January 30th 2001

GM

Dark Current Distributions
of the three first batches of phototubes

1. Introduction

The data provided with the tubes by Hamamatsu include the 800 Volts anode dark current: I_{db}. The dark current, measured with ATLAS test-benches, should be lower than 2 nA for 800 Volts and 8 nA for 900 Volts to accept the tube.

The dark current of the first delivered 1250 tubes is slowly increasing as clearly demonstrated on figure (1). The black line indicates the mean dark current as a function of the PMT number.

Figure (2) shows the Hamamatsu 800 Volts measured dark current distribution (I_{db}) for the 3 delivered batches. It is representative of Hamamatsu production since it corresponds to 1250 tubes, previously to any selection. The mean value is 180 pA

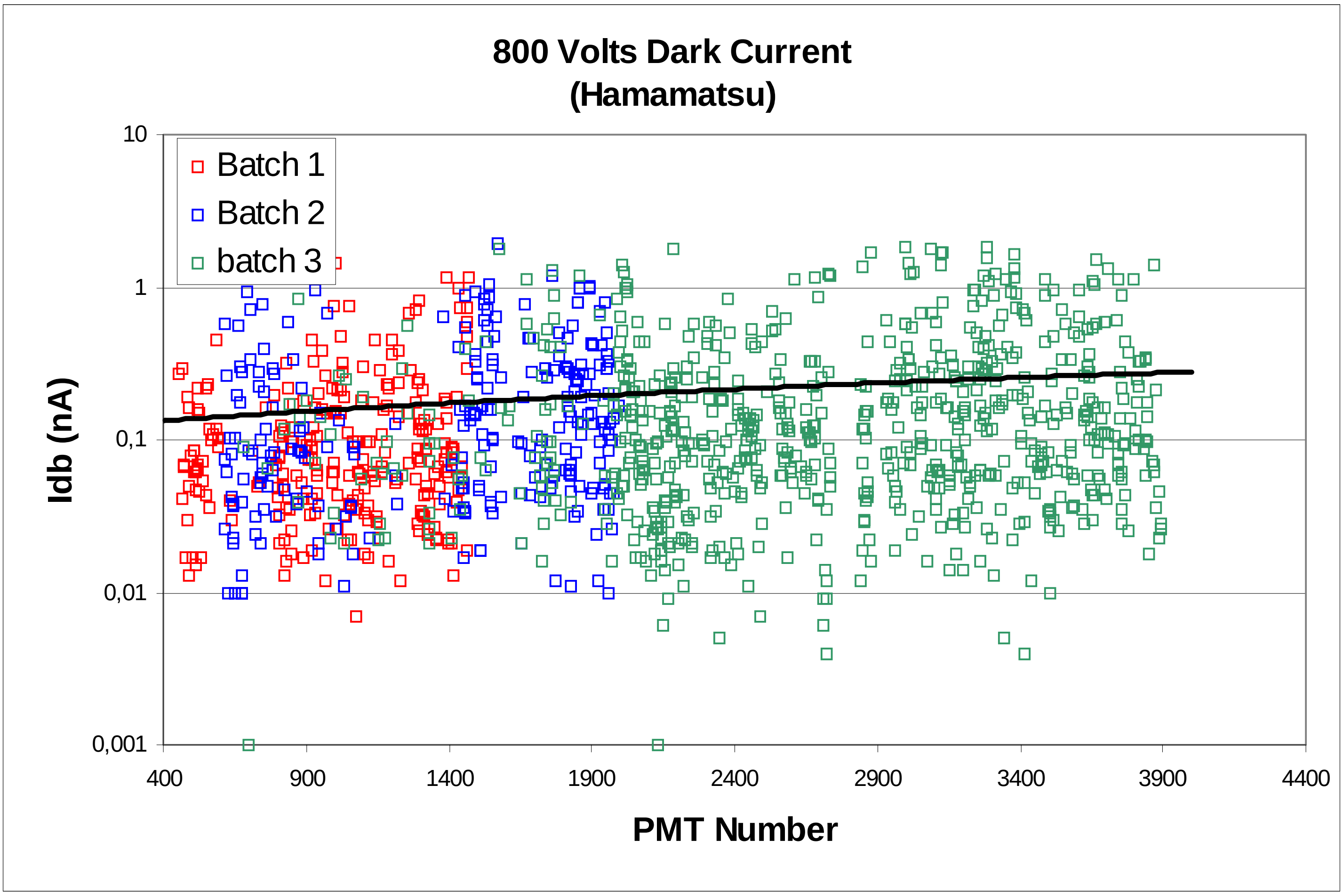


Figure (1) : 800 Volts dark current I_{db} (Hamamatsu data), as a fonction of phototube serial number. The black line indicates the mean dark current as a function of the PMT number.

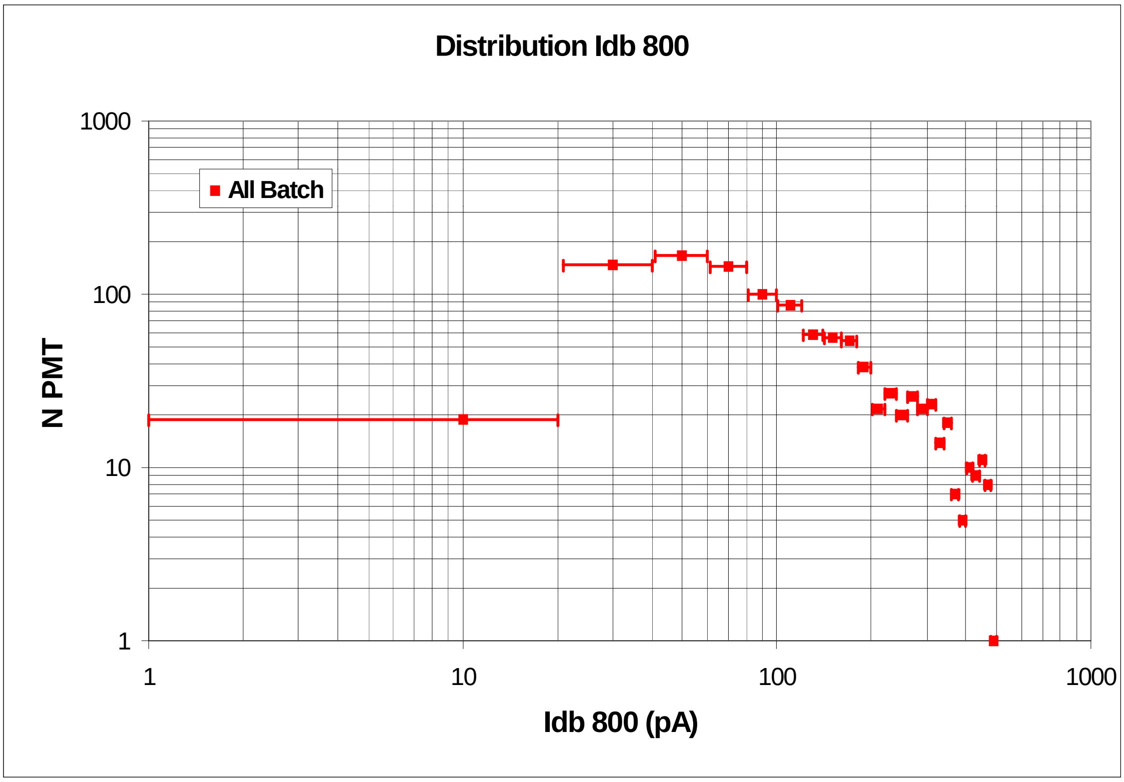


Figure (2) : Hamamatsu 800 Volts measured dark current distribution (I_{db}). The mean value is 180 pA previously to any selection.

2. Correlations with ATLAS data

As the 800 Volts dark current is also measured with the ATLAS test-benches, we check the correlation between the Hamamatsu and the ATLAS data for each sub-batch.

Figures (3) to (6) present these correlation for the different sub-batch of tubes. They are expressed using logarithm scale, that is Log(Idc) as a function of Log(Idb). The correlation line is so the visualization of :

$$\mathrm{Log}(I_{ATLAS}) = a\,\mathrm{Log}(I_{HAM}) + b = \mathrm{Log}(\beta\, I_{HAM}{}^{a})$$

With :

$$\beta = \exp(b).$$

Full correlation corresponds to the case a = 1 and b=0 (β=1). But such a case is difficult to reach when measuring dark current since such a characteristic is clearly depending of the history of the tubes previously to its measurement: temperature, illumination, burning time, shocks, cumulated vibrations,…

The results are summarized in next table. First conclusion on these data indicate that Pisa and Urbana data are the best compatible with Hamamatsu data. Nevertheless, keeping in mind the resolution on the determination of the correlation, one could conclude that the five sub-batches have quite identical distributions.

Sub-batch	Correlation in log scale	Correlation factor	Correlation
Batch#1 CL	0,691 $Log(I_{HAM}) + 1,04$	0,4576	2,83 $I_{HAM}^{0,69}$
Batch#2 CL	0,778 $Log(I_{HAM}) + 0,89$	0,668	2,44 $I_{HAM}^{0,78}$
Batch#3 Pisa	0,958 $Log(I_{HAM}) + 0,211$	0,518	0,81 $I_{HAM}^{0,96}$
Batch#3 Urbana	0,933 $Log(I_{HAM}) + 0,288$	0,681	1,33 $I_{HAM}^{0,93}$
Batch#3 Valencia	0,775 $Log(I_{HAM}) + 1,104$	0,757	3,01 $I_{HAM}^{0,77}$

Moreover, we are dealing with the measure of current of the order of some tens of picoAmpere, and in the low part of the dynamic (Idc > 100 pA) the resolution is not so good. That is why we redo this correlation with a threshold of 100 pA. Results are shown on figures (8) to (12).
On each figure, the correlation lines of the other sub-batches are indicated with different colors. For Batch #1, we cannot extract a precise correlation since most of the tubes, after 100pA I_{db} selection, are all around $Log(I_{dc})$ equal to 5. The four other correlation expressions are summarized in the next table.

Sub-batch	Correlation in log scale	Correlation factor	Correlation
Batch#2 CL	0,778 $Log(I_{HAM}) + 0,89$	0,668	2,44 $I_{HAM}^{0,78}$
Batch#3 Pisa	0,958 $Log(I_{HAM}) + 0,211$	0,518	0,81 $I_{HAM}^{0,96}$
Batch#3 Urbana	0,933 $Log(I_{HAM}) + 0,288$	0,681	1,33 $I_{HAM}^{0,93}$
Batch#3 Valencia	0,775 $Log(I_{HAM}) + 1,104$	0,757	3,01 $I_{HAM}^{0,77}$

The correlation with Hamamatsu data are better since a and β parameters are quite close to 1 in comparison when calculating them over all the dark current range.
Only Valencia β parameter seems rather low (β=0,5), but looking again on figure (12), one could conclude that this is an artifact of the correlation determination and that their data are also quite compatible with data of the other sub-batches.

Figure (13) represents the correlation between Hamamatsu and ATLAS 800 Volts dark current for all the 1250 tubes. The line indicates the full correlation line:

$$I_{HAM} = I_{ATLAS}$$

Considering again the difficulty to measure such low current, one could conclude that:
- both set of data are compatible
- Low dark currents are affected by fluctuations that make the correlation factor small in that range of the dark current,
- These fluctuations are smaller when the measured dark current is larger, so that we can be confident on the capacity to reject tubes when the dark current is of the order of some nA

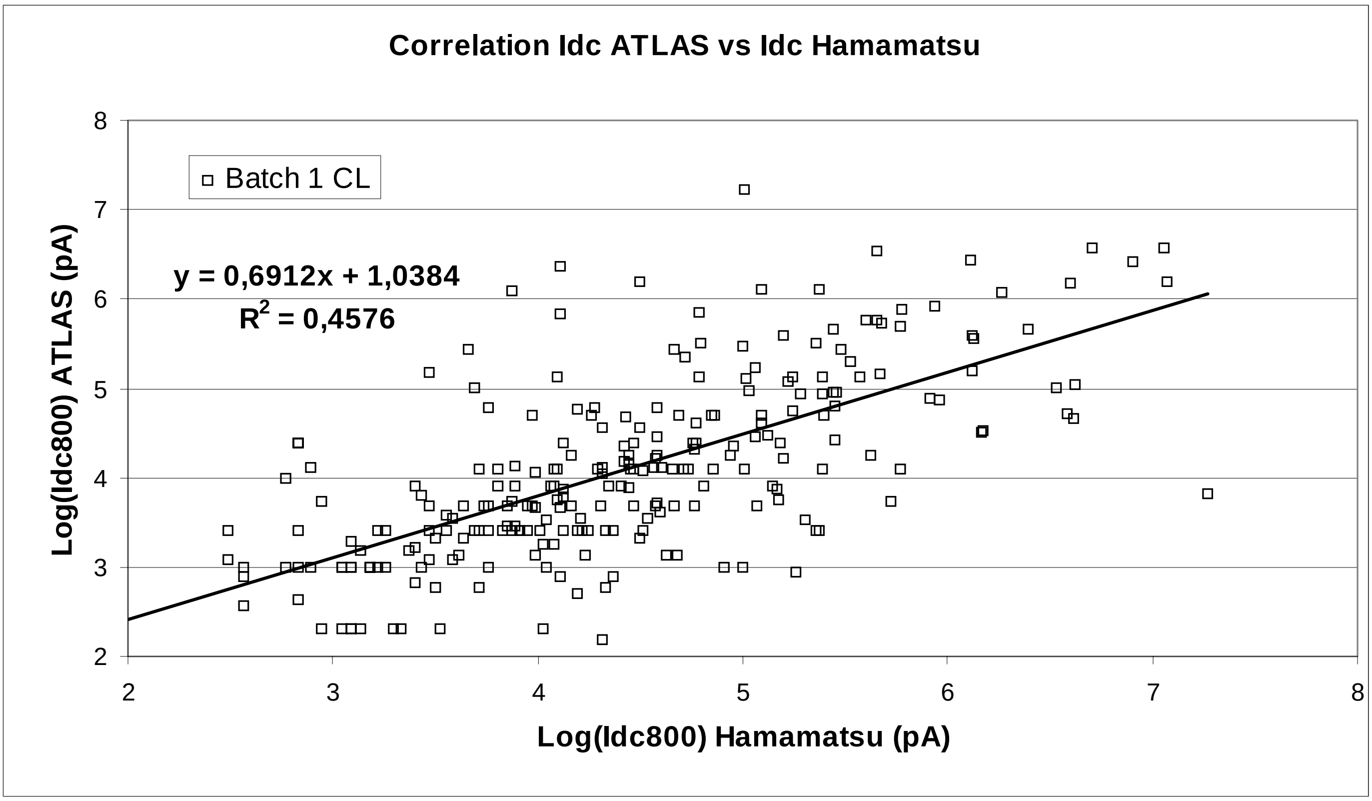


Figure (3) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#1 (CL). It is expressed using logarithm scale, that is Log(Idc) as a function of Log(Idb).

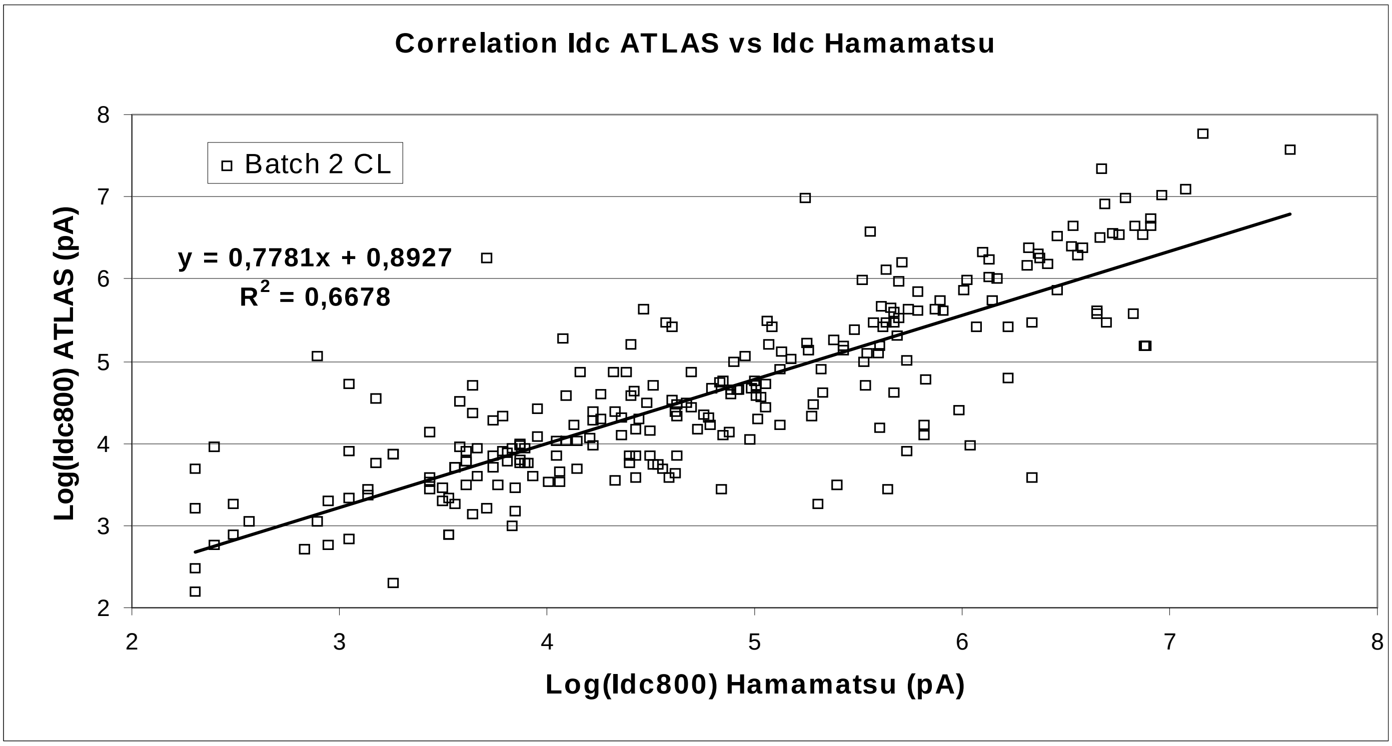


Figure (4) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#2 (CL). It is expressed using logarithm scale, that is Log(Idc) as a function of Log(Idb).

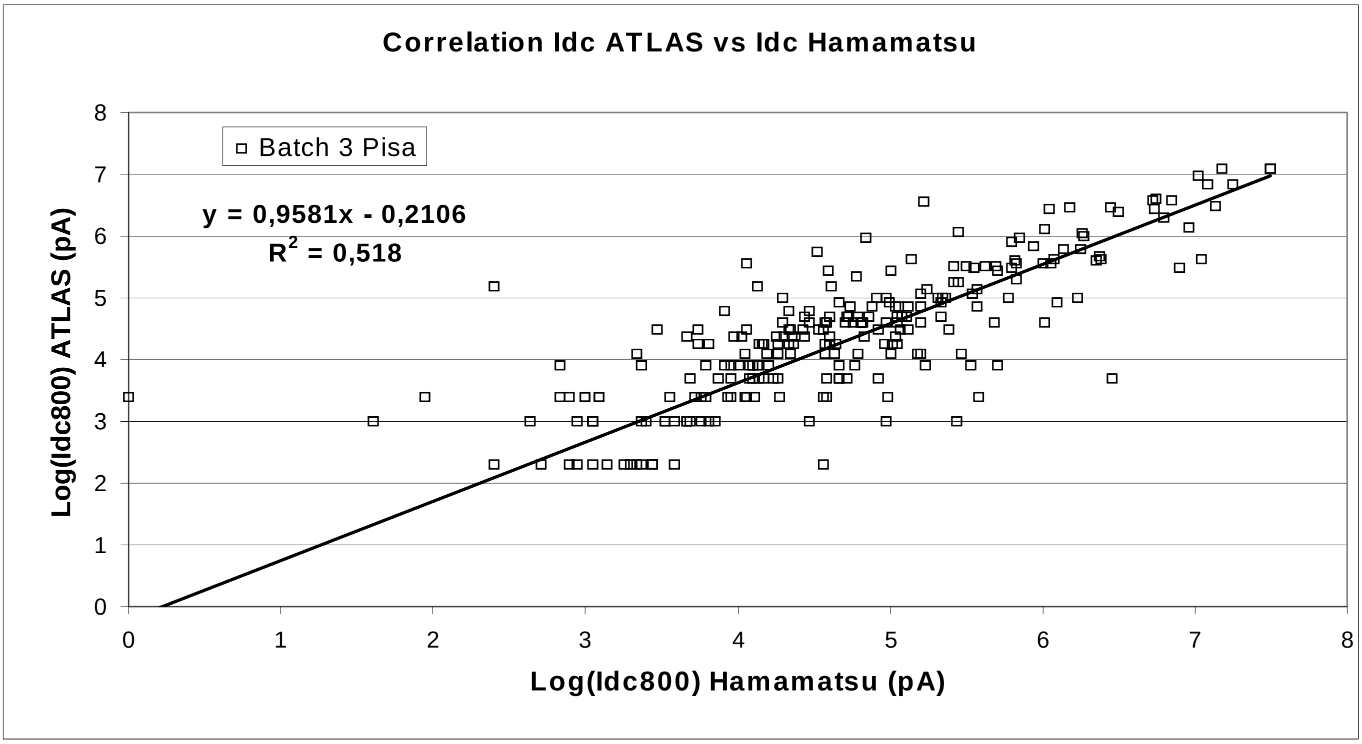


Figure (5) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#3 (Pisa). It is expressed using logarithm scale, that is Log(Idc) as a function of Log(Idb).

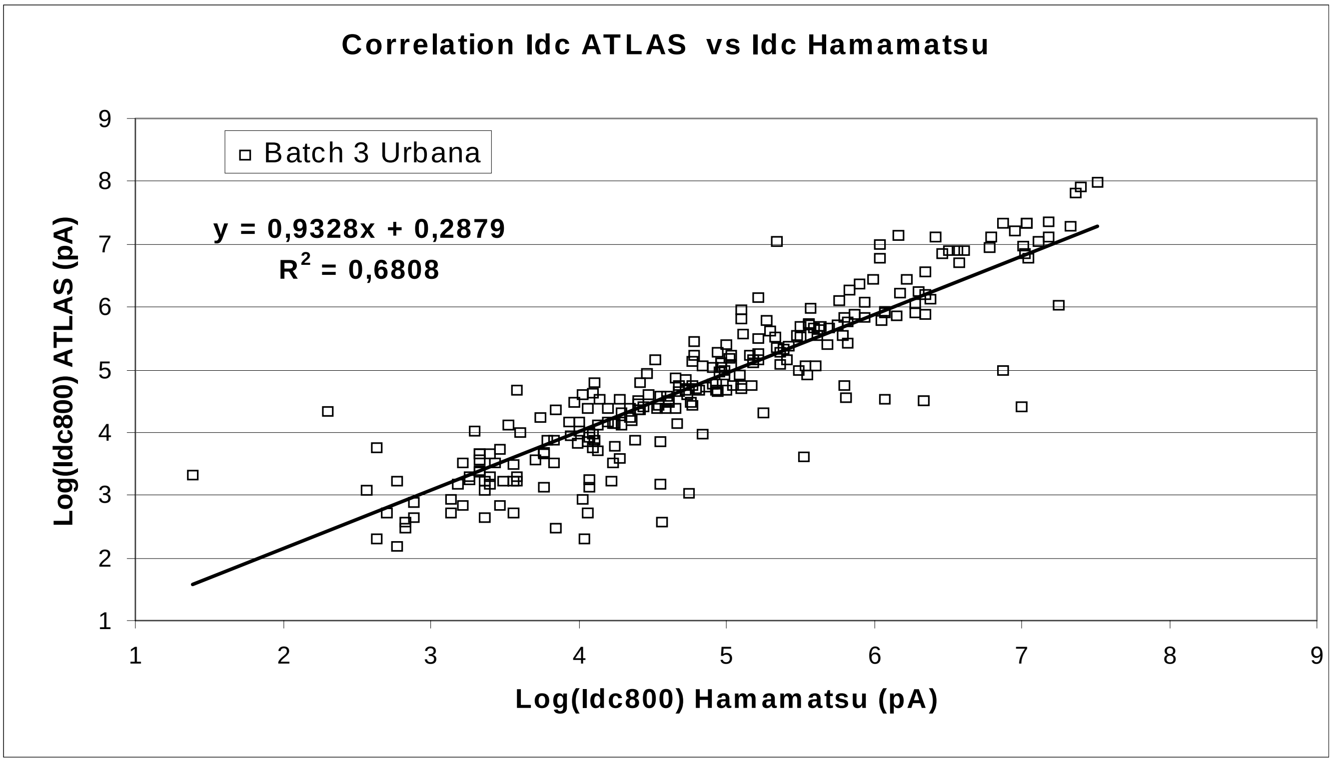


Figure (6) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#3 (Urbana). It is expressed using logarithm scale, that is Log(Idc) as a function of Log(Idb).

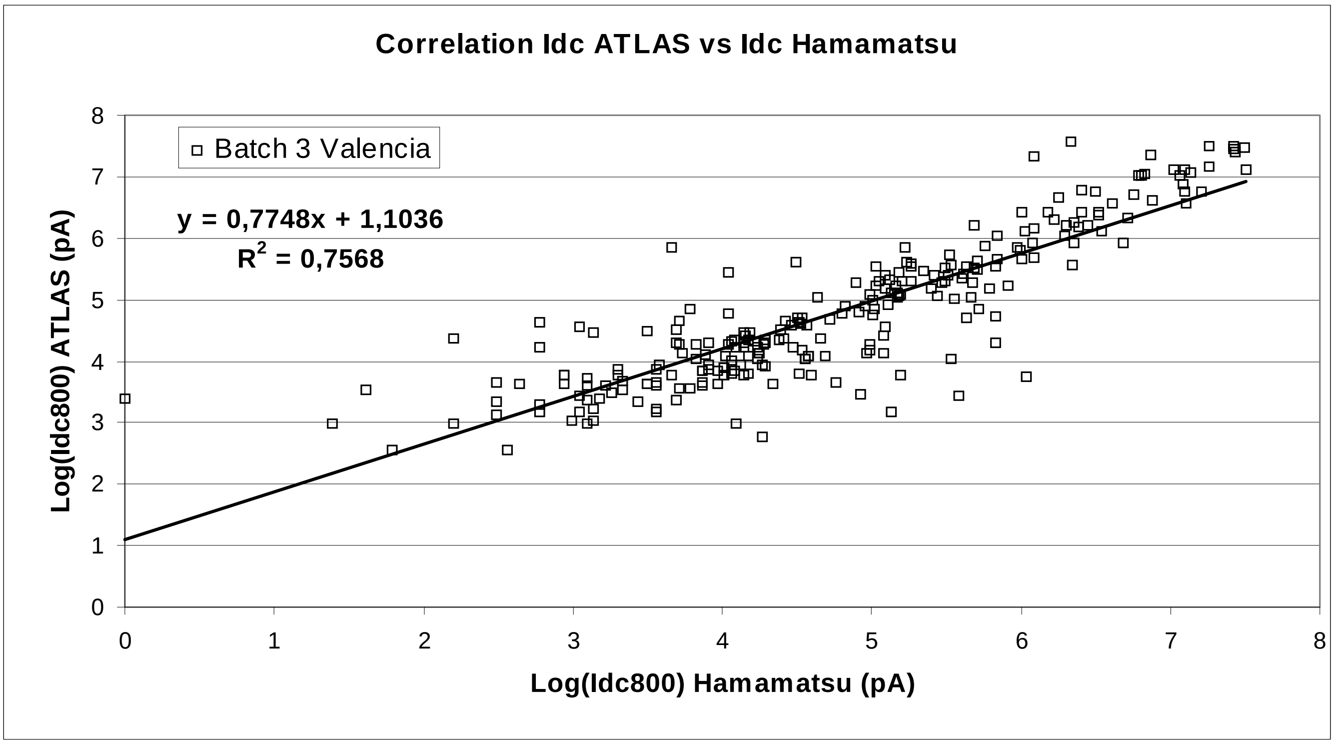


Figure (7) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#3 (Valencia). It is expressed using logarithm scale, that is Log(Idc) as a function of Log(Idb).

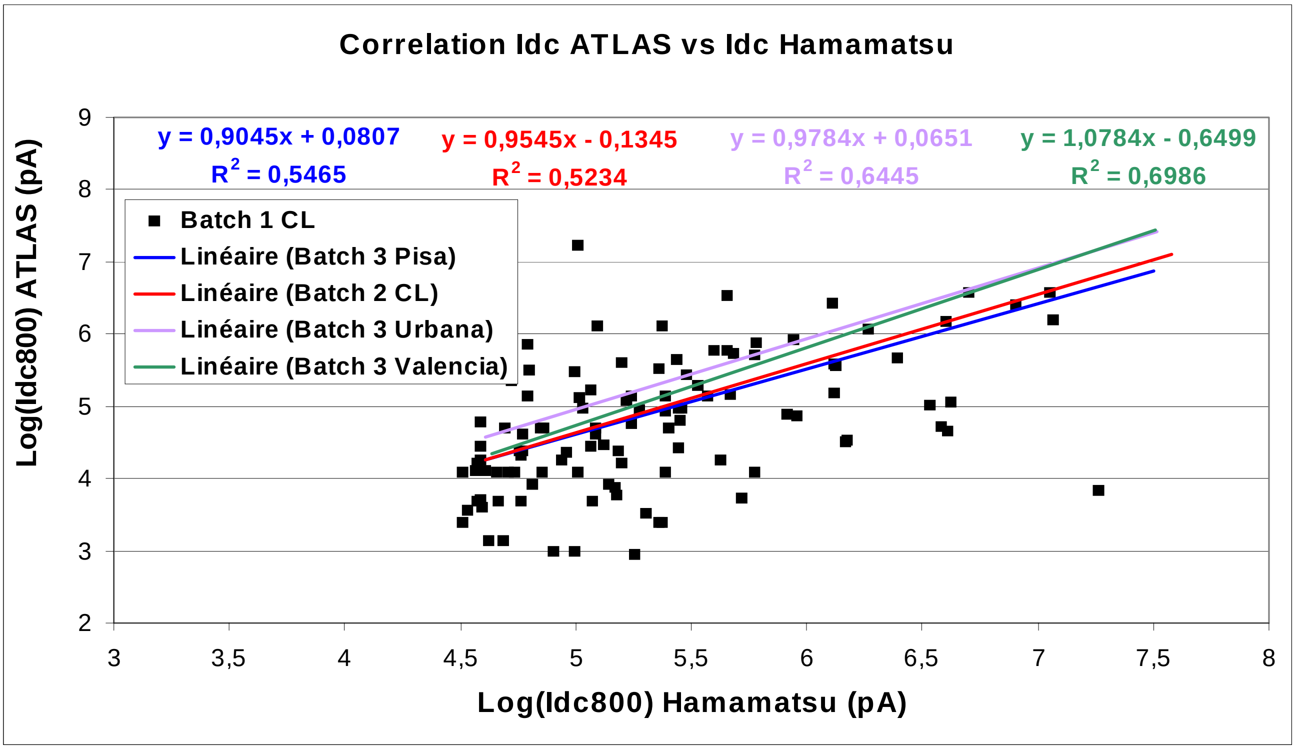


Figure (8) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#1 (CL). Only tubes with I_{db} (Hamamatsu 800 Volts measured current) larger than 100 pA are included in the plot. Correlation lines of the other sub-batches are also shown on the plot for a better comparison

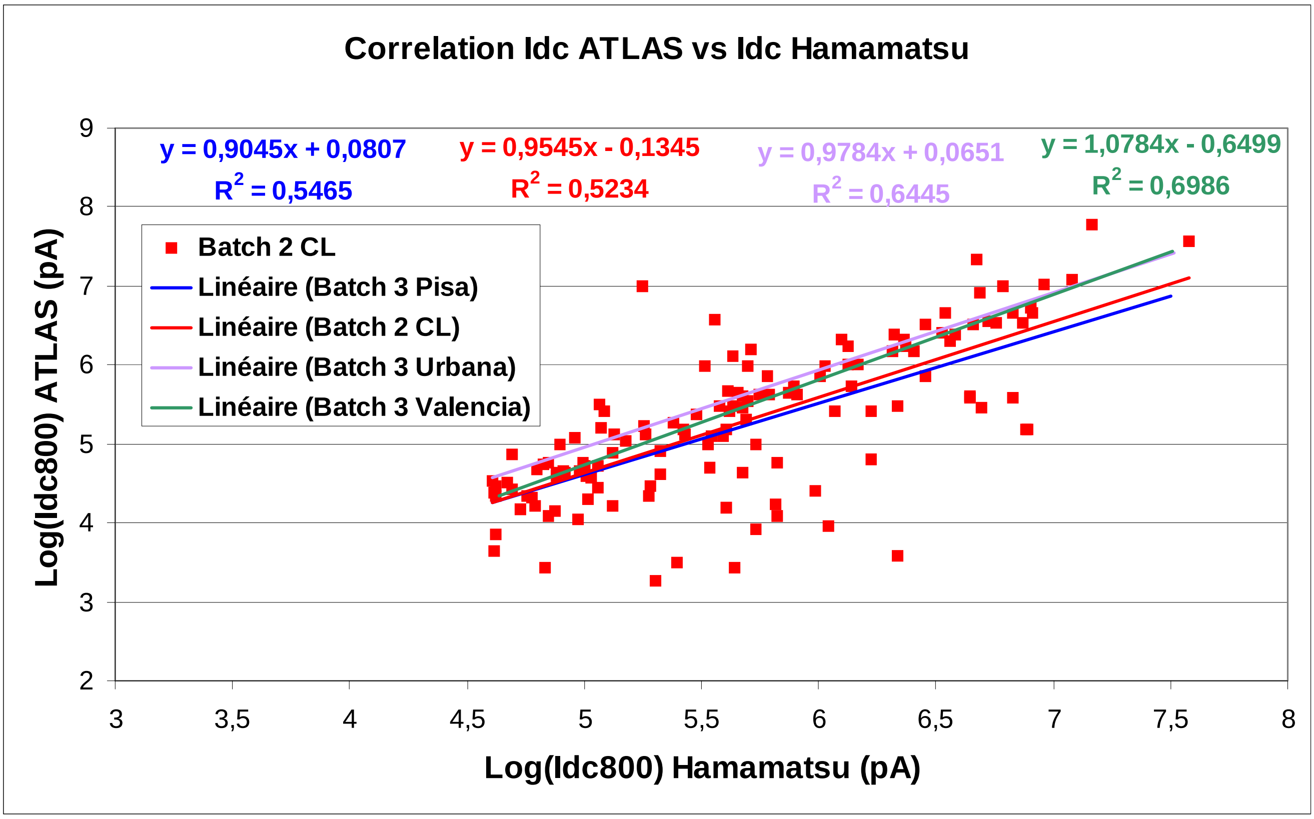


Figure (9) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#2 (CL). Only tubes with I_{db} (Hamamatsu 800 Volts measured current) larger than 100 pA are included in the plot..

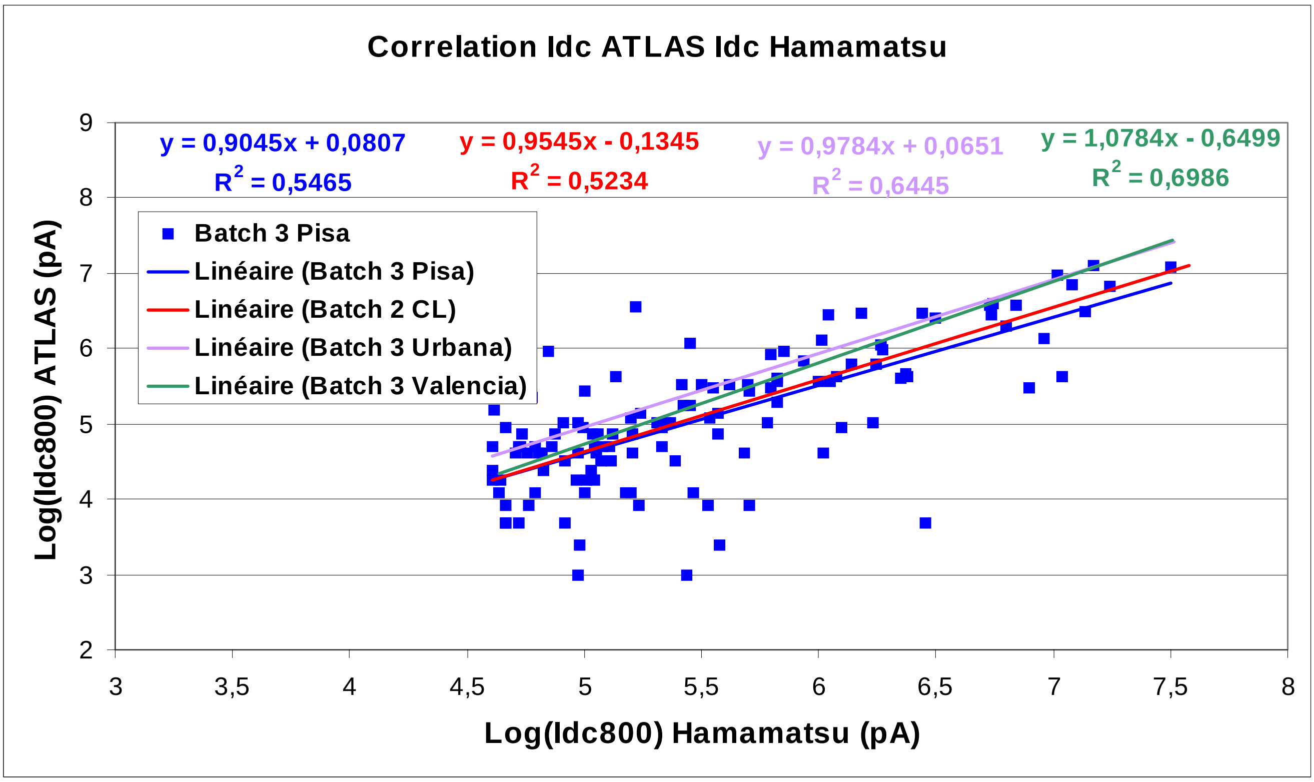


Figure (10) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#3 (Pisa). Only tubes with I_{db} (Hamamatsu 800 Volts measured current) larger than 100 pA are included in the plot.

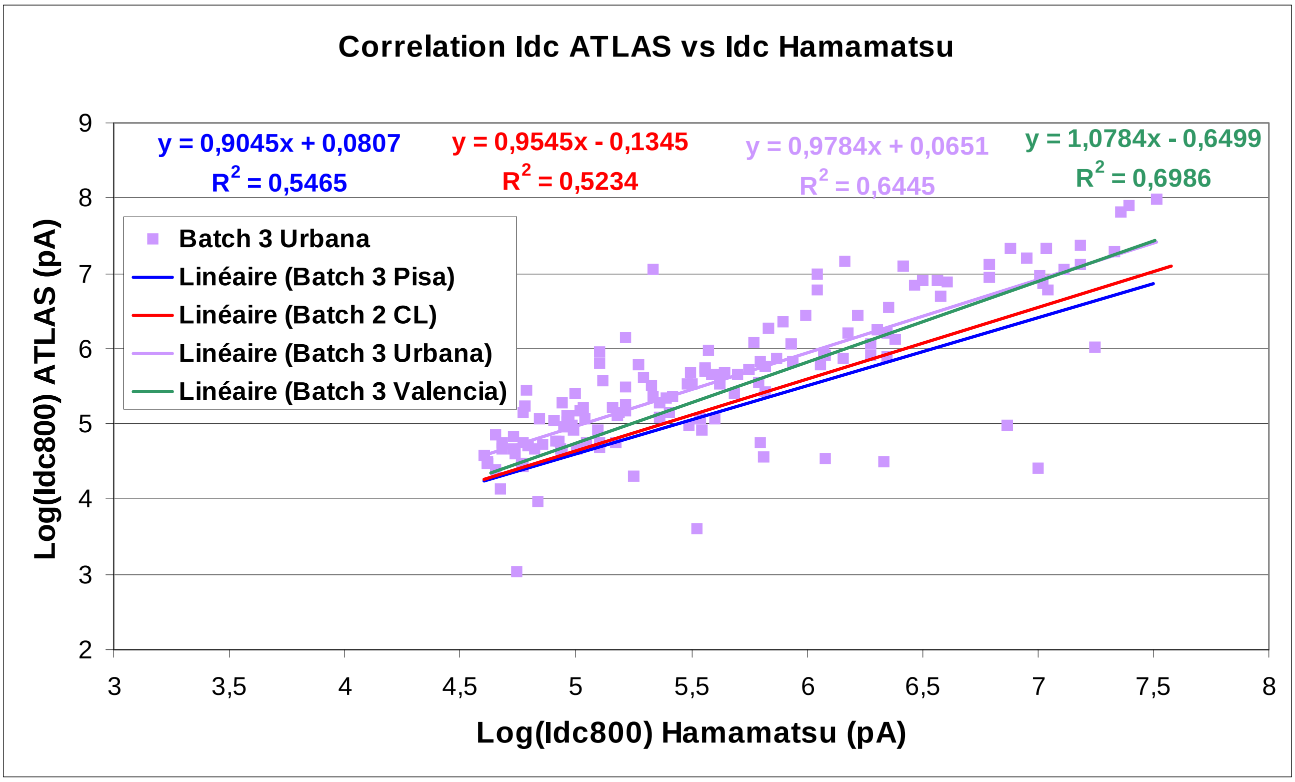
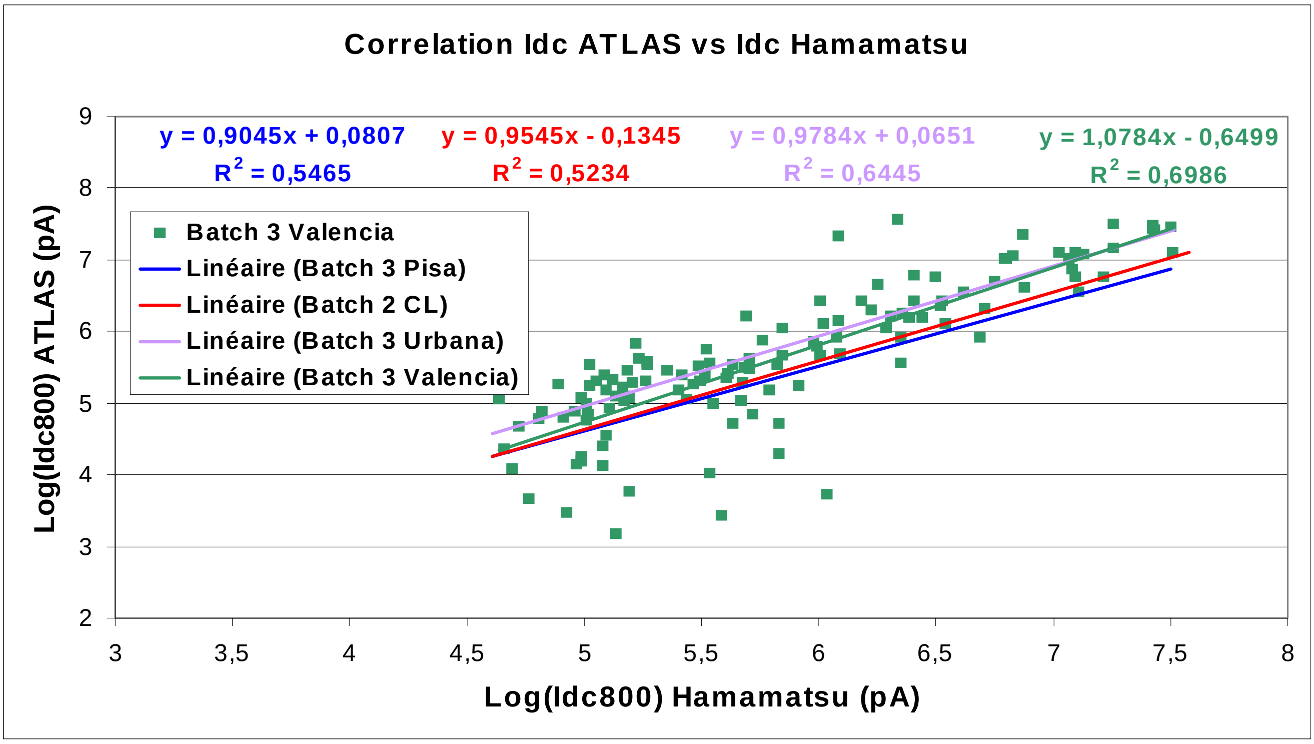


Figure (11) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#3 (Urbana) Only tubes with I_{db} (Hamamatsu 800 Volts measured current) larger than 100 pA are included in the plot..



Figures (12) : Correlation between 800 Volts Hamamatsu and ATLAS measured dark current for Batch#3 (Valencia). Only tubes with I_{db} (Hamamatsu 800 Volts measured current) larger than 100 pA are included in the plot..

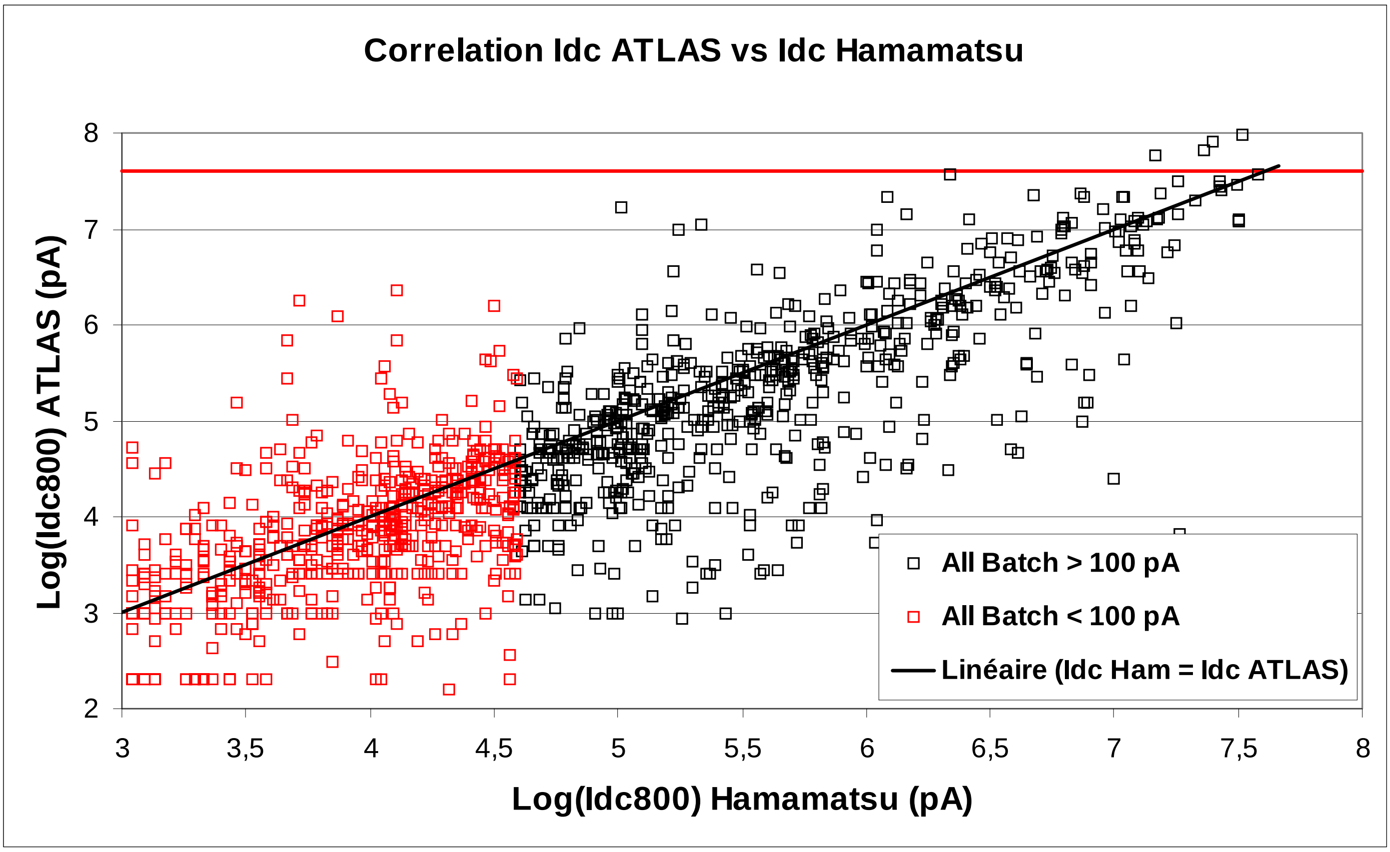


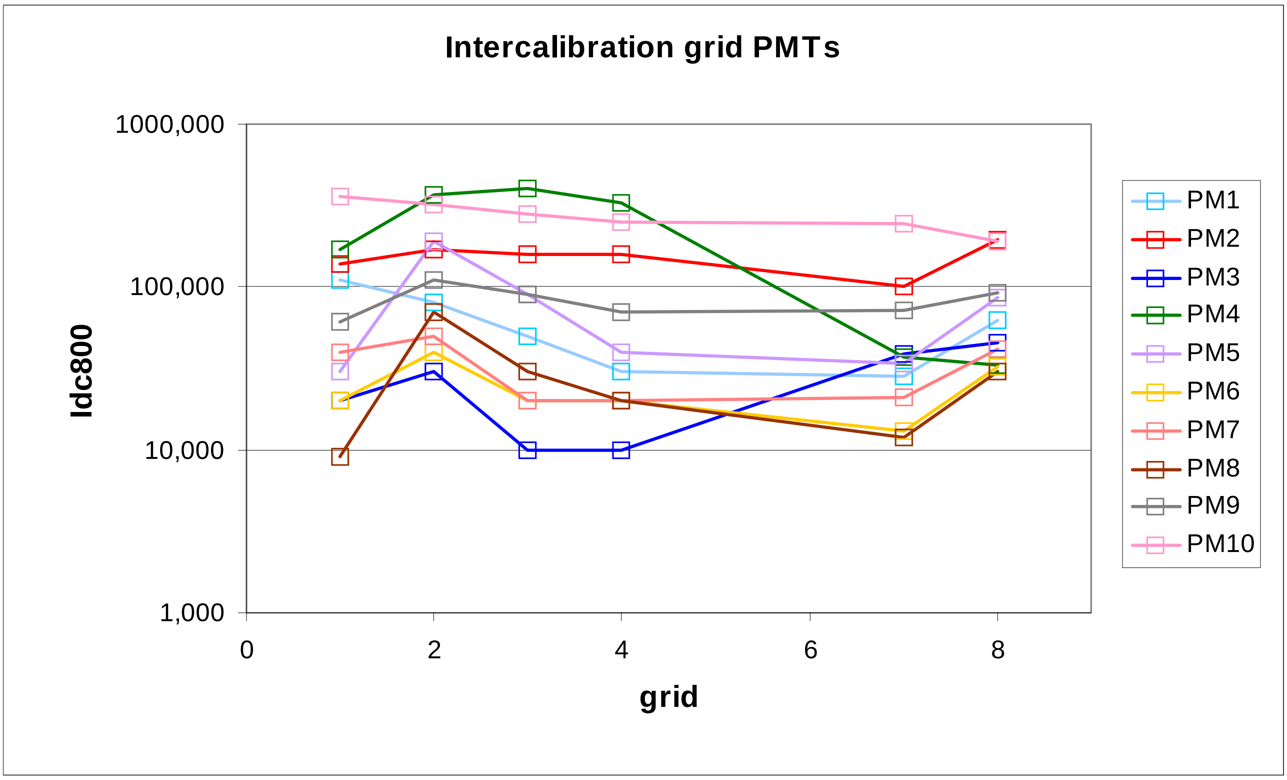
Figure (13) : Correlation between Hamamatsu and ATLAS 800 Volts dark current for all the 1250 tubes. The black line indicates the full correlation line: $I_{HAM} = I_{ATLAS}$ *The red horizontal line indicates the 800 Volts limit (2nA)*

3. Data of the intercalibration grid

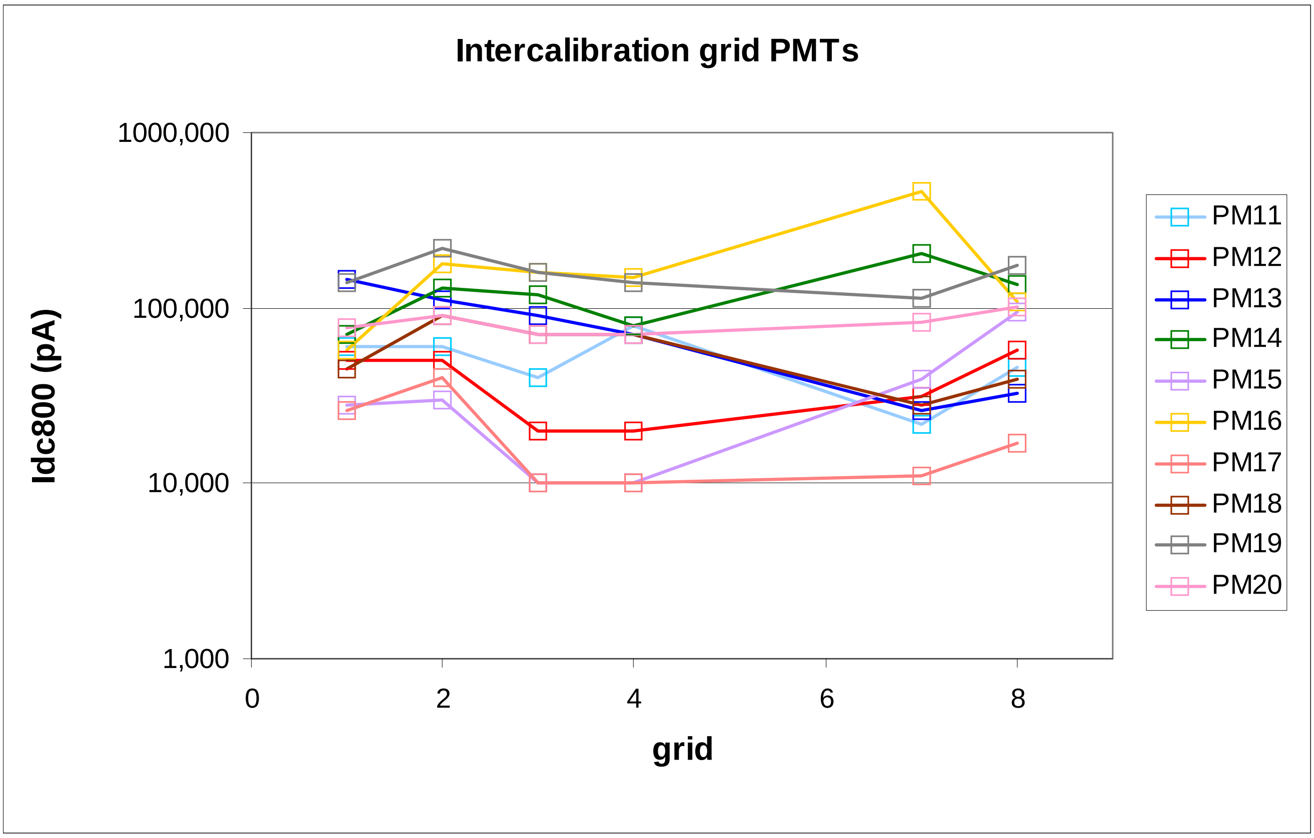
The set of 24 tubes of the intercalibration grid had been measured with the four benches, so that we have up to now for each tubes 8 different measures of its different characteristic. Hereafter we number the different measure as following:

1 ➔ first CL measurement,
2 ➔ first Pisa measurement,
3 ➔ second Pisa measurement,
4 ➔ third Pisa measurement,
5➔ first Valencia measurement,
6 ➔ first Urbana measurement,
7 ➔ second Urbana measurement,
8 ➔ second Valencia measurement,

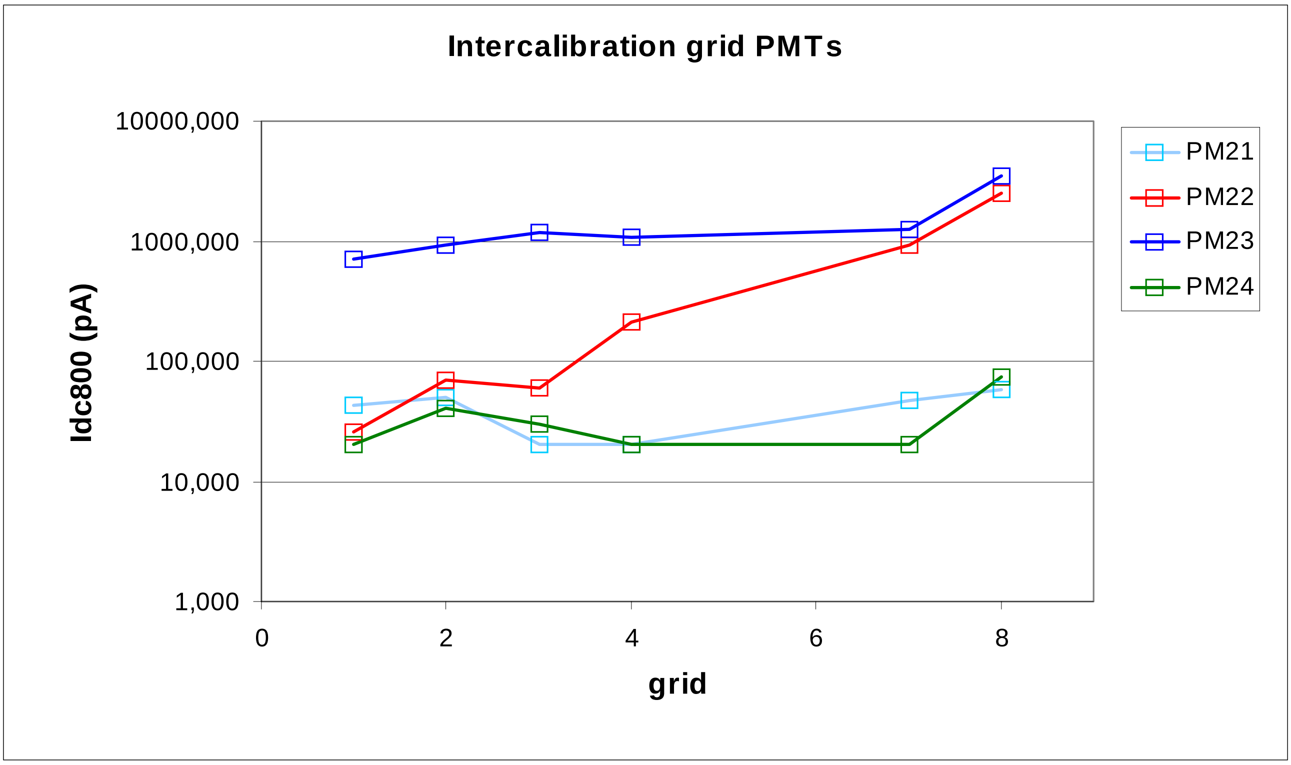
Figures (14) to (16) show evolution of the 800 Volts measured dark current (pA) for the 24 tubes. We only keep Urbana and Valencia second measurements (#7 and #8) that are more compatible with other set of data. Valencia and Urbana first measurement are certainly affected by some problems to be used with sufficient level of confidence.



Figures (14) : Evolution of the 800 Volts measured dark current (pA) for the tubes #1 to #10. We only keep Urbana and Valencia second measurements (#7 and #8)



Figures (15) : Evolution of the 800 Volts measured dark current (pA) for the tubes #11 to #20. We only keep Urbana and Valencia second measurements (#7 and #8)



Figures (16) : Evolution of the 800 Volts measured dark current for the tubes #21 to #24. We only keep Urbana and Valencia second measurements (#7 and #8)

The evolution of the 800 Volts measured dark current is a little bit difficult to summarize and to analyze. As demonstrated in previous section, small value of the dark current (~10 pA) could be affected by large fluctuations. Selecting tubes with dark current equal or larger 100 pA, that is a subset of 12 tubes:

- Tube #1 slowly decrease up to Urbana measure and then increase again for Valencia measurent,
- For all the tubes there is a systematic increase between Urbana and Valencia data.
- Tube #2 is rather constant up to Valencia measurement,
- Tube #4 start from 170 pA, goes up to 400 pA and finally decreases down to 33 pA,
- Tube #13 decreases continuously from 145 pA to 33 pA
- Tube #14 is around 100 pA with a maximum of 200 pA in Urbana,
- Tube #16 is increasing from for 57 pA in CL to 465 pA in Urbana,
- Tube #19 is stable,

As a conclusion, the intercalibration grid cannot be used to cross-check the data performed on the different test-benches. If there is a so large discrepancy between the 4 benches, we cannot get the quality of results shown in previous section.

4. Variation of dark current measured for the monitoring PMTs

Figures (17) to (20) present the evolution of the monitoring PMTs set in the corners of the benches when measuring the different sub-batches. These monitoring PMTs were not used for the batch#1 in CL.

First, we should keep in mind that the resolution for the measured dark current is of the order of some tens of picoAmpere and that fluctuations when the measured dark current is so low could be relatively large since first the bench resolution is roughly of the same order and also because dark current is itself a random phenomena with its own fluctuations in time.

It is difficult to represent correctly the four PMTs on the same plot, so we do the following:

- for each tube the mean value over all the runs (13) is first calculated,
- then the measured dark current is normalized to this average value,
- the average value is indicated on the legend of the plots for each tubes,

Batch# 2 (CL)

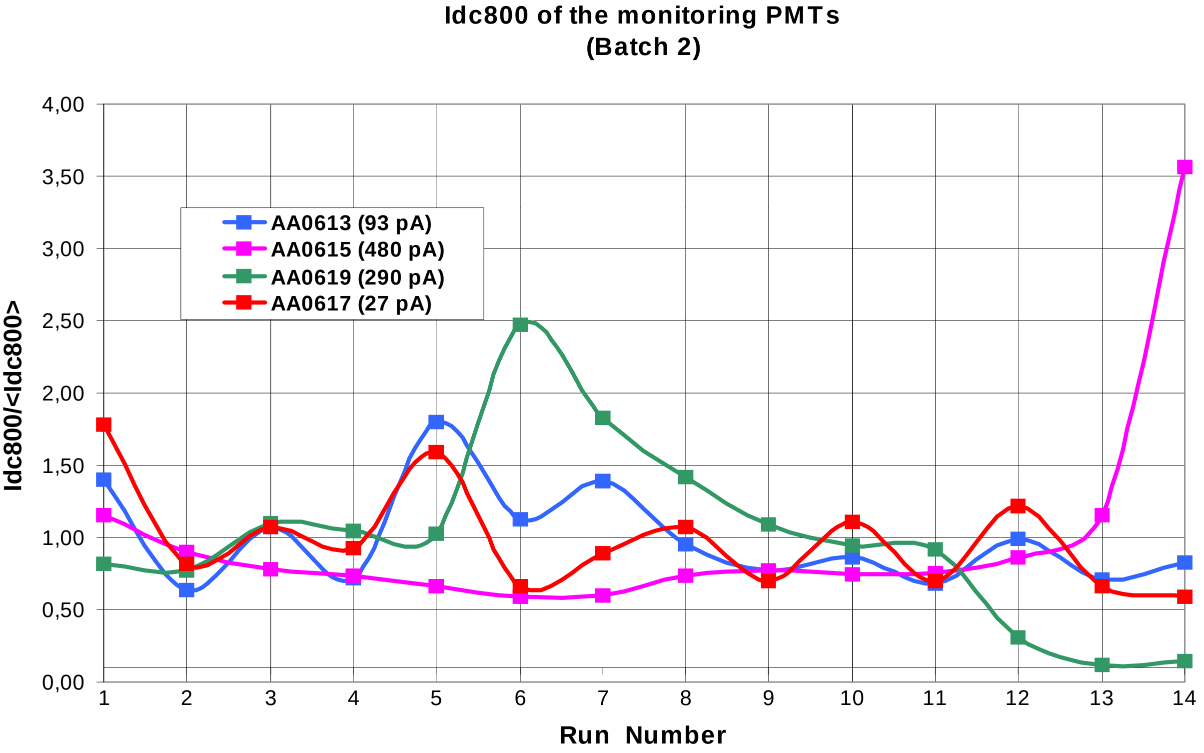


Figure (17) : Evolution of the 4 monitoring tubes, used during Batch#2 (CL) test.

The tube with the largest current (AA0615) is quite stable at the beginning, but suddenly increases up to ~4 times its mean value over the two last runs.

Evolution of tube AA0619 is quite interesting: the tubes start to be stable over the 5 first runs, then suddenly increases at the 6th runs (717 pA) and then slowly decreases, going to a very small value (40 pA) on the two last runs.

We already observe such an evolution: a disturbed tube that goes slowly to a more stable status over a long time.

Batch# 3 (Pisa)

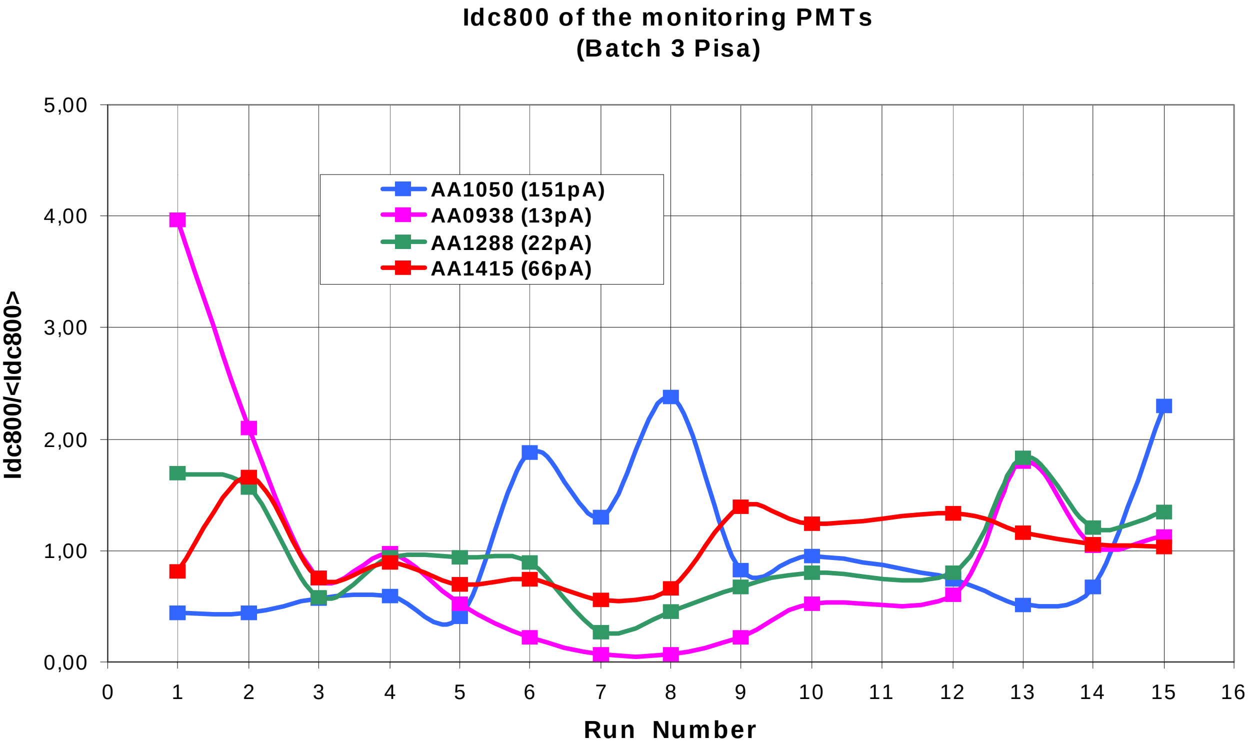


Figure (18) : Evolution of the 4 monitoring tubes, used during Batch#3 (Pisa) test.

The tube with the largest current (AA1050) is quite stable at the beginning (~70 pA), but suddenly increases up to 300 pA at runs #6 to #8, and then go down to some smaller values on the next 5 runs.

The tube with the smallest current (AA0938) is slowly decreasing from 53 pA down to a few pA at run #8. Considering measurement resolution, one could conclude that this tube, together with the two others are quite stable.

Batch# 3 (Urbana)

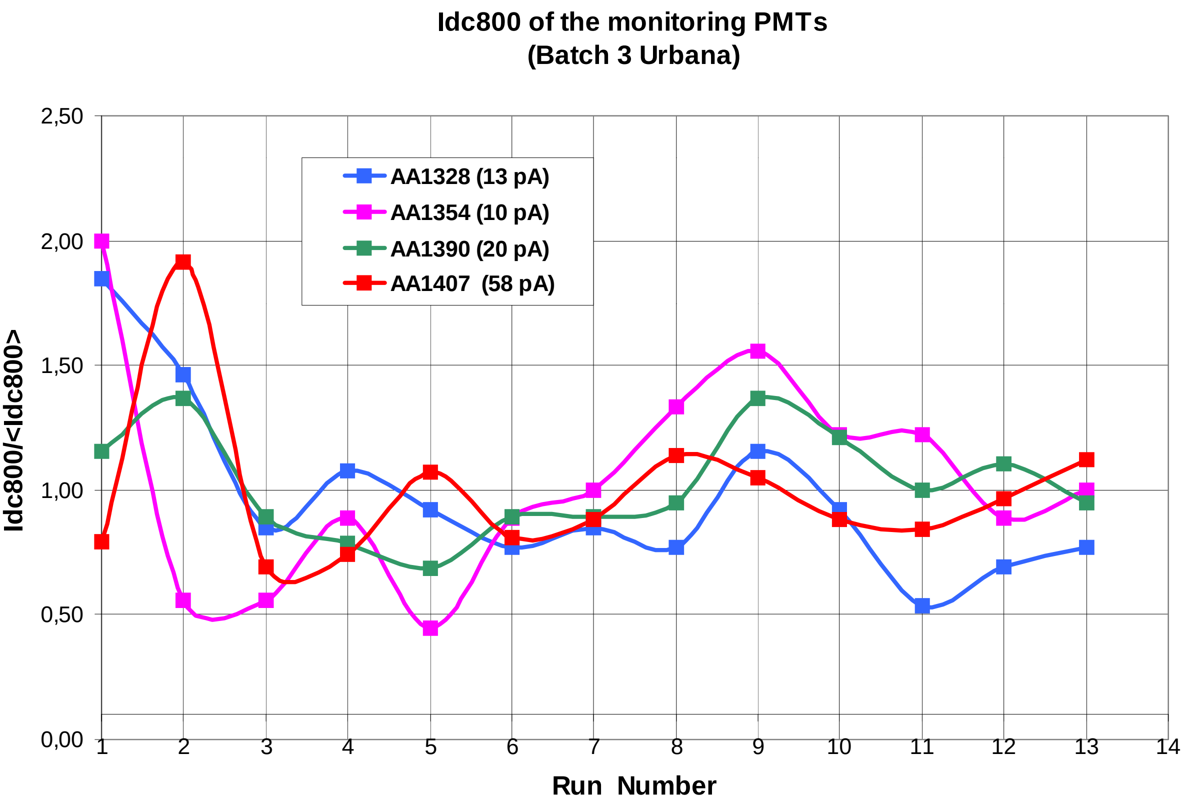


Figure (19) : Evolution of the 4 monitoring tubes, used during batch#3 (Urbana) test.

This is the more stable configuration, even if the tube AA1407 doubled its mean value (~50 pA ➔100 pA) at run #2. Other tubes fluctuate with the dark current measurement resolution.

Batch# 3 (Valencia)

Here the tube's dark current evolution is affected by some "spikes", especially AA0890, that could increase from ~50-60 pA up to 500-700 pA on 3 runs. Such a "spike" is incredibly large when measuring the 900 Volts dark current: 38 nA at run #19 !.

On the other way tube AA0551 is continuously increasing, starting from ~300 pA up to 9 nA for the last run. 900 Volts measured dark current for this tube is also increasing from 445 pA to 12 nA.

The two other tubes present also large fluctuations. Origin of such variation should be clarify before doing other measurements on this test-bench.

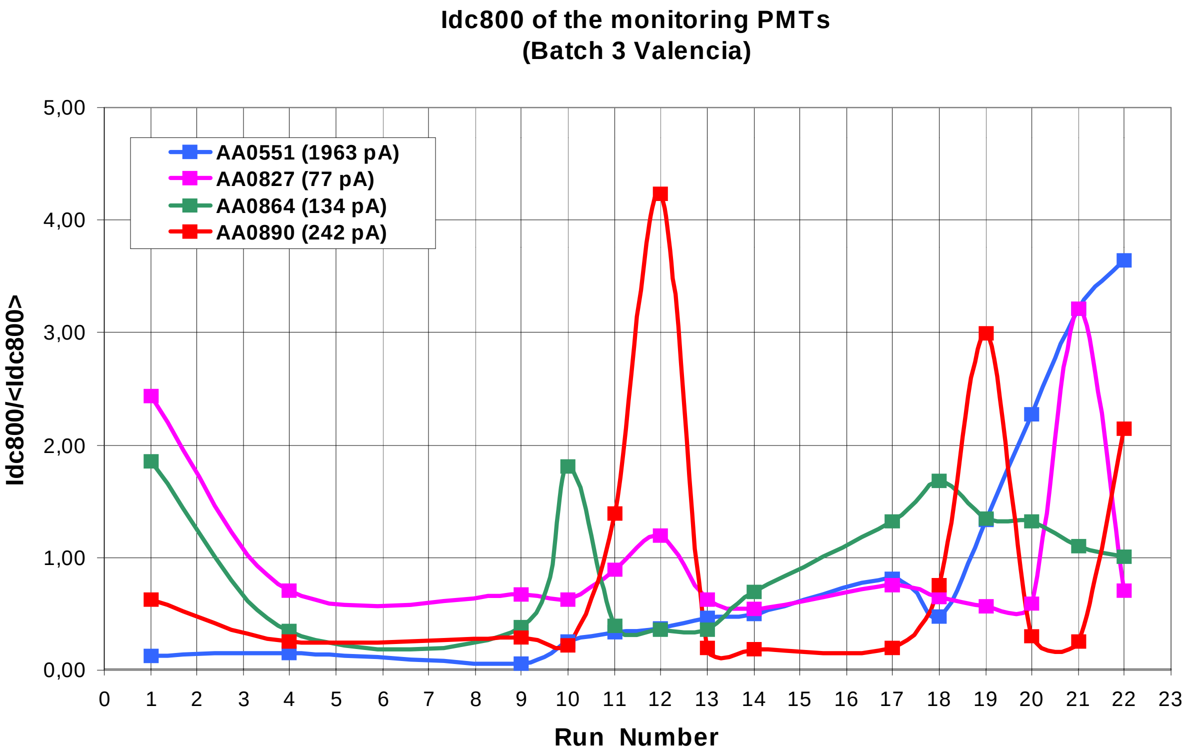


Figure (20) : Evolution of the 4 monitoring tubes, used during batch#3 (Valencia) test.

The conclusion of the analysis of the evolution of the monitoring PMTs for the different benches is that the resolution do not allow to reach full stability. But some bench's data are better.

This could originate from the tubes themselves. So before starting a sub-batch measurement, one should be sure that the tubes are in a quite status with a period of 4-5 days measuring the characteristics of the monitoring tubes only, and so detect a « bad » monitoring tube

Origin of such fluctuation could also a consequence of the manipulation of the tubes : such tubes are quite sensible to shocks, vibrations, i.e, all the tube's history just before the measurement.

PMTs should be carefully set on the grid; Final possibility of such variation could be also a consequence of some bench failure, but it could not explain variations spread over few runs

5. Correlation between 800 and 900 Volts measured dark currents

Figures (21) to (23) show the correlation between the 800 Volts and 900 Volts measured dark current for the 5 sub-batches.

In fact, we plot Log(I_{DC}) expressed in picoAmperes and get some clear correlation

Batch#1 (CL) ➔ $\mathrm{Log}(I_{DC900}) = 0{,}922\ \mathrm{Log}(I_{DC800}) + 1{,}01$

Batch#2 (CL) ➔ $\mathrm{Log}(I_{DC900}) = 0{,}926\ \mathrm{Log}(I_{DC800}) + 0{,}965$

Batch#3 (Pisa) ➔ $\mathrm{Log}(I_{DC900}) = 0{,}878\ \mathrm{Log}(I_{DC800}) + 1{,}075$

Batch#3 (Urbana) ➔ $\mathrm{Log}(I_{DC900}) = 0{,}928\ \mathrm{Log}(I_{DC800}) + 0{,}903$

Batch#3 (Valencia) ➔ $\mathrm{Log}(I_{DC900}) = 0{,}936\ \mathrm{Log}(I_{DC800}) + 0{,}794$

Correlation factor is close to 1 for every sub-batch, and the mean correlation for all the tubes could be expressed as:

$$\mathrm{Log}(I_{DC900}) = 0{,}918\ \mathrm{Log}(I_{DC800}) + 0{,}95$$

$$\mathrm{Log}(I_{DC900}) = 0{,}918\ \mathrm{Log}(I_{DC800}) + \mathrm{Log}(2{,}6)$$

Or in an other way:

$$\mathrm{Log}(R) = \mathrm{Log}\ (I_{DC900}/I_{DC800}) = \beta \times I_{DC800}{}^{0{,}0082}$$

The ratio is so not constant, going from 2,6 for low I_{DC800}, down to 1,77 for I_{DC800} equal to 100 pA and 1,46 for I_{DC800} equal to 1 nA

One could conclude that for a « good » tube, the dark current is partially depending of the high voltage. A dark current widely increasing with high voltage, indicates that the tube has some problem

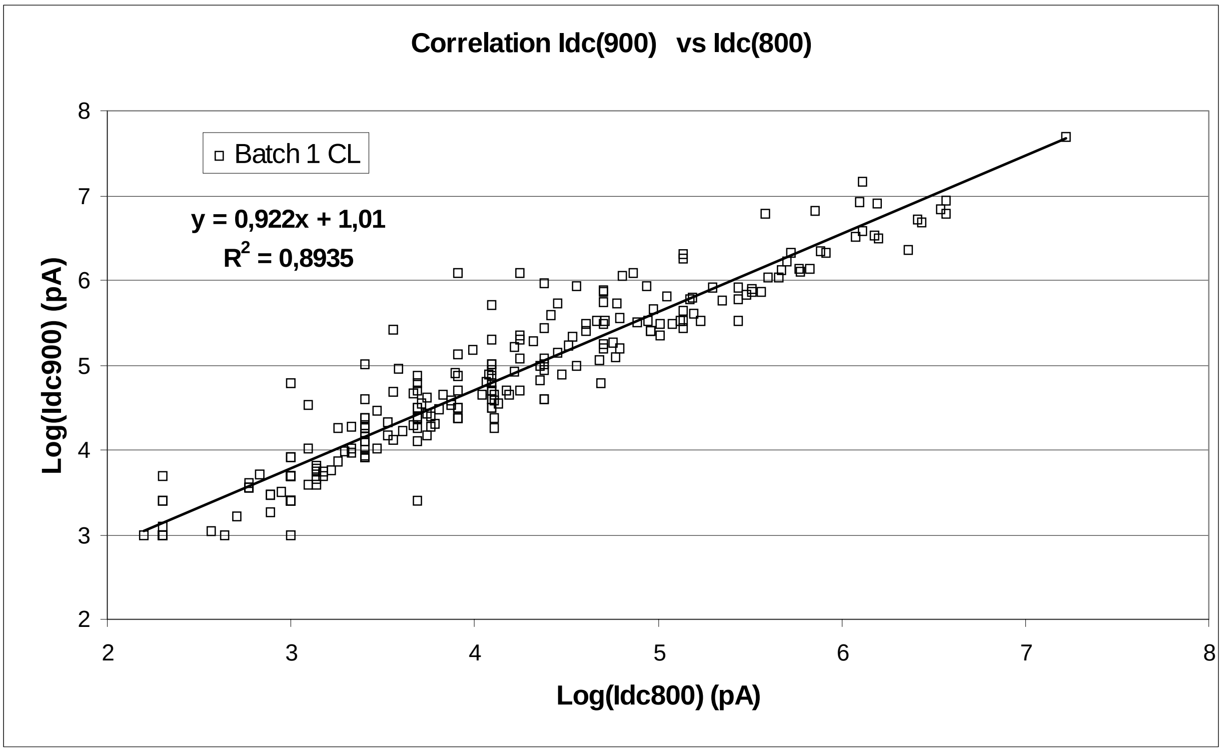


Figure (21) : Correlation of the 800 and 900 Volts measured dark current for Batch#1 (CL).

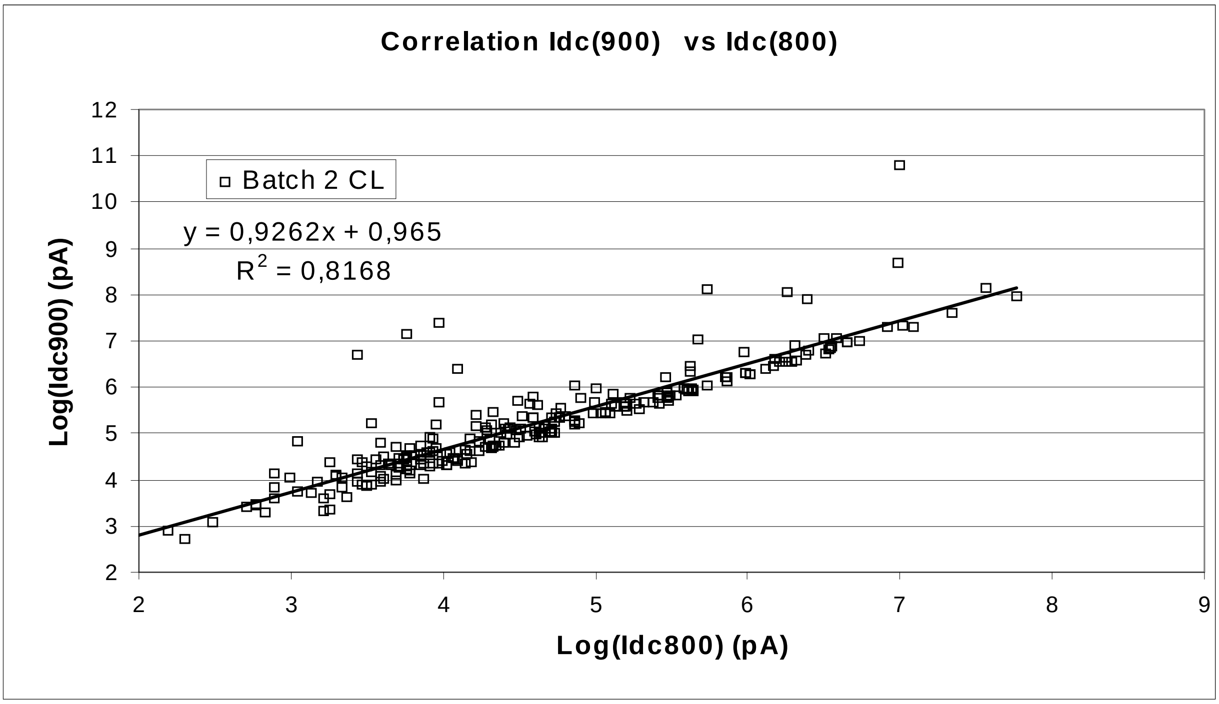


Figure (22) : Correlation of the 800 and 900 Volts measured dark current for Batch#2 (CL).

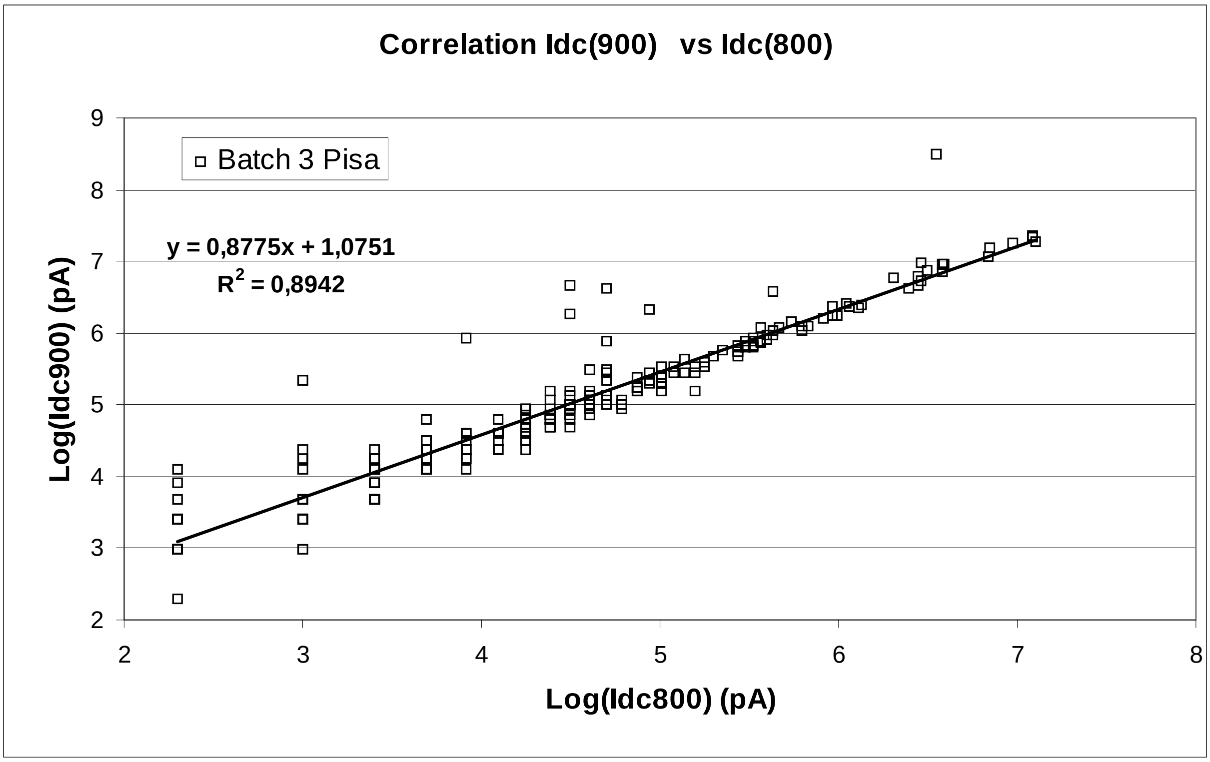


Figure (23) : Correlation of the 800 and 900 Volts measured dark current for Batch#3 (Pisa).

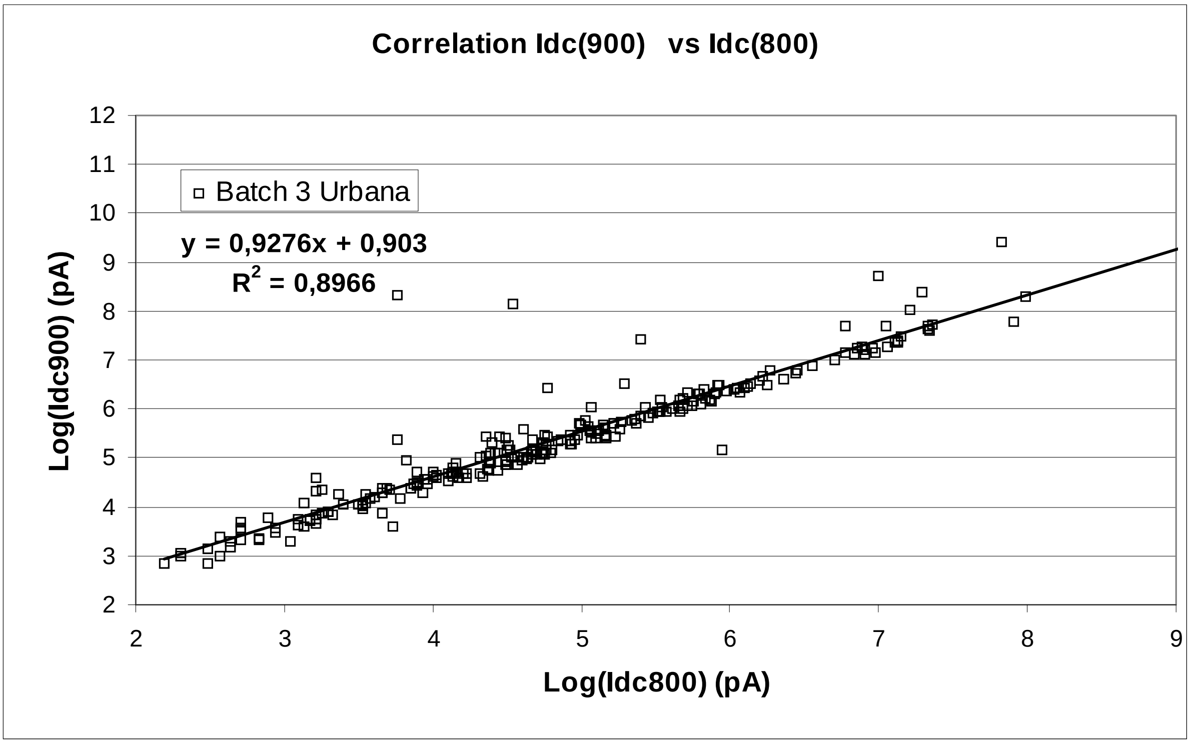


Figure (24) : Correlation of the 800 and 900 Volts measured dark current for Batch#3 (Urbana).

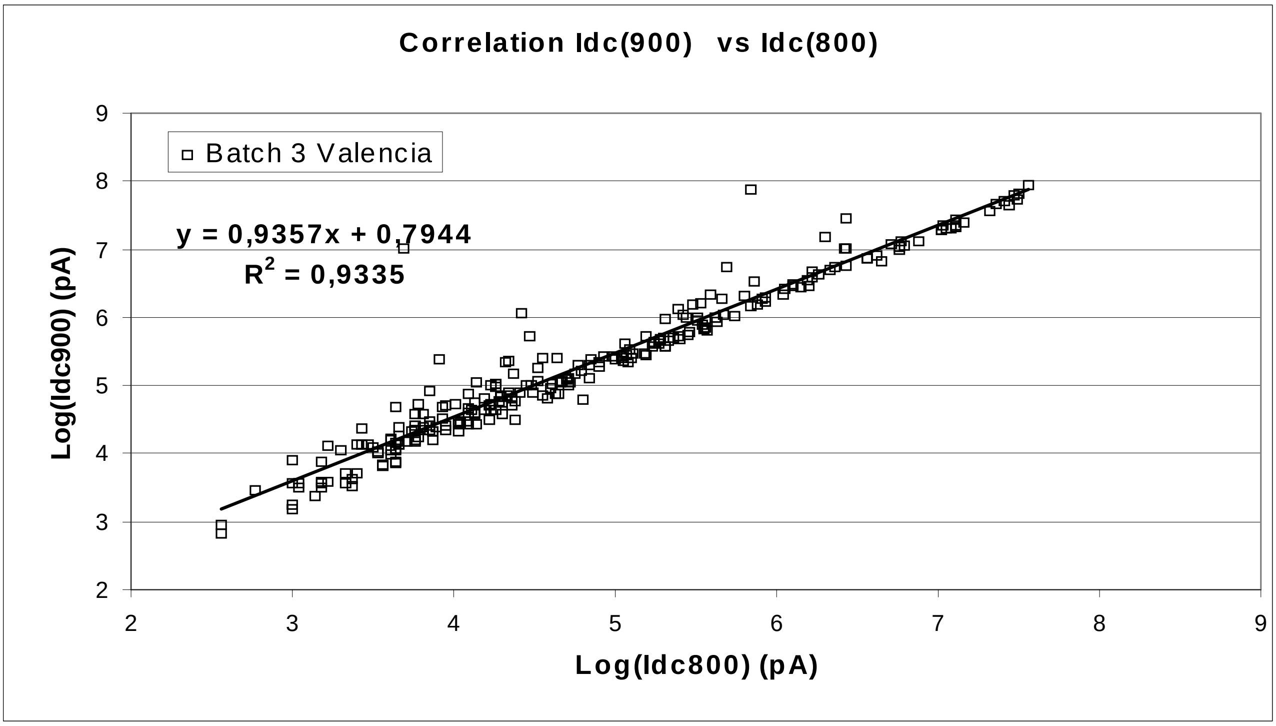


Figure (25) : Correlation of the 800 and 900 Volts measured dark current for Batch#3 (Valencia).

6. Global Distributions

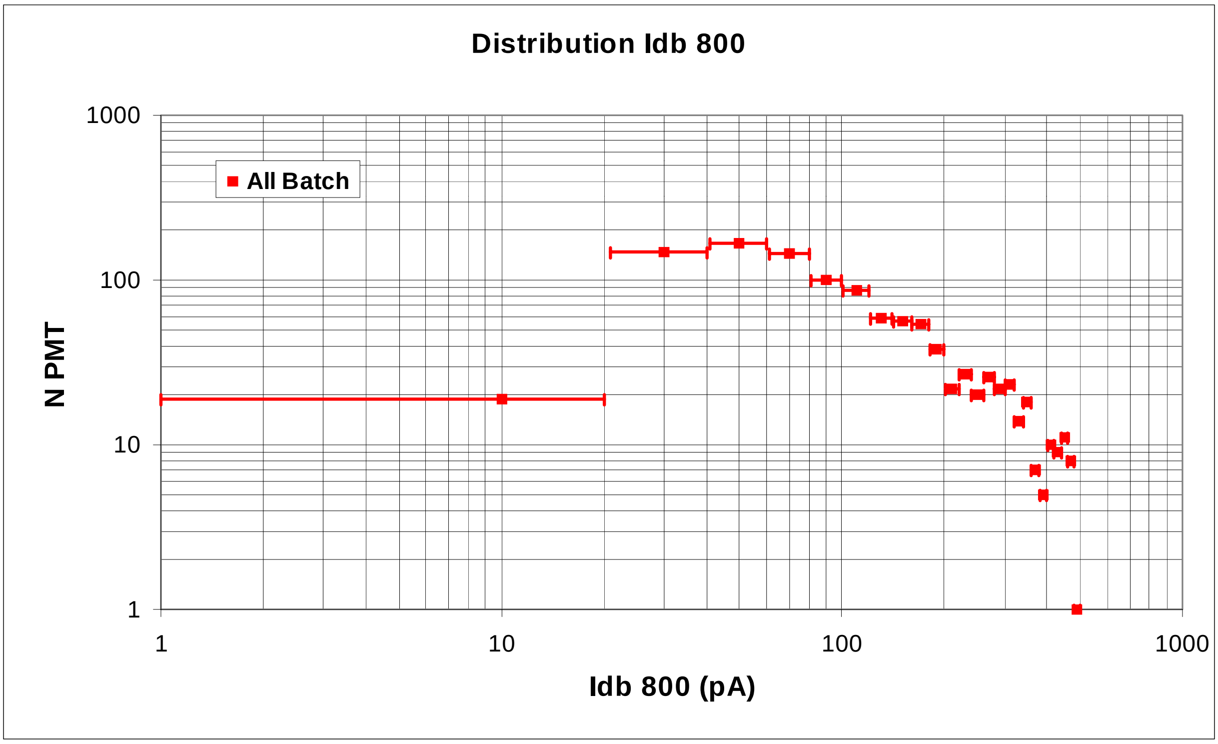
Figures (26) to (28) are the global distributions for the whole set of 1250 tubes :

- Figure(26) is the global distribution of the Hamamatsu 800 Volts measured dark current (IDB),

- Figure (27) is the ATLAS 800 Volts measured dark current (I_{DC800}),

- Figure (28) is the ATLAS 900 Volts measured dark current (I_{DC800}),

The most probable value for I_{DC800} is in the range 30-60 pA, and for I_{DC900} is in the range 50-150 pA.



Figure(26) : Global distribution of the Hamamatsu 800 Volts measured dark current (I_{DB})

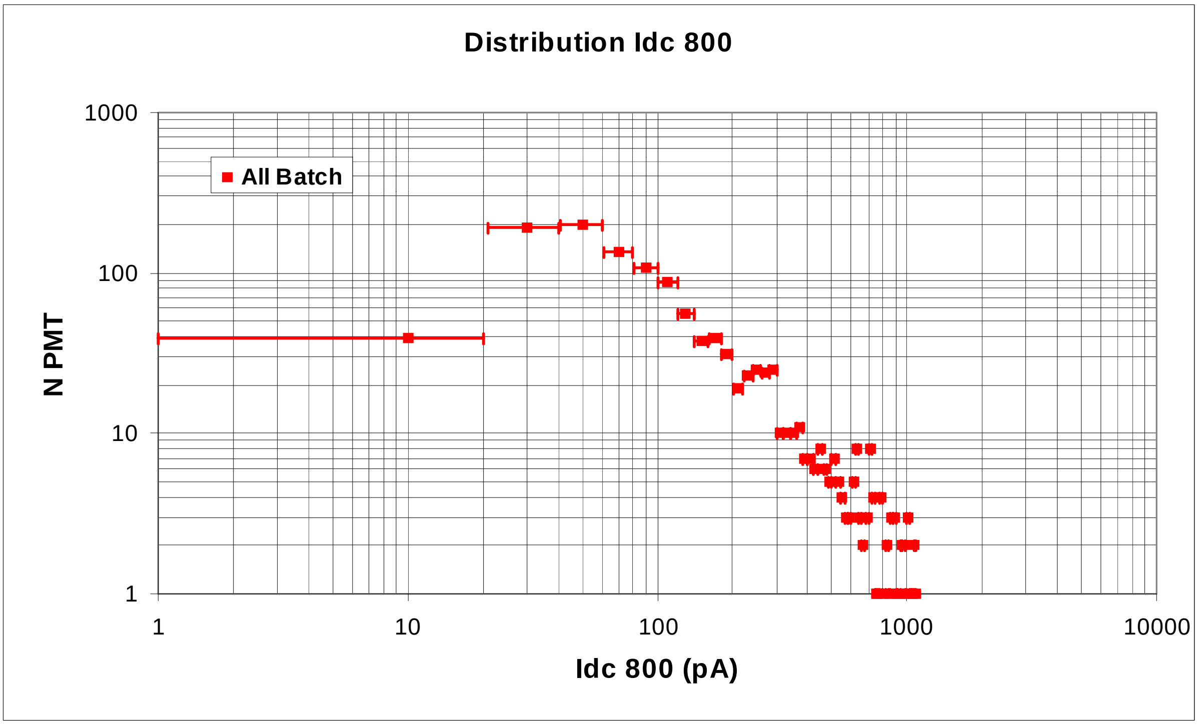


Figure (27) : Global distribution of the ATLAS 800 Volts measured dark current (I_{DC800})

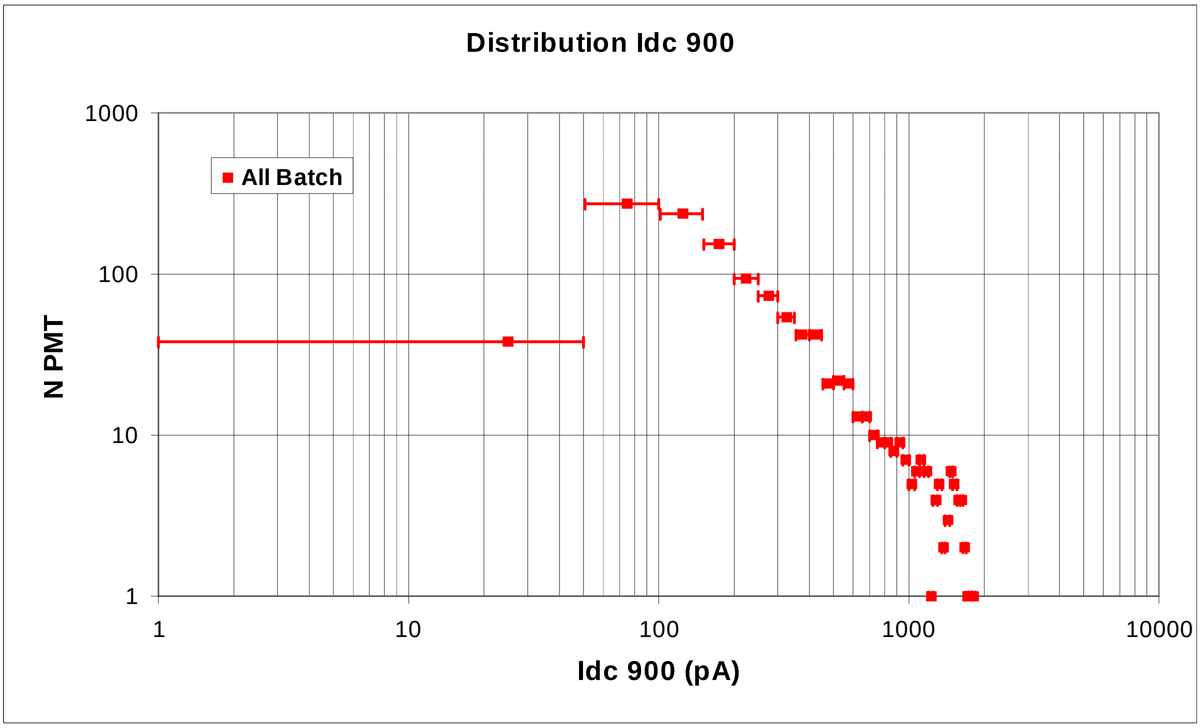


Figure (28) : Global distribution of the ATLAS 900 Volts measured dark current (I_{DC800})

7. Conclusions

Considering again the difficulty to measure dark current, one could conclude that:

1. all sets of data are compatible,
2. measured dark currents are affected by fluctuations that originate from bench resolution (a few tens of pA), but also from intrinsic variation of the dark current,
3. These fluctuations are smaller when the measured dark current increase, so that we can be confident on the capacity to reject tubes when the dark current is of the order of some nA

The analysis of the evolution of the monitoring PMTs for the different benches indicate that some bench's data looks better.
This could originate from the tubes themselves. So before starting a sub-batch measurement, one should be sure that the tubes are in a quite status with a period of 4-5 days measuring the characteristics of the monitoring tubes only, and so detect a « bad » monitoring tube.

Fluctuations could also be a consequence of the manipulation of the tubes : such tubes are quite sensible to shocks, vibrations, i.e, all the tube's history just before the measurement. PMTs should be carefully set on the grid.

Such variation could be also a consequence of some bench failure, but it could not explain variations spread over few runs

The "intercalibration" grid cannot be use to cross-check the data performed on the different test-benches since, as said previously, the dark current is depending of the history of the grid (memory of travelling conditions)

Anyway, looking on global distributions, one could conclude that the 1250 tubes are in the required specifications