Picosecond timing detectors and applications

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Abstract – Detector examples discussed: MRPCs, MCP-PMTs, Diamond detectors, SiPMTs, Low and high gain Avalanche diodes (LGADs) and Micromegas. We specifically discuss issues such as single pixel vs. multi-pixel tests, small test vs. large physics system results and hidden problems people usually do not want to talk about.

INTRODUCTION

This paper[1] is a follow up to a recent review paper [1]. This paper will update this review with new developments.

There is a general push for higher luminosity not only at LHC but also at Belle-II, Panda, Electron-ion collider, etc. Timing is more and more important. For example, ATLAS needs to connect charged tracks to the correct production vertices, using position resolution and timing resolution of ~30 ps/MIP [2]. Similarly, new DIRC applications aim for single photon timing resolution at a level of ~70-120 ps/photon. The new luminosity upgrades by a factor of 100-1000 compared to previous generation experiments will create a new demand on detectors. This means significant improvements are necessary in detector aging, electronics advances, and rate capability of detectors.
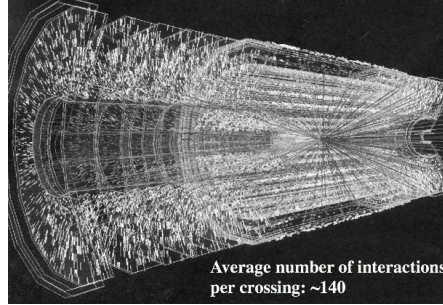

Fig.1 ATLAS event after an LHC upgrade to a luminosity of ~10^{35} cm^{-2} sec^{-1} (ATLAS collaboration).

1. Fast timing at a level of 20-30 ps per minimum ionizing particle (MIP)

A TOF technique seems simple, but there are many hidden effects which have to be overcome. There has been considerable progress with small single-pixel devices, however progress in very large systems has been slow. In the following I will discuss possible reasons.

One usually starts with a simple, somewhat naive formula in order to judge the timing resolution limit (σ_{time}):[2]

$$\sigma_{time} = \sigma_{noise}/(dS/dt)_{threshold} \sim t_{risetime}/(S/N), \tag{1}$$

where S is the signal amplitude, N = σ_{noise} is a noise. One can say: "Show me your pulses and noise level, and I will estimate your resolution." For a typical MCP-PMT risetime of $t_{risetime} \sim 200$ ps, one needs S/N ~10 to get into the ~20 ps regime. For a slower Si-detector risetime of $t_{risetime} \sim 2$ ns, one needs S/N ~100 to get into the same timing regime. However, there are many other contributions. First, we mention a few standard contributions due to electronics, chromatic effects, number of photoelectrons (N_{pe}), transit time spread (TTS), tracking, and t_0 time, which is experiment's start time (we neglect tracking effects as they depend on exact geometry):

$$(\sigma_{Total})^2 \sim [(\sigma_{Electronics})^2 + (\sigma_{Chromatic}/\sqrt{(N_{pe})})^2 + (\sigma_{TTS}/\sqrt{N_{pe}})^2 + (\sigma_{Track})^2 + (\sigma_{to})^2 +\dots] \tag{2}$$

The t_0 time can easily dominate. There are many other obscure effects, which can affect timing resolution. For example: time walk, cross-talk effects in multi-pixel detectors, baseline ringing in multi-pixel detectors affecting later arriving pulses, charge sharing in multi-pixel detectors, chromatic effects, clock distribution throughout the system, pulse tail recovery, calibration, etc. The electronics resolution can reach ~2 ps in the good examples [1], while the best overall is the DRS4 electronics reaching <1 ps for short delay between start & stop [3].

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[1] Invited talk at Micro-Pattern Gaseous Detector conference at La Rochelle, France, May 7, 2019
[2] Well known formula in the communication engineering.

1.1. MRPC

  Fig. 1.1.1a shows ALICE present MRPC TOF detector, which is now running about 15 years. It is delivering ~60 ps resolution and a maximum rate of ~500 Hz/cm^2 presently [4]. The most important design feature of this detector is a differential design, both on inputs and outputs, to minimize pick-up and cross-talk effects [4]. The detector uses the NINO ASIC with amplifier + discriminator + time-over-threshold (TOT) pulse height correction to time walk [5]. The NINO chip was a very significant instrumentation development in retrospect. Figure 1.1.1b shows a response of the NINO input stage to various input charges. It shows ~ 1ns peaking time independent of input charge. As a result of a well behaving design, the TOT correlation between time and width is very linear, as Fig.1.1.1c shows; in addition, it has a very low power consumption (40 mW/channel). I was not able to obtain raw MRPC detector pulses going into NINO chip from the ALICE MRPC.

  The present plan for ALICE is to develop a new detector for high luminosity upgrade using a lower resistivity 400 µm-thick glass, allowing to build 20-gap MRPC capable of handling rates up to ~50 kHz/cm^2 with aim for ~20 ps resolution per MIP [4].
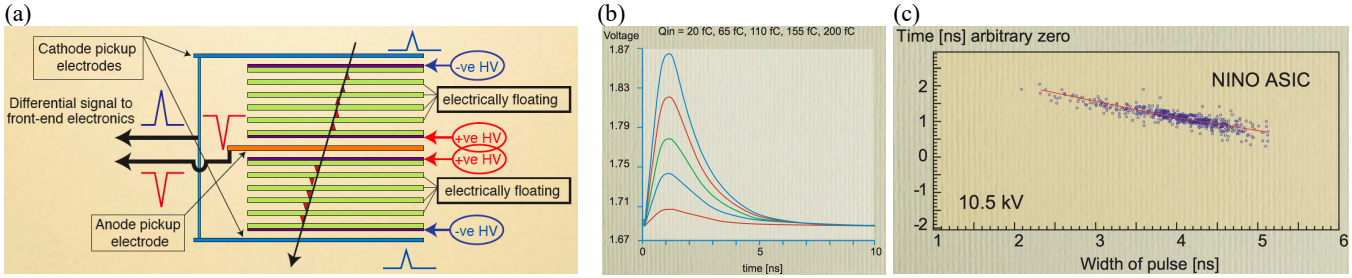

Fig.1.1.1 (a) ALICE 10-gap MRPC TOF detector and its differential signal to front-end electronics [4]. (b) Response of the NINO ASIC input stage to various input charges from a pulser. One can see that pulse response is perfect allowing the time-over-threshold (TOT) pulse height correction [5]. (c) The correlation between time and width is very linear in this design [5].

1.2. MCP-PMT
1.2.1 Single-pixel MCPs

  Microchannel plate detectors can achieve the best timing resolution presently. The Photek company measurements [6] demonstrated that the smaller pore size and higher MCP-to-anode electric field, faster the risetime. Figure 1.2.1.1 demonstrates this capability with an 18 GHz BW scope, indicating a 66 ps risetime for 3.2 µm pores and 95 ps for 6 µm pores using Photek-110 single pixel MCP [6]. This is the best demonstration of MCP timing capability to my knowledge. Using our simple equation 1, and neglecting all other contributions, one could get a single photon timing resolution of σ_{TTS} ~3 ps if we assume signal-to-noise ratio S/N ~20, or better if S/N is higher.

  There was an effort in the past 10 years to reach a limit of timing resolution in beam tests using <u>single pixel</u> MCPs with 6 µm pores. Figure 1.2.1.2 and Table 1 summarizes results. All three tests did not use amplifiers. The CERN RD-51 result by "Picosecond" group is presently the best result of any timing detector in a particle beam [9]. They reached a resolution of ~3.8 ps using a 20 GSa/sec scope employing a CFD algorithm.

Table 1: Best results achieved using single pixel detectors[3]

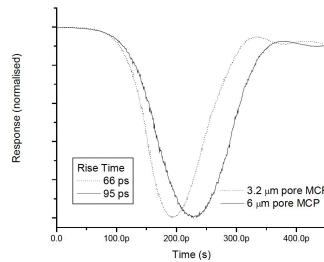| MCP Gain	Npe [electrons]	**Total charge [electrons]**	Electronics resolution	Final resolution per single MCP	MCP type (tandem of two MCPs)	Reference
~2x10^6	~70	**~1.4x10^8**	4.1 ps	6.2 ps	HPK R3809U-59-11	[7]
~10^6	~80	**~8x10^7**	2.0 ps	6.8 ps	Photek 240	[8]
~8x10^4	~44	**~3-4x10^6**	2.2 ps	~3.8 ps	HPK R3809U-50	[9]

Fig. 1.2.1.1 Photek tube single photon pulses [6].

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[3] Ref.7 used 10mm thick fused silica radiator and 3mm thick fused silica window, Ref.8 had 8mm fused silica window, which served as a radiator, and Ref.9 had 3.2mm fused silica window, which also acted as a radiator.
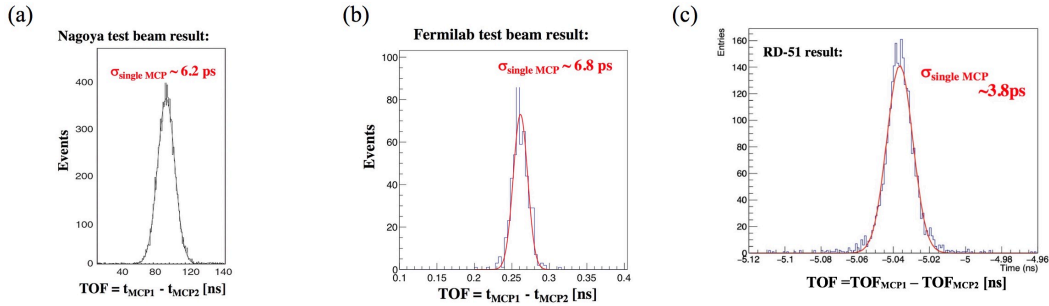
Fig. 1.2.1.2 Comparison of the best timing resolution results with single pixel MCP-PMTs with MIPs in test beams [7,8,9]. No amplifier was used in these tests. See Table 1 for details. (a) and (c) used Hamamatsu R3809U MCPs, and (b) used Photek-240 MCP.

The most significant number in Table 1 is the total anode charge per MIP. The problem with running a large total anode charge is a possibility of large after-pulsing rate (caused by ion-feedback), especially when a tube gets older. Figure1.2.1.3a&b shows author's measurement [10] using two old Burle Planacon MCPs 85013-501. One can see that as long as the total charge stays below a 2-3x10^6, the after-pulsing rate is reasonable even with an old Planacon. However, the ion feedback grows exponentially above the charge of 5x10^6. One can ask a question if the new MCPs, ~10 years later, behave better. Fig.1.2.1.3c shows Lehmann's measurements indicating that the new 64-pixel Hamamatsu R13266 (YH0250), with 10μm pores and ALD coating, starts having problems after a total charge of ~2-3x10^6 (measurements were done with the single electrons) [11]. On the other hand, a new Planacon Photonis XP85112 (90021008), with 10 μm pores and ALD coating, is OK up a total charge of ~3x10^6 [11]. From this point of view, I would question the choice of operating points on Fig.1.2.1.2a&b (also ref. [7] and [8] in Table 1), as their total anode charge was extremely large. Such tubes would not last very. On the other hand, the result in Fig.1.2.1.2c from Ref.[9] seems reasonable to me, as the total charge was only 3-4x10^6.
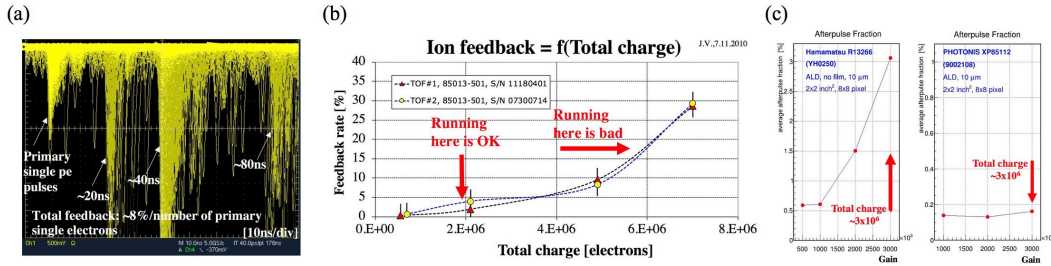

Fig. 1.2.1.3 (a) The after-pulsing rate (or ion feedback) observed in the early versions of Burle Planacon 85013-501 MCP. The primary signals are single electron primary pulses in this case. Peaks on a storage scope correspond to various ion drift times (H^+, H_2^+, He^+, etc.) [10]. (b) The after-pulsing rate gets worse at higher gain. (c) Lehmann's ion feedback measurement in the latest MCPs from Hamamatsu (R13266) and Photonis (XP85112) MCPs [11].

Because of the worry about the excessive after-pulsing rate, I have always argued to run TOF MCP detectors, operating with large Npe, at low gain with a good low noise fast amplifier. As is shown on Fig.1.2.1.4a, one can obtain a timing resolution of ~14ps for Npe ~40 and ~10ps for Npe ~80 with Hamamatsu C5504-44 amplifier. For Npe ~40, the total charge was only ~8x10^5. These results were obtained with several types of electronics (Ortec 9327 CFD, DRS-4 and Wavecatcher) [12,13].
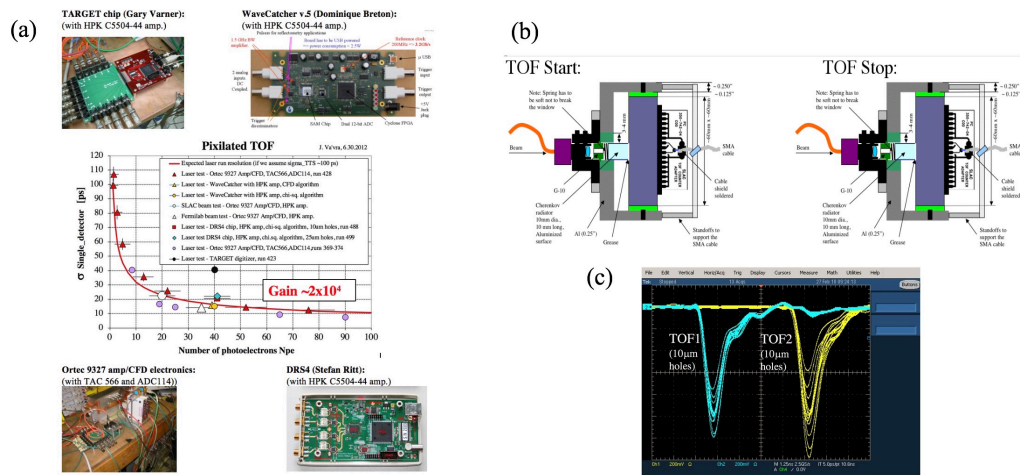

Fig.1.2.1.4 (a) The timing resolution when operating Planacon 85013-501 at low gain of ~2x10^4 as a function of number of photoelectron [12,13]. One can see that one can achieve a timing resolution of ~15ps for Npe ~40 and ~10ps for Npe ~80. (b) The setup used two Planacon 85013-501 MCPs (c) Typical MCP pulses using Hamamatsu C5504-44 1.5 GHz BW amplifier (63x) [12].

Another point we would like to stress that it is not necessary to have a super-fast electronics to obtain a good timing result. One can obtain a good TTS resolution even with a somewhat slower amplifier, if one has a good S/N ratio, and if one tunes the CFD discrimination carefully (every CFD discriminator as an optimum amplitude range, optimum delay and even then, the best results are obtained if one corrects its time determination with an additional pulse height correction). Figure 1.2.1.5 shows timing results with two different amplifiers, the best among five tested. The amplified signal was connected to Phillips 715 CFD and LeCroy 2248 TDC. Planacon 85013-501 MCP had 10μm pores, operated at a gain of ~10^6, and single photoelectron signals were produced by a laser. All pixels of the 64-pixel tube were grounded except the one tested. The quoted resolution was obtained as follows: $\sigma_{TTS} = \sqrt{(32^2 - \sigma_{Laser}^2 - \sigma_{Electronics}^2)}$ ~27 ps. Excellent results proved that the S/N ratio and tuning of CFD operating point are essential to get good timing results [14].
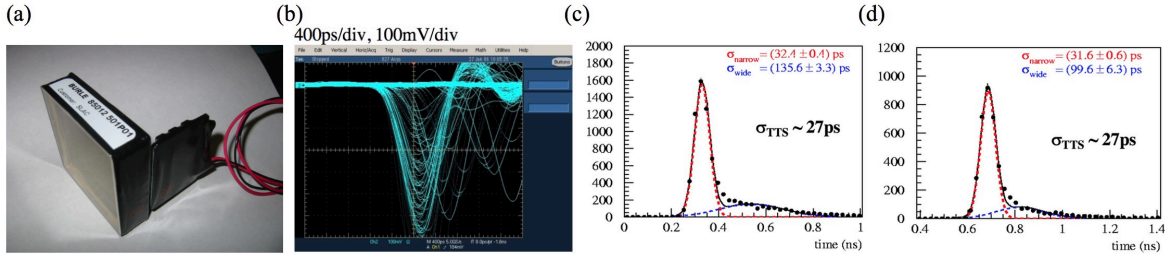

Fig.1.2.1.5 (a) Planacon 85013-501. (b) Single electron pulses with Hamamatsu 63x amplifier C5504-44. Single photon timing resolution with (c) Hamamatsu 1.5 GHz BW amplifier C5594-44 amplifier with 63x gain and (d) Ortec VT120A ~0.4 GHz BW amplifier at 100x gain (200x gain + 6dB). In both cases, Phillips 515 CFD was used [14].

1.2.2 Challenges of multi-pixel MCPs

Planacon 85011-501, made originally by Burle, was the the first multi-pixel MCP available for physics community and it delivered many good results.[4] For example our group used these tubes for Focusing DIRC prototype, which was the first RICH detector to correct the chromatic error contribution to Cherenkov angle by timing (red photons, which propagate in quartz faster than blue photons, could be tagged by timing in long DIRC bars) [42]. To do this, it was required to measure a single photon timing resolution to 100-200ps. Overall these tubes performed well, on detail level there were some issue.

Although multi-pixel MCPs are simple devices in principle, there are many challenges how to connect to them. One has to deal with cross-talk between pixels, charge sharing, ringing effects caused by too many hits at the same time, etc. MCP is inherently a single-ended device referenced to one common ground, which invites a possible pick-up problems. One needs a good RF-shielded box around the device to avoid noise. Early models had also unwanted capacitances, inductances, ground return issues, and low BW connectors, which contributed to cross-talk, pulse shape distortions, ringing, fake hits, etc. However, there is a good news: the latest MCP tubes are doing better.
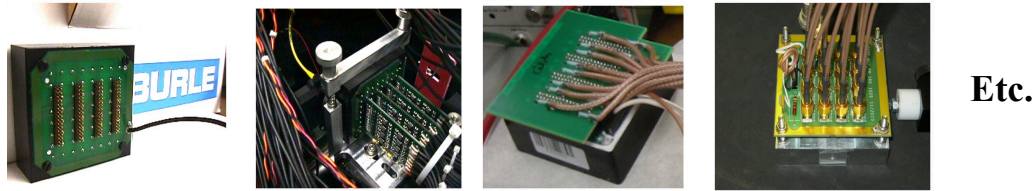

Fig.1.2.2.1 A few examples of connections to Planacon 85011-501 MCP. Although MCP-PMT is a simple device, connections to it are not simple.

Figure 1.2.2.1 shows a few examples how people connected to early Planacon tubes. They all had some pulse quality and cross-talk issues. For example, Fig.1.2.2.2 shows author's measurement of the cross talk of an old Burle Planacon 85011-501 MCP [1,15]. The cross-talk height was typically 3-4% of the primary pulse height and was spread throughout all pixels in a complicated manner. There was a hint that outer pixels are affected most. A possible explanation of the cross-talk, prefering the outer pixels, may have been provided ~12 years later [16]: Fig.1.2.2.3 shows a layout of this tube with its resistor divider placed on a PC board around outside boundary. This board may have influenced the cross-talk.

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[4] Although Planacon was nominally a 64-pixel device, it was also available as a 1024-pixel device already in 2005; this allowed a user to arrange for his preffered final pixel size by interconnecting small pixels together.
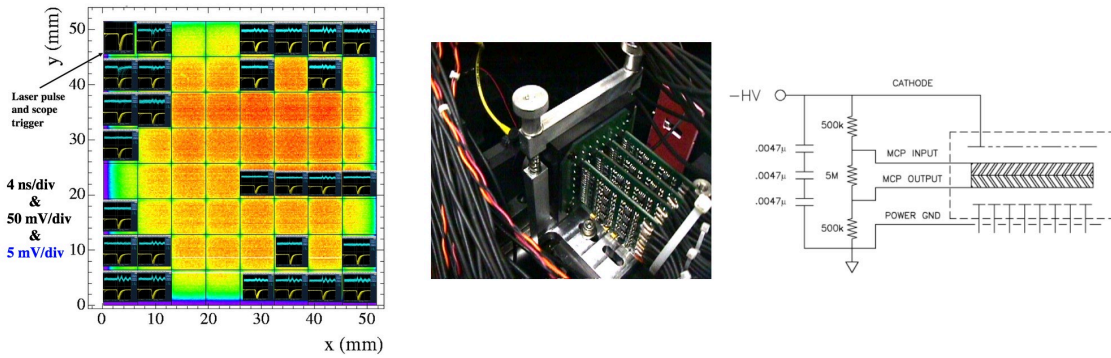
Fig.1.2.2.2 Author's measurement of the cross-talk of the old Burle Planacon 85011-501 with an internal voltage divider [15]. All pixels were connected to amplifiers with 130x voltage gain. The laser pulse is injected into pixel #1 (upper-left corner). The cross-talk was typically 3-4% of the primary signal and was observed even in far-away pixels in a rather complicated manner. This indicates that the noise is present on inductive ground and distributed around. The picture also shows Elantek amplifier boards used in this test and Burle Co. sketch of grounding.
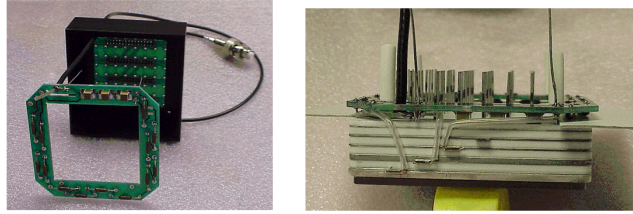

Fig.1.2.2.3 Outer PC-board layout of old Burle Planacon 85011-501 MCP with outside resistor divider board [16]. This board could influence the cross-talk.

As a consequence of this cross-talk, this MCP tube developed "ringing" in a coherent way when exposed to a high multiplicity event when more than 10 pixels/MCP would fire [17]. This is shown on Fig.1.2.2.4a, where one sees that the amplitude of ringing increases with number of photons/event. By the time all pixels fired, the ringing was significant. Such behaviour could create fake hits if the threshold was too low. Fig.1.2.2.4b shows that H-8500 MaPMT behaved better under the same conditions. Single photons were produced by a laser light reflecting from etched aluminum surface, which acted as a diffuser (Fig.1.2.2.4c).
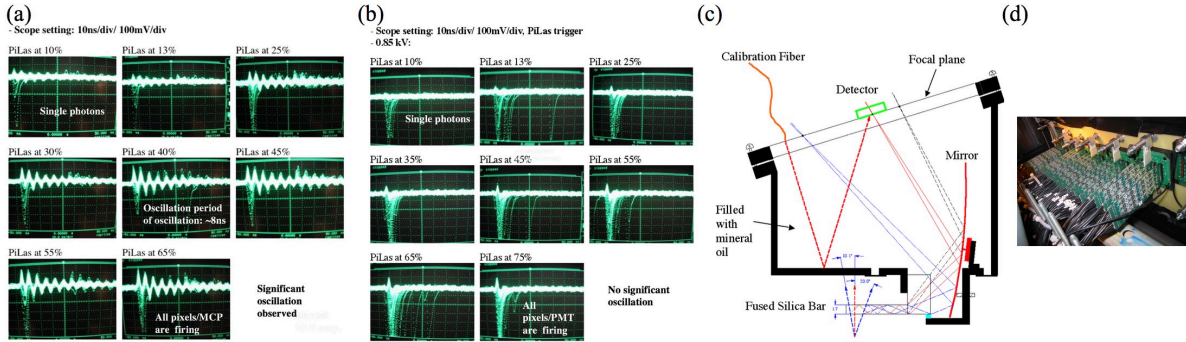

Fig.1.2.2.4 (a) As a result of cross-talk shown in Fig.5, one could create coherent ringing in the entire Burle Planacon 85011-501 MCP [17]. (b) No significant ringing was observed in Hamamatsu H-9500 MaPMT under the same conditions. (c) This effect was observed in the FDIRC prototype where a laser hit an etched aluminum surface, which acted as a diffuser illuminating all pixels at the same time. (d) Electronics for 320 pixels used in this test [42].
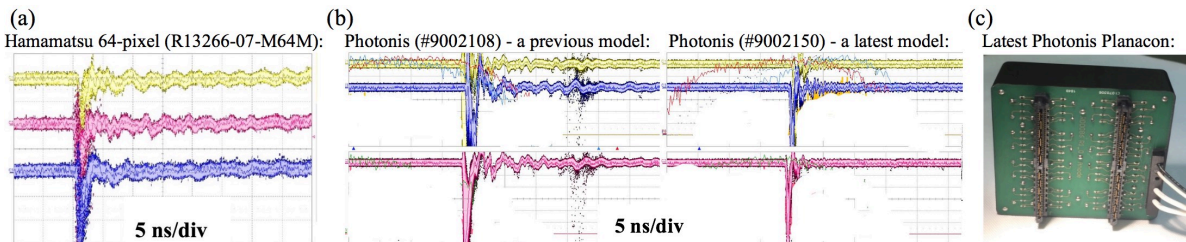

Fig.1.2.2.5 Lehmann's measurement of ringing of (a) Hamamatsu MCP when hit by 32 photons at the same time [11] (b) of Photonis tube is subject of an event when all pixels in MCP have a hit. The most recent Photonis Planacon MCP model #9002150 is clearly better than the previous models [18] There is clearly an improvement. (c) The latest Planacon MCP #9002150 with ground plane, improved HV ground return, new connector, smaller anode-ground capacitance [16].

The question is how the new Photonis and Hamamatsu MCPs behave when exposed to large number of photons/event. This problem is relevant to new experiments, such as Panda DIRCs, TORCH, Belle-II TOP DIRC, which will operate at large rates. Fig.1.2.2.5a shows a significant ringing response of Hamamatsu 64-pixel MCP R13266-07-M64M to ~32 photons/event on average, randomly populating the MCP face [11]. Fig.1.2.2.5b shows the response of older and very latest Photonis 64-pixel MCPs

[18]. Clearly the latest MCP #9002150 behaves much better than the old Planacon. The latest MCP, shown on Fig.1.2.2.5c, has a ground plane, an improved HV ground return, a new connector, and a smaller anode-ground capacitance [16].

One should also mention the effort of FIT group at ALICE [19]. Their aim was to reduce 64-pixel of Planacon XP85012 to only four channels, and use it as a TOF detector with four quartz radiators. As Fig.1.2.2.6 shows, the cross-talk improved significantly after the Planacon was modified by improving HV ground return and adding a capacitance along MCP edges.
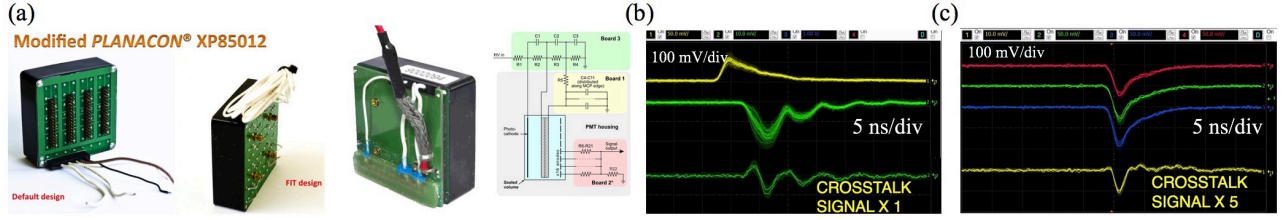

Fig.1.2.2.6 (a) A modification of 64-pixel Planacon XP85012 to reduce the cross-talk included a use of four SMA connectors, improvement of the HV ground return and increase of a distributed capacitance along MCP edges. The cross-talk and pulse ringing (b) before and (c) after the modification [19].

1.2.3 LAPPD Development

Generation-I Incom company MCPs are now commercially available. These MCPs have a large size of 20 cm x 20 cm, 25μm pore size, and strip readout. The Incom company has produced about 45 detectors with a typical single photon timing resolution of 60-70ps [20]. The quoted risetime is ~850 ps, therefore one would expect the single photon timing resolution of σ_{time}~60ps for S/N~15 using eq.(1). Figures 1.2.3.1a&b show the detector with its SMA connectors and typical single photon pulses. For many low-rate experiments, this type of detector is an excellent choice. Generation-II MCPs, with pixel-based readout, will have ceramic body, and capacitive coupling to external PCB board. This concept is still in the R&D stage. Figures 1.2.3.1c&d show a pixel-based detector concept [21] and single photon pulses from pixilated detector obtained either from a direct coupling (red) or from a capacitive coupling.
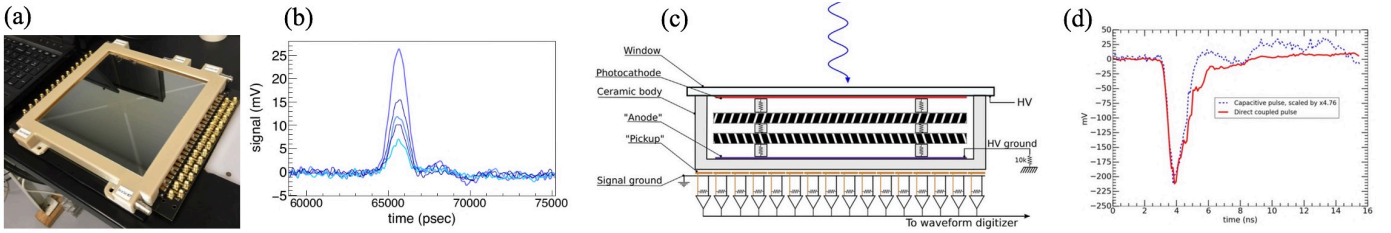

Fig.1.2.3.1 (a) LAPPD detector with strips and SMA connectors (b) Single photon pulses from the strip detector. (c) Concept of pixilated detector [21]. (d) Single photon pulses from pixilated detector obtained either from direct coupling (red) or from capacitive coupling, normalized to the same amplitude..

1.2.4. MCP Applications

We will mention three examples from Belle-II, Panda and TORCH.

1.2.4.1 Belle-II DIRC (TOP counter)

Belle-II is now taking data, and so they will develop real running experience with 16-pixel R10754-016-M16(N) MCPs. Figure 1.2.4.1.1a shows their electronics readout. The readout is based on the IRSX 2.7 GSa/sec waveform digitizer on each pixel. Each pixel is coupled to an amplifier with gain of ~120x with shaping time slowed down to provide 2 samples on the leading edge (Fig.1.2.4.1.1b). The pulse risetime is ~1 ns, and therefore one would expect TTS resolution of σ_{time} ~100ps for S/N~10. The bench tests measured TTS resolution of ~83ps (Fig.1.2.4.1.1c). Because of the background at Belle-II, the MCP gain was lowered to ~3×10^5. As a result of this and other effects, the TTS resolution in TOP counter in Belle-II is presently 80-120ps, and the background rate is kept strictly below ~4 MHz/MCP. Some early non-ALD coated MCPs may be replaced in 2020 [23].
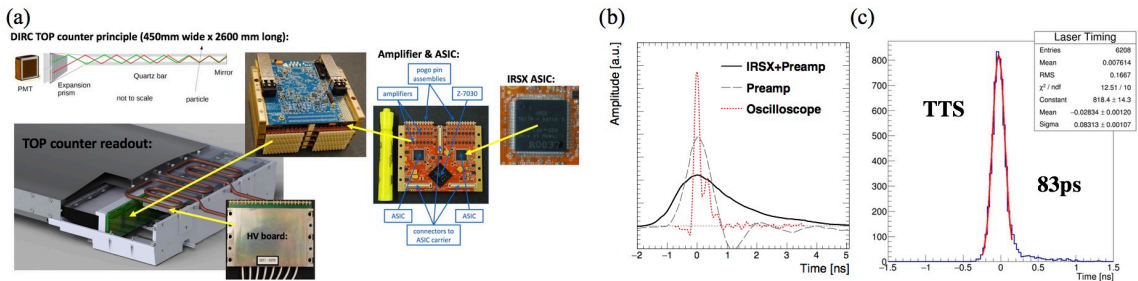

Fig.1.2.4.1.1 (a) Waveform digitizing electronics of TOP counter. (b) The MCP BW had to be slowed down to allow at least 2 samples on leading edge. (c) Single photon (TTS) resolution of ~83ps measured in the lab with the final electronics [22].

1.2.4.2 TORCH DIRC at LHCb

TORCH is a TOF detector concept using Cherenkov light to provide charged particle identification up to ~10 GeV/c, which requires a timing resolution of ~15ps/track. The TORCH fused silica radiator is covering a large area, with focusing optics and MCP readout located at two edges. Photons propagate in these plates up to path lengths of 5-8 meters. The detector design concept is taking advantage of the fact that there is a very long time of flight path between the vertex and TORCH detector in LHCb [24,25]. In theory, if all MCP time offsets are aligned, t_0 start time negligable, geometry of the detector is understood, the chromatic broadening corrected out by pixels, and number of photons Npe ~25 detected, the TORCH detector could achieve σ_{TOF} ~$\sigma_{TTS}/\sqrt{(Npe)}$ ~ 70/$\sqrt{25}$ ~14 ps in principle. In my view, this will not be easy in practice.

Each Photek MCP has 8 columns, each with 128 strips with pitch of 0.414 mm [26]. Initial prototype tests indicate a single photon timing resolution of 80-100 ps/photon at a gain of ~10^6 (see Fig.1.2.4.2.1c). The prototype used the NINO charge amplifier/discriminator ASIC with time-over-threshold (TOT) pulse height correction, coupled to HPTDC. Conditions at LHCb will be severe, with predicted rates up to 10-40 MHz/cm^2, and total anode charge doses up to ~5C/cm^2. So far, aging tests with Phase-I Photek MCP indicate a "good MCP QE behavior" up to ~3C/cm^2. I was not able to obtain raw pulses from the prototype.
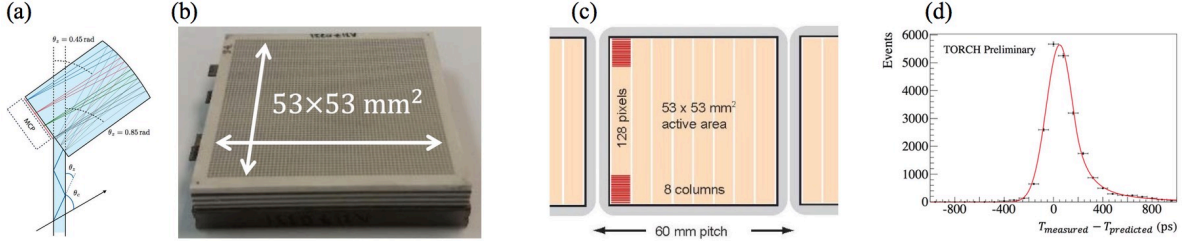

Fig.1.2.4.2.1 (a) Optics used at the end of fused silica plates. (b) MCP used in TORCH tests made by Photek, Ltd [26]. (c) MCP has 8 columns each with 128 strips with pitch of 0.414 mm. (d) The best single photon timing resolution achieved was 88.8 ± 1.3 ps (narrow portion of shape) for the shortest photon path length in their TORCH prototype, so there is an additional contribution to the TTS resolution [27]. The prototype used NINO ASIC [5].

1.2.4.3 Endcap Panda DIRC

Panda Endcap DIRC [28] has many similar features to TORCH. However, since it does not have an advantage of long particle path lenghts like TORCH, it will rely on pixel-based analysis of the Cerenkov angle with some help of timing. Figure 1.2.4.3.1 shows a focusing optics located along edges of large fused silica plates with MCP and electronics. The experiment plans to use Photonis XP85132-S-MD3 MCP with 3 rows x 100 strip configuration, 0.4 mm x 17 mm anode pads, and MCP-anode gap equal to 0.625 mm [28]. Figure 1.2.4.3.1c shows a very good position resolution when MCP was placed in a small magnetic field of 0.1T [29]. The electronics is based on TOPFET ASIC, which was developed initially for the Time-of-Flight Positron-Electron Tomography, where a TTS resolution of ~100ps was achieved with SiPMTs (Hamamatsu S13361) – see Fig. 1.2.4.3.1d. The main advantage of TOFET ASIC is that it has low cost, low mass, small power consumption and it is radiation hard. I was not able to obtain raw pulses.
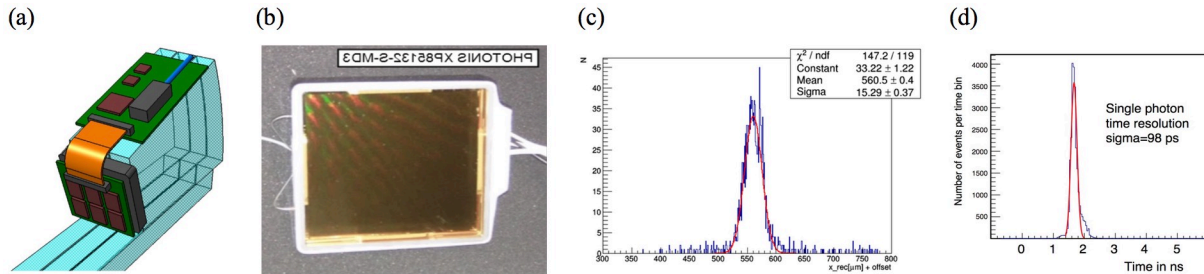

Fig.1.2.4.3.1 (a) Optics used at the end of fused silica plates with MCP and electronics layout. (b) The experiment plans to use Photonis XP85132-S-MD3 MCP with 3 rows x 100 strip configuration, 0.4 mm x 17 mm anode pads, and MCP-anode gap = 0.625 mm. The tube's anode strips are grounded by electronics, i.e., tube does not have a ground plane [16]. (c) A very good position resolution was achieved when MCP was placed in small magnetic field of 0.1T [29]. (d) TOPFET electronics has achieved previously a single photon resolution of ~100 ps with SiPMTs.

1.3 Silicon, Diamond and Gaseous detectors

Many examples were discussed in Ref.[1]. Here we provide only two important latest developments, one is the gaseous Micromegas and one is the ATLAS LGAD detector.

The main attraction of Micromegas detectors [30] is that they can be made in our labs and therefore one controls its basic design parameters. They use typically CsI photocathodes, deposited on a 3mm-thick MgF$_2$ window. Recent results are very impressive. Micromegas has achieved a timing resolution of ~24 ps with 150 GeV/c muons, and ~76 ps resolution with single photoelectrons in laser tests [31]. These results were achieved with a mean number of photoelectrons of ~10 per muon. Recently, new Diamond-Like Carbon (DLC) photocathodes are under investigation [32]. These photocathode are expected to be more radiation hard compared to CsI. So far, their QE is about ~3x lower than what one gets from CsI [40].
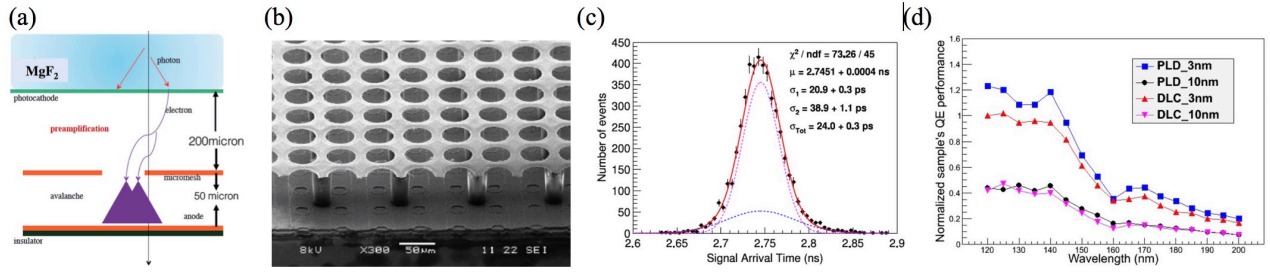
Fig.1.3.1 (a) Concept of the Micromegas gaseous detector. (b) A detail of the gain region of the Micromegas. (c) Timing resolution obtained in muon beam with 3mm MgF$_2$ widow and CsI photocathode [31]. (d) A measured relative QE of new Diamond-Like Carbon (DLC) photocathodes [32]; one needs another factor of 3x in absolute QE to get a similar result as from the CsI photocathode [40].

There is a strong motivation to develop new Si 3D-detecors. The idea is to connect charged tracks to the correct production vertices, using position resolution and timing resolution. The emerging technology of choice is low gain avalanche diode (LGAD) Si detectors. Figure 1.3.2a shows a principle of LGAD [33]. The proof of principle was provided in a test beam, where proponents measured σ_{time} ~34 ps for a single sensor, and ~16 ps with a tandem of three identical sensors (Fig.1.3.2.b,c) [34]. Each sensor size was 1.3mm x 1.3mm x 45 μm-thick, equipped with ~1.5 MHz BW amplifier and a 20 GSa/sec oscilloscope readout, providing 50 ps sampling. Fig.1.3.2b indicates a risetime of ~400ps and a S/N ratio of ~20; therefore, using formula (1), one would expect σ_{time} ~ $t_{risetime}$ /(S/N) ~20 ps.

ATLAS collaboration is developing a new AISC, which will be located on each sensor, as shown on Fig.1.3.2d [35]. It is now considered for the High-Granularity Timing Detector (HGTD) [35]. One should point out that the expected total doses at ATLAS are extremely challenging (~4×10^{15} n$_{eq}$/cm^2 and ~4.1 MGy = ~410 Mrads). For comparison, BaBar DIRC optical components were tested up to ~10-20 krads only. Initial tests indicate that HPK-50D LGAD sensor behaved stably up to a dose of ~3x10^{14} neutrons/cm^2, after which the gain had to be adjusted by increasing the bias voltage.
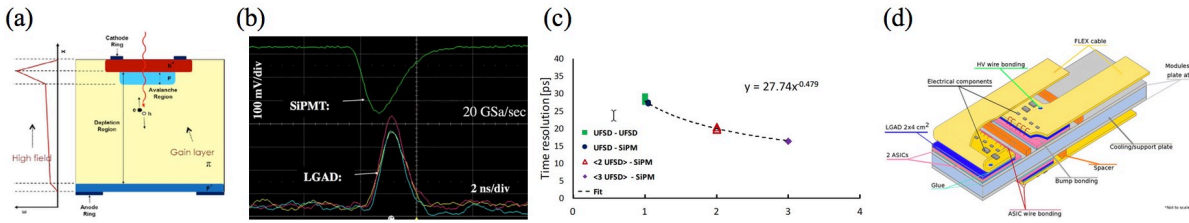

Fig.1.3.2 (a) Principle of the LGAD detector [33]. (b) Pulses from LGAD detector, compared to SiPMT in a test beam [34]. (c) Resolution as a function of number of layers in tandem of identical detectors, obtained in a test beam [34]. (d) A proposed LGAD tile structure for ATLAS HGTD detector [35].

1.4 Summary of timing resolution, rate capability and aging tests

It is useful to summarize the present status of MCP capability. Figure 1.4.1a shows Panda measurements of MCP rate capabilities [37]. Typically, the older MCPs show stable operation to ~200-300 kHz/cm^2 of single photons at gain of 10^6. Some of the latest MCPs can push the single photon rate up to ~10 MHz/cm^2 at this gain. Figures 1.4.2b,c show a stability of QE as a function of total anode charge [11,38]. Some of the latest Photonis and Hamamatsu ALD-coated MCPs seem to be stable up to ~20 C/cm^2. This represents a remarkable progress in the past ~10 years. However, it has to be proven in a real experiment.

Table 2 shows a summary of rate and aging measurements from other detectors. It also lists obtained timing resolutions.
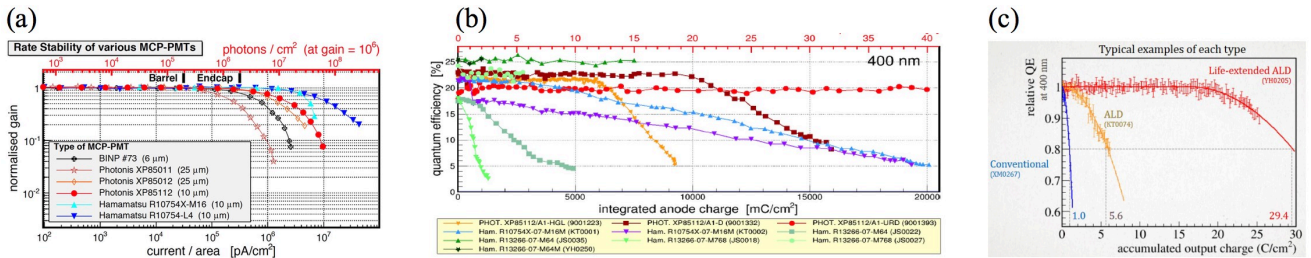

Fig.1.4.1 (a) Measured rate capability of MCPs [37]. (b) Measured photocathode deterioration as a function of accumulated anode charge. Some latest Photonics MCPs can reach anode charges of ~20 C/cm^2 [11]. (c) Measurement of QE aging of some Hamamatsu MCPs indicate that the latest tubes can reach ~20C/cm^2 [38].

Table 2: Timing resolution, maximum rate capability and anode charge doses, obtained in beam tests or laser tests, (some numbers are either not known to author presently or not measured).

Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm² *** (tracks)	-	~60 ps/track (present)***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm² ** (tracks)	-	Plan: ~20 ps/track	[4]
MCP-PMT	Beam test	-	-	< 10 ps/track *	[7,8,9]
MCP-PMT	Laser test	-	-	~27 ps/photon *	[14]
MCP-PMT	PANDA Barrel test	10 MHz/cm² * (laser)	~20 C/cm² *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm² ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm² *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm² ** (photons)	5 C/cm² **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon***	[23]
Low gain AD	ATLAS test	~40 MHz/cm² ** (tracks)	-	~ 34 ps/track/single sensor *	[34,35]
Medium gain AD	Beam test	-	-	< 18 ps/track *	[39]
Si PIN diode (no gain)	Beam test (electrons)	-	-	~23 ps/32 GeV e^-	[8]
SiPMT (high gain)	Beam test – quartz rad.	-	< 10^{10} neutrons/cm²	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm²	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm² * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm² * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm² * (laser test)	-	~76 ps/photon *	[31,32,40]

*   Measured in a test
**   Expect in the final experiment
*** Status of the present experiment

Summary

- MCP-PMT detectors timing resolution limit has been pushed to ~3.8 ps in beam tests using single pixel devices.
- MCP-PMTs are fastest detectors available presently. This speed creates challenges for multi-pixel applications. Although some of these problems were pointed out already ~15 years ago, it is finally now that we see a progress in design of these detectors. There is a significant progress in MCP aging and rate properties.
- There is a large effort, driven mainly by LHC, to develop a Si-tracker providing a time resolution at a 20-30 ps level per track, based on low gain avalanche detectors (LGAD). Expected total radiation doses at ATLAS are extremely challenging (~4×10^{15} n_{eq}/cm² and ~4.1 MGy = ~410 Mrads), which requires a new R&D.
- Micromegas gaseous detectors reached a timing resolution of ~24 ps. This is amazing achievement, not expected a few years ago. The main advantage of this type of detector is that one can create it in our labs. New Diamond-Like Carbon (DLC) photocathodes may be a significant step to improve their aging behavior. They still need a factor of 3 improvement in QE to compete with the CsI photocathodes.
- However, most results in this paper were obtained in small tests, usually with single-pixels. The timing resolution will be worse in large complex multi-pixel detector systems with a real background.

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