# SenSL C-Series SiPMs Characterization

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# Outline

- Scintillation light in liquid Argon (LAr) is abundant.
- Light detection helps determine event time for non-beam related events.
- Development of photon detection system in LAr is underway.
- Silicon Photomultipliers (SiPMs) have been chosen as photon detection sensors.
- Characterizations of SenSL C-Series SiPMs will be discussed in details in terms of their gain, dark rate, cross talk and afterpulse rate.

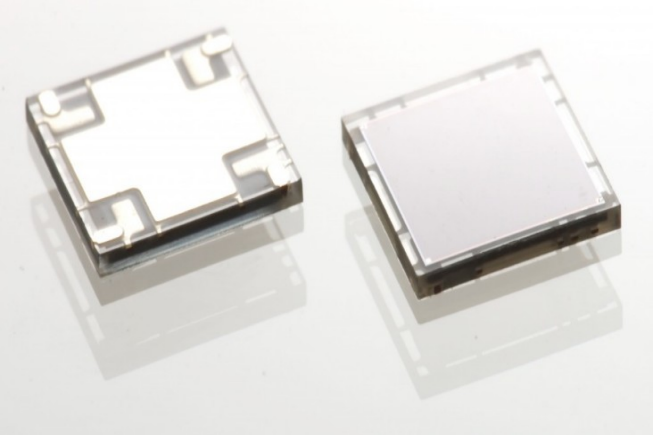
# Photon Detection

- Liquid argon is an excellent scintillating medium.
- The light yield of LAr is about 24,000 photons/MeV at 500 V/cm.
- Roughly 1/3 of the photons are prompt 2-6 ns and 2/3 are generated with a delay of 1100-1600 ns.
- LAr is highly transparent to the 128 VUV photons with a 95 cm Rayleigh scattering length and >200 cm absorption length.
- The embedded TPB or bis-MSB wavelength shifter on the surface of the detection modules absorbs and re-emits light at 425 nm which is detectable to the photon sensors.


- The relatively large light yield makes the scintillation process an excellent candidate for determination of event time t0 for non-beam related events.
- Detection of the scintillation light may also be helpful in background rejection.

# Silicon Photomultiplier (SiPM)

- SiPM is an array of Geiger-mode photon sensors.
- Single photon sensitivity.
- High gain (comparable to conventional PMT).
- UV through NIR sensitivity.
- Low operation voltage.
- Low cost comparing to conventional PMT.
- Temperature stability.
- Uniformity of the output response.
- Cannot be demaged by stray light.
- Scalability.
- Electromagnetic immunity.



# Current Most Desirable Candidate: SensL B/C-series 6 mm SMT SiPM

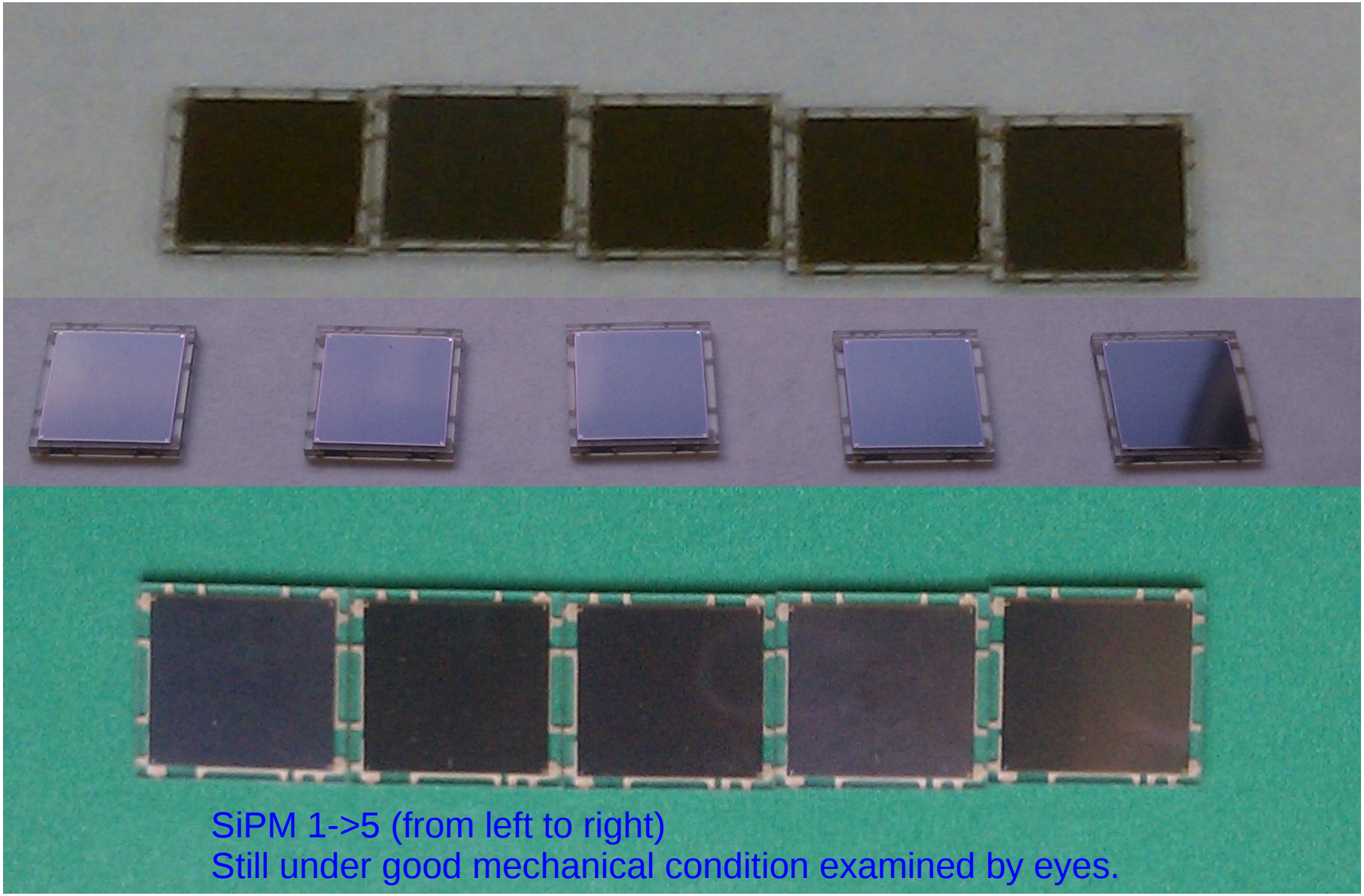
- C-Series is pin-for-pin compatible with the B-Series which are being used for 35t.
- Ultra-low dark count rates of 1.2 MHz comparing to 21.5 MHz for B-Series.
- Exceptional breakdown voltage uniformity at 24.65±0.25 V.
- 300 to 800 nm spectral range.
- 40% PDE at 420 nm (5 V overvoltage).
- Fast output feature: 1 ns rise time and 3.2 ns pulse width for multi-photon resolution capability.

# Data Sheet at Room Temperature 21$^{o}$C

- SenSL has characterized their products in room temperature. Since they will be used in LAr, we will test them in liquid Nitrogen ($LN_2$) which has similar temperature(~10$^{o}$C lower than LAr).
- Gain = 3 x $10^6$ ($V_{br}$ + 2.5 V) (Standard output)
  - Temperature dependence of Gain = -0.8%/$^{o}$C
  - Expected Gain in liquid nitrogen = 3 x $10^6$ x $(1+0.8\%)^{(21+196)}$ = 1.69 x $10^7$
- Cross talk = 7% ($V_{br}$ + 2.5 V) (Standard output)
- Afterpulsing = 0.2% ($V_{br}$ + 2.5 V) (Fast output)
- Dark rate = 1.2 MHz ($V_{br}$ + 2.5 V) (Standard output)
- $V_{br}$ = 24.65 V
  - Temperature dependence of $V_{br}$ = 21.5 mV/$^{o}$C
  - Expected $V_{br}$ in liquid nitrogen = 24.65 – (0.0215)x(21+196) = 19.98 V
- Meanwhile, the number of cycles and total time in the $LN_2$ have been logged for all SiPMs under test to check their durability.

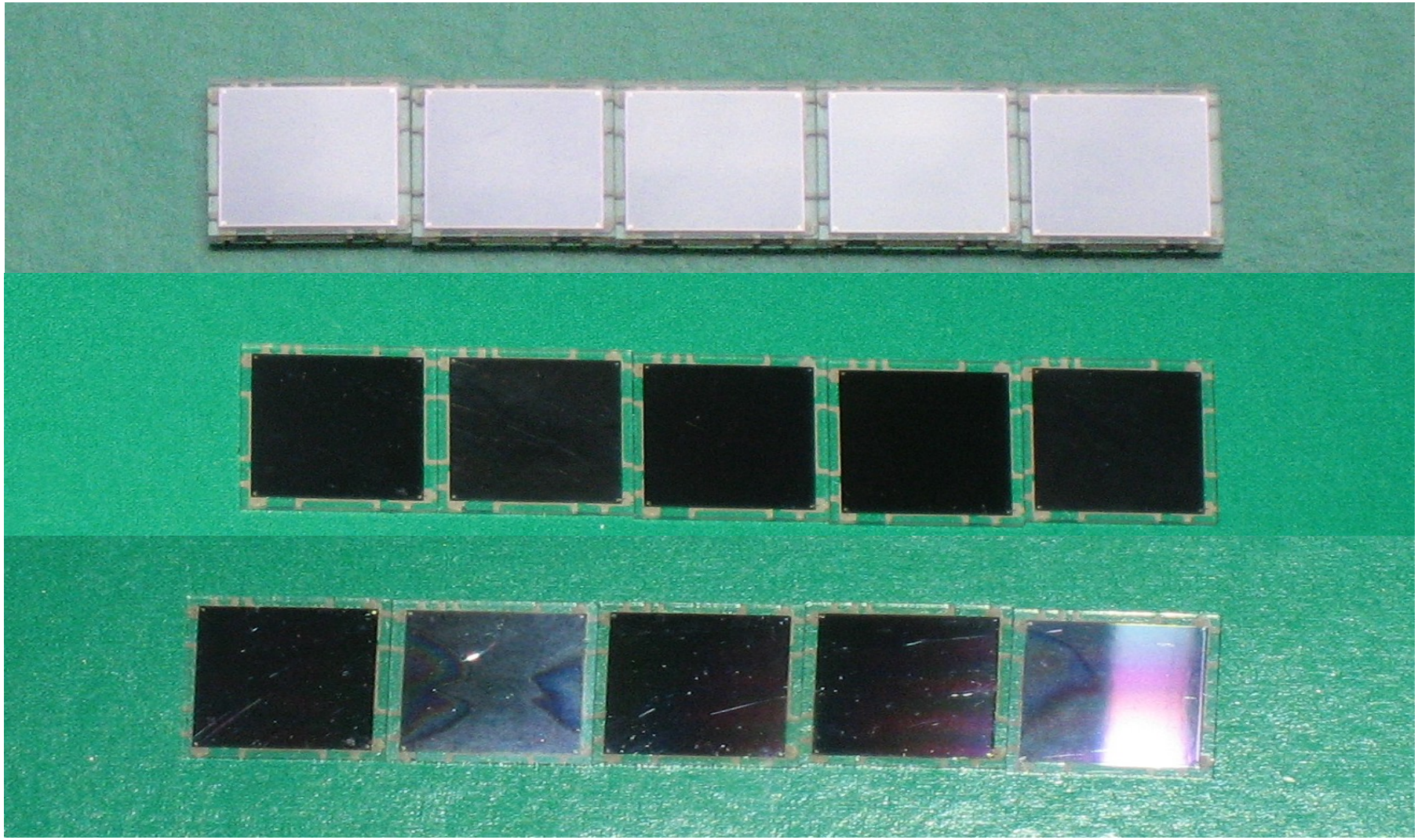
## Cryostat ($LN_2$) History and Photos of All 5 SiPMs By Dec 27th 2014)

| SiPM # | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Cycles | 16 | 12 | 11 | 5 | 4 |
| Hours | 154.6 | 117.1 | 109.1 | 45.5 | 37.5 |



## Cryostat ($LN_2$) History and Photos of All 5 SiPMs by Jan 15th 2015

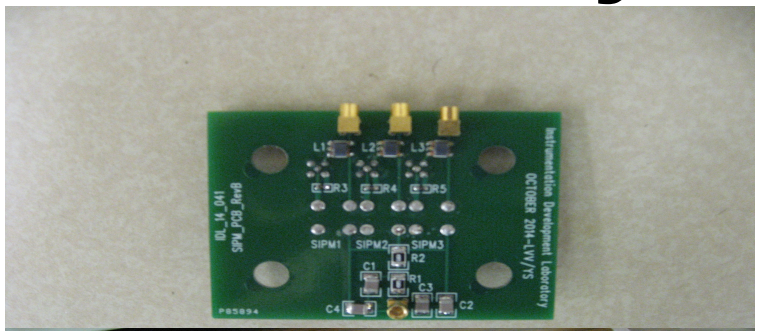
| SiPM # | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Cycles | 21 | 17 | 20 | 11 | 12 |
| Hours | 207.1 | 169.6 | 188.5 | 96.4 | 112.4 |

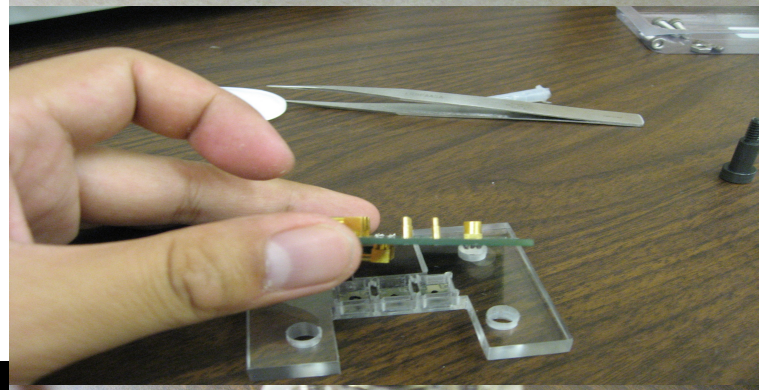


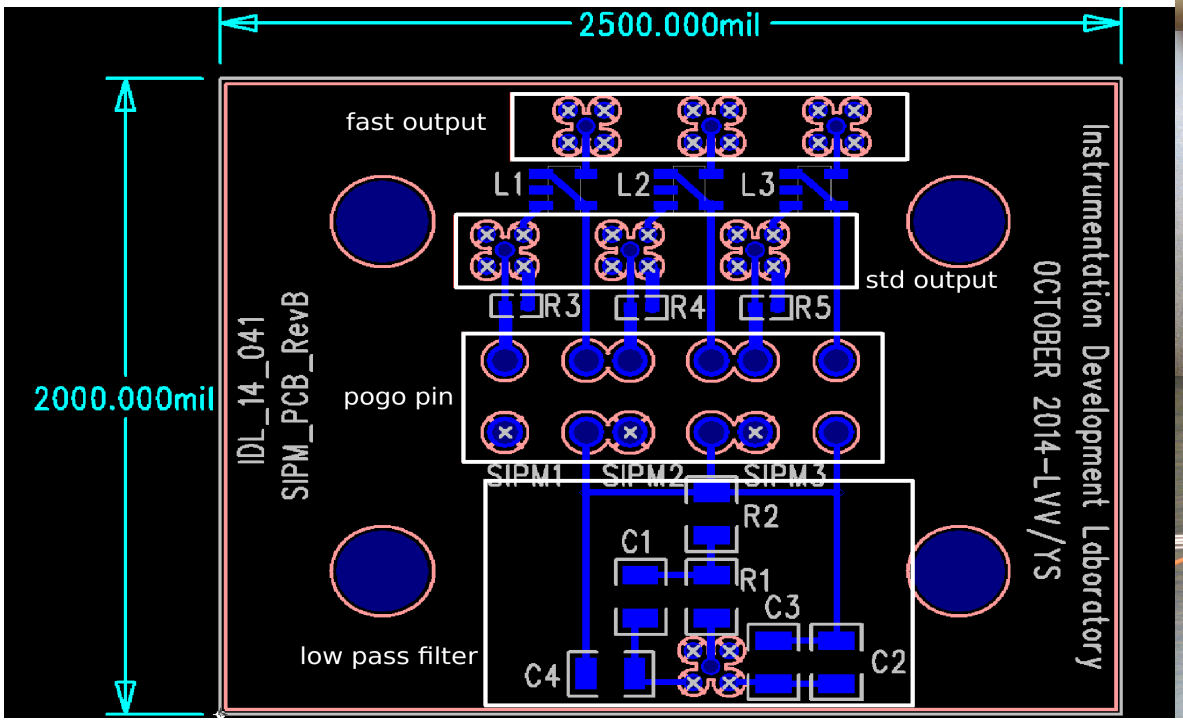
Spots and scratches are observed when shined from certain angle. We are ordering a microscope for better visual examination. So far, we have not observed any effect on optical performance caused by the mechanical condition.

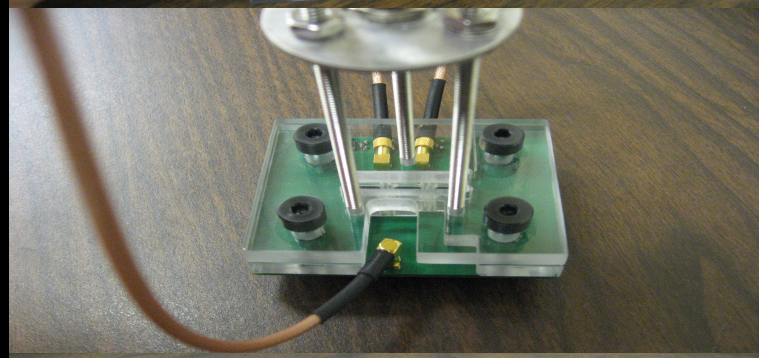
# PCB Design and Cryo Assembly

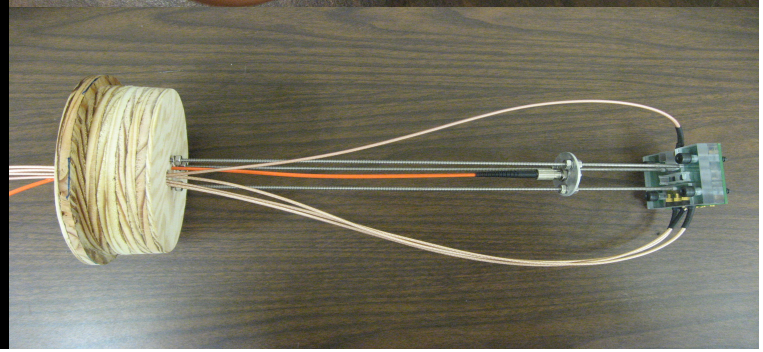
- Connections to SiPMs are via pogo pins by mechanical pressure (no need to solder).
- Three SiPMs can be tested at a time.
- Low pass filter on the PCB.
- The polycarbonate holder with the same dimension as the PCB.
- Nylatron shoulder screws and nylon hex nuts locked.
- MMCX to SMA cables go through top lid.
- Optic fiber (orange) for external light source.





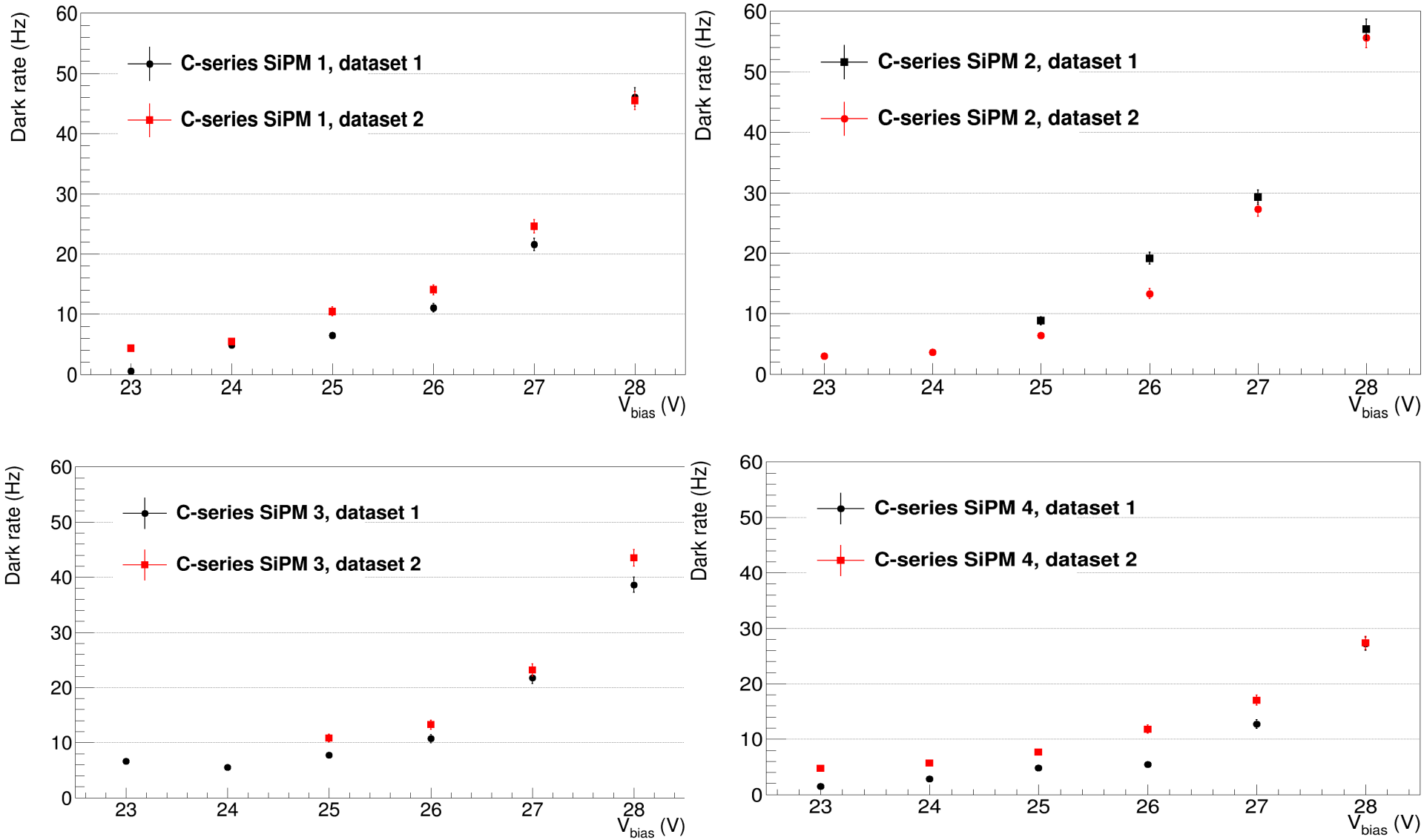


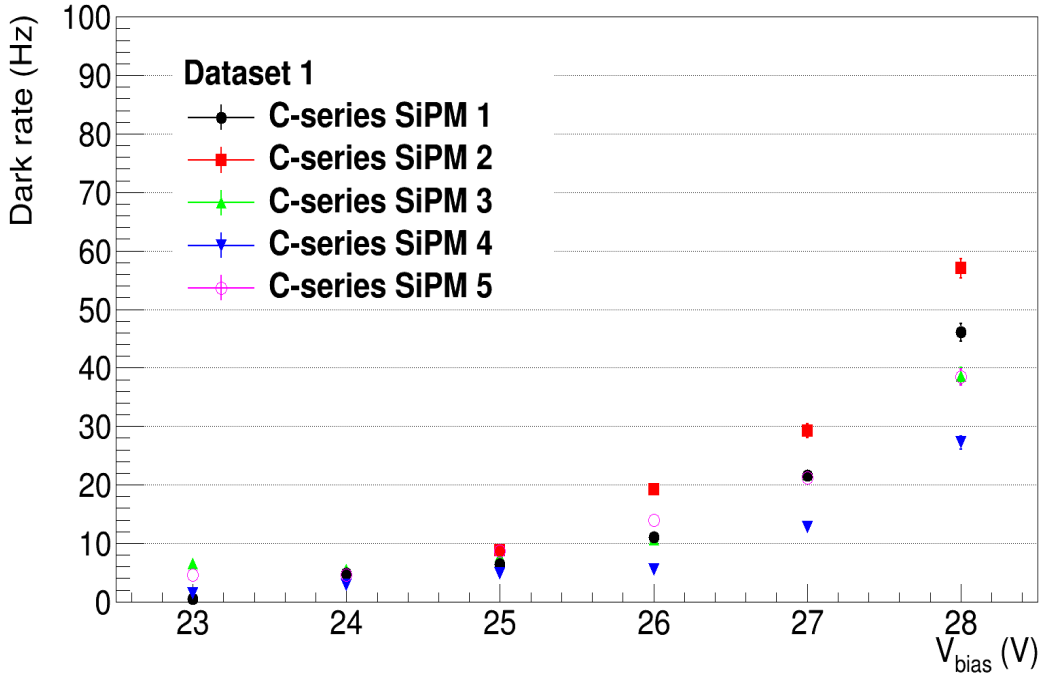



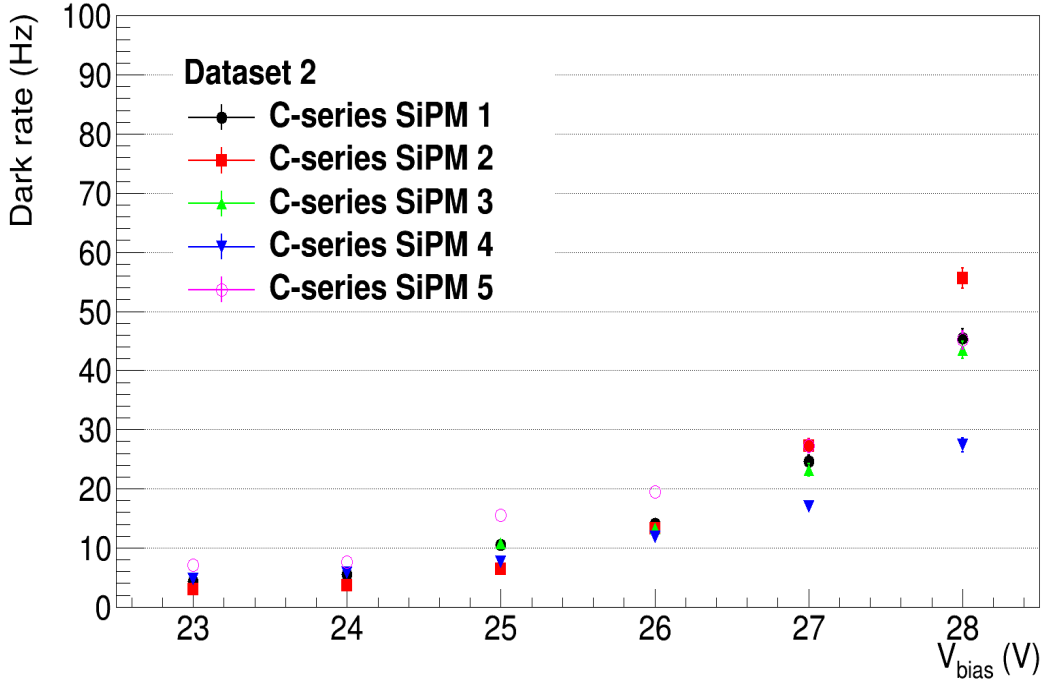


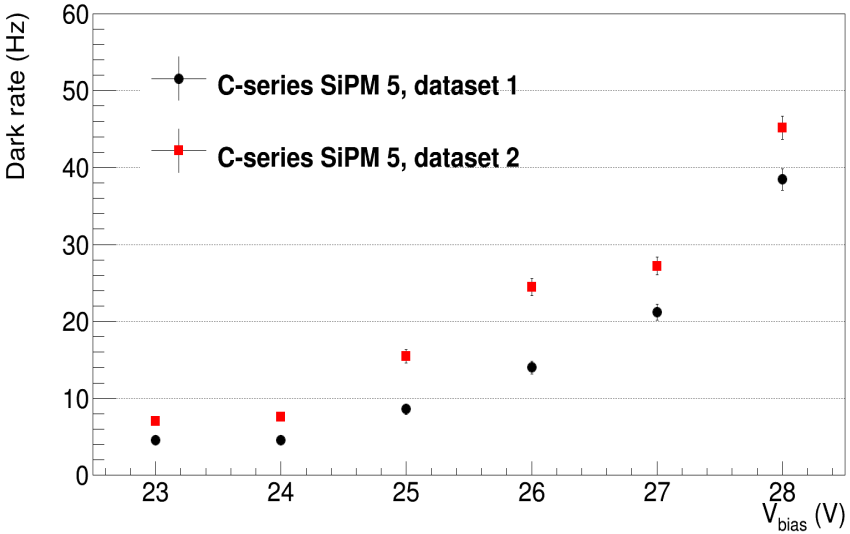
# Dark Rate for SiPM 1~4

- Randomly triggered dark rate data were taken with 10,000 X 2 ms window, 20 s in total.
- The data can be used in characterizing dark rate, gain and cross talk.
- Offline processing with threshold 0.35 mV.





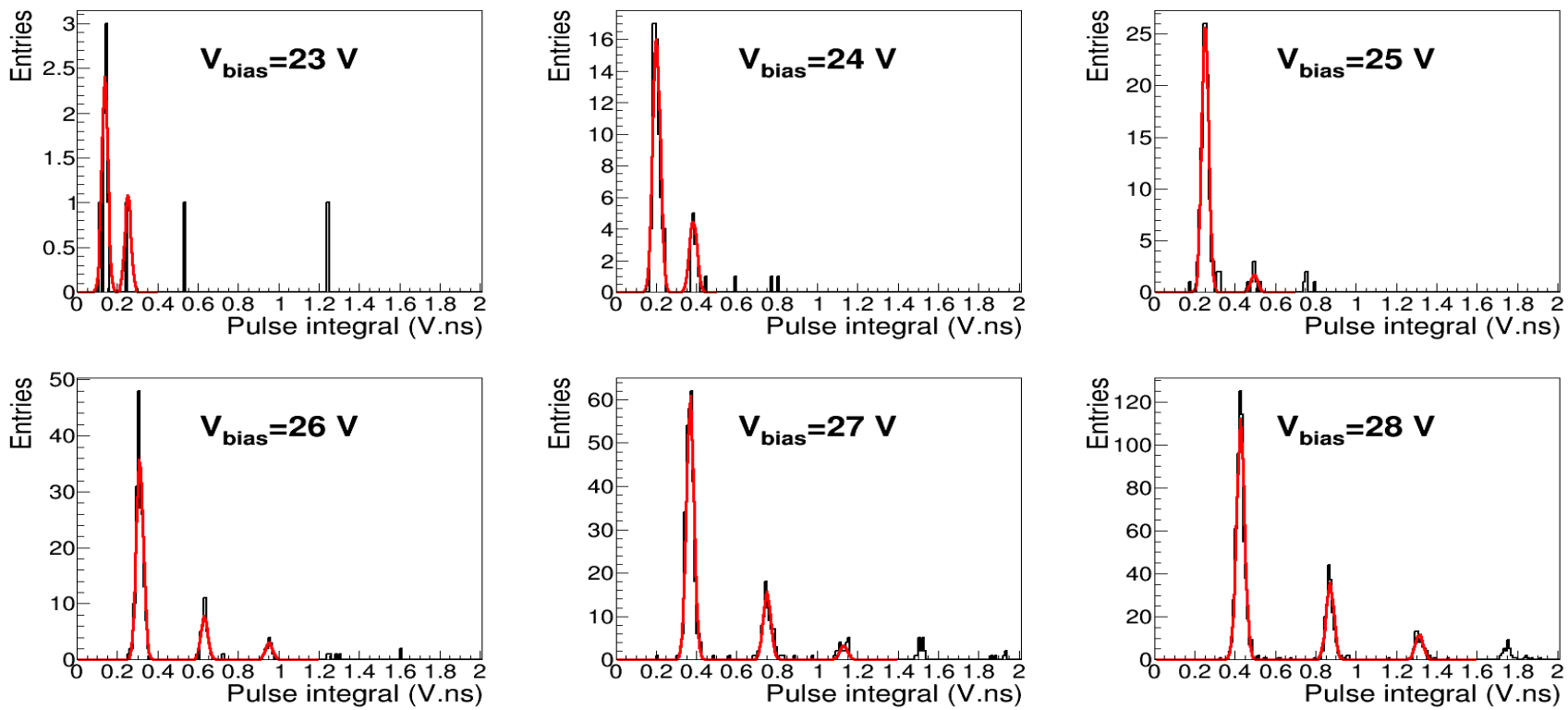



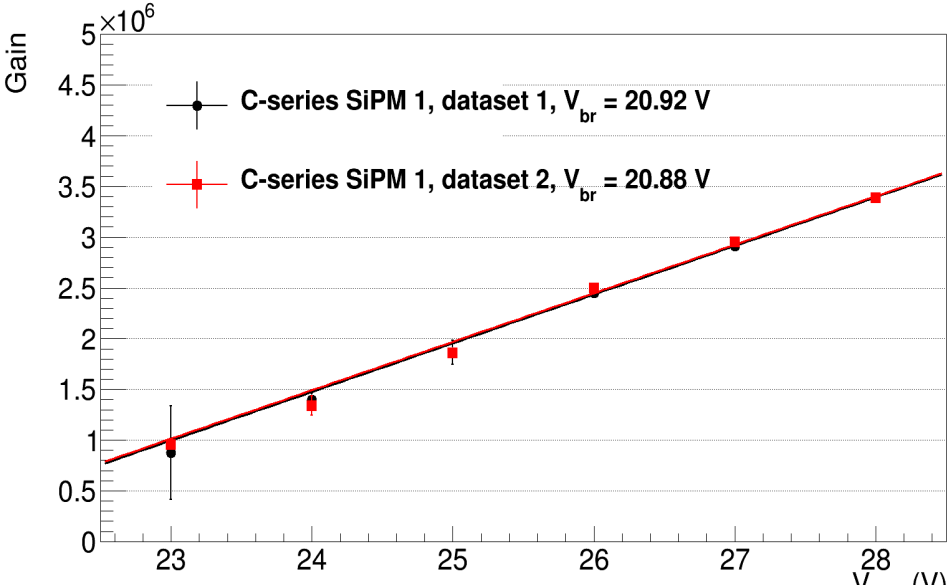

- The dark rate is extremely low for SiPMs in the cryogenic temperature.
- SiPMs running at 26 V (~5 V overvoltage in cryostat from linear extrapolation) generates only less than 20 Hz dark rate.
- There are some variations from SiPM to SiPM.

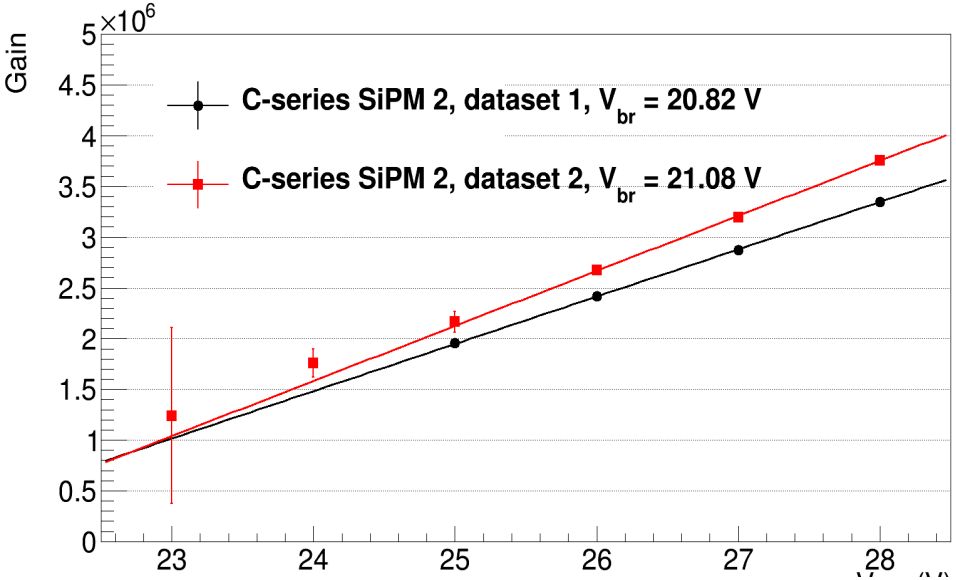
# Gain

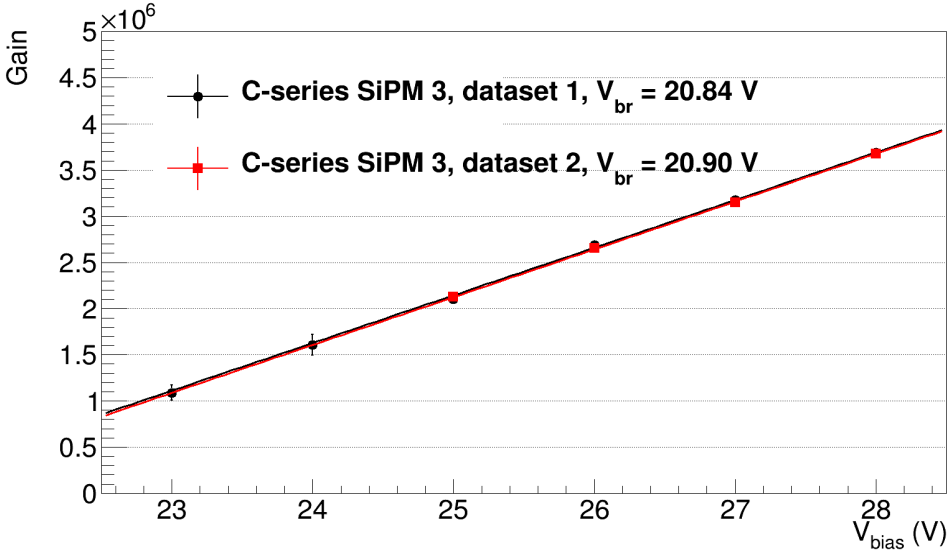
- Fit the dark rate pulse integral for the gain as shown below for SiPM 1.
- Pulse integral is summed from the pulse peak to both left and right until hitting an entry that is smaller than the baseline.
- Gain = $\int U(t)\cdot dt / (R \cdot e \cdot A)$, where R = 50 Ω is the impedance, electron charge e = $1.6 \times 10^{-19}$ C and amplification A.

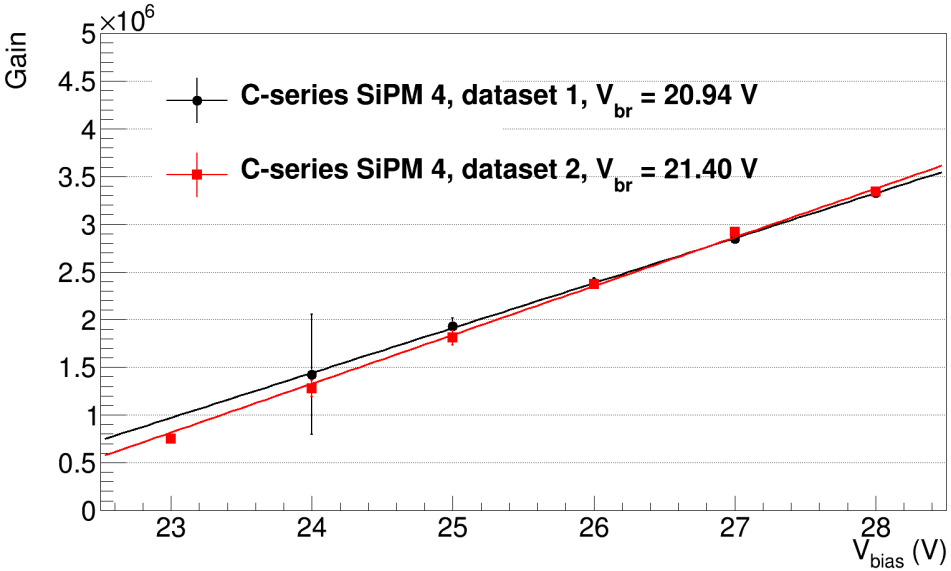


# Gain for SiPM 1~4

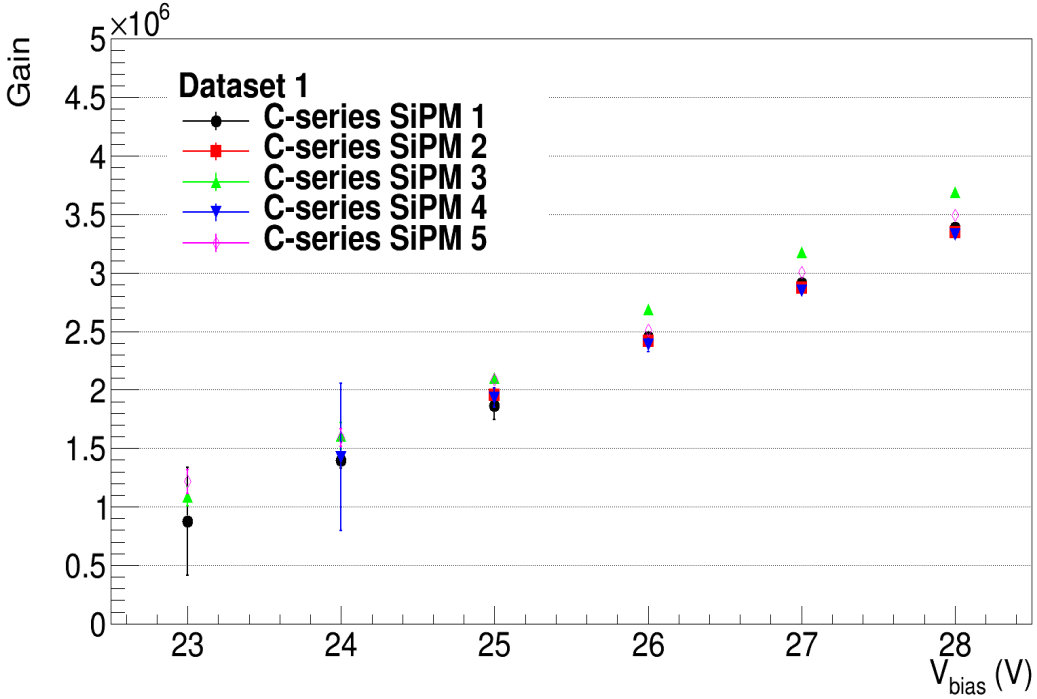


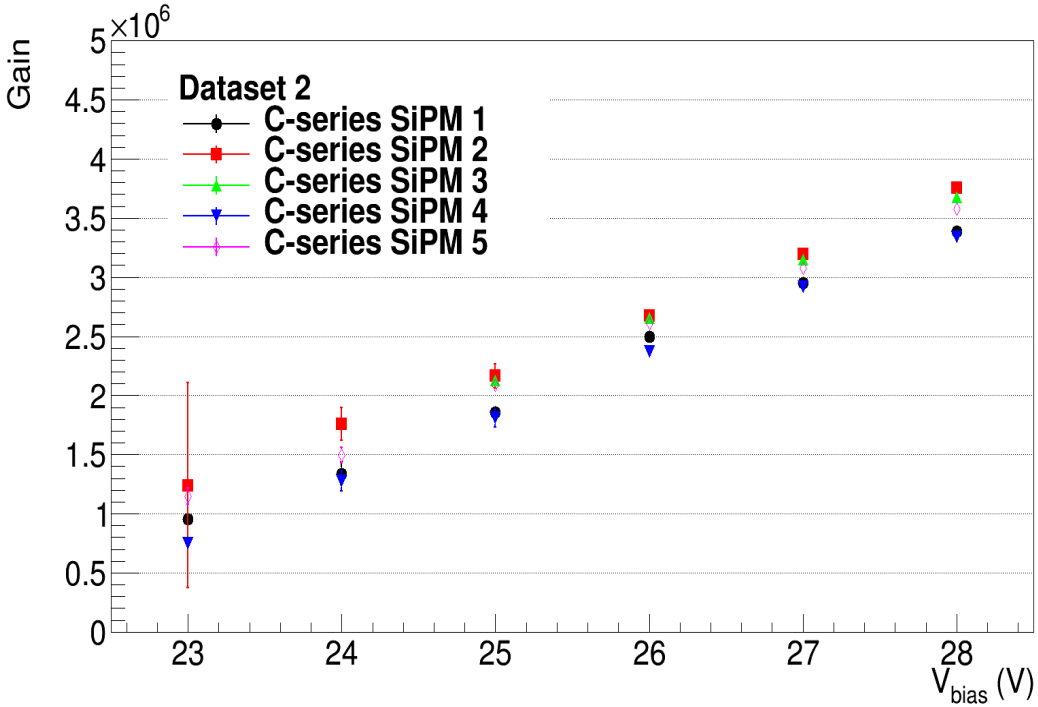



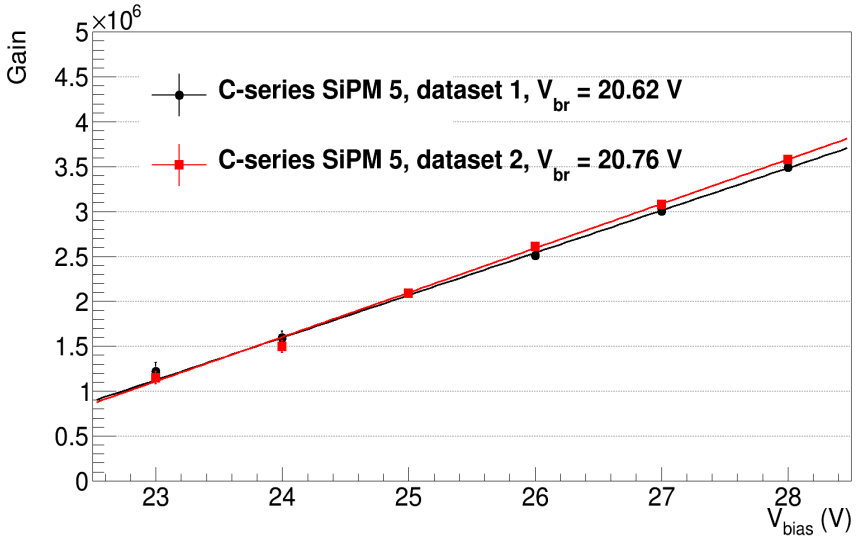




Pretty good consistency for two datasets.
Breakdown voltages are extrapolated to be ~21 V. Good uniformity.

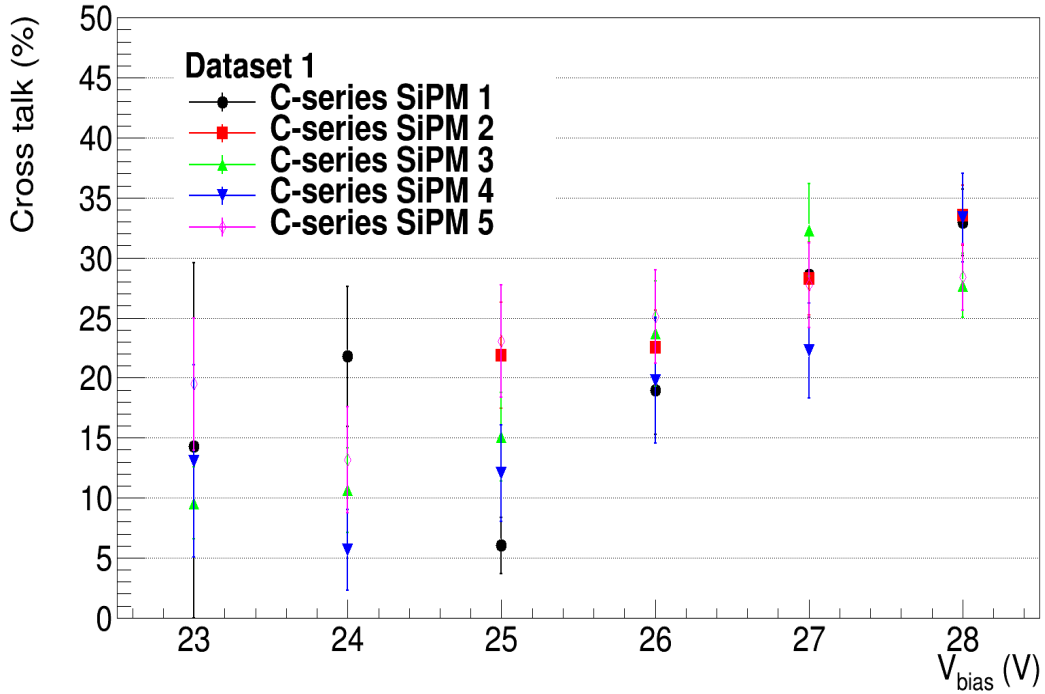


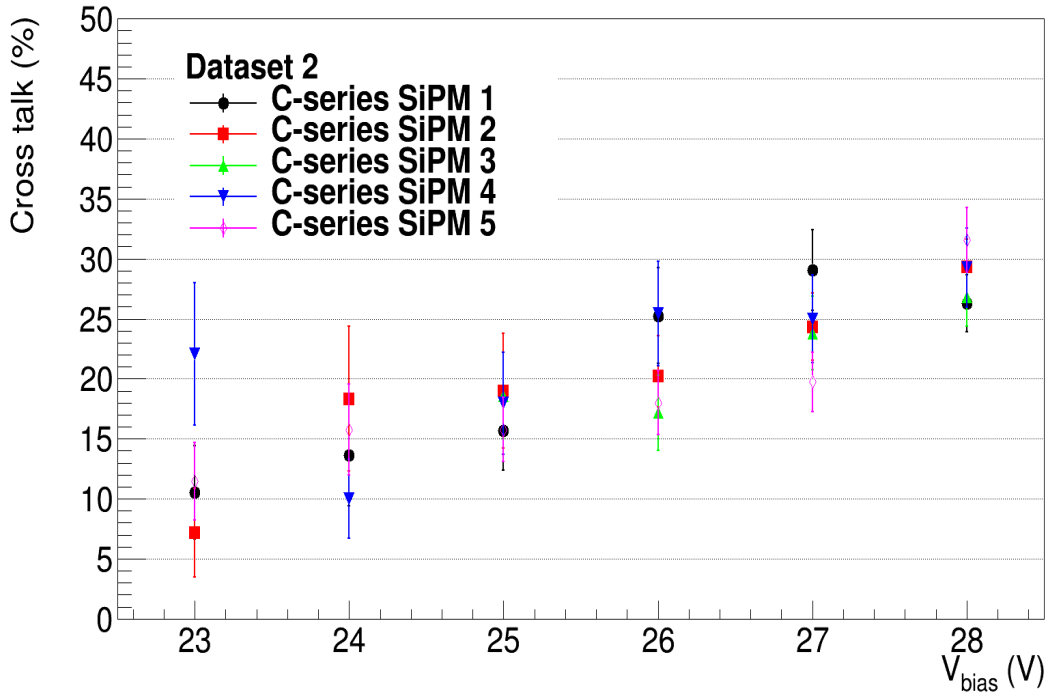



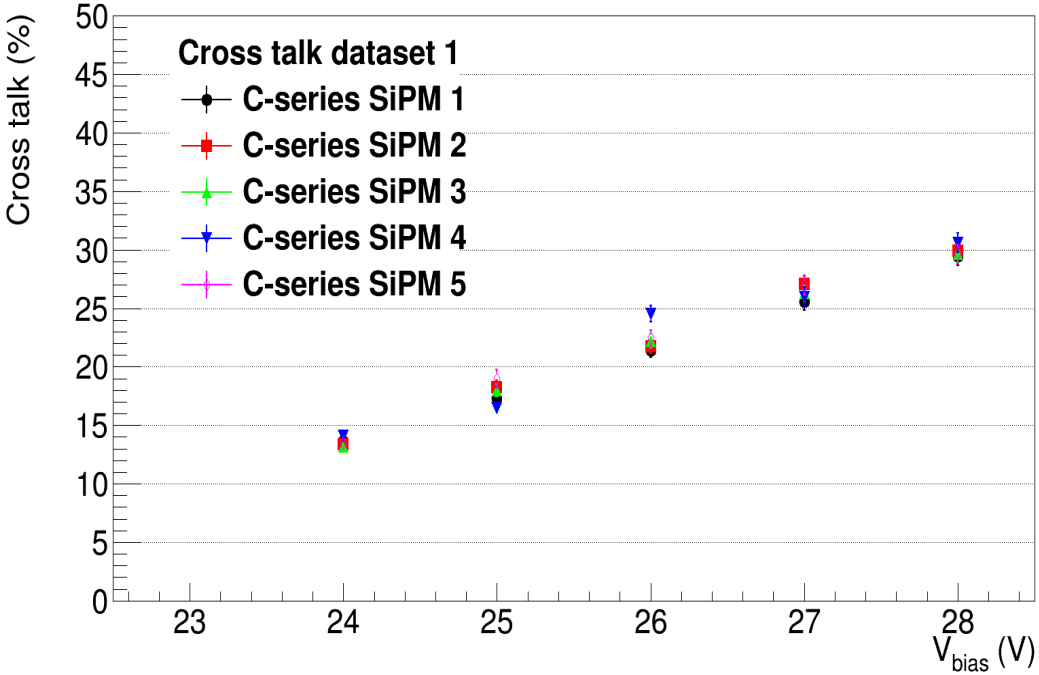

- The gain variations for 5 SiPMs are not large. A later test using cross talk dedicated data (more statistics and the same amplifier for all SiPMs) shows an even better agreement.
- The extrapolated breakdown voltage exhibits good uniformity around 21 V.

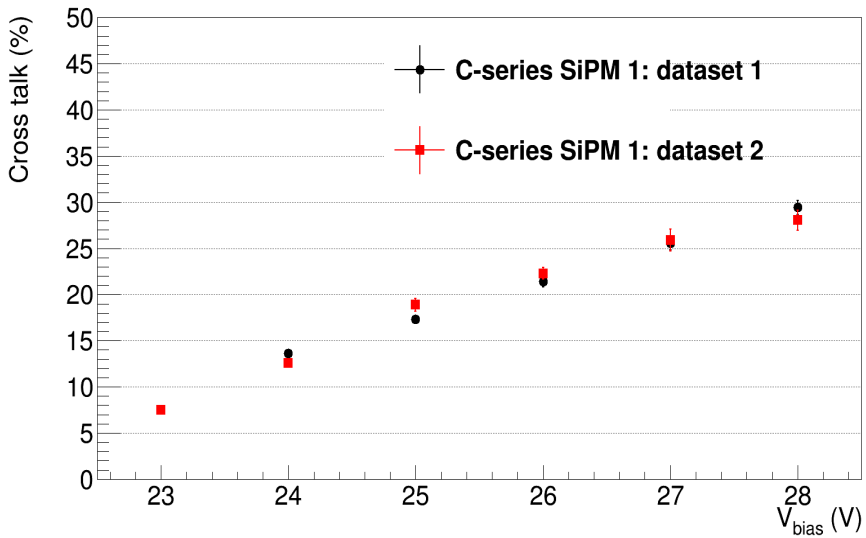
# Cross Talk

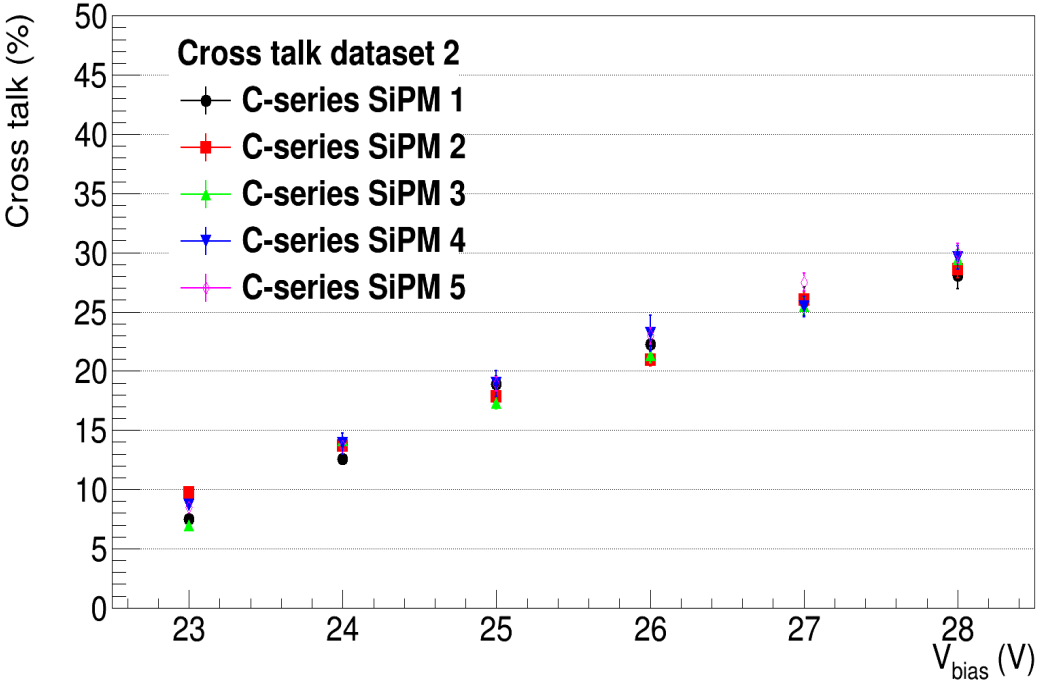



- Using the same data sets, cross talk is calculated as the ratio of the number of 2 PE to 1 PE pulses.
- Due to lack of statistics, the error bars especially on low bias voltages are large.
- Later study turns out these trends are around the ball park.



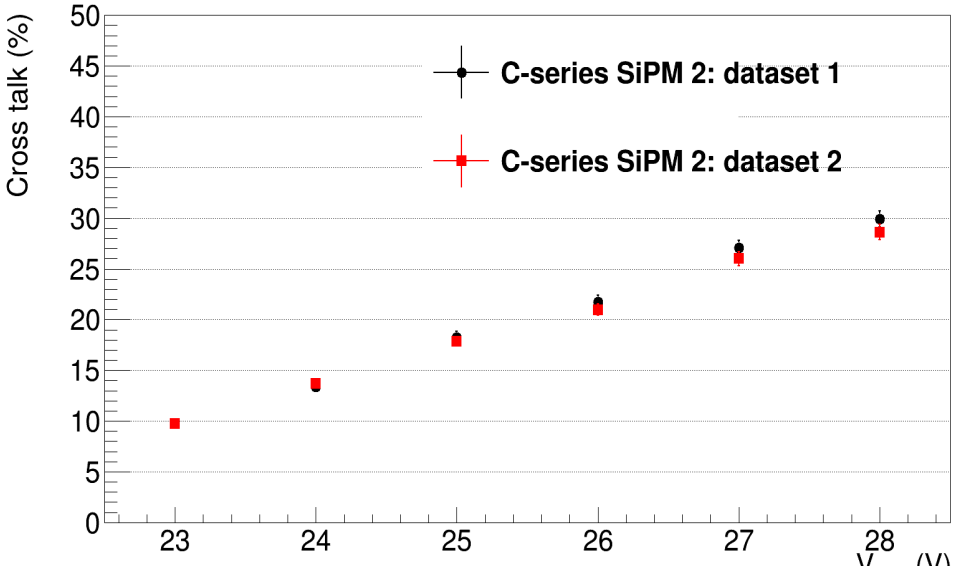



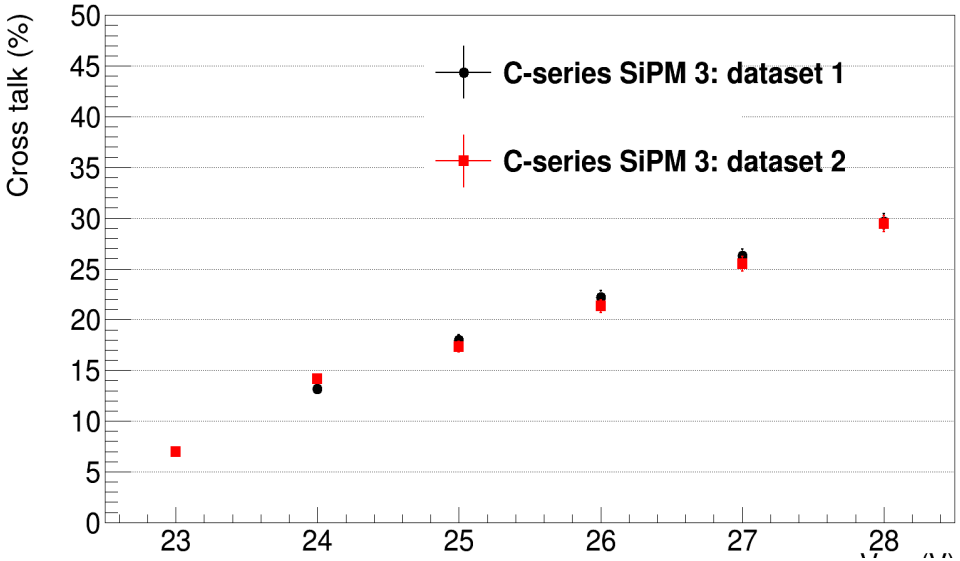



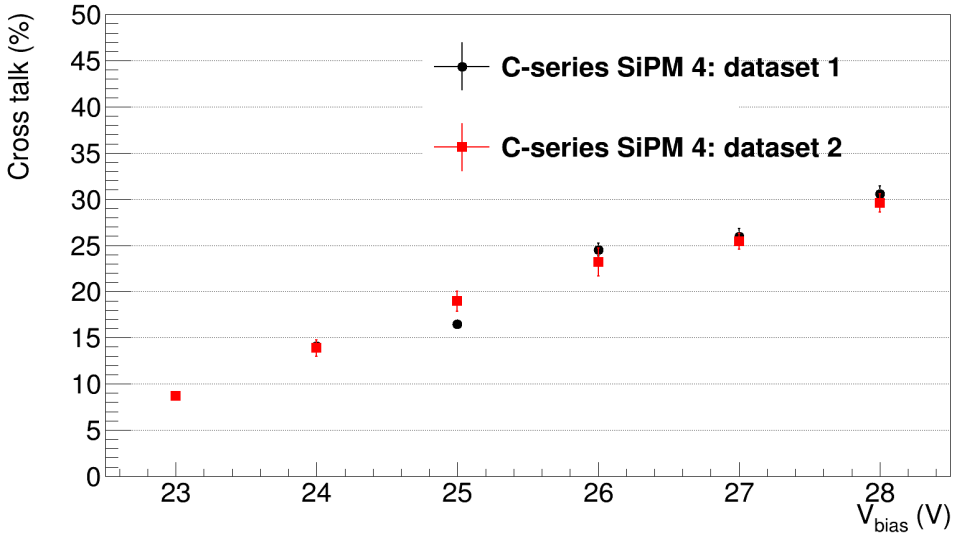

# Cross Talk Dedicated Data

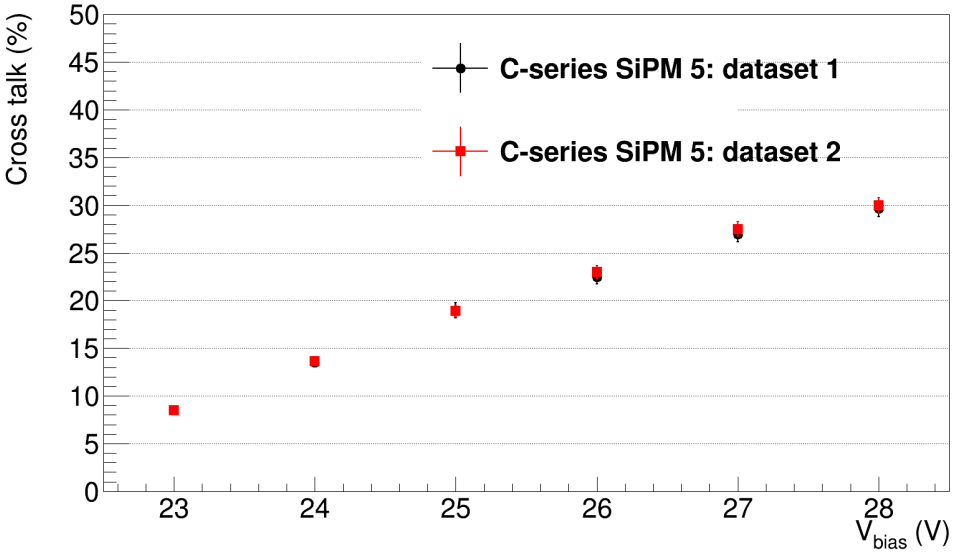
- Two sets of 10,000 dark noise triggered data were taken for more statistics on cross talk. The data can also be used in characterizing the gain.
- The single PE trigger rate has been estimate for each bias voltage to be 100% except 23 V which is about 90%. Corrections have been applied in dataset2.

# Cross Talk for SiPM 2~5



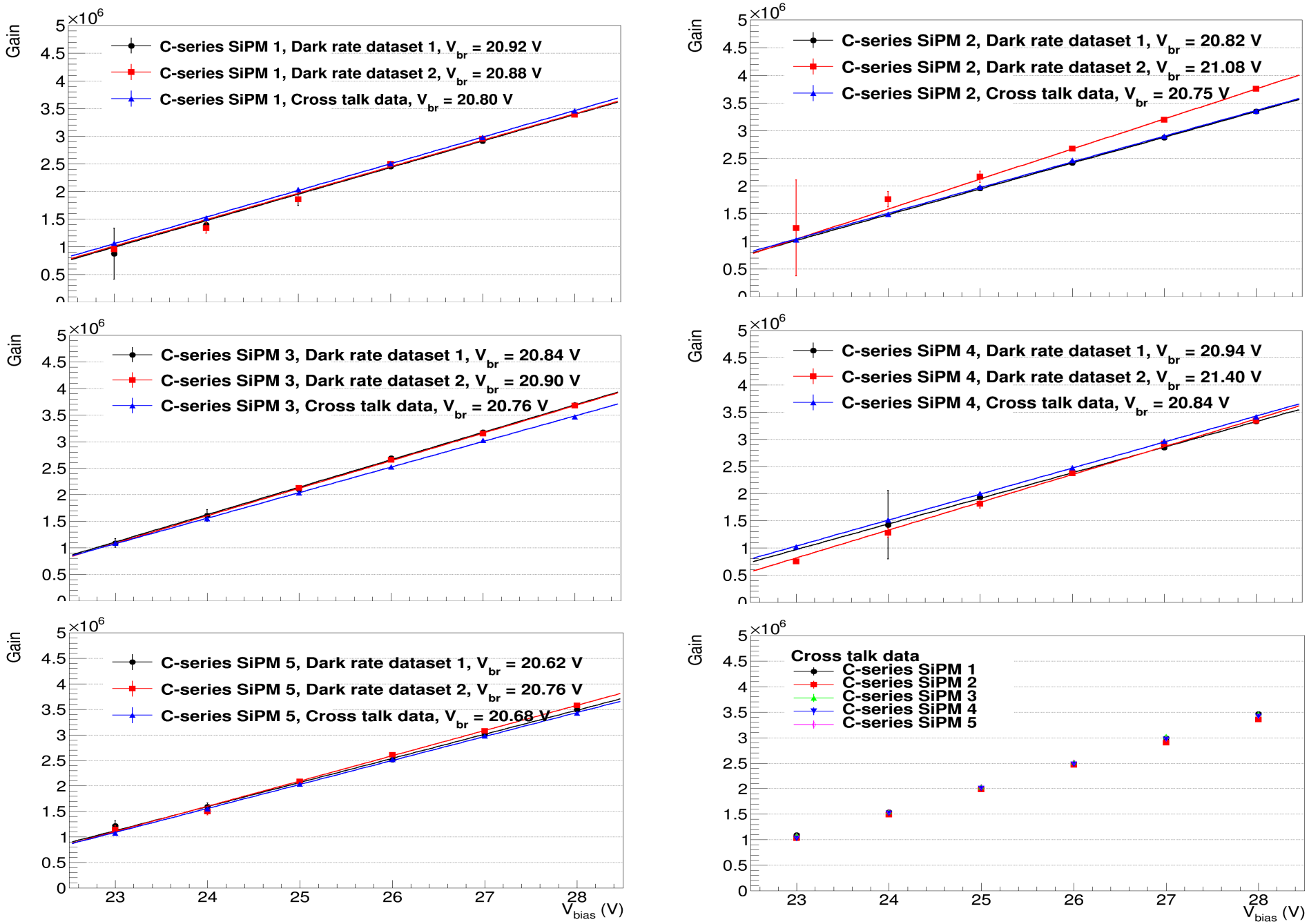




Great consistency on cross talk for two datasets.
Interpolated value at 23.5 V is a little higher than 7%. We will check it with SenSL.

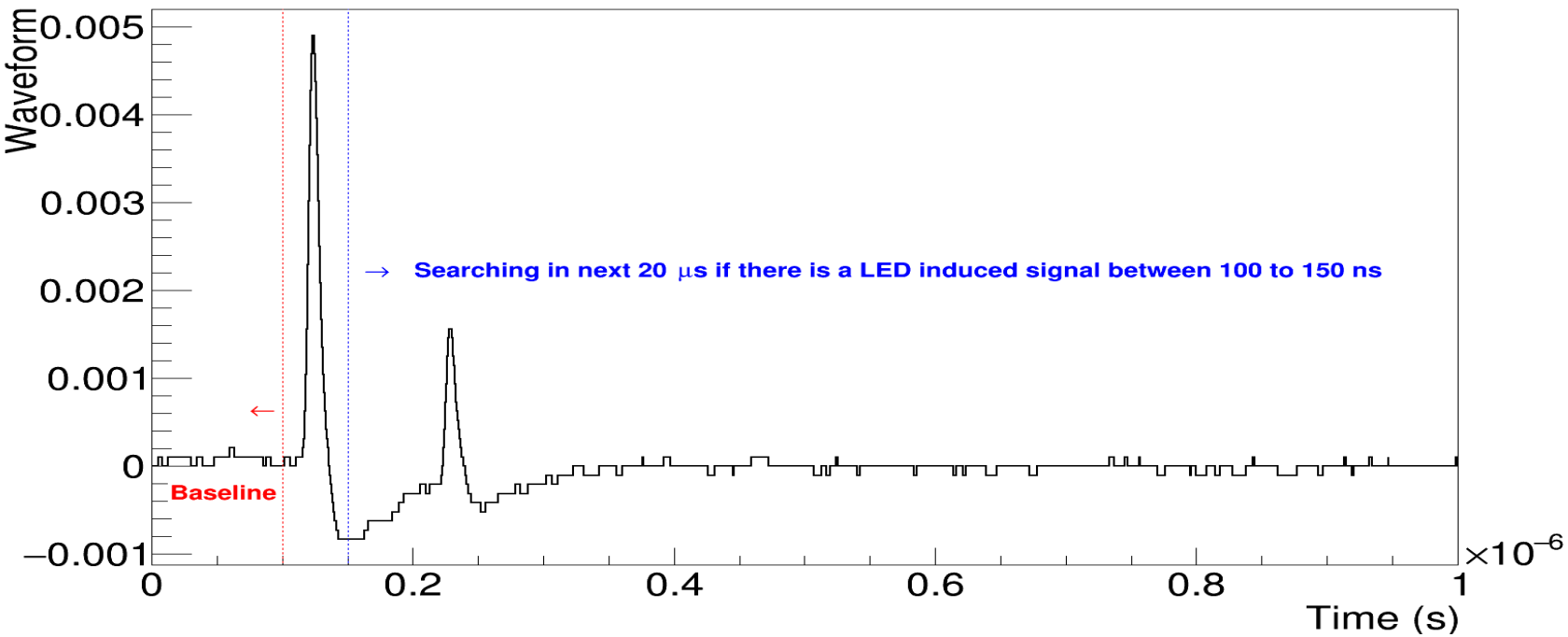
# Gain Comparison



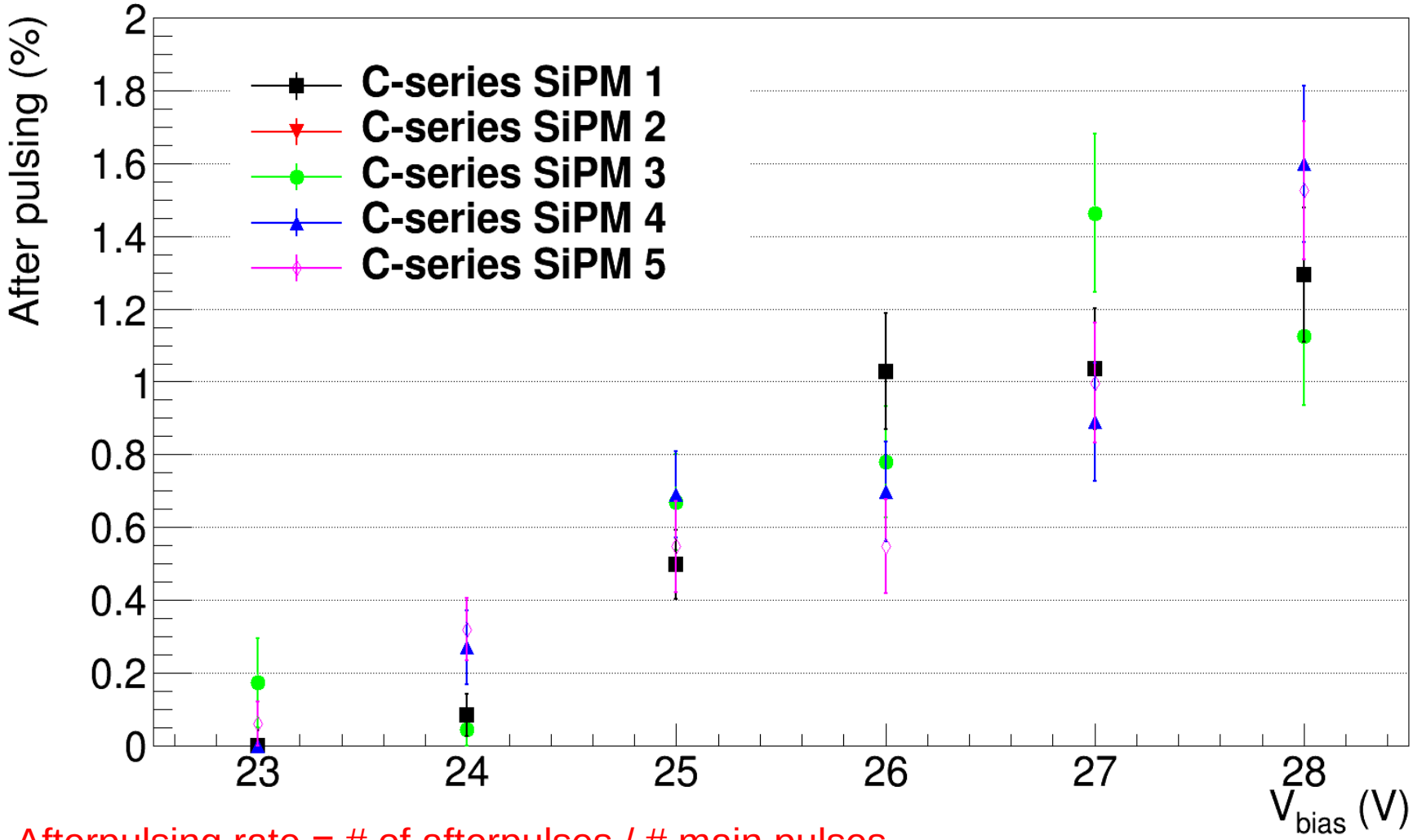

Great consistency in gain for both dark rate and cross talk data.

# Afterpulsing

- The afterpulsing data were taken with LED induced pulses with very low light intensity.
- Fast output data have been used for afterpulsing studies.
- The LED pulse position is always around 120 ns (as shown in the following figure), so the baseline is calculated from 0 to 100 ns.
- Afterpulse searching is from 150 ns to 20 μs if there is a LED pulse between 100 and 150 ns.
- The pulse time is defined as the first bin above the threshold which is 0.35 mV. If the afterpulse is within 200 ns after the main pulse, they share the same baseline; otherwise, the baseline will be recalculated.



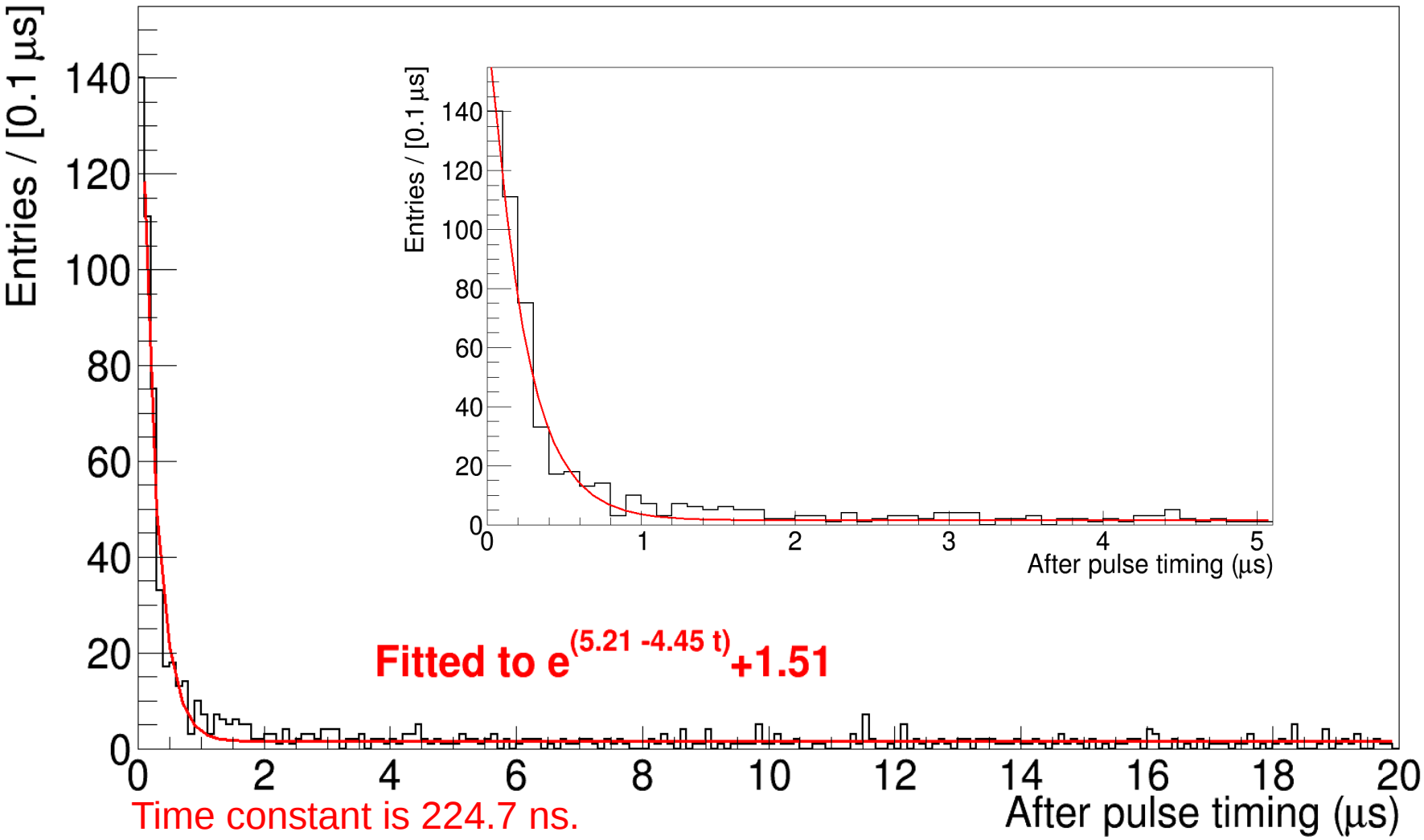
# AfterPulsing




Afterpulsing rate = # of afterpulses / # main pulses

More or less overestimated because only main pulses >= 1 PE are counted. No matter how low the light intensity is, there will be always certain fraction of multiple PE.

# Afterpulse Timing



# Conclusion

- The SenSL C-Series SiPM characterization results seem consistent with data sheet considering cryogenic temperature.
- Two sets of data show good consistency in terms of gain, dark rate and cross talk.
- There are some SiPM to SiPM variations in dark rate while the variation is relatively small for the gain.
- The extrapolated breakdown voltage shows good uniformity around 21 V.
- The afterpulsing rate agrees with data sheet which is extremely small.

# More SiPM Testing

- To avoid using a sole source and any potential problems associated with it, selection of at least two models from two different manufacturers is needed.

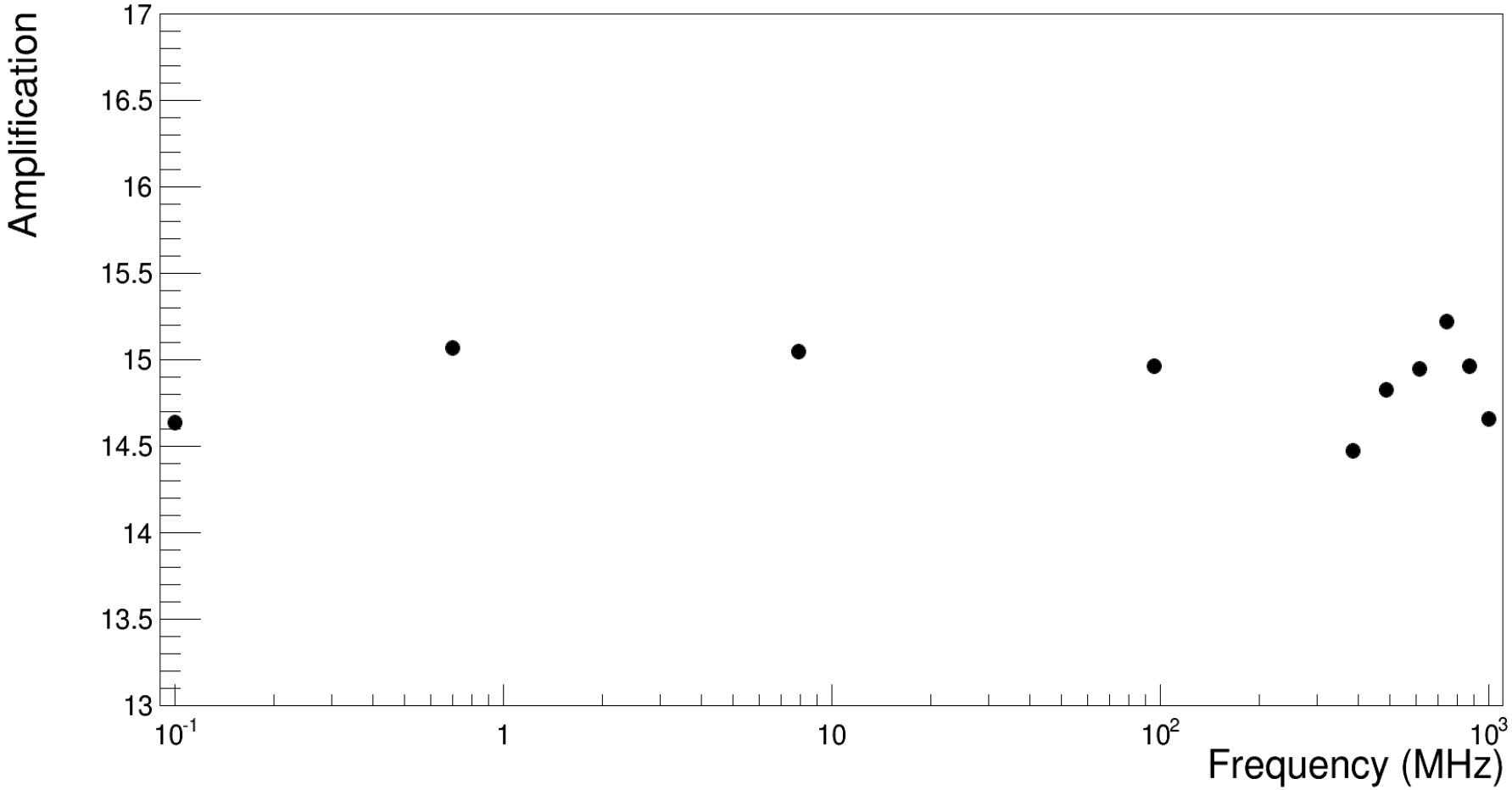
- We have received 5 NUV-SiPMs from AdvanSiD released Oct. 2014 (4X4 mm).
  - Ultra low afterpulse below 4% at very high overvoltage
  - Very low noise below 100 kHz/mm$^2$ at the maximum bias voltage
  - Detection efficiency of 43 % at 420 nm (+6 V overvoltage)
  - 350 to 900 nm spectral response range
  - Gain 3.6X10$^6$
  - Faster recovery time (70 ns cell recharge time constant)

- Even more tests are expected for SiPMs from Hamamatsu and KETEK.

# Backup Slides

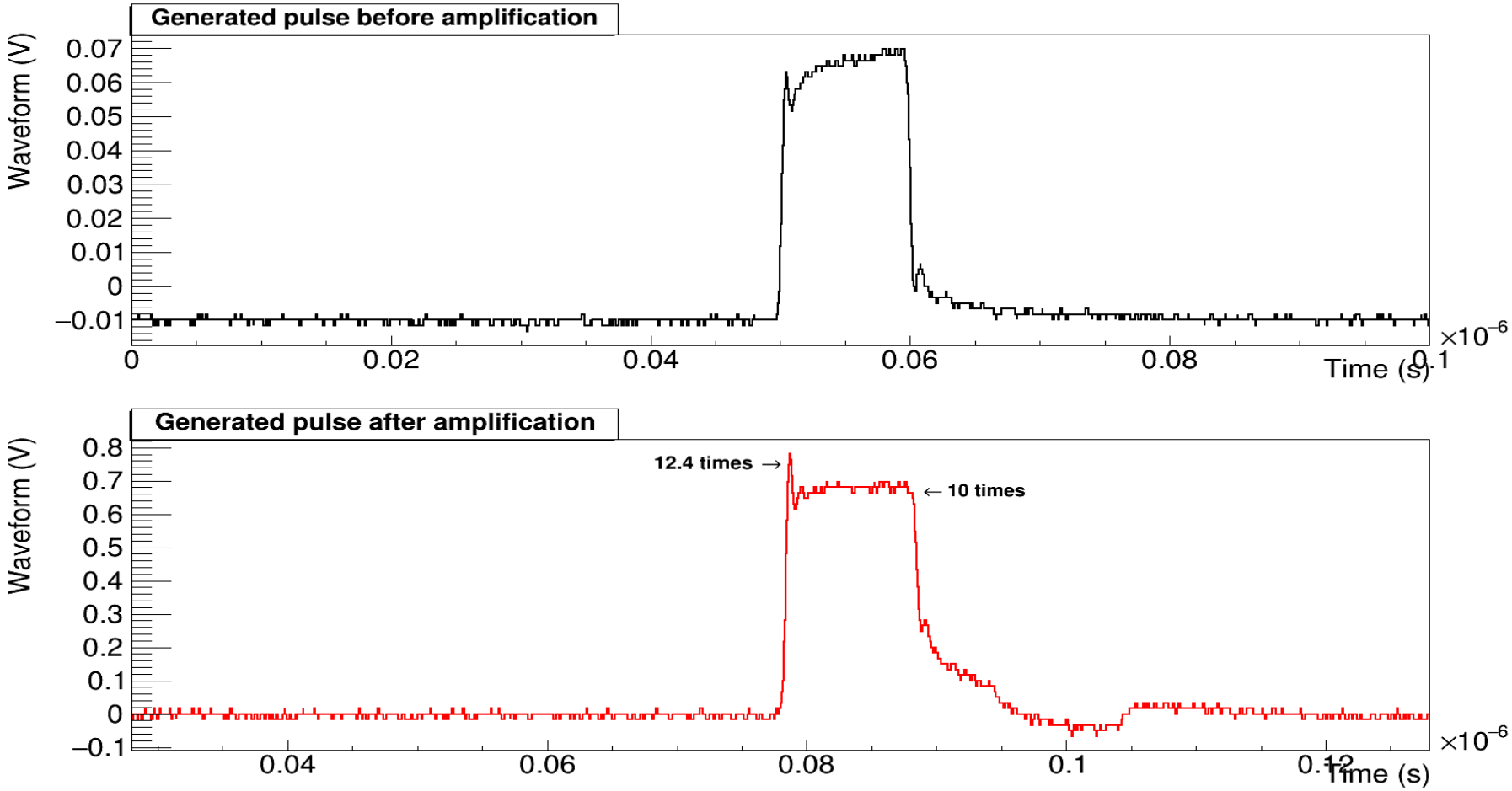
# Low Noise Amplifier ZFL-1000LN+

- The amplification from data sheet is flat over the entire frequency range.



# Amplification with Direct Connection to Pulse Generator

- Read out a 10 ns pulse w and w/o amplifier.
- The amplification is smaller and not as uniform as claimed.

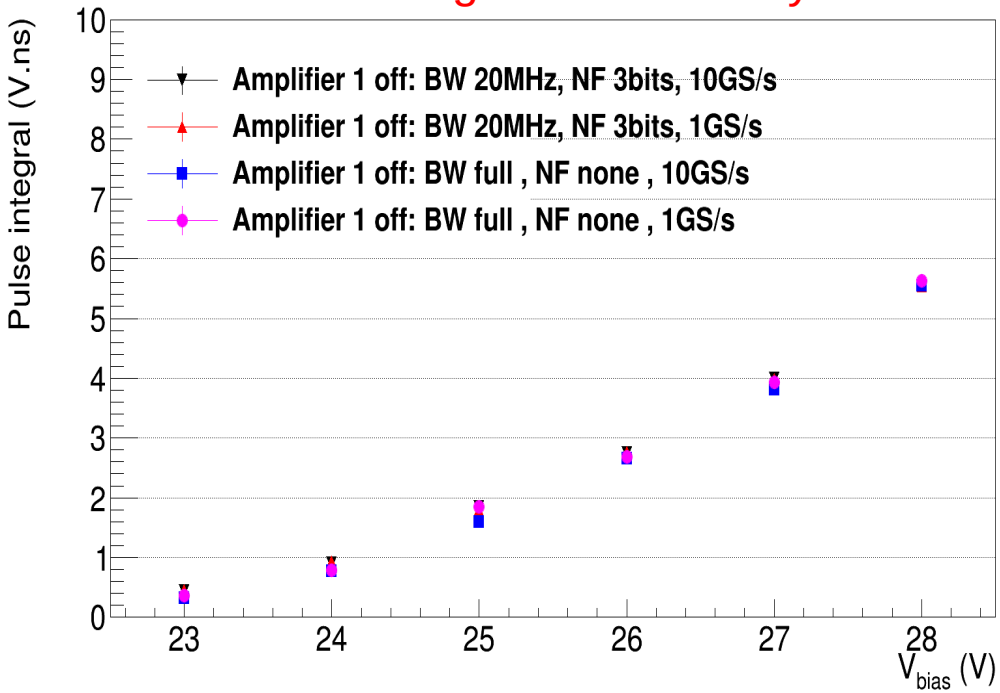


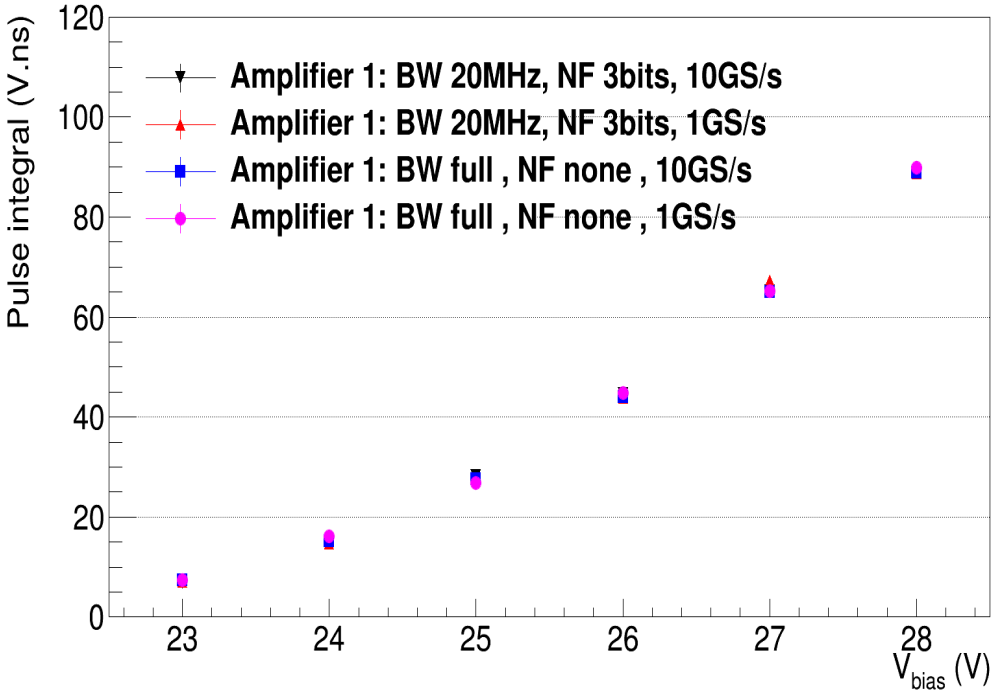
# Amplifier Calibration Using SiPM Signal from LED Pulse

Procedure: for each bias voltage, 1000 events have been taken:

1. w and w/o amplifier.
2. sampling rate: 10 and 1 GS/s.
3. w and w/o noise filters on the scope including bandwidth filter (BW) and noise filter (NF).

The noise filters on the scope filter out high frequency noise, therefore, the signal has been more or less reduced. The correction will be put back to the extracted gain if necessary.



# Amplifier Calibration Using SiPM Signal from LED Pulse

The data taken sequence:

Bias voltage: 28 V; Amplifier: on *and off
Bias voltage: 27 V; Amplifier off *and on
Bias voltage: 26 V; Amplifier: on *and off
Bias voltage: 25 V; Amplifier off *and on
Bias voltage: 24 V; Amplifier: on *and off
Bias voltage: 23 V; Amplifier off *and on

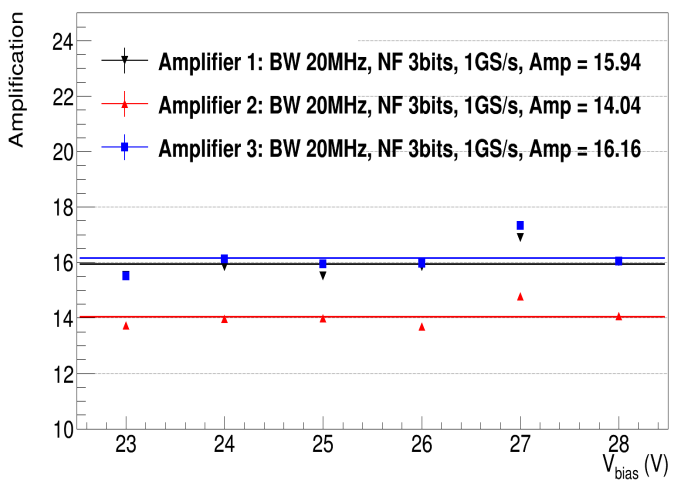
The data taken sequence:

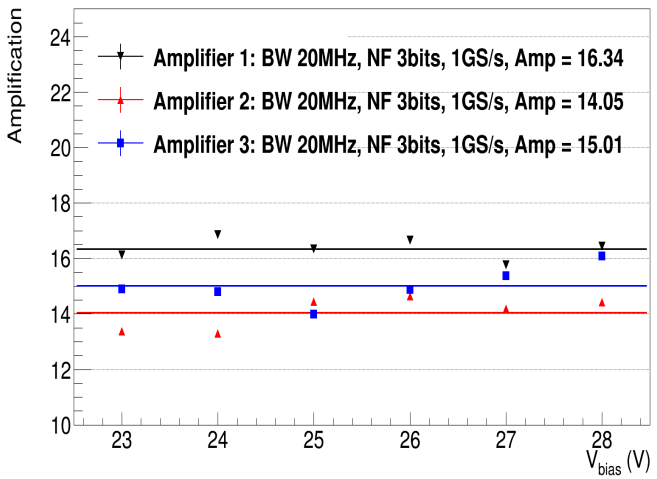
Bias voltage: 28, 27, 26, 25, 24, 23 V; Amplifier: on *
Bias voltage: 23, 24, 25, 26, 27, 28 V; Amplifier: off

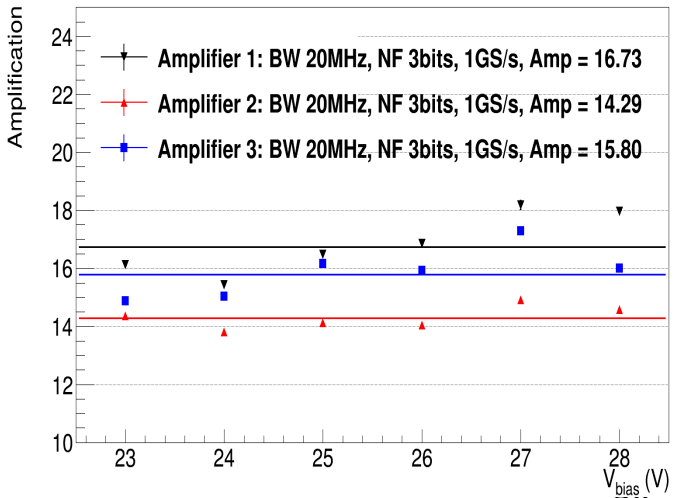
The data taken sequence:

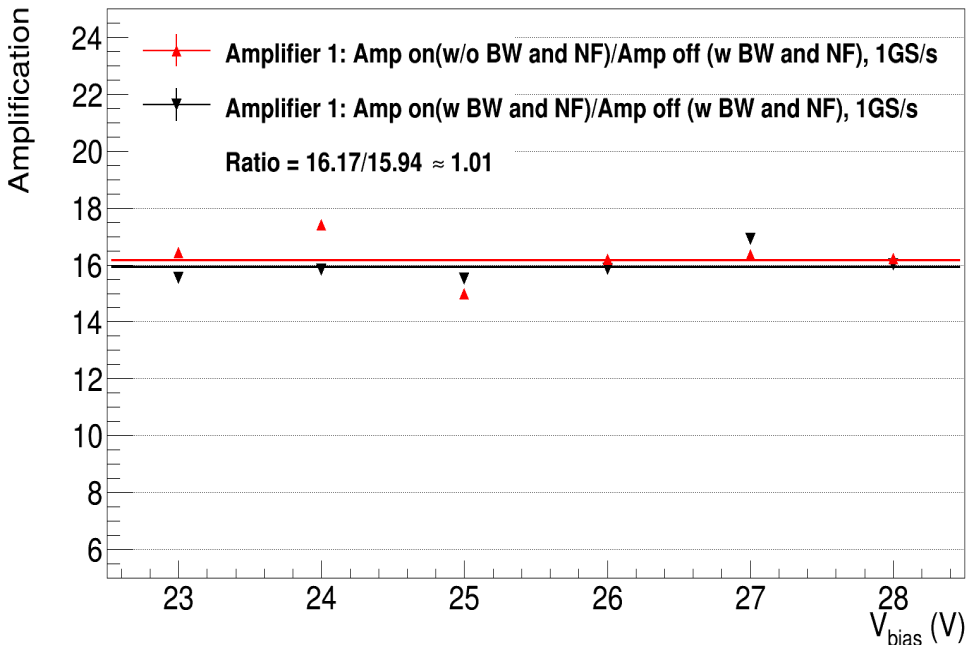
Bias voltage: 23, 24, 25, 26, 27, 28 V; Amplifier: on *
Bias voltage: 23, 24, 25, 26, 27, 28 V; Amplifier: off

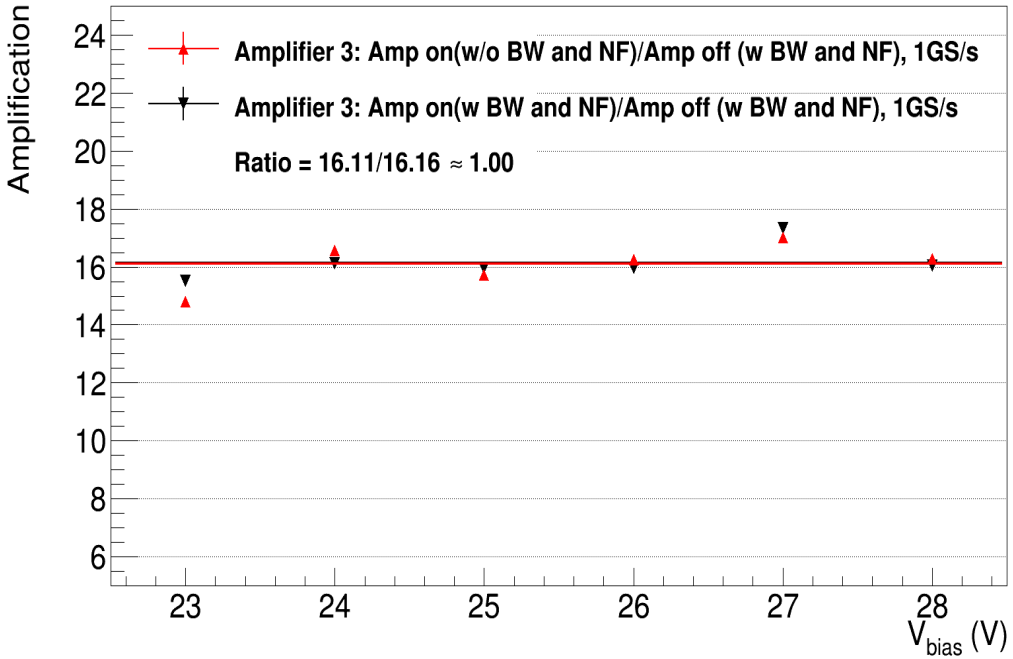
* is the time when adjustments need to be made inside the dark box.

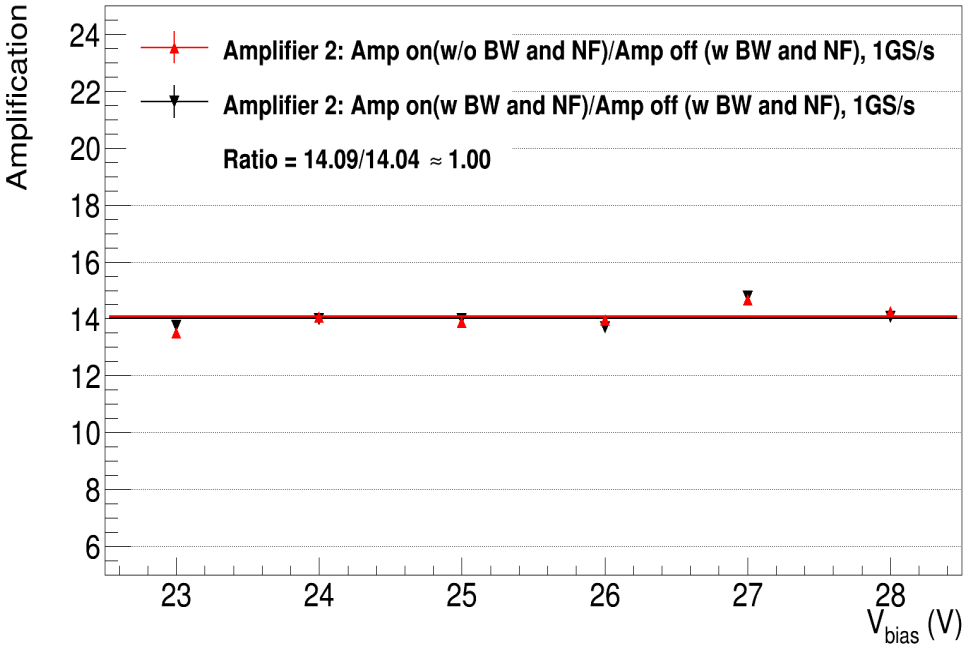





- Since the gain studies use 1 GS/s sampling rate, the amplifier calibrations are focusing on this sampling rate.
- As shown from these three plots, the noise filters effect on the standard output pulse is negligible.

# Conclusion on Amplifier Calibration

- The amplifier on pulse generator shows large deviation from the data sheet which is not as uniform as in the claimed frequency range either.
- The data on the SiPM standard output pulse shows a 14~17 times amplification which is around the ball park. However, there is small variations from one data set to another.
- The effect of bandwidth and noise filter on the standard output pulse is negligible.
- Amplifications used in the gain calibration are taken as the average of the three measurements.
  - Amp1 = 16.34
  - Amp2 = 14.13
  - Amp3 = 15.66