High precision time measurements in future experiments

J. Va’vra, SLAC
High luminosity drives new timing developments

- 4D tracking, which is a combination of Time & Position measurement:
  a) Tracking detector for ATLAS & CMS: ~ 10’s of ps & 10’s of µm per MIP/pixel.
  b) New RICH DIRC detector applications: ~ 80-100 ps/photon/pixel.

- There is a general push for higher luminosity at LHC, Belle-II, Panda, Electron-ion collider, etc.
Examples of high resolution timing at a level of ~30 ps for MIPs, and ~100ps for single photons

ATLAS High-Granularity Timing Detector (HGTD) with Low Gain Avalanche Diodes (LGAD):

TORCH DIRC at LHCb:

ALICE-like MRPC TOF counters:

Panda Barrel DIRC: Panda Endcap DIRC: Belle-II iTOP DIRC: EIC DIRC in USA: FIT at ALICE:

2/25/20 J. Va'vra, INSTR20, Novosibirsk, 2020
Rate capability of various detectors
MCP rate capability
A. Lehmann, Panda, RICH 2010, Cassis, France

- Older MCPs could operate up to \(~200-300\ \text{kHz/cm}^2\) at a gain of \(10^6\).
- Endcap Panda DIRC MCPs plan to operate rate up to \(~2\ \text{MHz/cm}^2\).
- Belle-II TOP counter MCPs plan to operate at a rate of \(~2\ \text{MHz/cm}^2\).
- LHCb TORCH MCPs plan to operate at a rate of up to \(~36\ \text{MHz/cm}^2\), or \(~2\ \text{MHz/one micro-pad}\).
MCP QE aging and total charge
A. Lehmann, RICH 2018 and K. Matsuoka, TIP 2017

- Lehmann & Matsuoka: Latest Photonis and Hamamatsu MCPs reached $\sim 20 \text{ C/cm}^2$.
- Belle-II: expect total of $\sim 10 \text{ C/cm}^2$.
- LHCb TORCH: expect total of $\sim 5 \text{ C/cm}^2$.

- Message: New ALD-based treatment has improved MCP QE lifetime significantly.

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Maximum rate and charge dose capability of other detectors

**ALICE MRPCs:**
- Present detector can run at \(~500\, \text{Hz/cm}^2\).
- New low resistivity MRPCs will run at \(~50\, \text{kHz/cm}^2\).

**Diamond (TOTEM):**
- This technology is very radiation hard.
- High rate capability achieved: \(~3\, \text{MHz/cm}^2\).

**SiPMs:**
- Operation of some RICH detectors in single photon regime at \(10^{11}\text{n_{eq/cm}^2} \& -30\, ^{\circ}\text{C}\) is possible.
- All SiPMs, even those irradiated up to \(10^{14}\, \text{n_{eq/cm}^2}\), are “usable” at liquid nitrogen temperature.

**LGADs (ATLAS UFSD project):**
- Expect rates up to \(~40\, \text{MHz/cm}^2\).
- Sensors & ASICs will be exposed to \(3.7\times10^{15}\, \text{n_{eq/cm}^2}\) and \(4.1\, \text{MGy} (!!!) \)!!!
- Present test results are very close to this goal.
Time measurement
Timing resolution for leading edge timing
(Well-known formula to fast electronics designers for a long time)

A simple formula:
\[ \sigma_{\text{time}} = \frac{\sigma_{\text{noise}}}{(ds/dt)_{\text{threshold}}} \sim \frac{t_{\text{rise-time}}}{(S/N)} \]

- For LGAD detector with \( t_{\text{rise-time}} \sim 400\text{ps} \), one needs \( S/N \sim 20 \) get to a \( \sim 20 \text{ ps} \) regime.
- However, this picture is over-simplified - see next slide.
Many other contributions to timing resolution, which makes timing measurement difficult

Example of contributions to the timing resolution:

\[ \sigma_{\text{Total}} \sim \sqrt{\left( \frac{\sigma_{\text{TTS}}}{\sqrt{N_{\text{pc}}}} \right)^2 + \left( \frac{\sigma_{\text{pixel}}}{\sqrt{12}} \right)^2 + \sigma^2_{\text{Electronics}} + \sigma^2_{\text{Track}} + \sigma^2_{\text{to}} \ldots} \]

- \( \sigma_{\text{Electronics}} \): electronics contribution
- \( \sigma_{\text{pixel}} \): pixel size
- \( \sigma_{\text{TTS}} \): single electron transit time spread
- \( \sigma_{\text{Track}} \): timing error due to track length \( L_{\text{path}} \)
- \( \sigma_{\text{Time walk}} \): time walk due to pulse height changes
- \( \sigma_{\text{to}} \): start time (often dominated by the bunch length)

+ There are many other possible effects in a large system:
  - clock distribution throughout a large system
  - cross-talk effects in multi-pixel detectors (ringing in a multi-photon environment)
  - baseline oscillation or other instability in multi-pixel detectors
  - charge sharing in multi-pixel detectors (pixel edge effects)
  - chromatic effects
  - unwanted pulse tails
  - Calibration
  - ground loops, current return, differential vs. single ended readout, etc.
Ultimate resolution using single-pixel MCP-PMTs
This is the fastest detector to my knowledge

J. Milnes and H. Howorth, Photek Co. info, 2005

Photek MCP 110:
- single photons
- no amplifier

Using the simple formula:
If we assume $S/N \sim 20$

$\tau_{\text{rise time}} \sim 66 \text{ ps}$

$\sigma_{\text{time}} \sim \frac{\tau_{\text{rise time}}}{(S/N)} \sim 3 \text{ ps}$
MCP-PMT: Single-pixel TOF counter, no amplifier, large Npe

K. Inami et al., NIMA560(2006)303
Two Hamamatsu R3809U-59-11 MCPs:
- 6 microns MCP hole sizes
- Fused silica radiator + window: 10+3 mm
- Single pixel
- MCP Gain ~ 2x10^6
- SPC-134, Becker & Hickl GmbH
- Electronics resolution: 4.1 ps
- Npe ~ 70
- Total anode charge: 1.4x10^8 el. !!

A. Ronzhin et al., NIMA795 (2015)288
Two back-to-back Photek 240 MCPs:
- 6 microns MCP hole sizes
- Fused silica window: 8 mm
- Single pixel
- MCP Gain ~ 10^6
- DRS4 waveform digitizer
- Electronics resolution: 2.0 ps
- Npe ~ 80
- Total anode charge: 8x10^7 el. !!

L. Sohl et al., Elba conf., 2018
Two Hamamatsu R3809U-50 MCPs:
- 6 microns MCP hole sizes
- Fused silica radiator: 3.2 mm
- Single pixel
- MCP Gain ~ 8x10^4
- 20 GSa/s scope + CFD algorithm
- Electronics resolution: 2.2 ps
- Npe ~ 44
- Total anode charge: 3-4x10^6 el.

K. Inami et al., NIMA560(2006)303

A. Ronzhin et al., NIMA795 (2015)288

L. Sohl et al., Elba conf., 2018

• **Message:** Excellent resolution can be achieved with a single-pixel MCP for MIP signals.
• **However, one has to be careful running large anode charges** – see next slide.

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Why do I want limit total charge on MCP?


Ion feedback (afterpulse fraction) with two old Burle Planacon tubes with 10 µm holes:

- Message: One should limit total charge to ~2-3x10^6.
- Are the new MCPs behaving better? – see next slide.
Challenges of multi-pixel detectors
ALICE MRPC TOF detector
C. Williams, private communication, and Jaron et al., Nucl.Instr.&Meth A 33(2004)183

• Message #1: Differential design throughout to minimize pick-up, cross-talk, etc.
• Message #2: Time-over-threshold pulse height correction works if pulse shapes are “clean”.
• Message #3: NINO electronics provides a low power consumption (40 mW/channel; 1ns-peaking time, 8 ch./chip).
• Message #4: ALICE timing resolution was limited by $t_0$ resolution $\Rightarrow \sigma_{\text{Total ALICE system resolution}} \approx 60$ ps.

• New R&D MRPC in progress:
  a) ALICE is doing R&D with lower resistivity 400 µm-thick glass, allowing to build 20-gap MRPC capable of rate up to $\sim 50$ kHz/cm$^2$
  b) sPHOENIX at BNL is doing R&D using 2.8 GHz differential preamp LMH 6881 and DRS4 digitizer (M. Chiu).

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How to connect to Planacon MCP-PMT?

In principle, MCP is a simple device, but….:

The issue is how to connect to it? Various schemes which were tried:

- MCP is inherently a single-ended device, which invites a possible pick-up problems. One needs a good RF-shielded box around the device to avoid noise on the ground reference.
- Early Planacon models had unwanted capacitances, inductances, ground return issues, and low BW connectors, which contributed to cross-talk, pulse shape distortions, ringing, fake hits, etc.
- Good news: There is a progress. See appendix.
SLAC 1-st FDIRC prototype with 320-pixels in MCPs

SLAC Amplifier based on Elantek 2075:
Voltage gain of ~130x, and a rise time of ~1.5ns.

SLAC CFD (32 ch/board):

- Old Burle Planacon:

Single photons from laser:

- SLAC Amplifier based on Elantek 2075:
- Single pixel timing resolutions with Planacon MCP:

• **Message:** This was still one of the best timing performance of any large RICH detector system with MCPs.

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Novosibirsk, 2020
Cross-talk in early version of Planacon MCP 85011-501

Inject signal to pixel #1 and observe cross-talk in other pixels:

- **Message:** The cross-talk was very complicated geometrically on the old Planacon.
- New MCPs behave better – progress after 15 years! See appendix.

Electronics used in this test:
Total voltage gain of 130x = Elantek 2075 amp. 13x + Phillips amp. 10x

All 64 pixel instrumented

Ringing if too many photons arrive at the same time
1024 pixel Burle Planacon – available already in 2005


1) **FDIRC at SLAC:**

Burle Planacon 85021-600 with 1024 pixels:
- Small margin around boundary
- 1024 pixels (32 x 32 pattern)
- Small pixel size: ~1.4mm x 1.4mm
- Pitch: 1.6 mm
- Bottom MCP-to-anode dist.: **5.2 mm**

2) **µPET:** David Brasse: read every pixel (MCP coupled to matrix of LYSO crystals)

**Planacon** 85022-600 (Jeff DeFazio):
- Bottom MCP-to-anode dist.: **3.6 mm**

**Message:** In retrospect, we at SLAC, could have chosen 8-channel NINO ASIC to readout every pixel.

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Several large physics applications with MCP-PMTs
Endcap Panda DIRC: Photonics MCP with TOFPET electronics

Panda Endcap DIRC TDR, 2019, and Jeff DeFazio, private communication

• **Goal:** TTS resolution of ~100ps; presently they got ~320 ps with negative MCP pulses.

• **Problem:** TOPFET ASIC was designed for positive pulses, i.e. it works well with SiPMTs. There is an effort to talk to company to provide a modification of the ASIC to work with negative MCP pulses.

• **Message:** TOPFET2 ASIC is using time-over-threshold timing, it is cheap, electronics has low mass, it is radiation hard and has low power consumption (<10mW/ch).

J. Va’vra, INSTR20, Novosibirsk, 2020
Belle-II: TOP DIRC counter waveform digitizing electronics

Work led by Gary Varner, Univ. of Hawaii, details in D. Kotchetkov et al., ArXiv:1804.10782, 2018

DIRC TOP counter principle (450mm wide x 2600 mm long):

- IRSX waveform digitizer: 2.7 GSa/sec, an equivalent to a cheap scope on every pixel.
- Amplifier gain: ~120x. They slowed down the risetime to have 2 samples on leading edge.
- Message: The total power consumption is very high: ~570 mW/channel!
Because of a large background, MCP gain had to be lowered to $\sim 3 \times 10^5$. As a result of this and other effects, the single photon timing resolution in Belle-II is presently: 80-120ps.

Max photon rate is kept $< 4$ MHz/MCP. Some non-ALD coated MCPs will have to be replaced in 2020.
LHCb: TORCH TOF MCP-PMTs

N. Harnew, RICH 2018, J.S. Lapington et al., NIMA 695(2012)78, T.M. Conneely et al., JINST, May 2015 and S. Bhasin et al., to be published in NIM

- Challenge #1: Required single photon resolution: ~70 ps/photon and ~10-15ps/track.
- Challenge #2: Expected rates at LHCb: 10-40 MHz/cm², and anode charge doses up to ~5C/cm².
  Aging tests with Phase-I MCP: good up to ~3C/cm² only at present.
- Message #1: TOT timing with 32-channel NINO ASIC works well, although calibration is complicated.
Si detectors
SiPMs radiation hardness is an issue for RICH detectors

• **Message #1:** High energy protons and neutrons produce the most damage. Damage from thermal neutrons is observed only at high doses. Gammas produce comparatively lower damage.

• **Message #2:** Lower temperature can reduce noise rate caused by the neutron damage. All SiPMs, even those irradiated up to $10^{14} \text{n}_{eq}/\text{cm}^2$, are “usable” at liquid nitrogen temperature. Operation for RICH detectors in single photon regime at $10^{11} \text{n}_{eq}\text{cm}^{-2}$ and –30 °C is possible.
EIC R&D on ARICH: SiPMTs noise rate = f(temperature)

C.P. Wong et. al., NIM A 871, 13 (2017)

- Hamamatsu SiPMT 16 x 16 matrix with 3 mm x 3 mm pixel sizes; ~100ps timing is possible.
- **Message:** Low temperature clearly helps to reduce the room temperature noise.

Optics with Fresnel lens:

Room temperature:

~120 GeV proton test beam of Aerogel RICH:
ATLAS Endcap Low Gain Avalanche Diodes

H. Sadrozinski, private communication, ATLAS technical proposal, 2019, and

- Bench tests: Very good timing and position resolution results using a laser (σ ~ 10’s of ps & 10’s of µm).
- Radiation damage: They reached ~3x10^{15} n_{eq}/cm^2 and 4 MGy, i.e., very close to the final goal. (1 MGy = 100 Mrads !!).
- Two ASICs, ALTIROC (ATLAS) and ETROC (CMS) under development.
- Message: There seems to be a real progress.

12 cm < r < 60 cm
7888 sensor modules

ATLAS UFSD Endcap:

LGAD sensors, ASICs, cooling and connection package:

12 cm < r < 60 cm
7888 sensor modules

Present design have a region of no gain:

Position and time are determined by amplitude-weighted centroid using four pads
Present design:
  Pitch: 1.3 mm
  Gap: ~70 µm
  Fill factor: ~90%

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Gas detectors
Gasous detectors: Timing with Micromegas

Y. Giomataris, private communication, and J. Bortfeldt et al., arXiv:1901.03355, 2019

- Pixel size: ~1cm² area
- Photocathodes: CsI or DLC (diamond-based photocathode)
- Gas: 80% Ne+10% CF₄+10% C₂H₆
- 3 mm MgF₂ window/radiator
- Cividec amp 1-2 GHz BW, and SAMPIC waveform digitizer or 20 GSa/s LeCroy scope

- CsI photocathode: ~24 ps/MIP (150 GeV/c muons), ~76 ps for single photoelectrons!! Mean number of photoelectrons with CsI: ~10 per/MIP.
- Diamond photocathode: ~40 ps/MIP with 97% det. eff.; need a factor of 3 improvement of QE.
- Message: Gaseous detectors are not dead yet.
Conclusions

• There has been a real progress in developing 4D LGAD detectors hoping to achieve a position resolution of 10’s of µm and 10’s of ps per MIP.

• Similarly photon detectors were developed providing ~100 ps per single photon with very small-pixel sizes.

• But future will tell if the promised timing resolution, which is inherently a very sensitive analog quantity, can be achieved in large background environment and in very large detector applications. It is very challenging task.
Appendix
Maximum rate and charge dose capability

**MRPC (ALICE):** System MIP resolution of \( \sim 60 \, \text{ps/MIP} \) and rate capability of \( \sim 500 \, \text{Hz/cm}^2 \).
New R&D: MIP rate up to \( \sim 50 \, \text{kHz/cm}^2 \) with a new low resistivity glass are under study.

**MCPs:** MIP timing resolution of \( < 10 \, \text{ps/MIP} \) with a single-pixel MCP achieved.
Single photon timing resolution of \( \sim 30-100 \, \text{ps/photon} \) achieved.
Endcap DIRC in Panda: expect rates up to \( \sim 1 \, \text{MHz/cm}^2 \) for single pe’s @ gain of \( 10^6 \).
TORCH at LHCb: expect rates up to \( \sim 40 \, \text{MHz/cm}^2 \) !!
Panda R&D: anode charge dose up to \( \sim 20 \, \text{C/cm}^2 \) using single pe’s with Photonis MCP.
TORCH: The 1-st generation of Photek MCPs reached \( \sim 3-4 \, \text{C/cm}^2 \).
The latest Hamamatsu MCPs almost reached \( \sim 20 \, \text{C/cm}^2 \).

**Diamond (TOTEM):** MIP timing resolution of \( \sim 80 \, \text{ps/MIP} \) achieved.
This technology is very radiation hard.
High rate capability achieved: \( \sim 3 \, \text{MHz/cm}^2 \).

**SiPMs:** MIP timing resolution of \( \sim 13 \, \text{ps} \) achieved in a beam test.
Significant noise increase after \( \sim 10^{10} \, \text{neutrons/cm}^2 \).
Cooling helps.

**LGADs (ATLAS UFSD project):**
MIP timing resolution of \( \sim 30 \, \text{ps/MIP} \), and \( \sim 16 \, \text{ps/MIP} \) for tandem of three achieved.
Expect rates up to \( \sim 40 \, \text{MHz/cm}^2 \).
Sensors & ASICs will be exposed to \( 3.7 \times 10^{15} \, \text{n}_{eq/cm}^2 \) and \( 4.1 \, \text{MGy} \) (!!!) in ATLAS !!!!
Present test results: OK up to \( 3 \times 10^{15} \, \text{n}_{eq/cm}^2 \) and \( 4 \, \text{MGy} \).

**Micromegas (CsI):** Timing resolution of \( \sim 24 \, \text{ps/MIP} \) and \( \sim 76 \, \text{ps/photon} \) achieved in a beam test.

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Novosibirsk, 2020
Electronics for the best timing result

- **Ortec 9327 Amp/CFD** can reach $\sigma_{\text{Electronics}} \approx 2\,\text{ps}$ resolution, if one avoids TAC electronics.
- **DRS4 waveform digitizer** can reach $\sigma_{\text{Electronics}} < 1\,\text{ps}$ for very small delay between start & stop.
- **20 GSa/s scope** with CFD algorithm can reach $\sigma_{\text{Electronics}} \approx 2\,\text{ps}$.

**Message:** If your electronics contributes $\approx 2\,\text{ps}$ to the resolution, you are doing very well.
Ion feedback in new MCPs, ALD-coated, Npe=1

A. Lehmann, private communication, April 22, 2018

Both are ALD-coated MCPs:

- Photonis XP85112 MCP-PMT performs well at a total charge of $\sim 3 \times 10^6$
- Hamamatsu R13266 sees an increase in the rate already at a total charge of $\sim 1.5 \times 10^6$. 
Cross-talk in Multi-pixel MCPs
**FIT group at ALICE: Modification of Planacon MCP 85012**

Y.A. Melikyan on behalf of ALICE, RICH 2018, MCP modifications done by Jeff DeFazio, Photonis.

Reduce 64 pixels to 4 pixels: Add two boards: The cross-talk and pulse ringing (b) before and (c) after:

- **Message:** A modification of 64-pixel Planacon XP85012 included:
  (a) reduced number of pixels from 64 to 4 (SMA connectors),
  (b) add two boards,
  (n) improved the HV ground return and
  (d) increased a distributed capacitance along MCP edges.

- **Goal of FIT:** Timing resolution $\sigma \sim 30$ ps/track

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Panda R&D: Latest update on ringing of new 64-pixel Planacon

Albert Lehman, private communication, May 7, 2019, and Jeff DeFazio, private communication, 2/25/20 J. Va'vra, INSTR20, Novosibirsk, 2020

32 pixels fire at the same time:  All pixels fire at the same time:  Latest Photonis Planacon, 2019:

Hamamatsu 64-pixel (R13266-07-M64M):  Photonis (#9002108) - a previous model:  Photonis (#9002150) - a latest model:  Latest Photonis Planacon:

5 ns/div  5 ns/div

New features (from Jeff DeFazio):
- New connector.
- Smaller anode-ground capacitance.
- Better ground return.
- Tube has the ground plane.
(Jeff thinks it helps to reduce ringing).

- **Message:** Latest Photonis MCP (#9002150) has much better ringing performance.
Ringing in early version of Planacon MCP vs. MaPMT


- Message: Amplitude of ringing increases with number of photons hitting MCP. Had to increase the discriminator threshold to avoid fake hits.

- H-8500 MaPMT with the same electronics was OK.
MCPs in magnetic field
Endcap Panda: MCP charge footprint in magnetic field can be very small
J. Rieke et al, JINST 11, 2016, and Panda Endcup DIRC TDR, 2019

- MCP has 0.4 mm x 17 mm anode pads.
- 3 rows x 100 strip configuration.
- MCP-Anode gap = 0.625 mm
- tube does not have a ground plane

Message: A magnetic field of only ~0.1 T will reduce the charge footprint to ~15µm!!
MCP gain in magnetic field

A. Lehman, RICH 2018, Moscow:

- ALD tubes seem to show faster gain drop in B-fields than non-ALD tubes!
- Photonis 9002108: gain drop by a factor of 2 at 1 Tesla, at 0 deg.
- Hamamatsu YH0250: gain drop by a factor of 4 at 1 Tesla, at 0 deg.
- Argonne ALD-coated MCP: gain drop by a factor of more than 10 at 1 Tesla, at 0 deg.

Xie et al., ANL R&D, 2019, submitted to NIMA:

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Ion feedback in MCP = f(B)

J. Va’vra, Log book #7, 2009

2. Single electron response regime (25 μm holes)
   - laser at 33%, 100 Hz, 9 mylar att., single fiber (no splitter)
   - VT-120 amplifier
   a) B = 0 kG, 2.4 kV, ~6x10⁵, measure the feedback rate, run for 20 minutes in each case:
      - Feedback rate : < 1%
   A special run lasting 2 hrs:
   b) ~5 kG, keep 2.4 kV to get the same gain.
      - 5.03 kG, 482 A, 40.4 V
      - Feedback rate : < 1%
   c) ~7.5 kG, set 2.5 kV to get the same gain
      - 7.54 kG, 726 A, 60.3 V
      - Feedback rate : < 1%
   d) ~10 kG, keep 2.65 kV to get the same gain.
      - 10.03 kG, 974 A, 81.1 V
      - Feedback rate : < 1%
   e) ~12 kG, keep 2.8 kV to get the same gain
      - Feedback rate : < 1%

- No difference within my errors.

• Message: No increase in the ion feedback observed within my errors.
FDIRC development at SLAC
Can one do timing with low total charge?


- Low gain ~2x10⁴, vary Npe (1-100)
- Total charge: ~8x10⁵ for Npe ~40
- For Npe ~ 40 pe, we reached ~14 ps.
- For Npe ~80, one could reach ~10ps.

Message: For TOF application, one can reach a good resolution even at low gain if Npe ~40-80.
Single pe MCP pulses, no amplifier


Burle Planacon MCP-PMT
(85013-501):

- 10 µm MCP hole dia.
- Gain ~$10^6$
- 64 pixels, pad size: 6 mm x 6 mm
  (ground all pads except four)
- Ganging 4 pixels together increases a capacitance.
- PiLas laser is used as a scope trigger

Using our simple formula:

$\sigma_{\text{noise}} \approx 0.4$ mV
$S \approx 8$ mV
$S/N \approx 8/0.4 \approx 20$

$t_{\text{rise time}} \approx 150$ps (with a better scope)

$\sigma_{\text{time}} \approx t_{\text{rise time}} / (S/N) \approx 7-10$ ps

- That told me that one can reach a very good resolution with this MCP

Using our simple formula:

$\sigma_{\text{noise}} \approx 0.4$ mV
$S \approx 8$ mV
$S/N \approx 8/0.4 \approx 20$

$t_{\text{rise time}} \approx 150$ps (with a better scope)

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- That told me that one can reach a very good resolution with this MCP
A good TTS resolution even with slower electronics


Planacon 85013-501 single electron pulses with Hamamatsu 63x amplifier C5504-44:

- 10 µm MCP hole diameter
- Gain ~$10^6$, $N_{pe} = 1$
- 64 pixels, pad size: 6 mm x 6 mm.
  (single pixel used)
- $\sigma_{TTS} < \sqrt{(32^2 - \sigma_{Laser}^2 - \sigma_{Electronics}^2)} \sim 27$ ps
- Philips 715 CFD, Pilas laser (635nm).
- LeCroy TDC 2248

**Hamamatsu C5594-44 amplifier**

1.5 GHz BW, 63x gain, 2.8kV

- $\sigma_{TTS} \sim 27$ ps

**Ortec VT120A amplifier**

~0.4 GHz BW, 200x gain + 6dB, 2.8kV

- $\sigma_{TTS} \sim 27$ ps

- One can obtain a good TTS resolution even with a slower amplifier, if one has a good S/N ratio, and one tunes CFD discrimination carefully.
MCP-to-cathode distance - a way to eliminate tail
SLAC effort: NIMA553(2005)96

MCP-to-Cathode distance = 6 mm
85011-501 Nominal design:

\[
\sigma_{\text{arrow}} = (70.6 \pm 1.6) \text{ ps} \\
\sigma_{\text{side}} = (217.0 \pm 8.5) \text{ ps}
\]

\[
\begin{array}{c}
\text{time (ns)} \\
0 & 2 & 2.5 & 3 & 3.5 & 4 & 4.5 & 5 & 5.5
\end{array}
\]

\[
\begin{array}{c}
0 & 100 & 200 & 300 & 400 & 500 & 600 & 700 & 800 & 900 & 1000
\end{array}
\]

MCP-to-Cathode distance ~0.85 mm
85014-430 Drop Faceplate:

\[
\sigma_{\text{arrow}} = (66.7 \pm 3.5) \text{ ps} \\
\sigma_{\text{side}} = (161.6 \pm 6.7) \text{ ps}
\]

\[
\begin{array}{c}
\text{time (ns)} \\
0 & 2 & 2.5 & 3 & 3.5 & 4 & 4.5 & 5 & 5.5
\end{array}
\]

\[
\begin{array}{c}
0 & 100 & 200 & 300 & 400 & 500 & 600 & 700 & 800 & 900 & 1000
\end{array}
\]

Planacon stepped face MCP (85014):

- Penalty: the efficiency drops to zero half way through all edge pads.
Pixel edge effects in MCP timing
SLAC effort: NIMA 553(2005)96-106

- Pixel edges and corners have worse timing resolution due to charge sharing.
- In principle, it can be corrected if one has knowledge of a photon entry. But that entry point is usually not known.
LAPPD MCPs
LAPPD 8”x8” MCP detectors with strip readout

LAPPD detector with strips:

- **Generation-I detectors**: Strip line readout is now commercially available from Incom, Inc.
- **For many low rate applications this is an excellent choice.**

**Strips**: Single pe pulses (LAPPD #25):

Using a simple formula:

\[
S/N \sim 15 \\
t_{\text{rise time}} \sim 850 \text{ ps} \\
\sigma_{\text{time}} \sim t_{\text{rise time}} / (S/N) \sim 60 \text{ ps}
\]

**Strips**: TTS resolution (LAPPD #25):

- **Strip cross-talk problem can be calculated, in principle**:
  H. Grabas, LAPPD simulation study at U. of Chicago/Saclay, May 2012

\[\sigma_{\text{TTS}} \sim 64 \text{ ps}\]
LAPPD detector concept with capacitively coupled pixels:

- Generation-II detectors: (a) ceramic body, (b) capacitive coupling to external PCB board.
- This concept is still in R&D stage and detectors are not yet available.
- See appendix for more info.
Si Detectors
Si detectors: High gain SiPMTs
A. Rozhnin et al., Fermilab, Talk at Picosecond timing workshop, Arlington, Oct. 5-7, 2015

Start: SiPMT, Stop: Photek-240 MCP-PMT
- SiPMT: 3x3mm²
- 6 µm holes MCP
- 3 cm-long Fused silica radiator
- No extra radiator used on MCP, only 8mm-thick window
- Fast amplifier on SiPMT
- DRS4 digitizer

RF-shielded box:

### 8 GeV/c e⁻ beam (distance between two detectors: 7.12 meters)

The most recent result:
\[ \sigma_{\text{SiPMT}} \sim 13 \text{ ps} \]

- Test achieved \( \sigma_{\text{SiPMT}} \sim 13 \text{ ps} \) resolution per MIP.

\( \sigma_{\text{SiPMT}} \sim \sqrt{14.5^2 - (8.3/\sqrt{2})^2} \sim 13 \text{ ps} \)
Timing + position + calorimeter + PIN diode

A. Ronzhin et al., Fermilab, SLAC talk, 2017

- Start: Photek-240 MCP
- Stop: Hamamatsu Si PIN diode – zero gain
- 6 x 6 mm² pad
- Absorber: Pb or W
- DRS4 digitizer

Si-PIN diode can achieve pretty good timing resolution in a calorimeter application.

RF-shielded box:

32 GeV Electron Beam

6X₀ tungsten absorber

Silicon PIN diode

Photek 240 MCP-PMT

Si PIN diode timing resolution: \( \sigma_{\text{PIN}} \approx 22 \) ps

TOF = \( t_{\text{MCP}} - t_{\text{PIN}} \) [ns]

Time resolution [ps]

Beam energy [GeV]

2/25/20

J. Va'vera, INSTR20, Novosibirsk, 2020
ATLAS: Low Gain Avalanche Diodes in test beam
Cartiglia et al., ArXiv:1608.08681, 2017

- Pixel size: 1.3mm x 1.3mm x ~45 µm thick
- AD from CNM
- Gain ~ 20 @ 200V on AD
- Cividec 100x amp., 1-2 MHz BW, CFD
- 20 GSa/sec (50 ps bins)

LGAD principle:

Using a simple formula:
\[ t_{\text{rise time}} \sim 400\text{ps} \]
\[ S/N \sim 20 \]
\[ \sigma_{\text{time}} \sim \frac{t_{\text{rise time}}}{(S/N)} \sim 20 \text{ ps} \]

- Test beam achieved: \( \sigma_{\text{time}} \sim 34 \) for a single sensor, and \( \sim 16 \text{ ps} \) with a tandem of 3 sensors.
SiPMTs for RICH detectors with TOPFET2 ASIC

R. Bughalo et al., Talk at IEEE/NSF, Atlanta, 2017

• TOFPET ASIC was developed for Time-of-Flight Positron-Electron Tomography.
• Test achieved $\sigma_{\text{SiPMT}} \sim 90-100$ ps resolution per single photon at 7.5V overvoltage.
• Lesson #???: Lower power consumption (5-8 mW/ch.)

2/25/20

J. Va'vra, INSTR20,
Novosibirsk, 2020
# Maximum rate and charge dose capability


<table>
<thead>
<tr>
<th>Detector</th>
<th>Experiment or beam test</th>
<th>Maximum rate</th>
<th>Maximum anode charge dose</th>
<th>Timing resolution</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRPC presently</td>
<td>ALICE</td>
<td>~500 Hz/cm² *** (tracks)</td>
<td>-</td>
<td>~60 ps/track (present) ***</td>
<td>[4]</td>
</tr>
<tr>
<td>MRPC after upgrade</td>
<td>ALICE</td>
<td>Plan: ~50 kHz/cm² ** (tracks)</td>
<td>-</td>
<td>Plan: ~20 ps/track</td>
<td>[4]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>Beam test</td>
<td>-</td>
<td>-</td>
<td>&lt; 10 ps/track *</td>
<td>[7,8,9]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>Laser test</td>
<td>-</td>
<td>-</td>
<td>~27 ps/ photon *</td>
<td>[14]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>PANDA Barrel test</td>
<td>10 MHz/cm² * (laser)</td>
<td>~20 C/cm² *</td>
<td>-</td>
<td>[11]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>Panda Endcap</td>
<td>~1 MHz/cm² ** (photons)</td>
<td>-</td>
<td>-</td>
<td>[28]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>TORCH test</td>
<td>-</td>
<td>3-4 C/cm² *</td>
<td>~90 ps/ photon *</td>
<td>[27]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>TORCH</td>
<td>10-40 MHz/cm² ** (photons)</td>
<td>5 C/cm² **</td>
<td>~70 ps/ photon **</td>
<td>[24-27]</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>Belle-II</td>
<td>&lt; 4MHz/MCP *** (photons)</td>
<td>-</td>
<td>80-120 ps/ photon ***</td>
<td>[23]</td>
</tr>
<tr>
<td>Low gain AD</td>
<td>ATLAS test</td>
<td>~40 MHz/cm² ** (tracks)</td>
<td>-</td>
<td>~34 ps/track/single sensor *</td>
<td>[34,35]</td>
</tr>
<tr>
<td>Medium gain AD</td>
<td>Beam test</td>
<td>-</td>
<td>-</td>
<td>&lt;18 ps/track *</td>
<td>[39]</td>
</tr>
<tr>
<td>Si PIN diode (no gain)</td>
<td>Beam test (electrons)</td>
<td>-</td>
<td>-</td>
<td>~23 ps/32 GeV e−</td>
<td>[8]</td>
</tr>
<tr>
<td>SiPMT (high gain)</td>
<td>Beam test – quartz rad.</td>
<td>-</td>
<td>&lt; 10ⁱ⁰ neutrons/cm²</td>
<td>~13 ps/track *</td>
<td>[8]</td>
</tr>
<tr>
<td>SiPMT (high gain)</td>
<td>Beam test - scint. tiles</td>
<td>-</td>
<td>&lt; 10ⁱ⁰ neutrons/cm²</td>
<td>&lt;75 ps/track *</td>
<td>[41]</td>
</tr>
<tr>
<td>Diamond (no gain)</td>
<td>TOTEM</td>
<td>~3 MHz/cm² * (tracks)</td>
<td>-</td>
<td>~90 ps/track/single sensor *</td>
<td>[36]</td>
</tr>
<tr>
<td>Micromegas</td>
<td>Beam test</td>
<td>~100 Hz/cm² * (tracks)</td>
<td>-</td>
<td>~24 ps/track *</td>
<td>[31,32,40]</td>
</tr>
<tr>
<td>Micromegas</td>
<td>Laser test</td>
<td>~50 kHz/cm² * (laser test)</td>
<td>-</td>
<td>~76 ps/ photon *</td>
<td>[31,32,40]</td>
</tr>
</tbody>
</table>

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