Gain Stabilization of SiPMs and Afterpulsing

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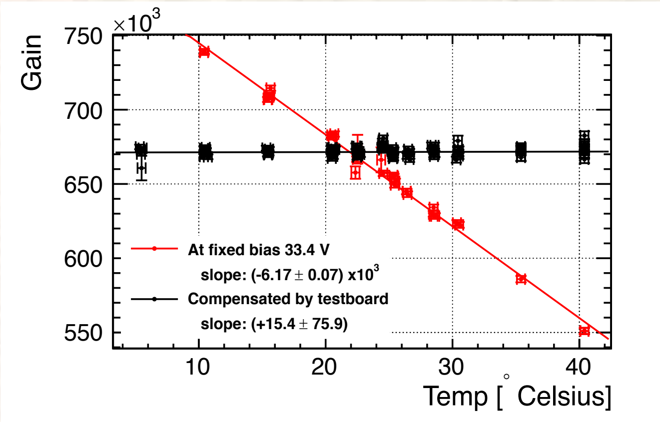
Outline

- Introduction
- Measurement methodology
- Determination of dV_b/dT
- Gain stabilization of Hamamatsu MPPCs
- Gain stabilization of KETEK SiPMs
- Gain stabilization of CPTA SiPMs
- Studies of afterpulsing
- Conclusions and outlook

Introduction

- The gain of SiPMs increases with bias voltage V_b and decreases with temperature T
- To operate SiPMs at stable gain, V_b can be readjusted to compensate for T changes
- This requires the knowledge of dV_b/dT, which is obtained from measurements of G vs V_b for different T to extract dG/dV and dG/dT and in turn dV/dT

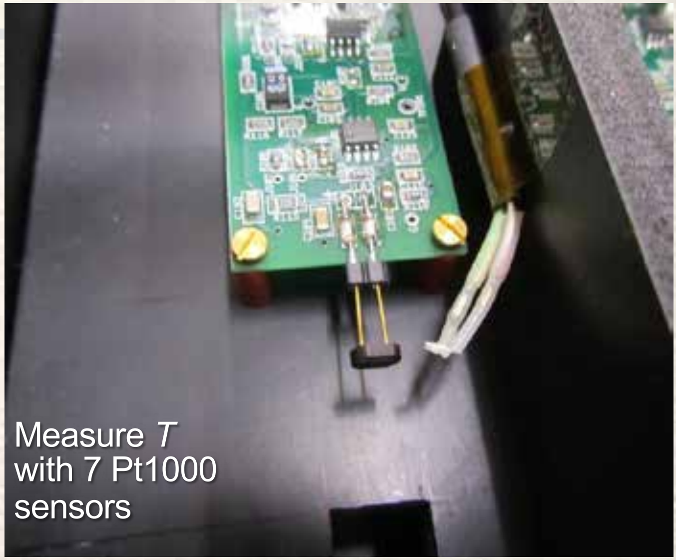


- Gain stability is important for large detector arrays such as an analog hadron calorimeter for ILC detector
- We tested this procedure in a climate chamber at CERN
  - 1.) For each of 30 SiPMs, we measured G vs V_b for different T to extract dV_b/dT from measurements of dG/dV_b and dG/dT
  - 2.) We performed gain stabilization of **30** SiPMs from Hamamatsu, KETEK & CPTA stabilizing 4 SiPMs simultaneously with one dV_b/dT compensation value
    ➔ perform automatic compensation with adaptive power supply

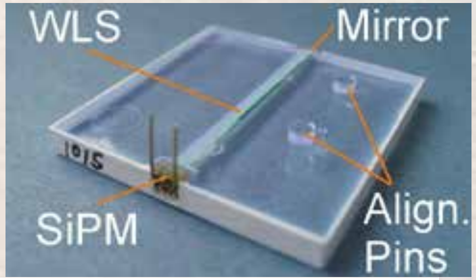
- Goal: **define stable gain if $\Delta G/G$ <±0.5% in 20°-30°C range**

Temperature Measurements

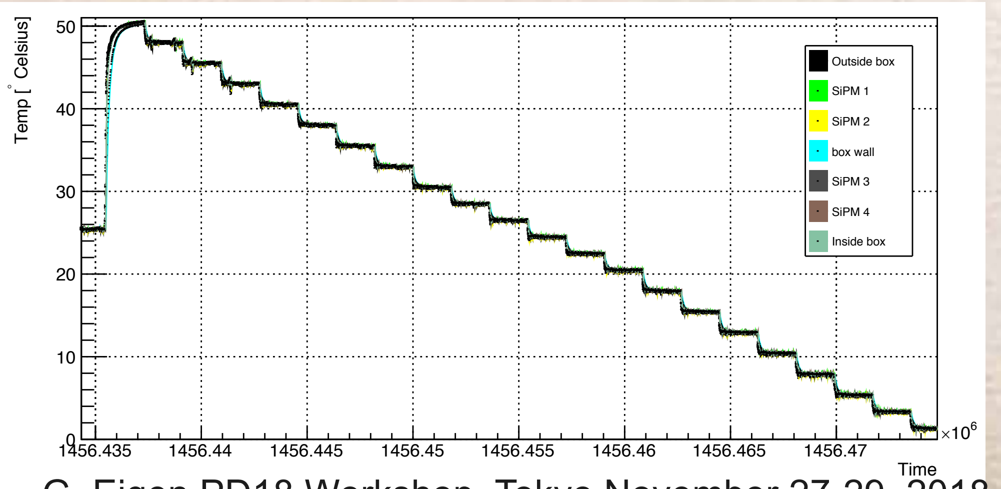
- We shine blue LED light of similar intensity via optical fibers on each SiPM
- At a rate of 10kHz, the light is pulsed using sinusoidal pulse above a fixed threshold; signal is 3.4 ns wide
- Each signal of the 4 SiPMs is recorded with a 12 bit digital scope after amplification by a 2-stage preamp
- Hamamatsu & KETEK SiPMs are illuminated directly

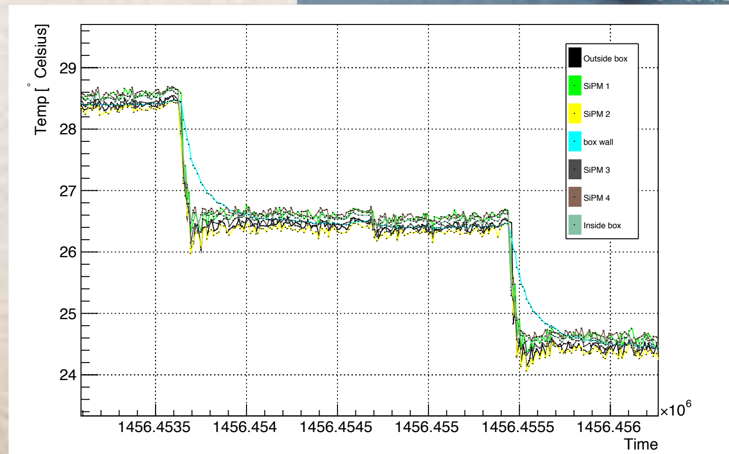


- CPTA sensors are glued to a WLS fiber placed in a groove in a scintillator tile
  ➔ light has to pass through the tile and WLS fiber



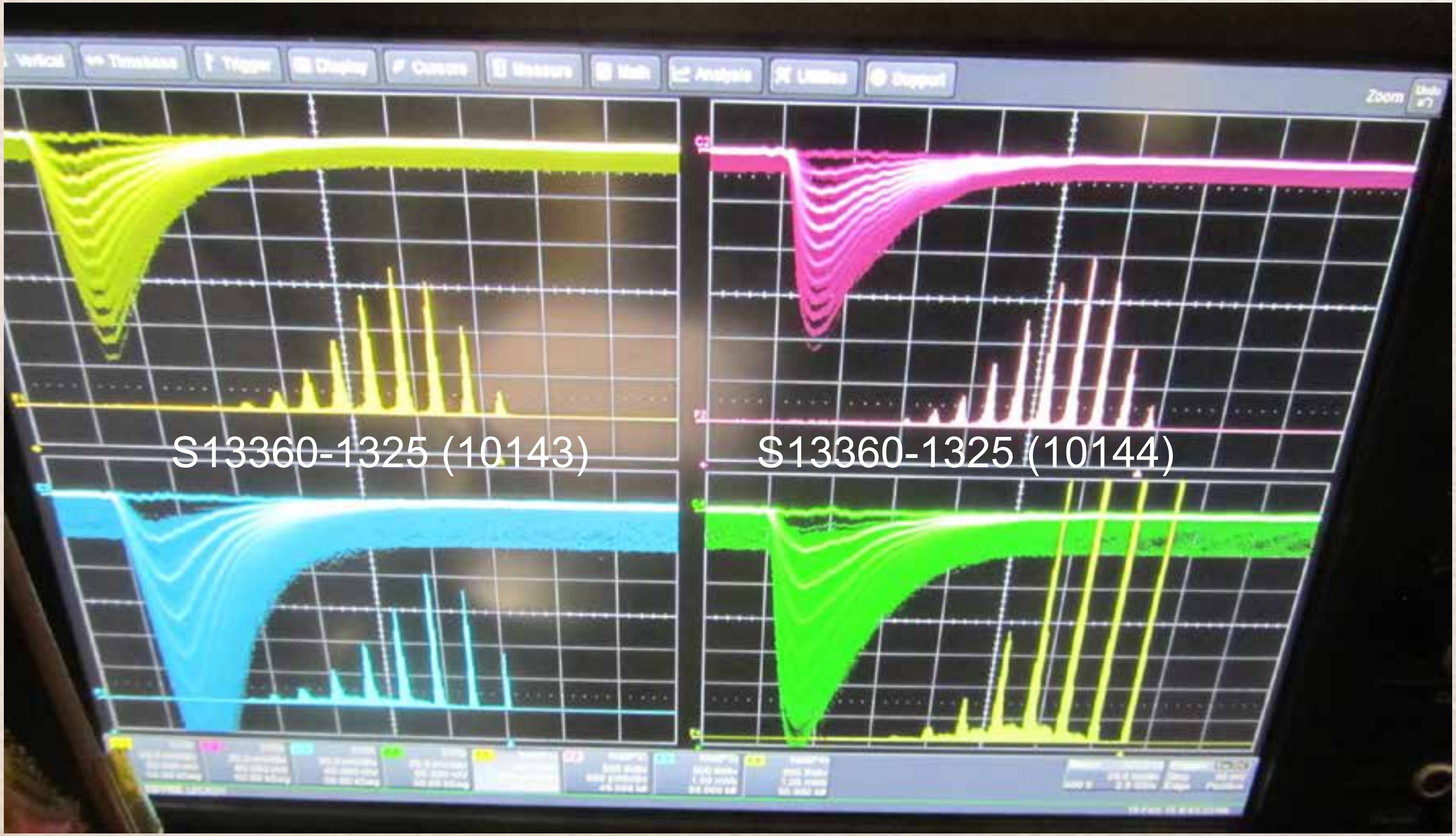
- Vary *T* from 48°-2°C (20°-30°C) in 2.5°C (2°C) steps
  - $T_{SiPM}=T_{set}$ ±0.5°C (ramp up/down); accuracy ~±0.2°C





Study of Hamamatsu MPPCs with Trenches

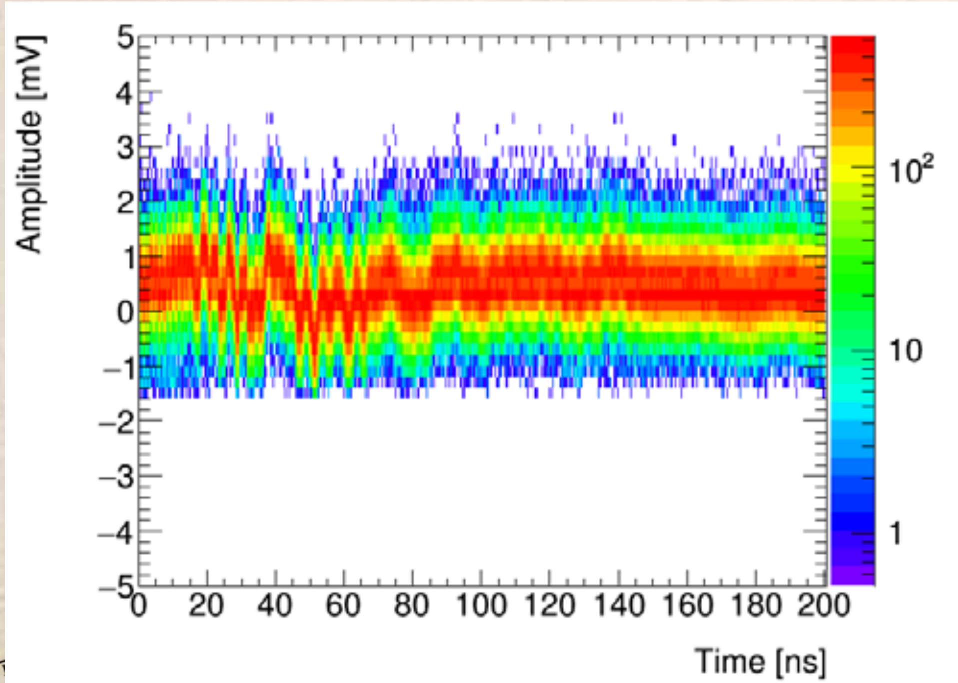
- Waveform and photoelectron spectra of 4 S13360 MPPCs (trenches)
- S13360-3025 (10103) S13360-3025 (10104)

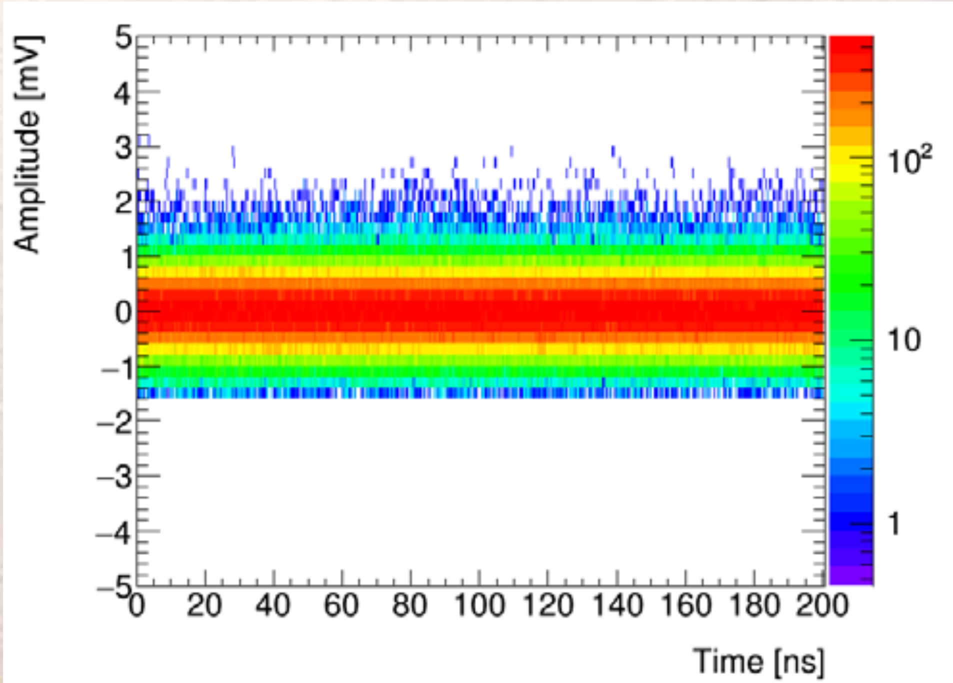


- S13360-1325 (10143) S13360-1325 (10144)

Removal of Parasitic Noise Signal

- We remove a parasitic noise signal caused by a defective light pulser cable
- First, we sample 21 points before the signal waveform starts (8.4 ns)
- We fit the distribution with a Gaussian function and define a threshold by $\mu - 3\sigma$
- We select all pedestal distributions that lie above the threshold
- We determine the average and subtract it from all waveforms

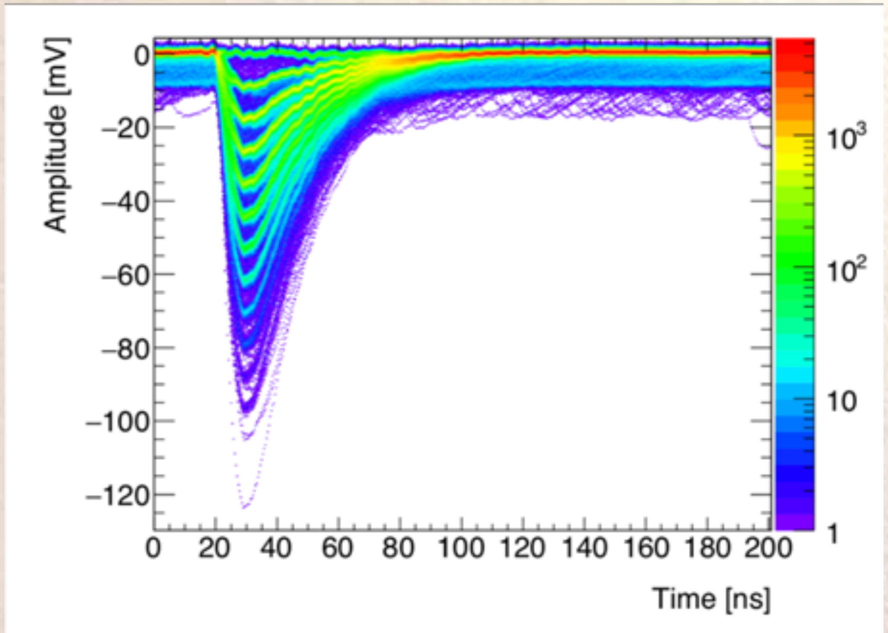




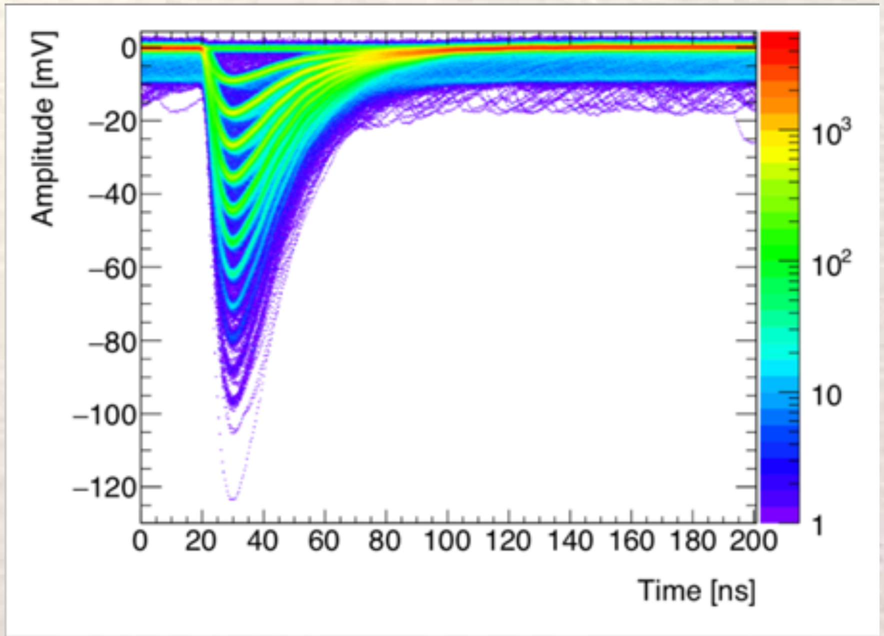
Removal of Parasitic Noise Signal

- Removing the parasitic noise signal improves the shape of the waveforms
- This, in turn, improves the determination of the peak positions

Before parasitic noise removal



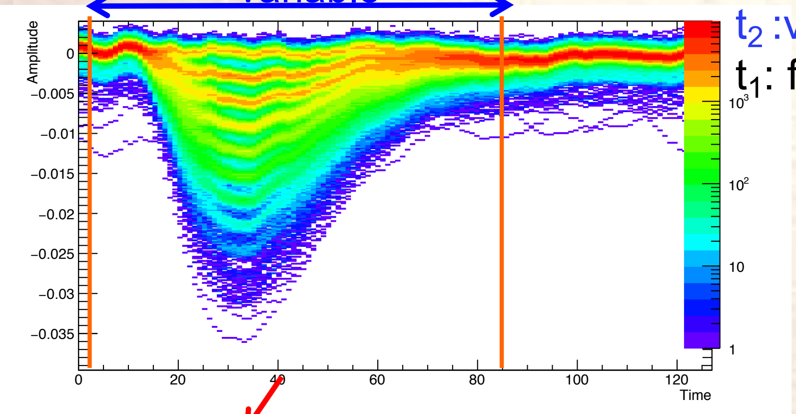
After parasitic noise removal

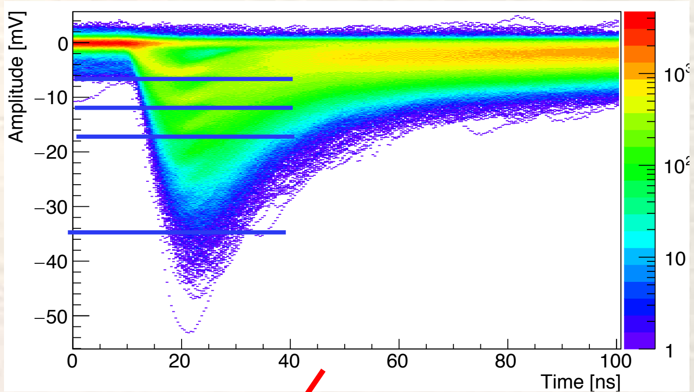


- We then extract the photoelectron spectra using 2 methods
  - Integrate waveform over variable time window (fixed start, variable end)
  - Determine minimum of the waveform

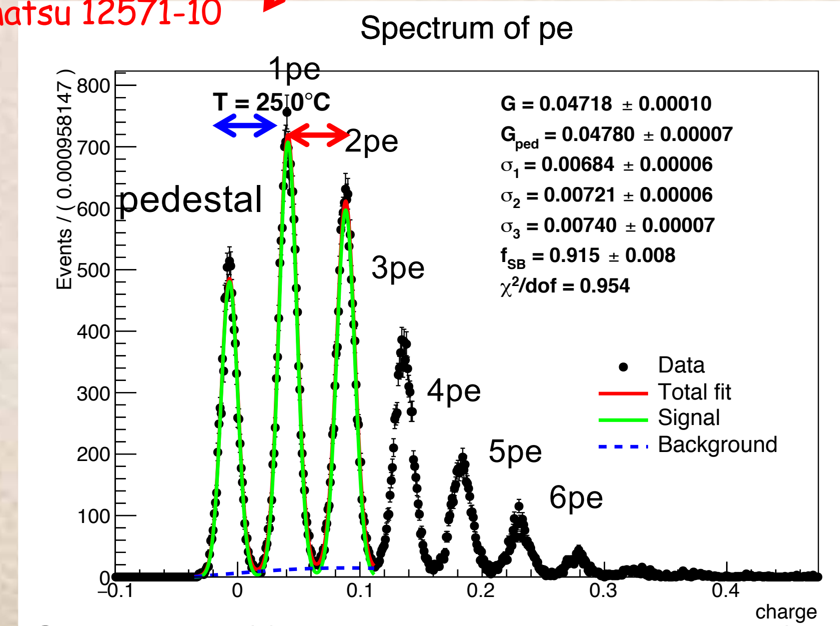
2 Methods to Extract Photoelectron Spectra

- We take 50000 waveforms at each V_b and T point and store them for offline analysis
- Integrate each waveform over t_2-t_1 window ➔ total charge, see integer # of pe
- Determine minimum of waveform amplitude ➔ A_{peak}, typically see integer # of pe



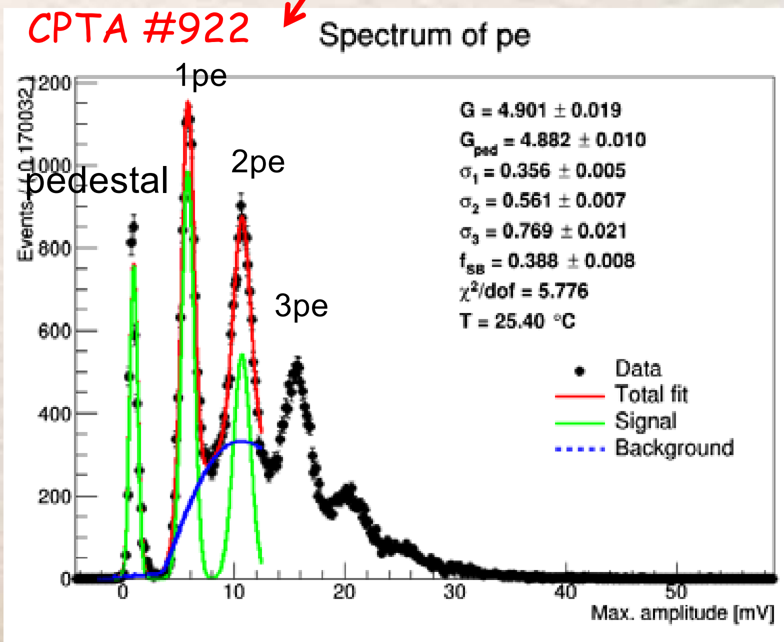


Hamamatsu 12571-10



T=25°C

CPTA #922



Gain Determination

- **Gain: distance between two adjacent photoelectron peaks**
- We choose distance between first and second photoelectron peaks
- Distance between pedestal and first photoelectron peak yields the same gain
- We fit the photoelectron spectra extracted from 50000 waveforms with a 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

- We use two different fit models

$$F_{sig} = f_{ped} G_{ped} + f_1 G_1 + \left(1 - f_{ped} - f_1\right) G_2$$

  - First model:
    separate Gaussian G_i for pedestal, first p.e. & second pe peaks and fractions f_{ped}, f_1; include background F_{bkg} determined by a sensitive nonlinear iterative peak-clipping algorithm (SNIP) available in ROOT
  - Second model:

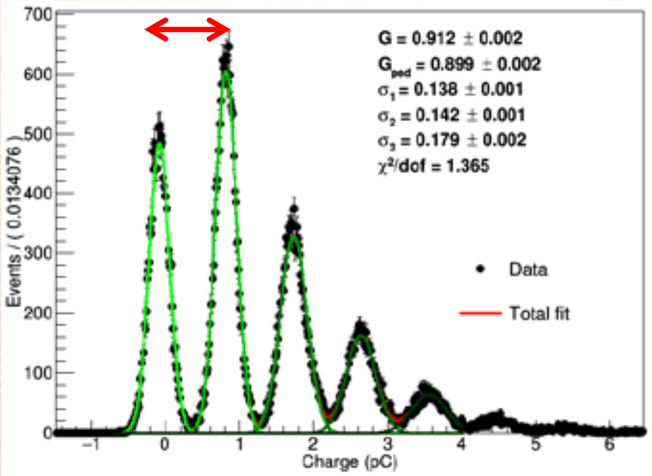
$$F_{sig} = f_{ped} G_{ped} + \sum_{i=1}^{n-1} f_i G_i + \left(1 - f_{ped} - \sum_{i=1}^{n-1} f_i\right) G_n$$

➔ fit pedestal and all visible peaks with Gaussians G_{ped} and G_i, where all widths and fit fractions are kept as free parameters, use no background pdf

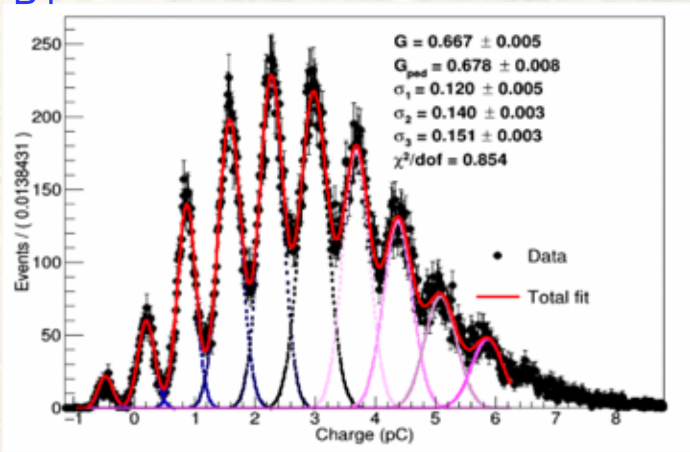
Two Fit Models

- First fit model | Second fit model

Hamamatsu S12571

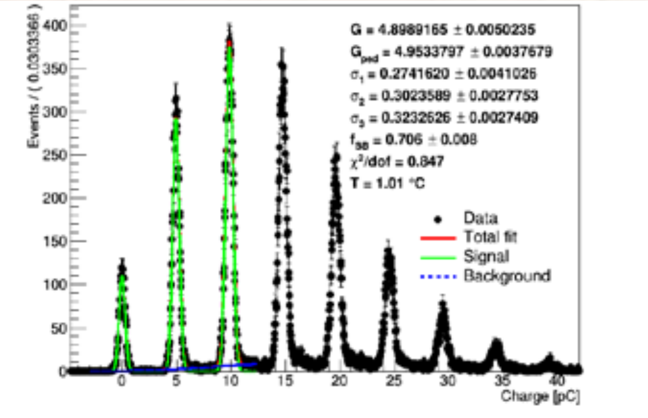


Hamamatsu B1



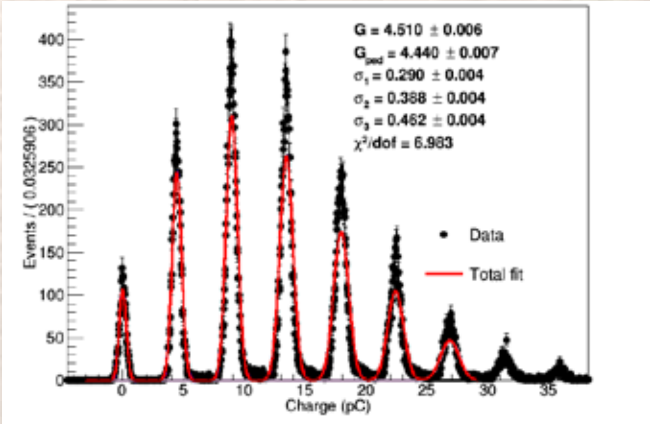
- Use first fit model for bias voltage scans of all SiPMs and gain stability tests of Hamamatsu MPPCs with trenches

Hamamatsu S13360 with fit model 1



Second fit model yields poor fits without modeling of tails on right-hand side

Hamamatsu S13360 with fit model 2

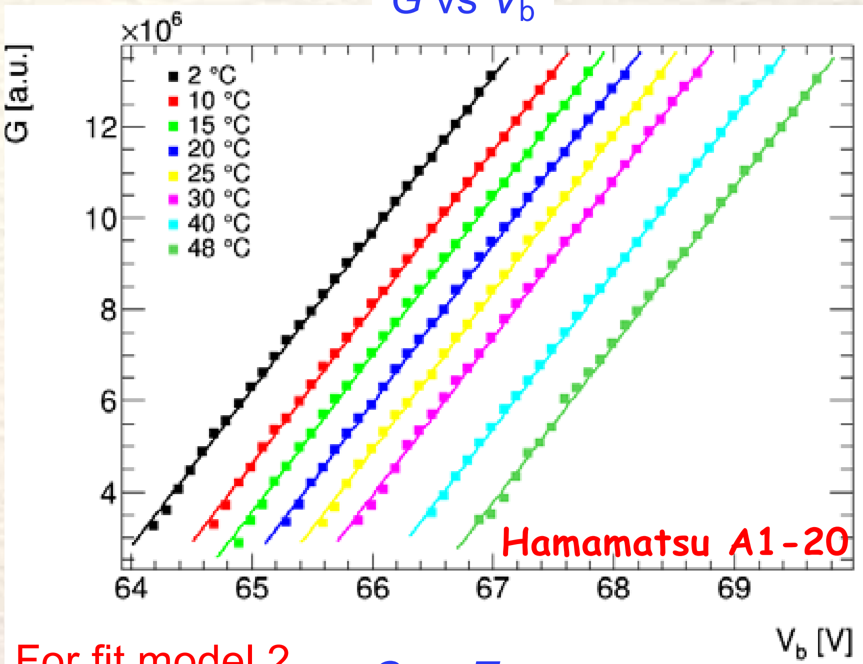


- Use second fit model for gain stability tests of all Hamamatsu MPPCs without trenches, all KETEK and CPTA SiPMs, for bias voltage scans of some MPPCs without trenches

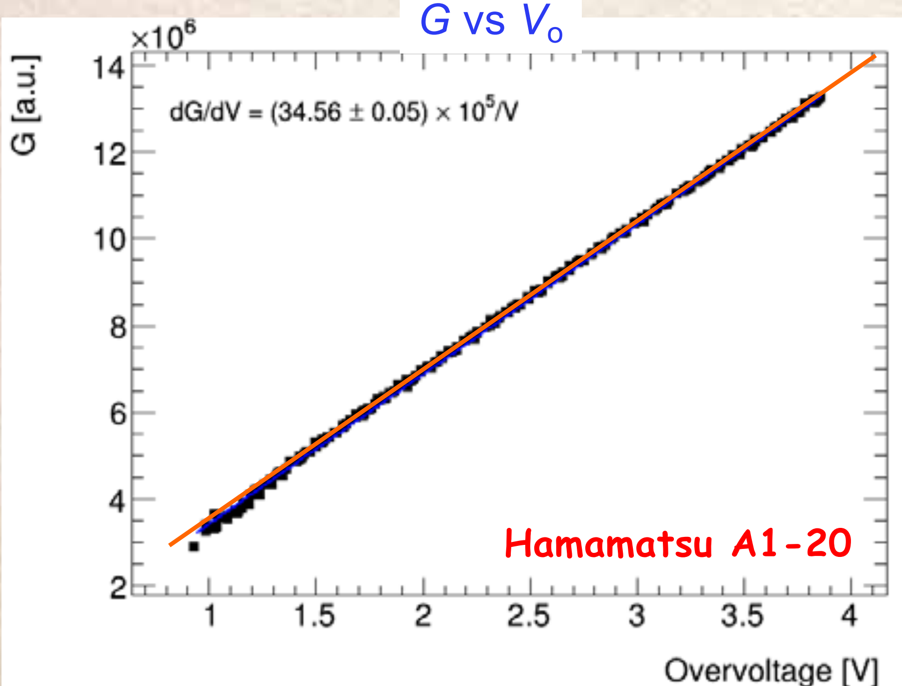
Measurement of *G* versus V_b and *T*

- We explore the 2°C-48°C temperature range
- At different fixed ***T***, we measure ***G*** vs V_b
  ➔ at each point we take 50k waveforms
- The dependences ***G*** vs V_b for each ***T*** and ***G*** vs ***T*** for each V_b are linear with similar slopes
- Plotting ***G*** vs overvoltage V_o shows that for V_o>1.5 V all gains show a linear dependence on V_o independent of *T*

G vs V_b

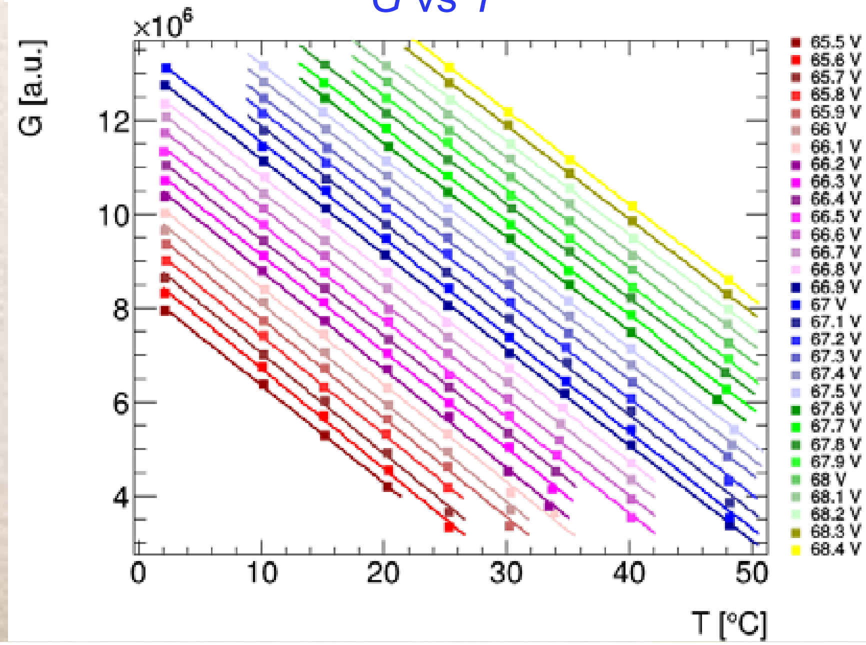


G vs V_o



For fit model 2

G vs *T*



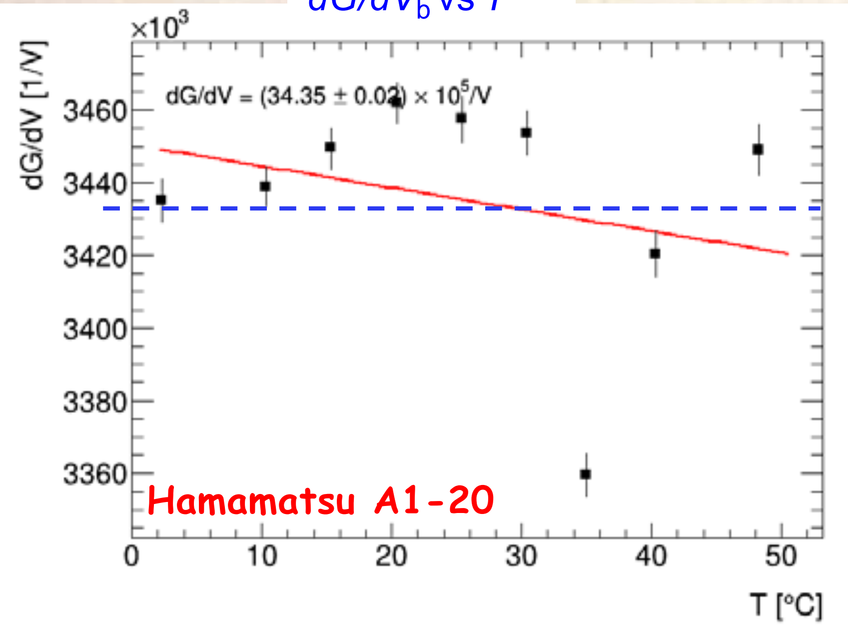
Determination of dG/dV_b and dG/dT

- We perform a simultaneous fit of G versus V_b and T to extract dG/dV_b and dG/dT

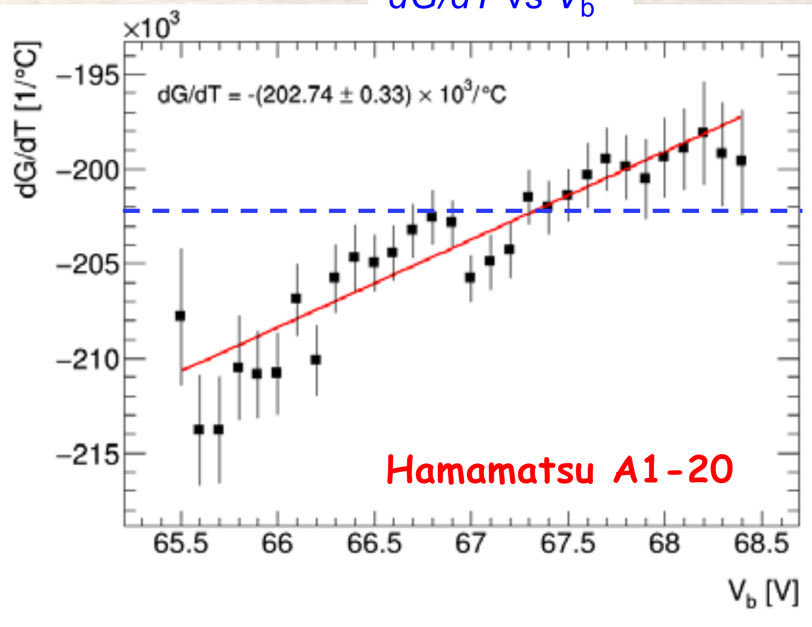
$$G = G(V_0,T_0) + \frac{dG(V_b,T)}{dV_b}((V - V_0)) + \frac{dG(V,T)}{dT}((T - T_0))$$

- We use fit model 2; we get consistent results with fit model 1
- We take averages for dG/dV_b and dG/dT; deviations from uniformity are < 2%

dG/dV_b vs T



dG/dT vs V_b



- $dG/dV_b = (34.35 \pm 0.1) \times 10^5/V$
- $dG/dT = -(2.0274 \pm 0.0033) \times 10^5/°C$

Determination of dV_b/dT

- We calculate dV_b/dT from dG/dT and dG/dV_b

$$\frac{dV_b}{dT} = \frac{dG(V_b,T)/dT}{dG(V_b,T)/dV_b}$$

- We determine

dV_b/dT=(59.1±0.1) mV/°C

- The error includes the covariance of (dG/dV_b,dG/dT)

- From the breakdown voltage V_{break} vs T we extract

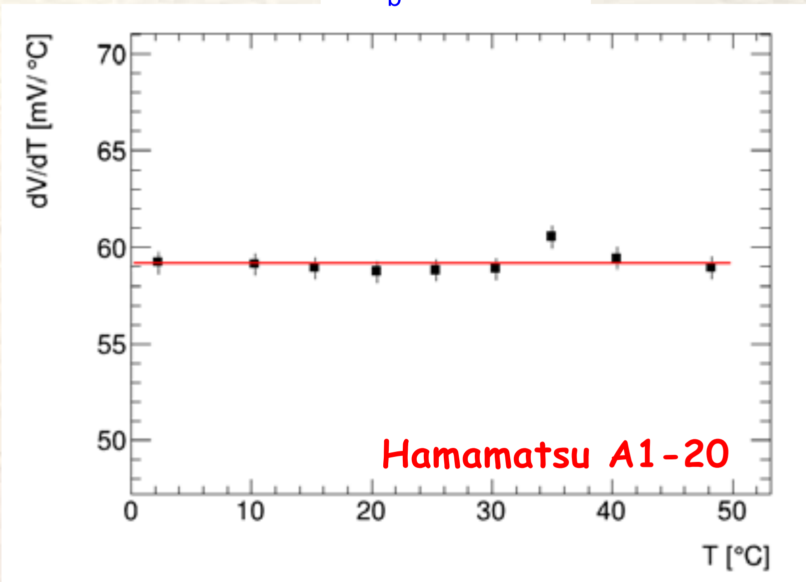
dV_b/dT=(58.7±0.3) mV/°C

- For stabilization of Hamamtsu type A MPPCs we used **dV_b/dT=59.0 mV/°C**

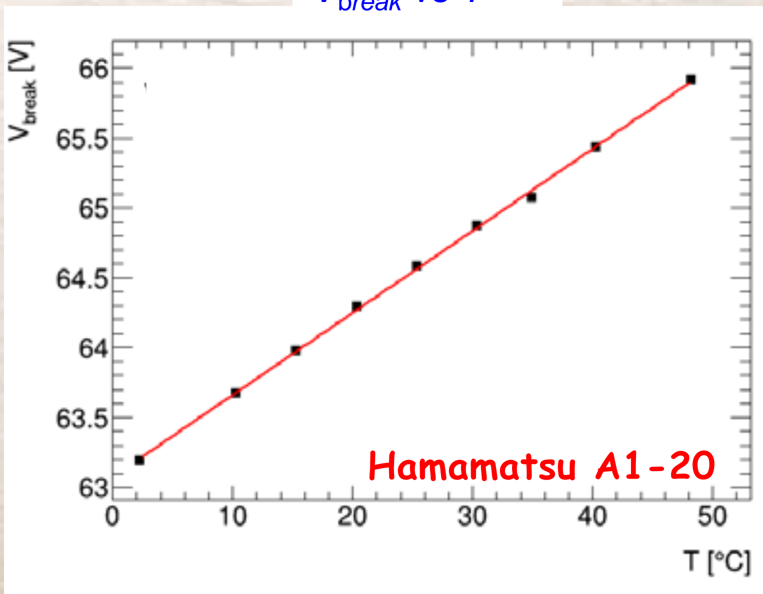
- The breakdown voltage increases linearly with T ➔ dV_b/dT

- The $V(T)$ dependence can be calculated analytically (see backup slides)

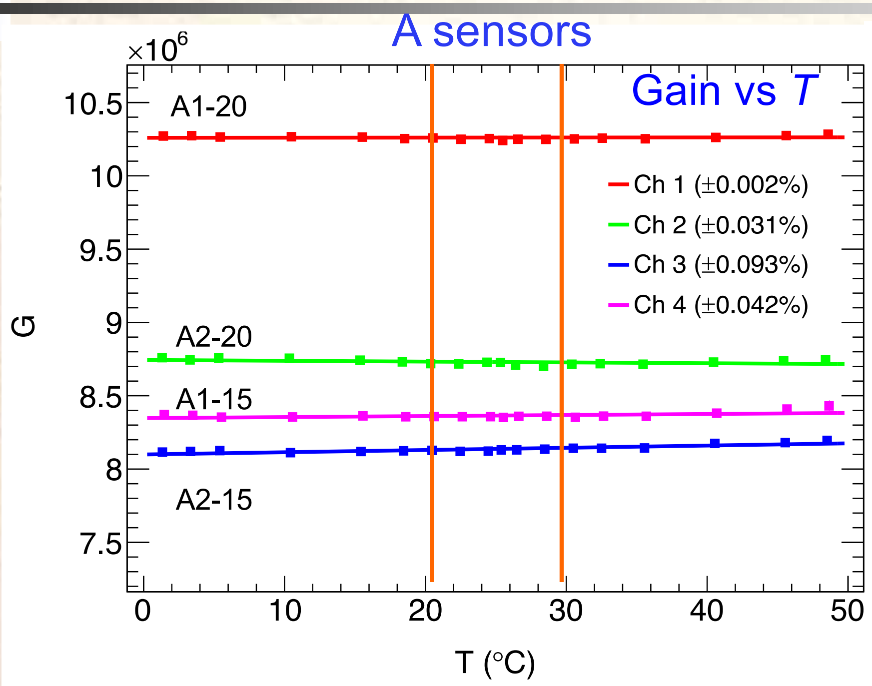
dV_b/dT vs T

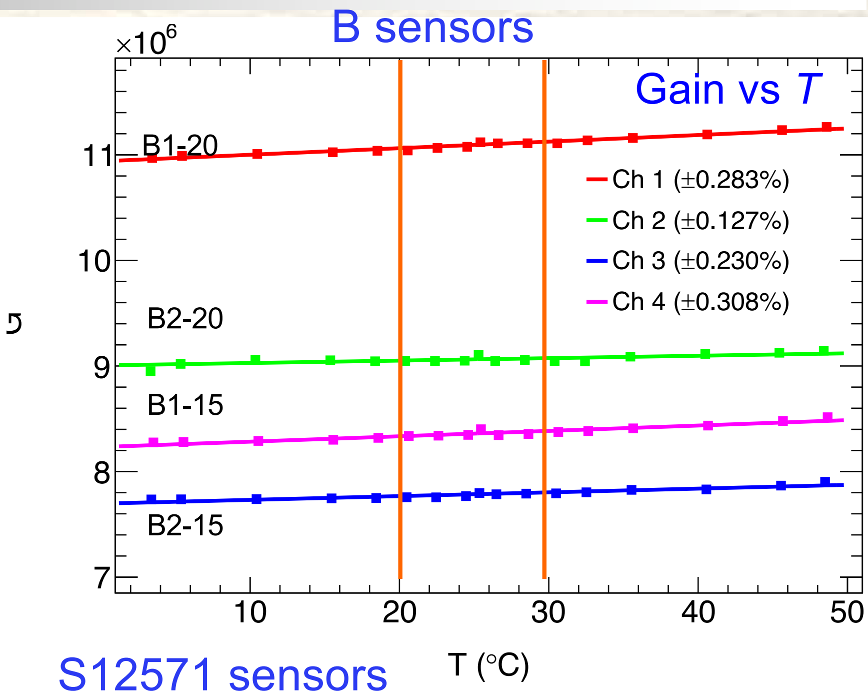


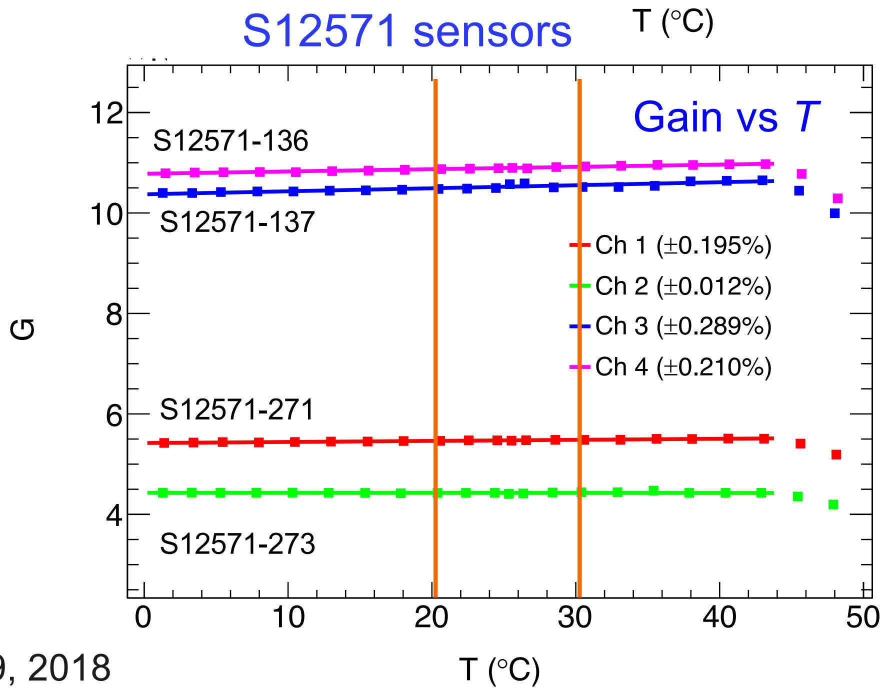
V_{break} vs T



Gain Stabilization: Hamamatsu MPPCs w/o Trenches



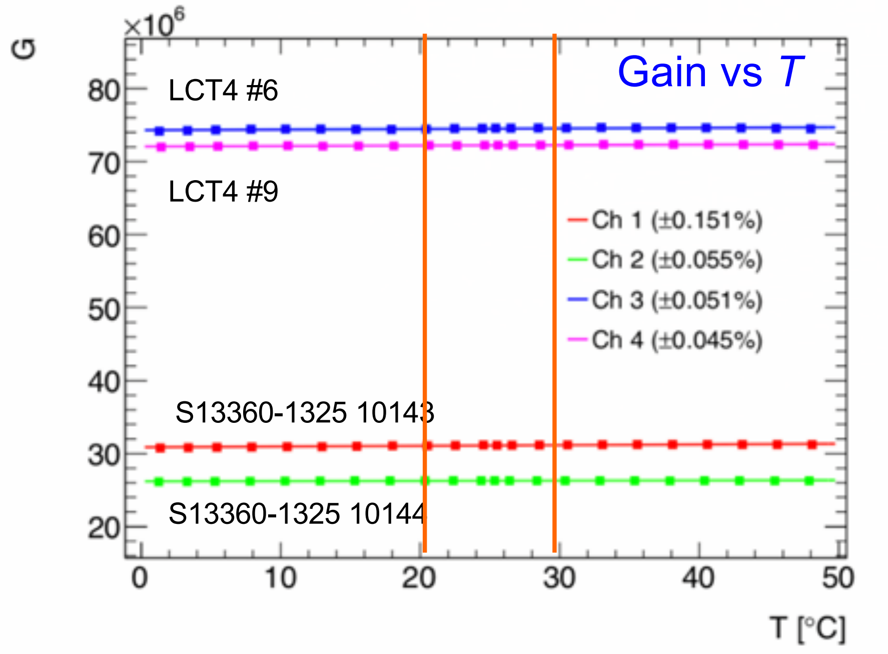




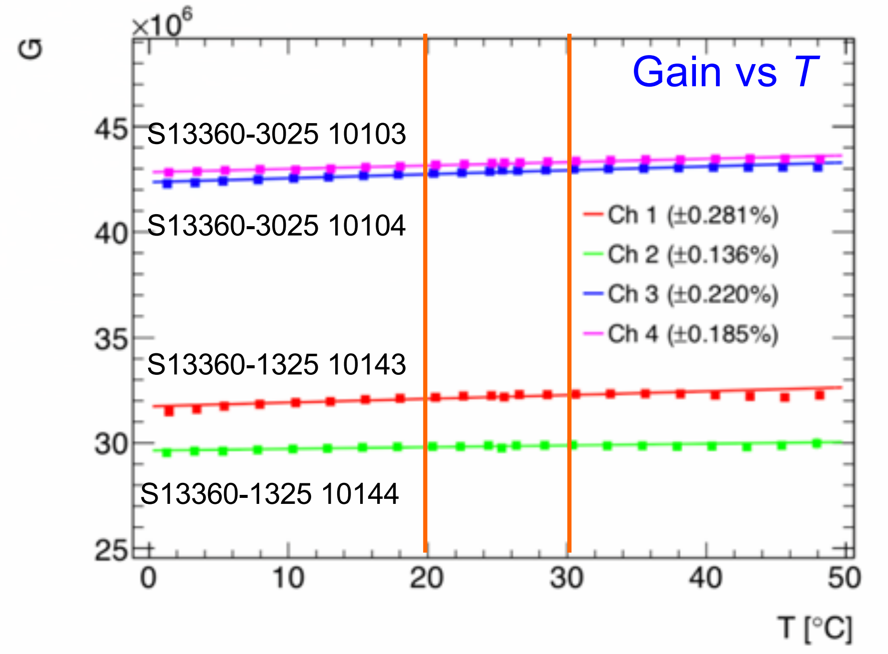
- Fit p.e. spectra of all MPPCs without trenches with **fit model 2**
- All 12 MPPCs satisfy our requirement of ***ΔG/G <±0.5%*** in 20° –30°C *T* range
- Some MPPCs satisfy this requirement In the entire *T* range 2° – 48°C

Gain Stabilization: Hamamatsu MPPCs w Trenches

S13360-1325 & LCT4 sensors



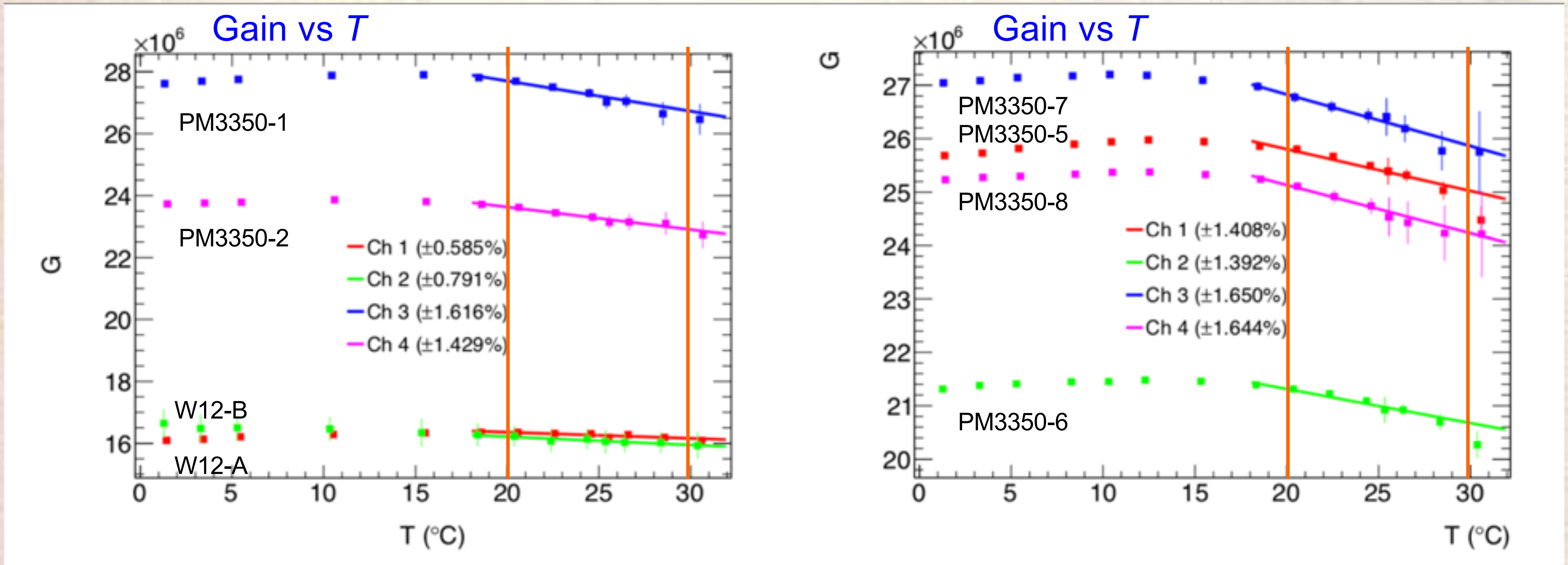
All S13360 sensors



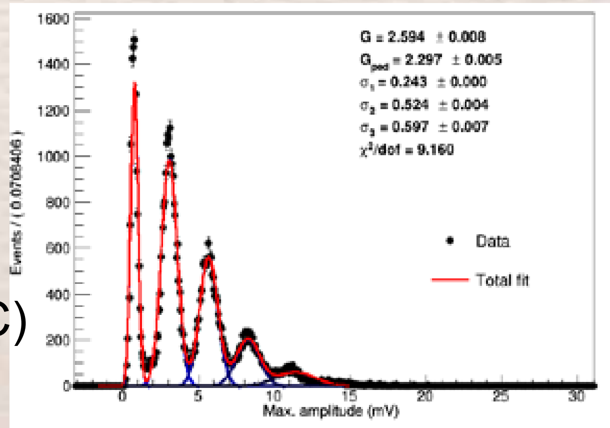
- Fit photoelectron spectra of all MPPCs with trenches with **fit model 1**
- All 6 MPPCs satisfy our requirement of ***ΔG/G <±0.5%*** in 20° –30°C *T* range
- Both LCT4 and some S13360 sensors satisfy ***ΔG/G <±0.5%*** in 2° – 48°C *T* range

Gain Stabilization of KETEK SiPMs

- Simultaneous gain stabilization for 4 KETEK SiPMs in two batches: ***dV_b/dT*=18.2 mV/°C**



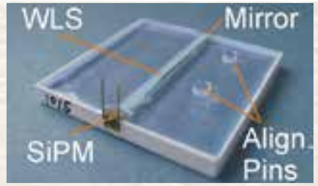
- Fit all photoelectron spectra with fit model 2



- KETEK SiPMs show more complicated V(T) behavior
  - ➔ linear correction is not sufficient
  - ➔ sensors do not function properly above 30°C
  - ➔ *G* rises (1-18°C); uniform *G* (18-22°C); *G* falls off (22-30°C)
  - ➔ due to this complicated V(T) behavior, ***dV_b/dT*~ 21 mV/°C**

- Thus, no SiPM satisfies the **<±0.5%** requirement for *T*=20° –30°C range

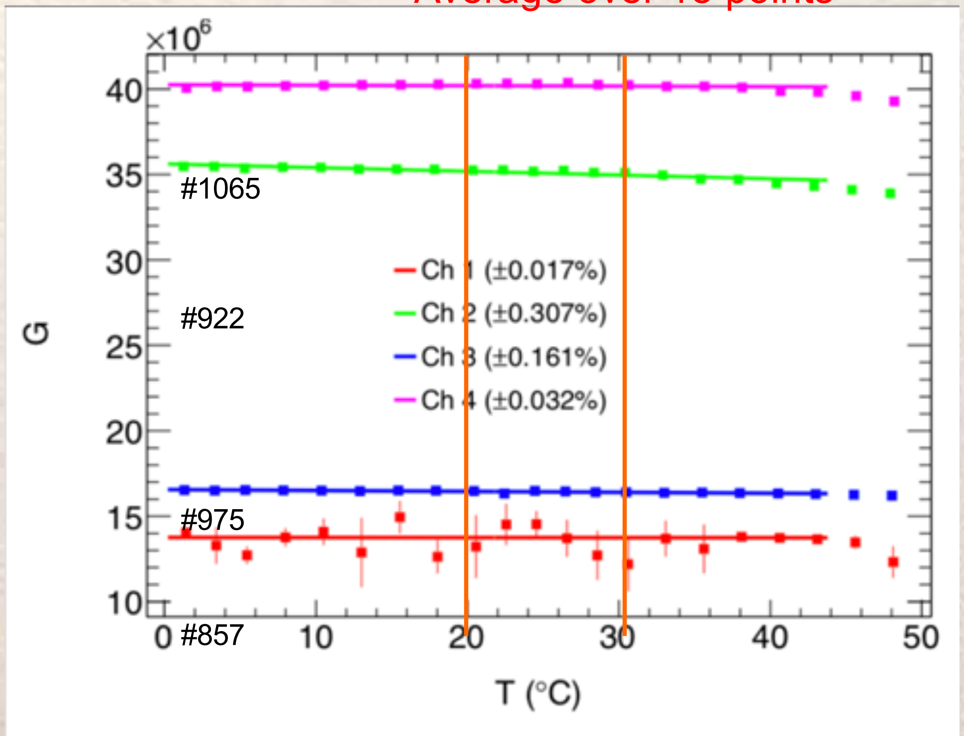
Gain Stabilization of CPTA SiPMs

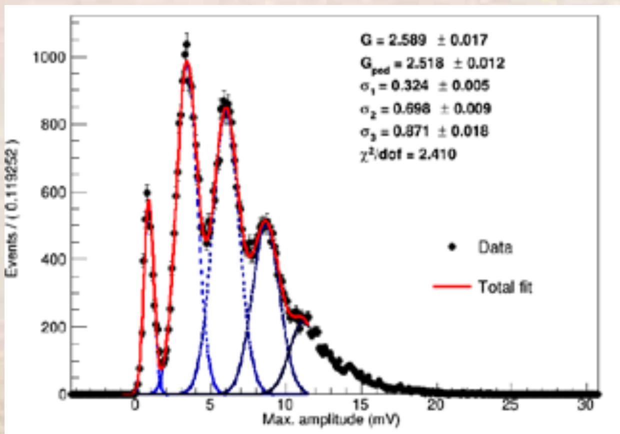


- CPTA SiPMs are illuminated via scintillator tile
- We adjust V_b with regulator board using dV_b/dT=21.2 mV/°C to stabilize 4 CPTA SiPMs simultaneously
- We test gain stability within T=2°- 48°C taking ≥ 18 samples of 50k waveform samples at each T
- The gain is nearly uniform up to 30°C
- SiPMs in ch#2 and ch#4 look fine; ch#1 is noisy, ch#3 changed gain at T=45°C but looks ok
- All 4 SiPMs satisfy our requirement of **>±0.5%** within 20°C -30°C T range

Gain vs T

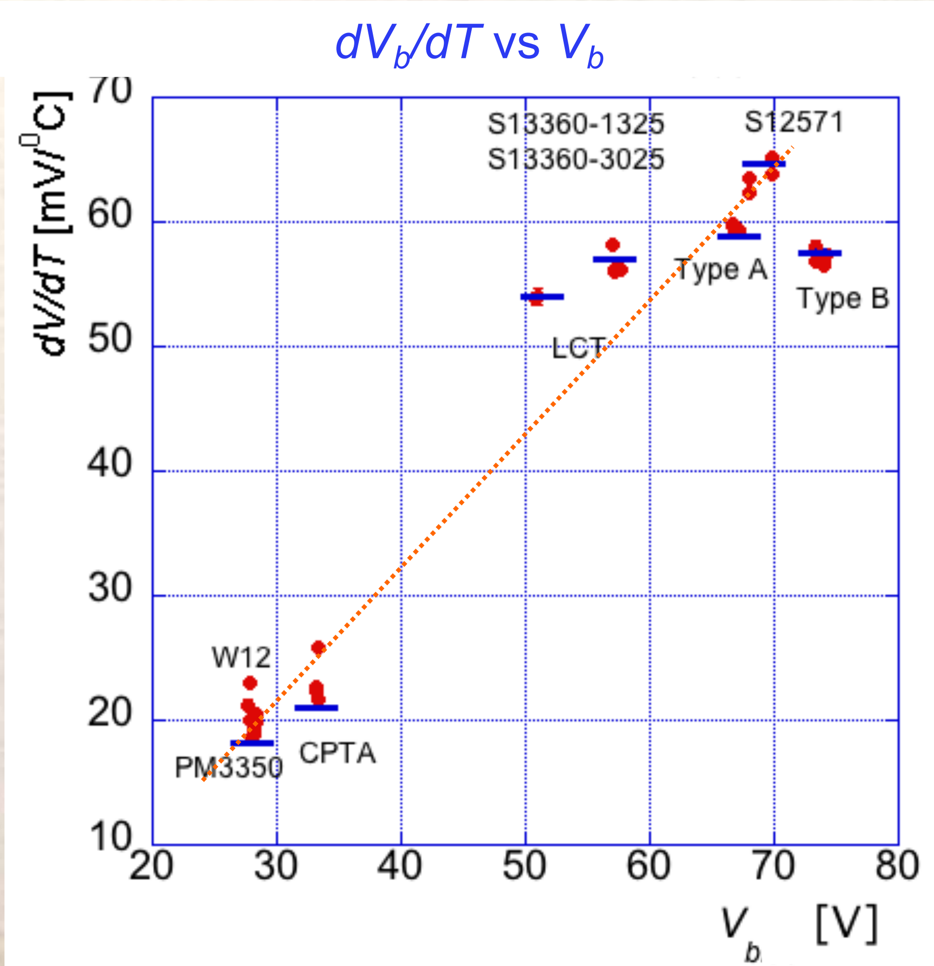
Average over 18 points





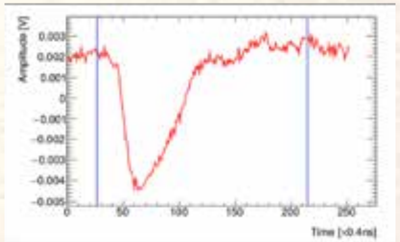
Measured dV_b/dT Values versus V_b

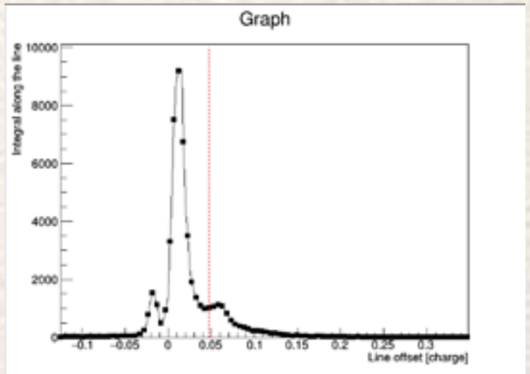
- Look for correlations between operating voltage and measured dV_b/dT for all SiPMs
- For most SiPMs dV_b/dT increases linearly with V_b
- Exceptions:
  - Hamamatsu B type MPPCs
  - Hamamatsu MPPCs with trenches
  - ➔ They have lower V_b for similar dV_b/dT
- KETEK & CPTA SiPMs have larger dV_b/dT spread than Hamamasu MPPCs without trenches



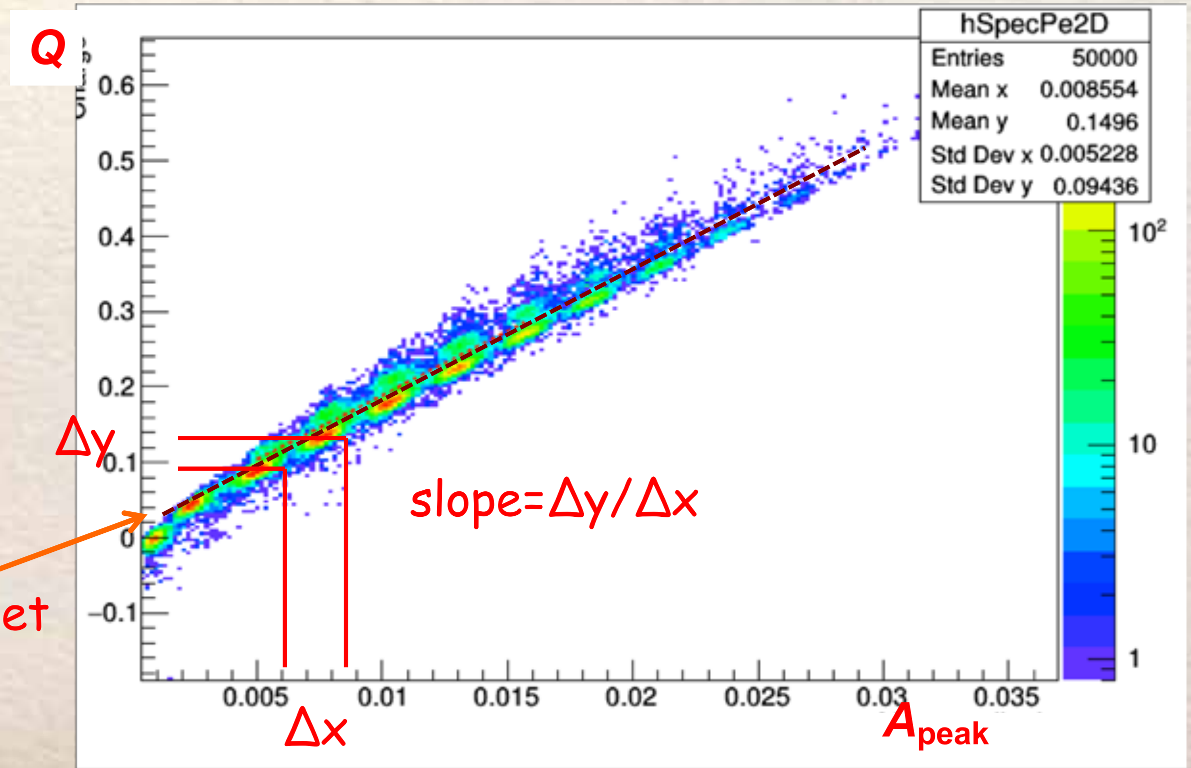
Does Afterpulsing affect Gain Stabilization?

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





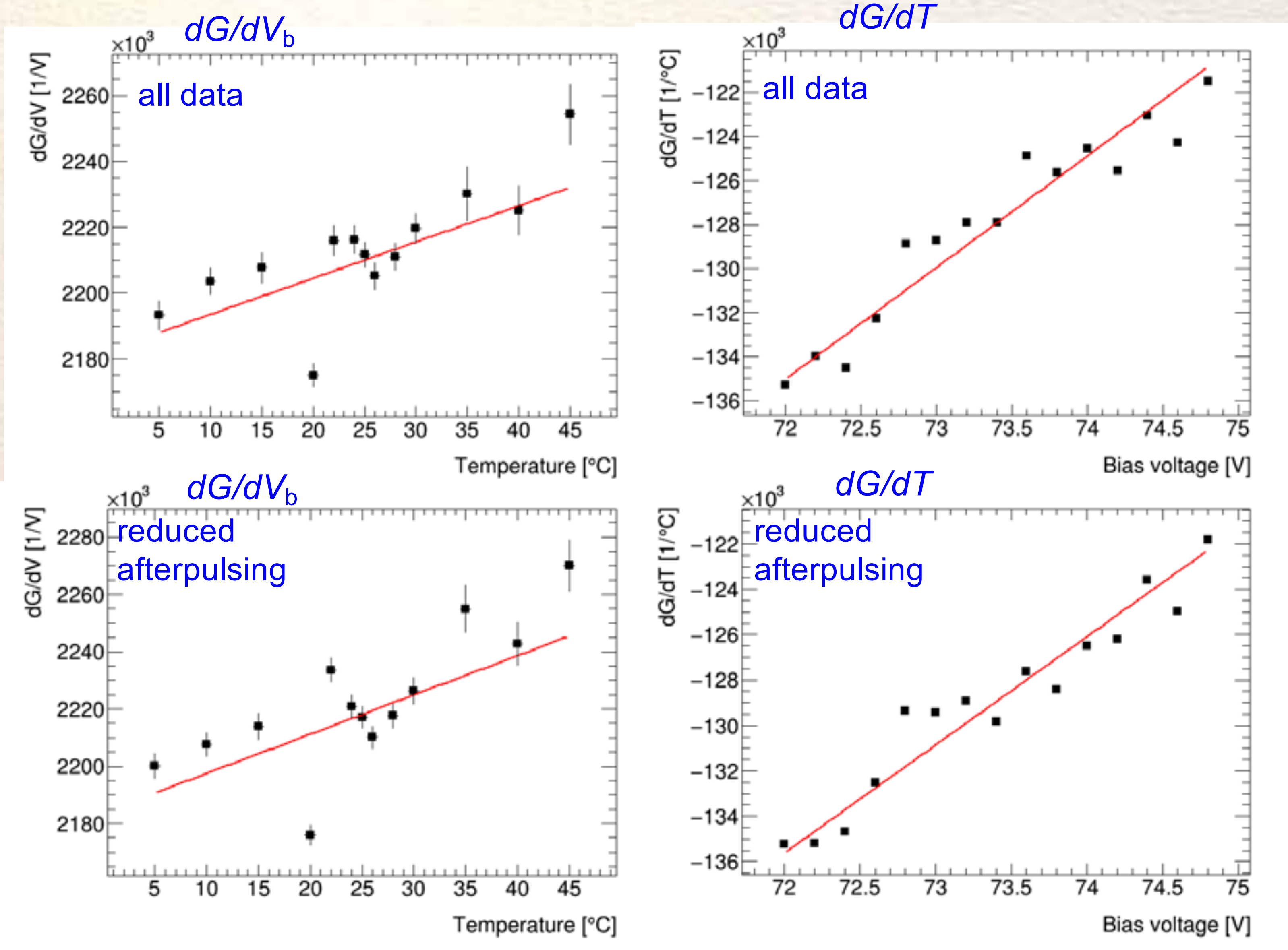
- We analyze the scatter plot of ***Q*** versus A_{peak}
- Signal without afterpulsing lies on the diagonal
- Signal with afterpulsing is shifted upwards since wave-form is broadened due to delayed secondary signal
- Set slope with 2pe & 3pe peaks
- Dashed line is chosen to be in valley between the 2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



dG/dV_b and *dG/dT* for Reduced Afterpulsing

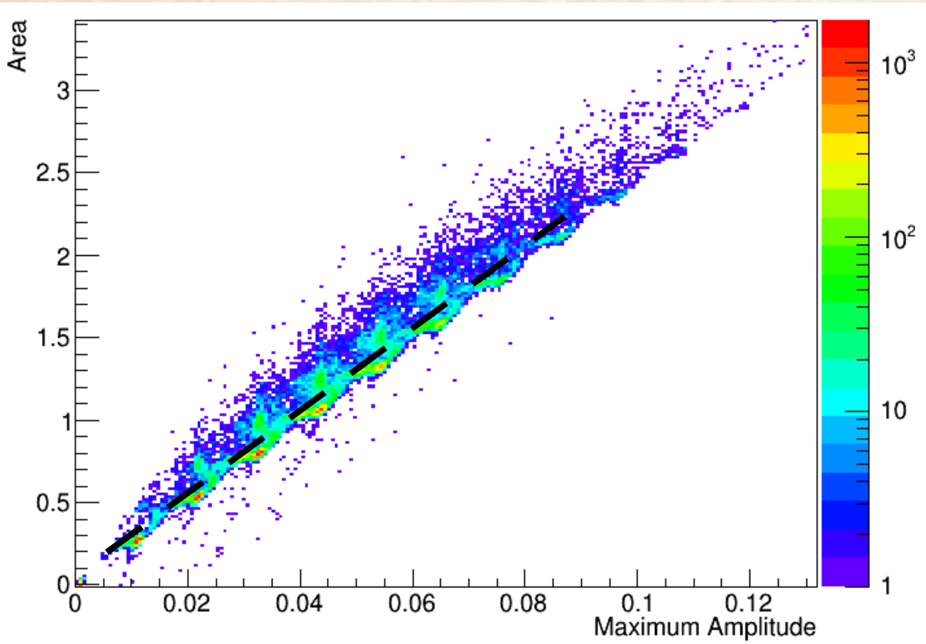
- The *dG/dV_b* & *dG/dT* distributions for sample with reduced afterpulsing look look similar as those for all data

- Within errors get the same fit results ➔ visually slopes of red lines are the same

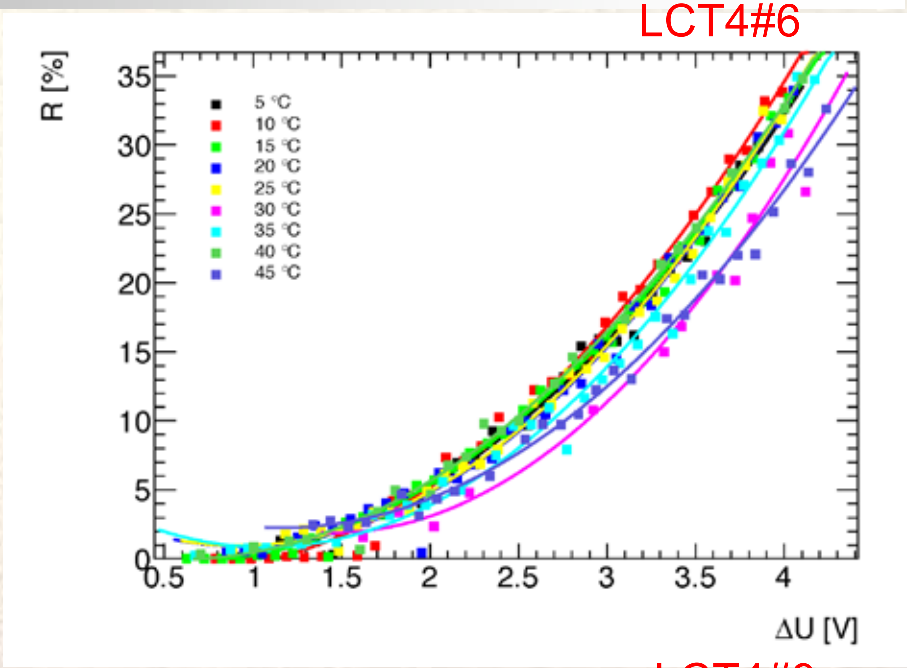


Afterpulsing of LCT4 MPPCs

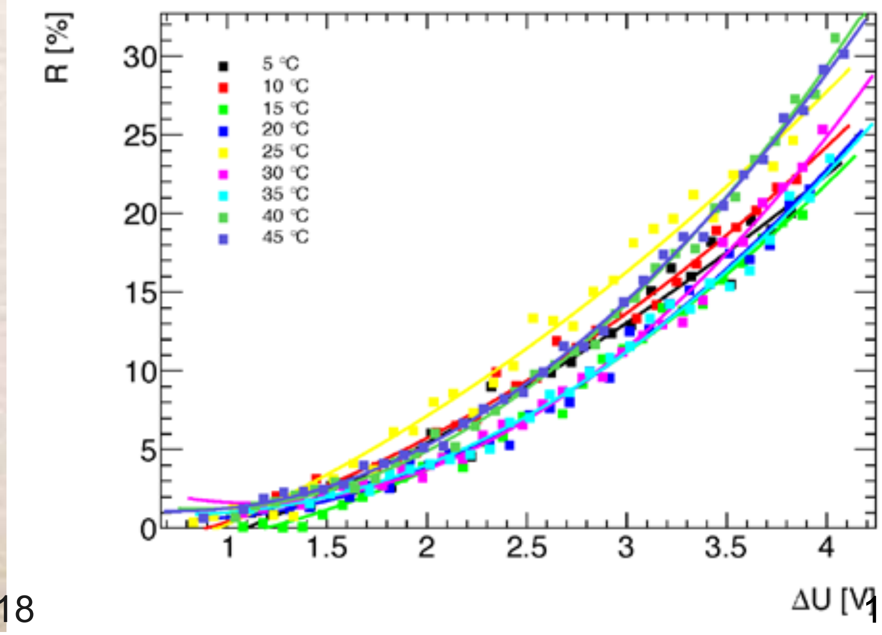
- Define afterpulsing
  R=events above dashed line/all events
- Study R as a function of V_b for each T
- R shows rapid increase with V_b
- R shows no explicit T dependence (T>0°C)
  ➔ Spread may indicate systematic effects of procedure



LCT4#6



LCT4#9



Conclusion and Outlook

- We successfully completed gain stabilization tests for 30 SiPMs and demonstrated that batches of similar SiPMs can be stabilized with **one** ***dV_b/dT*** compensation value
- All 18 Hamamatsu MPPCs satisfy the stabilization goal: ***$\Delta G/G < \pm 0.5\%$*** for T=20°C-30°C
  ➔ most MPPCs satisfy ***$\Delta G/G < \pm 0.5\%$*** in the extended *T* range 2°C-48°C
- Gain stabilization of KETEK SiPMs is more complicated
  - Range of stabilization is limited to 2°C-30°C *T* range
  - No SiPM satisfies our requirement ➔need individual ***dV_b/dT*** values
- Gain stabilization of CPTA SiPMs works fine
  ➔ for all 4 SiPMs, ***$\Delta G/G < \pm 0.5\%$*** is satisfied in 20°C-30°C range
- Afterpulsing does not affect gain stabilization results
- Afterpulsing strongly depends on overvoltage not temperature (T>0°C)
- Results are in the process of publication in JINST
- In the analog HCAL, *V_b* adjustment can be implemented on the electronics board
  ➔need array of temperature sensors to monitor *T* adequately in entire AHCAL

Acknowledgments

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- We thank Yamamoto-san for providing A, B and LCT4 sensors
- We further would like to thank the team of the climate chamber at CERN for their support

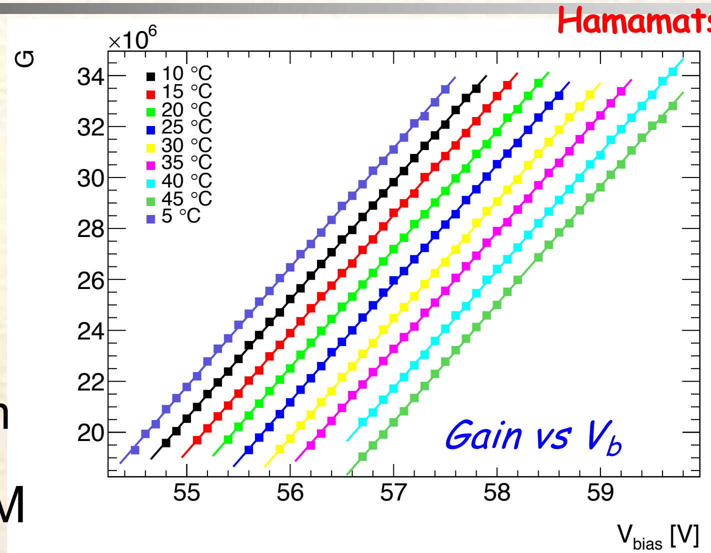
Backup

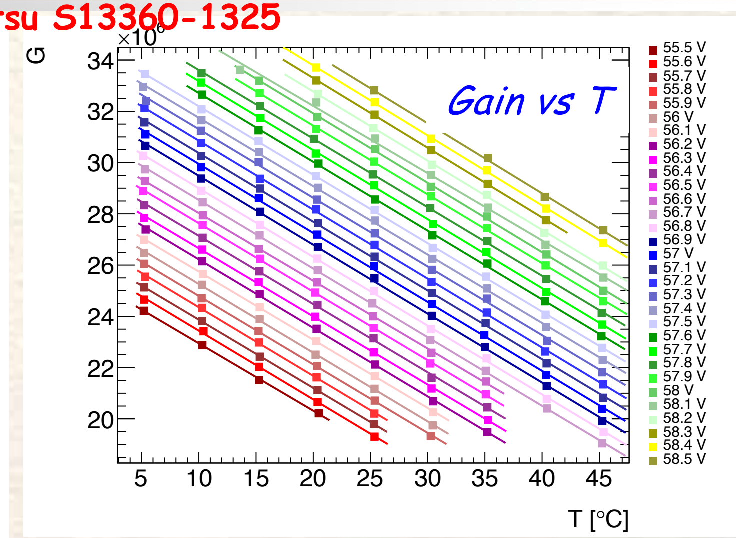
Slides

dG/dV_b, dG/dT & dV_b/dT Results for Fit Model 1

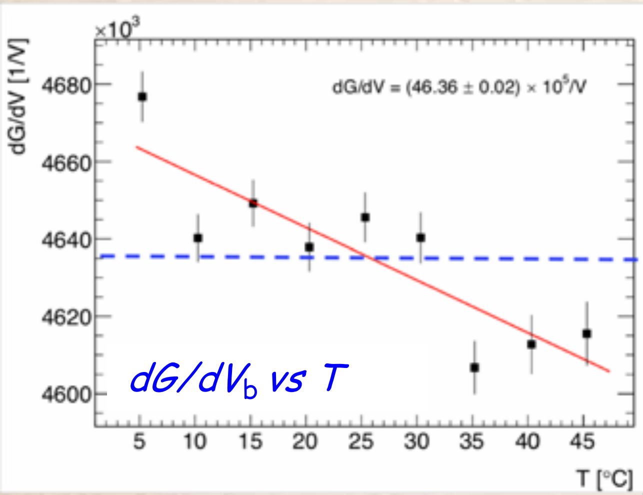
Hamamatsu S13360-1325

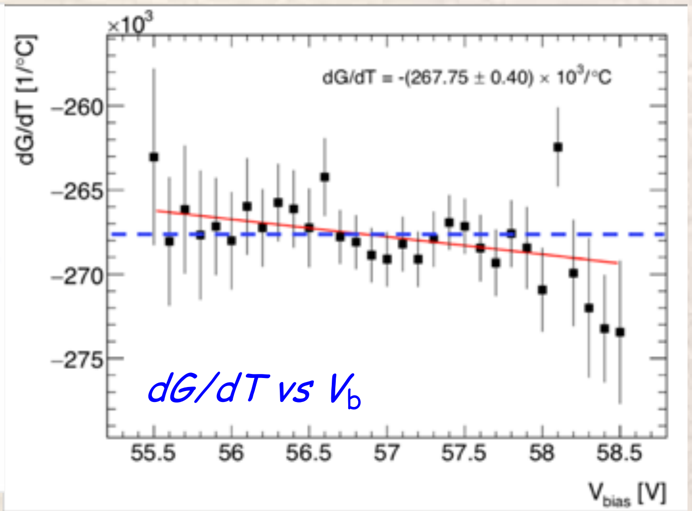
- For fixed T, measure *G vs V_b* ➔ *dG/dV_b*
- For fixed V_b plot *G vs T* ➔ *dG/dT*
- Extract all *dV_b/dT* for fixed T& average them
- Do this for each SiPM

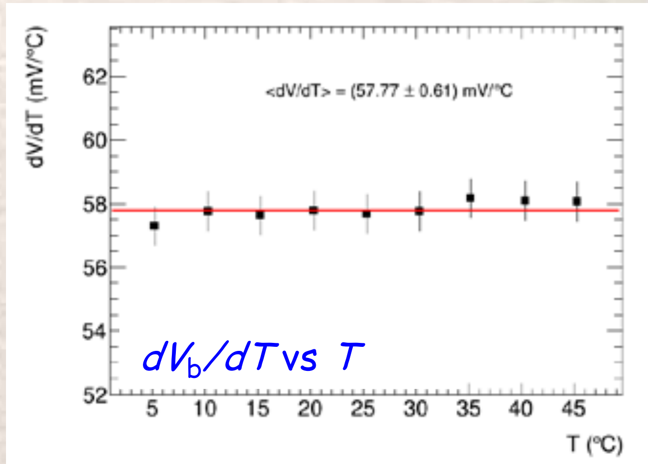




- Fit *dG/dV_b* and *dG/dT* with linear functions, use only constant (slope are small <1%)



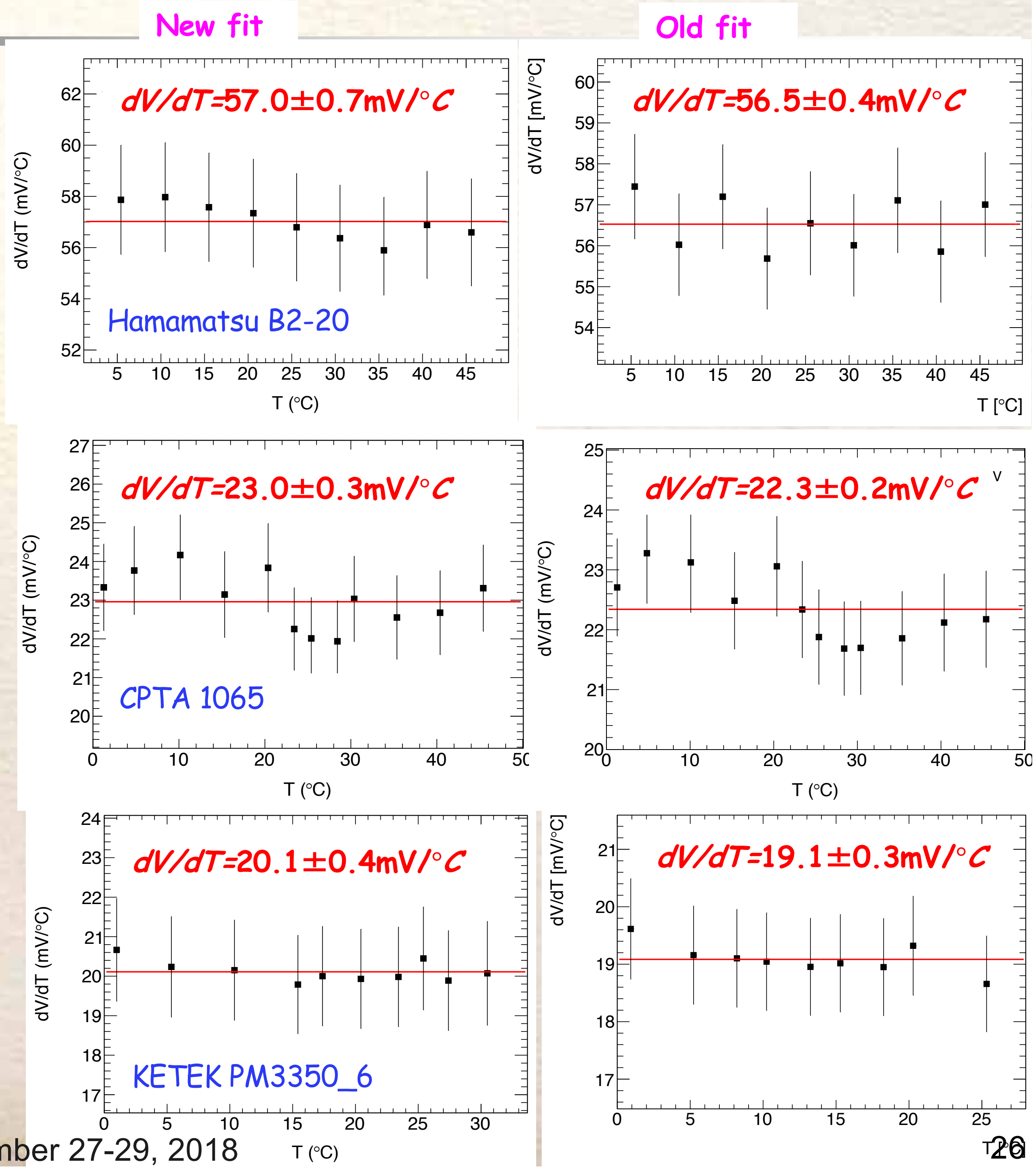




- ***$dG/dV=(46.36\pm0.02_{stat})\times10^5$/V***
- ***$dG/dT=(2.6775\pm0.004)\times10^5$/°C***
- ***$dV/dT=(57.8\pm0.1_{sys})$ mV/°C***

Comparision of the 2 Fitting Strategies

- We obtain the **same** dV/dT for Hamamatsu A, B & S12571 MPPCs within errors for both fitting strategies
- For KETEK and CPTA SIPMs we have tested the new fitting methodology on one channel so far
- For these two SiPMs, dV/dT values agree within two agree within 2 standard deviations
- We will do the remaining KETEK and CPTA SiPMs soon



SiPM Properties

- Test 18 Hamamatsu MPPCs (6 w trenches), 8 KETEK SiPMs and 4 CPTA SiPMs

SiPM	Serial#	Size [mm^2]	Pitch [μm]	#pixels	V_{bias} [V]	Gain [10^6]
Type A	A1	1×1	15	4440	67.22	0.2
Type A	A2	1×1	15	4440	67.15	0.2
Type A	A1	1×1	20	2500	66.73	0.23
Type A	A2	1×1	20	2500	67.7	0.23
Type B	B1	1×1	15	4440	74.16	0.2
Type B	B2	1×1	15	4440	73.99	0.2
Type B	B1	1×1	20	2500	73.33	0.23
Type B	B2	1×1	20	2500	73.39	0.23
S12571	271	1×1	10	10000	69.83	1.35
S12571	273	1×1	10	10000	69.87	1.35
S12571	136	1×1	15	4440	68.08	2.29
S12571	137	1×1	15	4440	68.03	2.30
LCT4	6	1×1	50	400	53.81	1.6
LCT4	9	1×1	50	400	53.98	1.6
S13360	10143	1.3×1.3	25	2668	57.18	0.7
S13360	10144	1.3×1.3	25	2668	57.11	0.7
S13360	10103	3×3	25	14400	57.6	1.7
S13360	10104	3×3	25	14400	56.97	1.7

SiPM	Serial#	Size [mm^2]	Pitch [μm]	#pixels	V_{bias} [V]	Gain [10^6]
W12	1	3×3	20	12100	28	0.54
W12	2	3×3	20	12100	28	0.54
PM33	1	3×3	50	3600	28	8
PM33	2	3×3	50	3600	28	8
PM33	5	3×3	50	3600	28	8
PM33	6	3×3	50	3600	28	8
PM33	7	3×3	50	3600	28	8
PM33	8	3×3	50	3600	28	8
CPTA	857	1×1	40	625	33.4	0.71
CPTA	922	1×1	40	625	33.1	0.63
CPTA	975	1×1	40	625	33.3	0.63
CPTA	1065	1×1	40	625	33.1	0.70

- Use 3 types of MPPCs with trenches
  - Two experimental samples (LCT4)
  - Two 1.3 × 1.3 mm^2 sensors
  - Two 3 × 3 mm^2 sensors

Exact dV_b/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

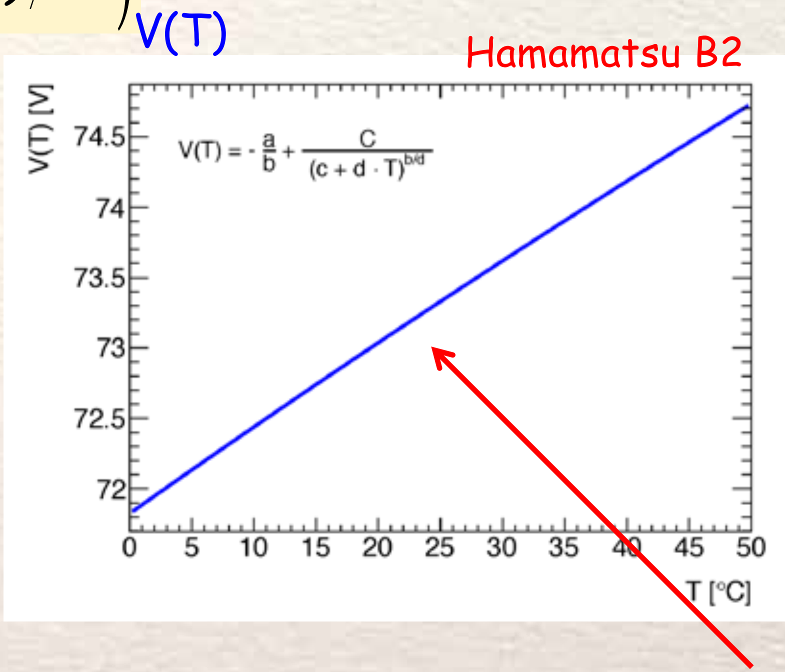
$$\frac{\partial G(V,T)}{\partial T} = a + bT \quad \text{and} \quad \frac{\partial G(V,T)}{\partial V} = c + dV$$

- 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



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

a=(-0.48266±0.0002)×10⁶; b=4835.9±0.3; c=(2.17±0.003)×10⁶; d=1295±152