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Performance of Planacon MCP-PMT photosensors under extreme working conditions

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ABSTRACT

The performance of the 25 μm-pore Planacon MCP-PMT is discussed here and the device is evaluated for the use as the main photosensor of the Cherenkov arrays of the Fast Interaction Trigger (FIT) detector for the upgrade of the ALICE apparatus at the CERN LHC. During the LHC Run 3 and 4 FIT has to operate in strong magnetic fields and in large particle fluxes without significant ageing effects. The expected dynamic range for central modules of Cherenkov arrays of FIT is from 1 to ~1000 MIPs. The required single-MIP time resolution is below 50 ps and the expected average repetition rate is 50 kHz. To fulfil these requests, the Planacon XP85012/A1-Q MCP-PMT has been customized into the XP85002/FIT-Q version. With the modified Planacon we were able to achieve a time resolution as low as 13 ps and ensure good timing of the device under the required dynamic range. A description of the implemented MCP-PMT modifications is presented here together with the outcome of the in-beam test of the assembled Cherenkov module and dedicated ageing- and magnetic field tests.

1. Introduction

The new Fast Interaction Trigger detector has been designed to serve as the main luminometer, collision time, multiplicity, centrality, and reaction plane detector for the upgraded ALICE during Run 3 and 4 of the LHC at CERN [1,2]. FIT will consist of a large segmented scintillator ring and 52 Cherenkov modules combined into two arrays (see Fig. 1) [3]. Each module is made of 4 quartz radiators optically coupled to a photosensor. Traditional vacuum or solid-state photosensors were not able to fulfil the stringent requirements imposed by the limited space (detector width <92 mm), 0.5 T magnetic field, hadron fluence in excess of $3 * 10^{11}$ 1-MeV-n_{eq}/cm^2 and the expected performance during more than 6 years of service [4].

The sensor chosen for FIT is a 25 μm-pore multianode Planacon XP85012/A1-Q microchannel plate-based PMT. Compared to its external size (59 × 59 × 28 mm^3), it has a very large sensitive area, corresponding to 80% of the front surface, making it an ideal sensor for a compact array assembly.

2. PMT modification

To increase the granularity of the FIT detector arrays, anodes of each Planacon photosensor are subdivided into four groups. Accordingly, there are 4 separate quartz radiators coupled to the matching sections of the photocathode. In that configuration each module provides 4 independent detector channels. We refer to them as quadrants.

Standard Planacon sensors have an auxiliary readout channel extracted from the output plane of the MCP stack. This common output has a positive polarity — the circuitry of the device is presented in Fig. 2a. The large capacitance between the MCP output and the anode plane generates cross-talk signals at all quadrant outputs. In case of a simultaneous detection of a given signal by all quadrants, the induced positive cross-talk pulse constitutes up to 45% of the original signal amplitude [5]. Such positive spikes distort the shape of the rising edge, deteriorating significantly the time resolution of the detector (see Fig. 3a).

To solve this cross-talk related problem, we have designed a new circuit for the internal PCBs eliminating the common output and the associated load resistance. In addition, the trace length and the ground plane location at the most inner PCB were optimized. The modifications halved the anode capacitance thus decreasing the negative cross-talk between the adjacent anodes (due to the capacitive coupling) and increasing the amplitude-to-charge ratio of the useful signals.

To obtain the best timing and to reduce the length of the device, signals from individual anodes are combined into quadrants on the same board (#2) where the equalization of traces was realized. The modified Planacon type was labelled by the manufacturer as XP85002/FIT-Q — its circuitry is shown in Fig. 2b. The 75 Ω in-line resistors on each anode output serve to reduce the Q-factor of the resonant circuits formed by the anode capacitance and by the inductance of their leads. All in all, the implemented modifications resulted in the following improvements of the customized MCP-PMT:

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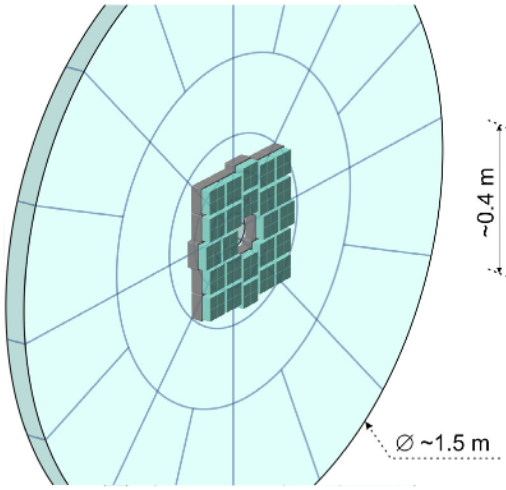

Fig. 1. Schematic layout of the FIT detector to be located at both sides from the interaction point.

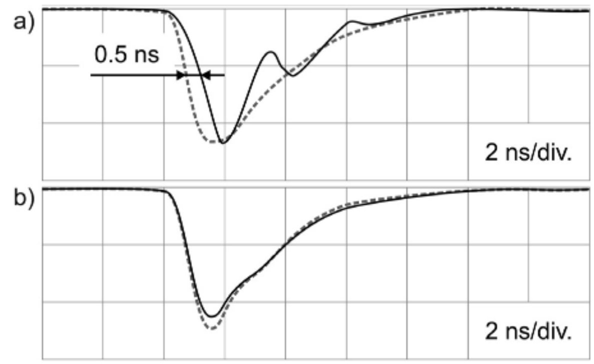

Fig. 3. Difference in pulse waveforms from a single quadrant: (a) default Planacon; (b) modified Planacon. Dashed curve – only one quadrant was hit. Solid black curve – all quadrants were hit. Signal amplitude is ~120 mV.

- The rising edge is no longer affected by the signals in the adjacent quadrants (see Fig. 3b);
- The average amplitude of the negative cross-talk signals in the adjacent quadrants is now reduced to ~5% of the original signal amplitude, and ~1% only in the diagonal quadrant (see Fig. 4);
- The overall thickness of the MCP-PMT is reduced from 28 mm to 23 mm;
- The reached intrinsic time resolution is better than 13 ps for each quadrant (see Fig. 5).

The time resolution was measured with relativistic pions at the CERN Proton Synchrotron. The setup included two identical FIT modules based on the customized Planacon sensors coupled to 2 cm-thick fused silica radiators. In these measurements, the signals from the tested Cherenkov modules were read out by a CAEN DT5742 pulse digitizer and then processed offline with the dedicated software based on an algorithm, similar to the operational principle of a constant fraction discriminator (CFD). The addition of ~40 m of coaxial cables and the actual front-end electronics based on an analog CFD [6] increased the single MIP (minimum ionizing particle) time resolution to $\sigma = 33$ ps. This is the time resolution expected for the actual detector with the MCP-PMT operating at the default gain of $\sim 1.5 * 10^4$.

3. Planacon performance in magnetic field

MCP-PMT sensors used by FIT have to produce a linear amplitude output over a large dynamic range. At the same time, we use 2 cm-thick fused silica radiators causing the emission of about 300 photoelectrons from the photocathode to ensure excellent timing. That is why, we are compelled to operate the sensors at a relatively low gain corresponding to ~10 mV/MIP. Although the behaviour of similar MCP-PMTs in a strong magnetic field has been reported before [7,8], there were no data on the operation of a 25 μm-pore MCP-PMTs at the low bias voltages required by FIT (1000–2000 V) in the magnetic field. To check the

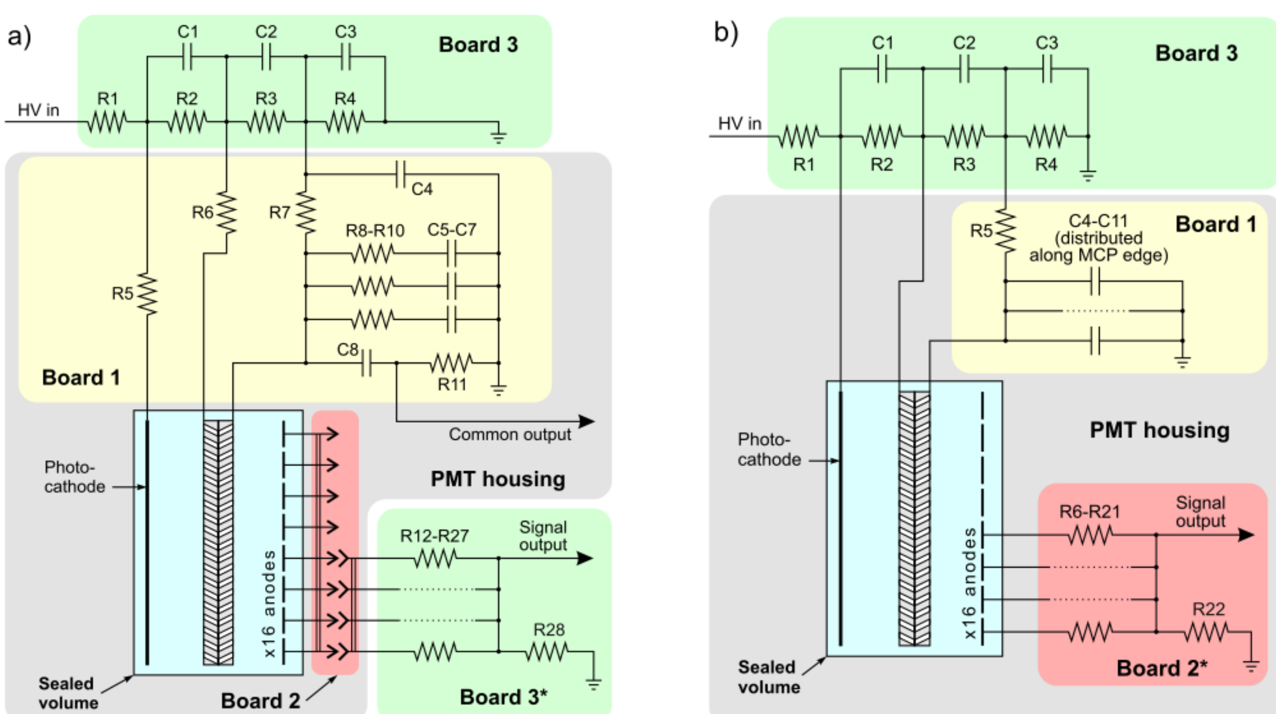

Fig. 2. Circuitry of the MCP-PMT: (a) off-the-shelf Planacon XP85012/A1-Q; (b) Planacon XP85002/FIT-Q customized for the use in the FIT detector. *only 16 out of 64 channels shown.

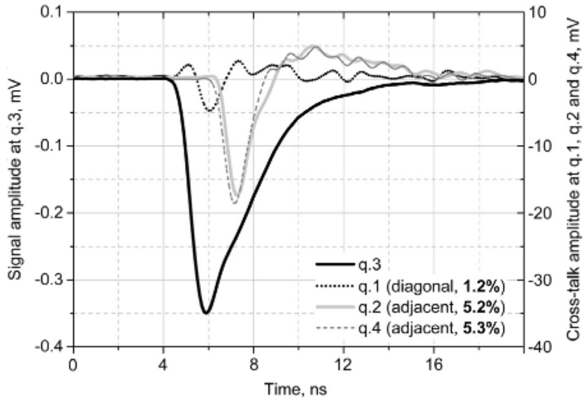

Fig. 4. Sample waveforms of a real signal at quadrant 3 and cross-talk signals at q.1, q.2 and q.4.

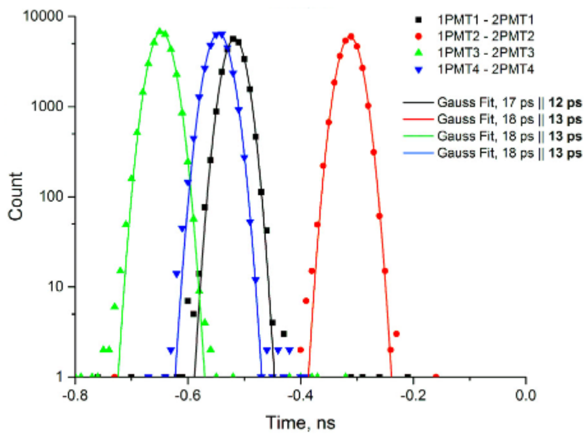

Fig. 5. Time-of-flight (TOF) spectra registered by two FIT Cherenkov modules placed one after another along the path of the PS beam. For each pair of quadrants both the TOF resolution and the intrinsic time resolution (bold numbers) are indicated.

lowest bias voltage suitable for operation in strong magnetic fields, we have performed dedicated tests. The results are presented in Fig. 6. The field strength of 0.2 T and 0.5 T was chosen to match the settings of the magnetic field used in the ALICE experiment.

As evident from Fig. 6, the Planacon gain drops by an order of magnitude at B = 0.5 T with the bias voltage below 1100 V, corresponding to ~870 V across the MCP stack. Because of that, the minimum acceptable bias voltage for FIT MCP-PMTs (for the 10^5 gain) is 1250 V.

One of the two FIT Cherenkov arrays will be located 80 cm away from the interaction point. To prevent the time and amplitude spread caused by the difference in the flight pass and the incident angle, this array will be concave (see Fig. 1). Since the magnetic field in ALICE is aligned with the beam line, the external modules of the concave array will have to operate in a tilted position. During the magnetic field study, we have observed a strong and asymmetric dependence of the Planacon gain with respect to the inclination plane. As shown in Fig. 7, at B = 0.5 T even a small inclination in the X-plane leads to a significant gain change, while the device rotation in Y-plane changes the gain less than twofold. In Planacon, the inclination angle of the microchannels is 16° [9]. The observed effect arises from mutual direction of the B-field and the microchannels of the first MCP in the chevron stack, which gives the main contribution to the gain of the device. This phenomenon, albeit for another type of MCP-MPT, is also described in [8].

4. Planacon ageing

MCP-PMTs are known to have significantly lower lifetime as compared to conventional PMTs [10,11]. Their ageing is mainly associated

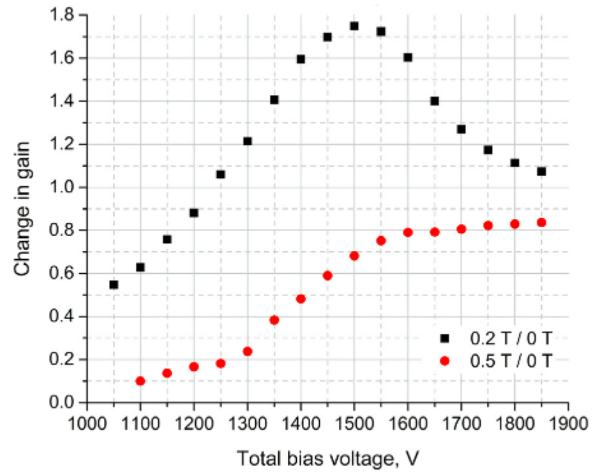

Fig. 6. The relative gain of the Planacon sensors as a function of the bias voltage. The measurements were done at B = 0.0, 0.2 and 0.5 T.

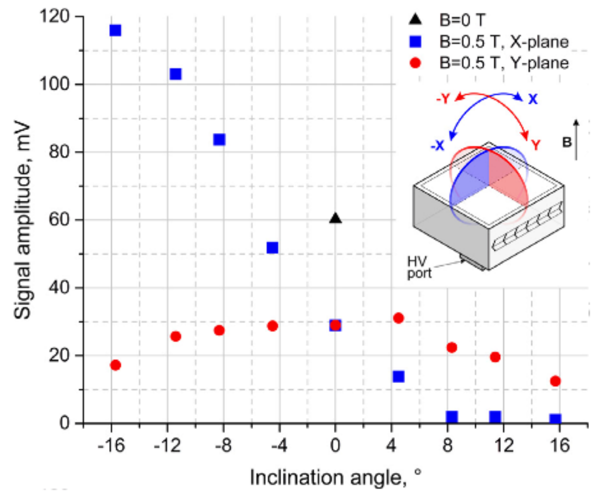

Fig. 7. Planacon gain as a function of the inclination angle at B = 0.0 (black triangle) and at B = 0.5 T with U = 1400 V. The X plane overlaps with the orientation of the chevron angle formed by MCP channels.

with Q.E. deterioration and/or MCP gain decrease at a given bias voltage after certain integral charge is collected at the anode. In 2011, 25 μm-pore Planacon MCP-PMTs were reported to sustain ~0.1 C/cm^2 IAC (Integrated Anode Charge) before a twofold decrease in the Q.E. [12]. Over the past years, the lifetime of such devices has already reached ~2 C/cm^2 thanks to the new MCP electron scrubbing procedures and improved vacuum [13]. The introduction of ALD-coated devices has increased the IAC limit even further to over 10 C/cm^2 IAC [14]. Unfortunately, ALD Planacon sensors do not yet fulfil the FIT requirements for the average anode current linearity and therefore cannot be used by us [15].

According to our simulations, during the 6 years of operation in the upgraded ALICE apparatus, the FIT MCP-PMTs will accumulate up to 0.6 C/cm^2 IAC. Consequently, we have conducted our own ageing studies of the Planacon XP85012/A1-Q using a dedicated setup. The measurements were made with two quadrants (#1 and #2) illuminated in sub-saturated mode, and two other quadrants (#3 and #4) shielded from light. We have established that collecting 0.5 C/cm^2 at quadrant 1 leads to ~27% drop in the pulse amplitude with respect to quadrant 4 (see Fig. 8). The subsequent tests by the manufacturer have shown that the observed drop in the pulse amplitude was caused exclusively by the gain loss and not by the degradation of the photocathode [13]. This is very reassuring as the gain loss can easily be compensated by HV

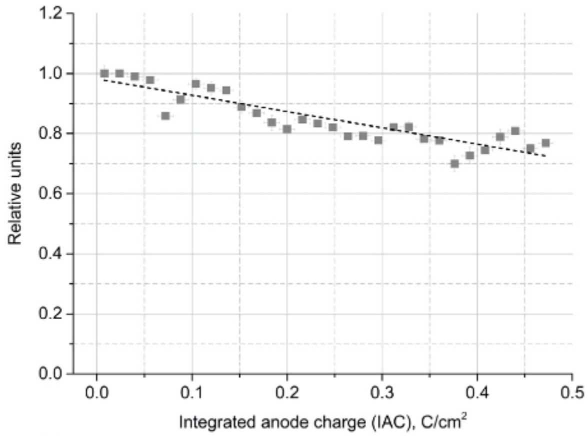

Fig. 8. Variation of the pulse amplitude at quadrant #1 relatively to quadrant #4 versus the value of charge integrated at quadrant #1 during the ageing test.

while the degradation of the photocathode and hence the drop in the number of photoelectrons would also affect the timing- and amplitude resolution.

5. Conclusions

Planacon XP85012/A1-Q is a compact and radiation-hard commercial photosensor. By modifying its readout PCBs we were able to improve the time resolution over a wide amplitude dynamic range from ~150 to $3 * 10^5$ photoelectrons (1:2000).

Our dedicated B-field study confirmed the possibility of using the cost-effective 25 μm pore size Planacon sensors in the magnetic fields up to 0.5 T even with bias voltages as low as 1250 V with ~80% gain loss. However, tilting the device in a strong magnetic field was found to have a significant and angle-dependent effect on the gain, so the optimal MCP-PMT location relatively to the B-field direction should be chosen in advance.

We have verified that the Q.E. of modern non-ALD-coated Planacon sensors remains constant for IAC up to 0.5 C/cm^2. The observed variation of the gain is easily correctable by a small (~30 V) increase in HV. The modified Planacon – XP85002/FIT-Q – is well suited for the use as the main photosensor of the Cherenkov modules for the FIT detector. The intrinsic single-MIP time resolution of the module is below 13 ps/channel and the time resolution of the entire chain, with the module connected via a 40 m long coaxial cable to the analog readout electronics, is better than 33 ps.

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