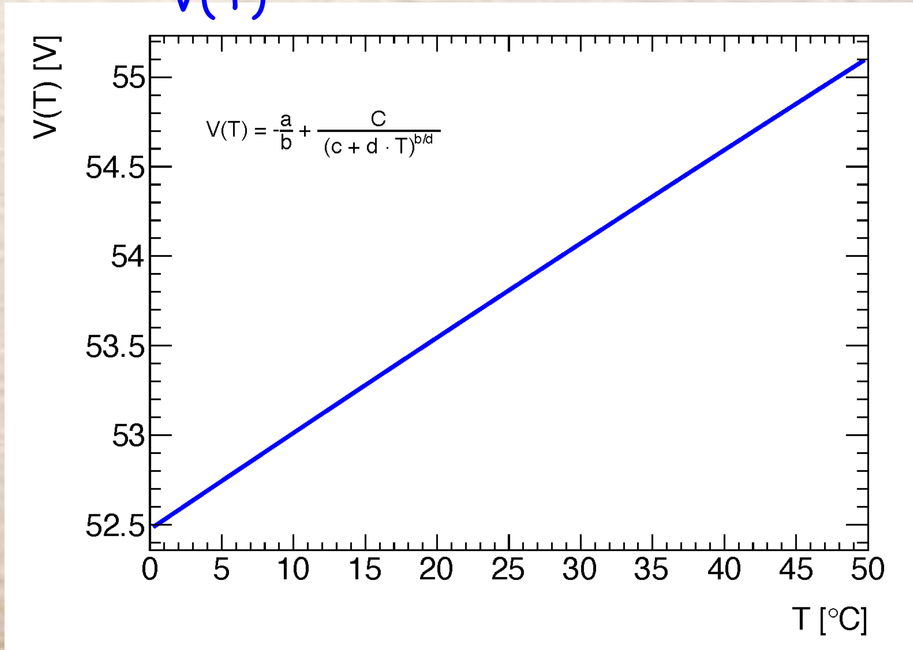
  $a=(1.52646\pm0.0009)\times10^{6}$
  $b=17644\pm2$
  $c=(11.004\pm0.005)\times10^{6}$
  $d=2749\pm192$

dV/dT

LCT4#6



V(T)



Gain Stabilization for LCT4 MPPCs

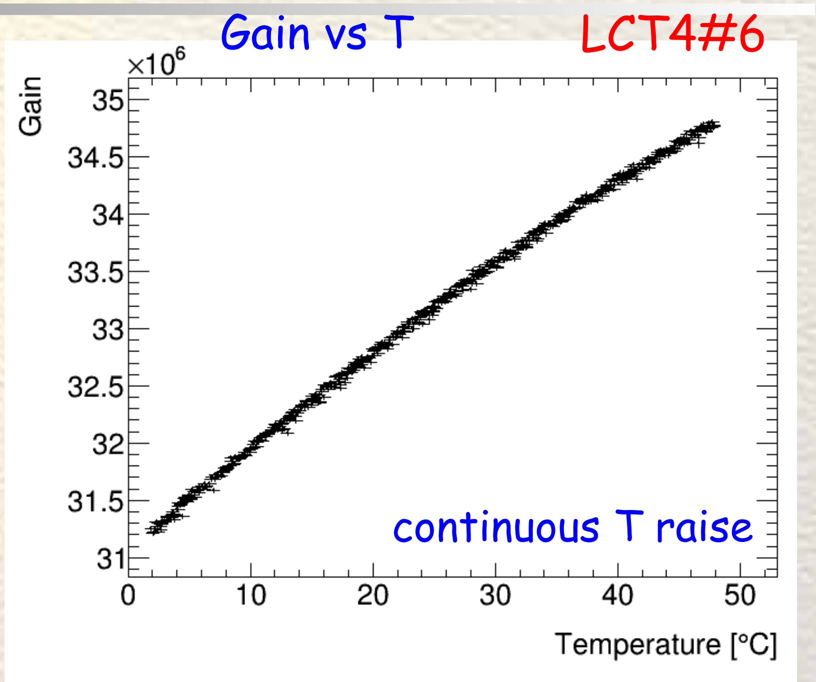
- Since the analysis of the data could not keep up with measurements in the climate chamber, we could not use the measured dV/dT value

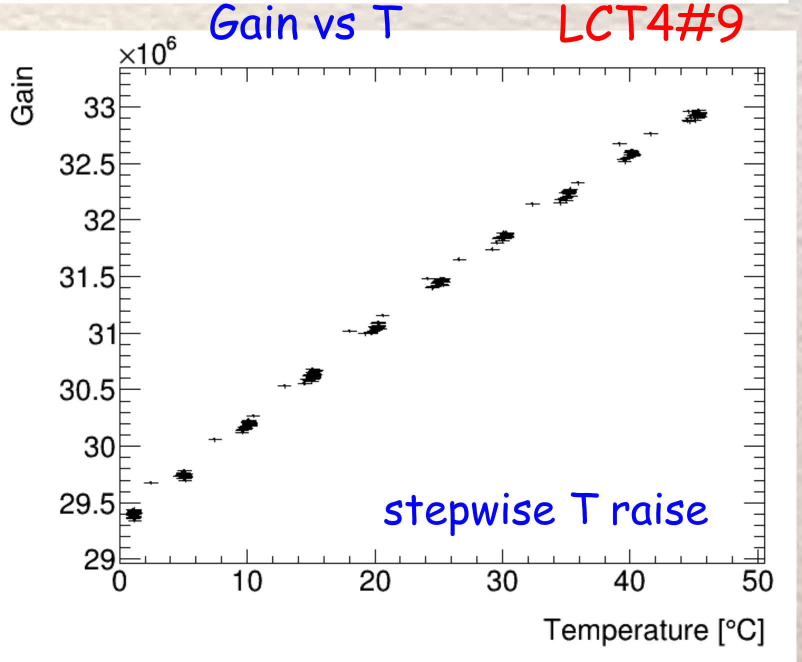
  → we used a compensation of 60 mV/°C instead of 53.9 mV/°C

- The gain versus T distribution clearly shows an overcompensation of the order of 10% for both LCT4#6 & LCT4#9 MPPCs

- From 2°C- 35°C, the relation is rather linear

- An offline correction of 1.085*54 mV/°C produces stable gain over the entire T region (5°C-45°C) → deviation ~2%



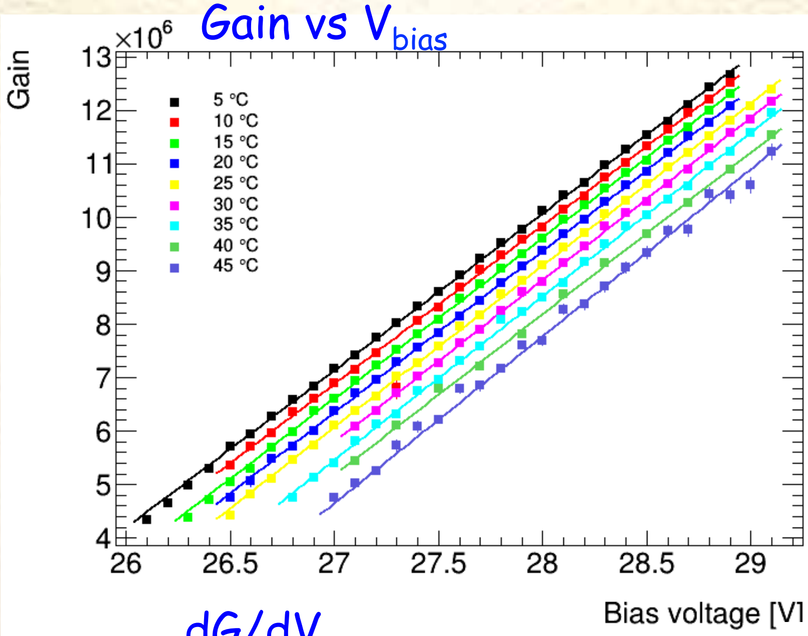


dG/dV & dG/dT Dependence for KETEK SiPM

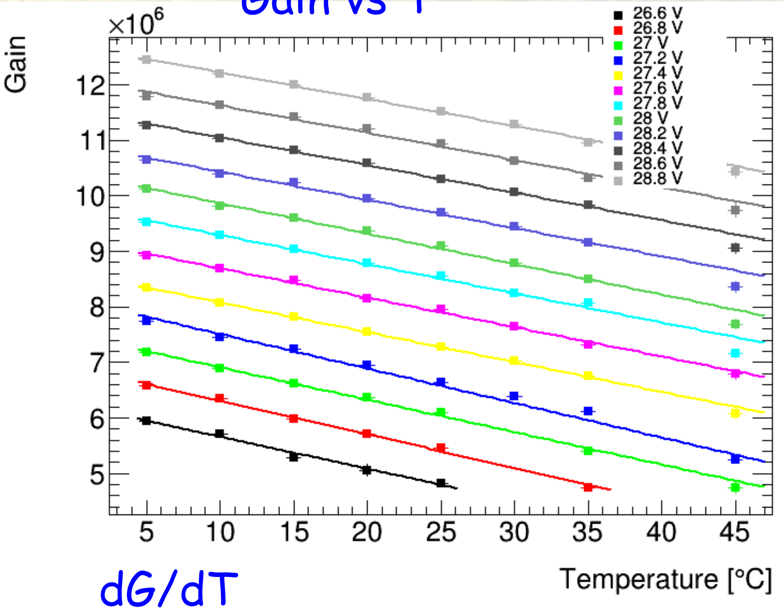
- We perform a similar analysis as that for the Hamamatsu B2 MPPC
- Results for LCT4#9 look very similar
- Capacitance shows small linear dependence of ~5% in 5°C-45°C T range

W12

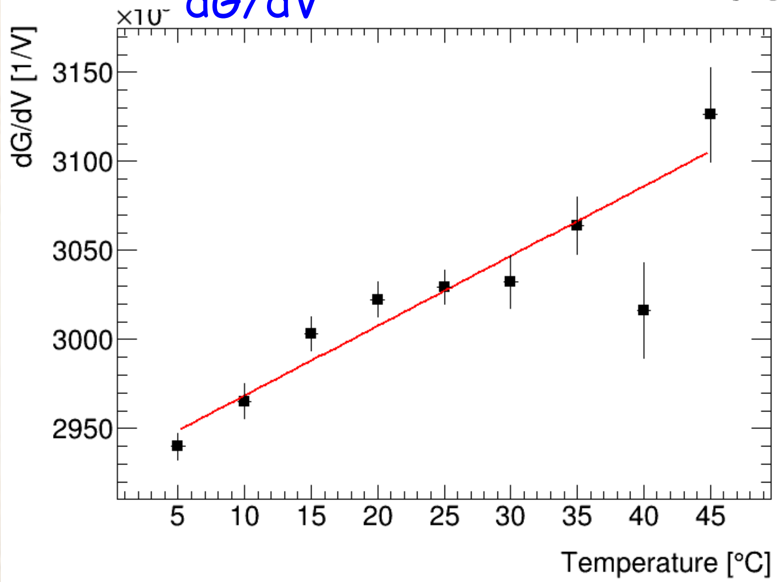
Gain vs V_{bias}



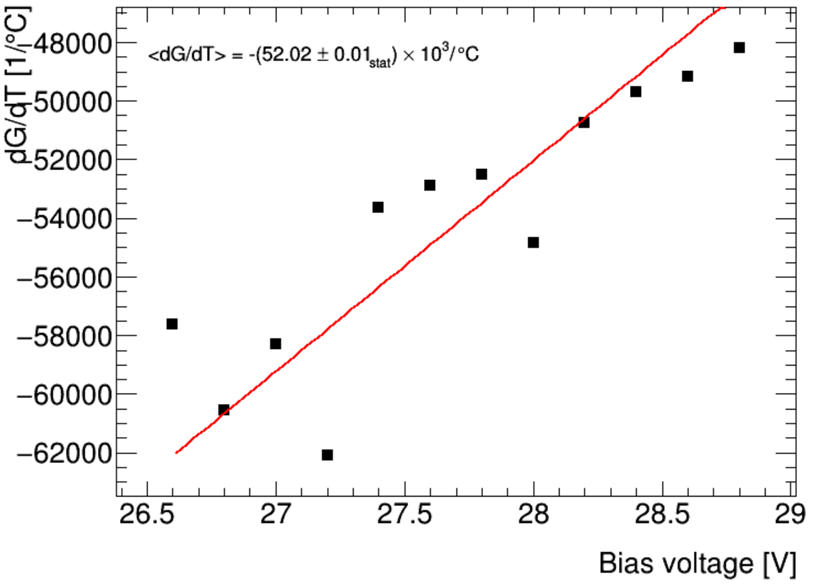
Gain vs T



dG/dV



dG/dT



Gain Stabilization for KETEK SiPm W12

- We measure

  $\langle dG/dV\rangle = (2.92932 \pm 0.00036) \times 10^6/°C$

  $\langle dG/dT\rangle = -(0.253358 \pm 0.000038) \times 10^6/V$

- We extract from these values

  $dV/dT = 17.2 \pm 0.4$ mV/°C

- This is somewhat smaller than our previous measurement of $dV/dT = 21.29 \pm 0.08$ mV/°C

- The analytical solution for results in a linear V(T) dependence

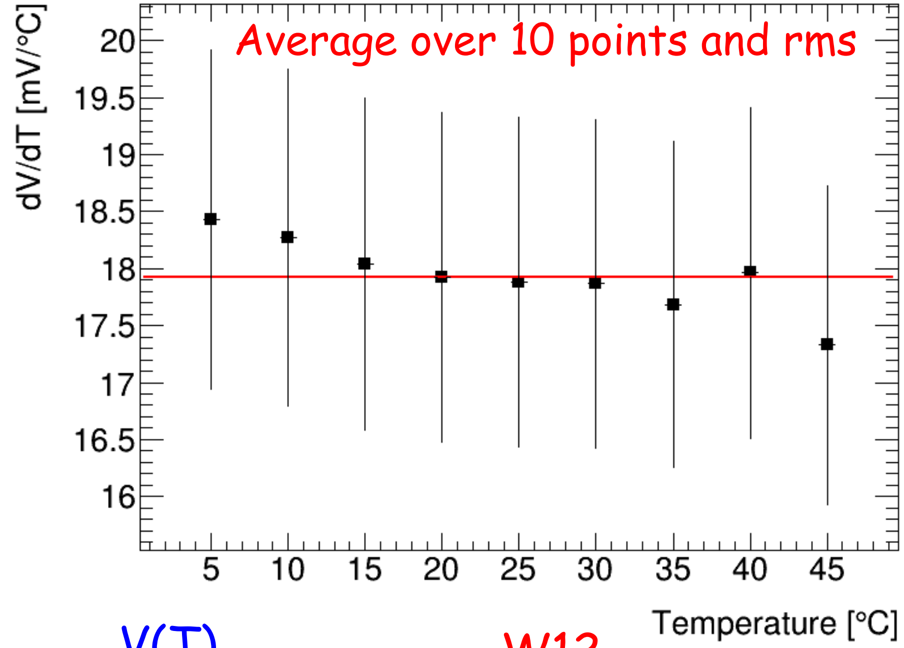
  $a = -253358 \pm 38$

  $b = 7190.5 \pm 1.4$

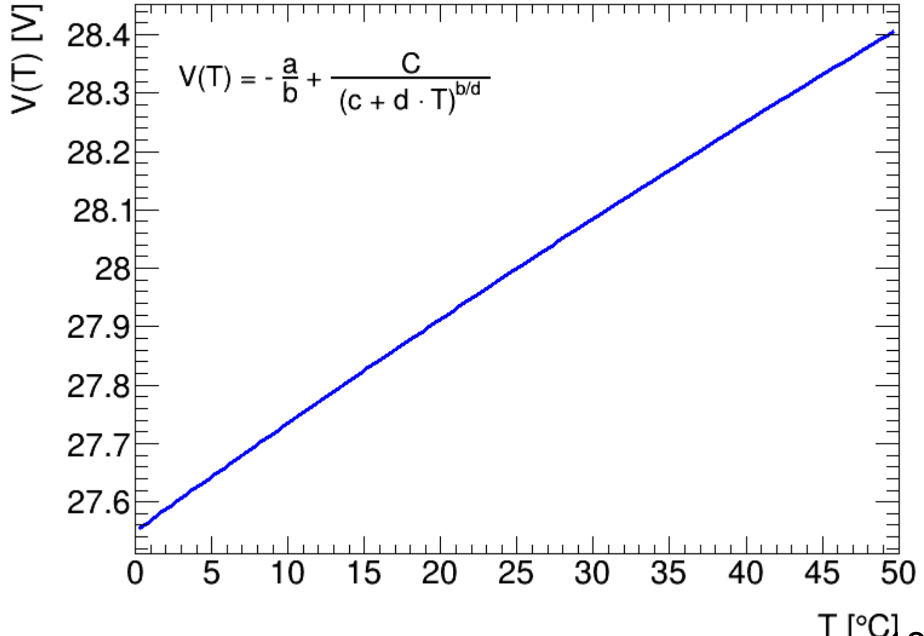
  $c = (2.92932 \pm 0.00036) \times 10^6$

  $d = 3918 \pm 360$

dV/dT W12

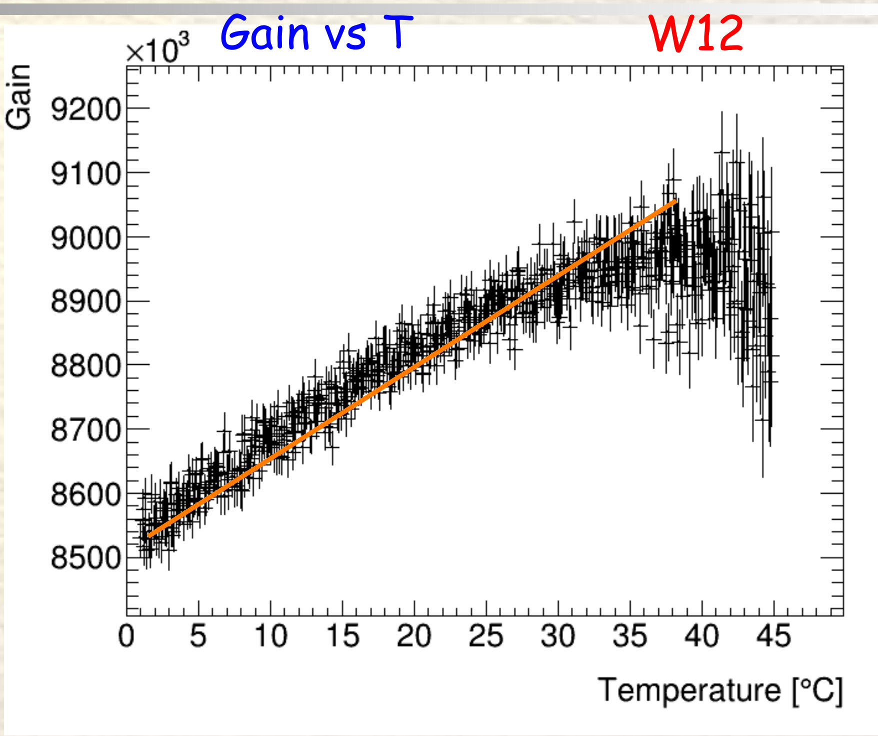


V(T) W12



Gain Stabilization for KETEK SiPM

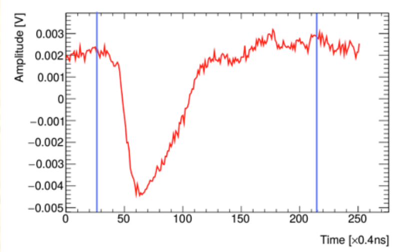
- Again, the analysis of the data could not keep up with the measurements in the climate chamber, we used a compensation of 21 mV/°C instead of 17.2 mV/°C
- The gain versus T distribution clearly shows an overcompensation of the order of 7%
- The gain increases linearly from 2°C- 30°C before leveling off

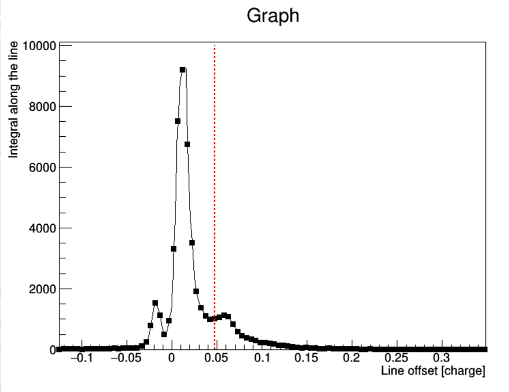


- We need further studies to understand the discrepancy between dV/dT measurements and which dV/dT is needed to stabilize gain

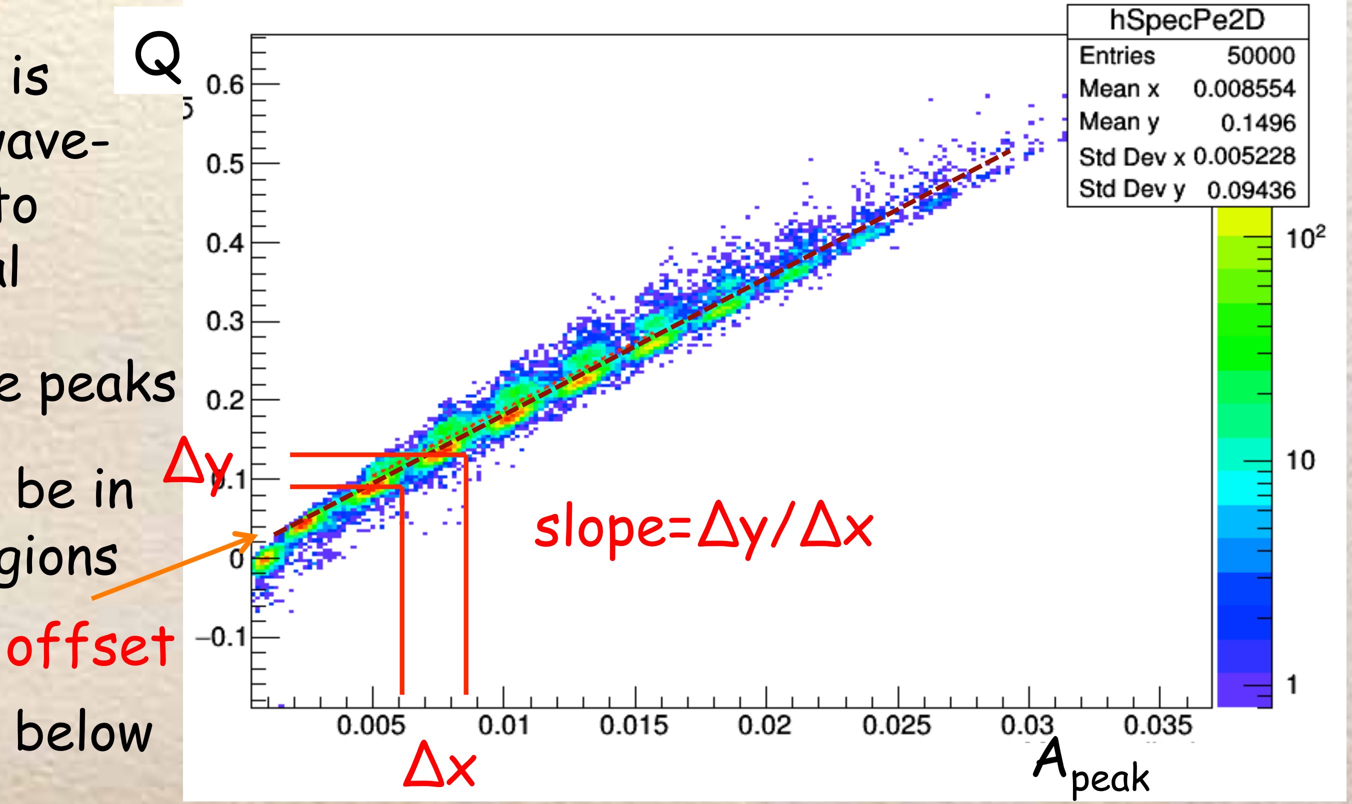
Does Afterpulsing affect Gain Stabilization?

- We determine the pe spectra from the waveforms in 2 ways
  - integrated charge Q
  - magnitude of the peak A_{peak}



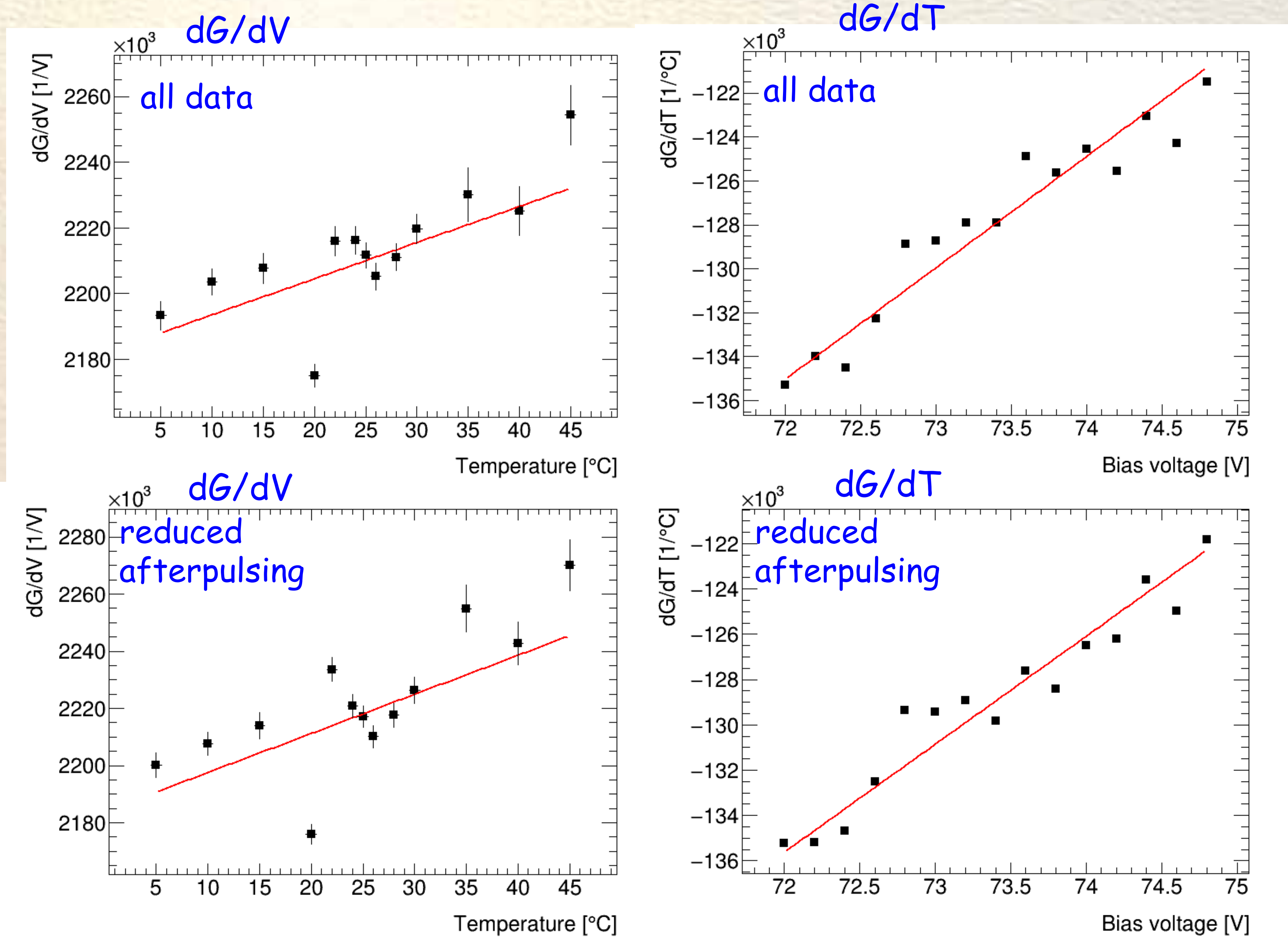


- We analyze the scatter plot of Q versus A_{peak}
- Signal without afterpulsing lies on the diagonal
- Signal with afterpulsing is shifted upwards since waveform is broadened due to delayed secondary signal
- Set slope with 2pe & 3pe peaks
- Dashed line is chosen to be in valley between the 2 regions ➔ best separation
- Redo analysis for region below dashed line



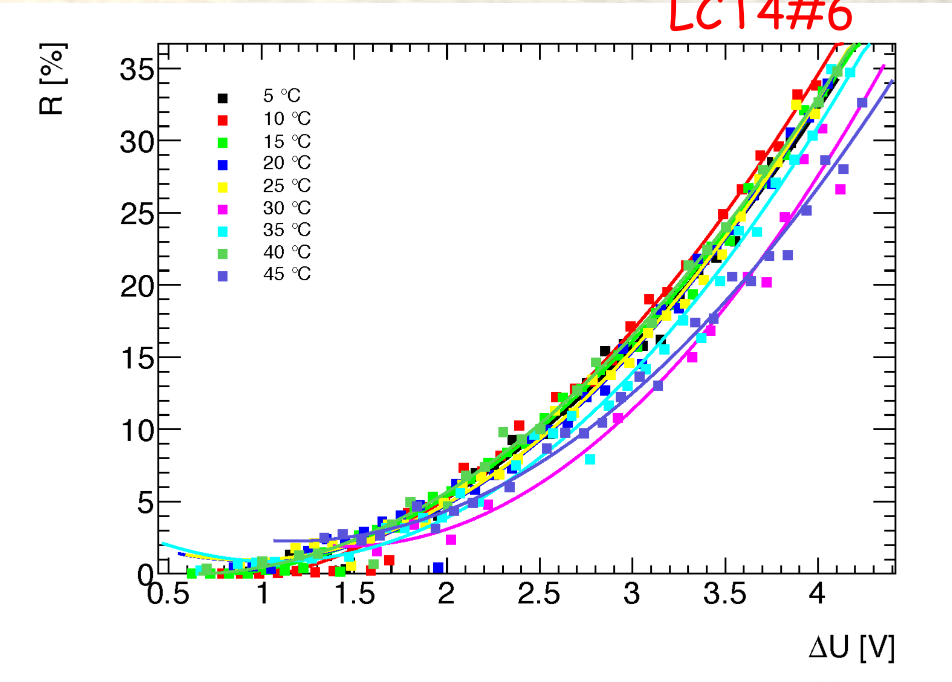
dG/dV & dG/dT for reduced afterpulsing

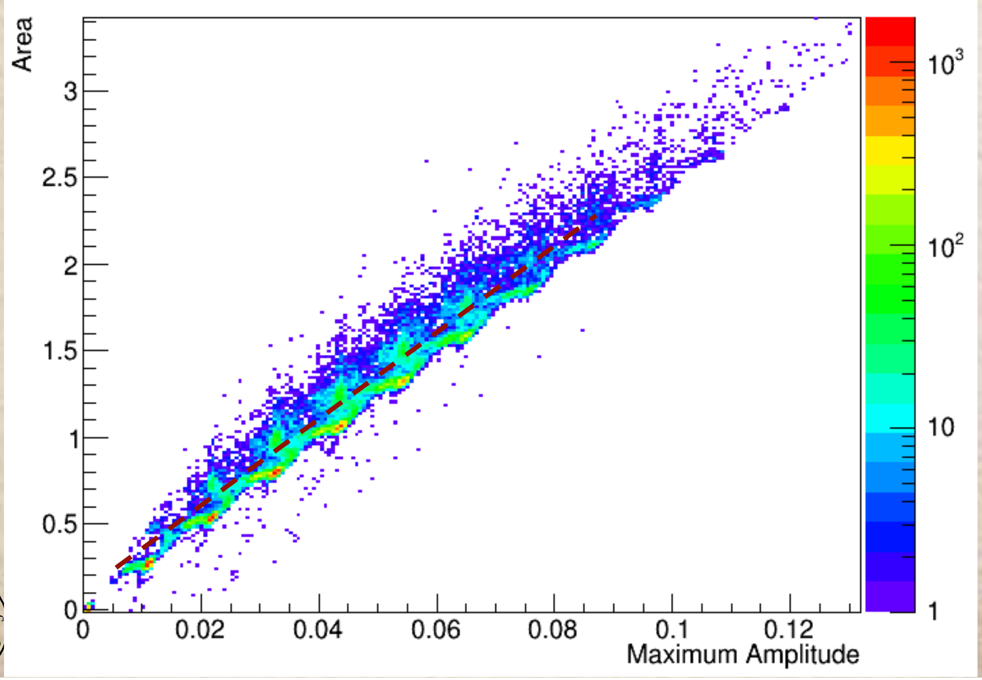
- The dG/dV & dG/dT distributions for sample with reduced afterpulsing look look similar as those for all data
- Within errors slopes are the same

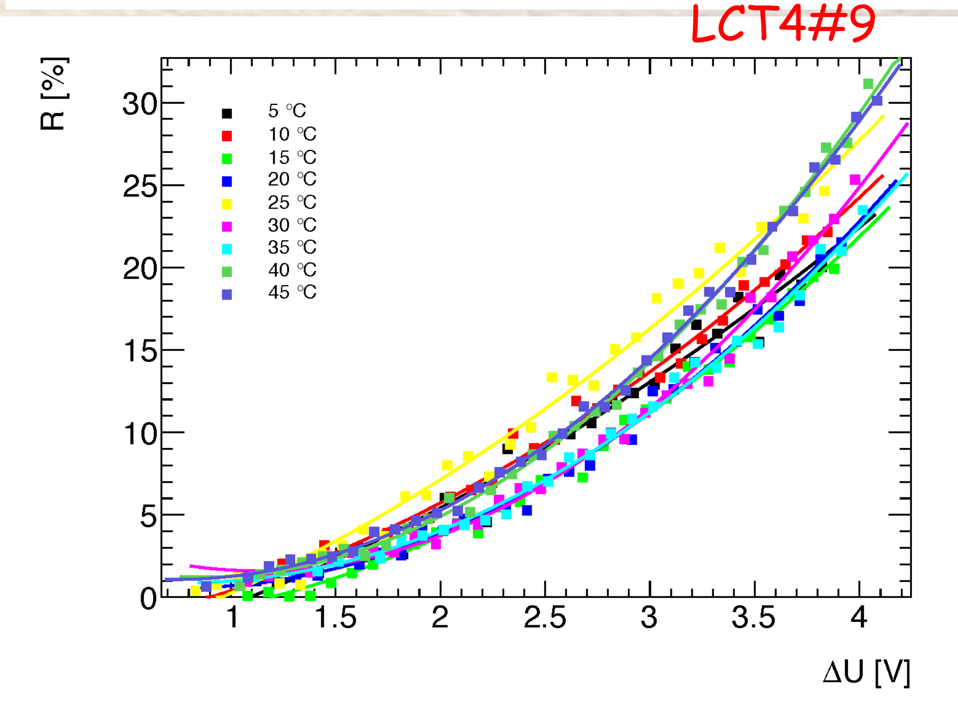


Afterpulsing of LCT4 MPPCs

- Define afterpulsing
  R=events above dashed line/all events
- Study R as a function of V_{bias} for each temperature
- R shows rapid increase with V_{bias}
- R shows no explicit T dependence
  ➔ Spread indicates systemematic effects of procedure


LCT4#6




LCT4#9

Conclusions and Outlook

- We performed more gain stabilization test in the climate chamber at CERN using an improved setup (12-bit digital oscilloscope controlled in labview)
- We read out 2 SiPMs simultaneously testing 8 detectors in total including 2 new MPPCs from Hamamatsu with trenches (LCT4 #6, #9)
- For MPPCs B2 we achieved excellent gain stabilization in entire T range (5-45°
- For MPPCs LCT4(#6 &#9), we overcorrected V_{bias} by using manufacturer's specs → since overcorrected G is quasi linear over entire T range, a simple correction factor yields stable gain →deviations are less <1%
- For KETEK W12 SiPMs, we need more studies to understand overcorrection
- Analysis of CPTA SiPMs is still in progress
- Gain stabilization is not affected by afterpulsing
- We plan another test with 4 detectors read out simultaneously early next year
- Main goal is to perform gain stabilization for a system with 10 to 20 SiPMs →this requires a new layout of the data acquistion since the digital oscilloscope has only 4 input channels
- Further goal is to implement this methodology into the power distribution system of the analog hadron calorimeter

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