GlueX-doc-2910
SVN: docs/GlueXdoc/SiPM_testing_comparison
Updated: January 22, 2016

Comparison of JLab and UTFSM SiPM measurements

E.S. Smith

1 Introduction

All 4000 SiPM arrays, Hamamatsu S12045(X) Multi-pixel photon counters (MPPCs), for the GlueX barrel calorimeter (BCAL) have been purchased, tested, installed and are currently operational. Each of the 16 cells in each array was tested against our specifications [1] and found to be compliant, except for 4 arrays, which were replaced by Hamamatsu with satisfactory replacements. The 48 BCAL modules in the experiment are instrumented with 3840 sensors and two packages (80 sensors) are ready spares. The acceptance testing of the sensors was shared between Jefferson Lab (1192) and the Universidad Técnica Federico Santa María (UTFSM) (2808). The first-article testing of 80 samples by JLab has been described in various internal notes [2, 3, 4] and reported at the New Developments in Photodetection NDIP11 [5]. The test results of the first 1700 arrays by UTFSM were reported at the Vienna Conference on Instrumentation in 2013 [6]. An updated summary on all 2800 tested units can be found in Ref. [7].

Each group developed its own test setup and procedures for evaluating the response of the SiPMs. The description of the testing apparatus is provided in the reference material. The data that was recorded at JLab for each array is the following:

1. Response measured for each of the 16 cells
2. Measurements performed at 15°C
3. Measurements taken at two different bias voltages above breakdown (V_{over} = 0.6 and 1.2 V)
4. Five different intensity levels from a calibrated light source
5. Total number of measurements per array = $16 \times 1 \times 2 \times 5 = 160$.

The data that was recorded at UTFSM for each array is the following:

1. Response measured for each of the 16 cells
2. Measurements performed at 5, 7 and 20°C

3. Measurements taken at thirteen bias voltage between 0.5 and 1.7 V above breakdown.

4. Data taken with LED light source on and off.

5. Total number of measurements per array = $16 \times 3 \times 13 \times 2 = 1248$

The amount of data for each array is considerable and an analysis is required to extract the parameters of interest, namely gain, photon detection efficiency (PDE), dark rate and cross talk. The procedures for determining the parameters for each cell is detailed in the references. Of particular note is the difference in the way the two groups determine the voltage over breakdown, sometimes called the over-bias (V_{over}). During the first-article testing [4], JLab used current versus voltage measurements (IV curves) to determine that the operating voltage specified by Hamamatsu corresponded to 0.9 V over breakdown. Based on this result, JLab made their measurements relative to the Hamamatsu operating voltage and assumed this corresponded to 0.9 V over the breakdown. The Hamamatsu voltage was given for a temperature of T=25°C and the voltages at other temperatures were adjusted assuming a slope of 56 mV/°C. Great care was taken that the temperature at the sensor was controlled and equal to the desired value of T=15°C. UTFSM, on the other hand, performed a voltage scan for each measurement and was able to measure the breakdown voltage under test conditions. This procedure relaxed the requirement of stringent control of temperature at the sensor and knowledge of the temperature coefficient.

The parameters assigned to each array is the average value of its 16 cells. These have been entered into the "halld_sipm" MySQL database [8] for two bias settings (V_{over}=0.6, 1.2 V) and one temperature (T=15°C) for the JLab data and one bias setting (V_{over}=1.2 V) and three temperatures (T=5, 7, 20°) for the data from UTFSM. The table that contains the combined data from all arrays is called *osoto_sipm_pde*. This table was constituted from JLab data in other tables in the same database and UTFSM measurements, which were provided to JLab.

2 JLab data

Before we compare the data sets from JLab and UTFSM, we summarize production measurements from JLab contained in the database table *sipm_pde* [8]. The rational is that the production tests from JLab are not summarized anywhere and the database is the original source for these measurements. The general features of the data are given in Fig. 1, which shows the range of serial numbers measured, the temperature setting and the operational voltage. The distributions of gain, PDE, dark rate per cell and cross talk are shown for 0.6 V over break down in Fig. 2 and for 1.2 V over breakdown in Fig. 3. The JLab dark rates include a relatively small number of cells with measured dark rates that are 4 times higher than the average. These were somewhat anomalous, but still met our specifications.

3 Comparison of measurements

We first compile the published measurements along with the JLab averages presented in the previous section. The four parameters (gain, PDE, dark rate and cross talk) are plotted as a function of voltage over breakdown in Fig. 4. The JLab first-article test results are taken from Ref. [4] and the JLab production measurements are taken from the database. The UTFSM results are taken from Ref. [7] unless otherwise indicated. The data are plotted at three voltages over breakdown (V_{over}=0.6, 0.9 and 1.2 V), except for the JLab production data where we only have data at the lower and higher voltages. We note that the statistical uncertainties of the production measurements are very small. In the case of the first-article testing, the measurements at 0.9 V over breakdown is the average of 80 sensors, but the determination at other bias voltages was made for only five samples. We make the following observations:

Gain. The JLab first-article measurements and production data are consistent with one another. The UTFSM data is lower by about 30%, but the expected linearity of gain versus voltage is evident in both data sets. We note that according to Hamamatsu, the sensors at their specified operating voltage have a gain of 7.5×10^5, which is even 30% higher than the JLab value of 5.7×10^5.

PDE. The PDE measurements for all data at an over bias of 0.6 and 0.9 V are consistent with each other. However, at the over bias of 1.2 V, the UTFSM PDE measurement[1] of extrapolates almost linearly from the other two points, whereas the JLab data starts to saturate. This leads to a measurement from UTFSM, which is about 25% higher than the one at JLab at the highest bias.

Dark rates per cell. We plot the data at different temperatures, as the rates are temperature dependent. The first-article and production data from JLab are in rough agreement ($\sim$ 50%) and the first-article measurements are lower by 50% of the Hamamatsu certification data, taken at a higher temperature. We note that the sensors produced at later dates had reduced dark rates, so some of these differences may be real. We take this agreement to be reasonable.

The UTFSM data for the dark rates contain inconsistencies both within each publication, as well as between publications. The histogram in Fig. 9 of Ref. [6] (T=20°) gives an average rate of 0.4 MHz at 1.2 V over bias, whereas a scatter plot fit (Fig. 12 of the reference) returns a value of 0.049 MHz that is lower by an order of magnitude. The scatter plots and fits seem to have been corrected in Ref. [7] and we plot rates based on these fits in Fig. 4. However, the data in summary Fig. 21 of the same reference appears to refer to the uncorrected values from the previous publication. For completeness, we include the point from this plot at the over-voltage of 1.2 V. If we only use the fit values from Fig. 20 of Ref. [7] and assume the other figures have some errors, we get good agreement with the JLab measurements.

[1]The equation describing the PDE in Fig. 24 of Ref. [7] has a typo. It appears the first coefficient should be -0.069 instead of -0.69.

Cross talk. The cross talk determined by JLab and UTFSM are consistent with each other and roughly independent of temperature. We note, however, that the after-pulsing is treated differently by the two groups, so that the agreement may be somewhat fortuitous. How the cross talk and after-pulsing affect a given experiment also depends on experimental and analysis details, so this quantity is to be used as a rough guide of the sensor performance in any case.

We now compare the data as compiled in the JLab database. The distributions for the JLab and UTFSM data are plotted in Fig. 5 at the over bias of 1.2 V, as specified in the database. One immediately sees that the averages of the UTFSM data do not correspond to the values plotted in Fig. 4 at that voltage, but rather are consistent with the measurements at an over bias of 0.9 V. From this we conclude that the database entries for UTFSM correspond to an over bias of 0.9, not 1.2 V. In order to compare the distributions of the two data sets, in Fig. 6 we plot the gain, PDE, dark rates and cross talk, but with the UTFSM data scaled to an over bias of 1.2 V using the mean values reported in Ref. [7]. We note that this also readjusts the mean value of the dark rates in the data base by a factor of 2.3 that brings the means up to the value reported in Fig. 20. This compensates for both possibly mistaken over-bias as well as any scale errors corresponding to those found in the references.

4 Summary

We have compared the parameters of the SiPMs for the BCAL as measured by JLab and UTFSM at an over bias of 1.2 V. We draw the following conclusions:

- We find the absolute gain measurements agree at the level of 30% and both sets of measurements show the expected linear behavior as a function of breakdown voltage. Taking the average and using the difference to estimate the uncertainly, we get a gain of $6.8 \pm 0.7 \times 10^5$ at an over-voltage of 1.2 V.

- The PDE measurements are consistent below an over bias of 0.9 V, but differ by 25% at 1.2 V. At 0.9 V over bias, the PDE is 0.22 ± 0.01. Splitting the difference at 1.2 V over bias, we estimate the average PDE to be 0.26 ± 0.04.

- There are some inconsistencies in the two UTFSM publications regarding dark rate measurements. However, the fits reported in Fig. 20 of Ref. [7] (T=20°C) are in good agreement with the JLab data (T=15°C), yielding a dark rate per cell of 0.77 ± 0.04 MHz at an over bias of 1.2 V. This corresponds to a typical dark rate per array of 12 MHz. The rates are 2.7 times lower at T=5°C.

- The cross talk measurements are in agreement and yield a cross talk of about 0.25 ± 0.03 at an over-voltage of 1.2 V.

References

[1] E.S. Smith. Hall D BCAL Readout: Silicon Photomultiplier Array Specification. Specification D00000-01-07-S004 Rev-B, Jefferson Lab, June 2012. https://misportal.jlab.org/jlabDocs/document.seam?id=70738. 1

[2] C. Zorn. 1st Article Test Setup for Hamamatsu MPPC arrays. Technical Report GlueX-doc-**1648**, Jefferson Lab, December 2010. http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=1648. 1

[3] Y. Qiang and C. Zorn. SiPM First Ariticle Testing. Technical Report GlueX-doc-**1754**, Jefferson Lab, May 2011. http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=1754. 1

[4] B. Barbosa et al. Test Results for the 80 First Article samples of the Hamamatsu S10943-0258(X) array. Technical Report GlueX-doc-**1777**, Jefferson Lab, May 2011. http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=1777. 1, 2, 3, 9

[5] F. Barbosa et al. Silicon photomultiplier characterization for the gluex barrel calorimeter. *Nucl. Instrum. Methods*, A695:100 – 104, 2012. 1, 9

[6] O. Soto et al. Characterization of novel Hamamatsu Multi Pixel Photon Counter (MPPC) arrays for the GlueX experiment. *Nucl. Instrum. Methods*, A732:431–436, 2013. 1, 3

[7] O. Soto et al. Novel Hamamatsu Multi-Pixel Photon Counter (MPPC) array studies for the GlueX experiment: New results. *Nucl. Instrum. Methods*, 739:89, 2014. 1, 3, 4, 9, 11

[8] Qiang, Y. Jefferson Lab MySQL database *halld_sipm*, 2014. https://halldweb.jlab.org/wiki/index.php/SiPM_Database. 2, 9

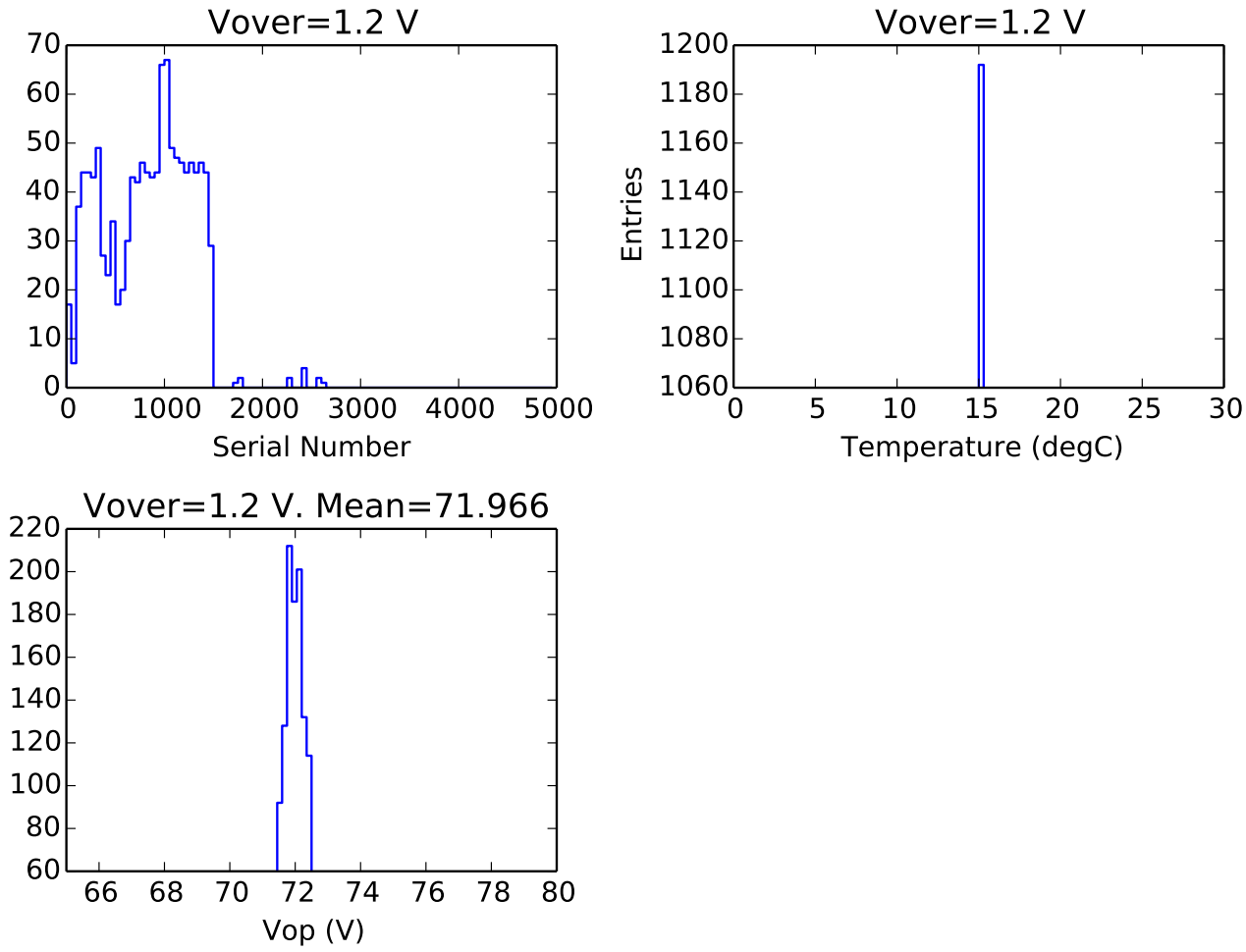

Figure 1: General features of the JLab data set. Top left) Serial numbers. Top right) Temperature of measurements. Bottom left) Operational voltage at 1.2 V over breakdown.

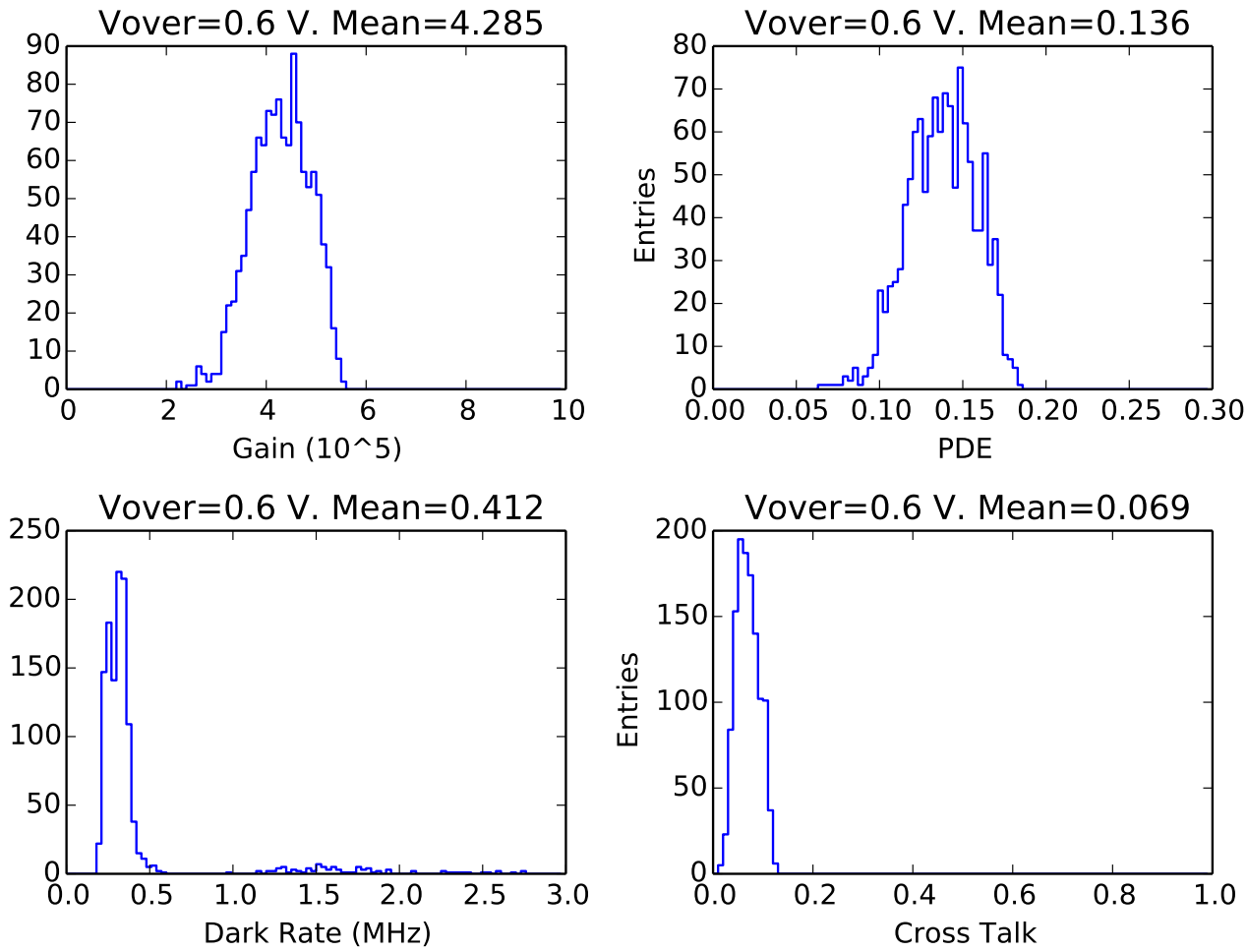

Figure 2: Parameters of the SiPMs measured at JLab at 0.6 V over breakdown. Top left) Gain in units of 10^5. Top right) PDE. Bottom left) Dark rate per cell (MHz). There is a handful of arrays with relatively large dark rate. They nevertheless met our specifications. Bottom right) Cross talk.

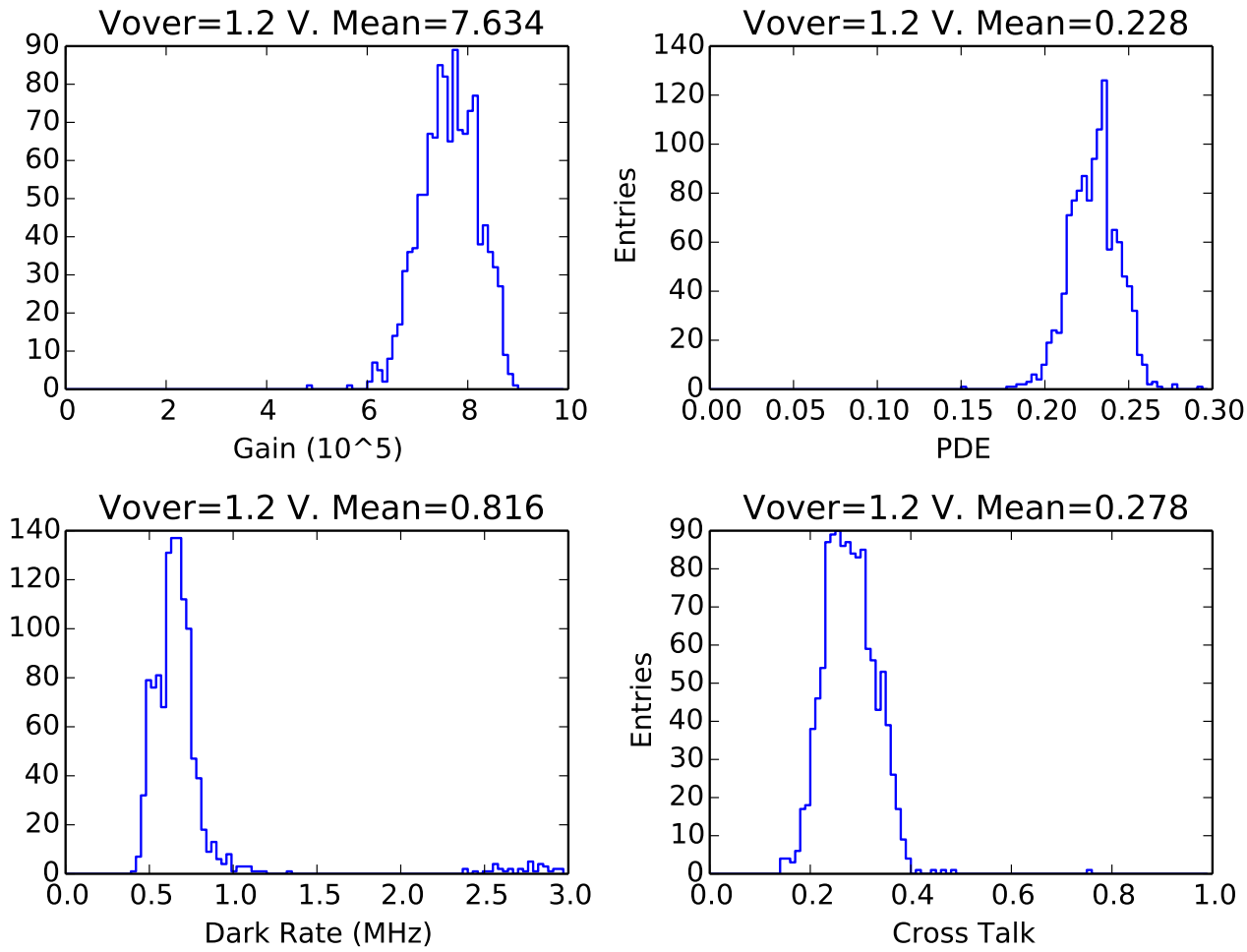

Figure 3: Parameters of the SiPMs measured at JLab at 1.2 V over breakdown. Top left) Gain in units of 10^5. Top right) PDE. Bottom left) Dark rate per cell (MHz). There is a handful of arrays with relatively large dark rate. They nevertheless met our specifications. Bottom right) Cross talk.

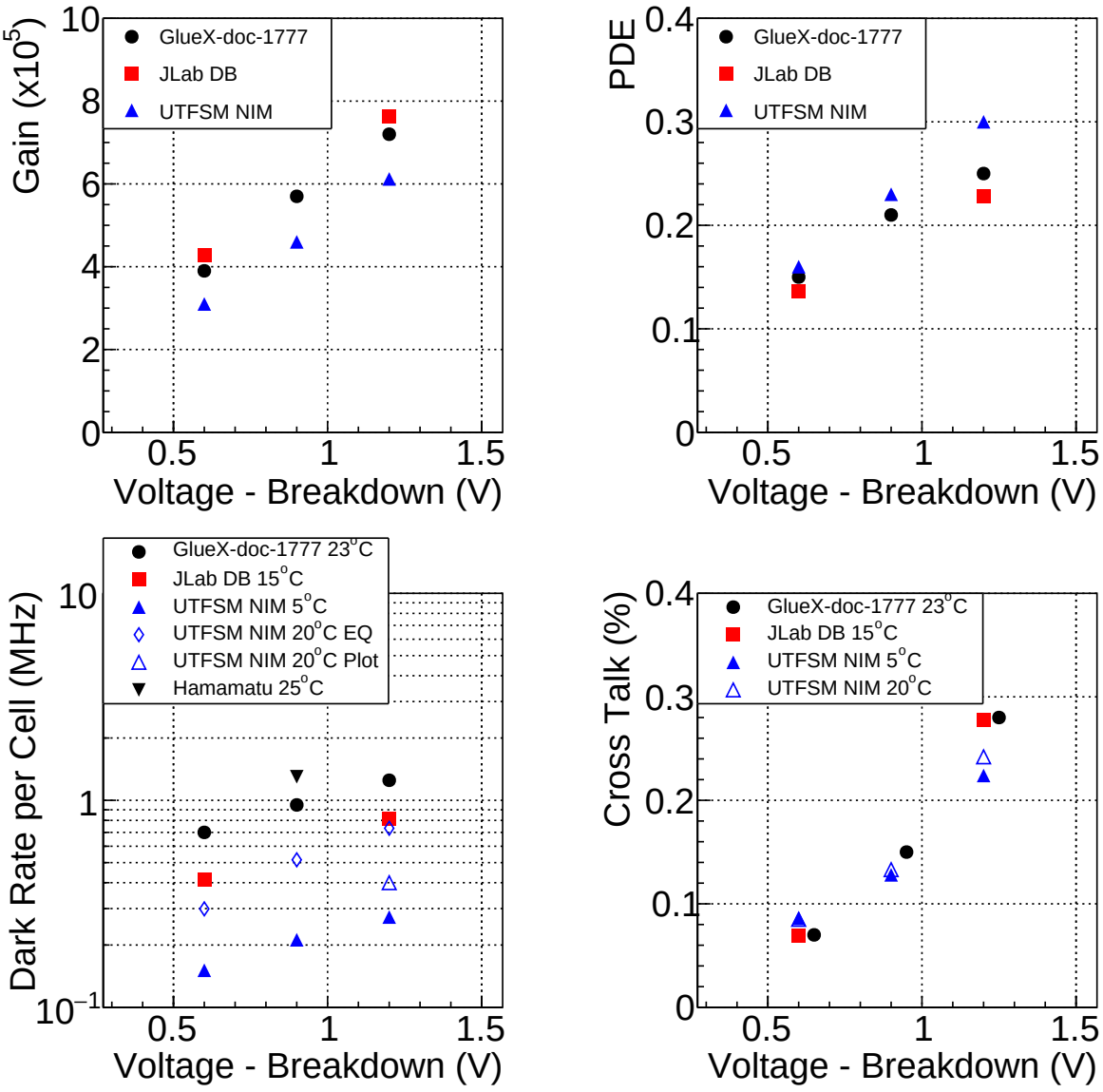

Figure 4: Comparison of measurements by JLab and UTFSM of four basic SiPM parameters as a function of the voltage over breakdown. Top left) Gain, Top right) PDE, Bottom left) Dark rate and Bottom right) Cross talk. The data plotted come from Ref. [4, 5] (GlueX-doc-1777), Ref. [8] (JLab DB) and Ref. [7] (UTFSM NIM). For the UTFSM dark rate at T=20°C there is a discrepancy between Figs. 20 and 21, so two values are plotted.

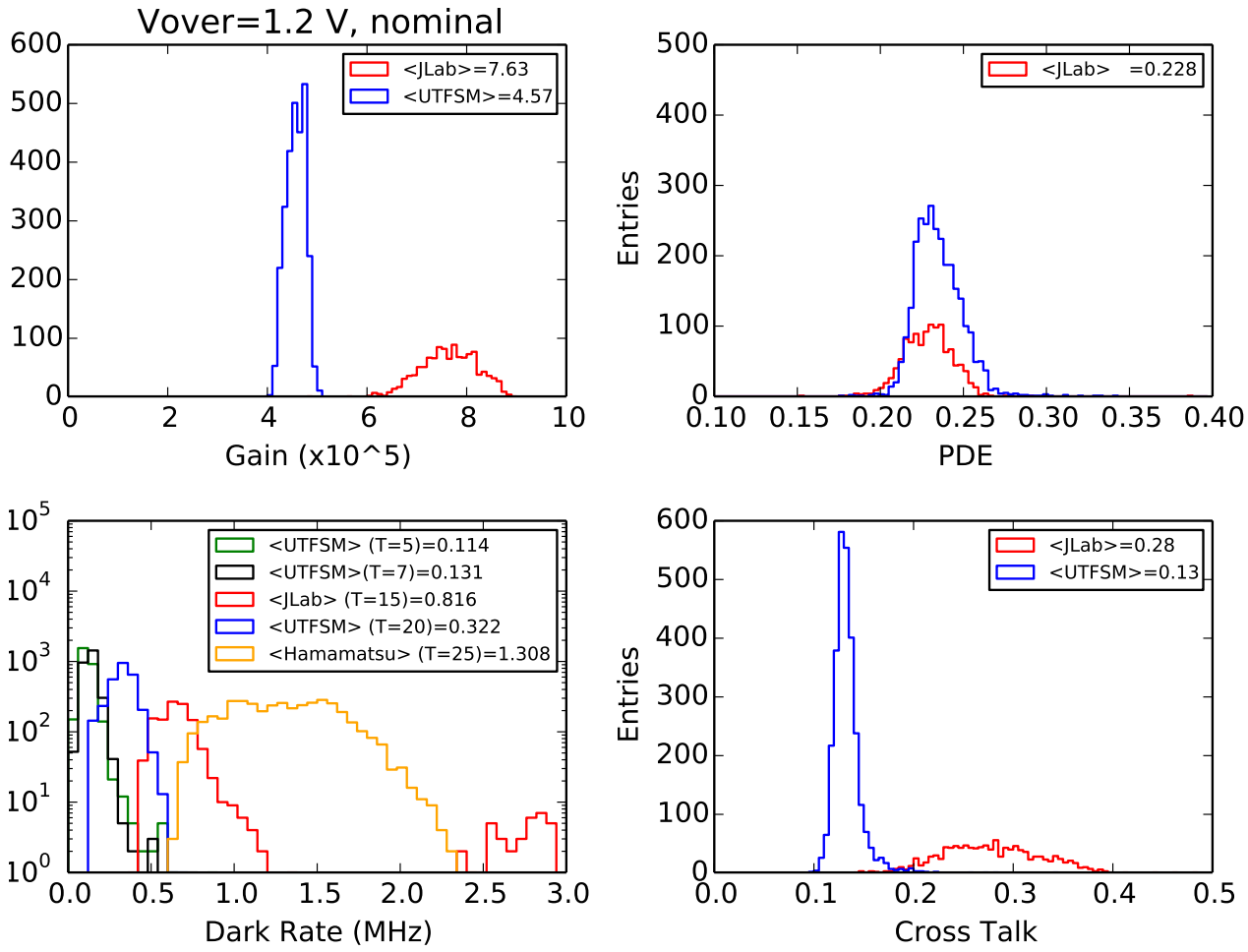

Figure 5: The distributions of the four SiPM parameters at an over bias of 1.2 V, as indicated in the database. Top left) Gain. Top right) PDE. Bottom left) Dark rate per cell. Bottom right) Cross talk. The average values of the parameters are shown in the labels. Note that the means of all UTFSM distributions correspond to the values given in Fig. 4 at an over bias of 0.9 V, not 1.2 V.

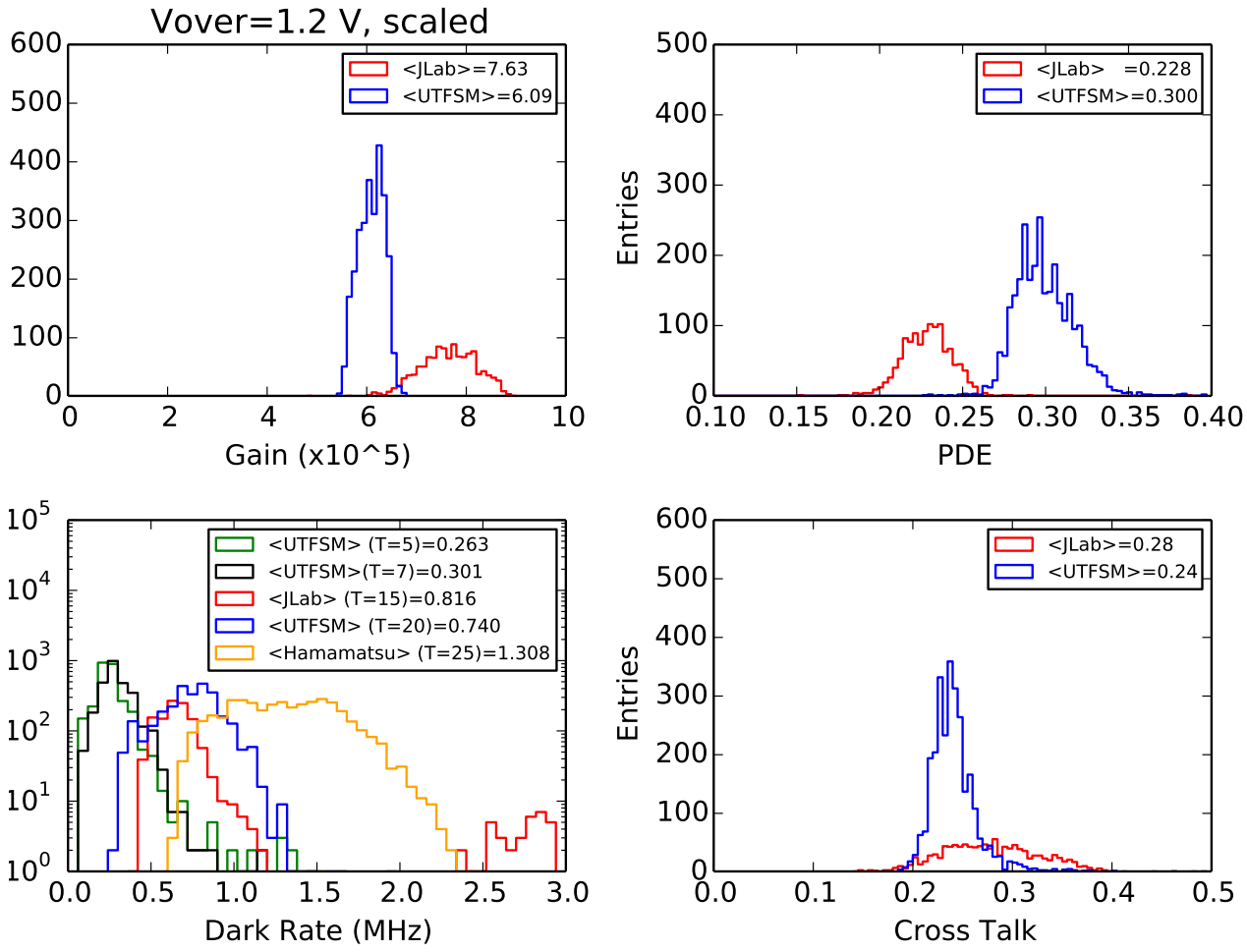

Figure 6: The distributions of the four SiPM parameters, but with the gain, PDE and cross talk for the UTFSM data scaled by the ratio of the values (V_{over}=1.2 V/V_{over}=0.9 V) from Fig. 4. The dark rates were scaled to match the means in Fig. 20 of Ref. [7]. Top left) Gain. Top right) PDE. Bottom left) Dark rate per cell. Bottom right) Cross talk. The average of the scaled values of the parameters are shown in the labels.