Comments about the Andor iXon3

Eric Magnan
First year student at Institut d'Optique Graduate School (SupOptique)
One month internship at LPL (Laboratoire de Physique pour les Lasers), CNRS UMR 7538,
Paris-XIII University, 99 avenue J.-B. Clement, 93430 Villetanneuse, France.

eric.magnan@institutoptique.fr

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***Abstract*—This document is a synthesis of my work on the Andor camera iXon3. As a part of my internship at LPL, I verified the main specifications of this camera before the team use it to capture chromium 2d gaz condensation. The main goal was to know in what extent we could trust the datasheet.**

I. Some important details about the camera

A. Gains properties

The Andor iXon3 benefits from two sorts of gain: *pre-amp gain* and "*electron gain*". The *electron gain* happens right after the shift register, the *pre-amp gain* happens next. This last gain can be set at only three values: $\times 1$, $\times 2.4$, $\times 4.9$.
For the *electron gain*, two modes are possible:

- Conventionnal: It is just a simple amplifier. Note that in this case, the gain is automatically set by the software.
- Electron Multiplying (EM): This is specific to the EM-CCD: Right after the register, the signal in electrons can be multiplied in order to deeply increase the sensitivity. Be carefull by using it, because high EM can saturate the register and aging the sensor very fast.

In order to protect the system, Andor advises to use strong pre-amp gain ($\times 4,9$), when using EM mode. Note also that on Andor Solis, if you click on Electron Multiplying without setting a value, it will be set to $\times 1$ by default.

B. Counts, electrons, photons

The camera can measure three values: *counts*, *photons* or *electrons*. It is automatically set on mode *counts*, but it is possible to change it in Andor Solis settings (before or after taking the photograph). If it is required to rely electrons to counts, the datasheet indicates the ratio in the column *CCD Sensitivity*. Note that this ratio depends on readout rate frequency and on the two gains. I suspect the values given by Andor to be slightly underestimated but it seems hard to verify it.

C. Image format

Andor Solis is the reference software for the iXon3. I always use this software to set the camera. I also use it to take all the photographs and to save them. Many file formats are available, the default one is *.sif*, which is only openable with Andor Solis. It has the great advantage to contain all the settings of the camera (exposure time, gains, readout rate, etc.) but it cannot be used to process the data.
I first converted all my pictures in *.bmp* : **This is not a good idea.** This format is optimized to show nice pictures (good contrast, good treshold), but does not signify anything physical, because the software changes the parameters at every shot. As a consequence, two pictures in this format are not comparable.
To work properly, I had to export the data in *.asc* (ASCII extension) and after that convert manually all the data's extensions into *.txt*, which is openable with IGOR.

D. Baseline correction

On Andor Solis settings, it is possible to set a baseline (follow *Acquisition≫Acquisition Settings*). This correction consists in dividing the signal by a continuous reference calculated by the software or set by the user.
At first sight, I would think that using no baseline or set it at 0 would be the same. **This is not the case**. So, it may be useful to note that Solis works properly when baseline correction is not enabled.

II. Measures of read noise

For this part, I chosed to close the shutter. The idea was to measure the noise, which includes dark noise, read noise and light noise.

$$\sigma = \sqrt{\sigma_{\text{read}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{light}}^2} \tag{1}$$

Since the camera is cooled at $-80°$C, we assume that the dark noise is very small. We mesured it, and our results were very closed to the datasheet's. The light noise should also be equal to zero when the shutter is closed. So we only measure read noise.

A. Read noise vs. Single pixel noise

The datasheet indicates the *single pixel noise*, which depends on readout rate frequency and the two gains. This noise correspond to the standart deviation of one pixel's counts when taking many photographs in the same experimental conditions.

I did not measure single pixel noise. I have been evaluating the standart deviation of one range (512 pixels long) of pixel. If the noise distribution is ergodic, read noise and single pixel noise should be exactly the same. But apparently, this approximation is not absolutely true. In fact, in order to work properly, we should make a map of the sensor by measuring the specifications of every pixel.

B. *Influence of gains on read noise*

Since read noise only depends on the signal intensity, it should not depend on gains. However, it is written in the datasheet that Electron Multiplying should increase the readout noise (approx. $\times 4$) and the preamp-gain should reduce it (approx. $\times 2$ between $G = 1$ and $G = 4,9$).
The following measures have been made without light (the shutter was closed). When "EM" is enable, I set it at 30.

System Readout Rate	Preamp Settings	Readout Noise *(mesured)*	Single Pixel Noise *(theorical)*
10 MHz (EM)	1	93,4	102,42
	2,4	41,10	57,8
	4,9	35,61	50,21
5 MHz (EM)	1	115,7	84,86
	2,4	46,37	49,75
	4,9	29,08	40,57
3 MHz	1	10,56	14,43
	2,4	7,97	10,67
	4,9	7,01	10,02
3 MHz (EM)	1	46,70	62,27
	2,4	26,32	36,98
	4,9	21,13	23,86
1 MHz	1	6,01	8,47
	2,4	4,55	6,49
	4,9	3,93	5,87
1 MHz (EM)	1	26,92	36,4
	2,4	14,44	22,06
	4,9	13,51	18,49

Fig. 1. Readout Noise Measures

Similary to what the datasheet indicates, we see that **in terms of read noise, "1 MHz - 16 bits - conventionnal gain" is the best setting.**

Our results are often below Andor's engineers observations. The cause could be that the electrons/counts ratio is not verifiable (I suspect the one in the datasheet to be slightly below the real one). In fact, some problems occure when we try to compare our results to the datasheet. For instance, while using Electron Multiplying mode, we do not know the value of the Electron Multiplying that has been used by Andor's engineers. So it is difficult to compare our results to the datasheet.

III. Measuring SNR dependance on counts and Electron Multiplying

Since the noise is increased by Electron Multiplying when the shutter is closed, I wanted to analyse it in a situation similar to what will happen with the BEC (laser pulse).

A. *Signal dependance on Electron Multiplying*

I first intended to analyse the noise, but it appears that my light source was not perfectly clean. So, small variations that were looking just like noise were also signal. In fact, by applying $G_{EM} = 30$, I had a signal level at $N_c = 16 \cdot 10^3$ (counts) and a global noise $\sigma = 700$. Assuming that the source follow the experimental law $N_c/\sigma \propto \sqrt{\langle N_{ph} \rangle}$, we should have found $\sigma \approx 126$. So, I do believe that this is *noise* coming from the laser, this is also a *signal* for the camera.
Reading the graphe leads me to this conclusion: **the signal linearly depend on the Electron Multiplying level** (and it is exactly what we expected).

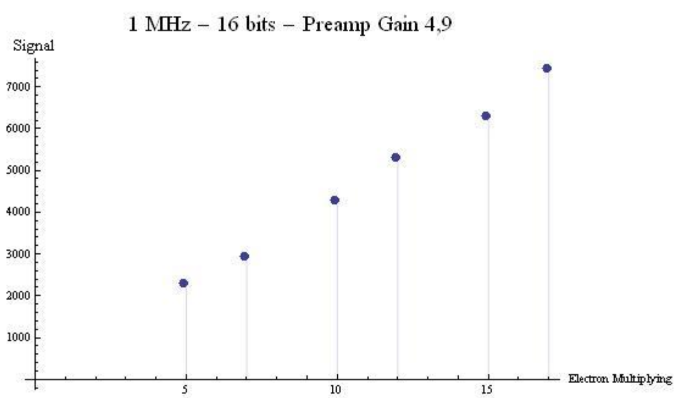

Fig. 2. Signal level vs. Electron Multplying

B. *Electron Multiplying and SNR*

Electron Multiplying and noise can be linked by a relation that I found in the user guide of the ProEM+ Camera from Princeton[1]. In presence of EM, we have,

$$\text{SNR} = \frac{\eta \langle N_{ph} \rangle}{\sqrt{\eta \langle N_{ph} \rangle F^2 + \sigma^2_{\text{dark}} F^2 + \left(\frac{\sigma_{\text{read}}}{G_{EM}} \right)^2}} \quad (2)$$

η also represents the quantum efficiency (QE), $\langle N_{ph} \rangle$ the RMS value of the signal, G_{EM} the EM value.
F is a correction factor which can be approximate to $F \approx \sqrt{2}$. While not applying EM, the previous relation turns into the following one,

$$\text{SNR} = \frac{\eta \langle N_{ph} \rangle}{\sqrt{\eta \langle N_{ph} \rangle + \sigma^2_{\text{dark}} + \sigma^2_{\text{read}}}} \quad (3)$$

To see better what it means, I have been drawing the a graphe showing Theorical SNR (red) - SNR with EM (green) - SNR with conventionnal gain (blue) in function of the number of photons. Depending on the value of the EM, there are two possible situations,

- When the gain EM is low, the SNR_{EM} looks like the SNR_C for the small amounts of photons. Of course, when the signal gets higher, the F factor makes that the green SNR_{EM} is always below the two others.
- On the contrary, when the EM gain is high, the SNR_{EM} looks like the theorical one, but is $\sqrt{2}$ below too.

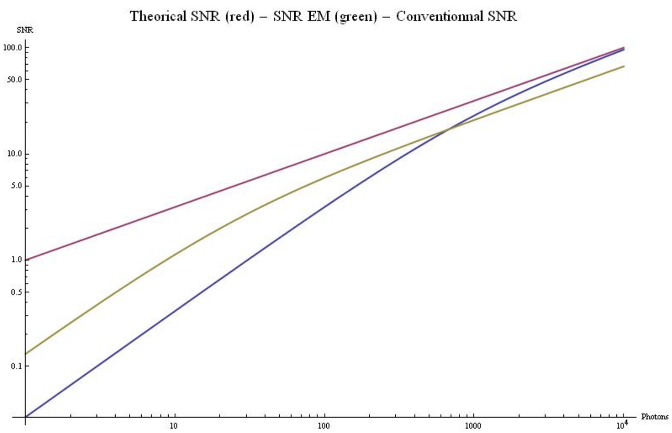

Fig. 3. Read Noise vs. Electron Multplying

In this Mathematica's modelisation, $G_{EM} = 6$ and $f_{\text{readout}} = 30\text{MHz}$.

So, while using low intensity, it is advisable to enable Electron Multiplying. Assuming that $\sigma_{\text{dark}} \approx 0$ (the camera is strongly cooled), we have,

$$\lim_{\langle N_{ph}\rangle \to 0} \text{SNR}_{EM} = \eta G \frac{\langle N_{ph}\rangle}{\sigma_{\text{read}}} > \text{SNR}_C \tag{4}$$

For high levels of light intensity, it is (in terms of SNR) better to use conventionnal gain.

$$\lim_{\langle N_{ph}\rangle \to +\infty} \text{SNR}_C = \sqrt{\eta \langle N_{ph}\rangle} > \text{SNR}_{EM} \tag{5}$$

Here we find the well-know result: $\text{SNR} \propto \sqrt{\langle N_{ph}\rangle}$

Andor's datasheet gives also the values of two critical points ($\text{SNR}_{EM} = \text{SNR}_C$), $N_{ph} \approx 2900$ **for 10MHz and** $N_{ph} \approx 42$ **for 1MHz. Below theses** N_{ph} **values, use Electron Multiplying, and above, use conventional gain.**

IV. Quantum efficiency

One of the most important specifications of this camera is its quantum efficiency.
Assuming that the camera shows a number of counts (and not a number of electrons), it is necessary to trust the α coefficient given in the datasheet (in section *CCD Sensitivity*).

$$\eta(\lambda) = \frac{N_e}{N_p} = \alpha \frac{N_c}{N_p} \tag{6}$$

N_e is the number of produced electrons, N_p the number of photons hitting the sensor, N_c, the number of counts given by the camera.

In the one hand, we can measure the incident power P. Also note that this type of measure is barely precise. In the other hand, assuming that the light intensity follows a Gaussian distribution, it is possible to determine w (the waist) and N_{ph} (the light intensity at $(x, y) = (0, 0)$). We also know Δt, the duration of the laser pulse, α (given by the datasheet and depending on the experiment settings) and λ. S_{px} is the surface of one pixel, which measures $256\ \mu\text{m}^2$.

$$\eta(\lambda) = \frac{\pi w^2}{2P} \frac{\alpha N_c}{\Delta t \cdot S_{px}} \frac{hc}{\lambda} \tag{7}$$

I measured quantum efficiency for many Δt pulse times. I used IGOR to fit a cross of the picture with a gaussian distribution. This allows me to know w and N_c with a good approximation.

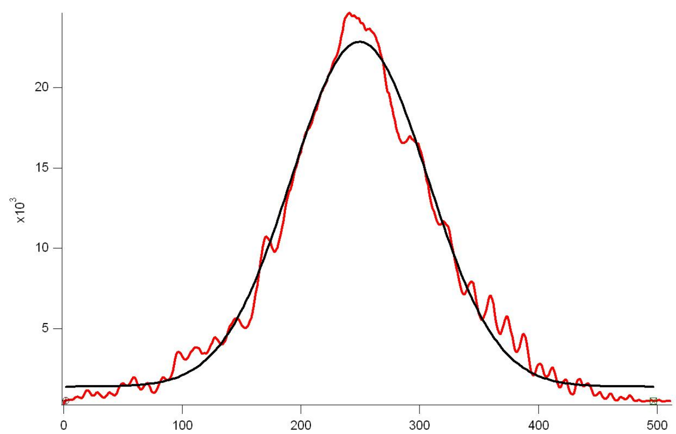

Fig. 4. Fitting a cross picture with a gaussian distribution

It appears that for very short pulses (about 10μs), the mesure suffers from a very high noise level (SNR ≈ 1). By applying longer Δt, we deeply improve the SNR (SNR ≈ 15 when $\Delta t = 0,2$ ms) and the measures become quantitative.
It appears that **the quantum efficiency is very good**. Due to the noise, I was often slightly above 100%, which should not be possible.
There is one last parameter that should be considered when it turns to quantum efficiency. The window in front of the sensor is not perfectly transmittive. It slightly reduces the quantum efficiency (about 3%). We choose the *Visible - Near UV* window (red on the graphe), because it is not absorbing to much at our wavelenght ($\lambda = 425, 7$ nm). Still, we cannot expect a quantum efficiency greater than 97%.

V. Jitter measures

Since imaging the BEC will happen very fast, knowing the jitter is very important. The jitter corresponds to the time between the trigger level turns up and the instant when the camera starts acquiering.

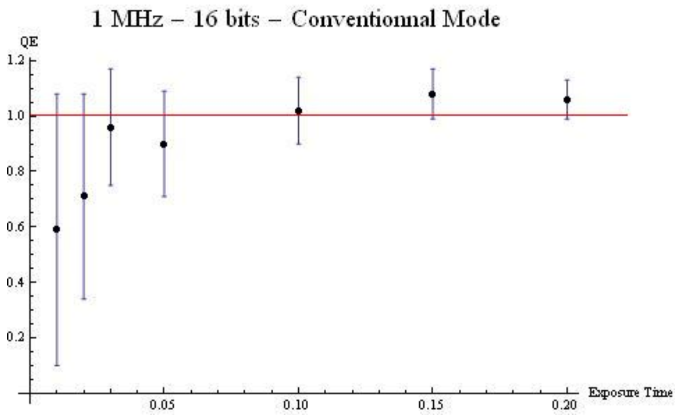

Fig. 5. Quantum Efficiency vs. acquisition time

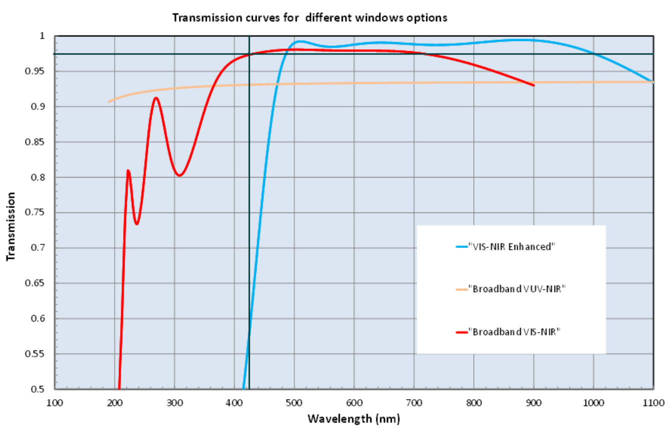

Fig. 6. Transmission of the window

For this measure, we used the *fire* signal, which is an external output of the iXon3 and indicates the acquisition duration. Assuming that between two frames, the jitter variates a little, we used the oscilloscope's *infinite persistance* mode in order to define the jitter's lowest and highest values.

Our experiments show that:

- Exposure time has no impact on the jitter.
- The jitter depends on readout rate.

Readout Rate (MHz)	Delay (μs)	Jitter (μs)
1	$13,4 \pm 0,5$	$7,6 \pm 1$
3	$11,9 \pm 0,5$	$7,0 \pm 1$
5	$11,3 \pm 0,5$	$6,6 \pm 1$
10	$11,1 \pm 0,5$	$6,6 \pm 1$

Fig. 7. Jitter's dependance on readout rate

The **delay** corresponds to the average time between the trigger pulse (instruction given by the software - *"start acquisition !"*) and the *fire* signal (response of the camera *"acquisition has begun !"*). The jitter correspond to the standart deviation of the delay. **So, for a proper use of this camera, it is necessary to respect the following condition,**

$$t_{\text{laser pulse}} \geqslant \Delta t_{\text{delay}} + \Delta t_{\text{jitter}} \tag{8}$$

Ex: At $f = 1MHz$, the laser pulse has to be at least $21\mu s$ after the trigger pulse.

VI. Conclusions & Important results

Concerning the proper use of this hardware, please note:

- Electron Multiplying accelerate the aging of the sensor. Always set *pre-amp gain* at $\times 4,9$ while using Electron Multiplying mode, this will narrow the EM effect and preserve the EMCCD. Of course **never enable high EM (higher than 300) with a light source**.
- Never use *.bmp* or file formats like that. **Image file formats cannot be used to compare different pictures because they do not show the real number of counts**[1]. A solution is to use ASCII files and to transform it into text files, but there is probably a better way to process the data.

Concerning the specifications of our Andor iXon3, the best configuration for imaging the chromium BEC seem to be the following one:

Criterion	**Setting**
Mode	Fast Kinetic
Readout Rate	1 MHz
Preamp Gain	$\times 4,9$
EM on	*Only if* $N_{ph} > 42$ photons
Vertical Shift-Speed	$3,3\ \mu s$ (max)
Trigger mode	External
File format	Text (ASCII)
Criterion	**Resulting specifications**
Encoding	16 bits
Jitter	$6,6 \pm 1\ \mu s$
Delay	$11,1 \pm 0,5\ \mu s$
Electrons/Count	$0,66$
Single Pixel Noise	5,87 electrons

Fig. 8. Recommanded settings for imaging a BEC

References

[1] Princeton Instruments, ProEM+, *Brochure RevA3*, p.21.

[1] And also because the treshold is automatically set by the computer between the frames, and because it is an 8-bits format whereas we work with 16 bits in order to reduce the noise.