PMT Gain Calibration for XENON100

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Abstract

The XENON100 project has been designed and implemented to attempt direct detection of potential Dark Matter candidates. It uses very low temperature Xenon in a dual-phase time projection chamber to detect possible interactions. Precise and recurring calibration of the over 200 Photo-Multiplier Tubes is necessary to ensure accurate background rejection capabilities. Both initial calibration in a blackbox as well as regular maintenance calibration will be discussed.

1 Introduction

There is a lot of convincing evidence for the existence of Dark Matter (DM) but perhaps the most compelling of this has been the study of the rotation curves of various galaxies. According to traditional Newtonian dynamics, the rotational velocity of a galaxy is expected to drop as the square root of the radius.

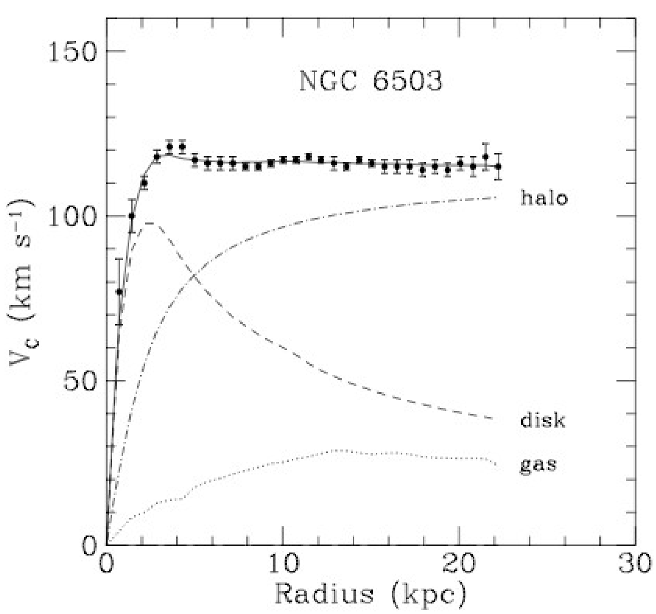

Figure 1.1: Rotational Curve of the spiral galaxy NBC 6503. (Begemen *et al*, 1991)

Figure 1.1 shows the rotational curve of the spiral galaxy NGC 6503. While the curve for the luminous disk of the galaxy follows our expectations, as a whole the rotational velocity of the galaxy remains constant out to a large radius. This suggests a complimentary non-luminous component which can account for the missing matter observed.

The WMAP and COBE studies of the cosmic microwave background radiation provide further evidence for the existence of dark matter. The anisotropies of such background information can be used to fit certain cosmological models, giving a prediction for the matter distribution of the early universe. Such fittings suggest that of over 80% of the matter content of the universe (excluding energy content) is DM, far dwarfing the luminous matter density.

The rotational curves suggest that DM must be neutral (ie non-luminous.) Further, the small scale of the anisotropic features of the cosmic microwave background points to a clustering of dark matter, suggesting that such a proposed particle must be cold, or massive and slow-moving. Further, due to the low cross section of DM with baryonic matter and the fact that it does not interact via the electromagnetic force, such DM has been dubbed weakly interacting massive particles, or WIMPs.

2 The XENON100 Dark Matter Search

Several methods have been proposed to detect either directly or indirectly the most likely candidates for DM. One such experiment is the XENON100 collaboration which is a direct detection experiment that utilizes 170 of cryogenic Xenon in a dual-phase time projection chamber. Figure 2.1 below shows the internal configuration of the XENON100 detector.

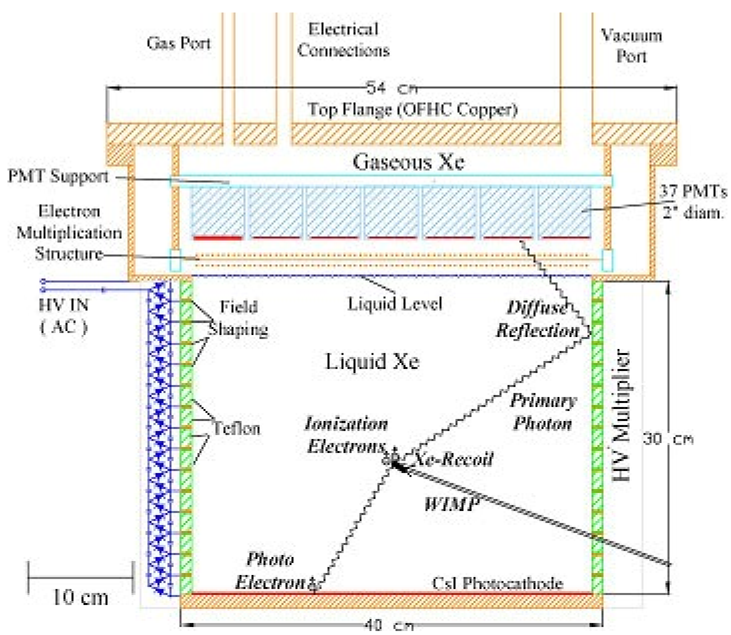

Figure 2.1: Diagram of the XENON100 detector

Removing background radiation is extremely important to long-term operation of the XENON detector, but no matter what precautions are taken, radiation will still enter the detector and has a chance to interact with the gaseous Xe in the detector. Whenever a particle interaction occurs it produces both scintillation photons via electron excitation and free electrons via ionization. The primary scintillation photons can be immediately collected and this signal is called S1. By applying an electric field across the volume of the detector, ionized electrons can be drifted to the gas stage of Xe where they are extracted and accelerated by a very high electric field applied across the small length of the gaseous Xe. This acceleration produces what is called proportional scintillation light and this signal is collected and called S2.

Two possible types of scattering events will occur: electron recoil and nuclear recoil. The main difference between these types of events is the amount of scintillation and ionization they produce. Because electron recoil events involve the interaction of particles with the electrons of a Xe atom, these type of events cause much greater ionization than scintillation and thus have a large ratio of S2 to S1. Nuclear recoil events, however produce much more primary scintillation than ionization and thus have a low S2/S1 ratio. This difference in signal strength can be used to further reduce background since a WIMP event (as well as other background phenomena) will interact via nuclear recoil only. In order to efficiently detect and reject electron recoil events it is necessary to properly calibrate the Photo-Multiplier Tubes (PMT) used to collect light at the top and the bottom of the detector.

3 PMT Calibration Methods

3.1 PMT Calibration Motivation

Identification of a WIMP signal requires an extremely low background. A lot of background can be removed by placing the detector underground, shielding it, using Xe for its efficient self-shielding qualities, using low background materials for detector construction, etc. Unfortunately it is not possible to remove all background radiation; neutrons and some gamma rays still penetrate the shielding and enter the detector. This is where proper PMT calibration becomes very important. We must be able to identify and reject any background signals that leak into the detector.

The main method for background rejection is by comparing the ratio of S2 (proportional scintillation light) to S1 (primary scintillation light.) Figure 3.1 below shows how the signal from an electron recoil differs from that of a nuclear recoil. In order to do this efficiently, we must produce a uniform response to photons throughout the detector. If one PMT responds more or less strongly to the same number of photons than another, it will skew the amount of light collected and would make background rejection difficult or impossible.

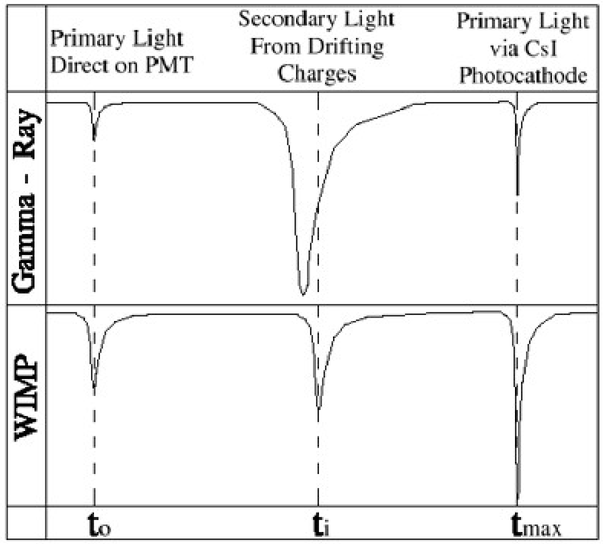

Figure 3.1: Signal differences between an electron recoil event and a nuclear recoil event

Also important to background rejection is efficient 3D positions reconstruction. When properly calibrated the XENON100 detector is capable of accurately reconstructing the position of scattering events. Because the drift electrons are highly localized in XY and the drift time provides an accurate measure of the Z-depth of an event, any event's position can be calculated from the amount of light collected and the position and timing of the light collection. Position reconstruction is useful in background elimination because background events are likely to occur near the edges of the detector (due to the self shielding properties of Xe.) Again, if different parts of the detector respond to light in varying strengths it makes position reconstruction inaccurate thus nullifying its usefulness.

3.2 PMT Introduction

Figure 3.2 below is a diagram of the inside of a PMT. It is comprised of a photocathode coated with a substance which induces the photoelectric effect, a series of dynodes, and a final anode which collects the charge produced. When a photon strikes the window of the PMT, there is a certain likelihood that this photon will produce, via the photoelectric effect, a photoelectron (PE). This likelihood is known as the quantum efficiency.

Once a PE is produced, it is focused by a set of electrodes so that it strikes the first dynode in the chain. Each dynode in the chain is held at a slightly higher potential so that once an electron strikes the first dynode it will continue along the chain, striking each successive dynode until it is collected at the final anode. Further, each dynode produces multiple electrons for each incident electron, known as secondary electron emission. Thus the total number of electrons grows exponentially as they are multiplied at each dynode.

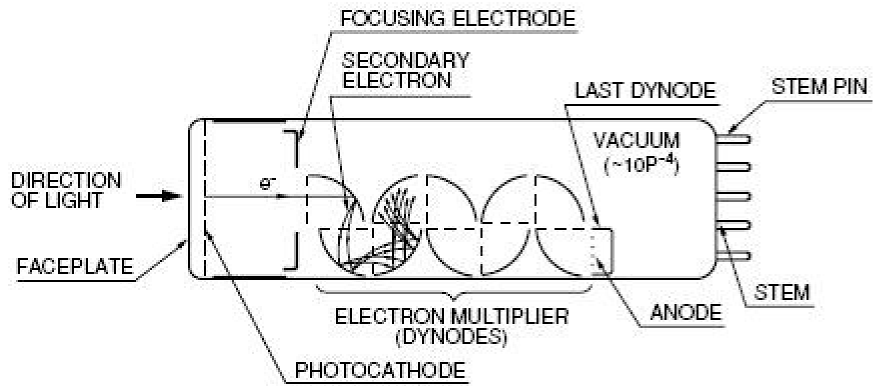

Figure 3.2: PMT construction

The factor by which the number of electrons is multiplied is known as the Gain and is of extreme interest in proper calibration. The gain can be found from the simple formula

$$N_e = \text{Gain} \times N_{pe} \qquad (3.1)$$

Where N_e is the number of electrons collected at the anode and N_{pe} is the number of photo-electrons produced at the PMT window. An easy way to calibrate the gain of a PMT is then to create a situation where a single PE is produced at the window, thus making the number of electrons produced exactly equal to the gain.

3.3 Calibration Setup

Figure 3.3 below shows the setup for the PMT blackbox calibration test. A clock with varying frequencies is used to trigger both an LED driver and data acquisition through an oscilloscope. Settings such as LED voltage and pulse width can be controlled with the LED driver. These settings can be used to control the brightness of the LED which affects the number photons released and the length of time over which they are released. The voltage supplied to the PMT can be controlled through the HV supply and this has an effect on the gain; higher voltages produced greater secondary electron emission and thus increase the gain of the PMT. The goal of this setup is to set the LED pulse width and voltage in such a way that the PMT registers a signal in about 10% of triggered events thus ensuring that a large majority of events show a single PE event. There will obviously be a large number of events with only noise and also a small number of multiple PE events.

The setup changes a bit for "maintenance" calibration. Once the PMTs are installed in the detector it becomes impossible to test them one by one and thus ensure that each PMT has a PE event only ~10% of the time. Instead, a much longer pulse is used. The voltage is still set so that only a single photon is emitted at a time. Because of the long pulse width it is highly likely that each PMT will be struck by at least one

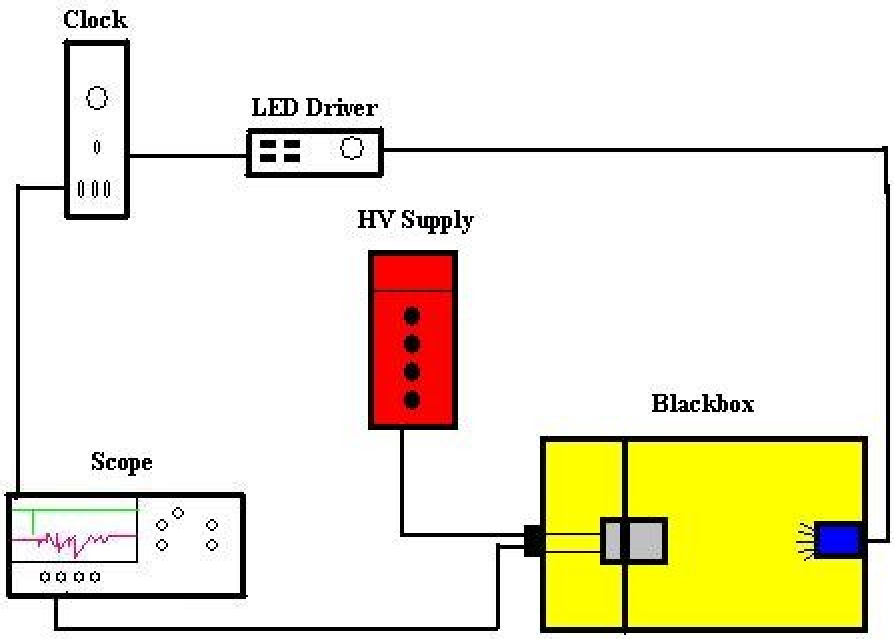

Figure 3.3: PMT calibration setup.

photon. In many cases this is fine, but for most, they are struck by several photons in each pulse window. To counteract this high-illumination, software is used to cut out unwanted events. This is possible because of the illumination is spaced over such a large window. Much like the blackbox calibration the software is designed to search a specific window so that a pulse is registered in about 10% of all events. Thus, by using software cuts it is possible to attain the same single-PE illumination that is used in blackbox testing.

3.4 Data Acquisition Software

Software was written which performed instant analysis of the acquired blackbox data. Before any data is taken, various settings such as the sampling rate of the oscilloscope and the number of events to process are input into a settings file. When run, the program first finds a baseline for the event by averaging every sample in it and then subtracts this baseline from every point. The single PE peak is then found and an integral is taken within a small window around this peak. Because the data is taken in the form of voltage, this is converted to total charge and plotted in a histogram using ROOT. We expect there to be a tall pedestal centered on 0 which represents the noise of the PMT followed by a Gaussian bump representing the gain of the PMT followed by possible tails for multiple PE events.

The analysis software has several fitting modes but the results presented here will use a 3 Gaussian fit in which the pedestal, 1st PE, and tail are all fitted with Gaussian curves. The center of the single-PE peak is then used as the gain for the PMT. Other useful information such as signal to noise ratio and peak to valley ratio as well as standard deviation are also calculated by the program.

A similar program was written to handle maintenance calibration. The analysis however is done offline as each waveform is stored, thus making software adjustments during analysis possible. It is in these programs that the software cuts are made which ensure that single-PE data is being processed correctly.

4 Results

Both types of calibration (pre-installation and maintenance) were to be conducted this summer. A batch of 10 new PMTs were brought in from Nevis labs as possible replacements for currently installed PMTs. The blackbox, however, had several issues.

First, the blackbox has 6 PMT bases installed but 1 of these had been removed. 3 other bases were not working properly and did not transmit HV across them. This left a total of 2 properly functioning PMT bases. For these two bases, however, several issues remained. Due to loose connections, the wires connecting the PMT bases to the signal outputs had become disconnected. Thus I had to open the blackbox and solder together these severed connections. Once this was done it was found that there was a short between the LED Driver and the LED. Again, I opened the box, found the short and repaired it. Other factors, most importantly time constraints, prevented me from ever taking black box data. Fortunately, I was still able to take maintenance data on currently installed PMTs.

For the following data, the LED was set to a pulse width of 3.0 μs and a voltage of 2.35 V. The HV setting for individual PMTs is shown in the graphic output of the analysis along with other relevant information. I generated the plots presented below using the software-cut programs and a 3-Gaussian fit.

Below in Figure 4.1 we see the output of a healthy and well-functioning PMT.

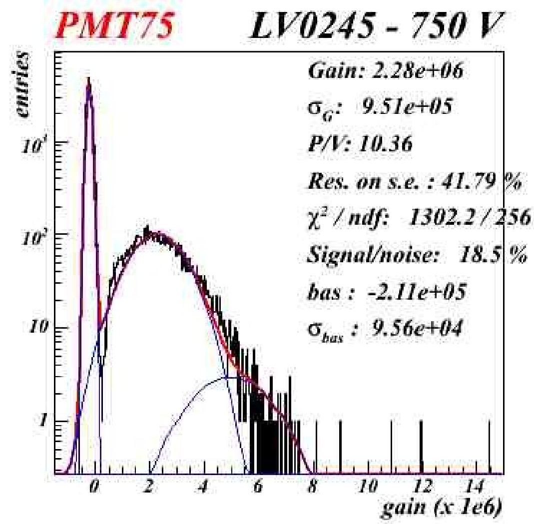

Figure 4.1: PMT calibration data on PMT 75, located in the top array taken on July 27, 2008.

It is clear that this PMT has a very well defined single-PE peak with an average gain of 2.28×10^6. It also has an excellent peak-to-valley ratio of 10.36 and signal/noise of 18.5%.

In Figure 4.2 we can compare the response of two different PMTs. This comparison highlights the inherent differences between PMTs and thus the necessity of their calibration. Though they have nearly identical gains, the voltage settings on the two differ by 60V. If these two PMTs had the same HV settings, their responses would be very different.

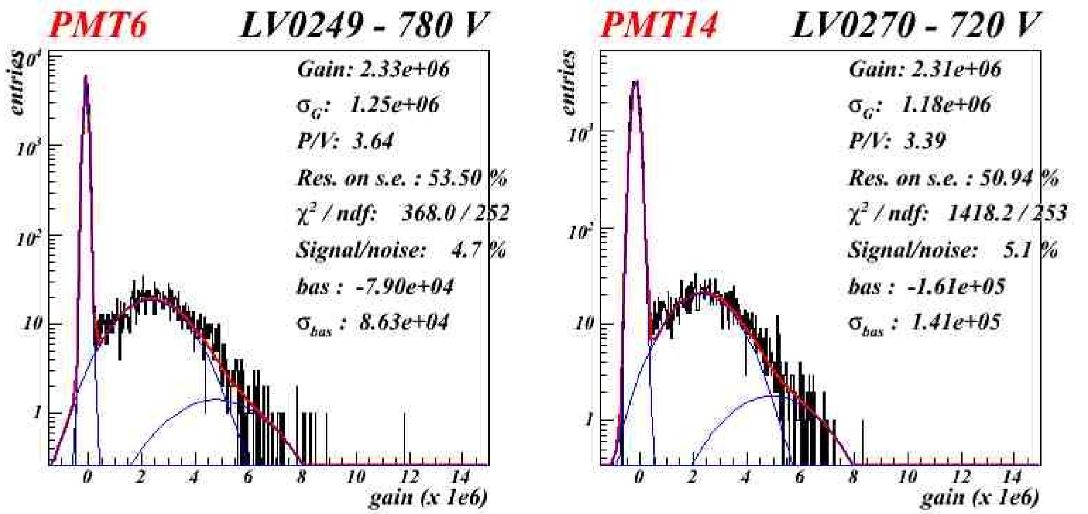

Figure 4.2: Calibration comparison for PMT 6 and PMT 14 on the top array taken on July 27, 2008.

Another motivation for maintenance calibration was to monitor the health of a PMT over time. In the following two figures we see why such maintenance is necessary. Figure 4.3 shows a PMT which has suddenly died. Though it was properly functioning when tested on July 16, 2008, it has suddenly stopped functioning properly when tested again on July 27, 2008.

Figure 4.4 shows a similar situation, but the PMT simply begins functioning at a lower gain rather than dying completely. By continually monitoring the health of the PMTs in this way we can identify and replace faulty PMTs as well as properly handle the analysis for PMTs which begin functioning at different gains.

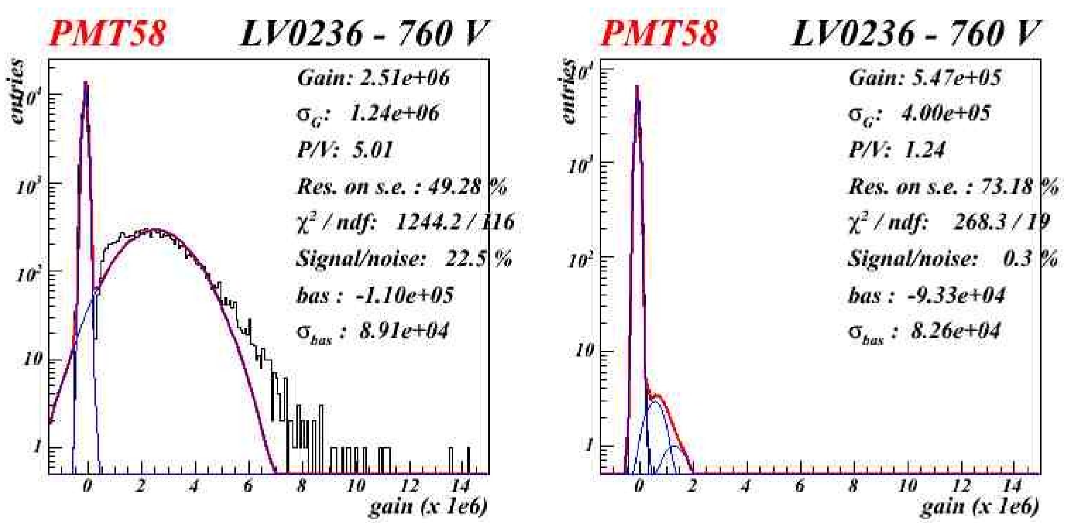

Figure 4.3: Calibration results for PMT 16 on July 16 (left) and July 27.

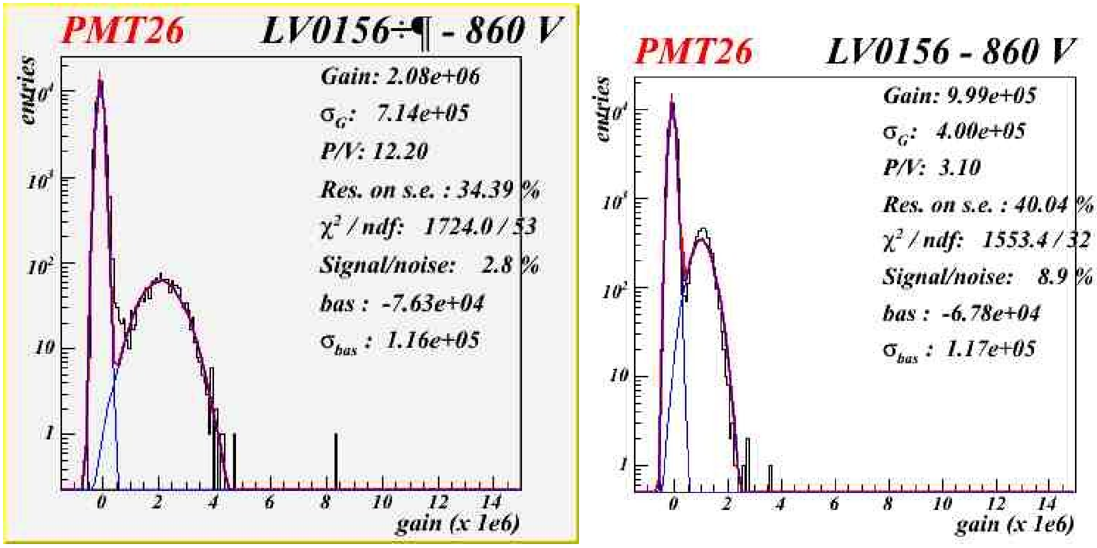

Figure 4.4: Calibration results for PMT 26. The PMT is shown to be functioning at a gain of around 2e6 on June 27 (left) and when tested 3 weeks later on July 16 it shows a gain of only ~1e6.

5 Conclusion

Looking at the data presented above, and seeing how quickly the calibration of a PMT can change, it is obvious that frequent and thorough PMT maintenance is necessary to maintain a high level of efficiency in the XENON100 detector. While most PMTs have shown consistently good response, there are always going to be a few cases where PMTs need to be re-evaluated or replaced in order to provide the best background rejection possible.

The analysis software has been undergoing changes as well in order to make it more efficient at identifying appropriate windows. Once the software has been finalized and the calibration LED settings standardized, PMT calibration will be a quick and easy way to ensure long-term and high-quality results from the XENON100 detector.