January 4st 2001

GM

Quantum efficiency Distributions and intercalibration of the three first batches of phototubes

1. Introduction

The data provided with the tubes by Hamamatsu include the photocathode sensibility distribution, S_k, expressed in μA per lumen and the anode sensibility, S_a, expressed in A per lumen.

All batches have the same photocathode sensibility distribution. This is confirmed by the S_k distribution, as a fonction of phototube serial number, shown on figure (1).

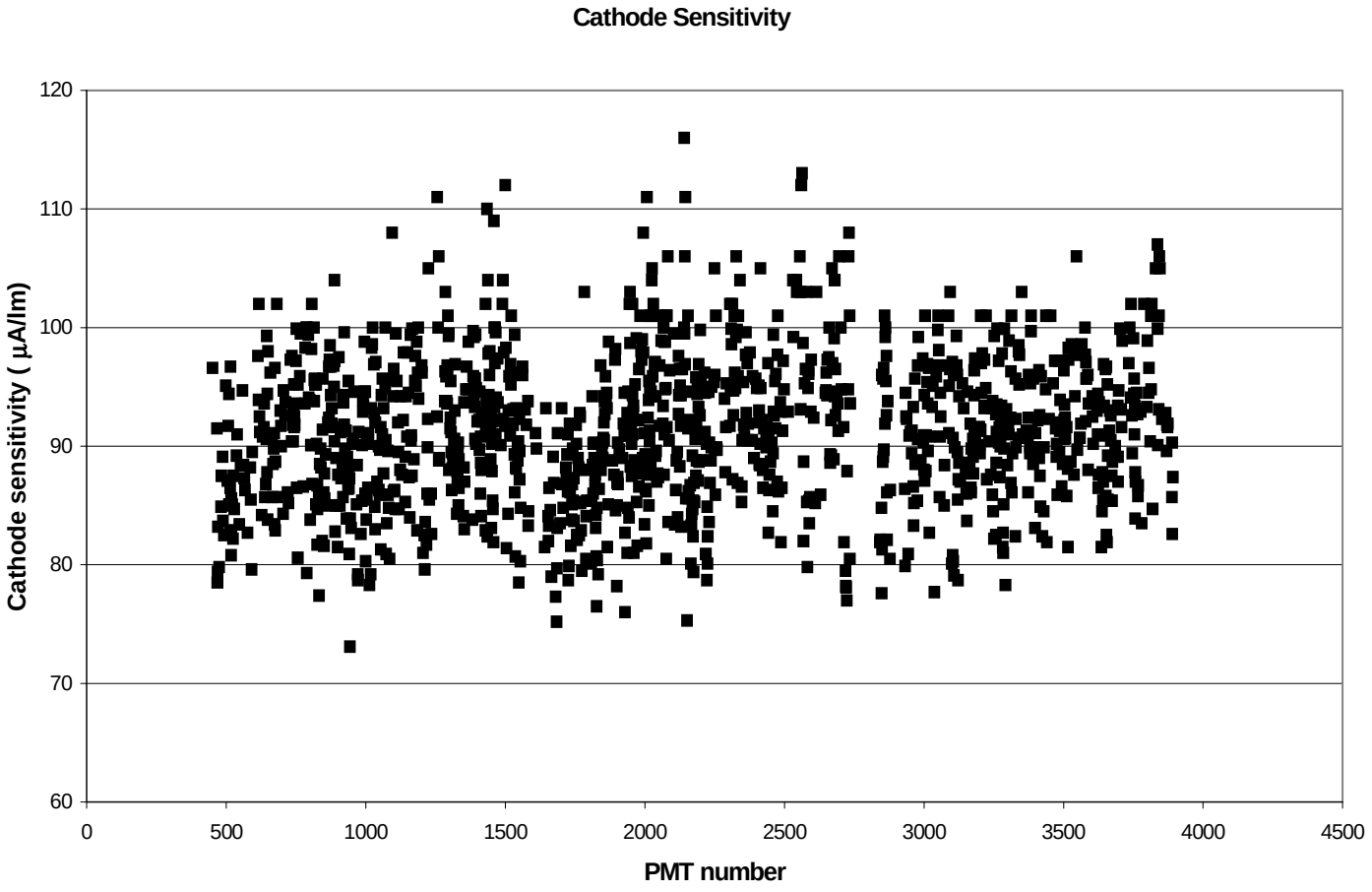

Figure (1) : Cathode sensibility (μA/lumen) for the 1250 tubes of the 3 first delivered batches, as a function of the PMT serial number

As the first batch was defined as the qualification batch, to fix the final definition selection criteria, 480 nm quantum efficiency of 50 tubes of this batch had been measured both by Hamamatsu and with CL test-bench, so that comparisons between two set of 480 nm quantum efficiency data could be done.

480 nm quantum efficiency, (QE), and photocathode sensitivity, ($S_{k)}$, of a tube are correlated. Figure (2) shows, for the 50 tubes of the batch #1, measured by

Hamamatsu, the plot S_k versus quantum efficiency. The correlation is expressed by the following formula:

$$S_k = 6{,}4792 \times QE - 27{,}346$$

With a correlation factor $R^2 = 0{,}7812$

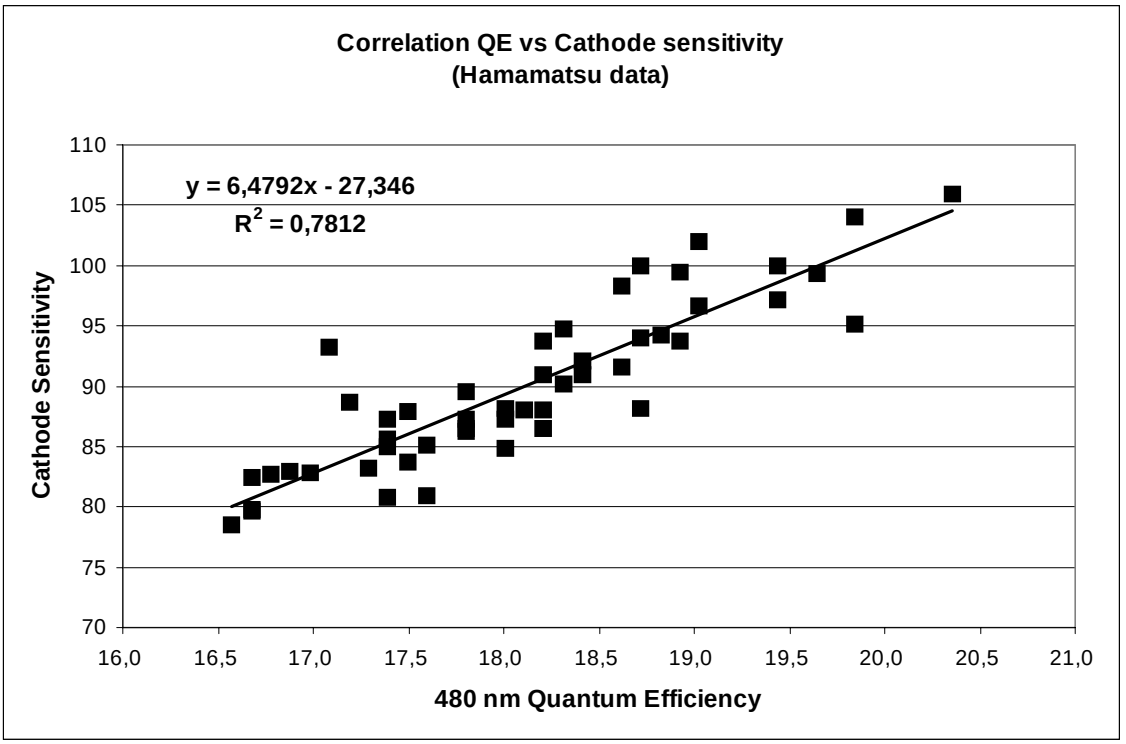

Figure (2) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 50 tubes of the first delivered batch (qualification batch). All data had been provided by Hamamatsu

Figure (3) presents same plot done using quantum efficiency measured for these tubes with the CL test-bench. The data indicate also a correlation, expressed as:

$$S_k = 6{,}3271 \times QE - 25{,}889$$

With a correlation factor $R^2 = 0{,}6952$

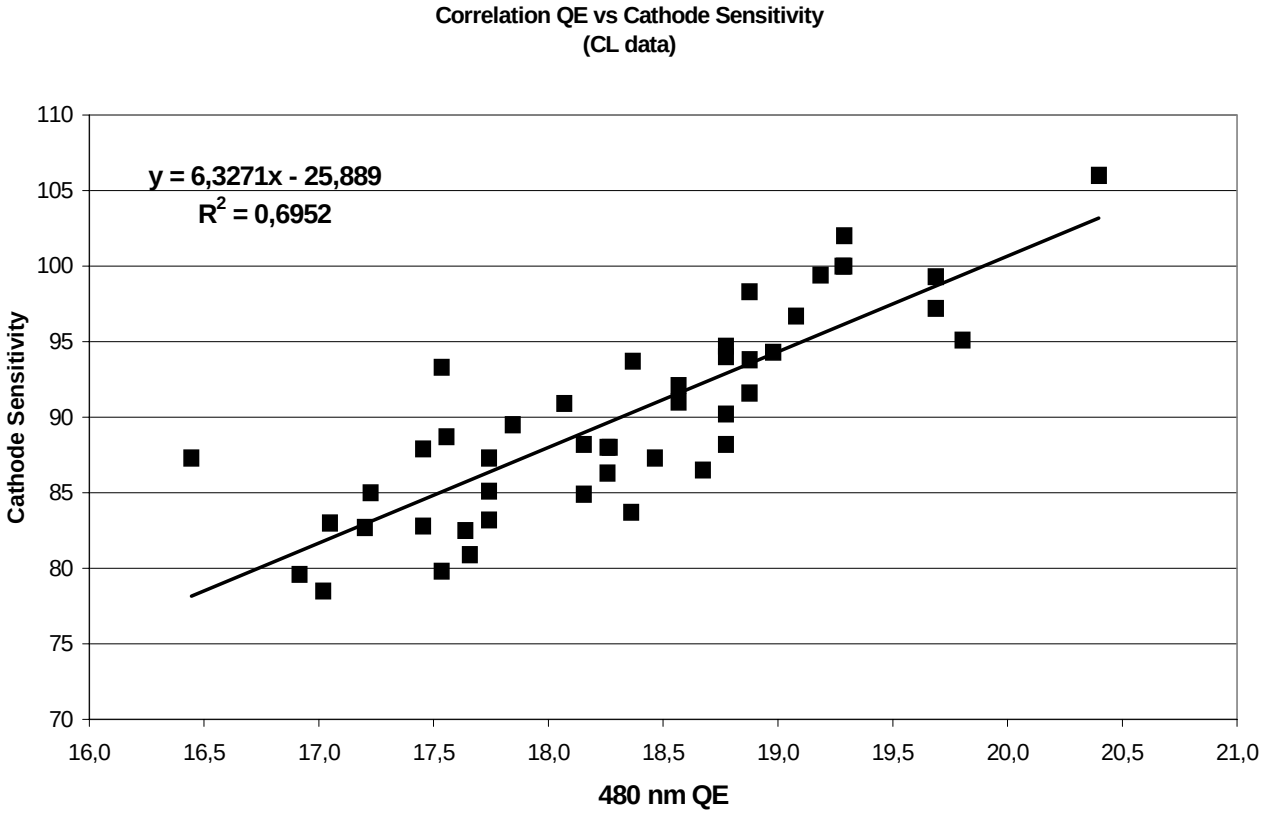

Figure (3) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 50 tubes of the first delivered batch (qualification batch). Quantum efficiency is now measured with CL test-bench.

This indicates that both set of data are compatible. This is clear on figure (4) that shows for these 50 tubes, the correlation between quantum efficiency measured by Hamamatsu and with the CL test-bench:

$$QE_{Ham.} = 0{,}9791 \times QE_{CL} + 0{,}1672$$

There is so a systematic constant error that certainly comes from the two different measurement methods.

The main principle to intercalibrate quantum efficiency measurements between the different batches is to assume as constant the correlation between the photocathode sensitivity and the 480 nm quantum efficiency.

We have also to point that these subset of 50 tubes, as part of the first batch were measured on different runs (grids), as shown on figure (5):

- 10 tubes were measured on run #1,
- 20 tubes were measured on run #2,
- 15 tubes were measured on run #5,
- all the remaining tubes were measured on run #13,

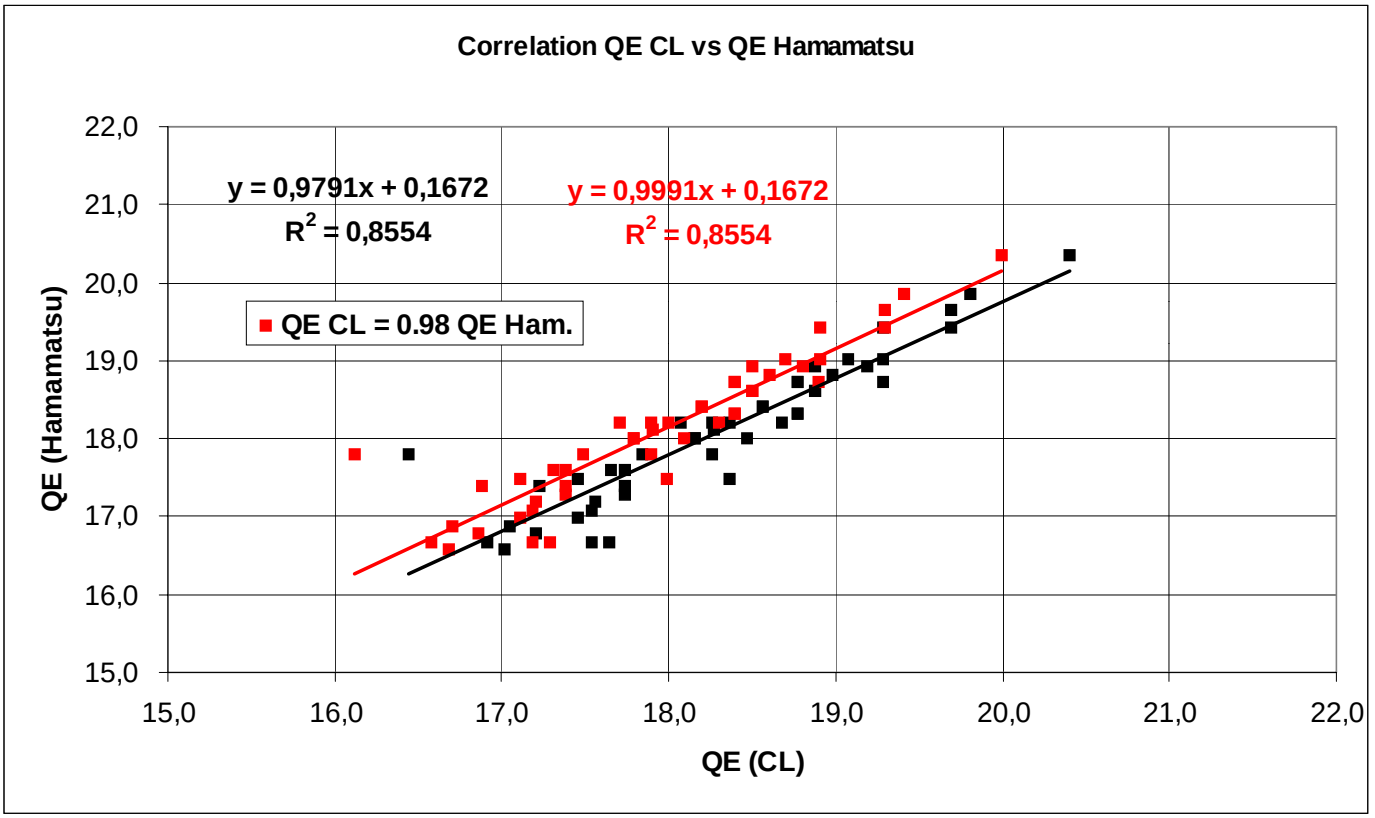

Figure (4) : Correlation between the 480 nm quantum efficiency for the 50 tubes of the first delivered batch (qualification batch) measured both by Hamamatsu and with CL test-bench

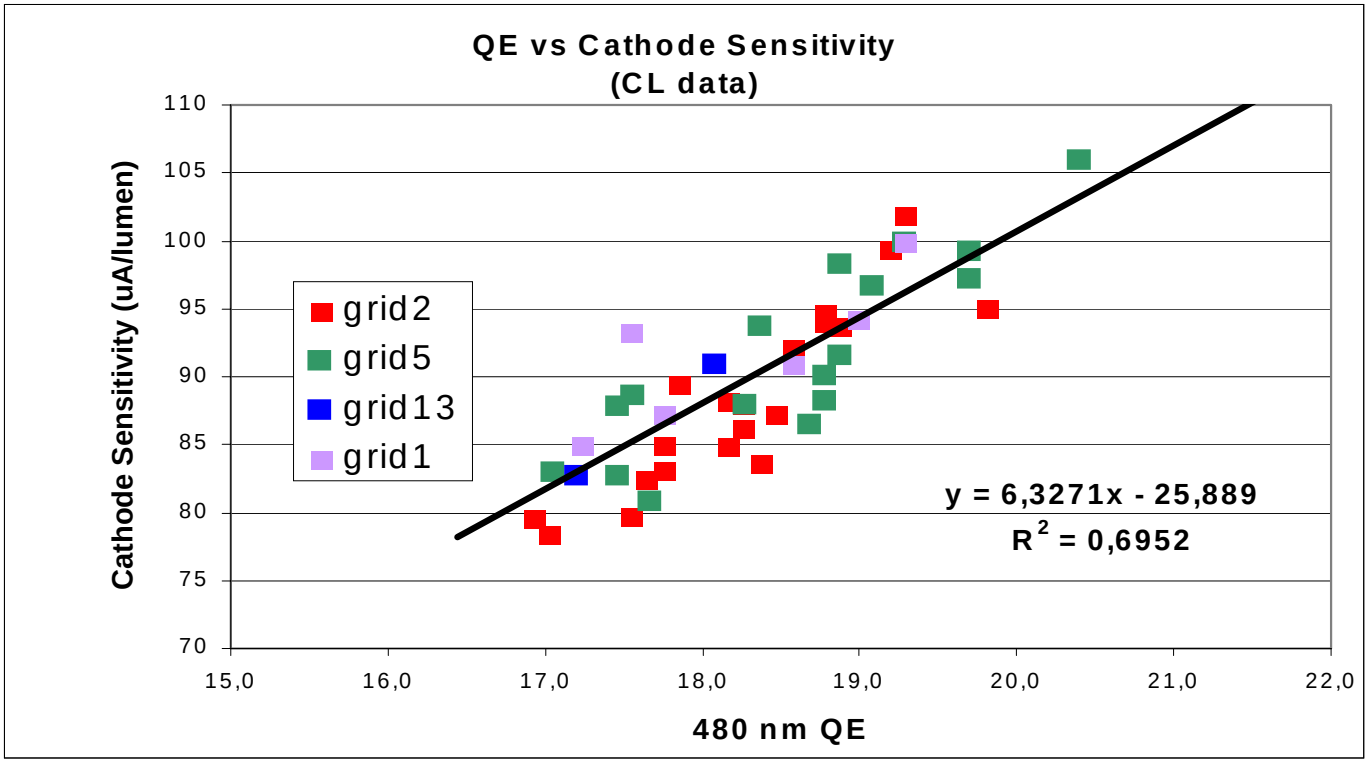

Figure (5) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 50 tubes of the first delivered batch (qualification batch). Quantum efficiency is now measured with CL test-bench. The runs (grid) are indicated by different colours.

2. Batch #1

Preliminaries studies show that the correlation between the provided S_K and the measured quantum efficiency on the tubes of the batch #1 is depending on the run number.

The difference could be clearly seen on the figure (6) that represent as red squares the correlation for tubes measured on run #1 to #6, and as blue squares for tubes measured on runs #7 to #13.

For the runs #1 to #6, the measured correlation is:

$$S_K = 6{,}1243 \times QE - 22{,}302$$

to be compared to the reference correlation (figure(2)),

$$S_K = 6{,}4792 \times QE - 27{,}346$$

For the runs #7 to #13, the measured correlation is:

$$S_K = 4{,}2439 \times QE + 16{,}661$$

And is so affected by some error.

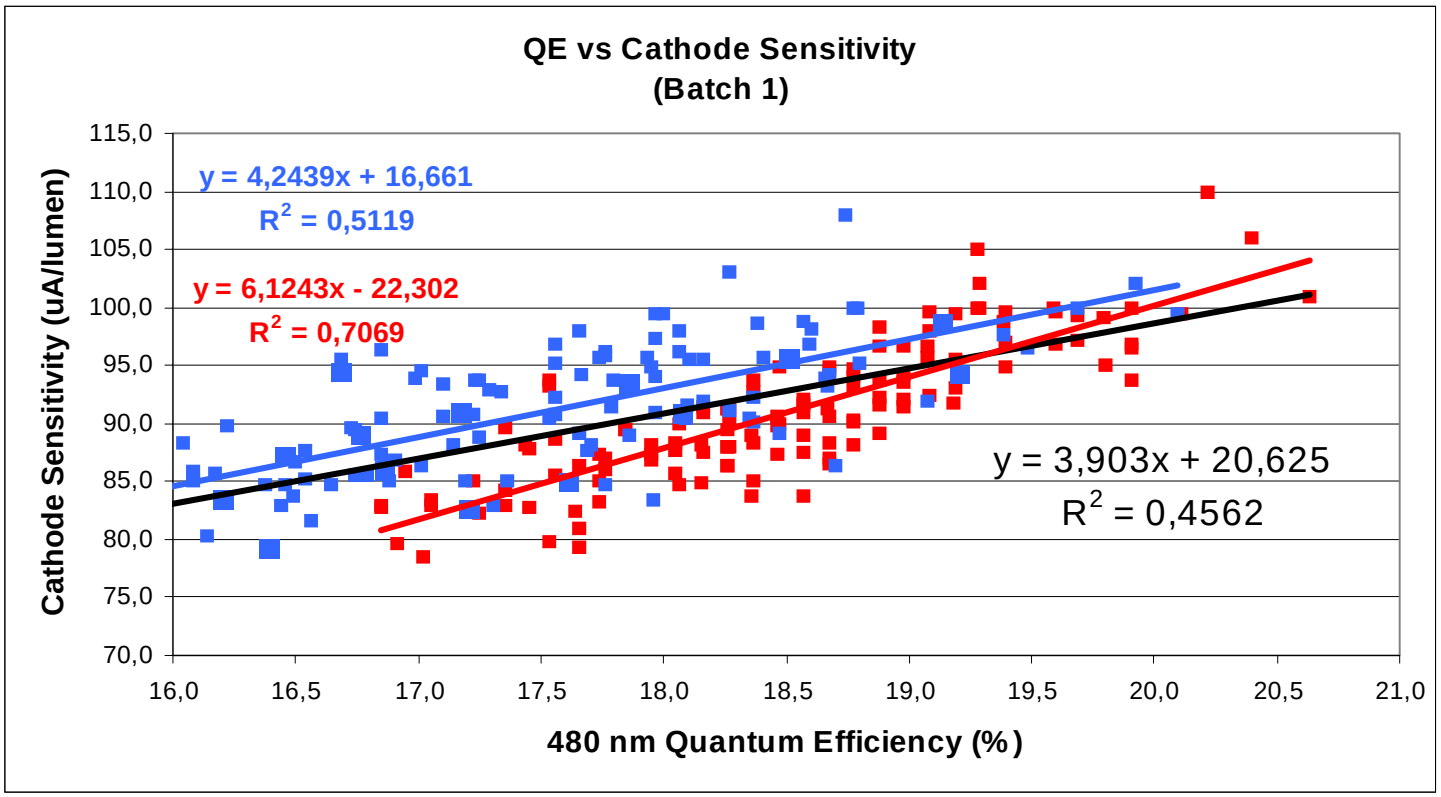

Figure (6) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the first delivered batch (qualification batch). Red symbols correspond to measurements performed on runs #1 to #6, and blue symbols for measurements done on runs #7 to #13.

If one assume as true the correlation S_K = 6,4792 x QE – 27,346 of the figure (2), the estimation of the quantum efficiency is:

$$QE_{Est.} = (S_K + 27{,}346) / 6{,}4792$$

And

$$DQE = QE_{Meas.} - QE_{Est.}$$

Figure (7) represents the variation of QDE as a function of the QE_{Meas} for tubes measured on runs #1 to #6 (red symbols) and on runs #7 to #13 (blue symbols).

- For measurements made on runs #7 to #13, the correction could be fitted as:

$$DQE = -0{,}345 \times QE_{Meas.} + 6{,}7921$$

- For runs #1 to #6, DQE = -0,2.

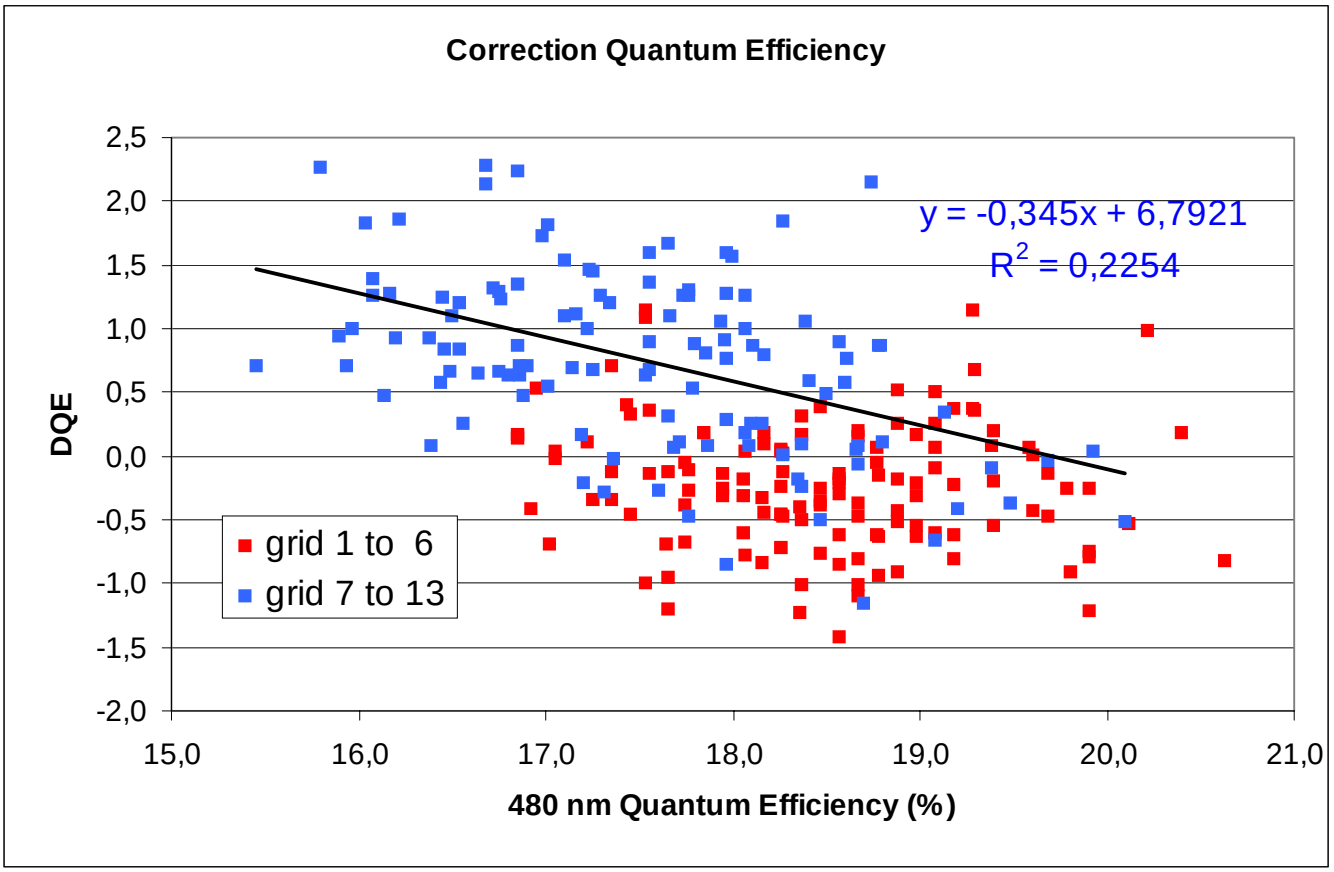

Figure (7) : DQE, estimed from cathode sensibility, as a function of the measured 480 nm quantum efficiency for the 250 tubes of the first delivered batch (qualification batch). Red symbols correspond to measurements performed on runs #1 to #6, and blue symbols for measurements done on runs #7 to #13.

When these corrections are applied to tubes of batch #1, the results is shown on figure (8). Now the correlation is :

$$S_K = 6{,}2486 \times QE - 23{,}245$$

With a correlation factor $R^2 = 0{,}6166$, to be compared with original correlation

$$S_K = 3{,}9233 \times QE - 20{,}299$$

It is clear looking on figure (6) and figure (8) that the correlation between S_K and QE seems better after the correction.

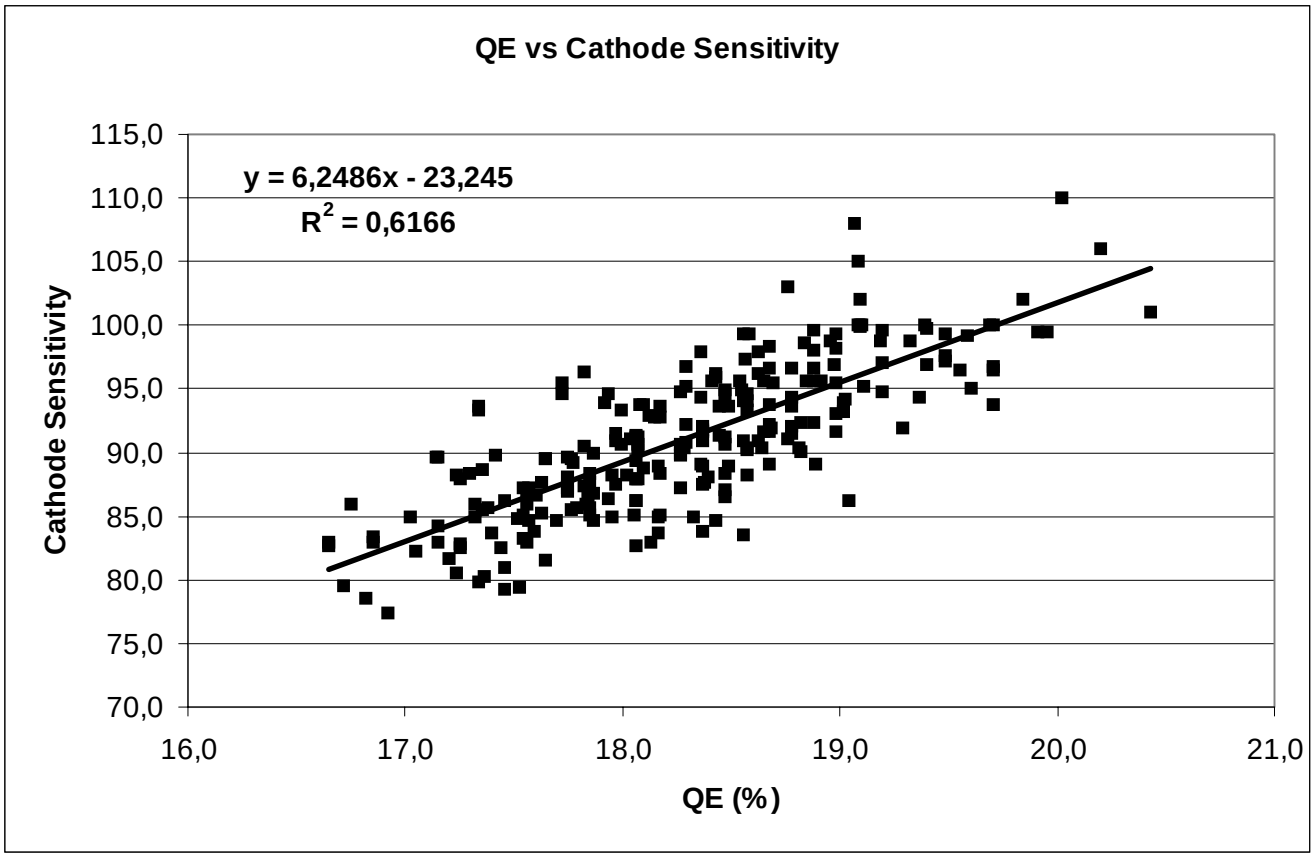

Figure (8) : cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the first delivered batch (qualification batch). Measurements performed on runs #1 to #6 had been corrected by a constant systematic error of –0,2, and measurements done on runs #7 to #13 by a systematic error depending of the quantum efficiency ($DQE = -0{,}345 \times QE_{Meas.} + 6{,}7921$*).*

Same correction could be applied also on data resulting of the measurement of the 24 PMTs of the intercalibration grid. Figure (9) shows the correlations between the S_K and the 480 nm quantum efficiency for the 24 tubes of the intercalibration grid measured on the four different test-benches. When looking on the correlation for the

first measurement of the grid, on the CL test-bench, the resulting slope is quite different from other set of data. But when applying the correction described above , we got some different but more compatible regression line.

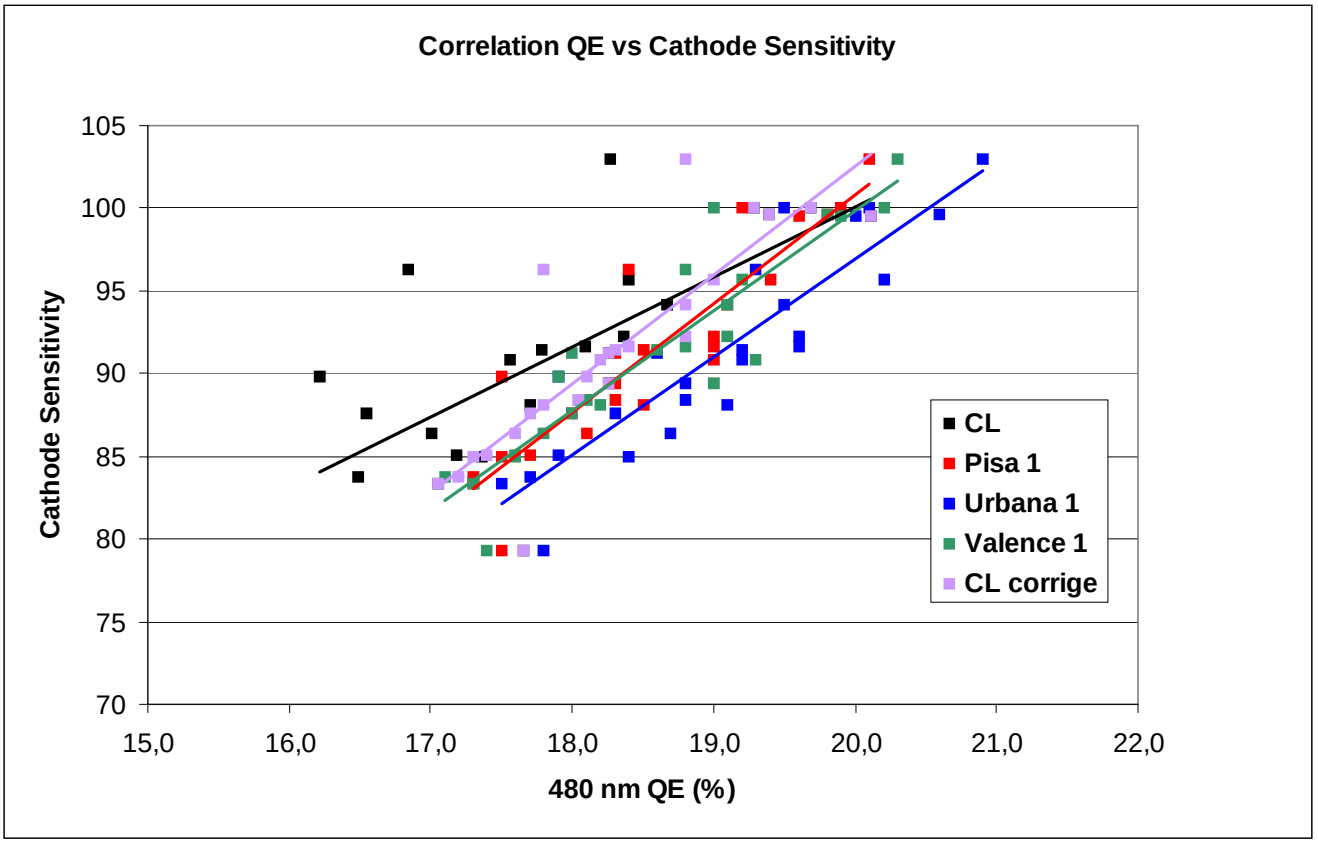

Figure (9) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 24 tubes of the intercalibration grid. CL raw data, measured in same time as other tubes of batch #1 corresponds to black symbols and black line. Corrected data correspond to purple symbols and line.

3. Batch #2

Figure (10) shows the original correlation between the measured quantum efficiency and the photocathode sensitivity. The fitted regression line is:

$$S_K = 6{,}1477 \times QE - 21{,}013$$

With a correlation factor $R^2 = 0{,}653$. If we look on the different set of data, corresponding to tubes measured on the same run:

- Figure (11) correspond to the runs #14 to #18,
- Figure (12) correspond to the runs #19 to #23,
- Figure (13) correspond to the run #24 to #27,

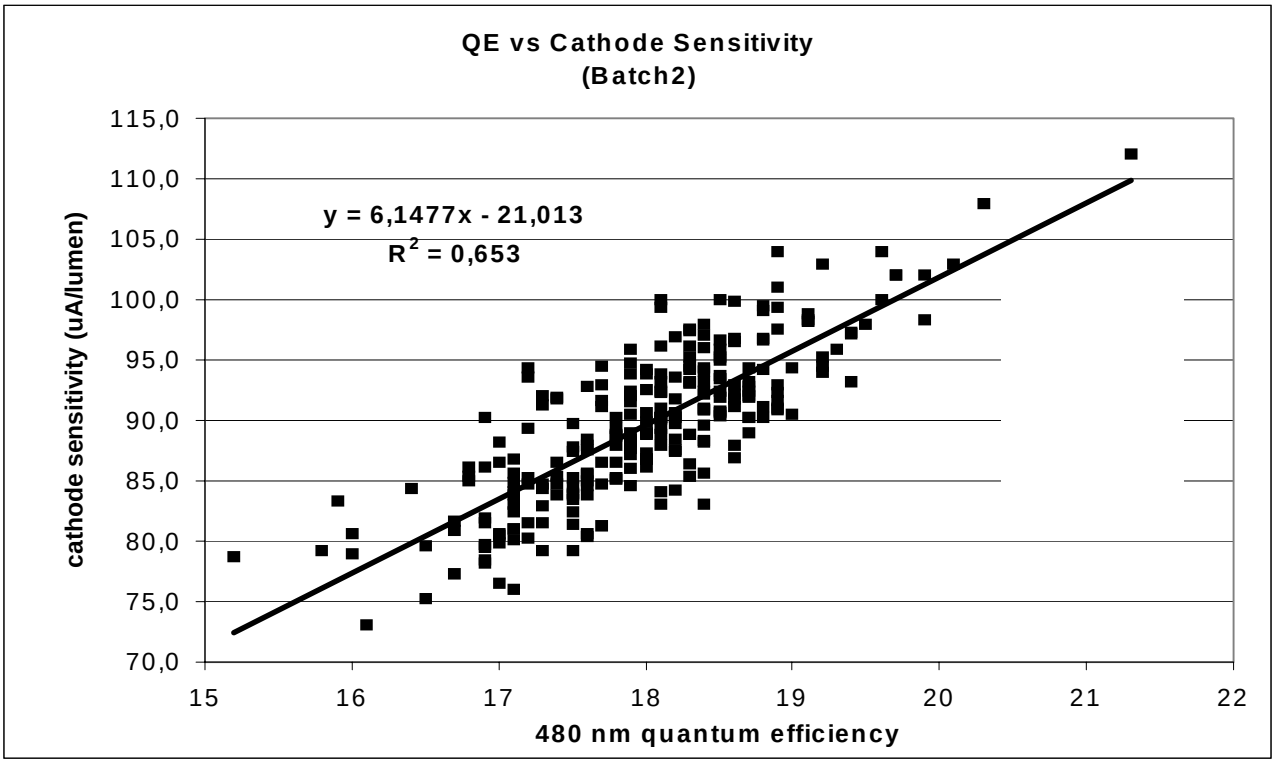

Figure (10) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the second delivered batch.

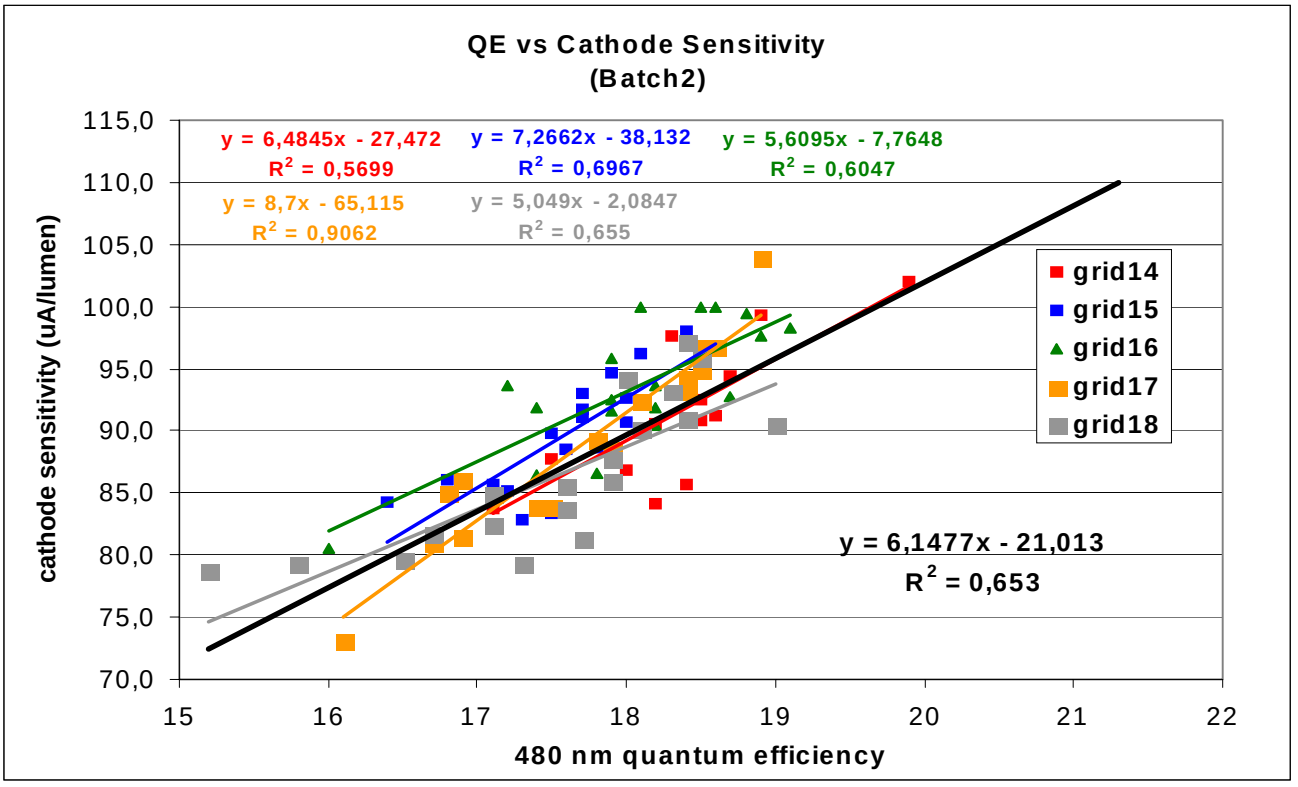

Figure (11) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the tubes of the second delivered batch measured on runs #14 to #18.

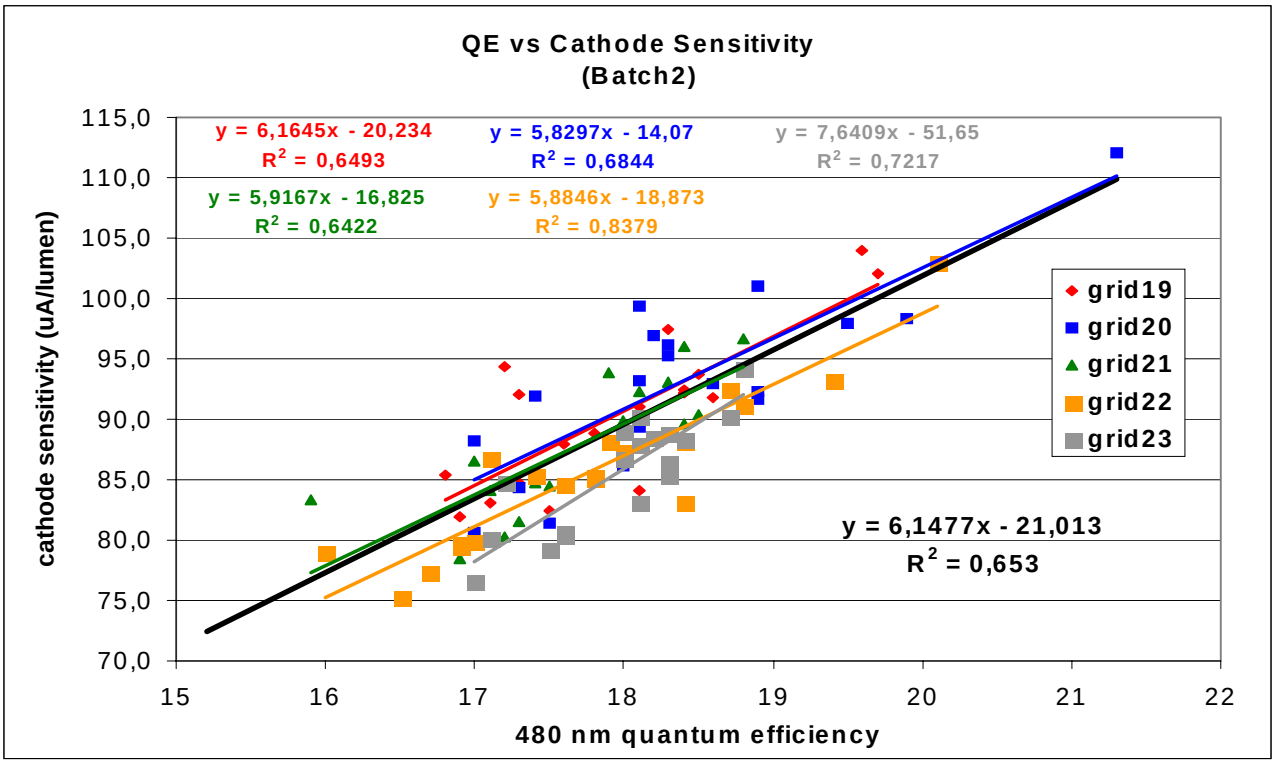

Figure (12) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the tubes of the second delivered batch measured on runs #19 to #23.

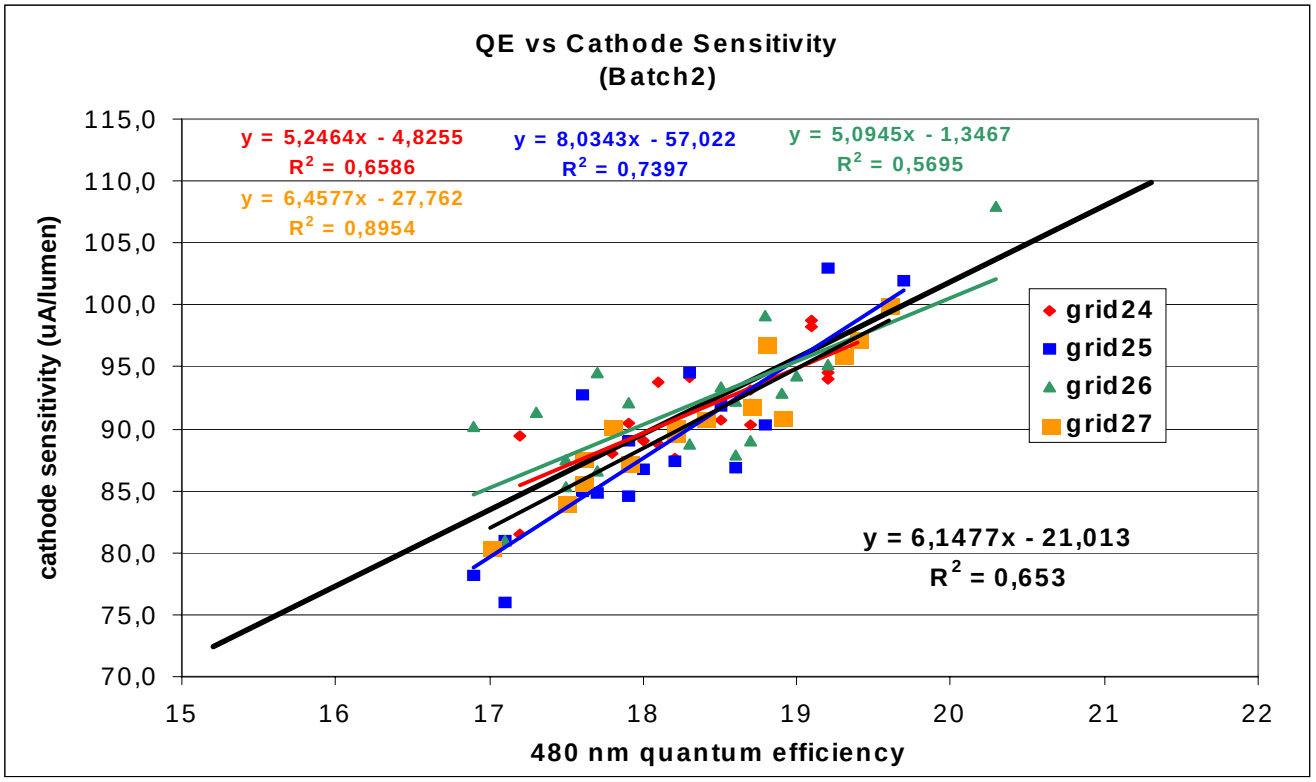

Figure (13) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the tubes of the second delivered batch measured on runs #24 to #27.

Once again one suppose that the true correlation is given by S_K = 6,4792 x QE – 27,346 and we calculate the estimated quantum efficiency :

$$QE_{Est.} = (S_K + 27{,}346) / 6{,}4792$$

the difference between the measured quantum efficiency and the estimed one is:

$$DQE = QE_{Meas.} - QE_{Est.}$$

- Figure (14) represent the variation of DQE as a function of QE Meas.

- Figure (15) represents the variation of DQE as a function of the run number, together with the mean value per run (red curve),

The original data are corrected of a systematic averaged error for each run:

$$QE = QE\ Meas. + DQE(Nrun)$$

In fact, only 4 run's data are corrected from a shift:

- Run#15 ➔ DQE = +0,45
- Run#16 ➔ DQE = +0,6
- Run#17 ➔ DQE = +0,25
- Run#23 ➔ DQE = -0,53

After this correction, the correlation is shown on figure (16):

$$S_K = 6{,}2462 \times QE - 23{,}139$$

With a correlation factor R^2= 0,7436, to be compared with the reference correlation: S_K = 6,4792 x QE – 27,346. The averaged 480 nm quantum efficiency on the whole batch is 18% before the correction, and 18,06% after the correction. Again looking on figures (10) and (16), correlation between S_K and QE looks better.

Origin of the systematic errors is not obvious, but looking on the evolution of the measured quantum efficiency of the 4 monitoring PMTs, shown on figure (17), there is also some variation for runs #15, #16, #17 and #25. Origin of the correction around grid #23 is not clear up to now. More complete studies of the test-bench autotest data could perhaps explain such a behaviour.

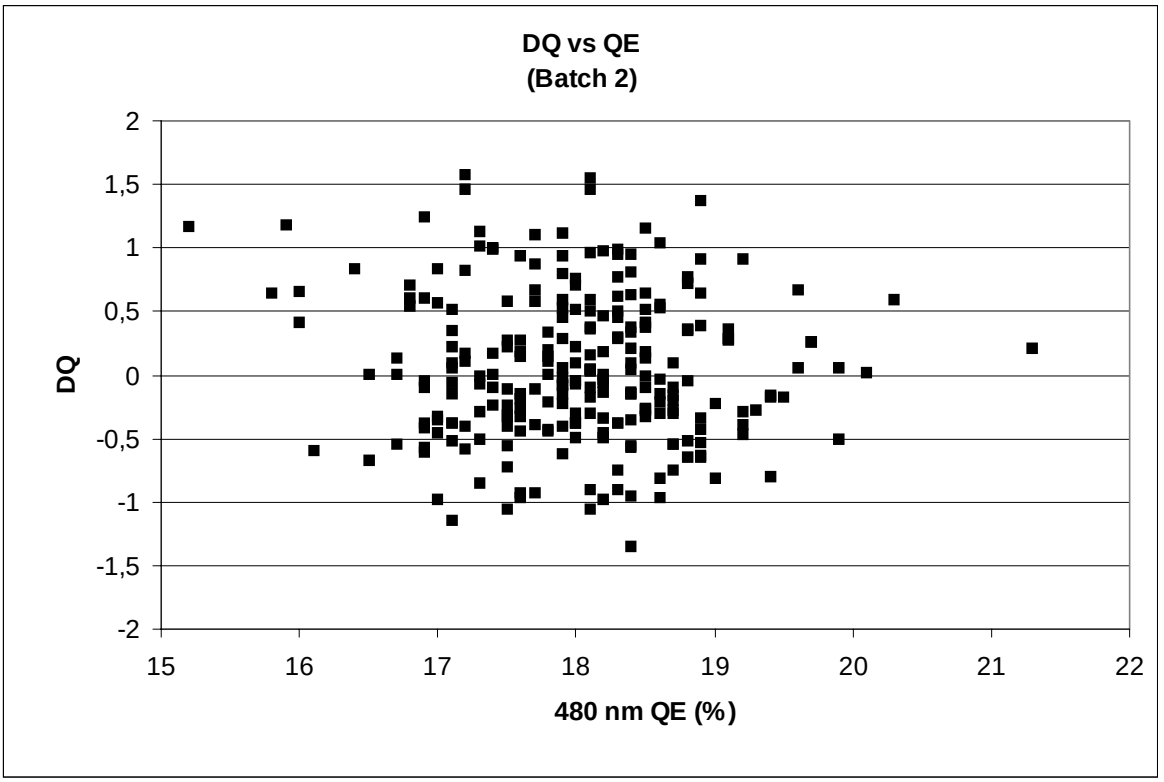

Figure (14) : variation of DQE as a function of the measured 480 nm quantum efficiency for the tubes of the second delivered batch

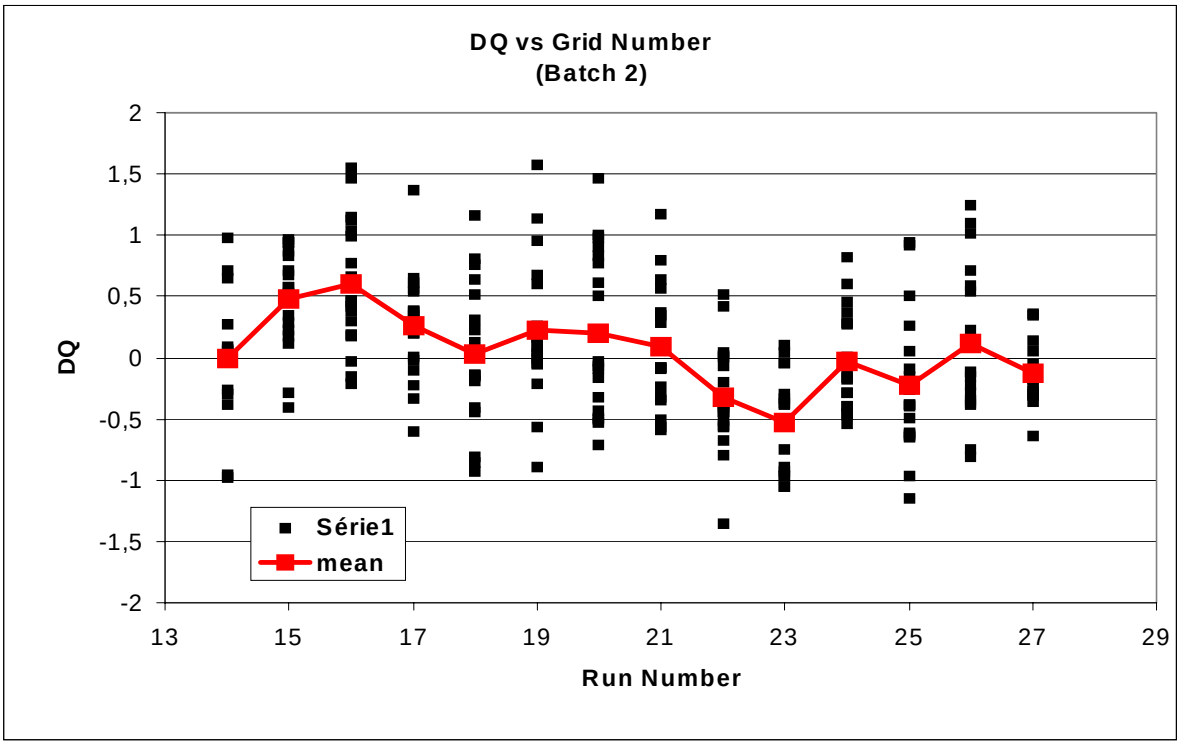

Figure (15) : variation of DQE as a function of the run number for the tubes of the second delivered batch. The red curve indicate the mean value

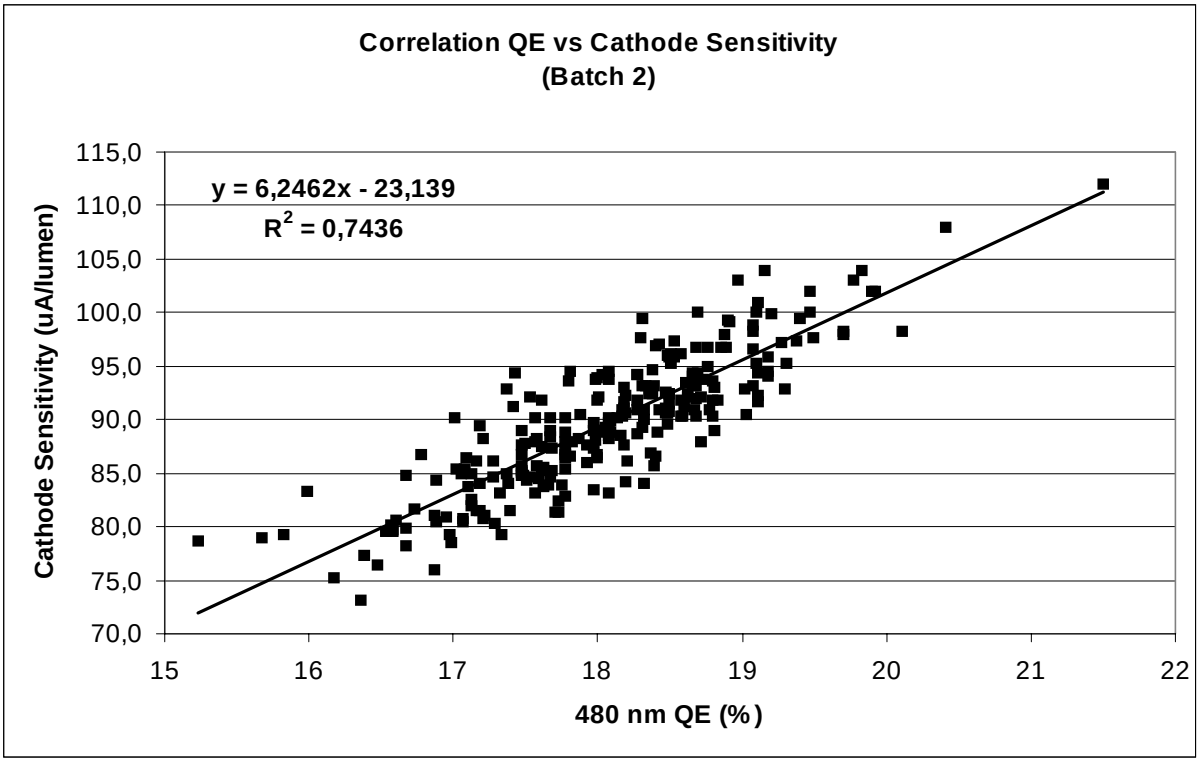

Figure (16) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the second delivered batch. Measurements performed on each runs had been corrected by a constant systematic error given by the red curve of figure (15).

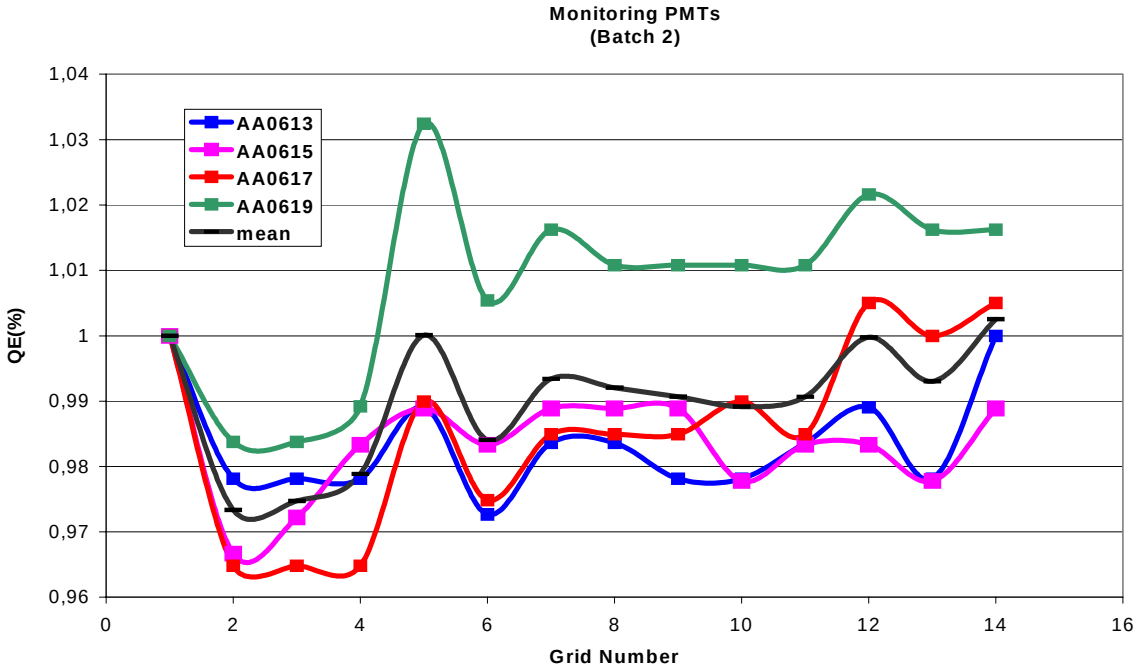

Figure (17) : 480 nm quantum efficiency of the 4 monitoring tubes when measuring the second delivered batch

4. Batch #3 (Pisa)

The S_k versus quantum efficiency correlation for these 250 tubes, measured on Pisa test-bench is shown on the figure (18), and is:

$$S_K = 6{,}7908 \times QE - 35{,}888$$

With a correlation factor $R_2 = 0{,}6551$. The mean value for the whole batch is 18,8%.

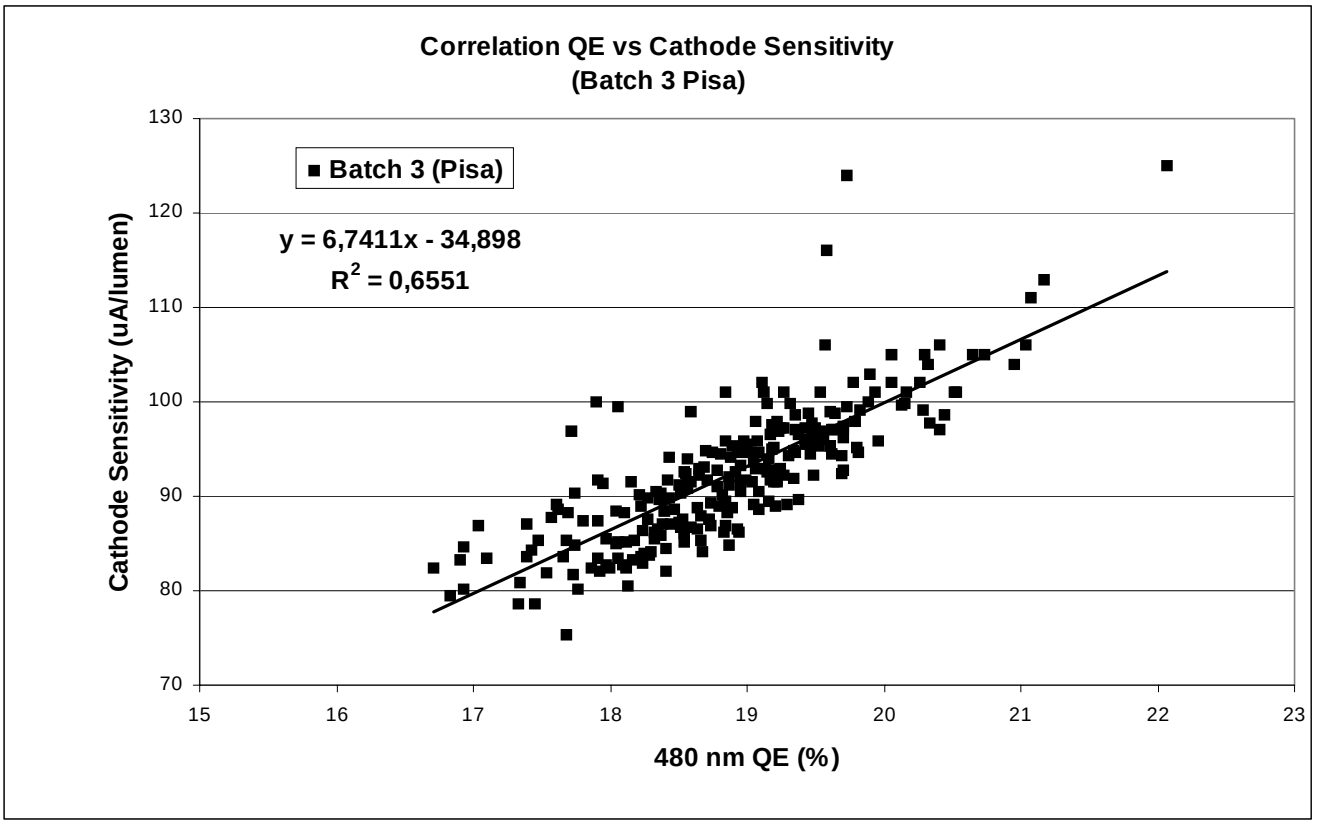

Figure (18) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the third delivered batch, and measured with Pisa test-bench

Once again, one assume that the true correlation is $S_K = 6{,}4792 \times QE - 27{,}346$ to estimate the 480 nm quantum efficiency, and by the way the DQE. Figure (19) is the variation of the DQE as a function of the run number. There is no correlation but a systematic shift confirmed by looking on quantum efficiency of the monitoring PMTs shown on figure (20): the maximum variation of these PMTs is less than 8\1000

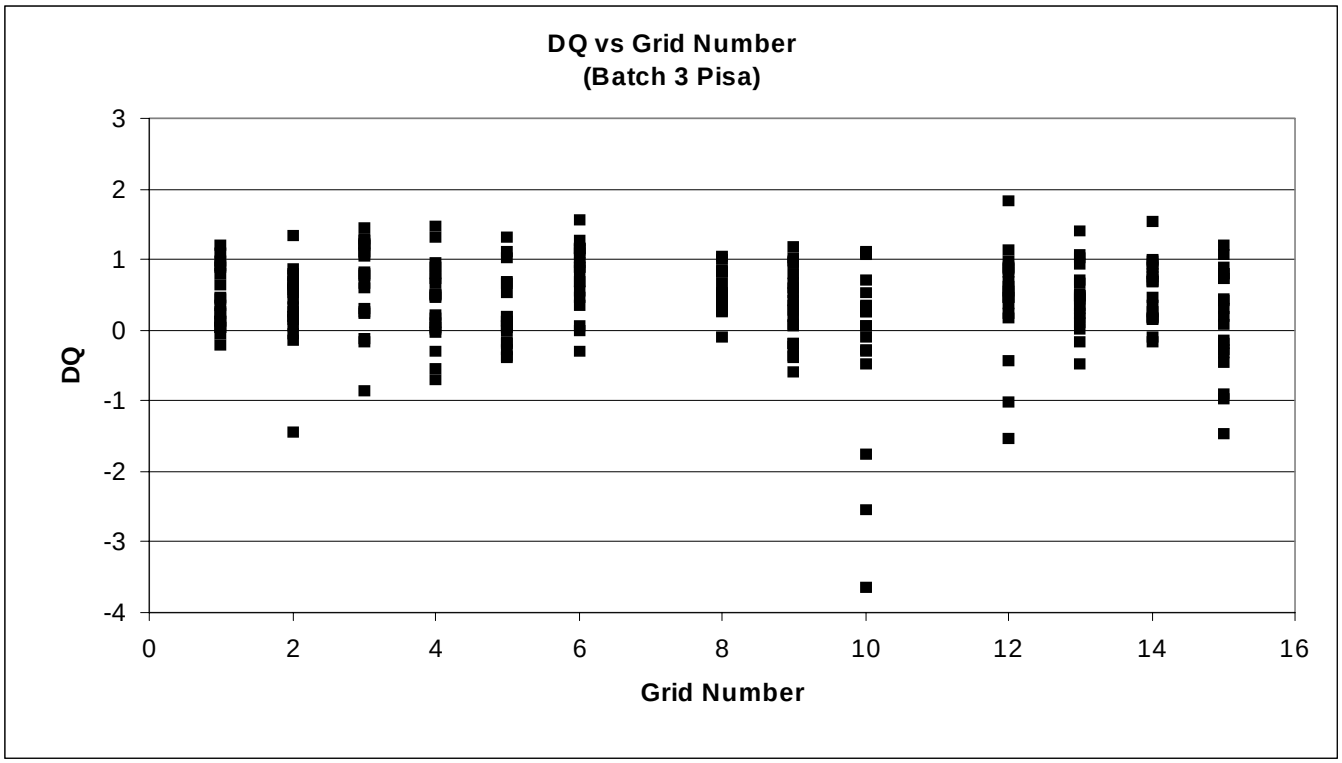

Figure (19) : variation of DQE as a function of the run number for the tubes of the third delivered batch and measured in Pisa.

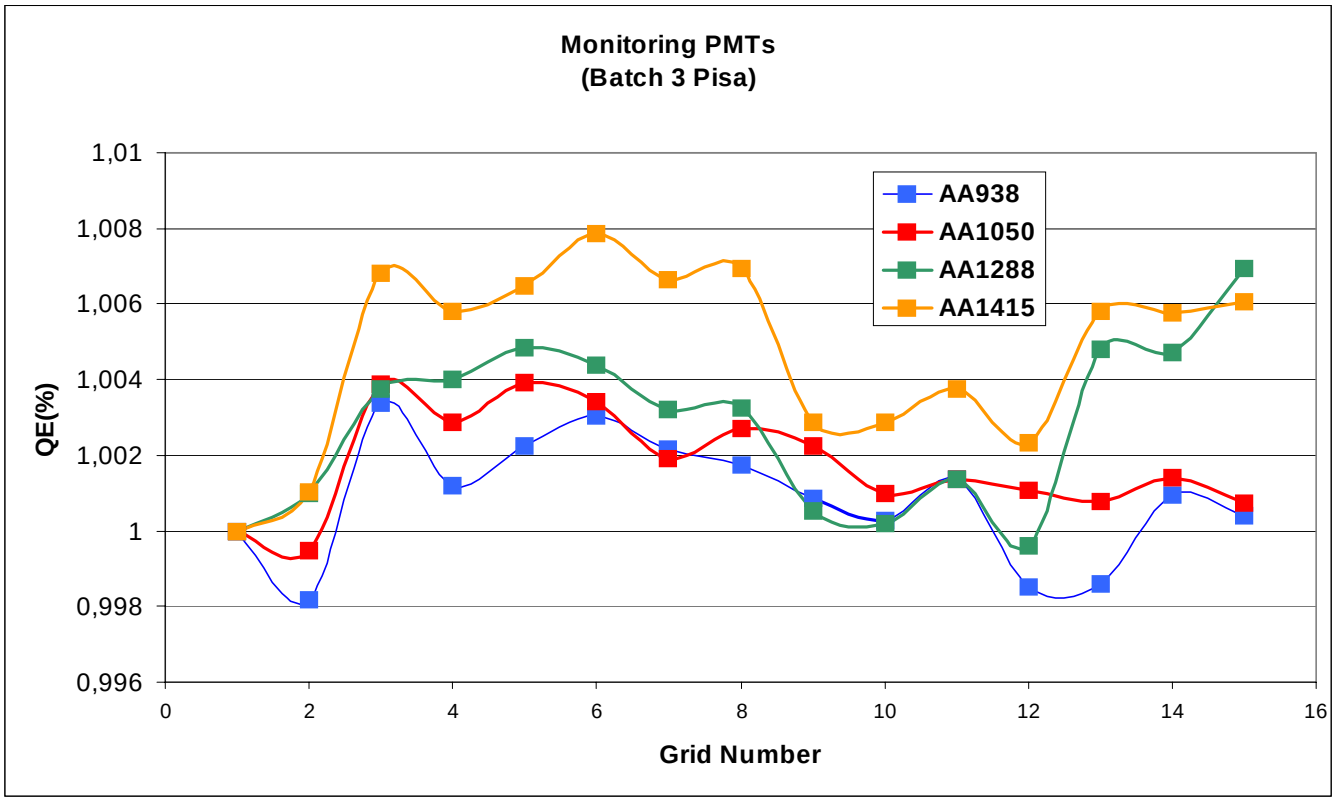

Figure (20) : 480 nm quantum efficiency of the 4 monitoring tubes when measuring the third delivered batch with Pisa test-bench

If one have a look on the results of the measurement of the intercalibration grid, especially the first measurement performed in Pisa. The averaged quantum efficiency is <QE> = 18,6% and the correlation with quantum efficiency is:

$$S_K = 6{,}5633 \times QE - 30{,}448$$

If one renormalize the averaged quantum efficiency to the one measured on the same PMTs measured in CL, after correction (18,3%), we have to apply a corrective factor of 0,9838. As shown on figure (21), the correlation is now:

$$S_K = 6{,}5708 \times QE - 28{,}843$$

To be compared with the reference correlation:

$$S_K = 6{,}4792 \times QE - 27{,}346$$

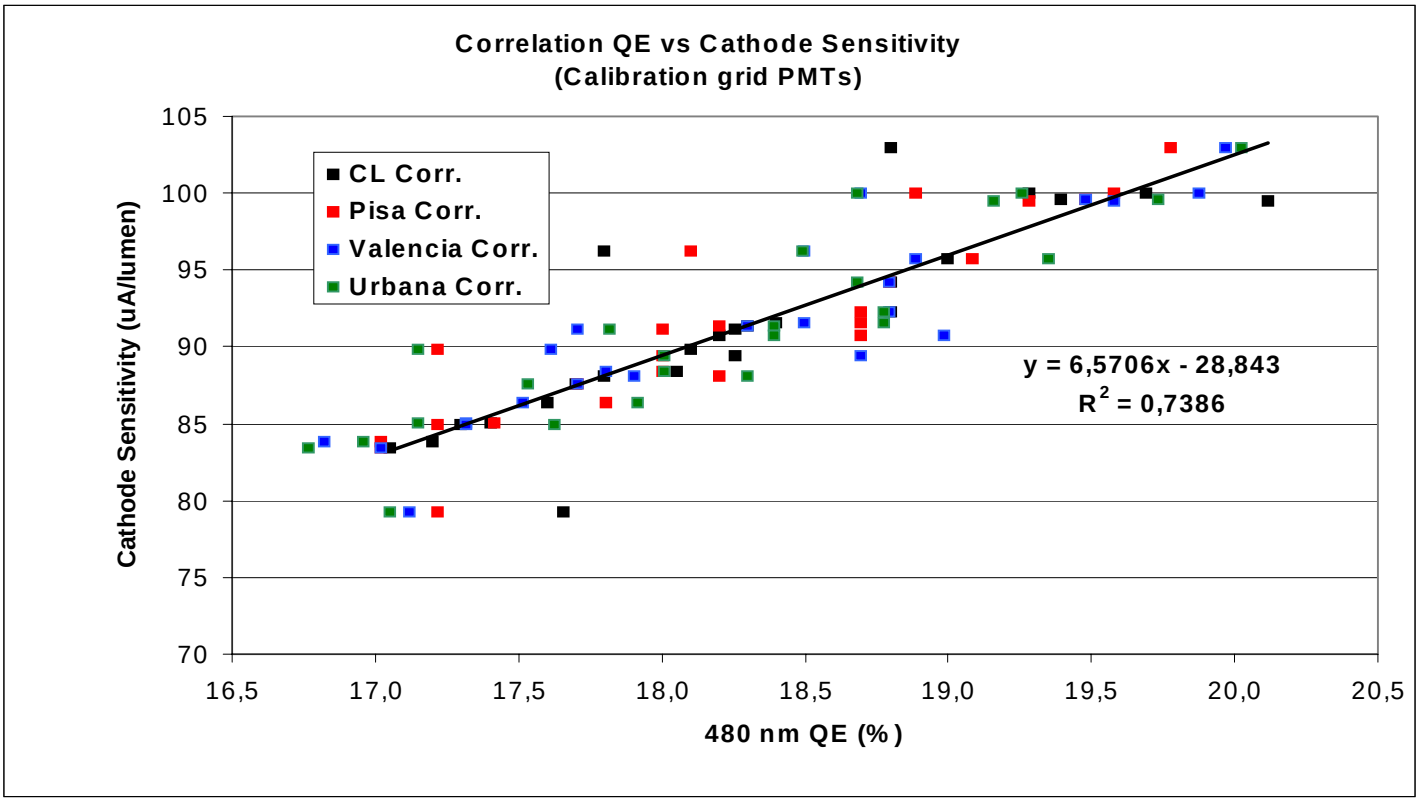

Figure (20) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the tubes of intercalibration grid measuredon the 4 test-benches. All measurements had been corrected so that the averaged value of the measured quantum efficiency on the calibration grid is equal to the averaged quantum efficiency of the CL test-bench after correction (figure(9)).

When applying the same corrective factor the whole batch, the averaged quantum efficiency is now <QE> =18,57%. Figure (22) represents the correlation for the corrected batch, compared to the reference correlation S_K = 6,4792 x QE – 27,346.

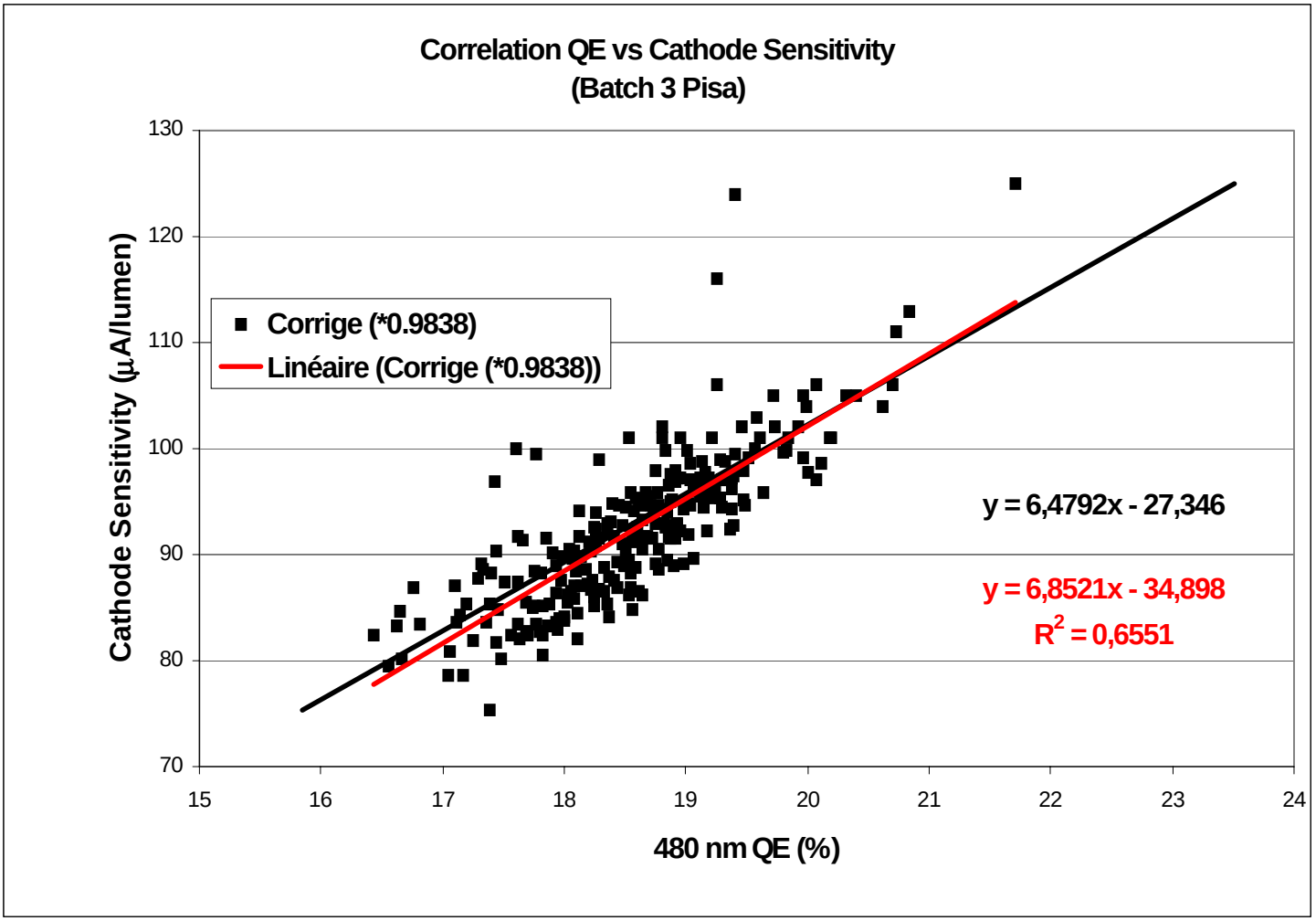

Figure (22) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the third delivered batch, and measured with Pisa test-bench. All measurements had been corrected so that the averaged value of the measured quantum efficiency on the intercalibration grid tube's is equal to the averaged quantum efficiency of the intercalibration grid tube's measured for batch #1 on CL test-bench and after correction (figure (20)

5. Batch #3 (Urbana)

The S_K versus quantum efficiency correlation for these 250 tubes, measured with Urbana test-bench is shown on the figure (23), and correlation is:

$$S_K = 6{,}0498 \times QE - 24{,}800$$

With a correlation factor R^2=0,6279

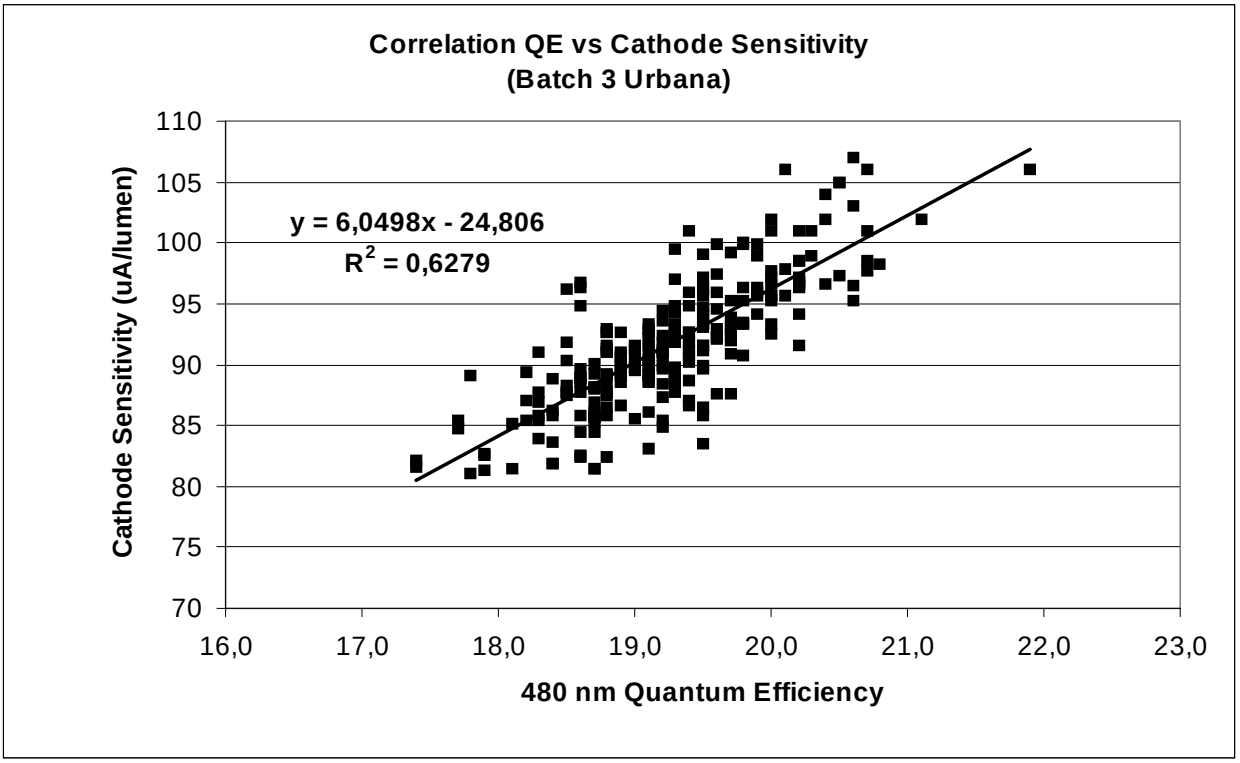

Figure (23) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the third delivered batch, and measured with Urbana test-bench

If one have a look on the results of the measurement of the intercalibration grids, especially the first measurements performed in Urbana, the averaged quantum efficiency is <QE> = 19,1% and the correlation with quantum efficiency is:

$$S_K = 5{,}9342 \times QE - 21{,}79$$

If one renormalize the averaged quantum efficiency to the one measured on the same PMTs measured in CL, after correction (18,3%), we have to apply a corrective factor of 0,9581. The correlation is now the one shown on figure (20), with an averaged quantum efficiency 18,2 %:

When applying the same corrective factor the whole batch, the averaged quantum efficiency is now <QE> =18,46%. Figure (24) represents the correlation for the corrected batch S_K = 6,3144 x QE – 24,806 , compared to the reference correlation S_K = 6,4792 x QE – 27,346.

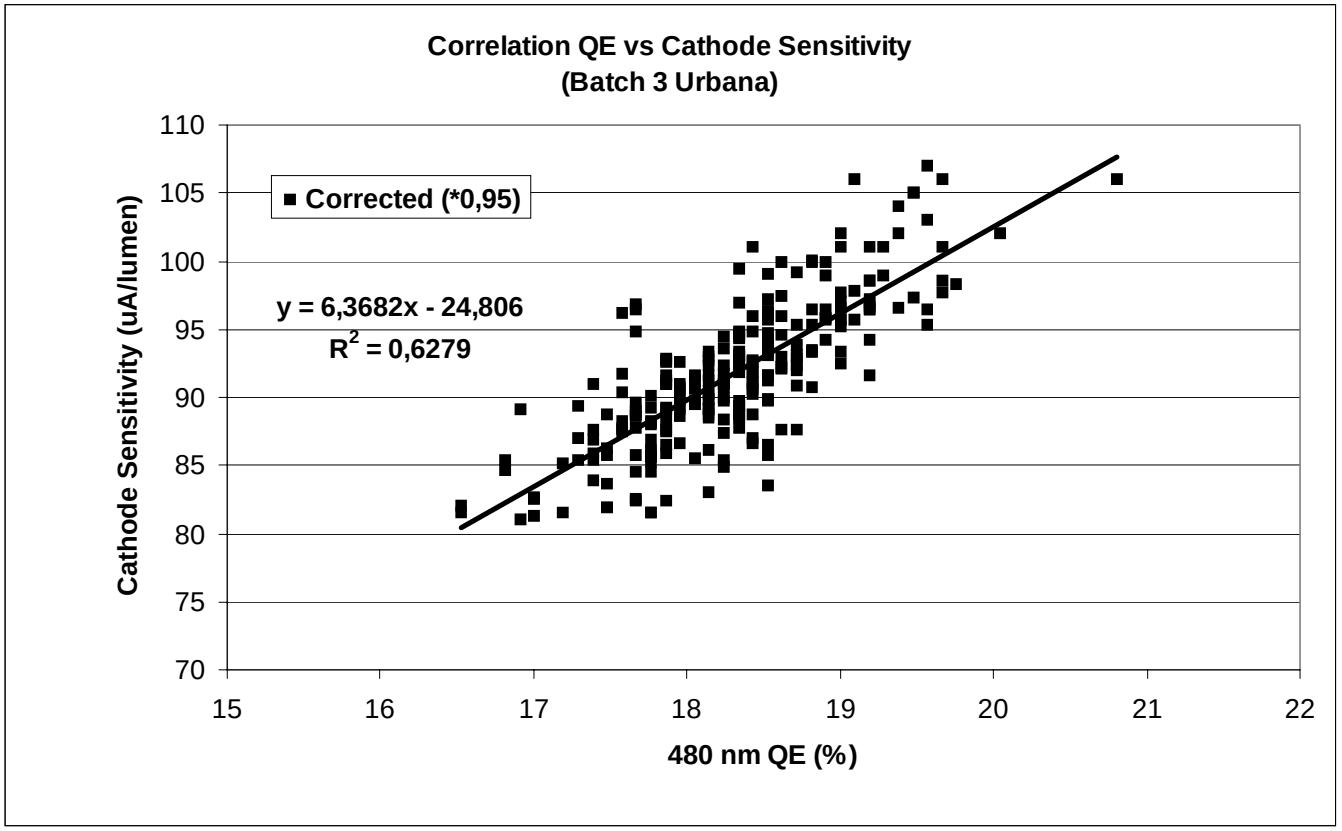

Figure (24) : Cathode sensibility (µA/lumen) as a function of the 480 nm quantum efficiency for the 250 tubes of the third delivered batch, and measured on Urbana test-bench. All measurements had been corrected so that the averaged value of the measured quantum efficiency on the intercalibration grid tube's is equal to the averaged quantum efficiency of the intercalibration grid tube's measured on CL test-bench during batch #1, and after correction (figure (21)

Figure (25) shows the variation of the quantum efficiency of the monitoring PMTs: variation is less than 1%.

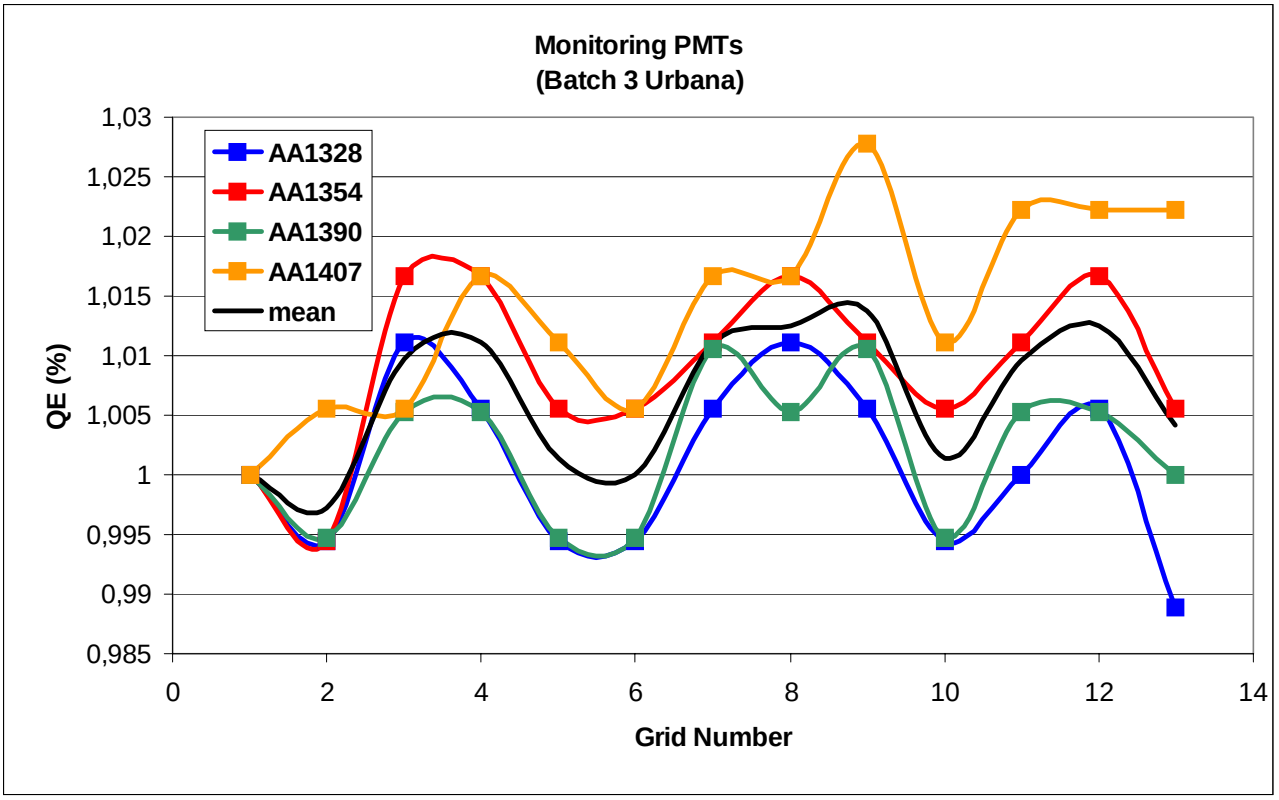

Figure (25) : 480 nm quantum efficiency of the 4 monitoring tubes when measuring the third delivered batch with Urbana test-bench

6. Conclusion

Figure (28) shows the correlation of SK versus quantum efficiency for the four sub-batches: CL#1, CL#2, Pisa and Urbana. We got the following average correlation:

$$S_K = 6{,}2462 \times QE - 23{,}139.$$

To be compared with the reference correlation (figure(2)) :

$$S_K = 6{,}4792 \times QE - 27{,}346$$

Figure (27) shows the quantum efficiency distribution of each of the four sub-batches, after correction and renormalisation:

- CL#1 (batch#1) ➔ averaged 480 nm QE is 18,3% with a dispersion of 0,73,
- CL#2 (batch#2) ➔ averaged 480 nm QE is 18,06% with a dispersion of 0,87,
- Pisa (batch#3) ➔ averaged 480 nm QE is 18,6% with a dispersion of 0,85,
- Urbana.(batch#3) ➔ averaged 480 nm QE is 18,3% with a dispersion of 0,66,

Figure (28) shows the quantum efficiency distribution as a function of the PMT serial number

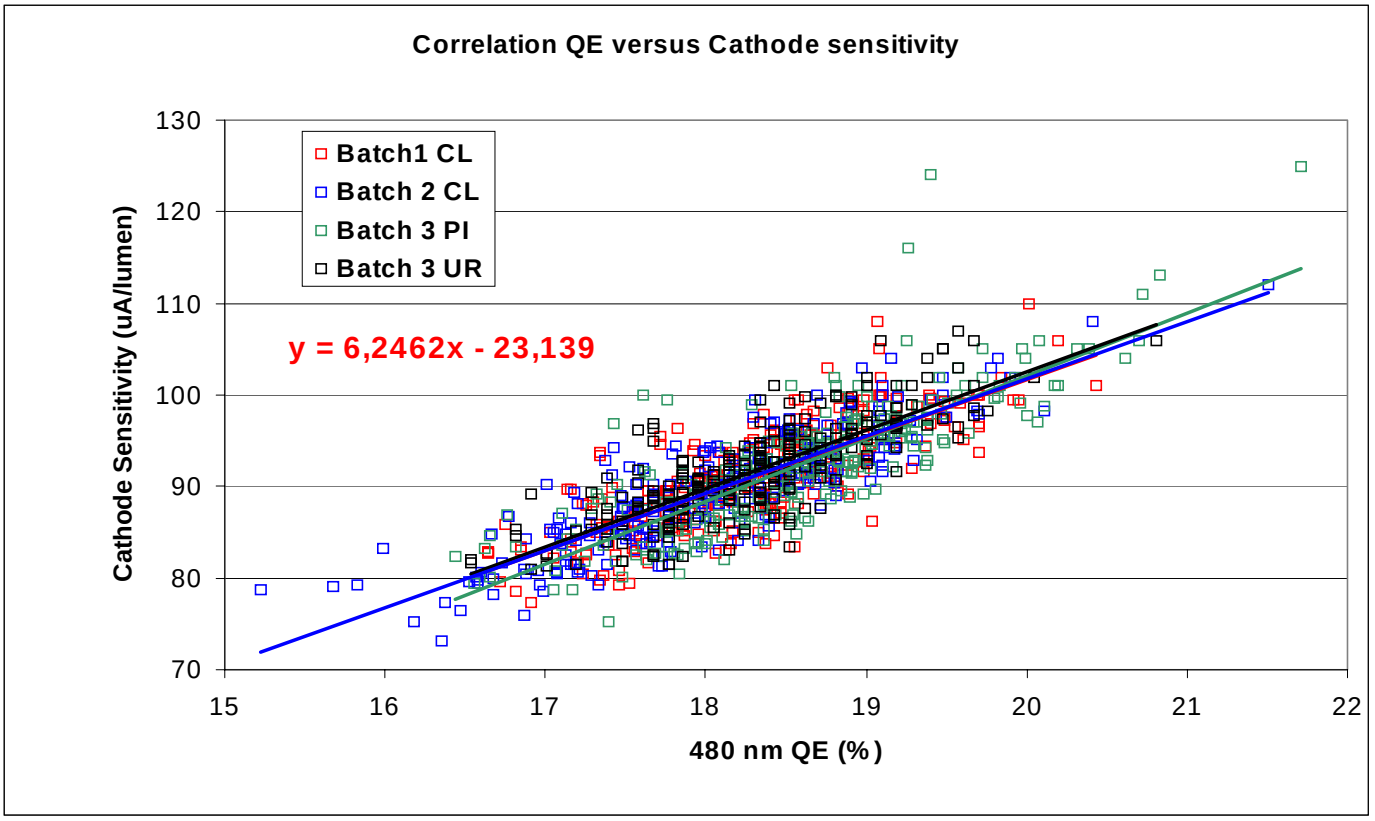

Figure (26) : Correlation of SK versus quantum efficiency for the four sub-batches: CL#1, CL#2, Pisa and Urbana

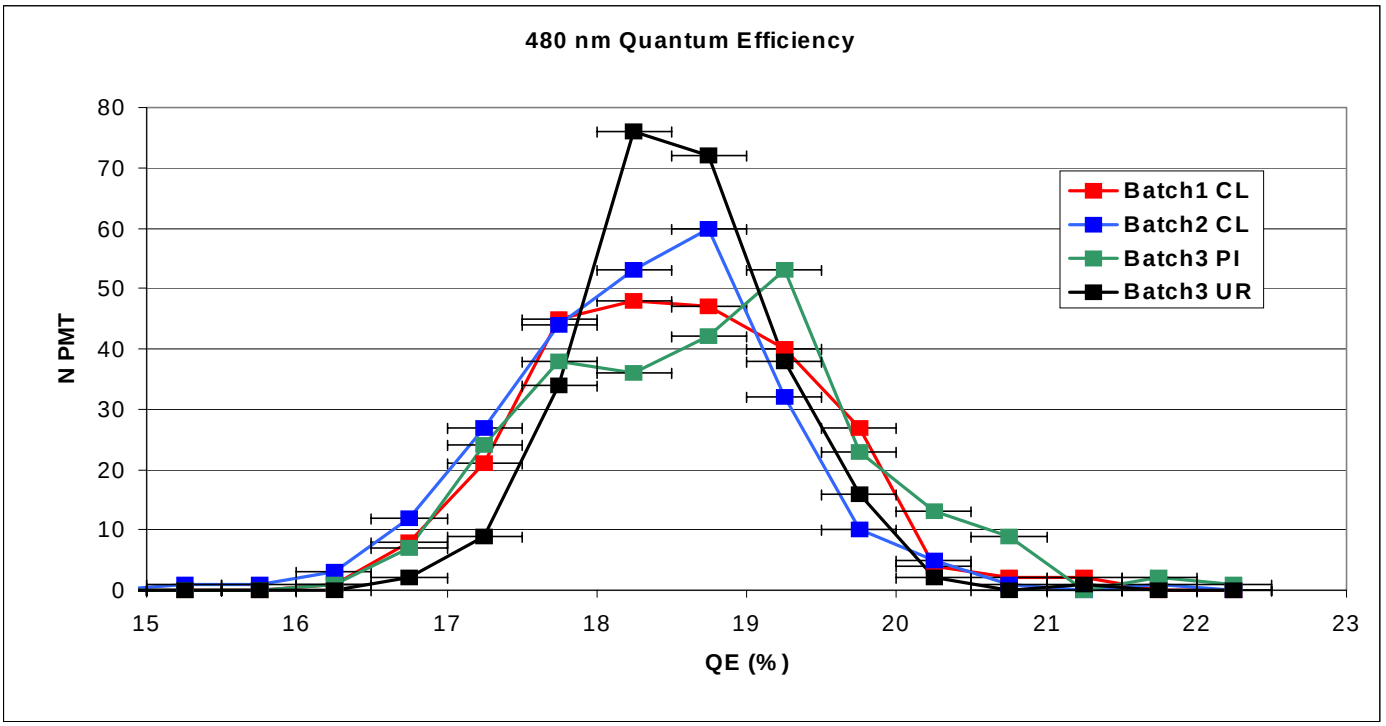

Figure (27) : Quantum efficiency distribution of each of the four sub-batches, after correction and renormalisation: CL#1 (batch#1) ➔ 18,3% (0,73), CL#2 (batch#2) ➔ 18,06% (0,87), Pisa (batch#3) ➔ 18,6% (0,85), Urbana.(batch#3) ➔ 18,3% (0,66)

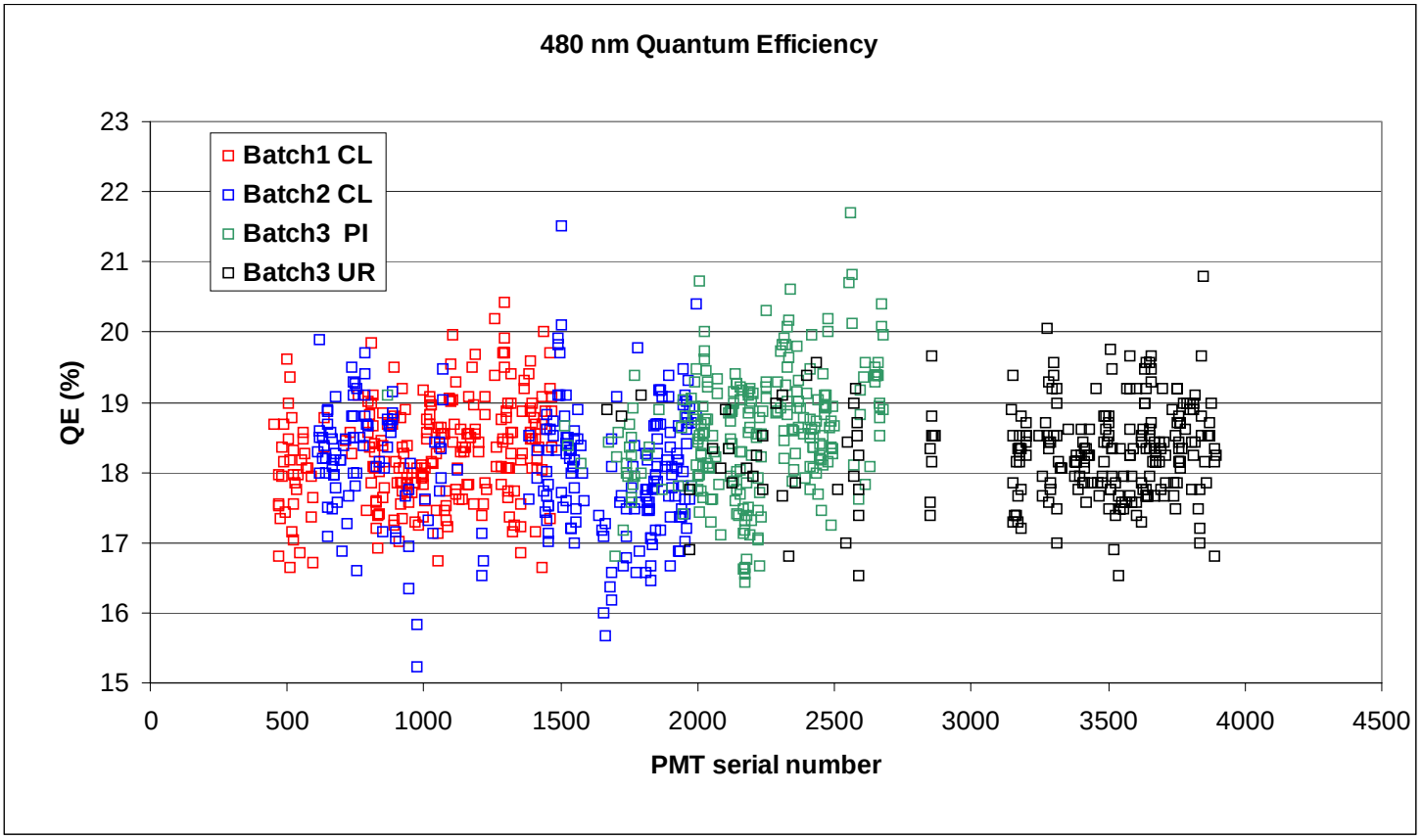

Figure (28) : Quantum efficiency distribution as a function of the PMT serial number

We could conclude from these three last plots that the 480 nm quantum efficiency is rather constant during the production of at least for 1000 of the 1250 tubes.

The mean 480 nm QE is ~18,3 %

The correlation of the photocathode sensitivity with QE, together with measurements on the intercalibration grid seems to be a coherent way to correct QE distribution from systematic error

Nevertheless, origin of the corrections to be applied is not obvious to understand. Further analysis of the test-bench autotest data and measurements on monitoring PMTs are needed .