SiPM Gain Studies for Adaptive Power Supply

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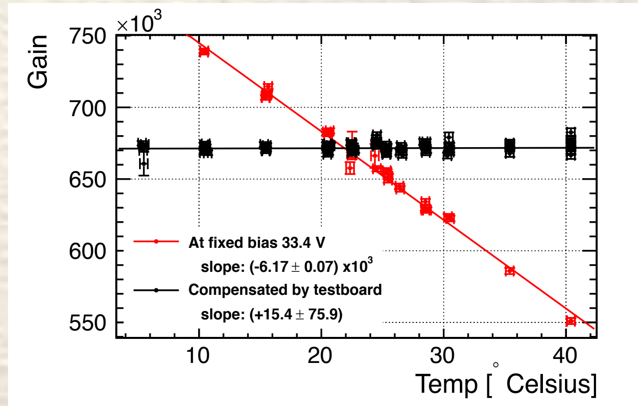
Outline

- Introduction
- Measurement setup at CERN
- Gain stabilization for 8 KEKETK SiPMs
- Gain stabilization for 4 CPTA SiPMs
- Final gain stabilization results for Hamamatsu MPPCs
- Conclusions and outlook

Introduction

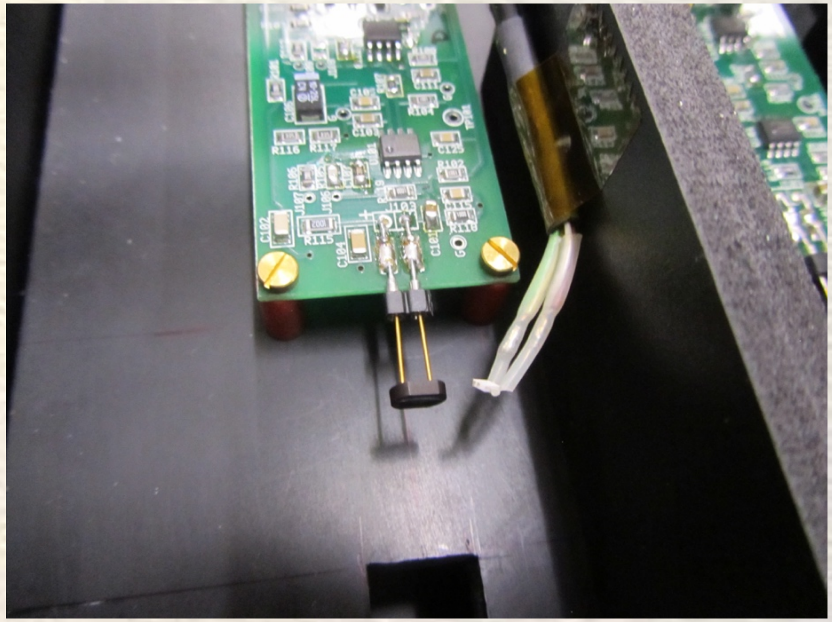
- The gain of SiPMs increases with V_{bias} and decreases with temperature T
- To operate at a stable gain, V_{bias} can be adjusted to compensate T changes
- This requires the knowledge of *dV/dT*, which is obtained from *dG/dV* and *dG/dT* measurements

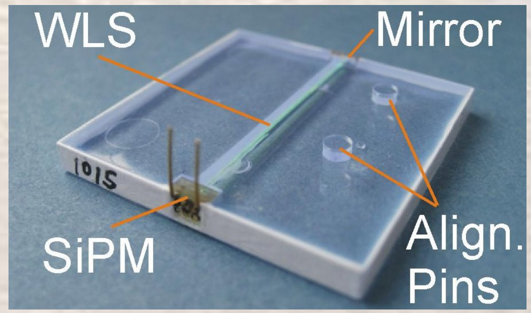


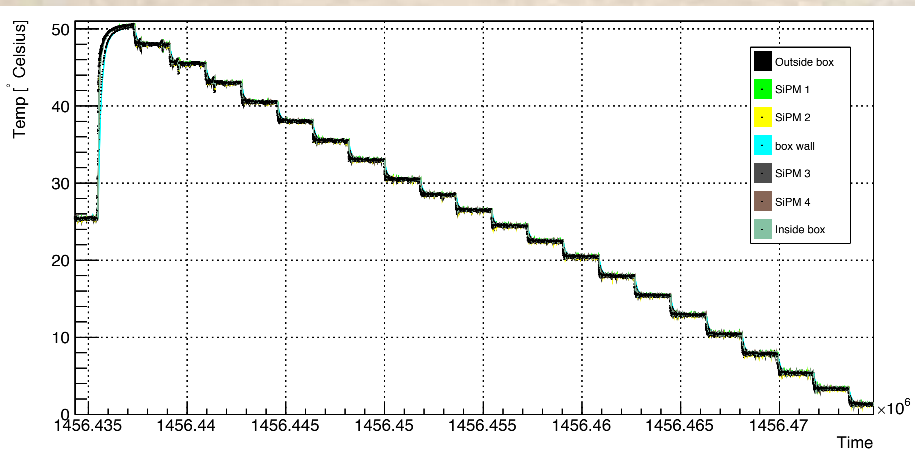
- We tested this procedure in a climate chamber at CERN in February 2016 using a linear approximation for *dV/dT*
- We tested gain stabilization on 30 SiPMs from Hamamatsu, KETEK and CPTA measuring 4 SiPMs simultaneously with one *dV/dT* setting
- We shine blue LED light via optical fibers on each SiPM
- 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 preamplifier (8/15 ns shaping time)

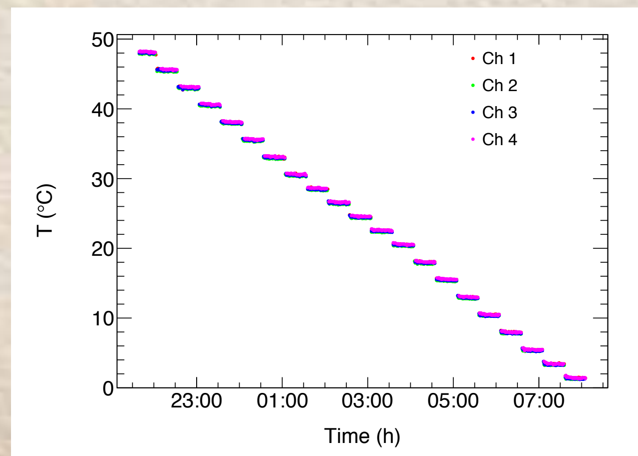
Temperature Measurements

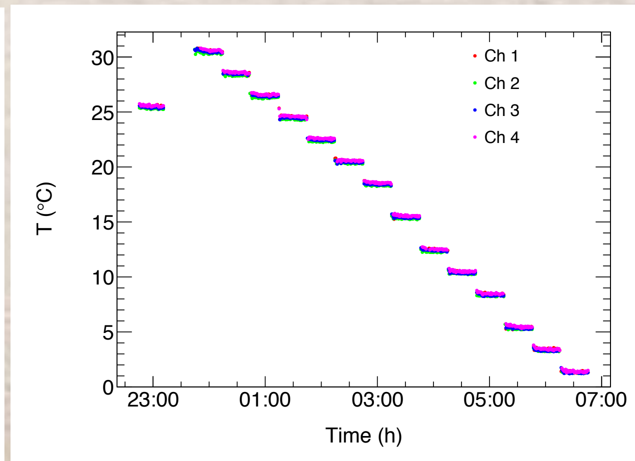
- Hamamatsu and KETEK SiPMs are illuminated directly by the LED light
- CPTA sensors are glued to a WLS fiber that is placed inside a groove in a scintillator tile
  ➔ light has to pass through the tile and WLS fiber
- Typically, we vary *T* from 50°C to 1°C in 2.5°C steps reduced to 2°C steps in the 20°-30°C range
  - $T_{SiPM}=T_{set}$ ±0.5°C (ramp up/down)
  - *T* accuracy ~±0.2°C
  - Use 7 PT1000 sensors to measure *T* in various places one each is placed near a SiPM







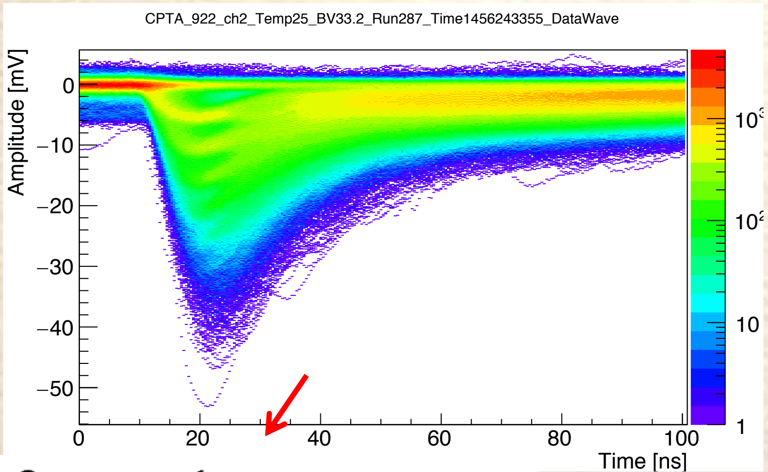


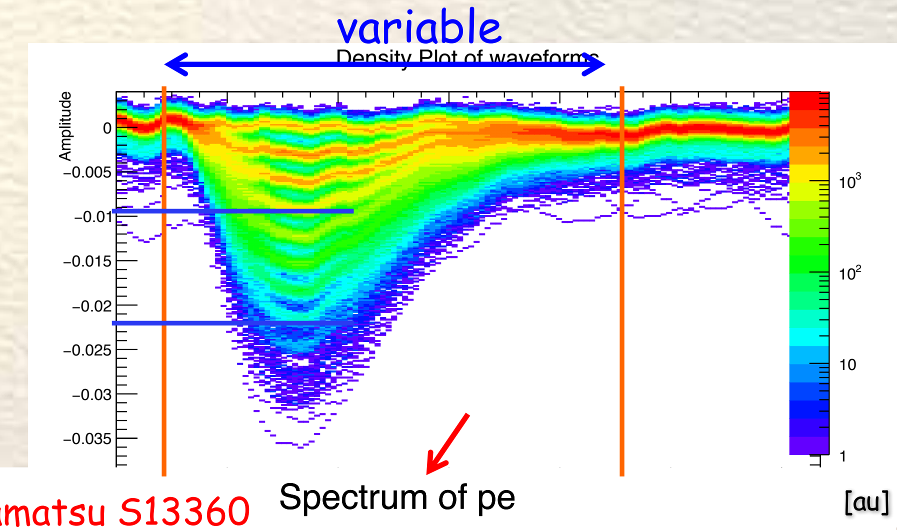


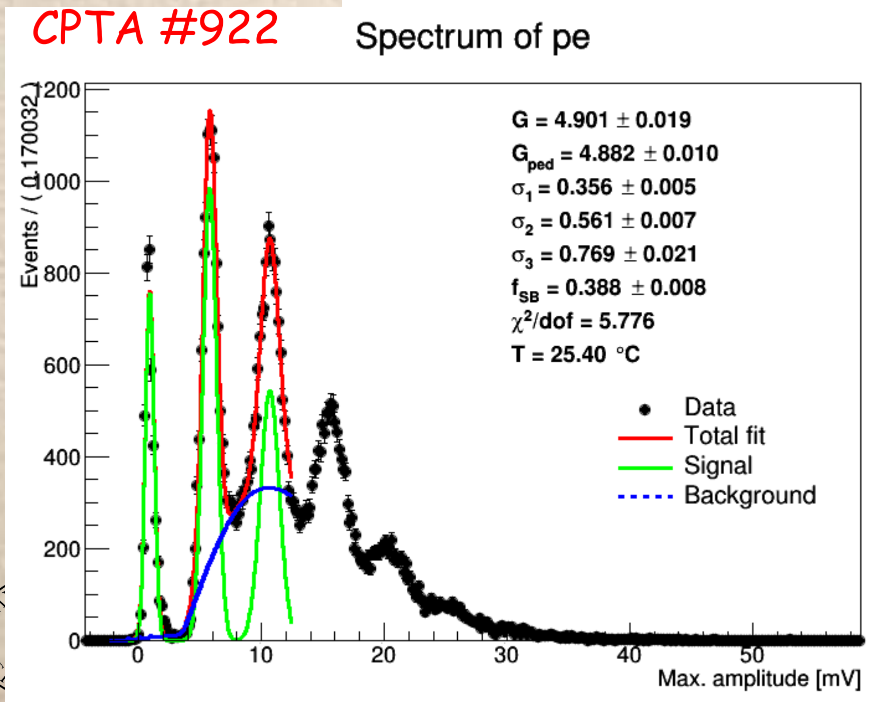
Gain Determination

- For Hamamatsu MPPCs, we integrate each waveform over a variable time window, i.e. the time for which the waveform stays below the baseline
  ➔ pe spectrum is obtained from the measured total charge

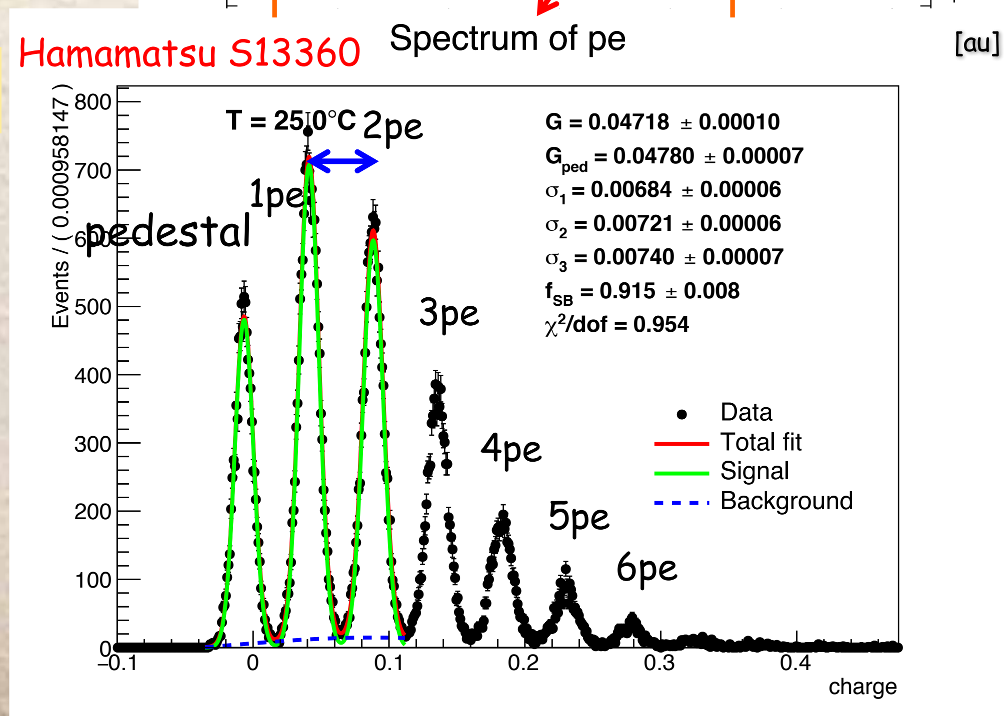
- For KETEK and CPTA SiPMs, we search for the waveform minimum from which we extract the pe spectrum







T=25°C



Gain Determination

- In both cases, we fit the pedestal, the first pe peak and the second pe peak with Gaussian functions G_i with fractions f_i (i=ped,1, 2)

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

- Besides the signal peaks, we include background F_{bkg} that is determined by a sensitive nonlinear iterative peak-clipping algorithm (SNIP), which implemented in ROOT TSpectrum class

- Thus the likelihood function is

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

f_s: signal fraction

- The gain is defined as the distance between the first and the second pe peaks

- The error on the gain takes the uncertainties of both peak positions into account

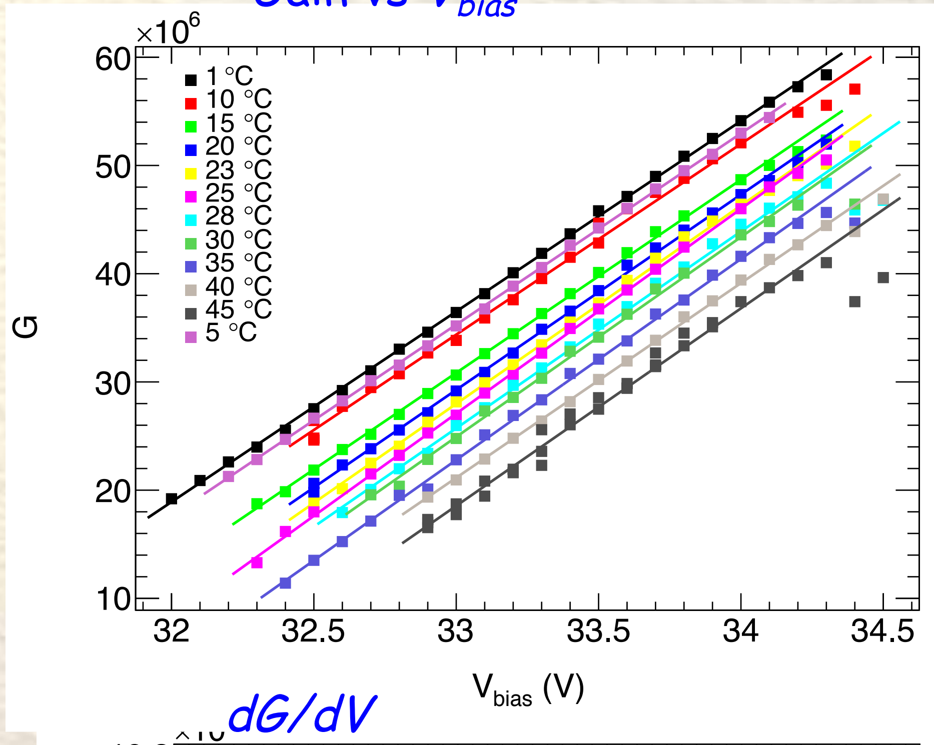
- We perform binned fits of the pe spectra

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

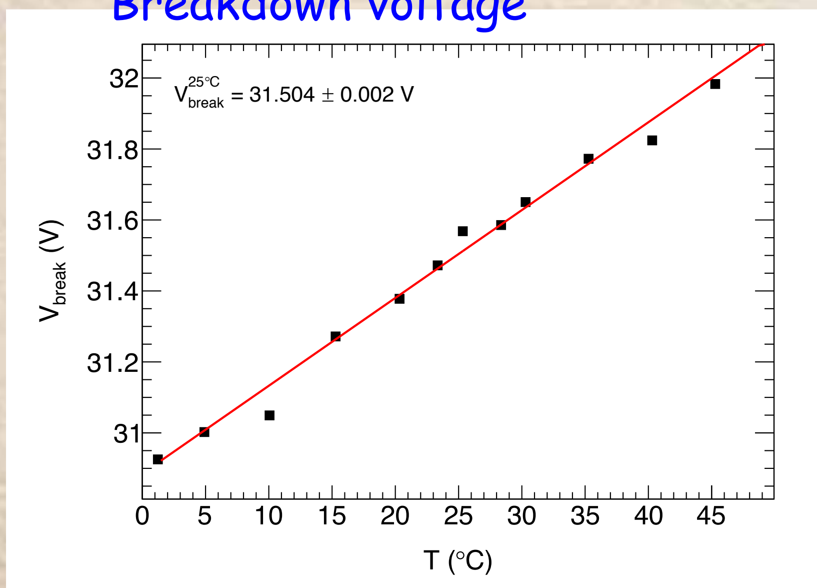
CPTA *dG/dV* Measurements

- We explore the temperature range 1°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*~capacitance increases with T (use linear fit)
  ➔6% increase in 1°C-45°C T range

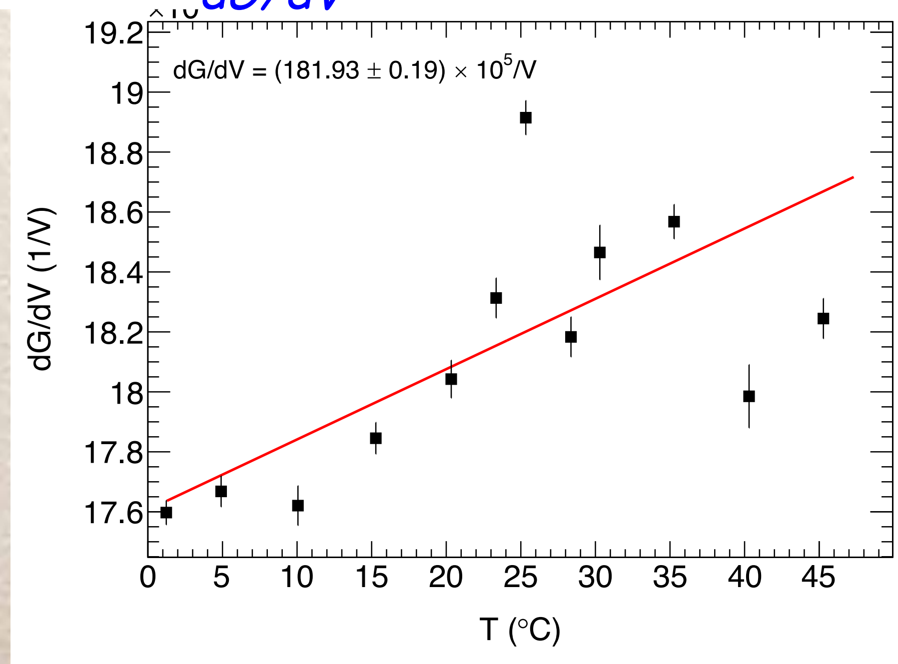
Gain vs V_{bias}



Breakdown voltage



dG/dV

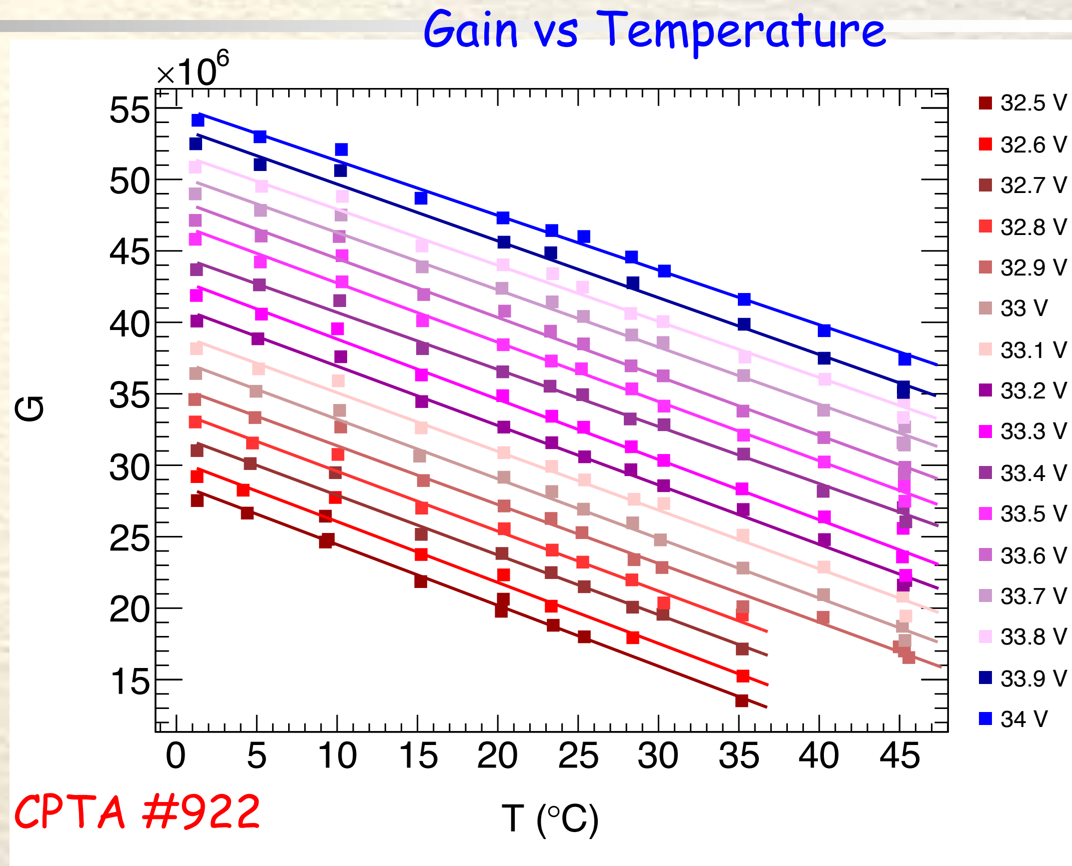


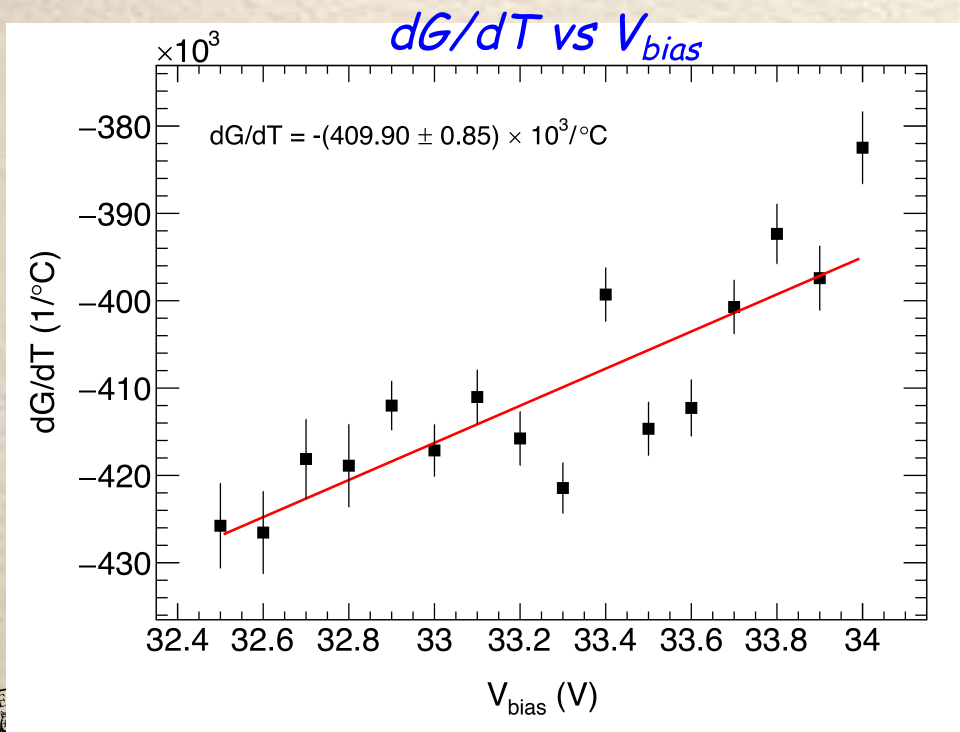
CPTA #922

- $dG/dV=(1.819\pm0.002)\times10^{7}/V$

CPTA *dG/dT* Measurements

- For fixed V_{bias}, we plot *G* versus *T*
- The gain decreases with temperature
  ➔ we perform linear fits to extract *dG/dT*
- dG/dT increases linearly with V_{bias} (8% variation from 32.5 V to 34 V)
  ➔ perform linear fit

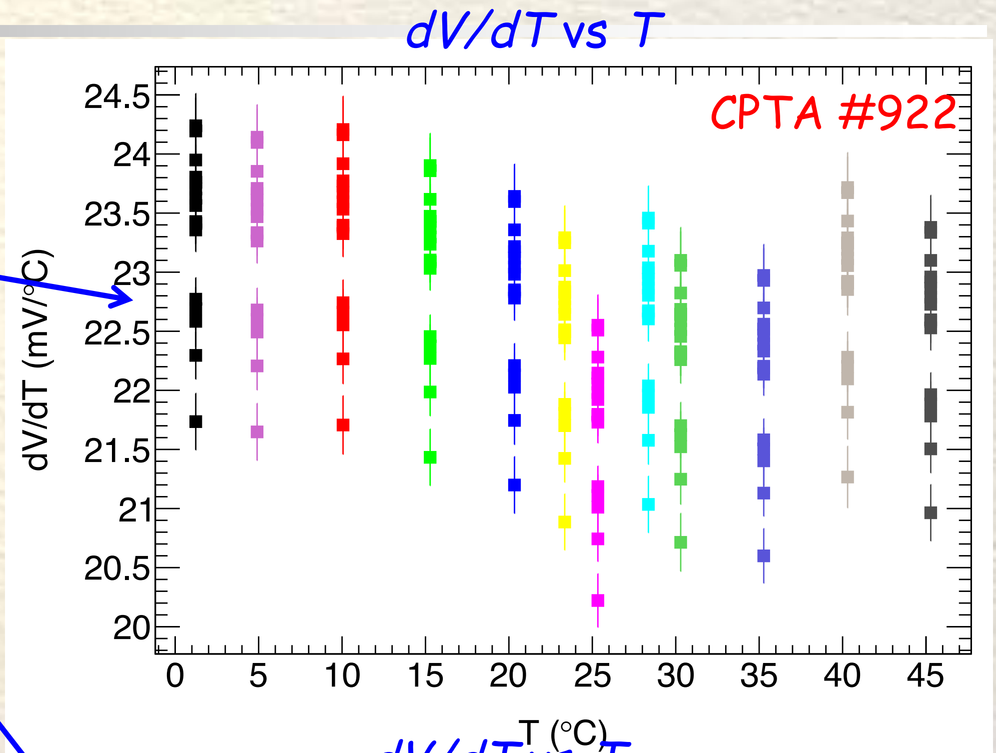


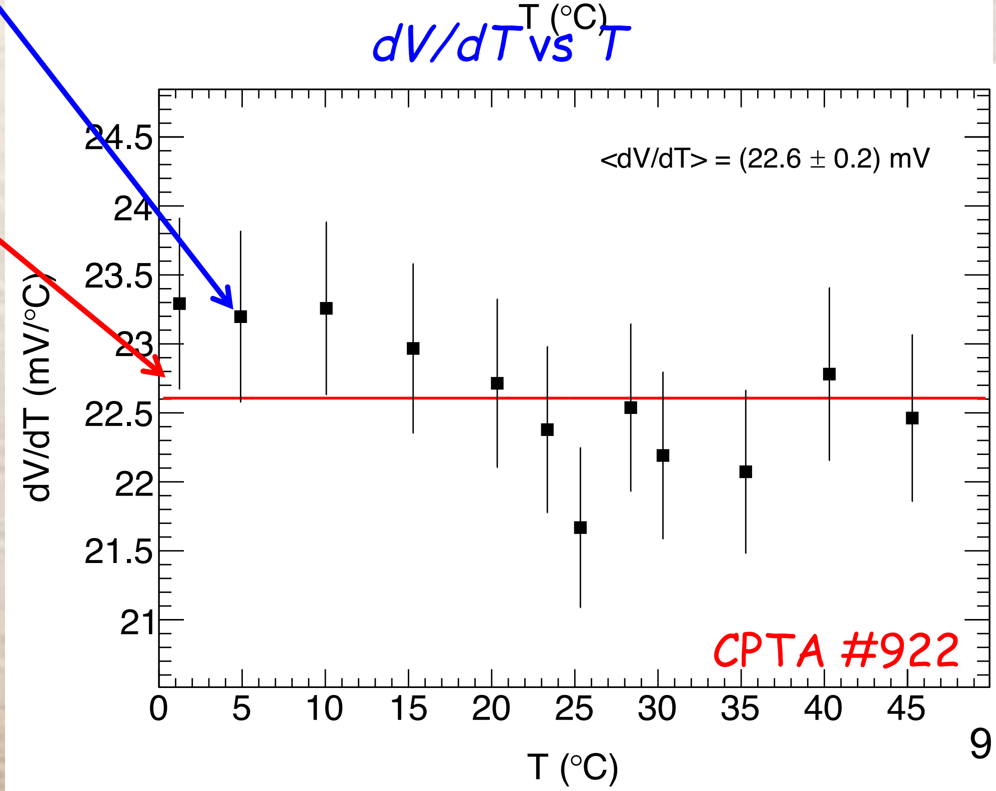


- From the fit, we measure
  $dG/dT=(4.099\pm0.009)\times10^5/°C$

Determination of *dV/dT*

- At each *T* point, we the determine *dV/dT* distribution by dividing all *dG/dT* measurements by all *dG/dV* values
- At each *T* point, we average *dV/dT* values and compute the standard deviation
- We fit the resulting distribution with a uniform distribution
  ➔ we estimate the systematic error by taking the fit parameter uncertainties
- We obtain: ***dV/dT*=(22.6±0.2$_{sys}$) mV/°C**
- We then test gain stability, typically in the 1°C-50°C T range
- We determine the deviation from gain stability in 20°C-30°C *T* range

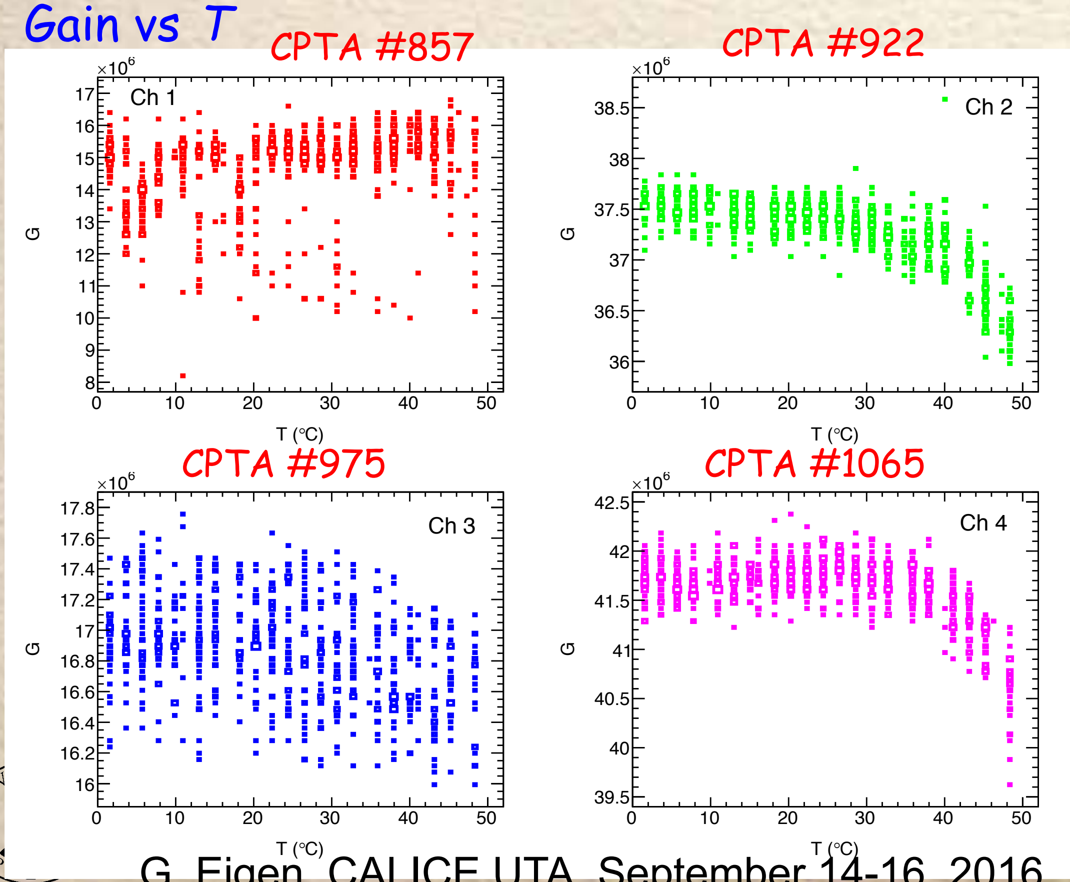




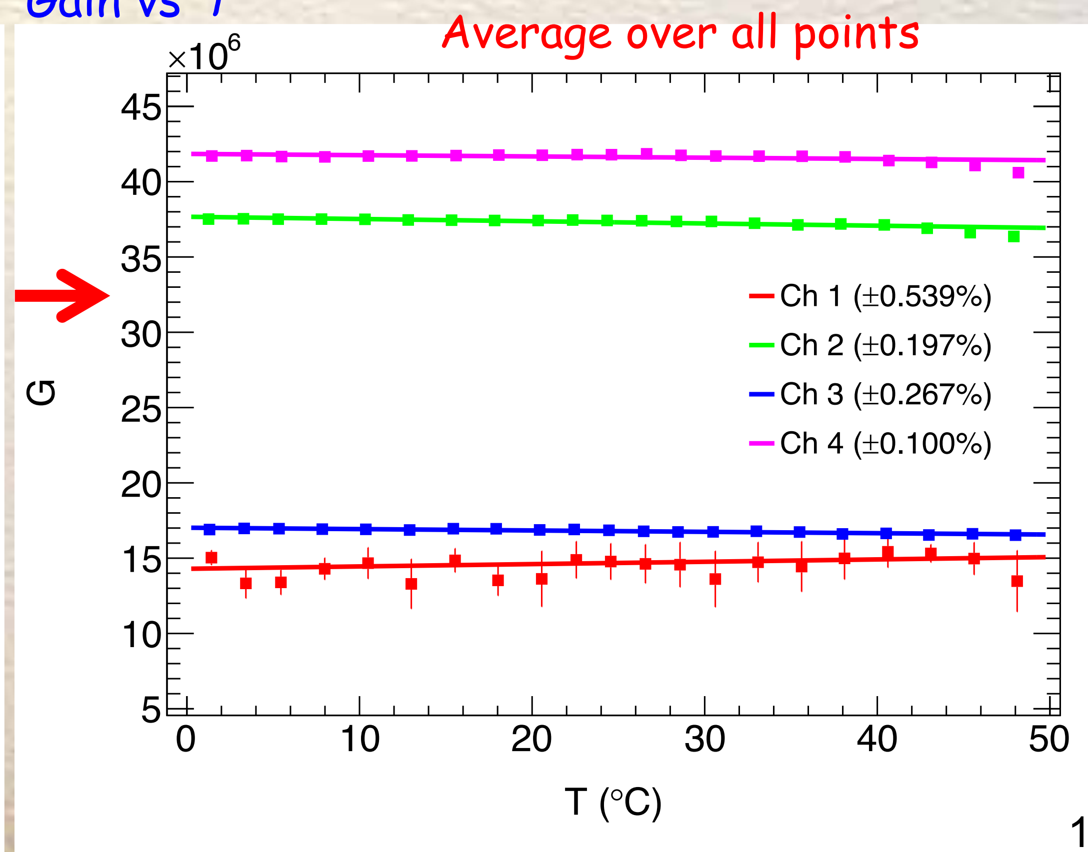
Gain Stabilization of CPTA SiPMs

- We adjust V_{bias} with regulator board using *dV/dT*=21.2 mV/°C to stabilize 4 CPTA SiPMs
- We test gain stability within *T*=1°-48°C taking ≥ 18 50k waveform samples of at each *T*
- The gain is nearly uniform up to 30°C, then falling off rapidly
- SiPMs in ch# 2 and ch#4 look fine; ch#1 is noisy, ch#3 changed gain but looks ok
- Three SiPMs satisfy our requirement of ±0.5% within 20°C -30°C *T* range

Gain vs *T*

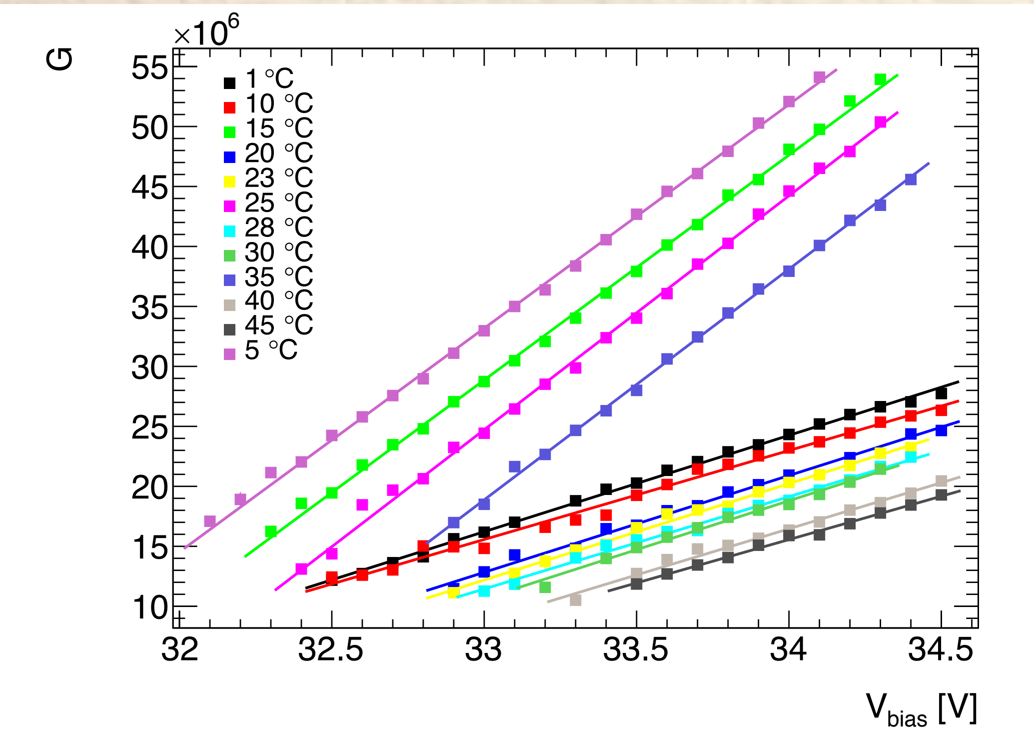


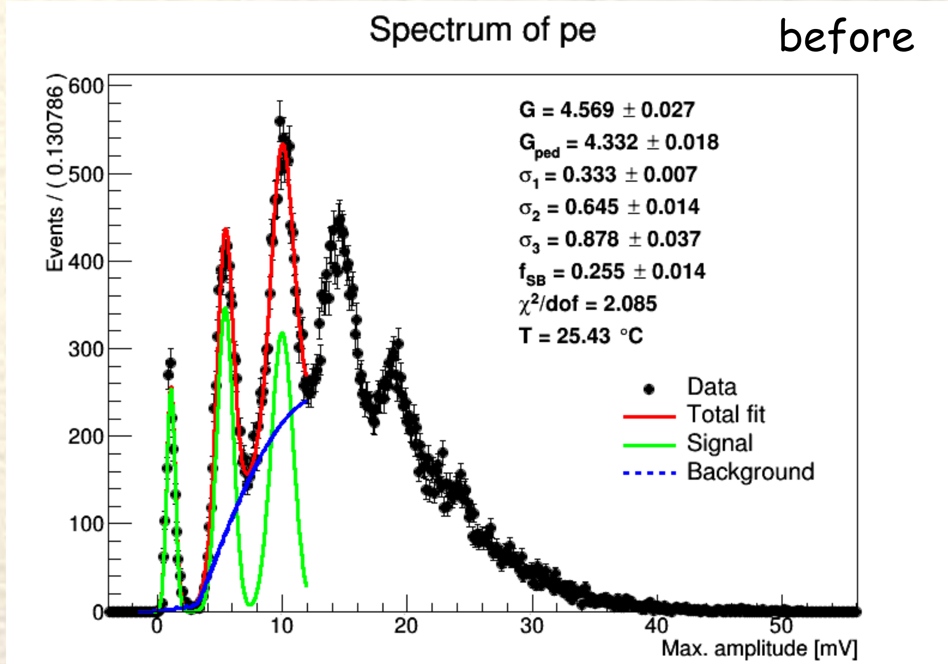
Gain vs *T*

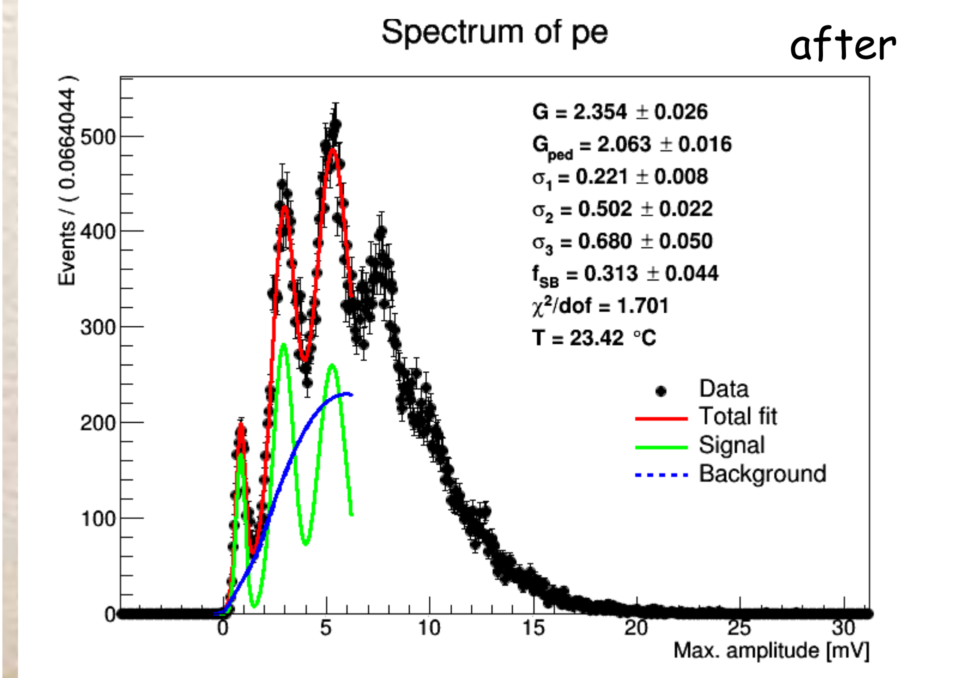


Study of CPTA #975

- CPTA sensor #975 changed gain during operation at 45°C by a factor of ~2
- After the gain change, the SiPM seemed to operate ”normally”
- The stabilization looks fine after gain change

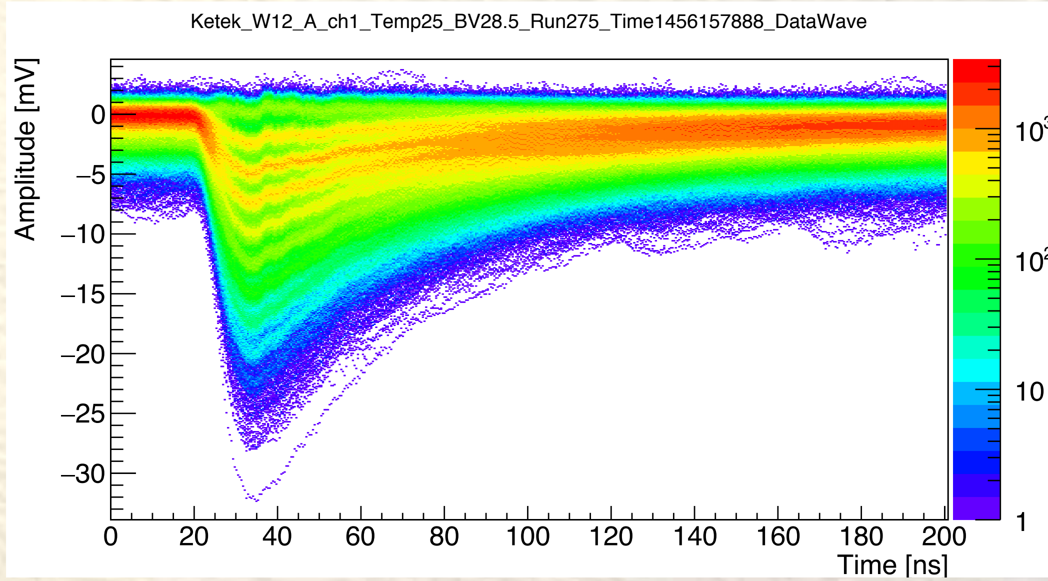


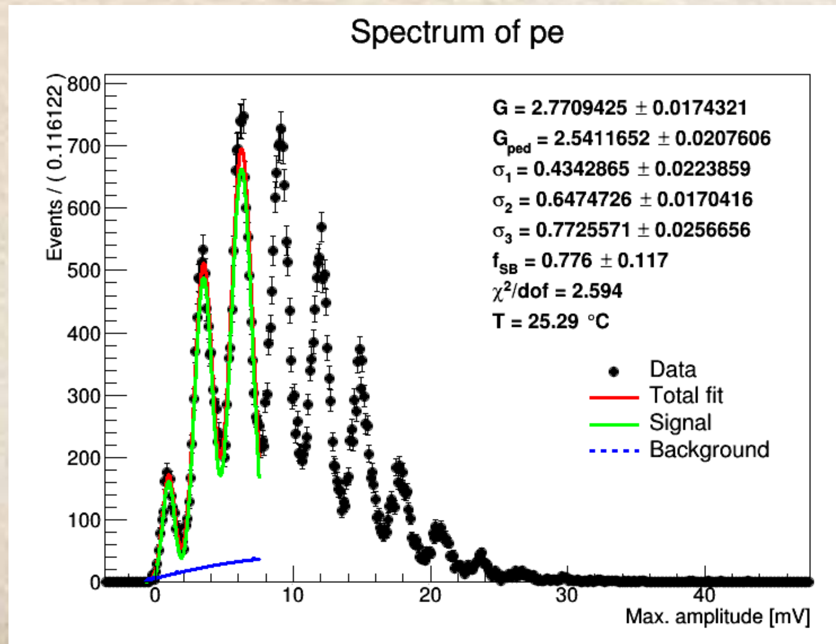


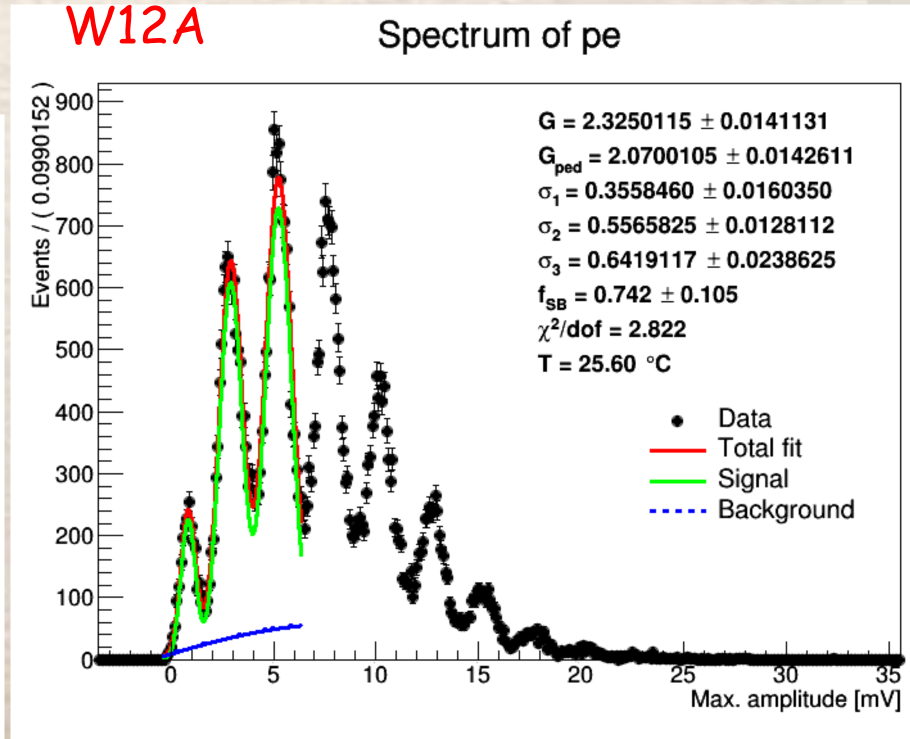


Study of KETEK SiPMs

- The decay time in KETEK SiPMs is rather long, much longer than that for CPTA and Hamamatsu MPPCs
- Within a 200 ns wide integration window the waveforms of multi photoelectrons typically do not return to the baseline
- In addition, signals are rather noisy and have many afterpulses
- Thus, we also use the method of minimum amplitude to determine the pe spectra
- For the 2 W12 sensors we could also use total the total charge to obtain the pe spectra



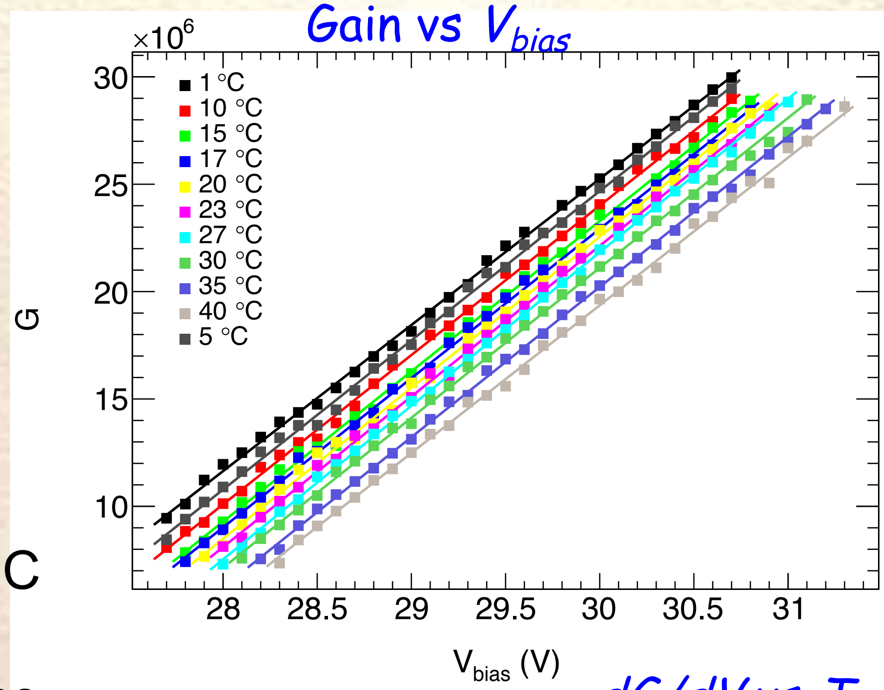


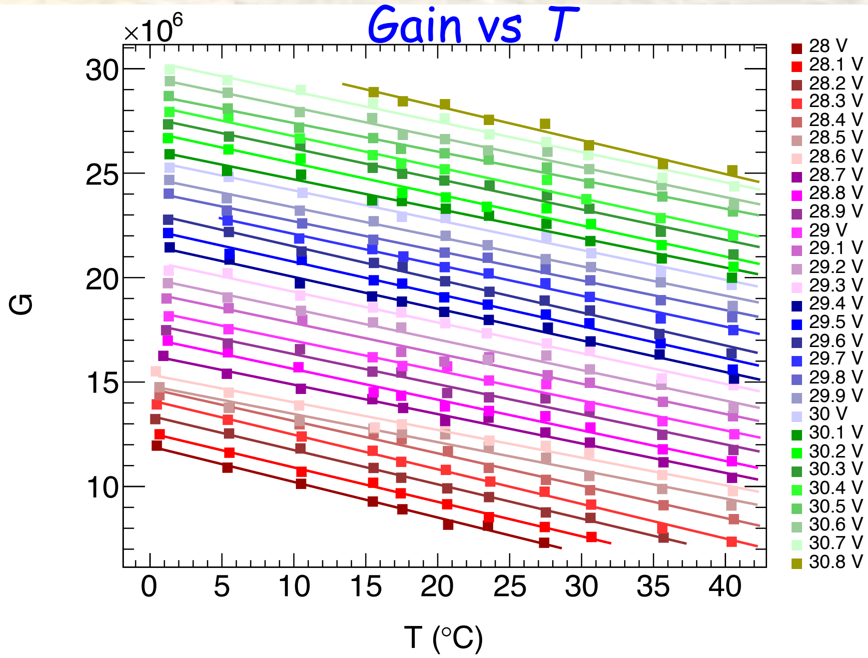


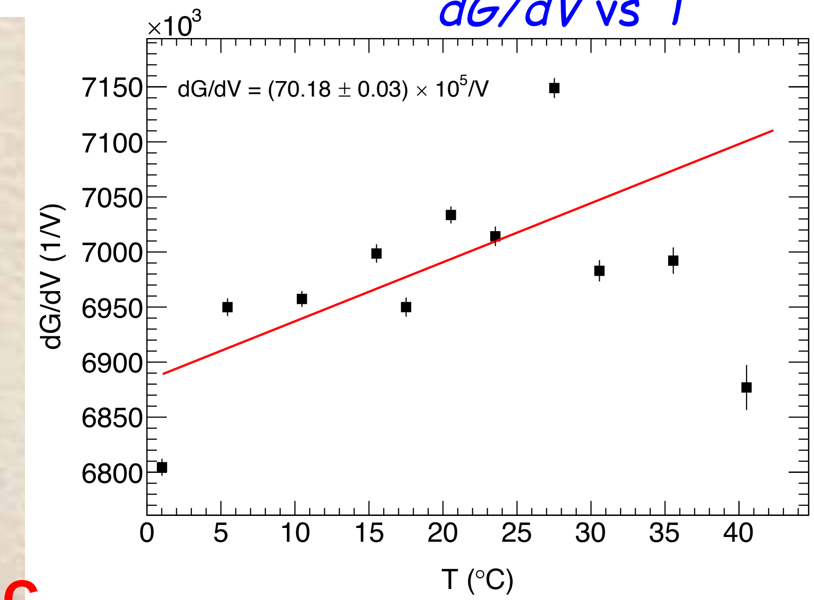
KETEK *dG/dV* Measurements

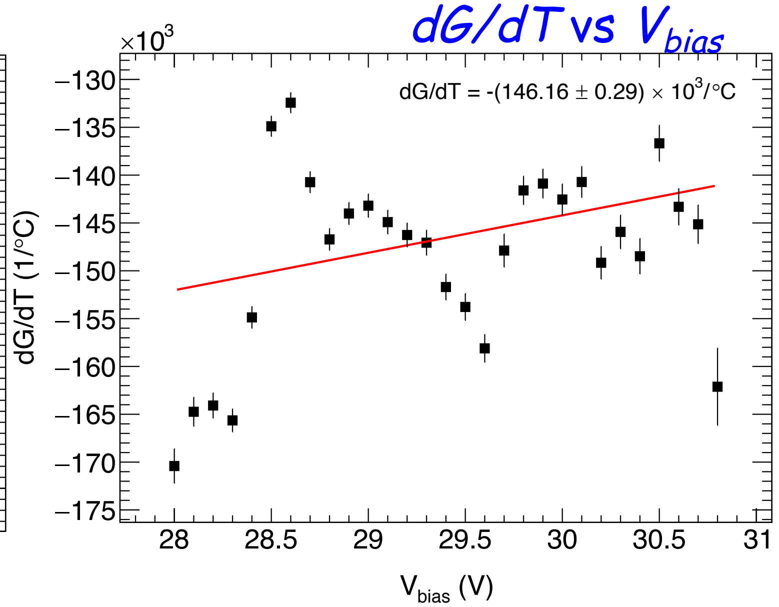
KETEK W12A

- We perform the amplitude analysis for all 8 KETEK SiPMs
- Results for other KETEK SiPMs look very similar
- The PM3350 SiPMs do not work properly > 30°C
- The capacitance increases by ~2% in the 5°C -40°C T range
- ***dG/dV*= (7.02±0.03)×10⁶/V**
- ***dG/dT*= (1.462±0.003)×10⁵/°C**



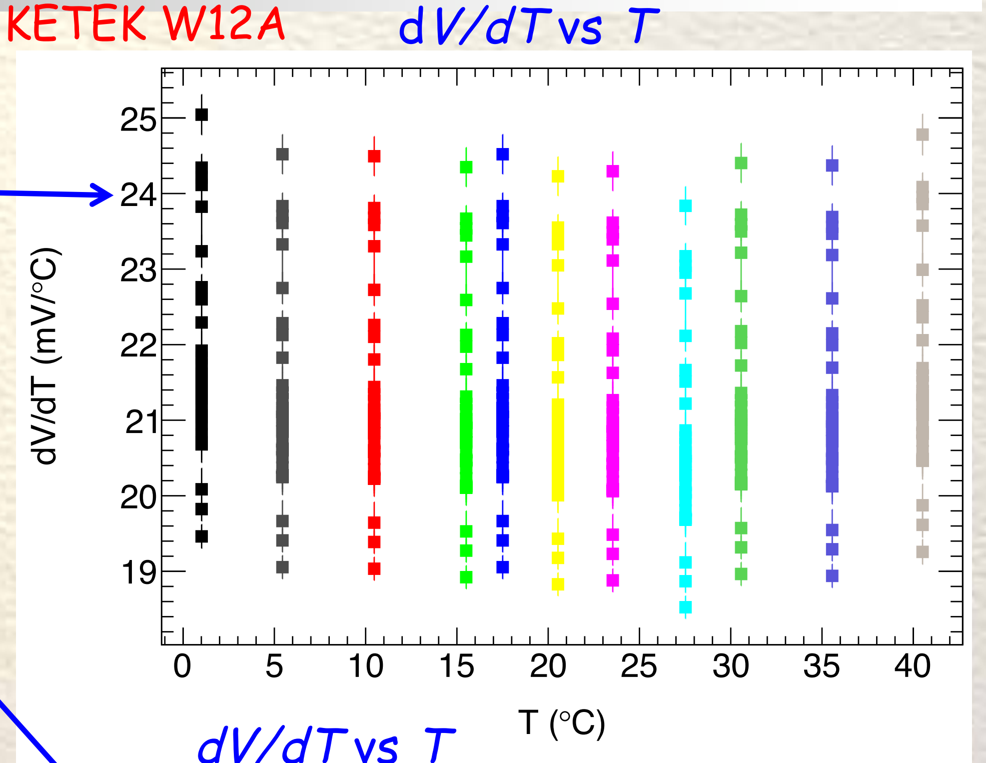


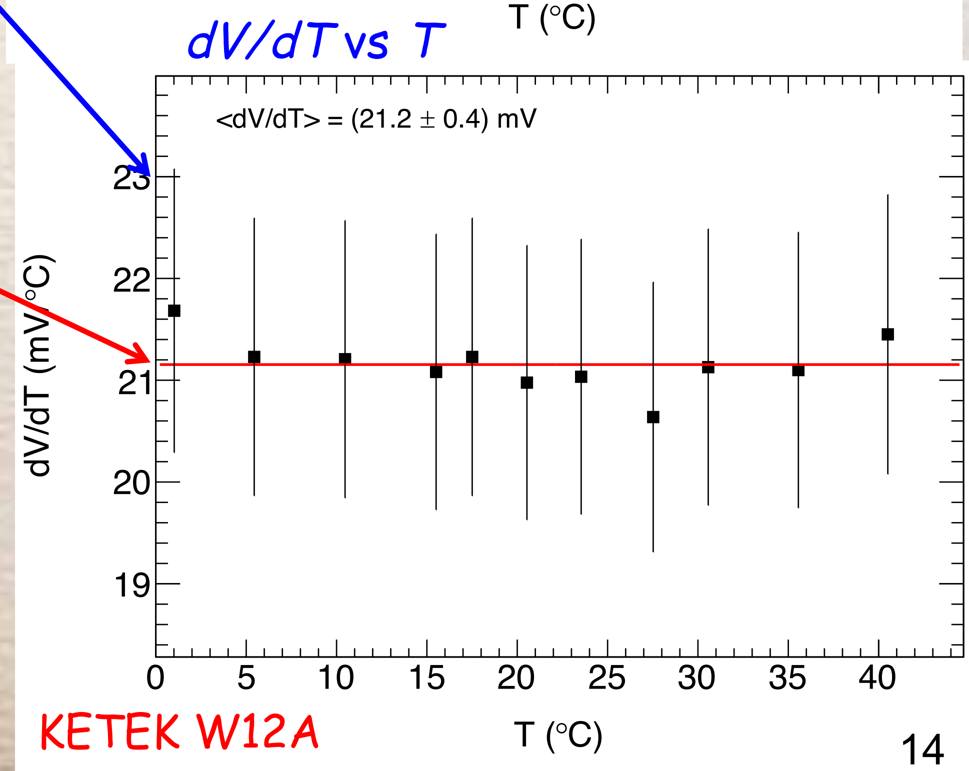




Determination of *dV/dT*

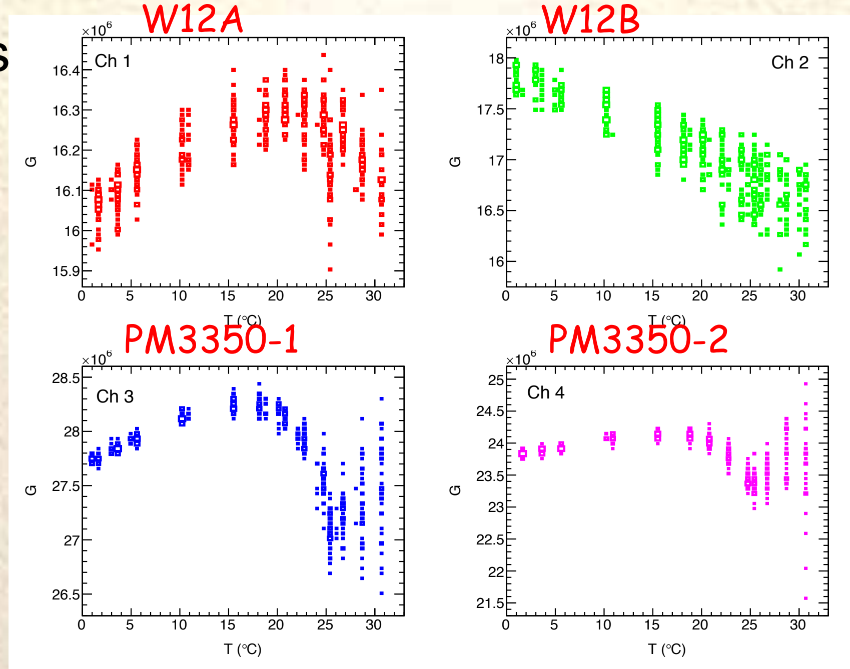
- At each *T* point, determine *dV/dT* distribution by dividing all *dG/dT* measurements by all *dG/dV* measurements
- At each *T* point, we average *dV/dT* values and compute the standard deviation
- We fit the resulting distribution with a uniform distribution
  ➔ we estimate systematic errors by taking the fit parameter uncertainties
- We obtain: **$dV/dT=(21.2\pm0.4_{sys})$ mV/°C**
- Adjust V_{bias} with regulator board
  - use compensation of 18.15 mV/°C to stabilize W12A, W12 B, PM3350-1,2
  - use compensation of 18.3 mV/°C to stabilize PM3350-5,6,7,8
- Test gain stability in 1°C-30°C T range
- At each T point take ≥18 50k waveform samples each

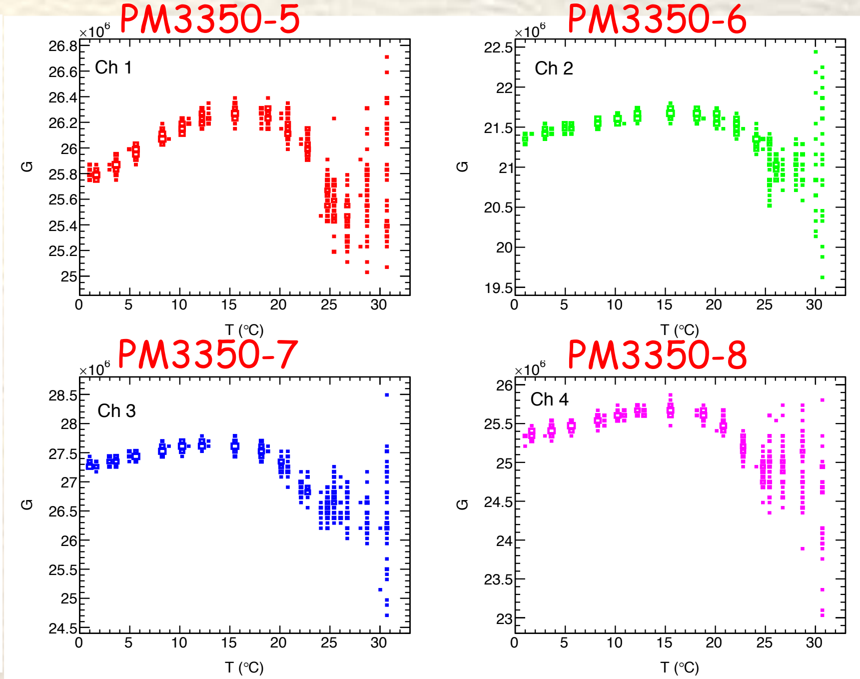


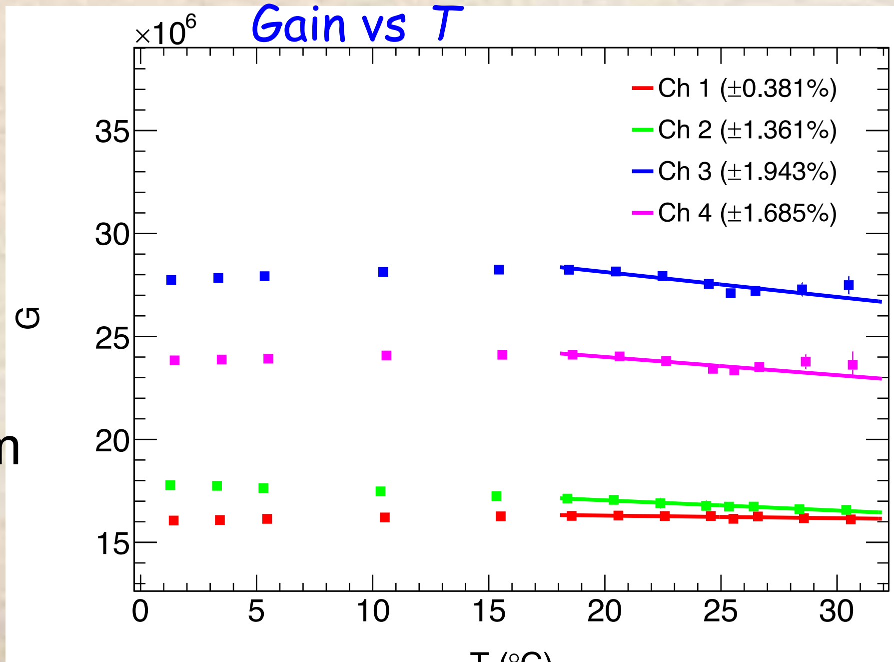


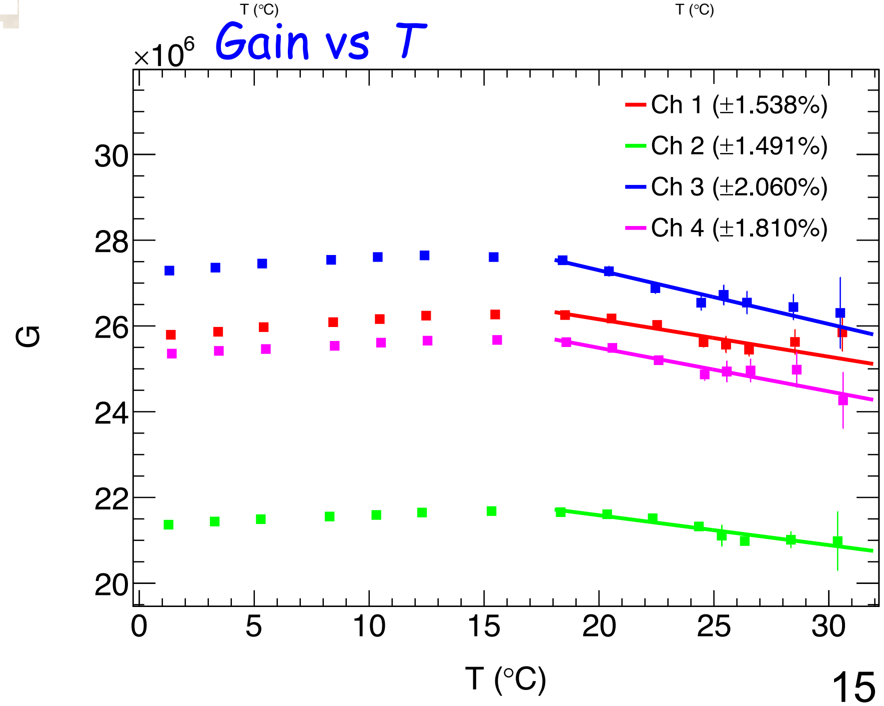
Gain Stabilization of KETEK SiPMs

- Simultaneous gain stabilization for 4 KETEK SiPMs in two batches
- KETEK sensors show more complicated V(T) behavior
  ➔linear correction is not sufficient
- *G* rises from 1°C -~18°C
- *G* is uniform in 18°C -22°C *T* range
- G falls off rapidly in 22°C -30°C *T* range
- Only 1 SiPM has **<±0.5%** deviation from uniformity in 20°C to 30°C range





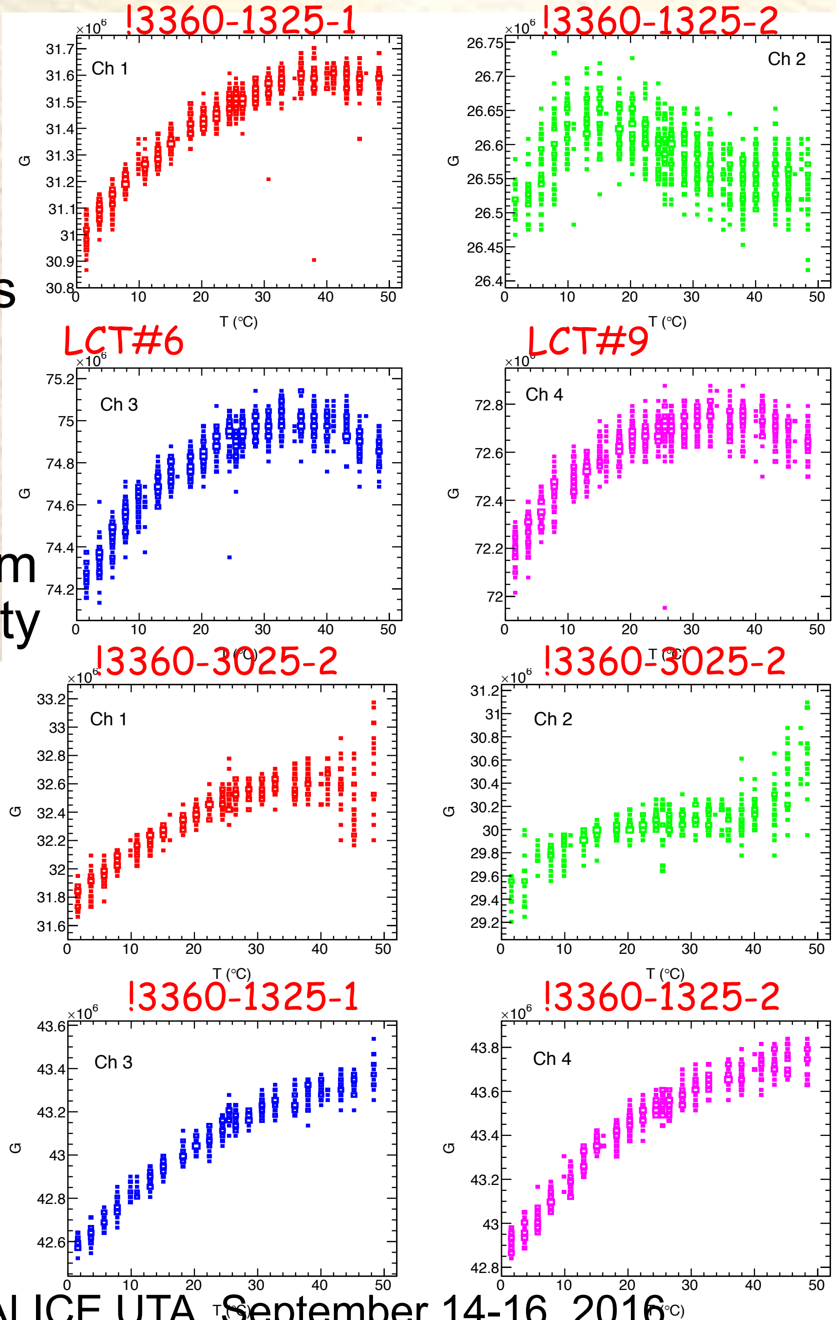


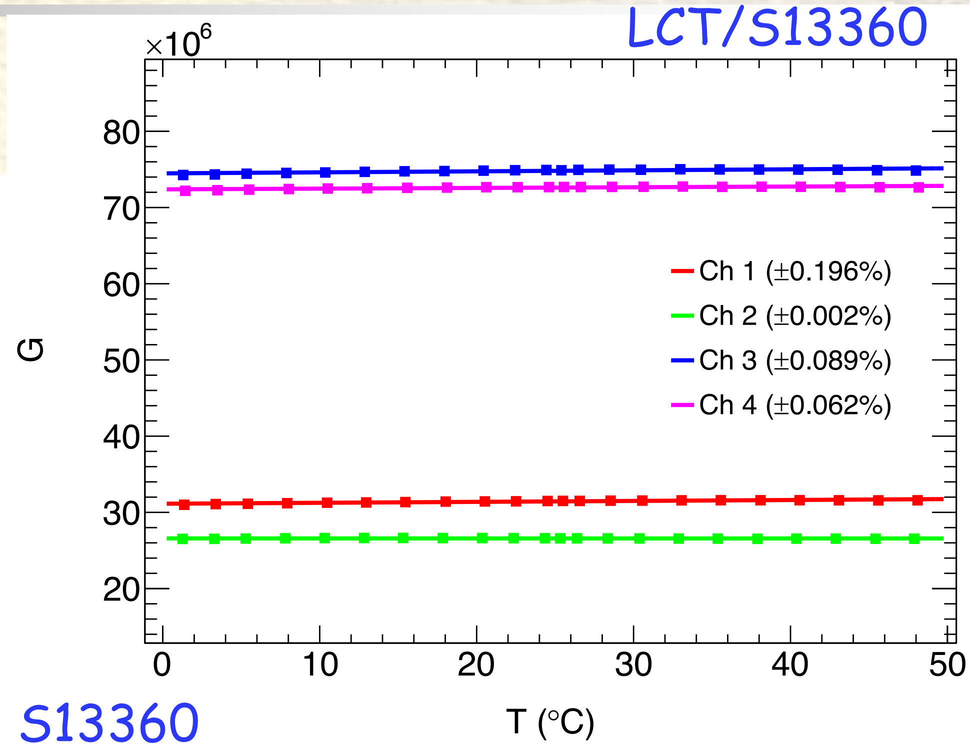


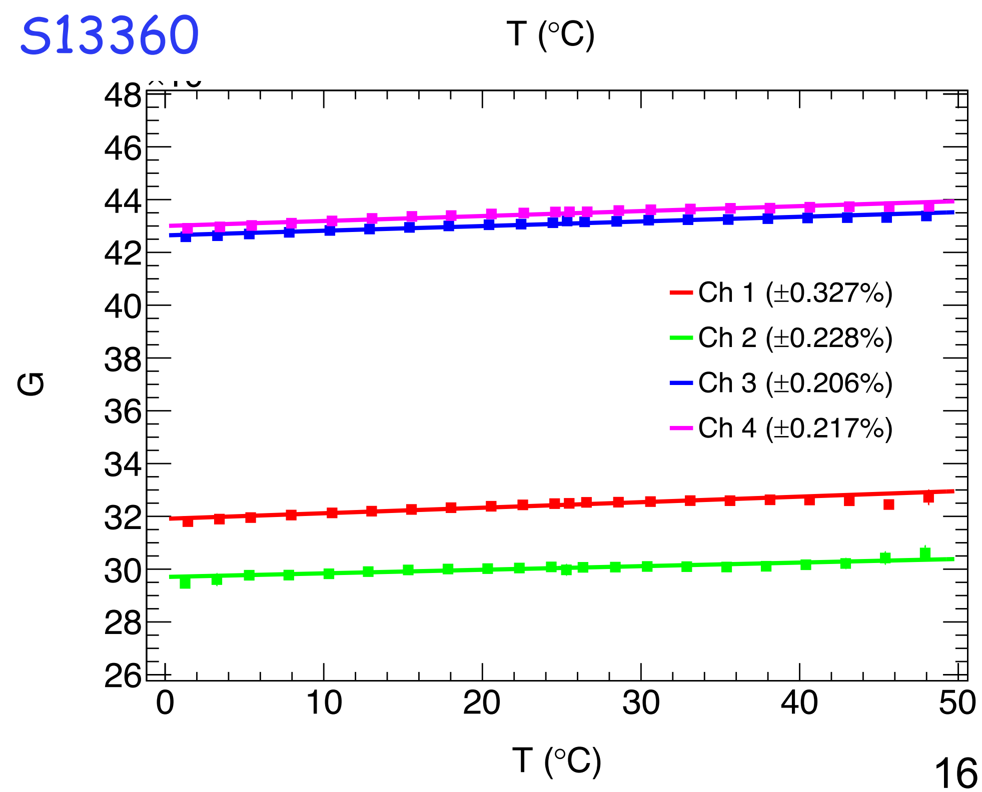
Gain Stabilization for MPPCs w Trenches

- Hamamatsu MPPCs gain stabilization results are finalized
- Linear gain stabilization works well for MPPCs with trenches

➔ all sensors satisfy a **<±0.5%** deviation from non-uniformity in the 20°C-30°C *T* range

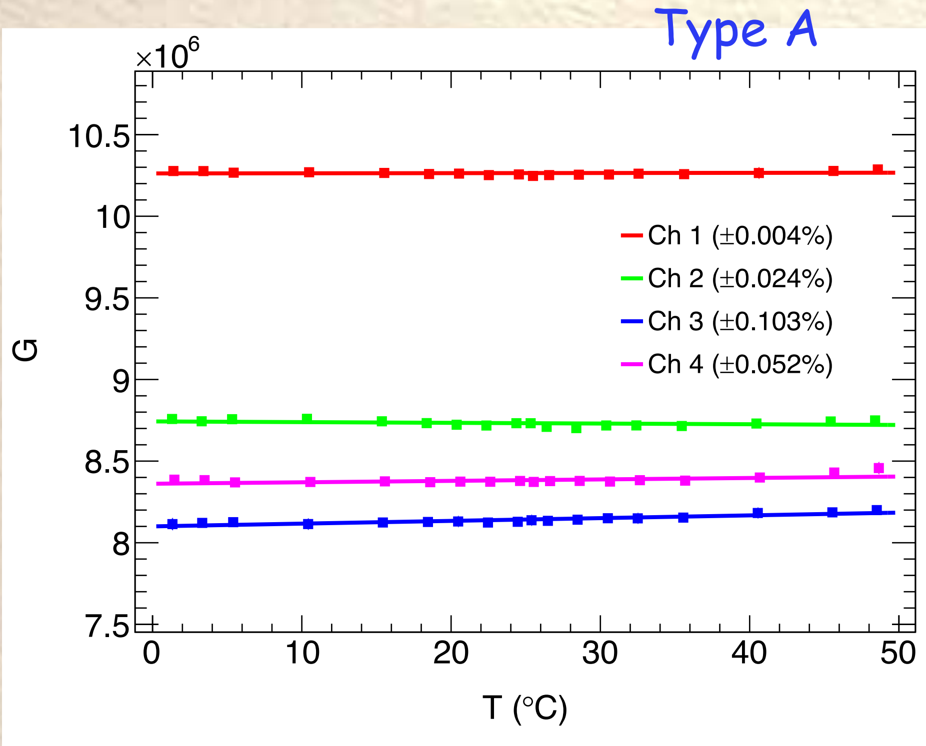


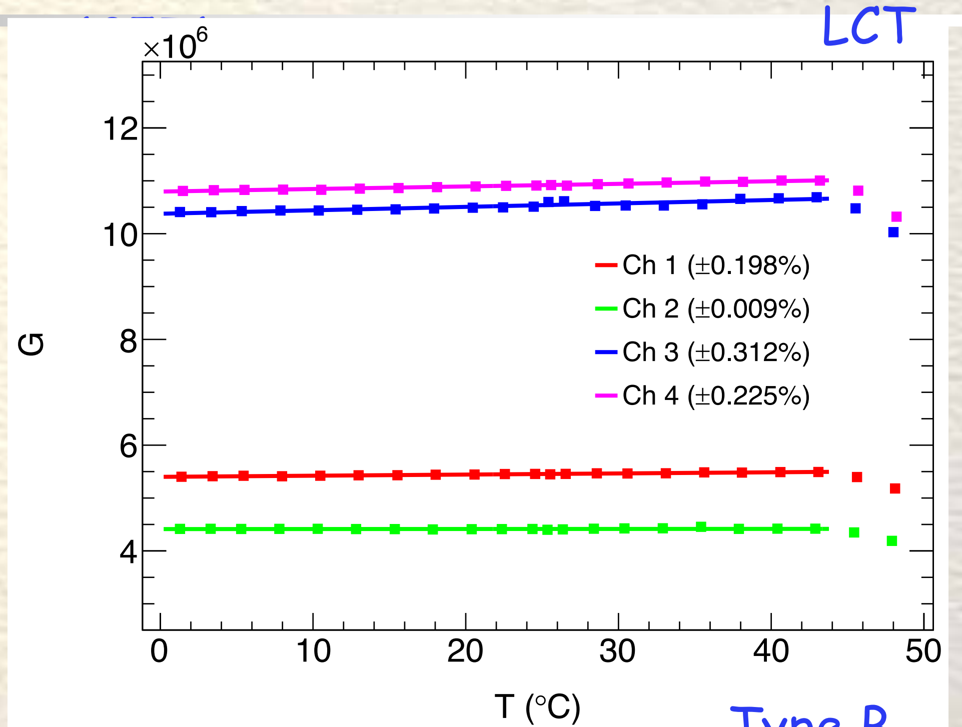


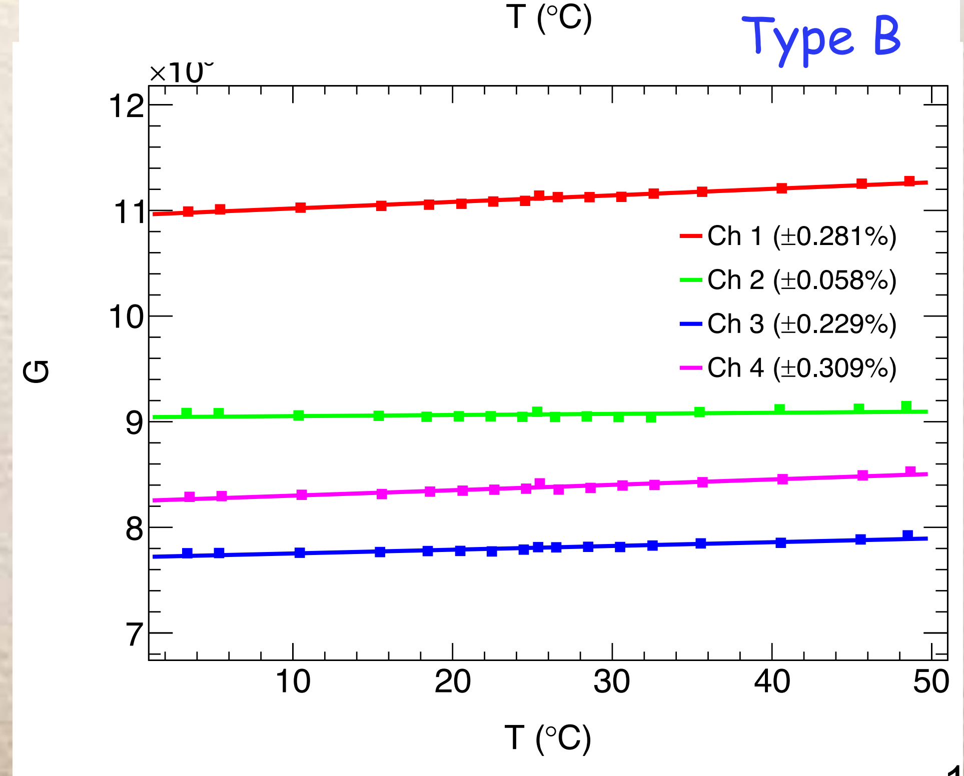


Gain Stabilization for MPPCs w/o Trenches

- Gain stabilization works well for all tested Hamamatsu MPPCs without trenches
- All 12 MPPCs satisfy the requirement a **<±0.5%** deviation from uniformity within the 20°C -30°C *T* range

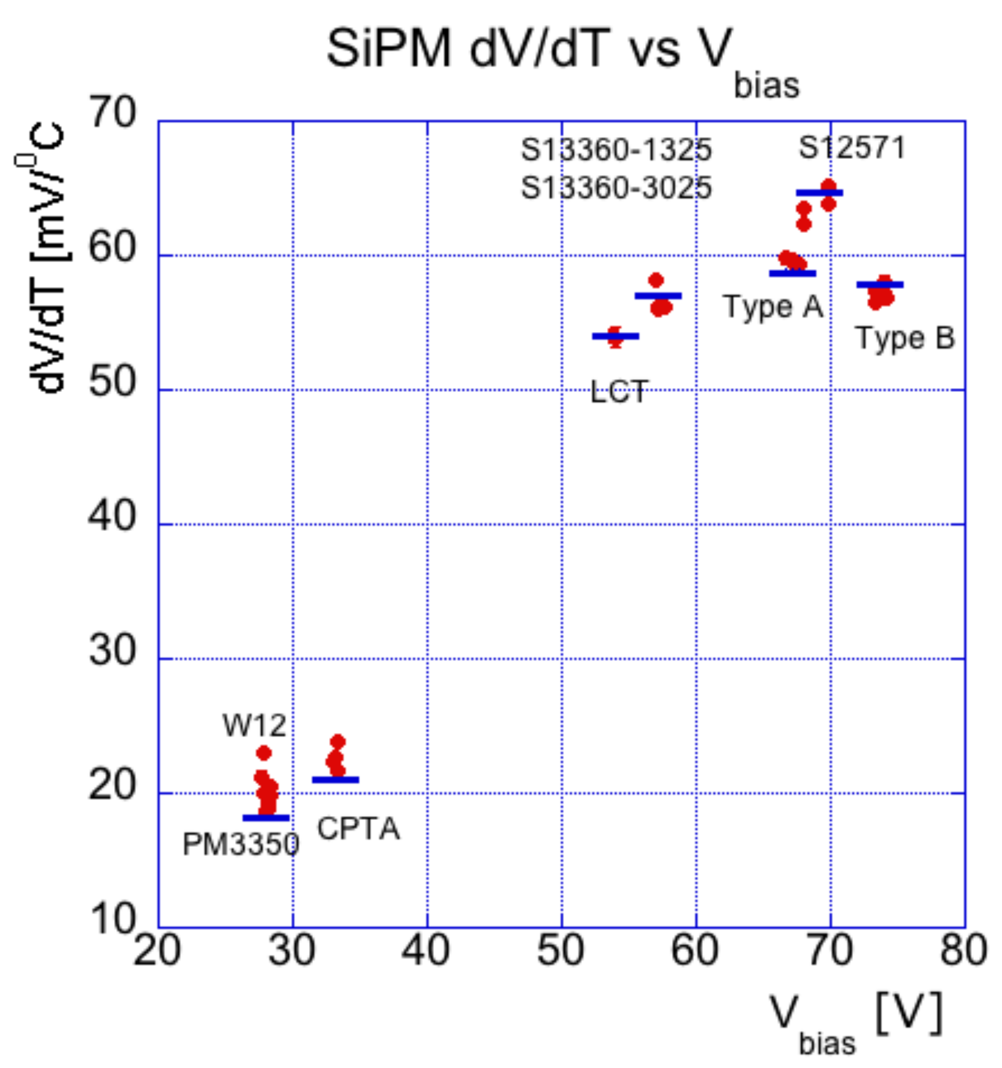






Measured *dV/dT* Values vs V_{bias}

- Look for correlations between operating voltage and measured dV/dT for all SiPMs
- dV/dT increases with V_{bias}



MPPC	dV/dT [mV/°C]
A1-15	59.45±0.49
A2-15	57.84±0.67
A1-20	59.84±0.78
A2-20	59.06±1.47
B1-15	56.8±0.2
B2-15	58.0±0.1
B1-20	57.1±0.2
B2-20	56.9±0.1
S12571-271	64.31±0.23
S12571-273	65.32±0.19
S12571-136	63.36±0.29
S12571-137	64.80±0.30
LCT4#6	53.9±0.5
LCT4#9	54.0±0.7
S13360-10143	55.85±0.26
S13360-10144	58,17±0.09
S13360-10103	
S13360-10104	54.47±1.5

SiPM	dV/dT [mV/°C]
W12	21.2±0.4
W12	23.0±0.2
PM3350	20.0±0.3
PM3350	18.7±0.4
PM3350	18.8±0.2
PM3350	19.1±0.3
PM3350	20.5±0.2
PM3350	19.8±0.4
#857	21.6±0.4
#922	22.6±0.2
#875	25.9±0.3
#1065	22.3±0.2

Conclusions and Outlook

- We tested gain stabilization for 30 SiPMs in a climate chamber at CERN testing 4 SiPMs simultaneously with one *dV/dT* value

- All 18 Hamamatsu MPPCs, 6 with trenches and 12 without trenches, show excellent gain stabilization
  ➔ non-uniformities **<±0.5%** in the 20°C-30°C *T* range, work well in extended *T* range 1°C-50°C

- Gain stabilization of KETEK SiPMs is more complicated,
  - Signals are rather long and are affected by afterpulsing
  - range of stabilization is limited to 1°C-30°C *T* range
  - SiPMs have more complicated V(T) behavior in the 1°C-30°C *T* range

  ➔different ***dV/dT*** values are needed to stabilize the gain in 1°C-30°C *T* range

- Gain stabilization of CPTA SiPMs works fine
  ➔ for 3 SiPMs deviations from uniformity are less than **±0.5%** in 20°C-30°C range,

- We need to check the KETEK results

- We completed the first draft for publication in JINST

Acknowledgment

- We would like to thank L. Linssen, Ch. Joram, W. Klempt, and D. Dannheim for using the E-lab and for supplying electronic equipment

- We further would like to thank the team of the climate chamber at CERN for their support

SiPM Properties

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

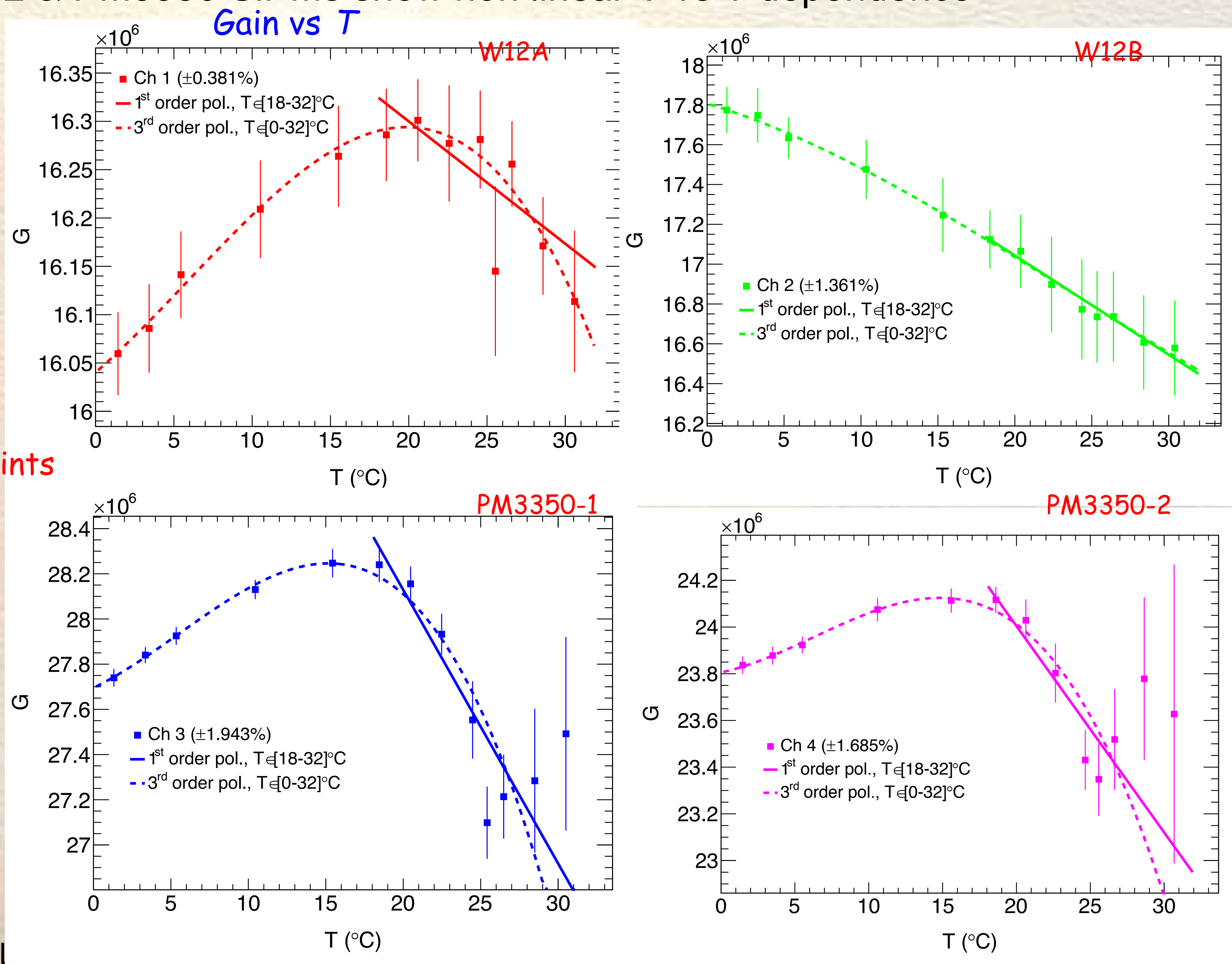
SiPM	Serial#	Size [mm²]	Pitch [μm]	#pixels	V_{bias} [V]	Gain [10^6]	SiPM	Serial#	Size [mm²]	Pitch [μm]	#pixels	V_{bias} [V]	Gain [10^6]
Type A	A1	1×1	15	4440	67.22	0.2	W12	1	3×3	20	12100	28	0.54
Type A	A2	1×1	15	4440	67.15	0.2	W12	2	3×3	20	12100	28	0.54
Type A	A1	1×1	20	2500	66.73	0.23	PM33	1	3×3	50	3600	28	8
Type A	A2	1×1	20	2500	67.7	0.23	PM33	2	3×3	50	3600	28	8
Type B	B1	1×1	15	4440	74.16	0.2	PM33	5	3×3	50	3600	28	8
Type B	B2	1×1	15	4440	73.99	0.2	PM33	6	3×3	50	3600	28	8
Type B	B1	1×1	20	2500	73.33	0.23	PM33	7	3×3	50	3600	28	8
Type B	B2	1×1	20	2500	73.39	0.23	PM33	8	3×3	50	3600	28	8
S12571	271	1×1	10	10000	69.83	1.35	CPTA	857	1×1	40	625	33.4	0.71
S12571	273	1×1	10	10000	69.87	1.35	CPTA	922	1×1	40	625	33.1	0.63
S12571	136	1×1	15	4440	68.08	2.29	CPTA	975	1×1	40	625	33.3	0.63
S12571	137	1×1	15	4440	68.03	2.30	CPTA	1065	1×1	40	625	33.1	0.70
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							

- Use 3 types of MPPCs with trenches
  - Two experimental samples (LCT4)
  - Two 1.3 × 1.3 mm² sensors
  - Two 3 × 3 mm² sensors

Test of Gain Stabilization for KETEK SiPMs

- KETEK W12 & PM3350 SiPMs show non linear V vs T dependence

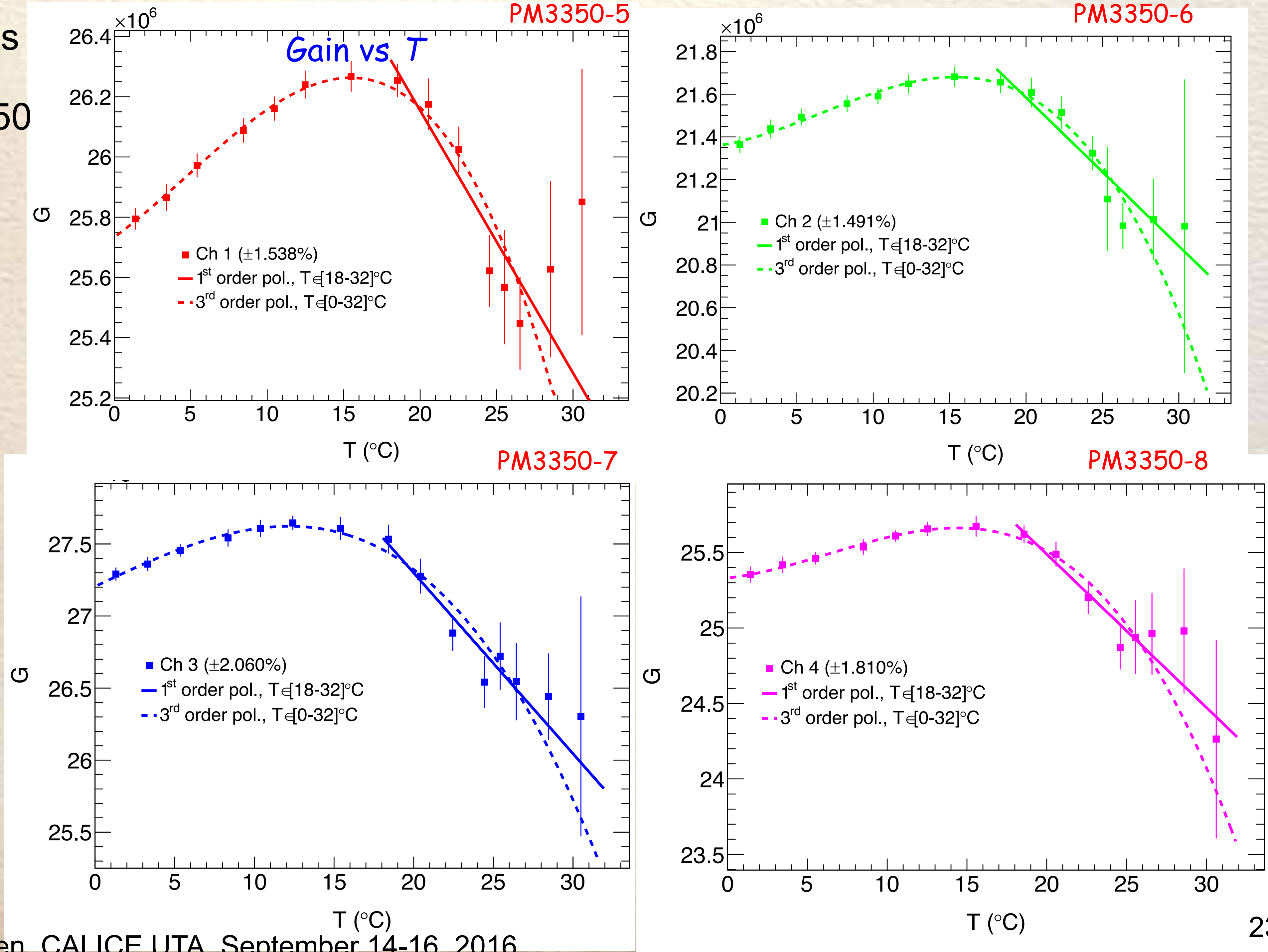
Average over all points



Test of Gain Stabilization for KETEK SiPMs

Average over all points

- Results for PM3350 SiPMs



Gain Stabilization of KETEK SiPMs

- The 5°C -15°C *T* range is better stabilized
  ➔ Here 6 of the 8 SiPMs are non-uniform to less than ±0.5%