Equalisation of the PMT response to charge particles for the Lucid detector of the ATLAS experiment

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With a view to the Run II of LHC, 44 Hamamatsu R760 PMTs have been calibrated with a ^{207}Bi source. The working point of each PMT has been fixed in order to equalise the PMT gain at a value smaller than 10^5. Studies on the reproducibility and the stability in time of such calibration permitted to reach a 5% accuracy on PMT gain. In addition, an evaluation of the relative gain of 10 modified PMTs has been performed.

Introduction

LUCID is the main system which measures luminosity in ATLAS. In order to make the detector performances appropriate for the Run II of LHC, which will start in March 2015 at increased centre-of-mass energy and luminosity, LUCID will be subjected to some technology improvements. In particular, the principal sensors (photomultipliers, PMTs) and the readout electronics will change. The new Hamamatsu R760 PMTs will have a quartz window, which has the properties to be radiation resistant and to emit Cherenkov light when passed through by a charged particle. This implies that the quartz window itself can detect particles and can thus be used as a radiator medium. Before the installation, the new PMTs have been equalised to charge particles, that means finding the high voltage

at which each PMT has the same gain ($< 10^5$ to limit the ageing). PMTs have been calibrated with a ^{207}Bi source, which emits monochromatic electrons. The signal on PMTs is thus due to the Cherenkov light emitted by electrons passing through the quartz window.
For every PMT the working point has been determined in the aim of limit their ageing and avoid the saturation at high voltage. Two different techniques have been employed: a scan in the voltage range in which the charge peak is around 300 mV·ns (due to the experimental setup) and a linear interpolation of the two closest-to-300 mV·ns measurements. A study of the systematics associated to the calibration results has been performed, focusing on the reproducibility and on the stability in time. The final systematic uncertainties have been evaluated to be 5 V on HV measurements which correspond to a 5% accuracy in PMT gain. The same analysis has been made on a sample of 10 modified PMTs with no success, because of the too small quartz window which make the number of electrons hitting the PMTs decrease. Indeed the relative gain of these PMTs was extrapolated from a linear fit of the anodic current measurement as a function of a HV scan and compared with Bologna measurements. Some discrepancies, principally due to the dark current, have been found and are going to be studied.

1 LUCID

For experiments at particle accelerators, the measurement of the machine luminosity is essential in the cross-section determination of all processes. *Luminosity Cherenkov Integrating Detector* (LUCID) is the dedicated luminosity monitor of the ATLAS experiment [1]. It measures inelastic proton-proton interactions in the forward direction, providing bunch-by-bunch luminosity with a precision of 2-4% and beam background information. It is composed by two modules placed around the beam-pipe on both forward ends of ATLAS, 17 m far from the interaction point. Each module is formed by 16 photomultipliers (PMTs) and 4 quartz fibre bundles which carry the light produced in them to further PMTs, placed far away from the interaction region. PMTs detect Cherenkov light emitted by charge particles passing through their quartz window; the light is carried on 1.5 m long coaxial cables at low noise to the front-end electronics. In every bunch crossing, PMT signals are discriminated by the acquisition system and converted in digital “hits” if over the threshold (equivalent on a average of 15 photoelectrons); the “event” is then defined from specific hit configurations. To measure the bunch-per-bunch luminosity, LUCID exploits event-algorithms or hit-algorithms [2]; additionally another method has been developed for the Run II which measures the charge produced by PMTs. In fact the produced Cherenkov light, and thus the generated charge, is proportional to the charged particle path in the quartz window, if the energy of the particle is above threshold.

1.1 Updates

Starting from March 2015, when the LHC centre-of-mass energy will reach the value of $\sqrt{s} = 14$ TeV, the average number of bunch crossings will increase. This implies a large collected charge in the PMTs due to a greater number of particles passing through the detector, resulting in a faster PMT ageing. The increasing particle fluxes originate a strong anodic current which causes the PMT saturation, that is the loss of linearity of the PMT gain as a function of the electron current.
In order to be efficient at the new experimental conditions, LUCID will be supported by a new readout electronic system to digitalize PMT signals in the neighbourhood of PMTs themselves. These signals will be used to measure the charge generated every 25 ns (bunch crossing spacing); LUCID will be supported by new algorithms for the luminosity measurement based on the collected charge. In addition, LUCID Hamamatsu R762 PMTs have been replaced by the Hamamatsu R760 PMTs, which are smaller, in order to decrease the acceptance and the anodic current. Consequently, the working tension and the gain will be reduced by an order of magnitude, down to 10^5. The diameter of the new photo-cathodes have been reduced from 15 to 10 mm. For a subset of 10 PMTs, a further acceptance reduction to 5 mm has been achieved through an innovative technique implemented by Hamamatsu, consisting in the introduction of a thin aluminium layer between the window and the photo-cathode ("modified" PMTs). The reduced size will limit the current collected and thus PMT ageing and signal saturation problems.

2 Photomultiplier Characteristics

A photomultiplier is a measure instrument which reveals photons belonging to a spectrum slightly larger than the visible one, and converts them in an electric current. Photons cross the quartz window and hit a photocathode, where they generate photoelectrons by photoelectric effect. Photoelectrons are then accelerated by an electric field and collected on an electrode. The resulting signal is amplified by a dinode chain separated by a

potential difference.
The main PMT parameters on which our attention has been focused are the **gain** and the **charge** collected on the anode. The gain is the ratio between anodic and cathodic currents. Assuming a constant potential difference between each dinode pair, the gain can be expressed as $G = \delta^n$, where δ is the average number of secondary electrons generated after the collision with a dinode and n is the number of dinodes (usually $8 < n < 12$). The δ term is a function of the tension applied to the PMT $\delta = A \cdot \Delta V \beta$, in which A is a constant, ΔV is the potential difference between two dinodes and β is a parameter which represents the material of which they are made and their geometry ($0.7 < \beta < 0.8$). If ΔV is constant of each dinode pair, the working voltage V can be expressed as $V = n\Delta V$ and the gain becomes

$$G_{PMT} = (A \cdot \Delta V)^n = [A \cdot (\frac{V}{n})^\beta]^n = KV^{\beta n} = KV^\alpha \quad , \tag{1}$$

where all the constant terms have been absorbed in K and α will be indicated in the following as "relative gain".
The charge gathered on the anode can be expressed as

$$Q = N_{ph}\, G_{PMT}\, Q_e \quad , \tag{2}$$

in which Q_e is the electric charge and N_{ph} is the number of primary electrons. In previous tests on the same PMTs with cosmic rays, this number was around 35, according to the thickness of the quartz window and to the chosen G_{PMT} value. Considering the electron emission by ^{207}Bi source in all the direction, N_{ph} decreases to 30 (the 85% of its value). Inserting Eq.(1) in the expression for the charge, the dependence of the latter from the working voltage is a function of the relative gain α

$$\frac{Q_1}{Q_2} = (\frac{V_1}{V_2})^\alpha \quad . \tag{3}$$

3 Experimental Setup

In order to find the best working point, the PMTs calibration necessitated of an experimental setup composed by:

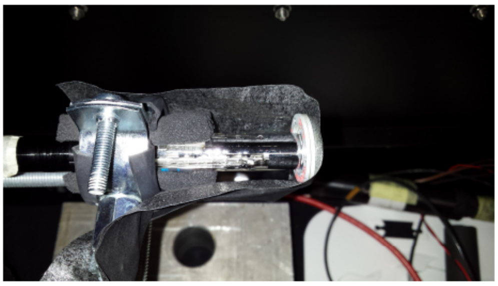
- a **Black Box** totally isolated from the outside environment. PMTs were placed inside the box in order to be sensitive only to the source and not to other lights.

- two **Hamamatsu R760 PMTs** have been calibrated at the same time. They were located in the black box in the same basement coupled with two ^{207}Bi sources (Fig.1): one was in the vertical position and the other in the horizontal position. Two different electronic channels were connected with them.

- two disk-shaped ^{207}Bi **sources** have been placed in close contact to the PMTs. ^{207}Bi emits monochromatic electrons from internal conversion with maximum energies of about 1 MeV and dis-excitation photons with an energy between 0.5 and 2 MeV. In order to increase the number of electrons hitting the PMT with a sufficient energy to emit Cherenkov light, the source dimensions where larger than the PMTs (Fig.1).

- two **Power Supplies** in a NIM crate both calibrated which give high voltage to PMTs.

- a **LUCROD** prototype in a VME crate. It is made by two FADCs sampling the analogical signal every 3.125 ns, that corresponds to 8 measurements in every bunch-crossing time (25 ns). LUCROD performs 64 digital samplings, 16 after the trigger, and stores them in a readout schedule (FIFO). The trigger has been setted over the signal itself. For the calibration measurements the logic OR of the two input channels has been required as trigger.



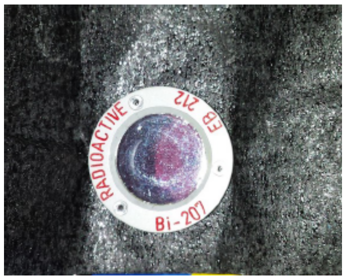


Figure 1: PMT basement and connection to the source in the black box (*right*) and the disk-shaped ^{207}Bi source (*left*).

4 Measurement strategy and results

The goal of this measurement is to find a working voltage for all the PMTs that will be installed in LUCID II at low gain. The two main requirements are:

- PMT gain less than 10^5, in order to reduce the ageing;
- signal induced by the ^{207}Bi source well separated from the electronic noise.

The expression for the collected charge is

$$Q(mV \cdot ns) = 10^{12}\, 50(\Omega)\, Q_e\, N_{ph}\, G_{PMT}\, G_{FADC} \quad . \tag{4}$$

With the chosen LUCROD settings $G_{FADC} = 13.92$, $G_{PMT} = 0.89 \cdot 10^5$ is the gain corresponding to a charge of 300 mV·ns. It allows to a single-track amplitude in the PMT of less than 4 mV; this implies that at least 25 tracks are needed to reach the saturation voltage. For each PMT five ^{207}Bi signal measurements have been taken with a 10 V spread, starting from the high voltage value at which the charge distribution peaked around 300 mV·ns. For each HV value, FADC thresholds have been setted in order to reach the best signal from the source in both channels. Fig.2 shows the measured signal and the integrated charge distributions; Fig.3 illustrates the amplitude of the signal. In particular the request of the logic OR of the two channels implies the presence of the distributions of both PMTs: in Fig.3 the pedestal is due to the second PMT in the box, while the gaussian curve indicates the amplitude of the PMT in exam. Finally there is another effect caused by the electrons belonging to the source and emitting photons without passing through the quartz window. The interesting signal is due to electrons losing their energy inside the PMT window, easily discriminable from the other effects regulating the FADC threshold.

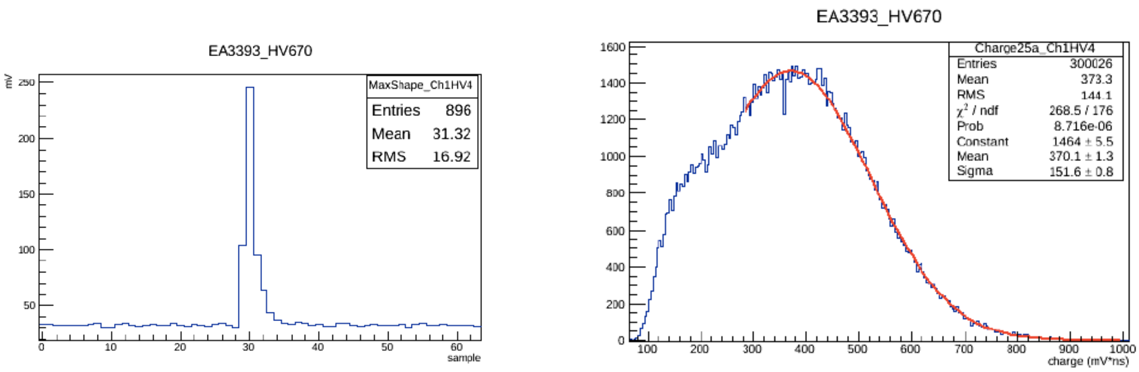


Figure 2: Measured signal (*right*) and charge (*left*) at 670 V for the EA3393 PMT.

The HV working point has been obtained through two different techniques. First, it was derived according to Eq.(3): the charge measurements Q_i and the relative gain α have

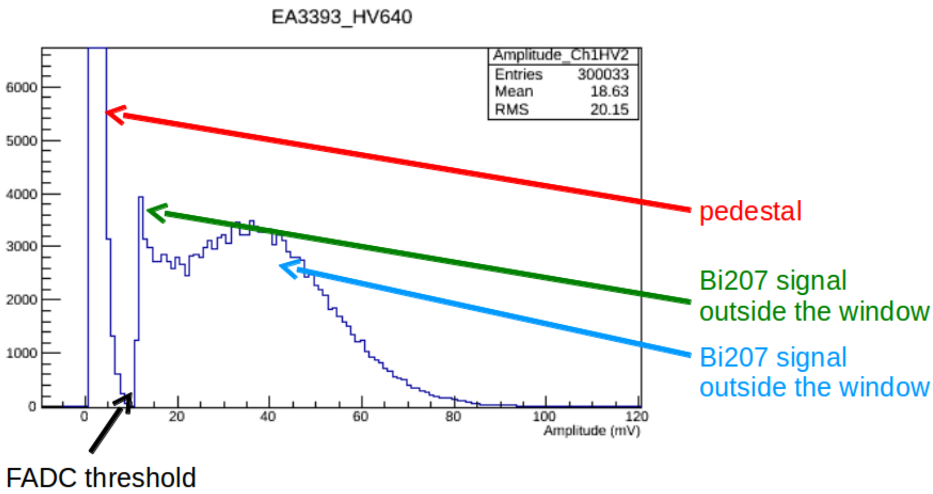


Figure 3: Amplitude distribution for 3393 PMT at 640 V. Some features can be observed: the pedestal trigger from the second PMT in the box (*red*), the FADC threshold (*black*), the ^{207}Bi signal outside (*green*) and inside (*blue*) the PMT quartz window.

been employed to evaluate the voltage corresponding to a 300 mV·ns charge. Subsequently in the charge distribution as a function of the HV, the two closest-to-300 mV·ns have been linearly interpolated; the HV working point is again the tension value referring to the peak charge (see Fig.4). Finally, a comparison of the two methods has been made.

The results of the calibration measurements are summarized in Tab.1, where the values of the HV working point are listed for each PMT. In addition, after inserting charge and amplitude measurements in Eq.(3), a check on the relative gain has been made, in order to verify the previous evaluation with cosmic rays: the obtained value $\alpha = 0.08$ is compatible with prediction for each PMT.

4.1 Systematics

In order to verify the stability on time of the results, EA3375 and EA3388 PMTs charge measurements have been repeated 30 min and 10 h after they switched on (see Fig.5). Fixing their tension to the HV working voltage, the fit on charge distribution should give a charge value around 300 mV·ns; the obtained charge values are

Table 1: Relative gain and HV working point calibration results for each PMT for LUCID II

PMT	α	HV (V)	PMT	α	HV (V)
EA3362	7.94 ± 0.08	672^{+2}_{-1}	EA3395	8.38 ± 0.08	645^{+1}_{-1}
EA3363	8.11 ± 0.08	641^{+2}_{-1}	EA3396	7.98 ± 0.08	654^{+3}_{-2}
EA3365	8.10 ± 0.08	629^{+2}_{-1}	EA3397	8.34 ± 0.08	652^{+1}_{-2}
EA3366	8.01 ± 0.08	637^{+2}_{-1}	EA3398	8.14 ± 0.08	637^{+1}_{-1}
EA3367	8.31 ± 0.08	645^{+2}_{-1}	EA3399	8.30 ± 0.08	638^{+2}_{-1}
EA3368	8.34 ± 0.08	644^{+1}_{-1}	EA3400	8.13 ± 0.08	645^{+2}_{-2}
EA3373	8.20 ± 0.08	641^{+1}_{-1}	EA3401	8.15 ± 0.08	667^{+3}_{-2}
EA3375	8.18 ± 0.08	614^{+1}_{-1}	EA3402	8.21 ± 0.08	675^{+4}_{-2}
EA3376	8.31 ± 0.08	663^{+1}_{-1}	EA3403	8.40 ± 0.08	637^{+}_{-1}
EA3378	7.76 ± 0.08	648^{+3}_{-2}	EA3404	8.28 ± 0.08	634^{+2}_{-2}
EA3379	8.19 ± 0.08	649^{+2}_{-2}	EA3405	8.13 ± 0.08	642^{+2}_{-2}
EA3383	8.22 ± 0.08	634^{+1}_{-1}	EA3406	8.22 ± 0.08	645^{+1}_{-2}
EA3384	8.26 ± 0.08	654^{+1}_{-1}	EA3407	7.83 ± 0.08	636^{+3}_{-2}
EA3385	8.14 ± 0.08	646^{+3}_{-2}	EA3408	8.27 ± 0.08	638^{+1}_{-2}
EA3386	8.37 ± 0.08	643^{+2}_{-2}	EA3419	8.19 ± 0.08	620^{+2}_{-1}
EA3387	8.17 ± 0.08	594^{+2}_{-1}	EA3410	8.21 ± 0.08	617^{+1}_{-1}
EA3388	8.37 ± 0.08	610^{+1}_{-1}	EA3411	8.13 ± 0.08	642^{+2}_{-2}
EA3390	8.14 ± 0.08	614^{+1}_{-1}	EA3412	8.25 ± 0.08	654^{+1}_{-1}
EA3391	8.26 ± 0.08	651^{+3}_{-2}	EA3414	8.10 ± 0.08	621^{+1}_{-1}
EA3392	8.08 ± 0.08	633^{+1}_{-1}	EA3415	8.33 ± 0.08	623^{+2}_{-1}
EA3393	8.17 ± 0.08	653^{+2}_{-2}	EA3416	8.34 ± 0.08	612^{+1}_{-2}
EA3394	8.08 ± 0.08	668^{+1}_{-1}	EA3420	8.17 ± 0.08	713^{+1}_{-1}

$$\begin{aligned} EA3375 \quad Q_{30\,min} &= 287.9 \pm 1.0 \quad mV \cdot ns \\ Q_{10\,h} &= 287.9 \pm 1.1 \quad mV \cdot ns \\ EA3388 \quad Q_{30\,min} &= 312.7 \pm 1.2 \quad mV \cdot ns \\ Q_{10\,h} &= 310.3 \pm 1.3 \quad mV \cdot ns \end{aligned}$$

in agreement with expectations.

Fitting the PMT charge peak at the working voltage, a charge measurement with a maximum spread of 15 mV·ns from the expected value has been obtained. Therefore 15 mV·ns for 300 mV·ns charge imply a gain accuracy of 5%.

In order to study the dependence of the measurement from the coupling with the source, HV scans have been repeated for EA3401, EA3402, EA3405, EA3406 and EA3414 PMTs: as shown in Tab.2, the final systematic uncertainties on the working voltage is about 5

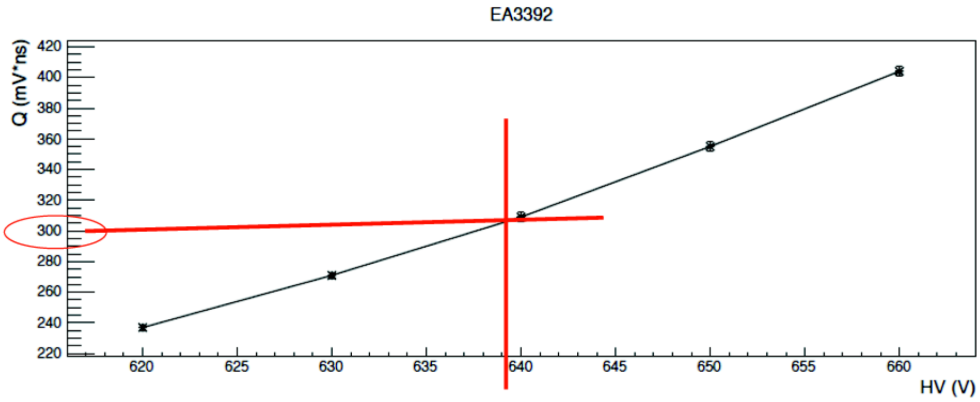


Figure 4: Linear interpolation technique for the EA3392 PMT.

V, which corresponds to a 5% level of systematic error on PMT gain, in agreement with the previous check.

Table 2: Comparison between HV working point evaluated in two different scan for some PMTs.

PMT	HV I scan (V)	HV II scan (V)
EA3401	663	667
EA3402	670	675
EA3405	643	642
EA3406	649	645
EA3414	613	621

4.2 Modified PMTs

The equalisation of the modified PMTs with the ^{207}Bi source has not been possible. In fact because of their smaller window, the number of electrons passing through the quartz is not enough to produce an easily recognisable anodic current and thus a visible peak in the amplitude and charge distributions, as illustrated in Fig.6.

Due to the impossibility to find their HV working point, a different study on the determination of the relative gain through the anodic current was performed. The current in fact is linearly proportional to the gain and thus to the voltage ($I \propto G \propto V^{\alpha}$): this means that from a linear fit of the I measurements as a function of HV, the relative gain can be inferred, as shown in Fig.7. The voltage scan has been performed in a range

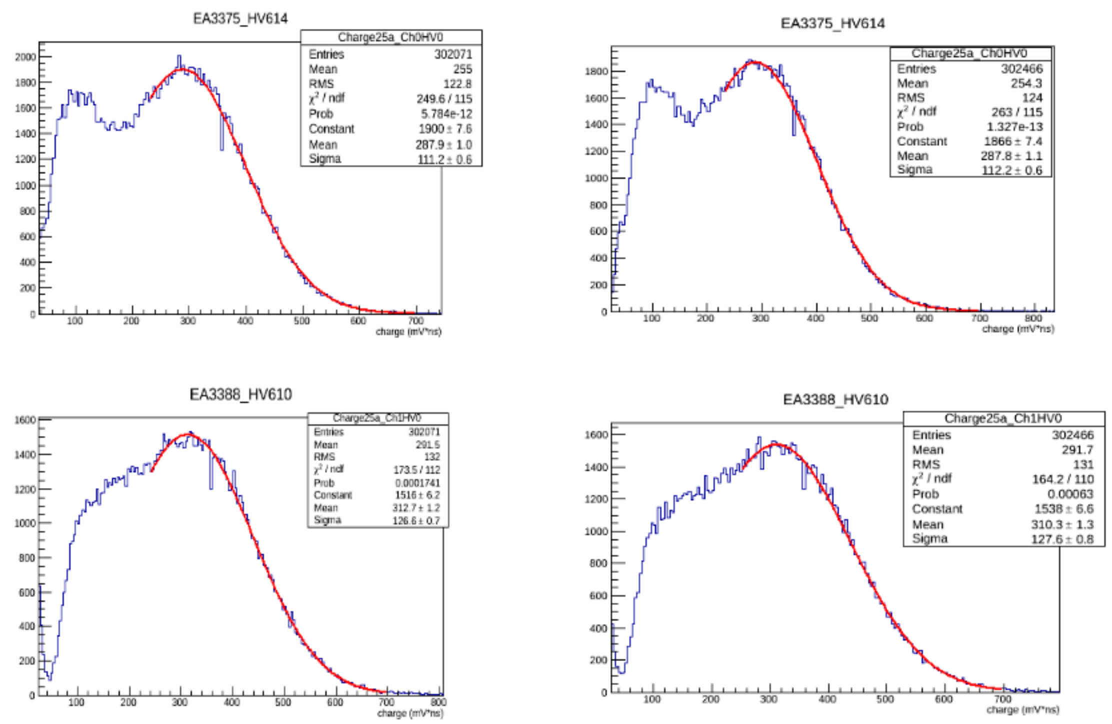


Figure 5: Charge distribution repeated 30 min (*left*) and 10 h (*right*) after the switching on of the EA3375 (*top*) and EA3388 (*bottom*) PMTs.

between 500 V and 800 V in steps of 50 V, both increasing and decreasing the tension. In Tab.3 the relative gain for each modified PMT is compared with the same measurement taken in Bologna, with a different setup (studies ongoing).

Table 3:

PMT	α	α_{Bo}	PMT	α	α_{Bo}
XN1839	8.58 ± 0.08	/	XN1849	8.30 ± 0.08	/
XN1843	8.30 ± 0.08	8.53 ± 0.08	XN1851	8.33 ± 0.08	8.49 ± 0.08
XN1844	8.53 ± 0.08	/	XN1852	8.12 ± 0.08	8.26 ± 0.08
XN1846	8.50 ± 0.08	/	XN1853	8.37 ± 0.08	8.75 ± 0.08
XN1848	8.36 ± 0.08	7.78 ± 0.08	XN1854	8.30 ± 0.08	/

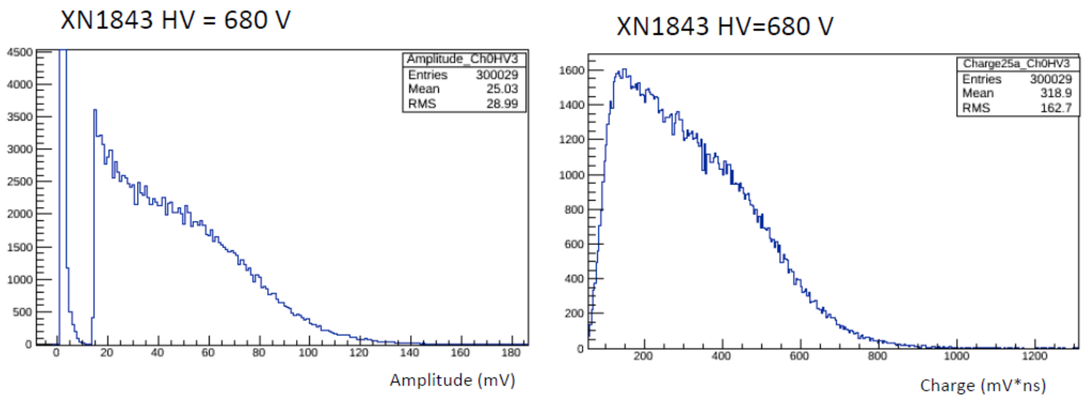


Figure 6: Amplitude (*left*) and charge (*right*) distributions of XN1843 modified PMT.

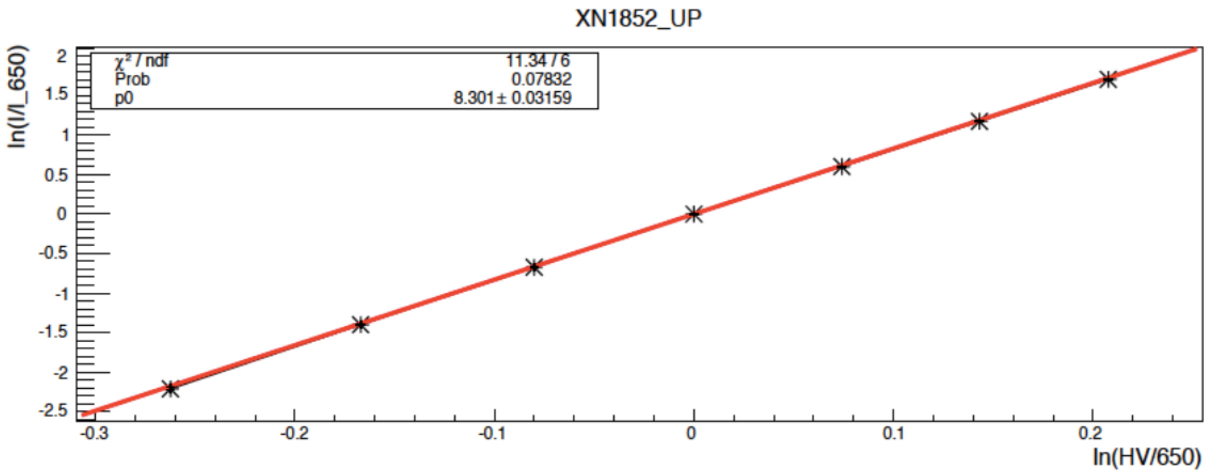


Figure 7: Linear fit of anodic current distribution as a function of the increasing HV for XN1852 modified PMT.

5 Conclusions

With a view to the LHC Run II, some LUCID characteristics have been improved in order to be efficient for the new experimental conditions. In particular the new Hamamatsu R760 PMTs will be installed on LUCID II coupled with a new electronic system. 44 PMTs have been equalised to charged tracks: the HV working point has been fixed in order to well separate signal from noise and to equalise the PMT gain at a value smaller than 10^5 to reduce their ageing. The calibration measurements have been obtained using a ^{207}Bi source. Studies of the reproducibility and the stability in time have been performed reaching a final systematic uncertainty of 5 V on HV measurements which corresponds to a 5% accuracy on PMT gain. In conclusion, the relative gain of 10 modified PMTs have been evaluated through anodic current measurements with a HV scan and compared with Bologna previous measurements.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 S08003, 2008.

[2] ATLAS Collaboration, *Updated Luminosity Determination in pp collision at* $\sqrt{7}$ *TeV using the ATLAS Detector*, ATLAS-CONF-2011-011.