Long term aging studies of the new PMTs for the HL-LHC ATLAS hadronic calorimeter upgrade

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Introduction

- Photomultiplier (PMT) aging effects are known since PMT invention about one century ago (L.A. Kubetsky, 1930).

- A review of the mechanisms generating PMT response variation with time can be found in literature:
  S.O. Flyckt, C. Marmonier, Photomultiplier Tubes, principle and applications, Re-edit 2002, Photonis, Brive, France

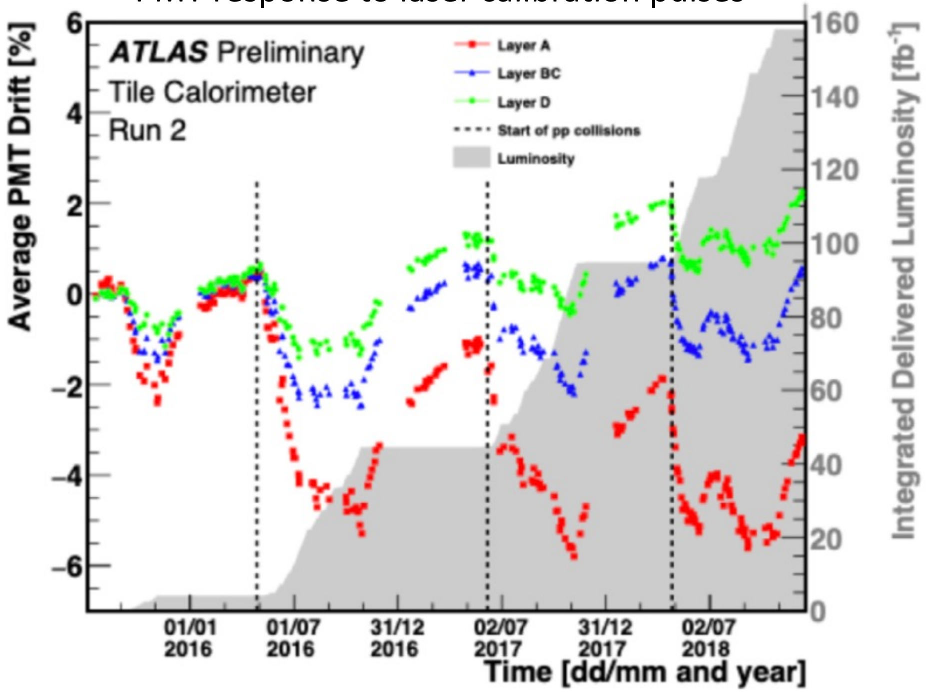
- PMT response with time changes in different ways:
  a) short term (a few hours) drifts induced by any change in the operation conditions;
  b) long term drifts at stable conditions and whose size depends on the average anode current (larger drifts occur at anode current above 10 uA);

- More recently PMTs were widely used as photodetectors of light produced by interacting particles in large volume experiments for high energy physics where PMTs must operate for several years.

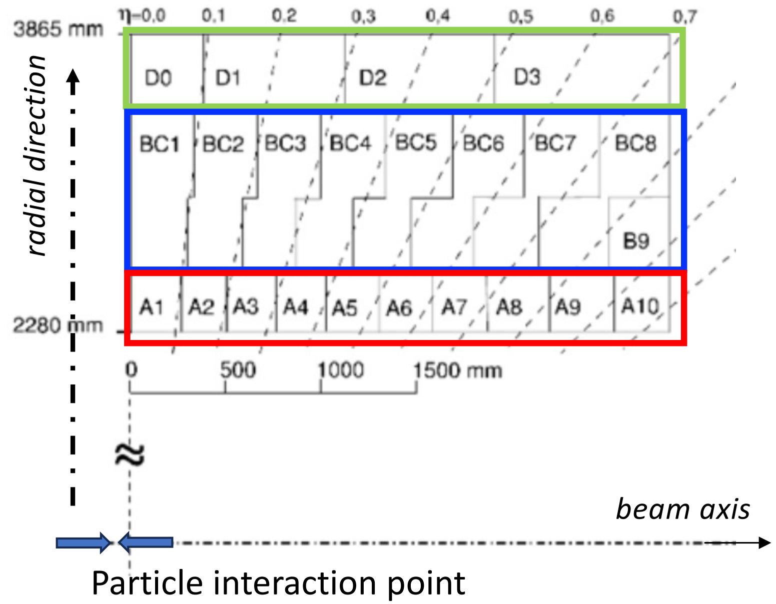
- In the following, a specific study is presented for better understanding the aging effects of long term operation for the PMTs used to readout the cells of TileCal, the barrel hadron calorimeter of the ATLAS experiment running at the Large Hadron Collider (LHC) at CERN (Geneva) since 2011.

The case of the PMTs reading out the cells of the ATLAS/TileCal hadron calorimeter

PMT response to laser calibration pulses



Cell geometry of the long barrel section of TileCal



Cell layer A : innermost layer, most irradiated cells, larger PMT anode current, larger response loss
Cell layer BC : intermediate layer
Cell layer D : outermost layer, less irradiated cells, smaller PMT anode current, no relevant response loss

PMT response recovery is observed during no collision periods

TileCal decided to replace the PMTs reading out the most irradiated cells of layer A for the High Luminosity LHC program when some cells will generate PMT anode current up to 10 uA

The program for PMT aging studies and new PMT qualification in the Pisa labs

- TileCal will replace about 1,000 of 10,000 readout PMTs for the High Luminosity (HL) LHC operation

- Key point is to understand whether replacement PMTs to be installed for reading out the most exposed cells will perform well untill the end of the HL-LHC program

- A new set-up for long term PMT stress test was commissioned and it is operating since 2020 in Pisa

- Aim is to study the evolution of the performance of the replacement PMTs as a function of the integrated anode charge and to test them up to 1,000 C and more

- Replacement PMTs are the latest version (model R11187) of the original PMTs Hamamatsu model R7877, a 8 dynode fine mesh structure specifically produced for TileCal

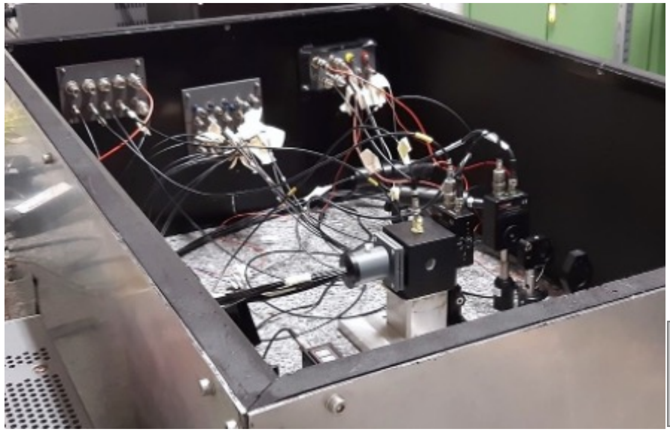
- Additional goal is to understand which mechanisms may induce response variation and, namely, response loss

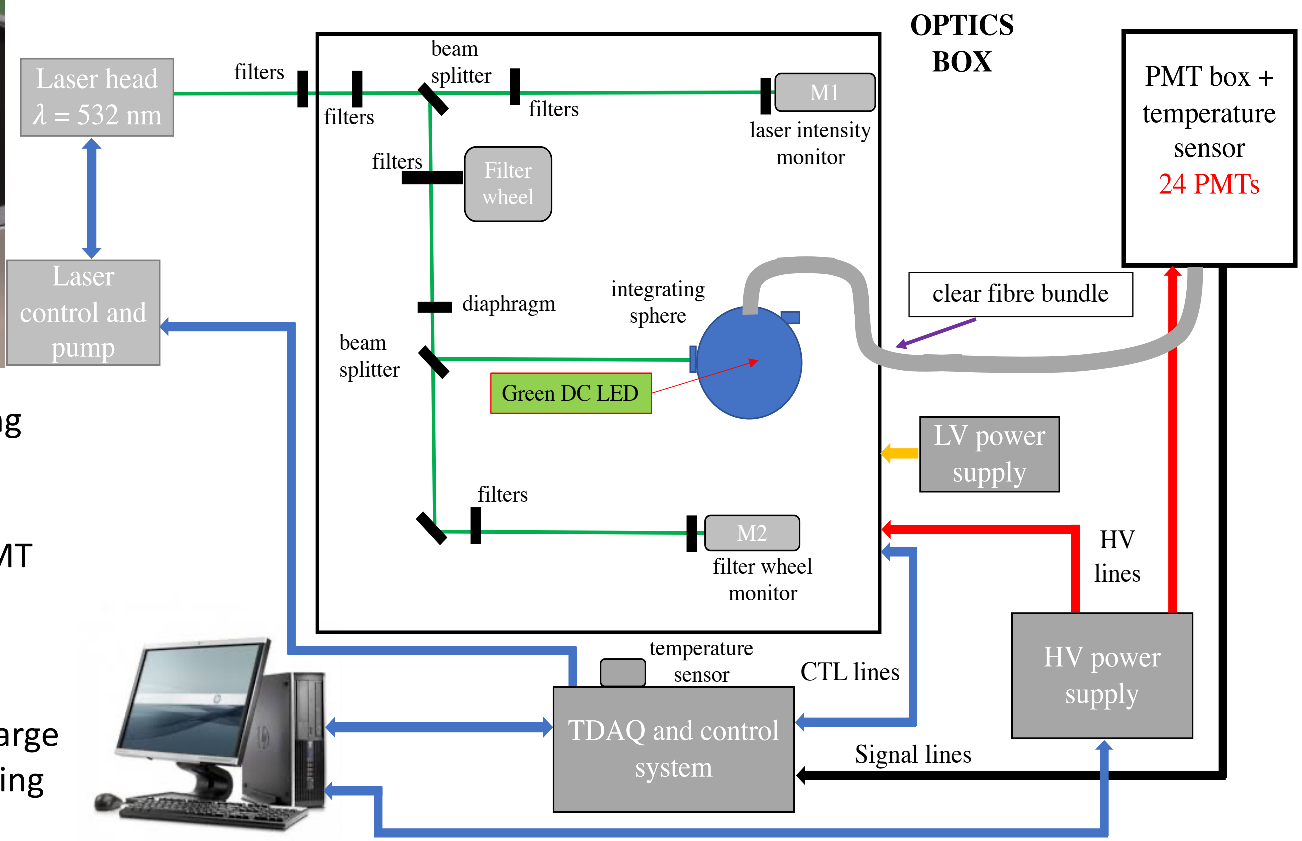
- To do this, independent measurements of the cathode Quantum Efficiency (QE) and absolute Gain (G) are needed

- Gain variation can be measured with the set-up for long term stress test

- QE variation can be measured with a special set-up that will be used for qualifiying the delivered new PMTs.

Pisa test bench for PMT long term stress test





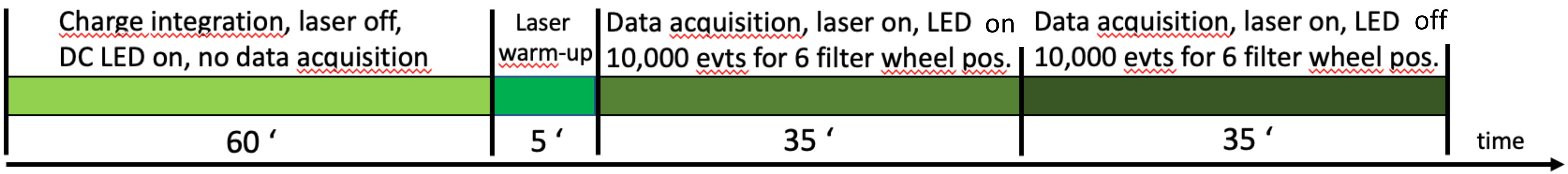
- Pulsed laser light is used for monitoring the time evolution of the PMT response
- LED DC light is used to induce large PMT anode current (about 10 uA)
- A daily procedure is repeated by alternating time intervals of anode charge integration (DC light) with data recording of the PMT response to laser pulses

The daily procedure

- The daily procedure is made of 10 identical sequences of about 135‘;
- A four phase procedure:

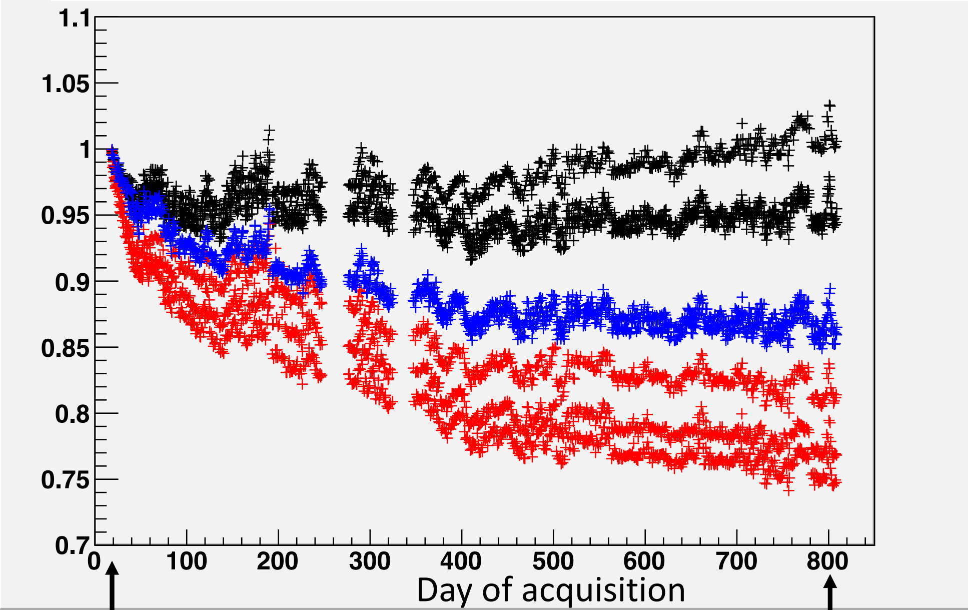
1) Anode charge integration (60’)
2) Laser warm-up (5’)
3) Data acquisition of the PMT response to laser pulses, **DC light superimposed**, 6 laser intensity values (35’)
4) Data acquisition of the PMT response to laser pulses, **no DC light**, 6 laser intensity values (35’)

- The mean values of the PMT pulse height distribution of the 10 sequences are used to monitor the response evolution
- PMT average integration rate is 1 C / day at 10 μA anode current
- The procedure was repeated every day for testing 3 old model PMT R7877, 2 special, high QE PMTs model R11187-SEL (new model prototypes), and 19 PMTs R11187-A01, latest version for TileCal



PMT response evolution: comparison of different PMT models

PMT signal normalized to the laser intensity monitor.
and to the first acquisition day

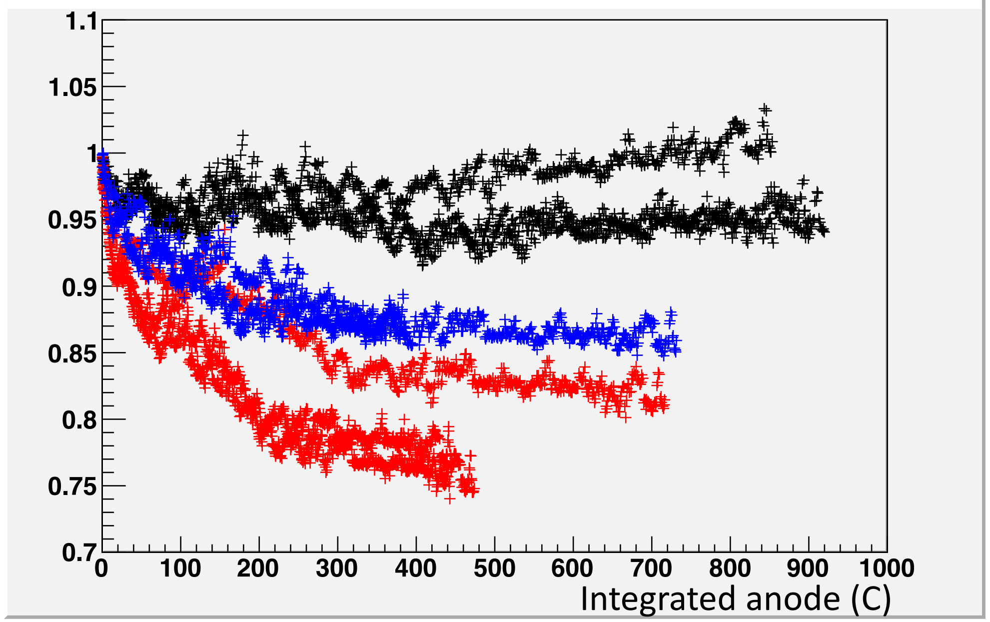


2020/12/18

2023/02/14

More than 2 years of almost continuous data taking !!

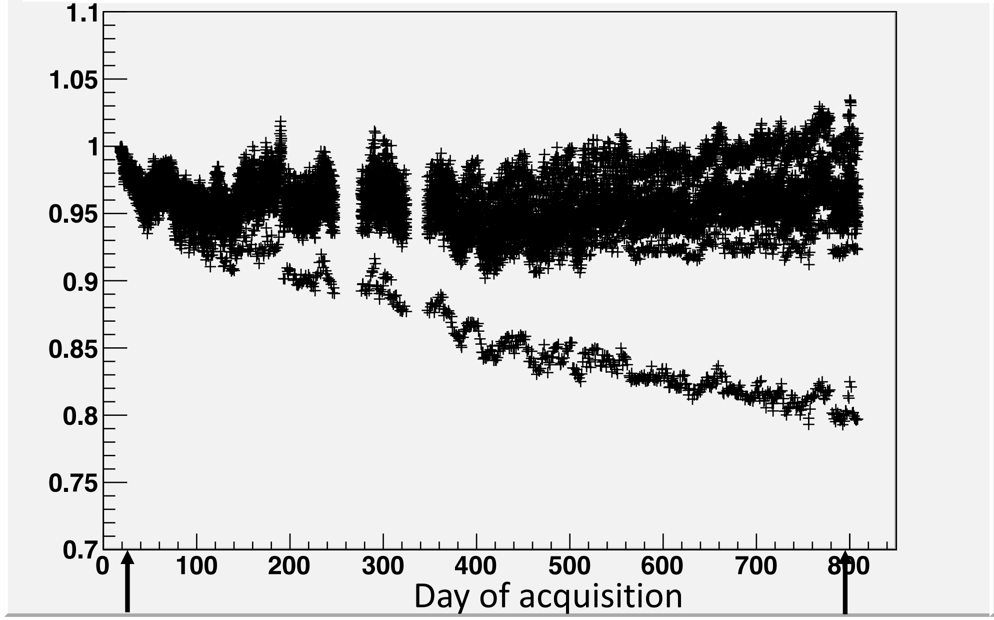
PMT signal normalized to the laser intensity monitor.
and to the first acquisition day vs. anode integrated charge



+ : 3 PMTs new model R11187-A01 (2019 production)
+ : 2 PMTs model R11187-SEL (2010) production, high QE)
+ : 3 PMTs old model R7877 (2004 production)

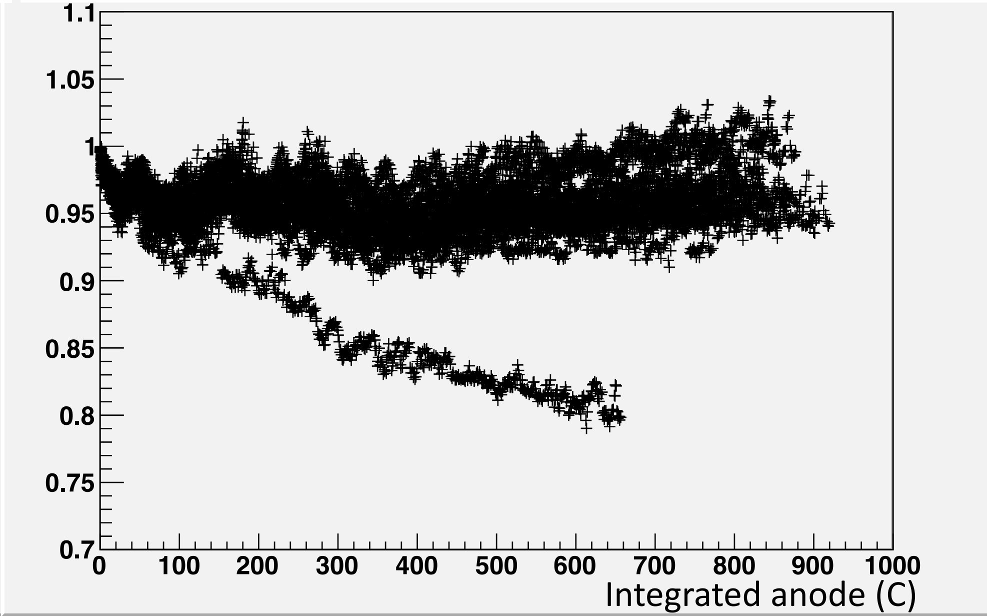
PMT response evolution: spread of same model R11187-A01 19 samples

PMT signal normalized to the laser intensity monitor.
and to the first acquisition day



2020/12/18 2023/02/14

PMT signal normalized to the laser intensity monitor.
and to the first acquisition day vs. anode integrated charge



- One of 19 PMTs went bad
- Spread relative to the average response evolution less than 10% and stable after 200-300 C of integrated charge for all other 18 samples

New PMT set under test since Febraury 20, 2023

- Beginning of 2023, a set of old model PMTs dismounted from TileCal after the end of LHC run 2 was sent to Pisa

- At that time, most of new PMTs under test since more than 2 years reached almost 900 C of anode integrated charge (600 C is the expected maximum value of integrated charge at the end of HL-LHC data taking for PMTs reading out the most exposed calorimeter cells)

- All tested PMTs were never dismounted from the optics box and no QE measurment was done in that long observation period

- We decided to modify the procedure and to test 14 old model PMTs dismounted from TileCal and to continue testing 10 new model PMTs with the important new step of the procedure:

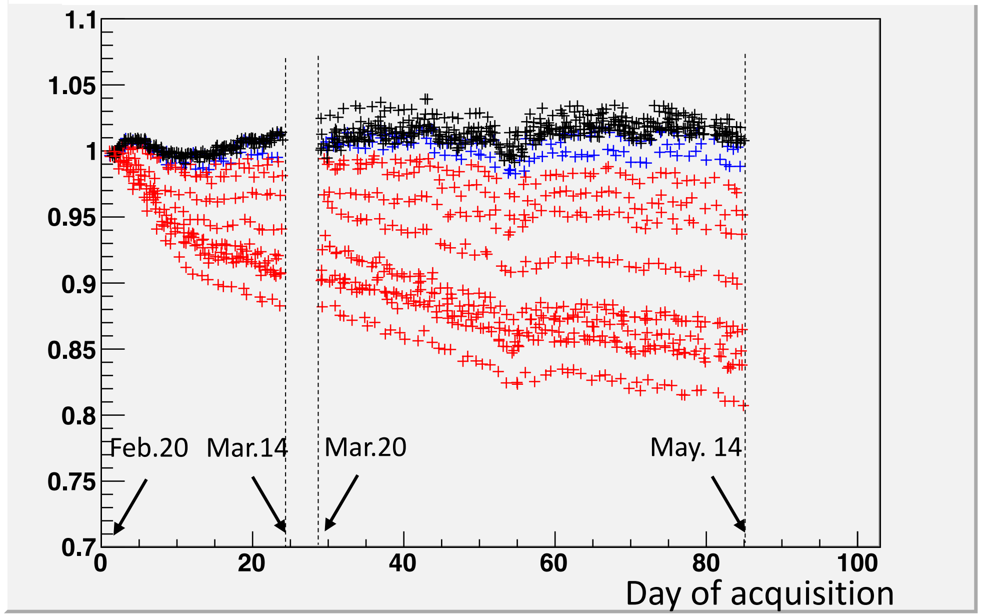
  ===> QE efficiency of all observed PMTs is measured each 50 C (approximately) of integrated charge

- To implement this step, PMTs are dismonted every 50 days from the test bench for long term stress test, then they are put in the PMT qualification test bench for QE measurement, and finally remounted in the long term test set-up for charge integration after each QE measurment

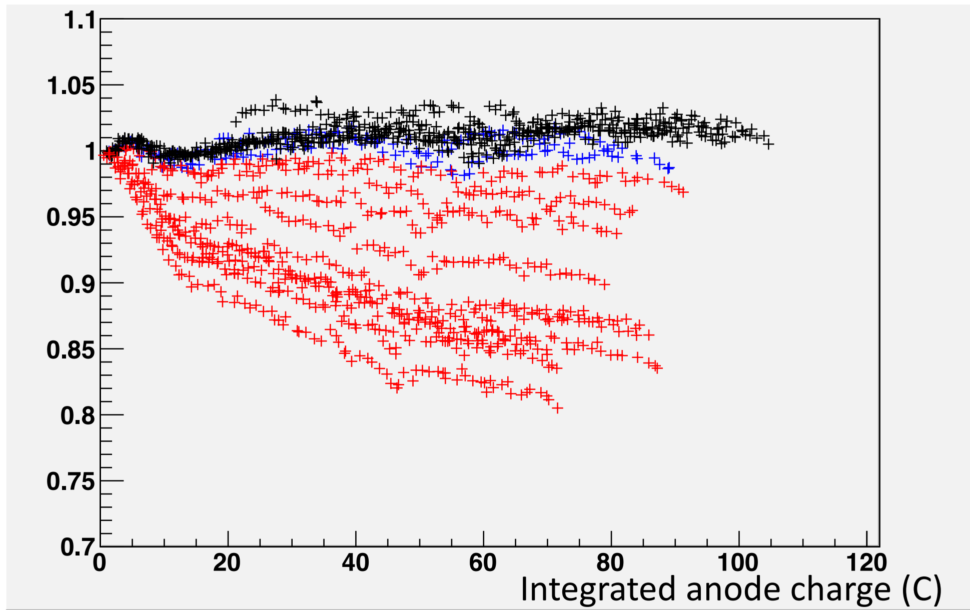
Final PMT set under test from February 20, 2023

4 PMTs changed during a maintenance intervention between Mar.15 and Mar.19, 2023, kept in place the other 20 samples …

PMT signal normalized to the laser intensity monitor.
and to the first acquisition day



PMT signal normalized to the laser intensity monitor.
and to the first acquisition day vs. anode integrated charge



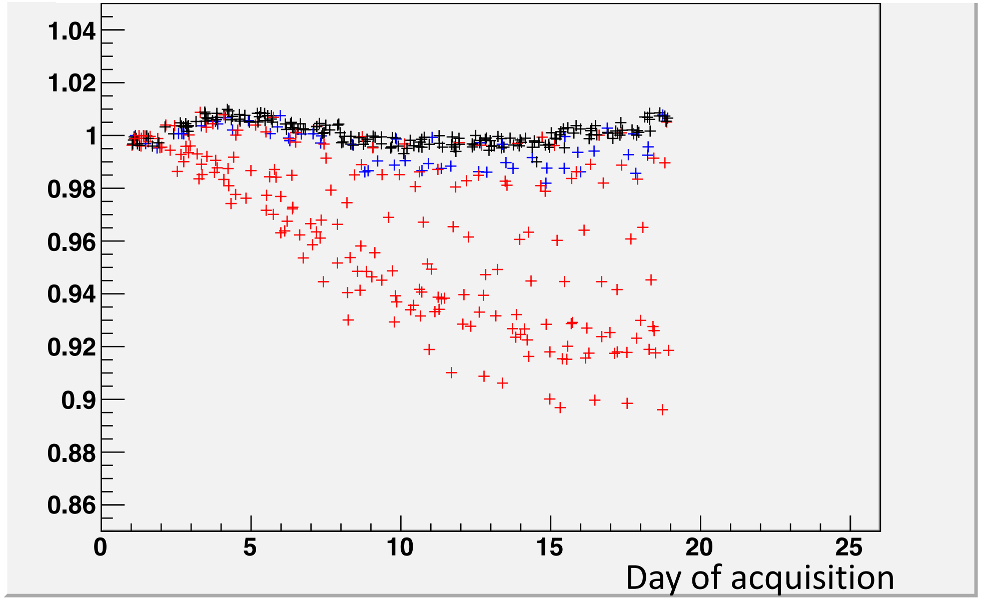
+ : 8 PMTs new model R11187-A01 having integrated more than 900 C before
+ : 2 PMTs old model R7877 having inegrated more than 500 C before
+ : 10 PMTs old model R7877 dimounted from TileCal after LHC run 2 and having integrated in Tile Cal less than 90 C (less than 10 C for most of them)

- Confirmed that the most response loss happens before 20 C anode integrated charge
- Same observation made with laser calibrations of all TileCal PMTs

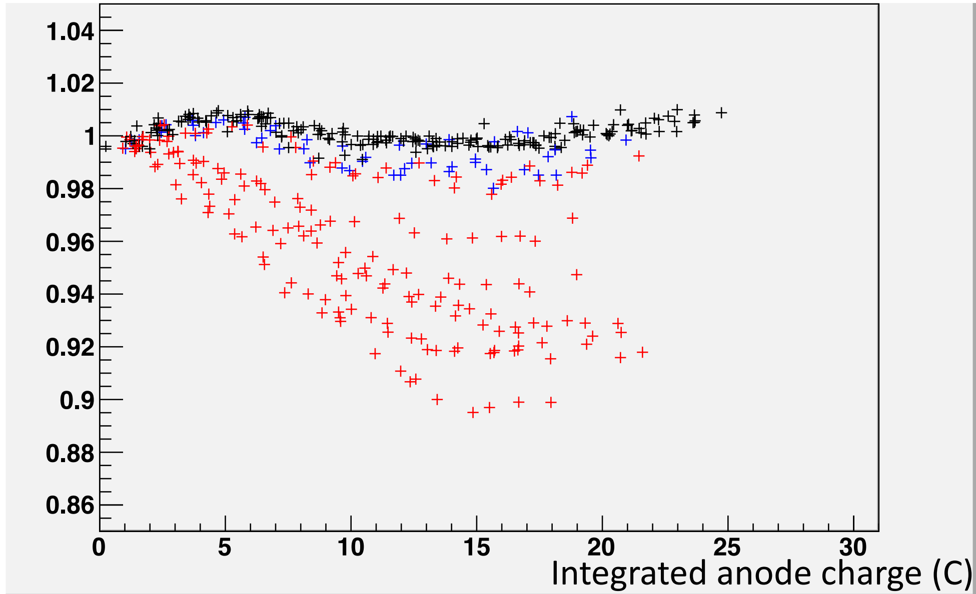
Final PMT set under test from February 20, 2023 – First 20 C of integrated charge

Improved uniformity of light distribution to PMTs, all integrating now about 1 C / day of anode charge

PMT signal normalized to the laser intensity monitor.
and to the first acquisition day



PMT signal normalized to the laser intensity monitor.
and to the first acquisition day vs. anode integrated charge



+ : 3 PMTs new model R11187-A01 having integrated more than 900 C before
+ : 2 PMTs old model R7877 having inegrated more than 500 C before
+ : 10 PMTs old model R7877 dismounted from TileCal after LHC run 2 and having integrated in Tile Cal less than 90 C (less than 10 C for most of them)

- All PMTs (**+** and **+**) having integrated a large amount of anode charge show stable response within 1%
- PMTs (**+**) having integrated less charge show response loss, faster before 10-20 C

Understanding the PMT response variation mechanisms

- The PMT response to excitation from fixed light intensity may vary due to changes in:

  a) the photocathode quantum efficiency (QE);

  b) the dynode gain G.

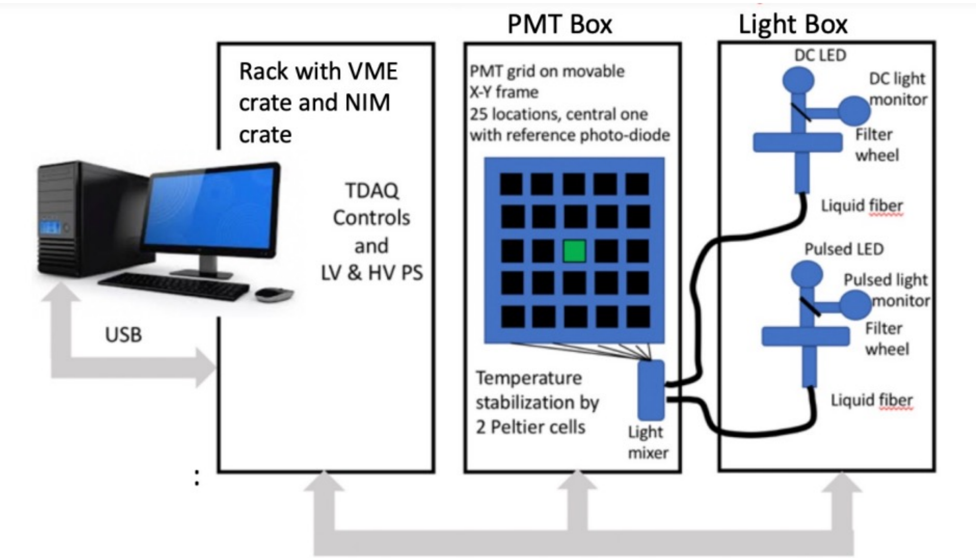
- Measurement of the cathode QE requires a special set-up

- Measurement of the PMT absolute gain can be done by combining measurements at different light intensity (number of photelectrons Np.e.) at fixed PMT voltage

- One goal of the present study is to disentangle the contributions of QE and gain changes to the global variation with time of the PMT response.

- A special arrangement to qualify the TileCal replacement PMTs was used to measure the QE of PMTs observed during the long term stress test

- The measurement of the PMT gain variation from data at different light intensity is in progress



Test bench for measuring the PMT QE

- A ''light box'' contains pulsed and DC LED sources with filter wheels for light intensity regulation and with intensity monitors

- A PMT box contains a 25 location grid. Central location hosts a reference photo-diode (PD), other locations host the tested PMTs. LED light, received from liquid fibers, is distributed to each location through clear fibers from a light mixer

- The PMT grid is mounted on a X-Y frame remote controlled. Before each measurement, the reference PD is moved onto each location for measuring the light intensity from each clear fiber

- All system settings, LED excitation and PMT signal digitization is managed by a host computer running a Labview SW package

Measurement of the PMT cathode QE

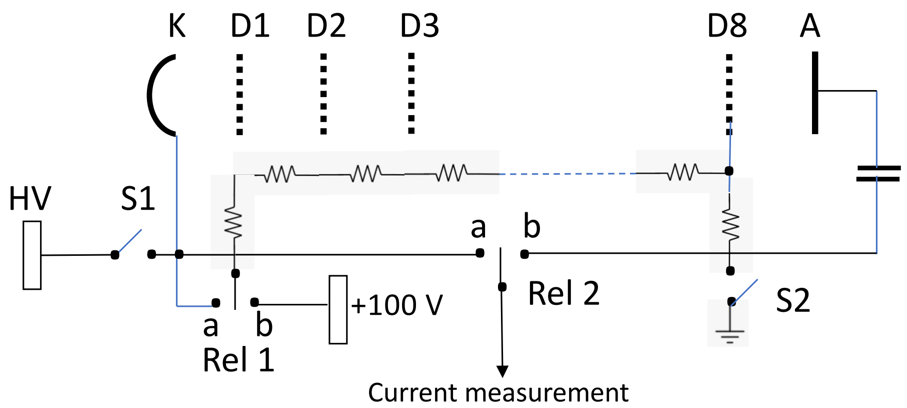
- Measurements of the PMT QE are done by using special dividers to measure the current drain by the first dynode when +100 V are applied relative to the cathode, once the dynode collection efficiency is known.
- The PMT QE is derived by comparing the 1st dynode current $\boldsymbol{i_{PMT}}$ with the current $\boldsymbol{i_{PD}}$ from the reference PD whose photo-detection efficiency PDE (0.66) is known:

$$\boldsymbol{i_{PMT}} = \mathrm{Int}_{LED} \times C_{PMT} \times QE;$$

$$QE = (\boldsymbol{i_{PMT}} / \boldsymbol{i_{PD}}) \times (C_{PD} / C_{PMT}) \times PDE;$$

$$\boldsymbol{i_{PD}} = \mathrm{Int}_{LED} \times C_{PD} \times PDE;$$

where Int_{LED} is the luminous intensty of the LED and (C_{PD} / C_{PMT}) is the ratio of light collection and transmission efficiency for the LED light fed by the clear fibers to PMTs and to the reference PD

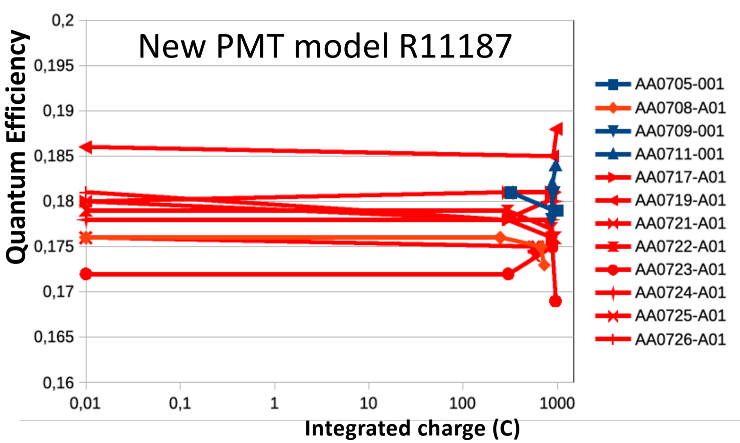


Special dividers for QE measurements

- Normal PMT operation:
switches S1 and S2 closed, relay 1 in pos. a) and relay 2 in b)

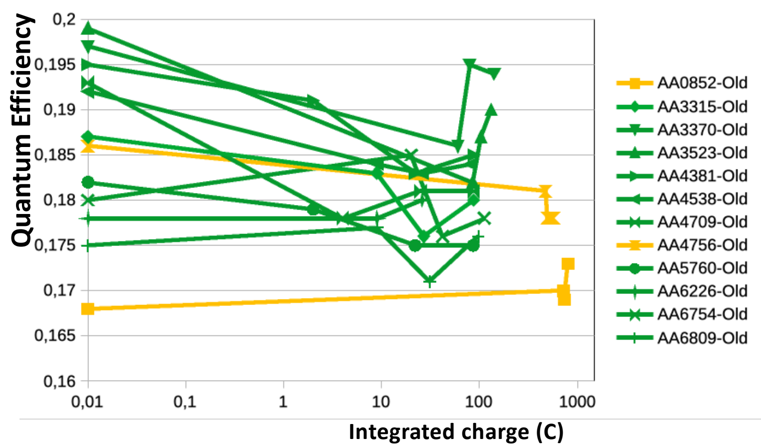
- QE measurements:
switches S1 and S2 open, relay 1 in pos. b) and relay 2 in a)
(all dynodes at same +100V voltage, cathode current measured)

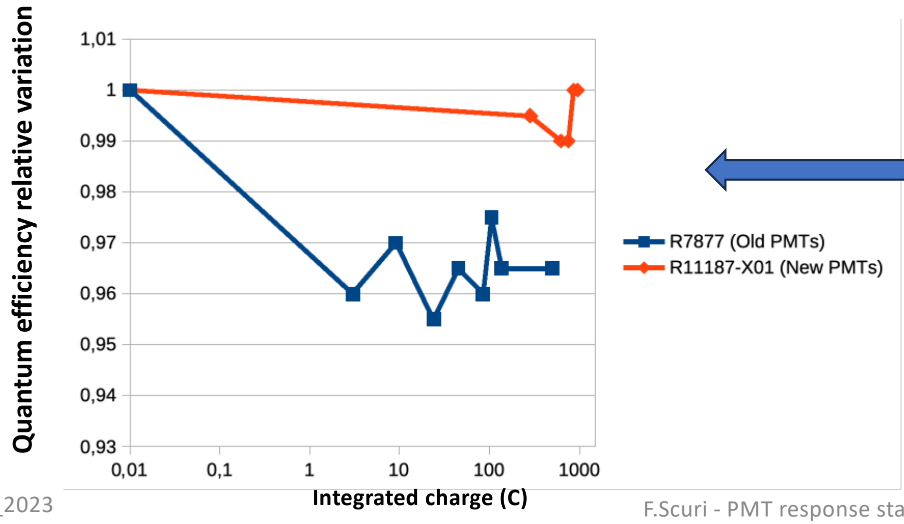
Quantum efficiency measurements for PMTs under long term stress test



Old PMTs R7877 dismounted from Tile after LHC run 2

Old PMTs R7877 used only in Pisa tests since 2020





Average variation of the PMT QE relative to its first measurment before any charge integration:

Initial QE value taken from Tile original PMT qualification (old PMTs) or from Hamamatsu data sheets (new PMTs)

First lessons from the QE evolution studies ….

- A wide sample-to-sample spread in the QE evolution as a function of the integrated charge is seen as for the case of the PMT global response evolution.

- For both PMT types (old model R7877 and new model R11187) the average QE variation is small:

  < 5% after 100 C of integrated anode charge for old model R7877

  < 3% after 100 C of integrated anode charge for new model R11187

- The QE variation is, in average, significantly smaller than the global PMT response variation as a function of the integrated anode charge

  ===>>> more accurate studies on the independent variations of gain and QE are required

- In the following the first attempt to measure the PMT absolute gain evolution is presented

Measurement of the PMT absolute gain (in progress)

- The PMT absolute gain **G** can be derived by measuring the PMT response at different light intensities
- The average and the variance of the distribution of the anode charge digitized with QDCs are combined:

$$<Q> = <QDC\_counts> \cdot x\ 10^{-13}\ C = <N_{pe}> x\ G\ x\ e; \qquad (1)$$

$$var(Q) = var(N_{pe})\ x\ F_{enf}\ x\ G^2\ x\ e^2 + var(Light\_Int) + var(dark\_current); \qquad (2)$$

- The variance var (Q) of the anode charge distribution is the sum of three terms:

  1) Stochastics term $var(N_{pe})\ x\ F_{enf}\ x\ G^2\ x\ e^2$;

  - F_{enf} is the PMT ***excess noise factor*** and represents the broading of the initial photo-electron distribution due to the stochastics process of the electron multiplication in the PMT dynodes.
    $F_{enf} = 1.3$ for the TileCal 8 dynodes PMTs at $G=10^5$.

  - In the Poisson hypothesis for the photo-electron emisssion statistics $var(N_{pe}) = <N_{pe}>$
    in this case: $var(N_{pe})\ x\ F_{enf}\ x\ G^2\ x\ e^2 = <q>\ F_{enf}\ x\ G\ x\ e$

  2) $var(Light\_intensity) = k^2\ x\ (<Light\_intensity>)^2$ is the width of the laser light pulses distribution (k=5%)
  - $var(Light\_Int) = C\ x\ (<Q>)^2$

  3) Dark current fluctuations (pulse baseline) are independent from the pulse height

- By combining all previuos equations, the following relationship between var(Q) and <Q> is obtained:

$$Var(Q) = A + B <Q> + C<Q>^{2.} \quad (3) \qquad \text{with } B = F_{enf}\ x\ G\ x\ e$$

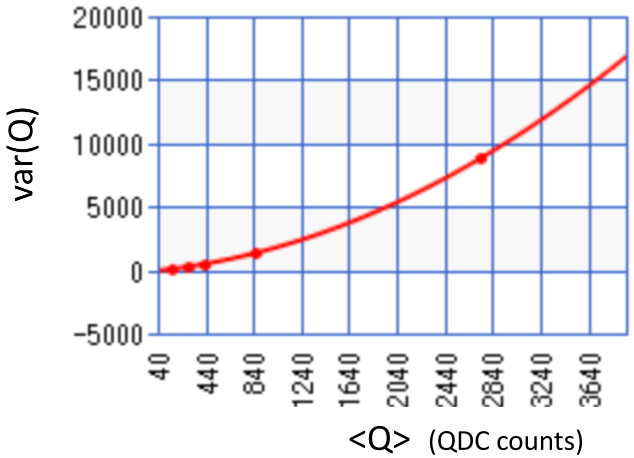
An example of study of absolute gain evolution (in progress)

For the moment a few measurements from laser intensity scans (5 points) of one PMT sample were studied

An example of var(Q) vs <Q>: PMT R7877 s/n 5760

$$Var(Q) = A + B\,\langle Q\rangle + C\langle Q\rangle^2 \quad (3)$$

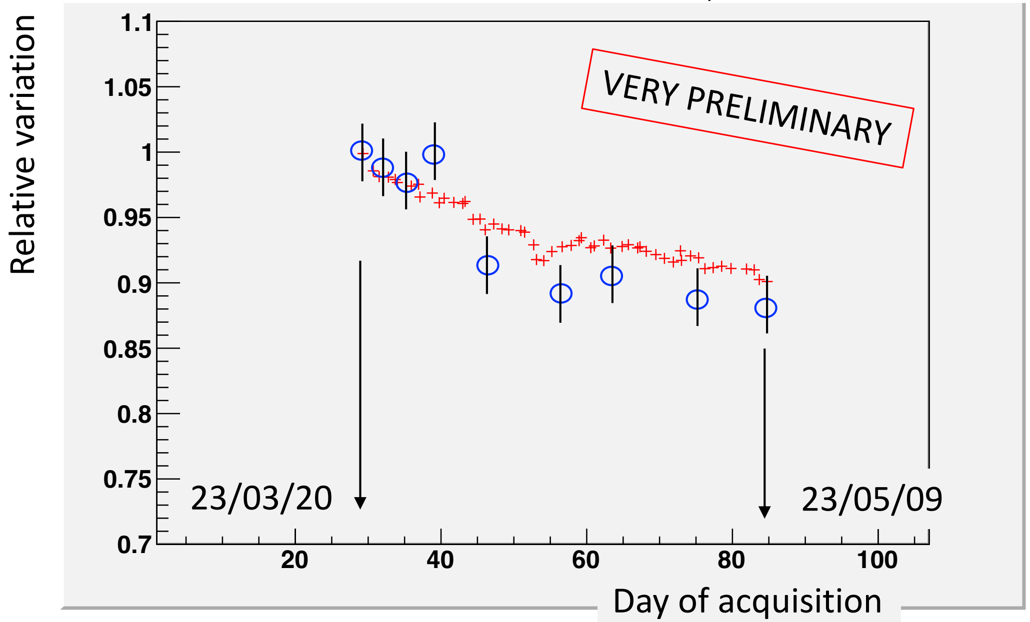
The PMT gain G is extracted from the $B = F_{enf} \times G \times e$ parameter of eq. (3)



Eq. (3) seems to fit quite well the data points .....

PMT R7877 s/n 5760 (HV = 760 V)									
date	23/03/20	23/03/23	23/03/26	23/03/30	23/04/07	23/04/16	23/04/23	23/05/01	23/05/09
G (x 10^{-5})	4.75	4.68	4.66	4.75	4.32	4.13	4.32	4.18	4.13
QE	0.175	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0,175

PMT relative global response (+) and gain (o) normalized to the 1st day



Conclusions and plans

- Old model and new model PMTs for the ATLAS TileCal hadron calorimeter were tested over a long operation period at high (10 uA) anode current up to about 1,000 C integrated charge.
- Time evolution of the PMT response was monitored for more than 2 years and the PMT performance of new and old models compared
- New model PMTs are better both in terms of response stability and of sample-to-sample response spread
- New PMT model is certified for being safely operated in the harsh HL-LHC conditions up to about 1,000 C at 10 uA anode current
- Old model PMTs show a fast response loss below 100 C integrated charge followed with a smoother variation with time above 100 C.
- First attempts to separately measure to gain and quantum efficiency variations were made
- Very preliminary results indicate that QE is slightly varying with charge integration, while gain variation seem to be consistent with the PMT global response variation
- In general, all results indicate that using new model PMTs for reading out most exposed cells and old model PMTs for less exposed cells should allow safe operation of the ATLAS/TileCal readout for the full HL-LHC data taking period

workplan: 1) perform more accurate gain measurements with the available data
2) continue with charge integration to test to which extent new PMT performce is not degraded by aging