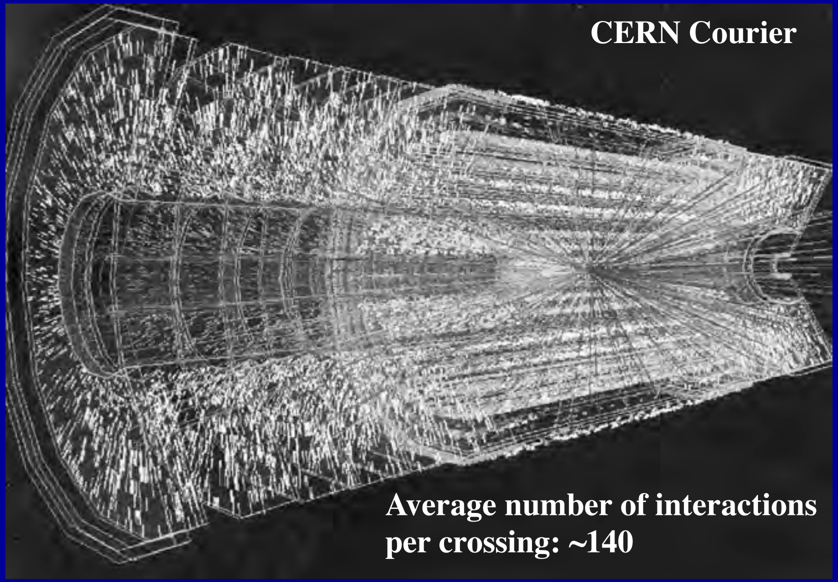
High precision time measurements in future experiments

J. Va’vra, SLAC

J. Va’vra, https://www.slac.stanford.edu/~jjv/activity/Vavra_Invited_paper_La_Rochelle_2019.pdf

High luminosity drives new timing developments

ATLAS event after high luminosity upgrade:



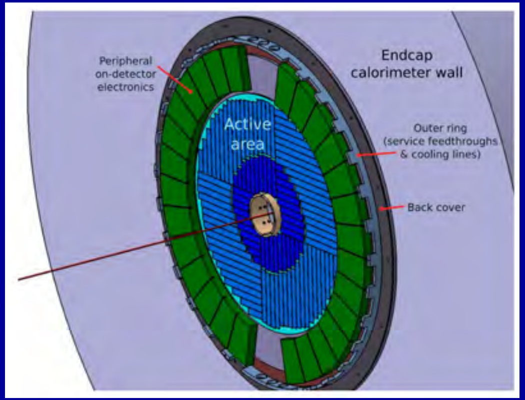
**Challenge:
Connect charged tracks to the correct production vertices**

- **4D tracking , which is a combination of <u>Time & Position</u> 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.

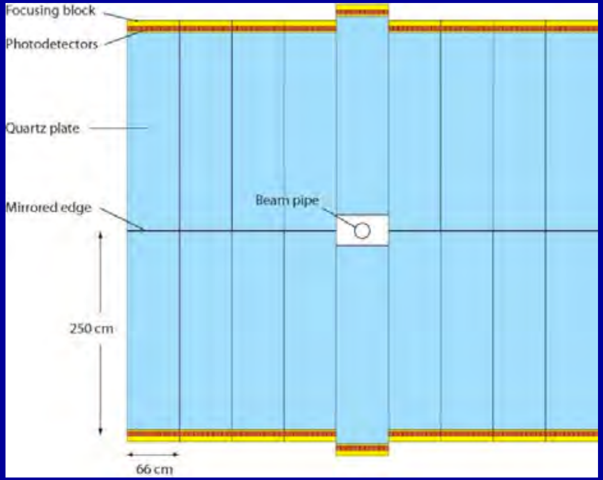
- **There is a general push for higher luminosity at LHC, Belle-II, Panda, Electron-ion collider, etc.**

Examples of high resolution timing at a level of ~30 ps for MIPs, and ~100ps for single photons

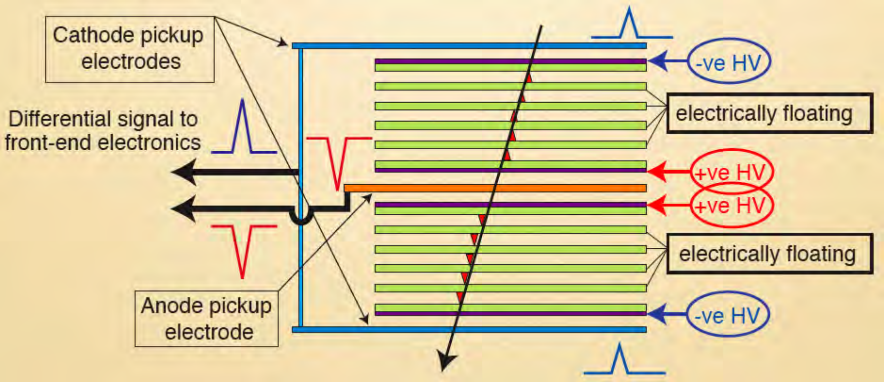
ATLAS High-Granularity Timing Detector (HGTD) with Low Gain Avalanche Diodes (LGAD):



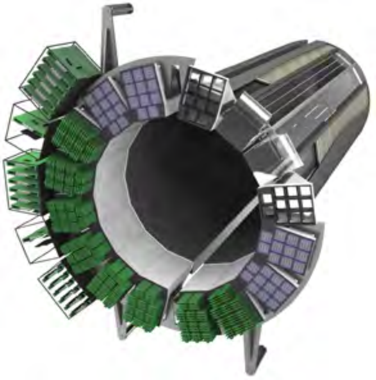
TORCH DIRC at LHCb:



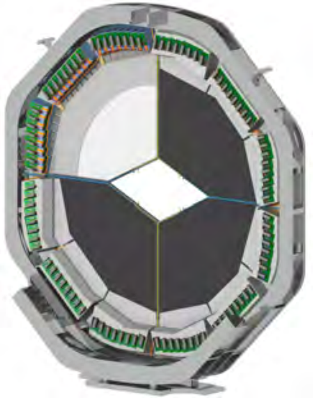
ALICE-like MRPC TOF counters:



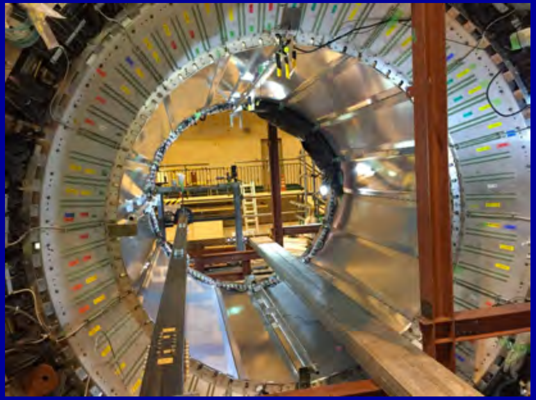
Panda Barrel DIRC:



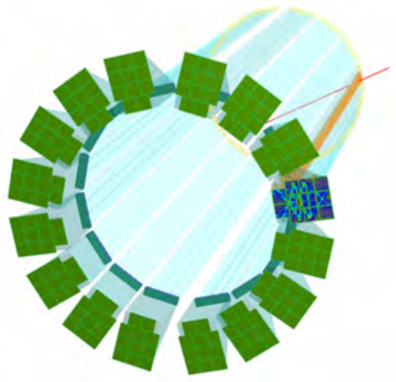
Panda Endcap DIRC:



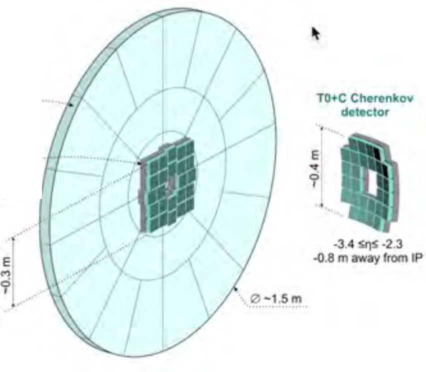
Belle-II iTOP DIRC:



EIC DIRC in USA:



FIT at ALICE:

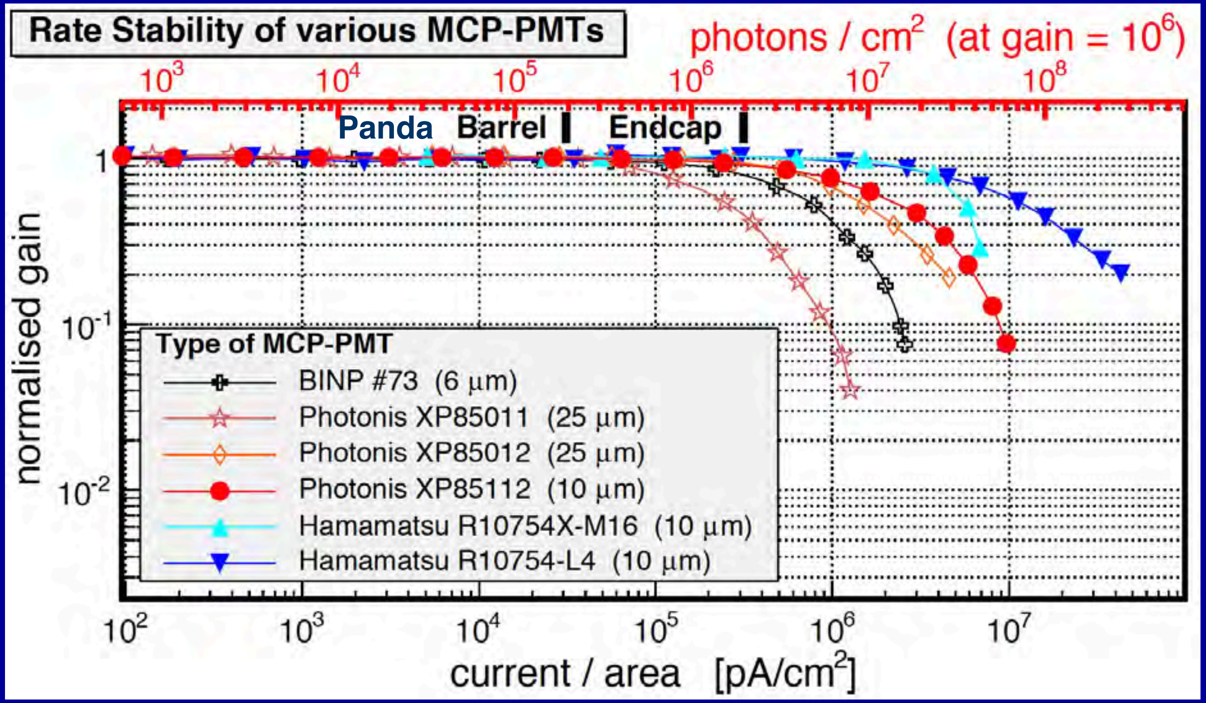


…etc.

Rate capability of various detectors

MCP rate capability

A. Lehmann, Panda, RICH 2010, Cassis, France

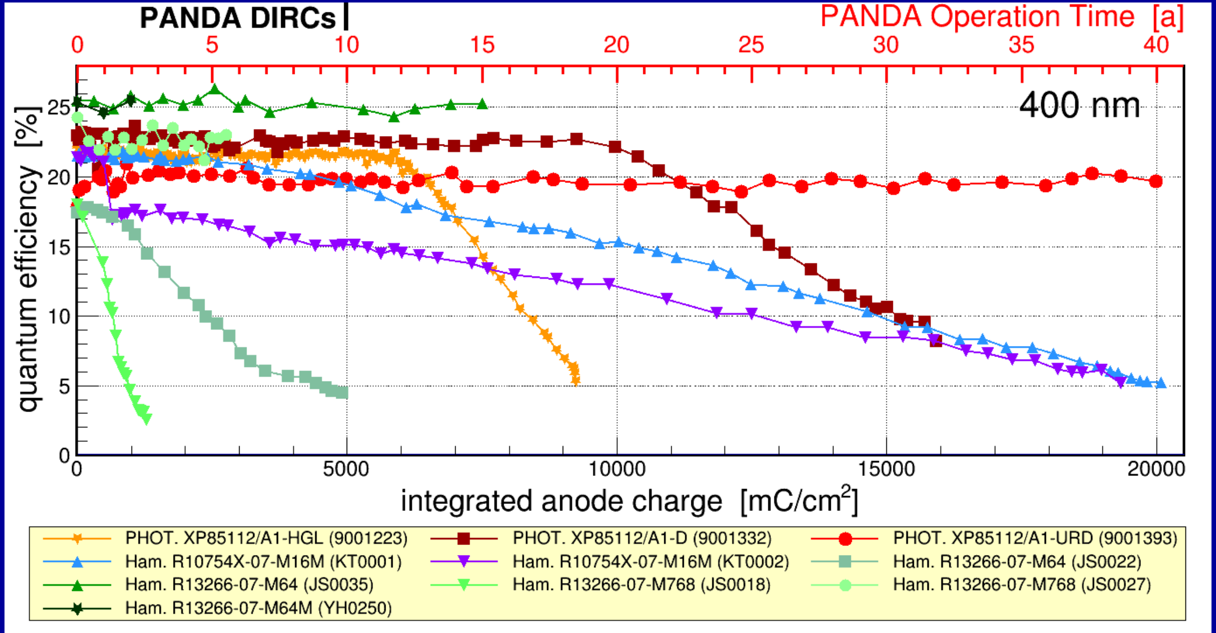


- Older MCPs could operate up to **~200-300 kHz/cm^2** at a gain of 10^6.
- Endcap Panda DIRC MCPs plan to operate rate up to **~2 MHz/cm^2 .**
- Belle-II TOP counter MCPs plan to operate at a rate of **~2 MHz/cm^2**.
- LHCb TORCH MCPs plan to operate at a rate of up to **~36 MHz/cm^2**, or **~2 MHz/one micro-pad**.

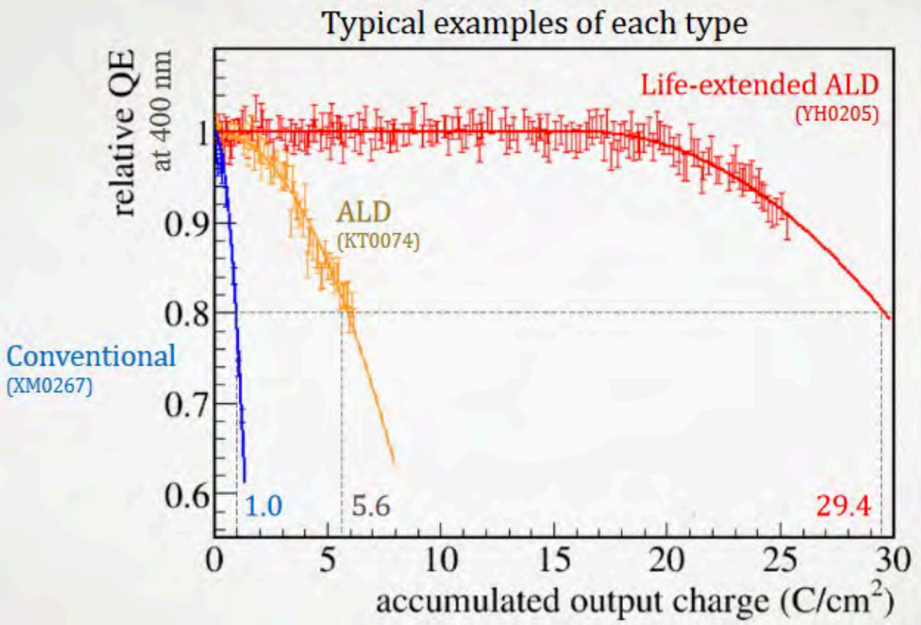
MCP QE aging and total charge

A. Lehmann, RICH 2018 and K. Matsuoka, TIP 2017

PANDA: Albert Lehman, RICH 2018:



Belle-II: K.Matsuaoka, TIPP 2017:



- **Lehmann & Matsuaoka:** Latest Photonis and Hamamatsu MCPs reached **~20 C/cm^2.**
- **Belle-II:** expect total of **~10 C/cm**^{2}.
- **LHCb TORCH:** expect total of **~5 C/cm^2**.

- **<u>Message:</u> New ALD-based treatment has improved MCP QE lifetime significantly.**

Maximum rate and charge dose capability of other detectors

ALICE MRPCs:

Present detector can run at **~500 Hz/cm^2**.

New low resistivity MRPCs will run at **~50 kHz/cm^2.**

Diamond (TOTEM):

This technology is very radiation hard.

High rate capability achieved: **~3 MHz/cm^2.**

SiPMTs:

Operation of some RICH detectors in single photon regime at **$10^{11}n_{eq}cm^{-2}$ & –30 ^oC** is possible.

All SiPMs, even those irradiated up to **10^{14} n_{eq}/cm^2**, are "usable" at **liquid nitrogen** temperature.

LGADs (ATLAS UFSD project) :

Expect rates up to **~40 MHz/cm^2**.

Sensors & ASICs will be exposed to **$3.7x10^{15}$ n_{eq}/cm^2 and 4.1 MGy (!!!)** !!!!

Present test results are very close to this goal.

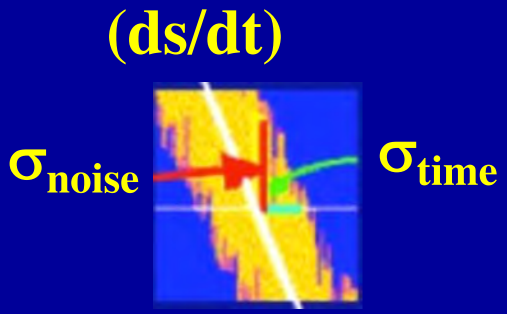
Time measurement

Timing resolution for leading edge timing

(Well-known formula to fast electronics designers for a long time)

A simple formula:

$$\sigma_{time} = \sigma_{noise} / (ds/dt)_{threshold} \sim t_{rise\text{-}time} / (S/N)$$



$S/N = S / \sigma_{noise}$
S = Signal amplitude
$(ds/dt)_{threshold} \sim S / t_{rise\text{-}time}$

- **For LGAD detector with $t_{rise\text{-}time} \sim 400$ps, one needs S/N ~20 get to a ~20 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:

$$\sigma_{Total} \sim \sqrt{[\, (\sigma_{TTS}/\sqrt{N_{pe}})^2 + (\sigma_{pixel}/\sqrt{12})^2 + \sigma^2_{Electronics} + \sigma^2_{Track} + \sigma^2_{to} \ldots]}$$

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

+ there are many other possible effects in a large system:

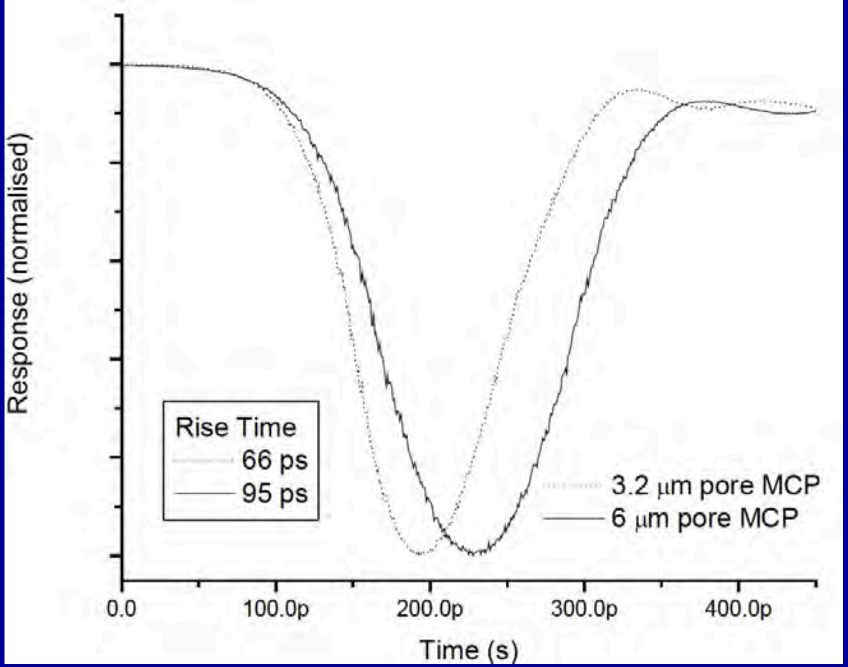
- clock distribution throughout a large system
- cross-talk effects in multi-pixel detectors (ringing in a multi-photon environment)
- baseline oscillation or other instability instability in multi-pixel detectors
- charge sharing in multi-pixel detectors (pixel edge effects)
- chromatic effects
- Unwanted 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**



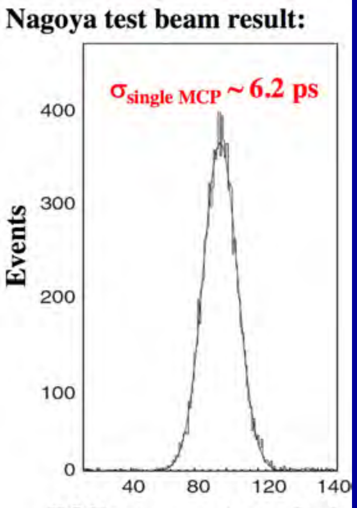
Using the simple formula:
If we assume S/N ~ 20
$t_{\text{rise time}}$ ~66 ps
$\sigma_{\text{time}} \sim t_{\text{rise time}} /(S/N) \sim 3$ ps

MCP-PMT: Single-pixel TOF counter, <u>no amplifier</u>, 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. !!**

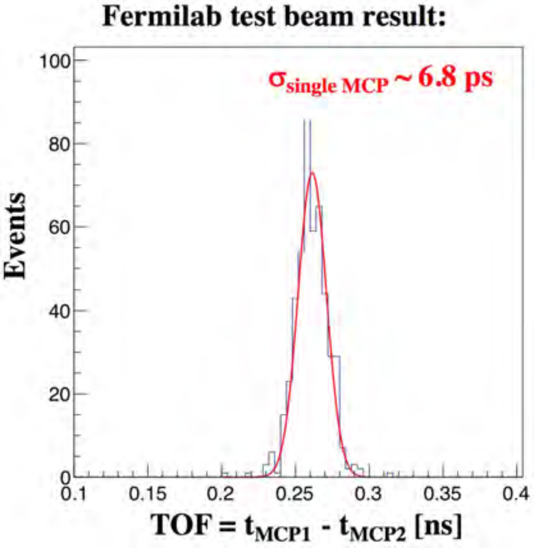


Nagoya test beam result:

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. !!**

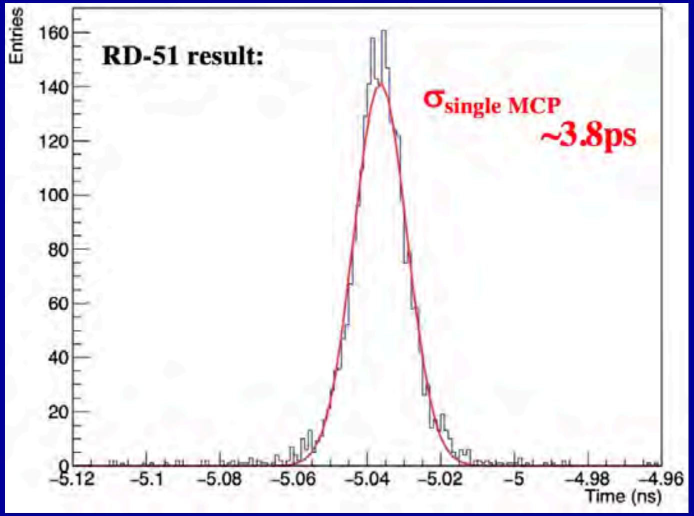


Fermilab test beam result:

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.**



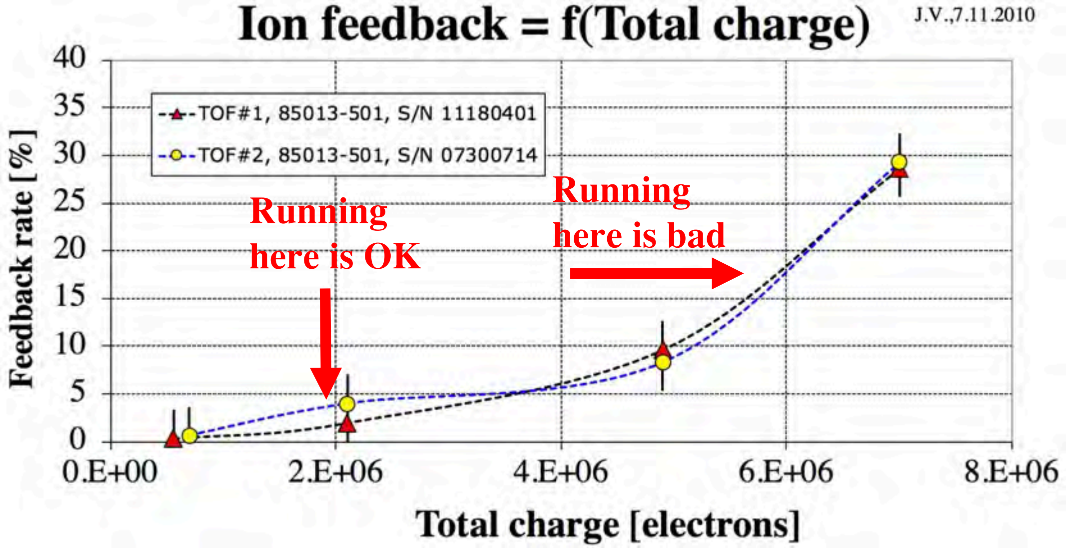
RD-51 result:

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

Why do I want limit total charge on MCP ?

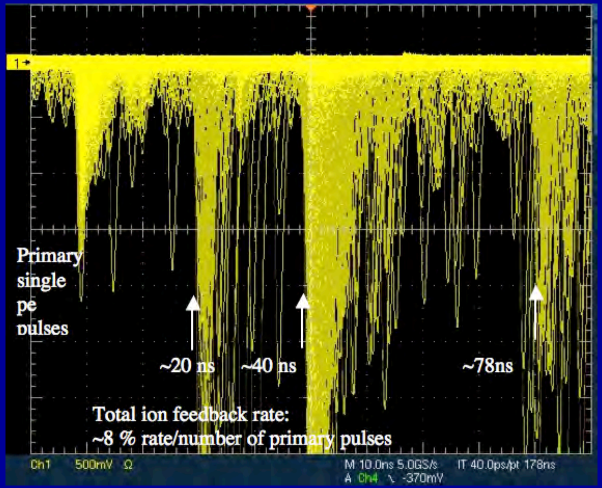
J. Va’vra, MCP logbook #6, page 122, 2010, and https://www.slac.stanford.edu/~jjv/activity/Vavra_Invited_paper_La_Rochelle_2019.pdf.

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



Old Burle Planacon MCP-PMT 85013-501:

Peaks on storage scope correspond to various ions (H$^+$, He$^+$…) **:**



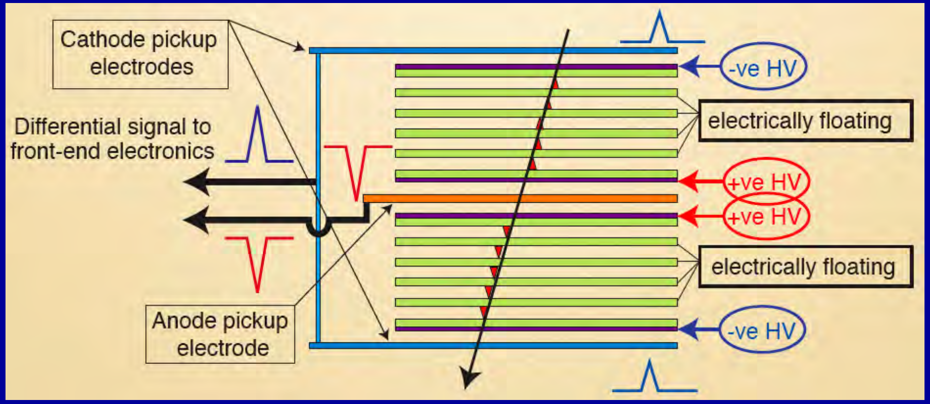
- **<u>Message:</u> One should limit total charge to ~2-3x10^6.**
- Are the new MCPs behaving better ? – see next slide.

Challenges of multi-pixel detectors

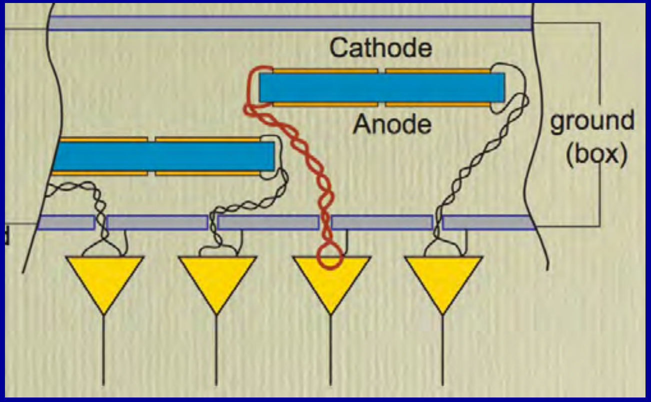
ALICE MRPC TOF detector

C. Williams, private communication, and Jaron et al., Nucl.Instr.&Meth A 33(2004)183

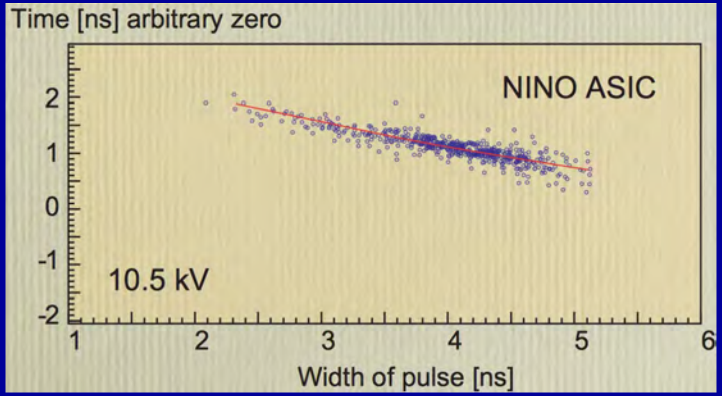
ALICE MRPCs:



Differential input to amplifier:



TOT pulse height correction:

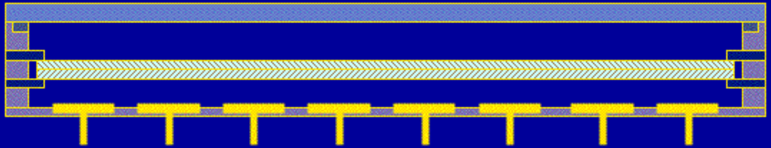


- **Message #1: Differential design throughout to minimize pick-up, cross-talk, etc.**
- **Message #2: Time-over-threshold pulse height correction works if pulse shapes are "clean".**
- **Message #3: NINO electronics provides a low power consumption (40 mW/channel; 1ns-peaking time, 8 ch./chip).**
-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

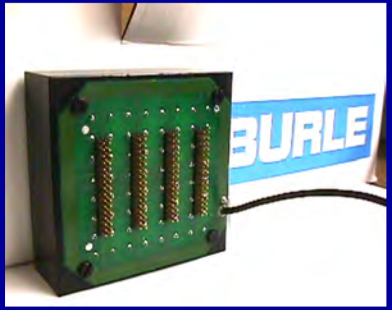
How to connect to Planacon MCP-PMT ?

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

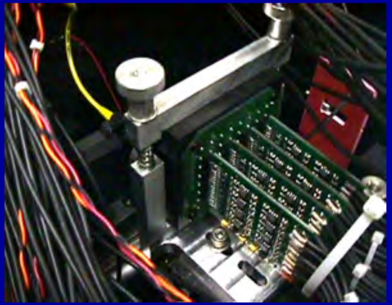


The issue is how to connect to it ? Various schemes which were tried:

Old Burle Planacon:

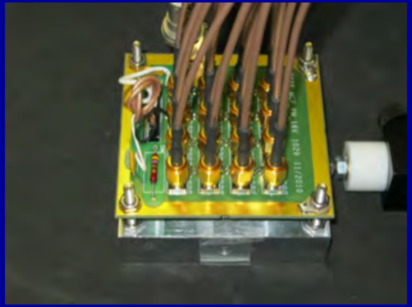


With SLAC amplifier:

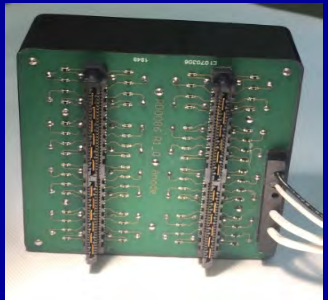


TOP TOF counter:

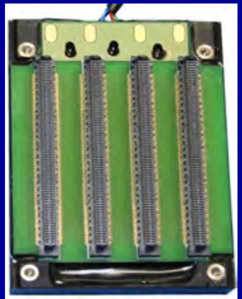
Saclay test:



Latest Planacon:



Latest Photek:



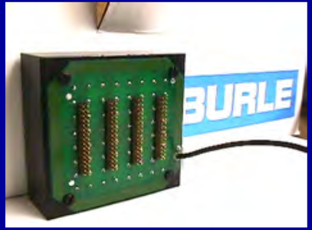
…etc.

- **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.

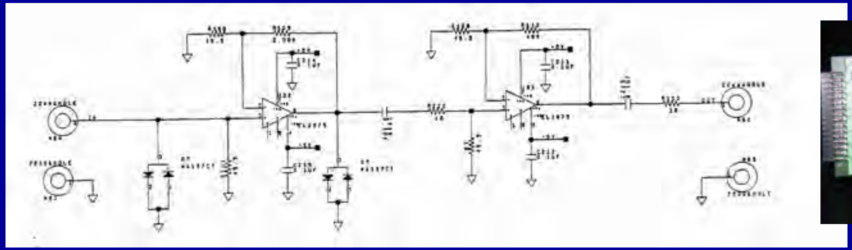
SLAC 1-st FDIRC prototype with 320-pixels in MCPs

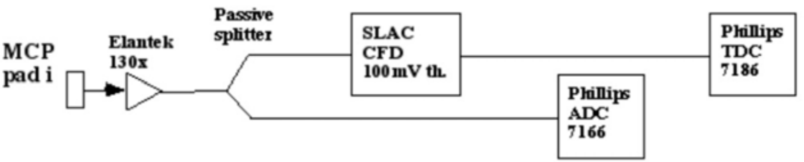
SLAC effort: NIMA 553 (2005) 96

Old Burle Planacon:

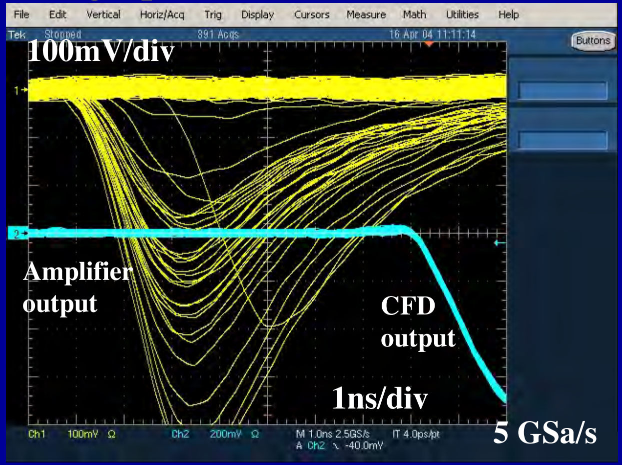


SLAC Amplifier based on Elantek 2075:
Voltage gain of ~130x, and a rise time of ~1.5ns.

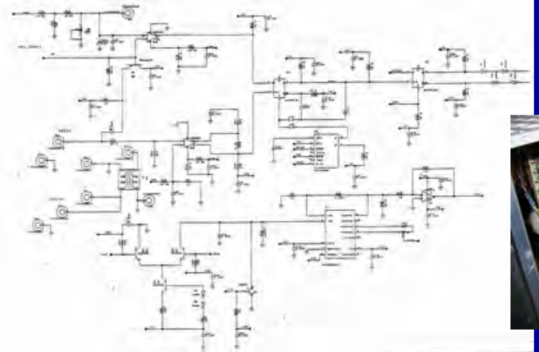




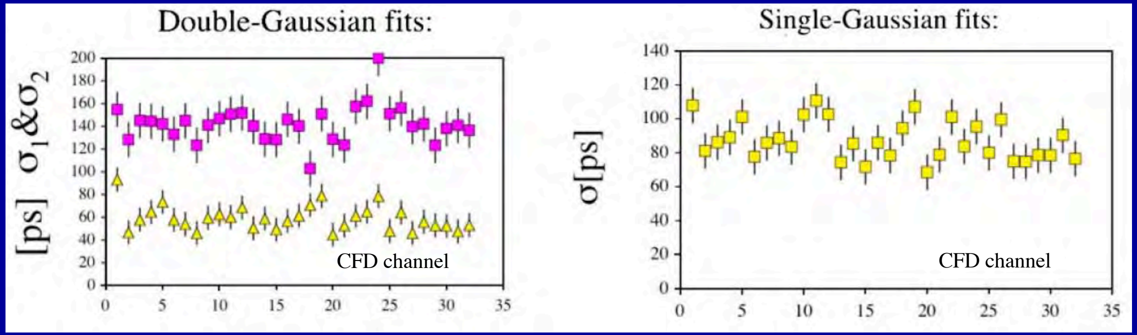
Single photons from laser:



SLAC CFD (32 ch./board):



Single pixel timing resolutions with Planacon MCP:



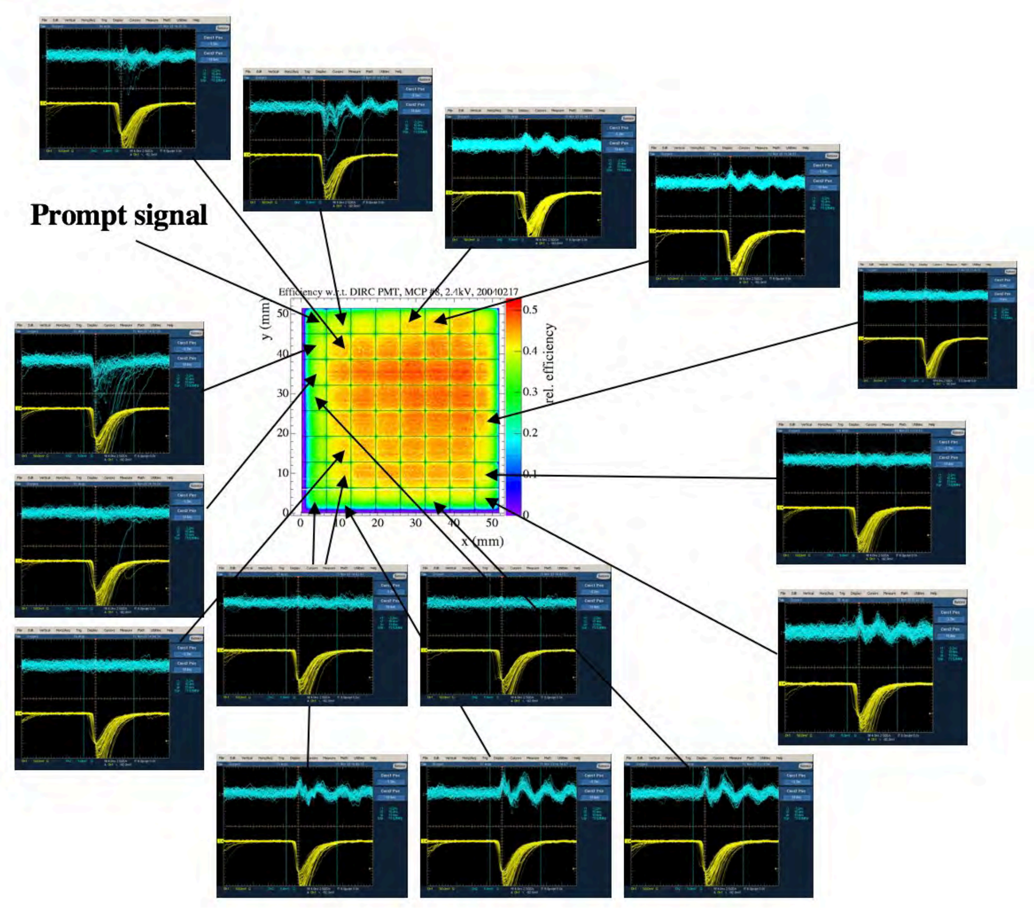
- **Message:** This was still one of the best timing performance of any large RICH detector system with MCPs.

Cross-talk in early version of Planacon MCP 85011-501

J.Va'vra, MCP-PMT log book #1, p.81, 2005

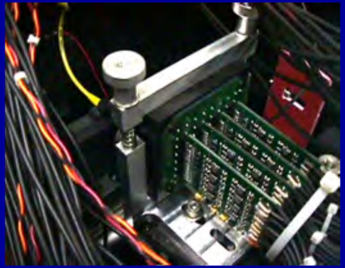
Inject signal to pixel #1 and observe cross-talk in other pixels:

4 ns/div
&
50 mV/div
&
5 mV/div



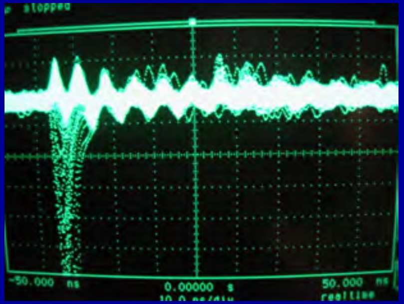
Elctronics used in this test:

Total voltage gain of 130x =
Elantek 2075 amp. 13x + Phillips amp. 10x

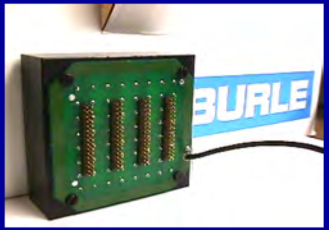


All 64 pixel instrumented

Ringing if too many photons arrive at the same time



Old Burle Planacon:



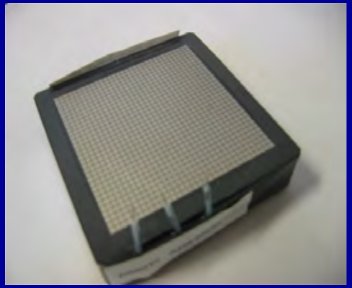
- **<u>Message:</u> The cross-talk was very complicated geometrically on the old Planacon.**
- New MCPs behave better – progress after 15 years ! See appendix.

1024 pixel Burle Planacon – available already in 2005

J. Va'vra, https://www.slac.stanford.edu/~jjv/activity/Vavra_Photon_detector_studies.pdf, 2005, and D. Brasse, Workshop on timing detectors, Clermont, 2010

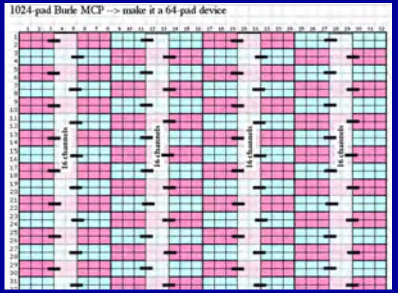
1) FDIRC at SLAC:

Burle Planacon 85021-600 with 1024 pixels:

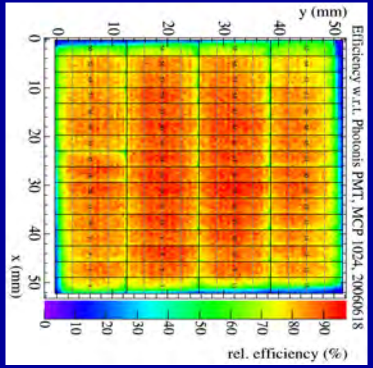


- Small margin around boundary
- 1024 pixels (32 x 32 pattern)
- Small pixel size: ~1.4mm x 1.4mm
- Pitch: 1.6 mm
- Bottom MCP-to-anode dist.: **5.2 mm**

Combine 2 x 8 pixels:

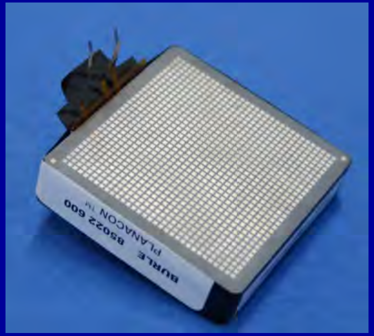


Laser scan:

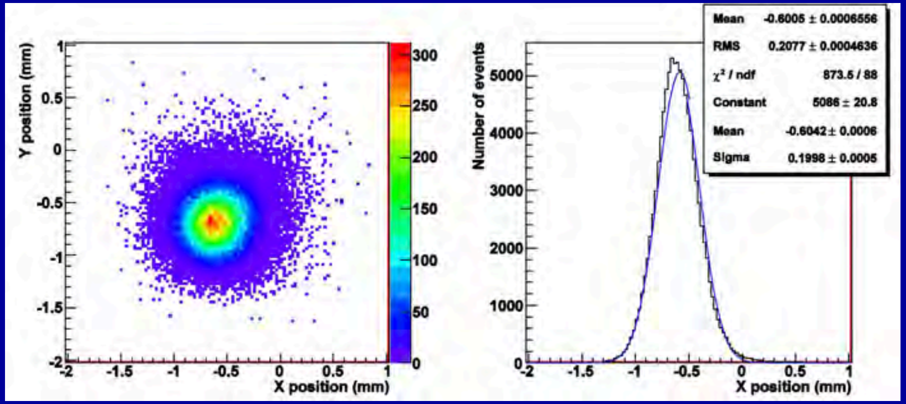


2) µPET: **David Brasse: read every pixel** (MCP coupled to matrix of LYSO crystals)

Planacon 85022-600 (Jeff DeFazio)**:**



- Bottom MCP-to-anode dist.: **3.6 mm**



Point resolution radius ~0.4 mm

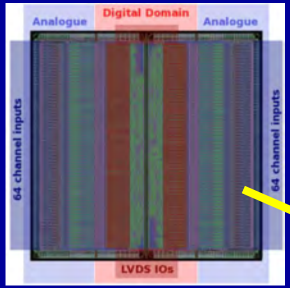
- **Message: In retrospect, we at SLAC, could have chosen 8-channel NINO ASIC to readout every pixel.**

Several large physics applications with MCP-PMTs

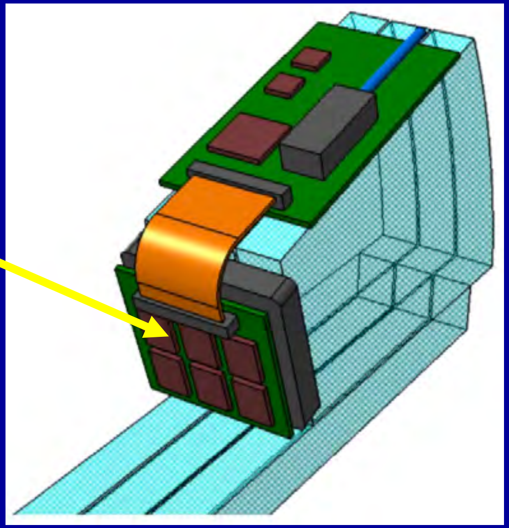
Endcap Panda DIRC: Photonics MCP with TOFPET electronics

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

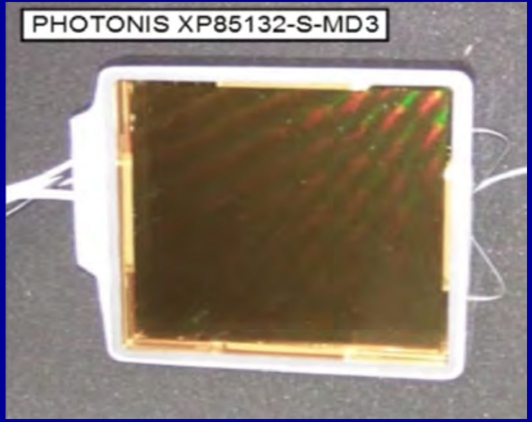
TOPFET ASIC:



Panda Endcap DIRC readout:



New Photonis MCP for Endcap Panda:



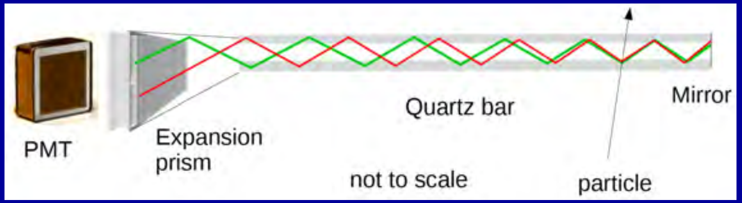
- MCP has 0.4 mm x 17 mm anode pixels.
- 3 rows x 100 strip configuration.
- MCP-Anode gap = 0.625 mm
- Anode strips are grounded by electronics.
- tube does not have a ground plane
(Jeff DeFazio)

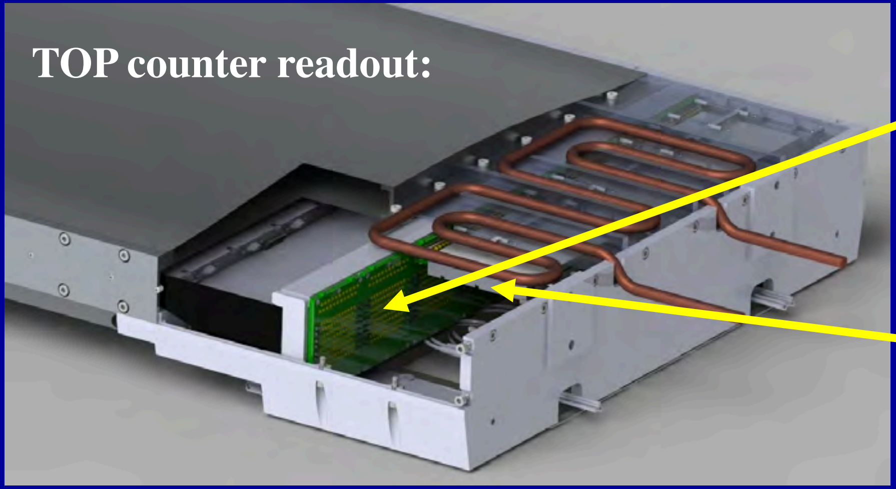
- **Goal:** TTS resolution of ~100ps; presently they got ~320 ps with negative MCP pulses.
- Problem: TOPFET ASIC was designed for positive pulses, i.e. it works well with SiPMTs. There is an effort to talk to company to provide a modification of the ASIC to work with negative MCP pulses.
- **Message: TOPFET2 ASICS is using time-over-threshold timing, it is cheap, electronics has low mass, it is radiation hard and has low power consumption (<10mW/ch).**

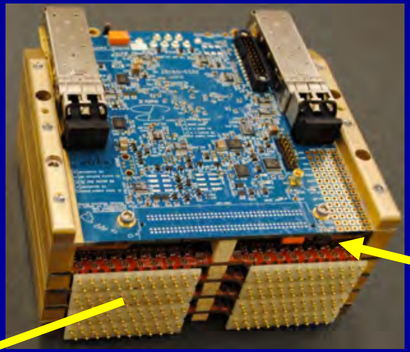
Belle-II: TOP DIRC counter waveform digitizing electronics

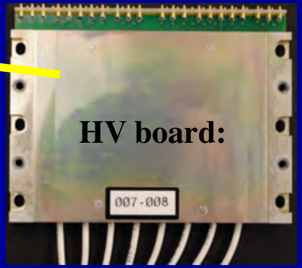
Work led by Gary Varner, Univ. of Hawaii, details in D. Kotchetkov et al., ArXiv:1804.10782, 2018

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

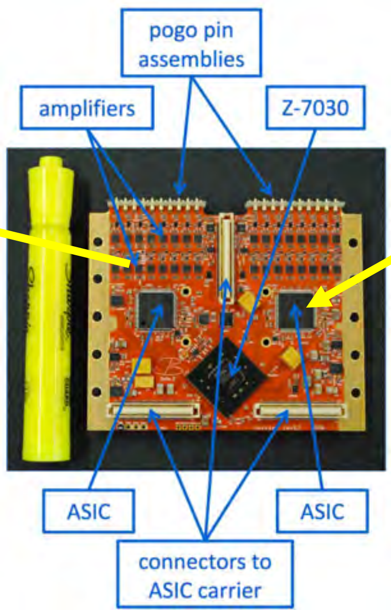



TOP counter readout:



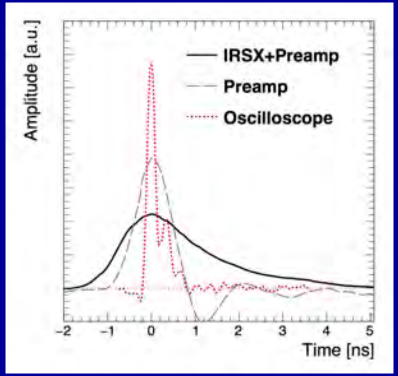

HV board:

Amplifier & ASIC:



IRSX ASIC:

Slow down risetime of preamp to have 2 samples on leading edge:

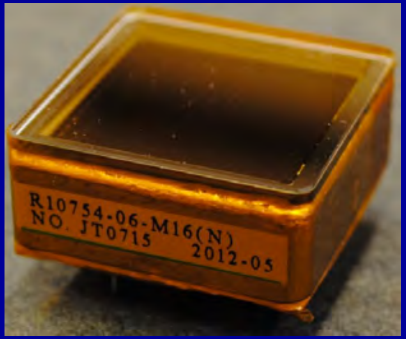


- **IRSX waveform digitizer: 2.7 GSa/sec, an equivalent to a cheap scope on every pixel.**
- **Amplifier gain: ~120x. They slowed down the risetime to have 2 samples on leading edge.**
- **<u>Message:</u> The total power consumption is very high: ~570 mW/channel !**

Belle-II: TOP counter SL-10 MCP-PMT present results

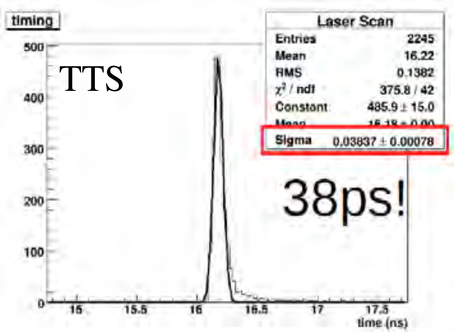
M. Bessner et al., Submitted to NIMA, 2019 and D. Kotchetkov et al., ArXiv:1804.10782, 2018

HPK SL-10 16 pixel MCP:

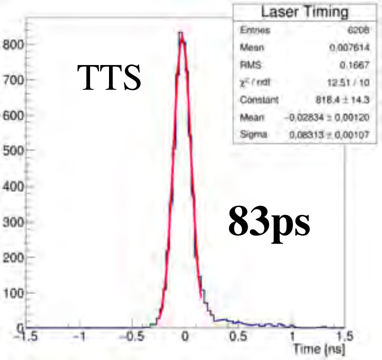


- **16 pixels (4 x 4)**
- **5.3mm x 5.3mm pixel size**

This MCP is capable of excellent TTS resolution:



Bench laser test TTS resolution with final IRSX electronics:

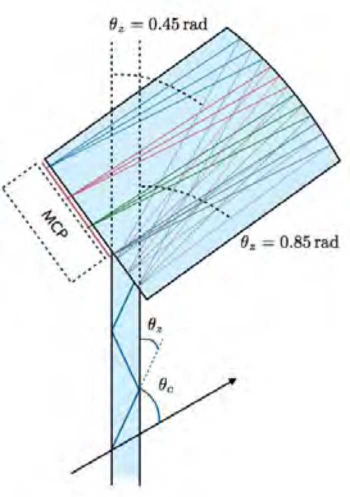


- **Because of a large background, MCP gain had to be lowered to ~3x10^5. As a result of this and other effects, the single photon timing resolution in Belle-II is presently: 80-120ps.**
- **Max photon rate is kept < 4 MHz/MCP. Some non-ALD coated MCPs will have to be replaced in 2020.**

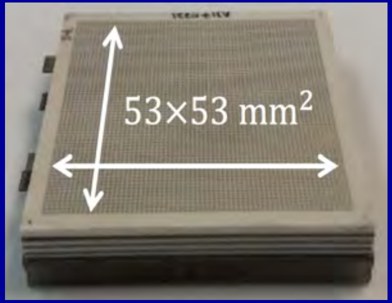
LHCb: TORCH TOF MCP-PMTs

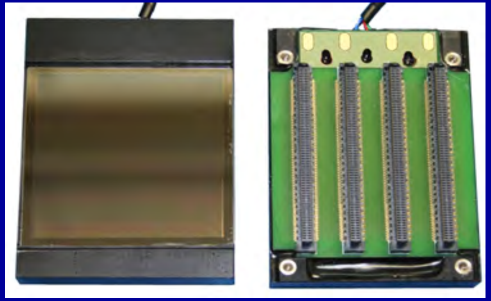
N. Harnew, RICH 2018, J.S. Lapington et al., NIMA 695(2012)78, T.M. Conneely et al., JINST, May 2015 and S. Bhasin et al., to be published in NIM

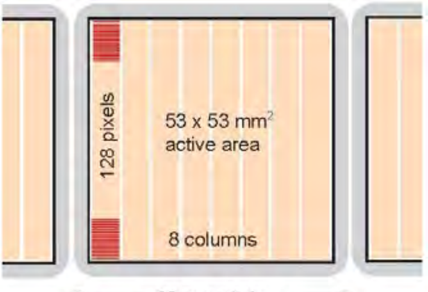
TORCH DIRC:



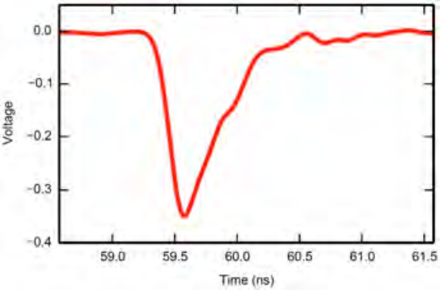
Photek MCP:







Single pe raw pulse:



- **Charge is collected on resistive layer and capacitively coupled to the anode pads. This allows charge sharing to improve the spatial resolution beyond the anode-pad pitch of 0.828 mm.**
- **8 × 64 pixel readout (with charge sharing it makes an effective 8x128 pixel readout)**
- **Active area: 53 × 53 mm²**
- **Point spread function: ~1.3 mm (FWHM) – with a laser**

- **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.
- **<u>Message #1</u>: TOT timing with 32-channel NINO ASIC works well, although calibration is complicated.**

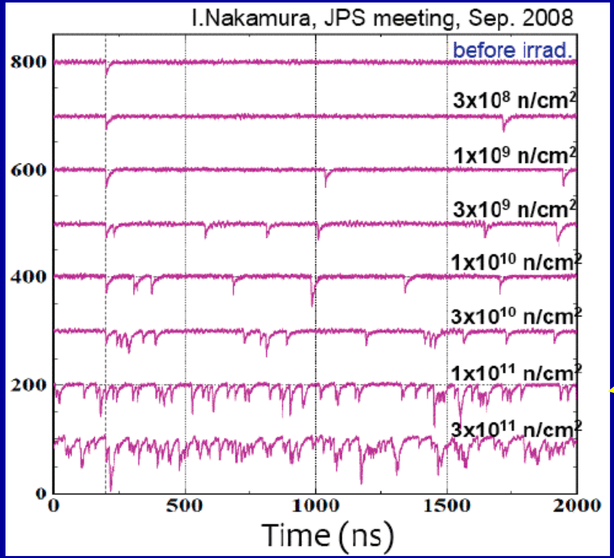
Si detectors

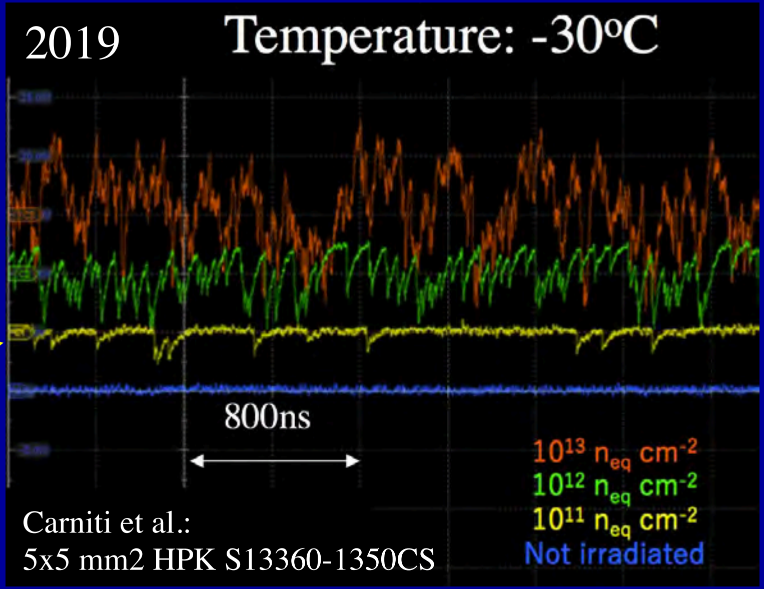
SiPMTs radiation hardness is an issue for RICH detectors

Nakamura, JPS meeting, 2008, M. Calvi et al., NIMA 922(2019)243, C.Woody, EIC PID workshop, 2019, and B. Biro et al., arXiv:1809.04594, 2019

Room temperature:

~1 MeV proton or neutron irradiation:


I.Nakamura, JPS meeting, Sep. 2008



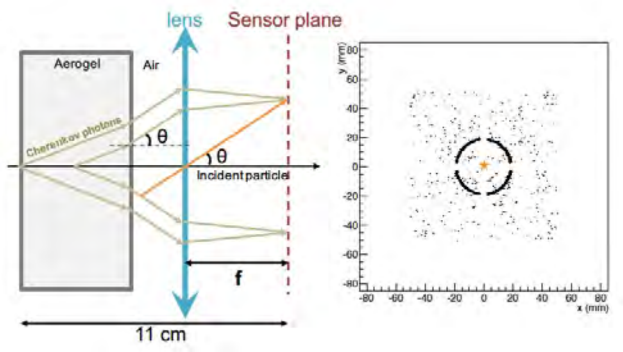
Carniti et al.:
5x5 mm2 HPK S13360-1350CS

- **<u>Message #1</u>: High energy protons and neutrons produce the most damage. Damage from thermal neutrons is observed only at high doses. Gammas produce comparatively lower damage.**
- **<u>Message #2</u>: Lower temperature can reduce noise rate caused by the neutron damage. All SiPMs, even those irradiated up to 10^{14} n_{eq}/cm^2, are “usable” at liquid nitrogen temperature. Operation for RICH detectors in single photon regime at $10^{11} n_{eq} cm^{-2}$ 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)

Optics with Fresnel lens:



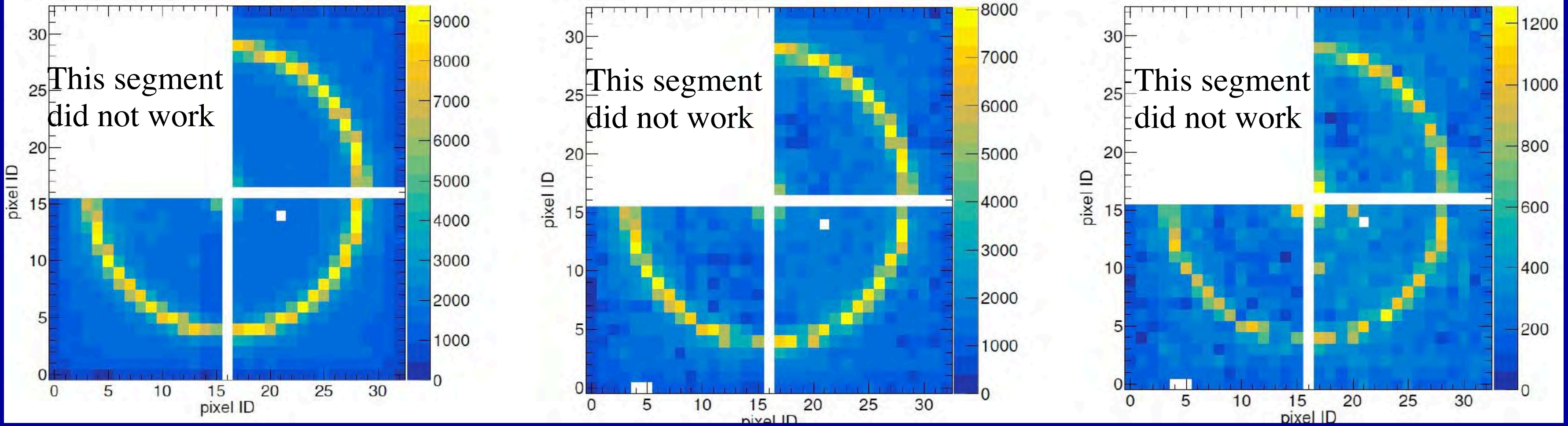
Smaller and thinner ring image compared to Belle-II dual radiator proximity focusing ARICH

~120 GeV proton test beam of Aerogel RICH:

-30 ^{o}C:

-20 ^{o}C:

Room temperature:

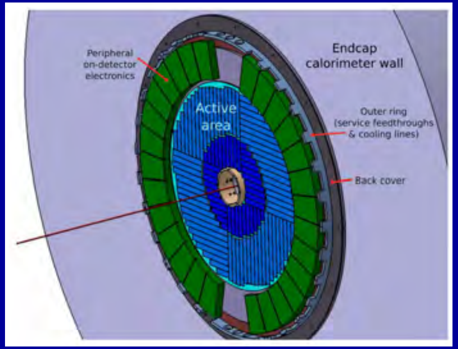


- **Hamamatsu SiPMT 16 x 16 matrix with 3 mm x 3 mm pixel sizes; ~100ps timing is possible.**
- **<u>Message:</u> Low temperature clearly helps to reduce the room temperature noise.**

ATLAS Endcap Low Gain Avalanche Diodes

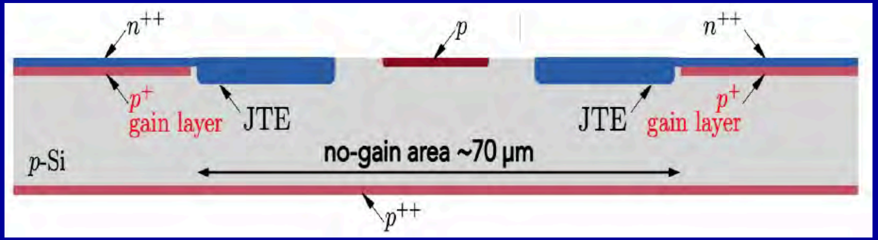
H. Sadrozinski, private communication, ATLAS technical proposal, 2019, and
G. Paternoster, https://indico.cern.ch/event/803258/contributions/3582777/attachments/1963858/3265168/203-Arcidiacono-UFSDstatus.pdf
R. Arcidiacono, https://indico.cern.ch/event/803258/contributions/3582956/attachments/1963922/3265196/362_Paternoster_HSTD12-2.pdf

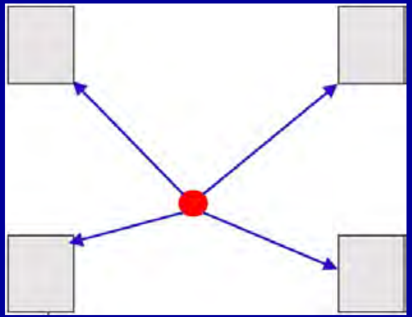
ATLAS UFSD Endcap:



12 cm < r < 60cm
7888 sensor modules

Present design have a region of no gain:



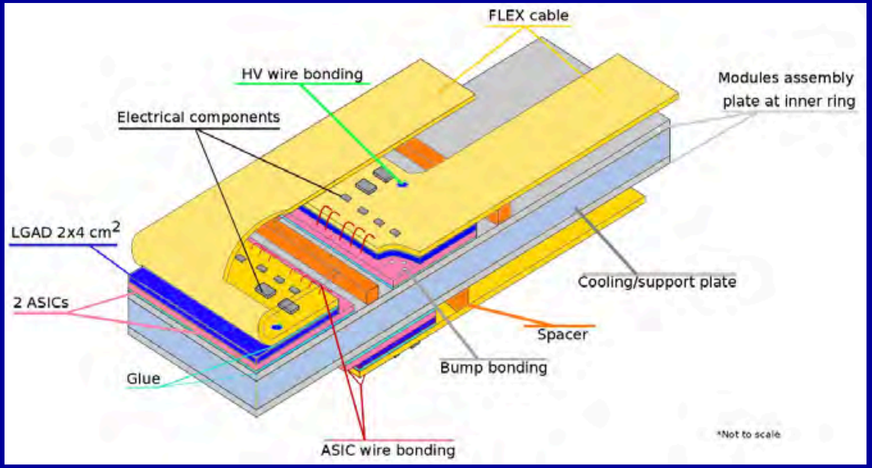


Position and time are determined by amplitude-weighted centroid using four pads

Present design:

Pitch: 1.3 mm
Gap: ~ 70μm
Fill factor: ~90%

LGAD sensors, ASICs, cooling and connection package:



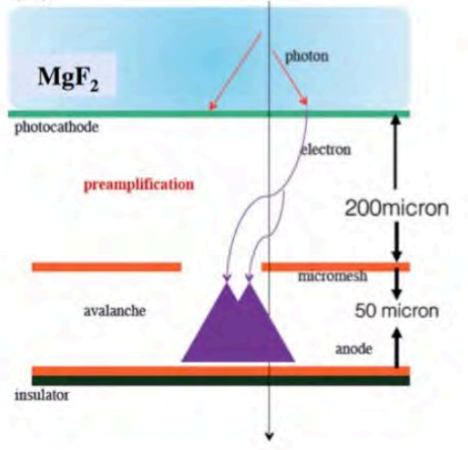
- **Bench tests: Very good timing and position resolution results using a laser (σ ~ 10's of ps & 10's of μm).**
- **Radiation damage: They reached ~3x10^{15} n$_{eq}$/cm^{2} and 4 MGy, i.e., very close to the final goal.** (1 MGy = 100 Mrads !!).
- Two ASICs, ALTIROC (ATLAS) and ETROC (CMS) under development.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

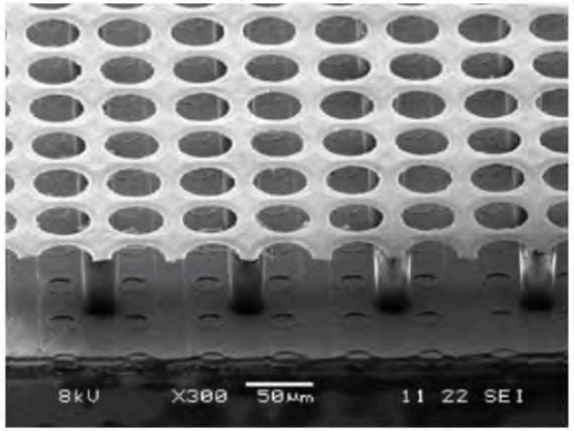
Gas detectors

Gasous detectors: Timing with Micromegas

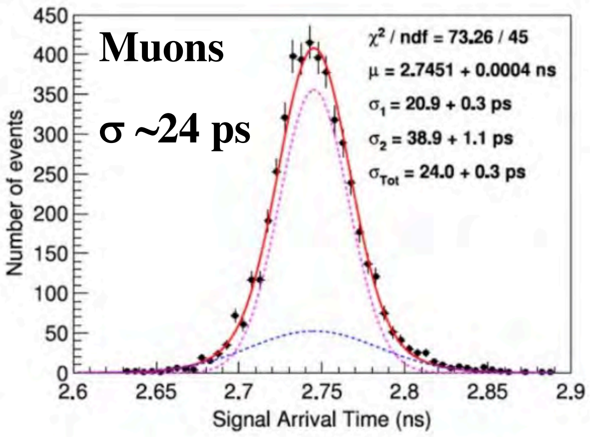
Y. Giomataris, private communication, and J. Bortfeldt et al., arXiv:1901.03355, 2019

Micromegas principle:

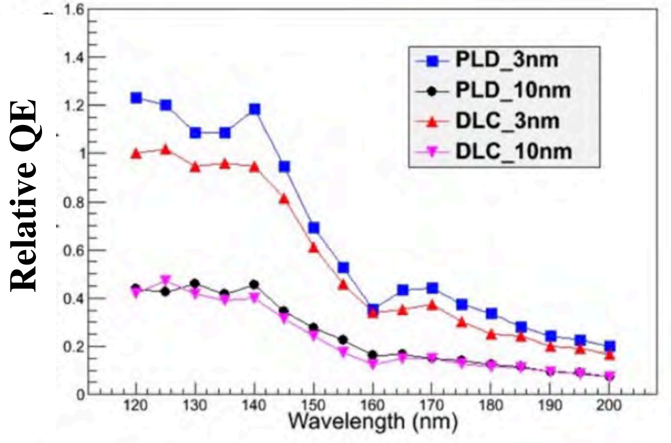




Result with CsI photocathode:



Diamond-based photocathode:



- **Pixel size: ~1cm^2 area**
- Photocathodes: CsI or DLC (diamond-based photocathode)
- Gas: 80% Ne+10% CF_4+10% C_2H_6
- **3 mm MgF_2 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.; <u>need a factor of 3 improvement of QE</u>.**
- **<u>Message:</u> 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 promissed 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 **~60 ps/MIP** and rate capability of **~500 Hz/cm^2**.

New R&D: MIP rate up to **~50 kHz/cm^2** with a new low resistivity glass are under study.

MCPs: MIP timing resolution of **<10 ps/MIP** with a single-pixel MCP achieved.

Single photon timing resolution of **~30-100 ps/photon** achieved.

Endcap DIRC in Panda: expect rates up to **~1 MHz/cm^2** for single pe's @gain of 10^6 .

TORCH at LHCb: expect rates up to **~40 MHz/cm^2** !!

Panda R&D: anode charge dose up to **~20 C/cm^2** using single pe's with Photonis MCP.

TORCH: The 1-st generation of Photek MCPs reached **~3-4 C/cm^2**.

The latest Hamamatsu MCPs almost reached **~20C/cm^2**.

Diamond (TOTEM): MIP timing resolution of **~80 ps/MIP** achieved.

This technology is very radiation hard.

High rate capability achieved: **~3 MHz/cm^2.**

SiPMTs: MIP timing resolution of **~13 ps** achieved in a beam test.

Significant noise increase after ~10^{10} neutrons/cm^2.

Cooling helps.

LGADs (ATLAS UFSD project) :

MIP timing resolution of **~30 ps/MIP**, and **~16 ps/MIP** for tandem of three achieved.

Expect rates up to **~40 MHz/cm^2**.

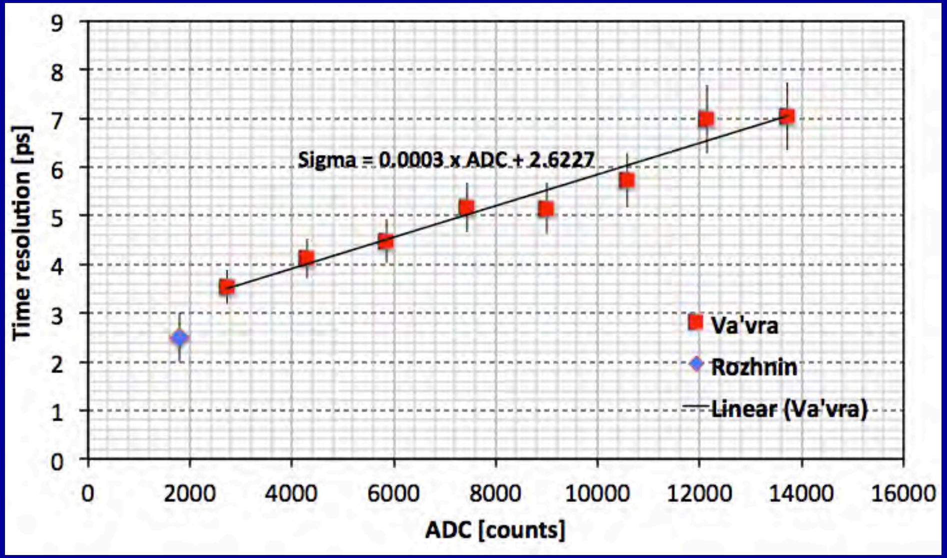
Sensors & ASICs will be exposed to **3.7×10^{15} n_{eq}/cm^2 and 4.1 MGy (!!!)** in ATLAS !!!!

Present test results: OK up to **3×10^{15} n_{eq}/cm^2 and 4 MGy** .

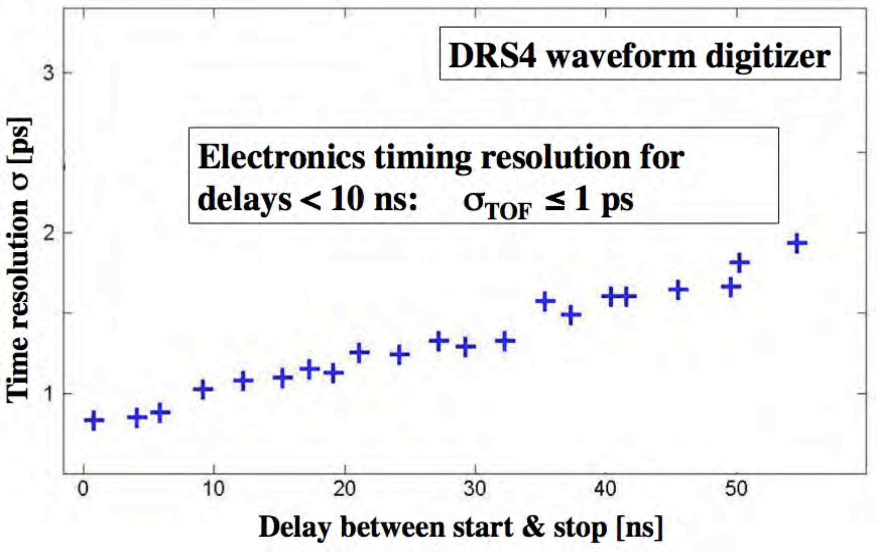
Micromegas (CsI): Timing resolution of **~24 ps/MIP** and **~76 ps/photon** achieved in a beam test.

Electronics for the best timing result

Ortec 9327 amp. + CFD + TAC electronics:
SLAC: J. Va'vra, MCP-PMT log book #4
Fermilab: A. Ronzhin et al., NIM A 623 (2010) 931



DRS4 waveform digitizing electronics
made by Stefan Ritt:
http://dx.doi.org/10.1109/TNS.2014.2366071



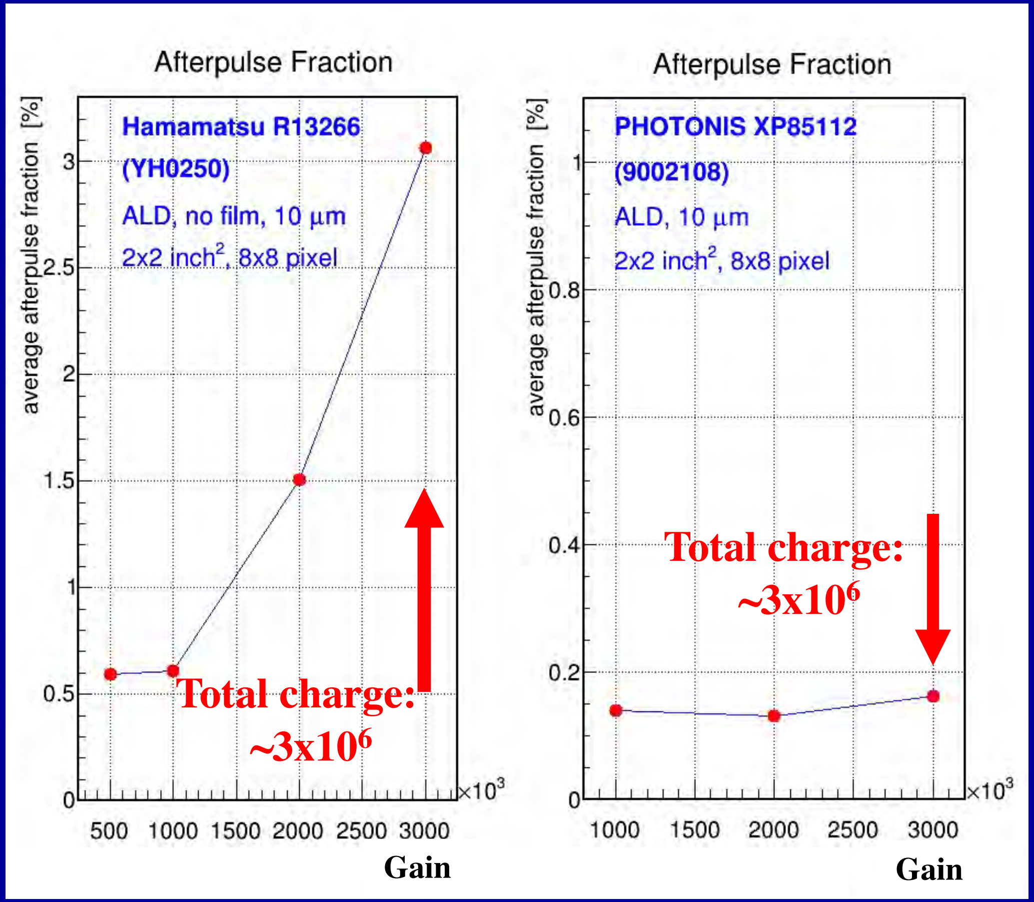
- **Ortec 9327 Amp/CFD can reach $\sigma_{Electronics}$ ~2 ps resolution, if one avoids TAC electronics.**
- **DRS4 waveform digitizer can reach $\sigma_{Electronics}$ < 1 ps for very small delay between start & stop.**
- **20 GSa/s scope with CFD algorithm can reach $\sigma_{Electronics}$ ~2 ps.**

- **Message: If your electronics contributes ~2 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:



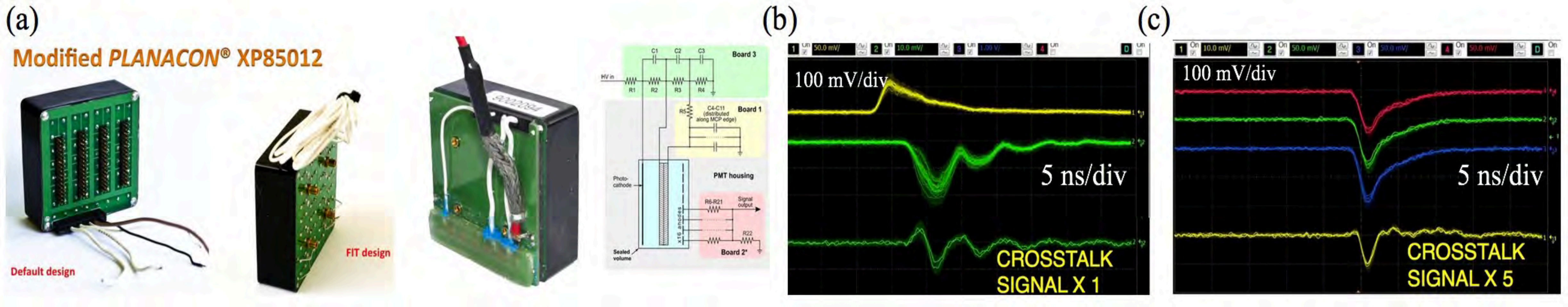
- **Photonis XP85112 MCP-PMT performs well at a total charge of ~3x10^6**
- **Hamamatsu R13266 sees an increase in the rate already at a total charge of ~1.5x10^6.**

Cross-talk in Multi-pixel MCPs

FIT group at ALICE: Modification of Planacon MCP 85012

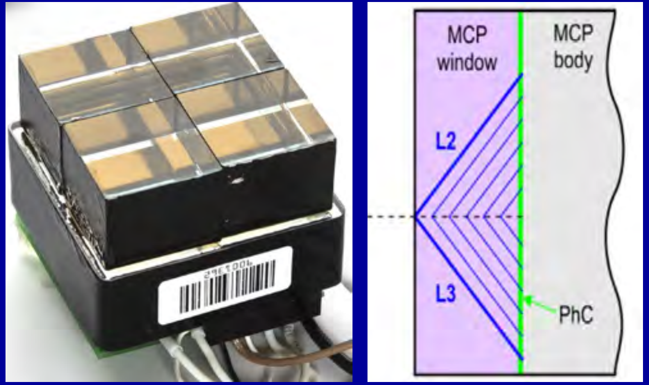
Y.A. Melikyan on behalf of ALICE, RICH 2018, MCP modifications done by Jeff DeFazio, Photonis.

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



- **<u>Message:</u> 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.**

FIT detector concept to detects MIPs:



- **<u>Goal of FIT:</u> Timing resolution σ ~ 30 ps/track**

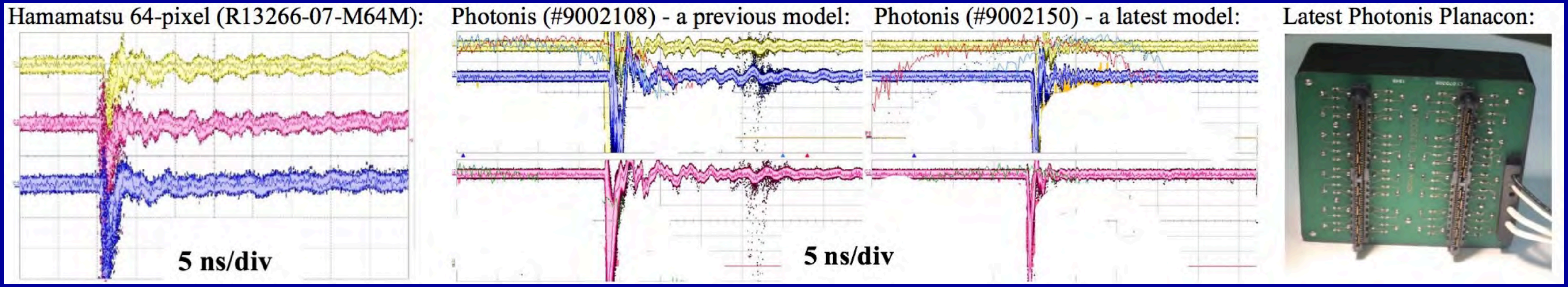
Panda R&D: Latest update on ringing of new 64-pixel Planacon

Albert Lehman, private communication, May 7, 2019, and Jeff DeFazio, private communication,

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:

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.**

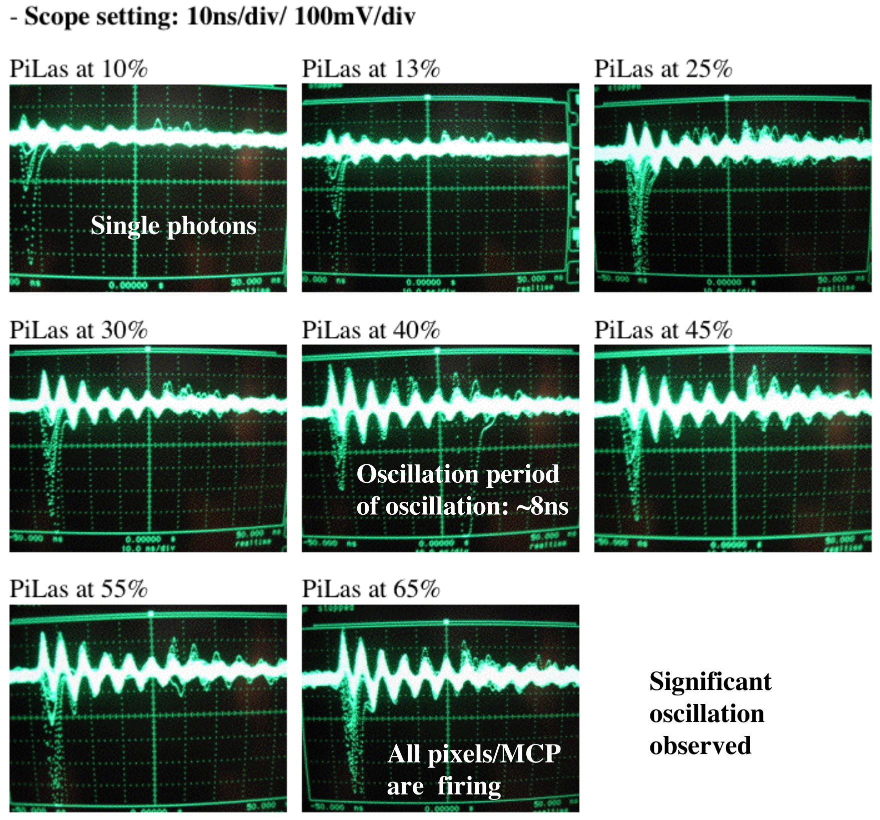
Ringing in early version of Planacon MCP vs. MaPMT

J. Va'vra, FDIRC logbook "Beam_test_Focusing_DIRC_3.pdf", p.53, 2006

Pilas laser

10ns/div
&
100mV/div

Early version of Planacon MCP-PMT 85011-501:



- **Scope setting: 10ns/div/ 100mV/div**

PiLas at 10%

Single photons

PiLas at 13%

PiLas at 25%

PiLas at 30%

PiLas at 40%

Oscillation period of oscillation: ~8ns

PiLas at 45%

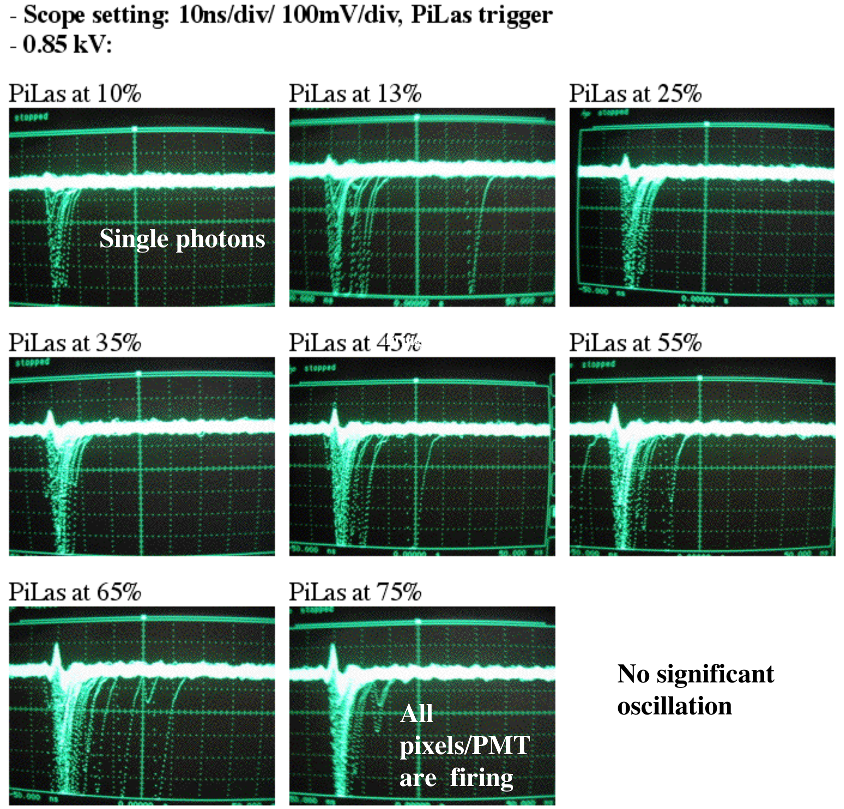
PiLas at 55%

PiLas at 65%

All pixels/MCP are firing

Significant oscillation observed

8500 MaPMT:



- **Scope setting: 10ns/div/ 100mV/div, PiLas trigger**
- **0.85 kV:**

PiLas at 10%

Single photons

PiLas at 13%

PiLas at 25%

PiLas at 35%

PiLas at 45%

PiLas at 55%

PiLas at 65%

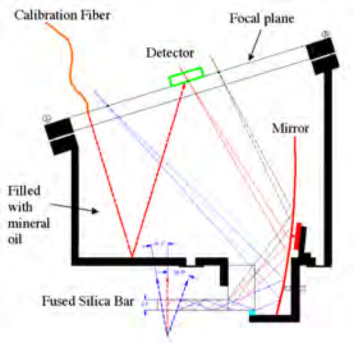
PiLas at 75%

All pixels/PMT are firing

No significant oscillation

Scope trigger: Pilas laser

FDIRC



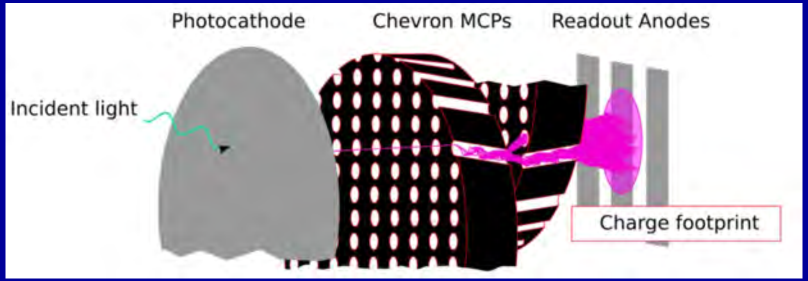
- **Message:** Amplitude of ringing increases with number of photons hitting MCP. Had to increase the discriminator threshold to avoid fake hits.
- **H-8500 MaPMT with the same electronics was OK.**

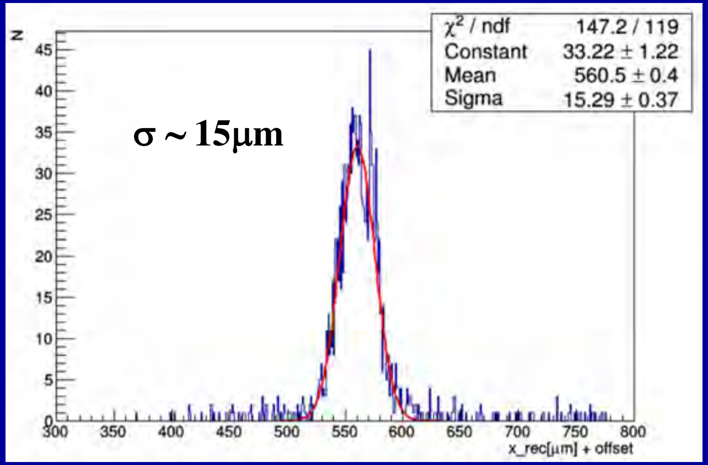
MCPs in magnetic field

Endcap Panda: MCP charge footprint in magnetic field can be very small

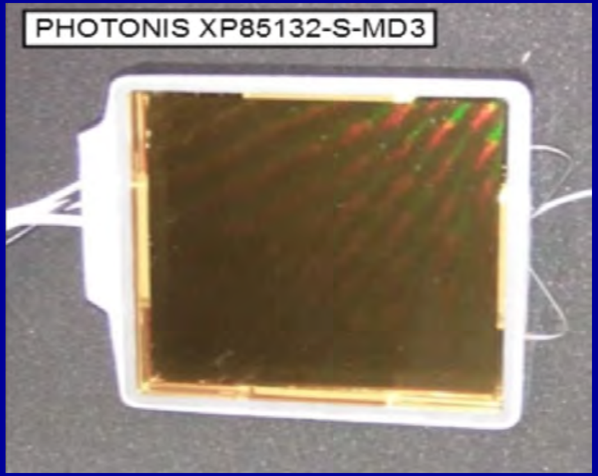
J. Rieke et al, JINST 11, 2016, and Panda Endcup DIRC TDR, 2019

Anode charge footprint:





New Photonis MCP for Endcap Panda:

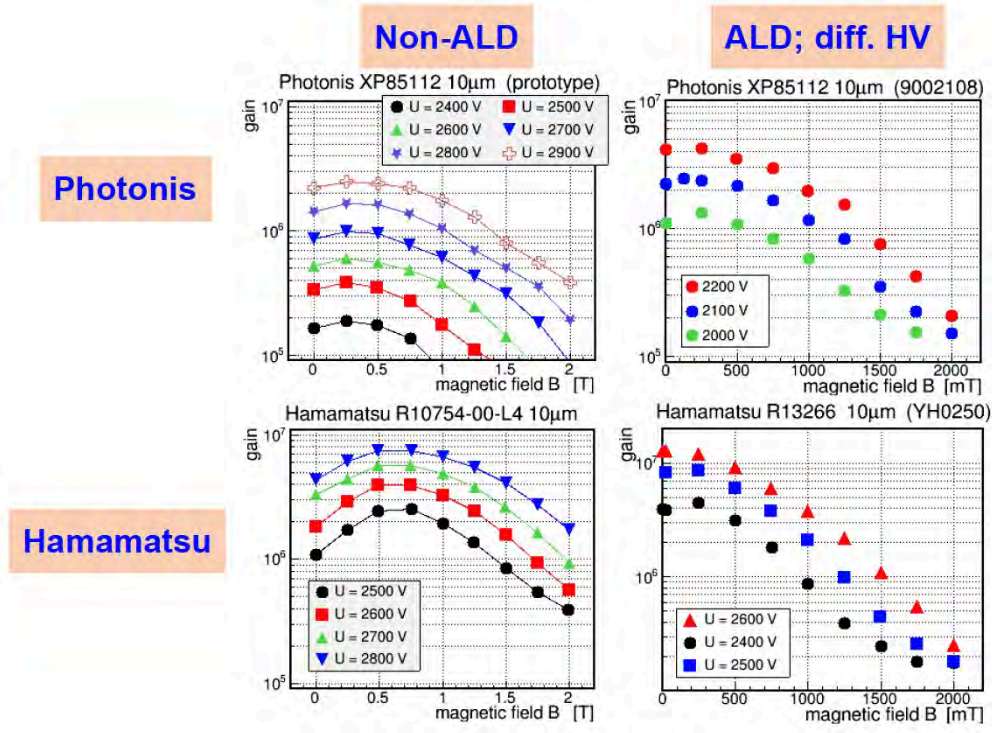


- MCP has 0.4 mm x 17 mm anode pads.
- 3 rows x 100 strip configuration.
- MCP-Anode gap = 0.625 mm
- tube does not have a ground plane

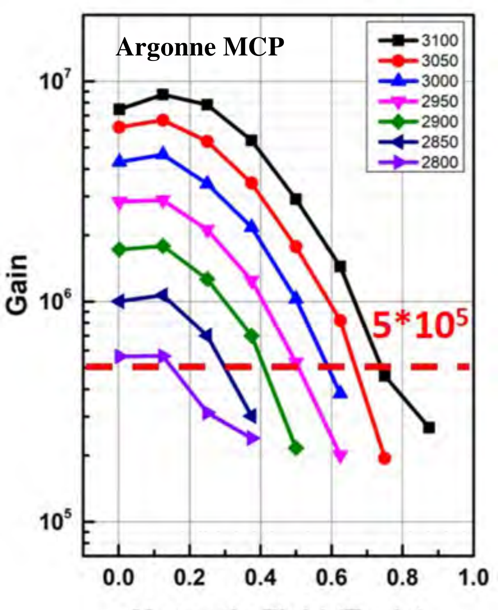
- Message: A magnetic field of only ~0.1 T will reduce the charge footprint to ~15μm !!

MCP gain in magnetic field

A. Lehman, RICH 2018, Moscow:



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



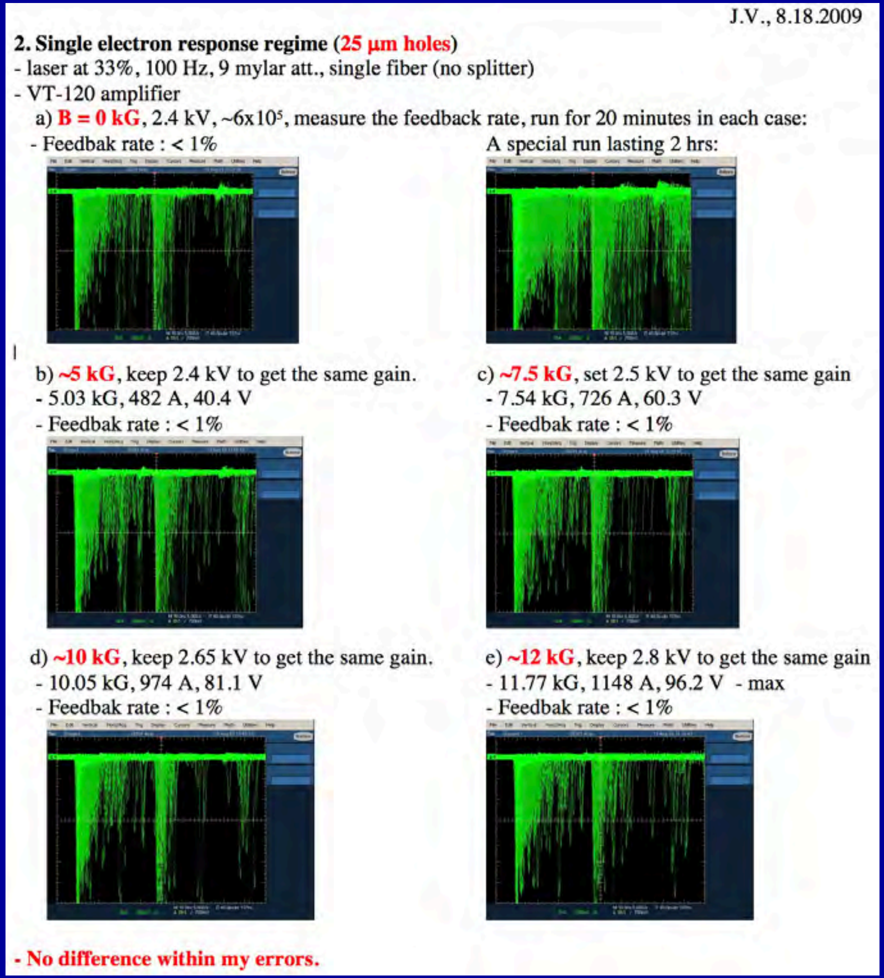
- **ALD tubes seem to show faster gain drop in B-fields than non-ALD tubes !**
- Photonis 9002108: gain drop by a factor of 2 at 1 Tesla, at 0 deg.
- Hamamatsu YH0250: gain drop by a factor of 4 at 1 Tesla, at 0 deg.
- Argonne ALD-coated MCP: gain drop by a factor of more than 10 at 1 Tesla, at 0 deg.

Ion feedback in MCP = f(B)

J. Va'vra, Log book #7, 2009

Single photoelectrons:

As magnetic field increased adjust voltage to keep the gain constant at ~6x10^5:



J.V., 8.18.2009

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, ~6x10^5, measure the feedback rate, run for 20 minutes in each case:
- Feedbak 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
- Feedbak rate : < 1%

c) **~7.5 kG**, set 2.5 kV to get the same gain
- 7.54 kG, 726 A, 60.3 V
- Feedbak rate : < 1%

d) **~10 kG**, keep 2.65 kV to get the same gain.
- 10.05 kG, 974 A, 81.1 V
- Feedbak rate : < 1%

e) **~12 kG**, keep 2.8 kV to get the same gain
- 11.77 kG, 1148 A, 96.2 V - max
- Feedbak rate : < 1%

- No difference within my errors.

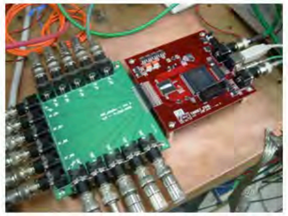
- **Message:** No increase in the ion feedback observed within my errors.

FDIRC development at SLAC

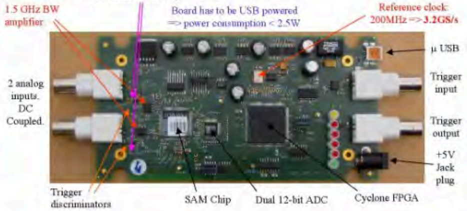
Can one do timing with low total charge ?

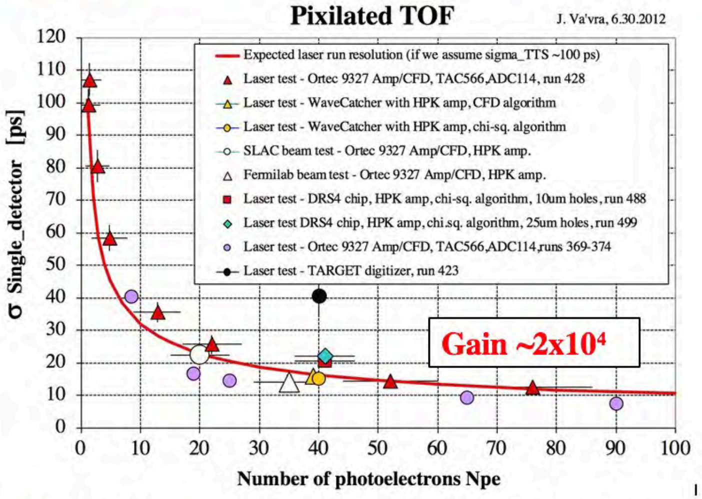
J. Va'vra, MCP log book #7, 2012, NIMA 629 (2011)123, and NIMA 606 (2009) 404

TARGET chip (Gary Varner):
(with HPK C5504-44 amp.)

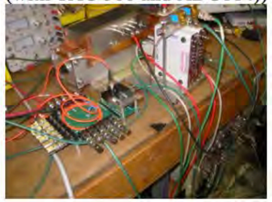


WaveCatcher v.5 (Dominique Breton):
(with HPK C5504-44 amp.)

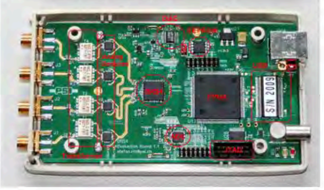




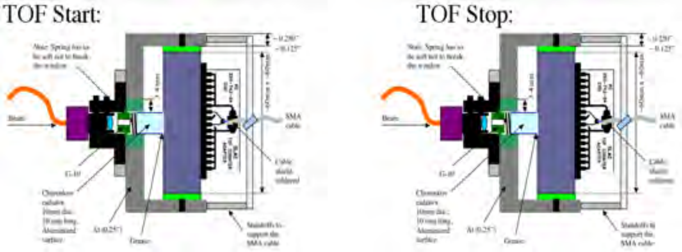
Ortec 9327 amp/CFD electronics:
(with TAC 566 and ADC114))



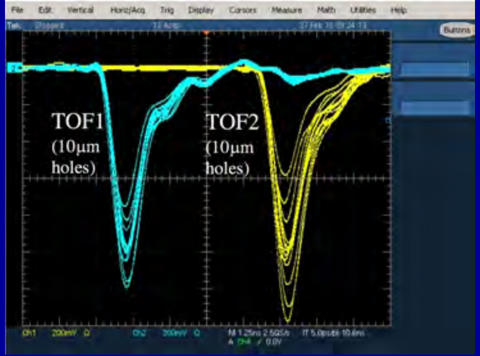
DRS4 (Stefan Ritt):
(with HPK C5504-44 amp.)



2 Burle old Planacon 10µm MCP-PMT 85013-501:
(4 pixels ganged together, others grounded)



Pulses from Planacon 85013-501 with HPK C5504-44 amp. with a gain of 63x :



- Low gain ~2×10^4 , vary Npe (1-100)
- Total charge: ~8×10^5 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

SLAC effort: J.Va' vra, log book #3, p.23, 2006

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

<u>Using our simple formula</u>:

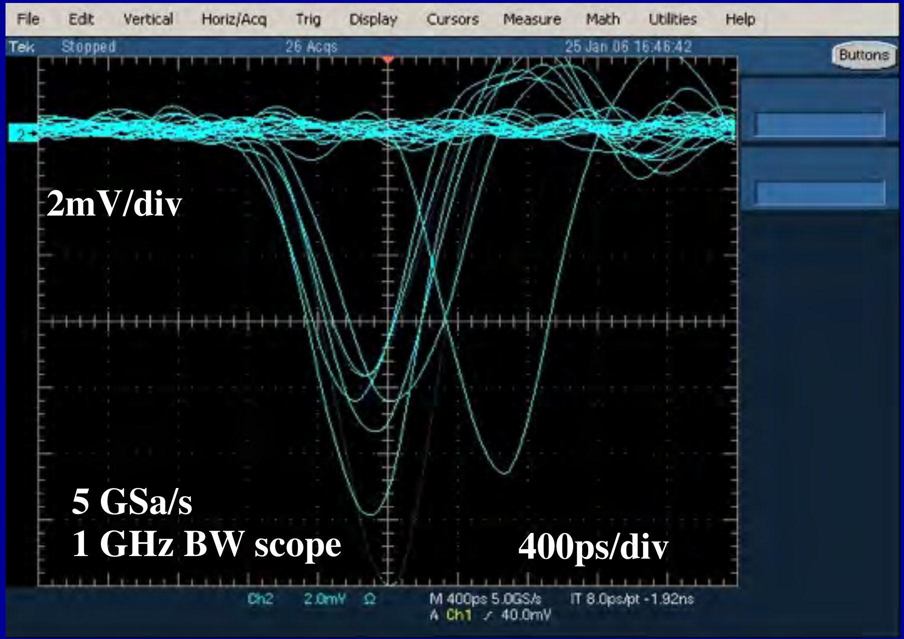
σ_{noise} ~ 0.4 mV

S ~ 8 mV

S/N ~ 8/0.4 ~ 20

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

σ_{time} ~ $t_{rise\ time}$ /(S/N) ~7-10 ps

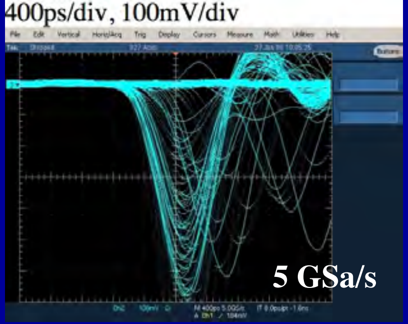


- **That told me that one can reach a very good resolution with this MCP**

A good TTS resolution even with slower electronics

SLAC effort: J.Va'vra, log book 3, p. 27, 28 & 37, 2006, and NIMA 572 (2007) 459

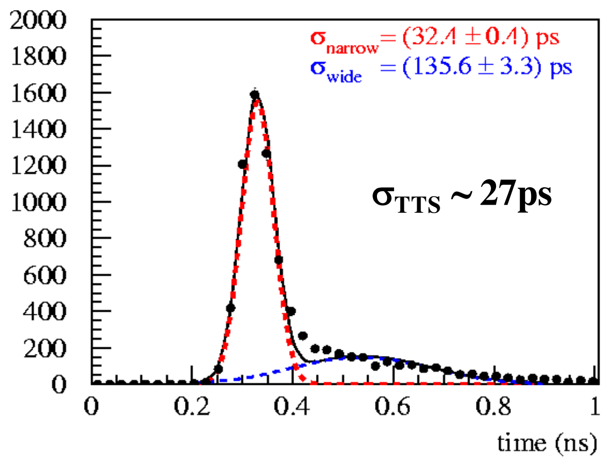
Planacon 85013-501 single electron pulses with Hamamastu 63x amplifier C5504-44 :



- **10 µm MCP hole diameter**
- **Gain ~10^6 , Npe = 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

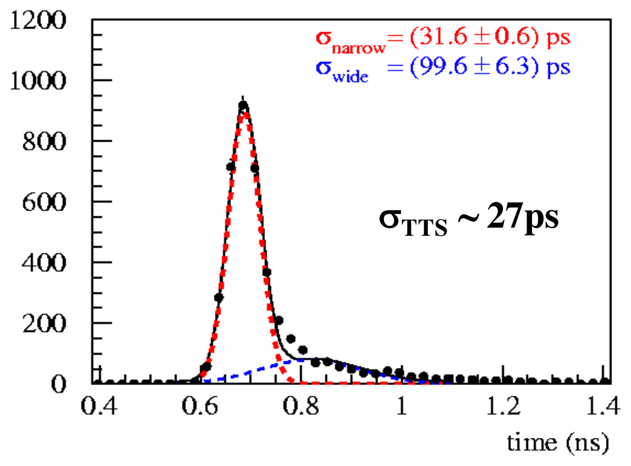
Hamamatsu C5594-44 amplifier

1.5 GHz BW, 63x gain, 2.8kV



Ortec VT120A amplifier

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

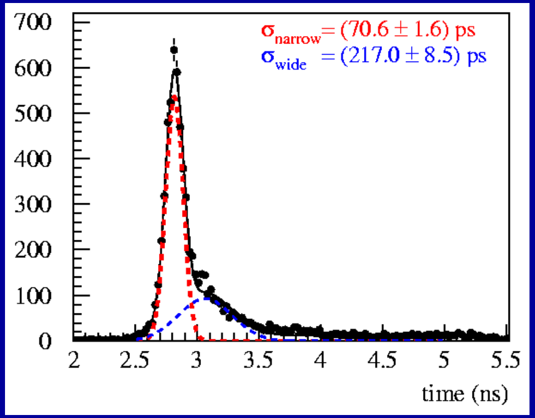


- **One can obtain a good TTS resolution even with a slower amplifier, if one has a good S/N ratio, and one tunes CFD discrimination carefully.**

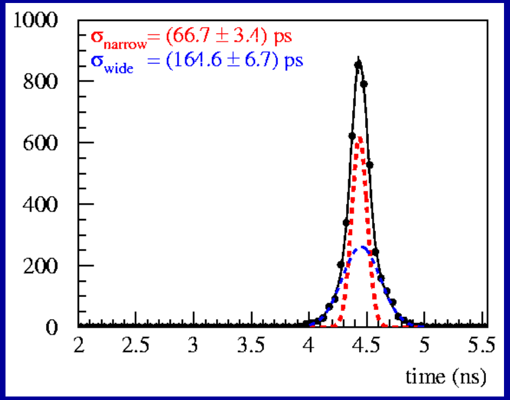
MCP-to-cathode distance - a way to eliminate tail

SLAC effort: NIMA553(2005)96

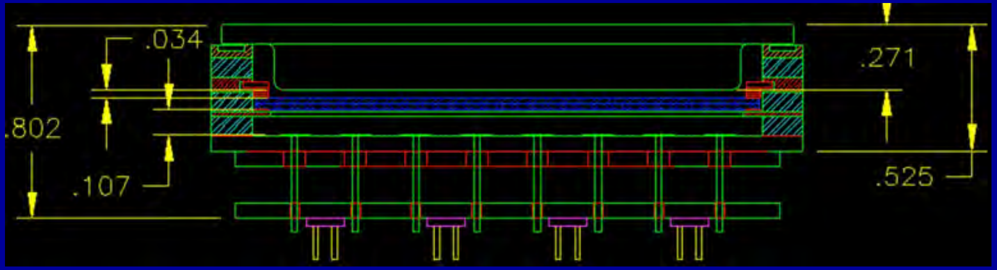
MCP-to-Cathode distance = 6 mm
85011-501 Nominal design:

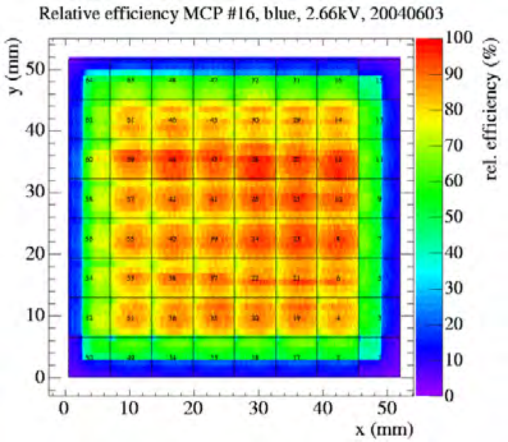


MCP-to-Cathode distance ~0.85 mm
85014-430 Drop Faceplate:



Planacon stepped face MCP (85014):



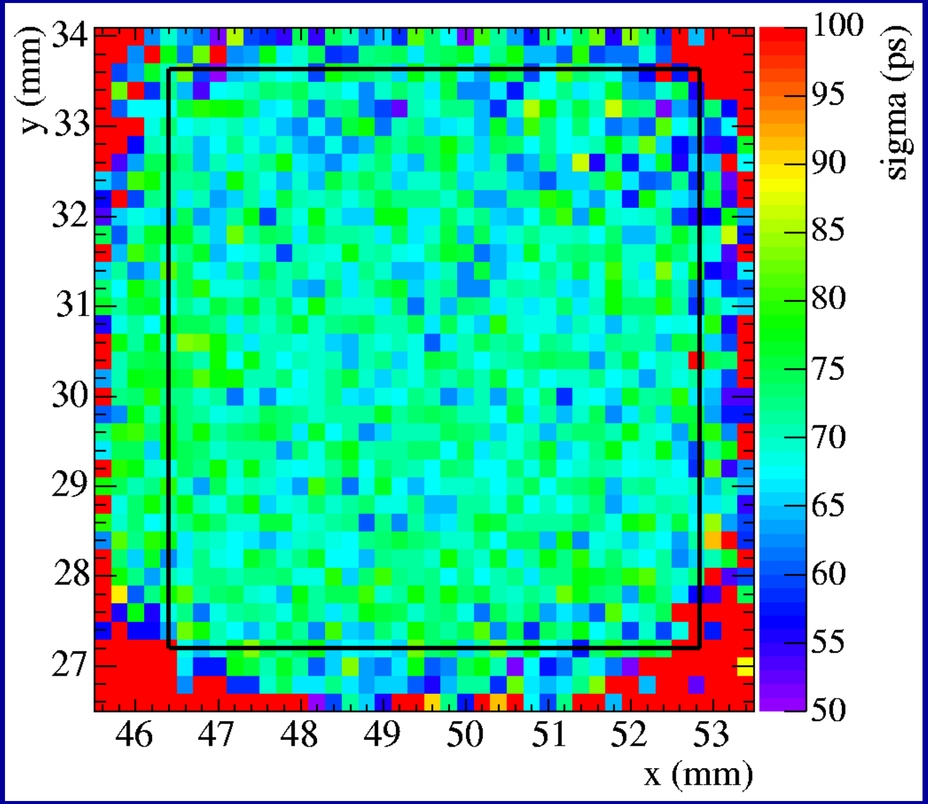


- **Penalty: the efficiency drops to zero half way through all edge pads.**

Pixel edge effects in MCP timing

SLAC effort: NIMA 553(2005)96-106

Scan of timing resolution on one 5mm x 5mm pixel with single photoelectrons:



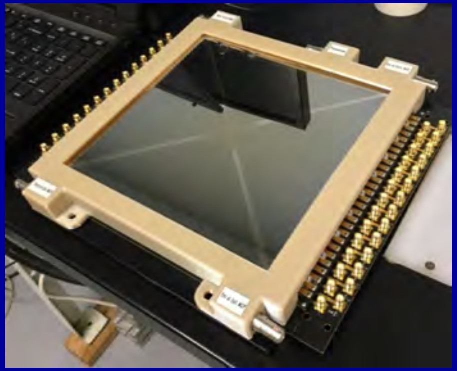
- **Pixel edges and corners have worse timing resolution due to charge sharing.**
- **In principle, it can be corrected if one has knowledge of a photon entry. But that entry point is usually not known.**

LAPPD MCPs

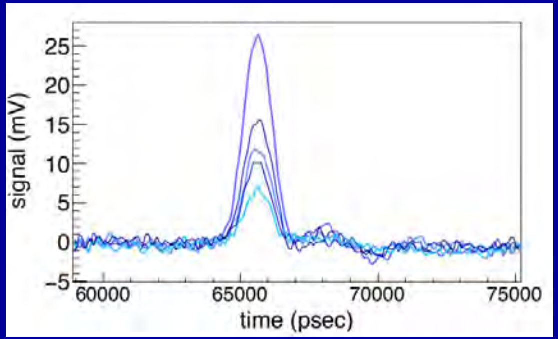
LAPPD 8”x8” MCP detectors with strip readout

M.J. Minot et al., http://www.incomusa.com/mcp-and-lappd-documents/, 2/6/2019

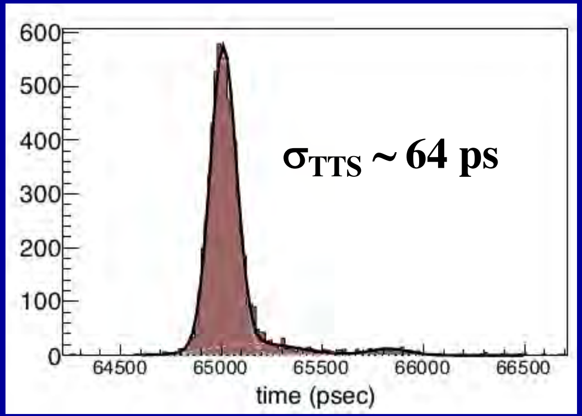
LAPPD detector with strips:



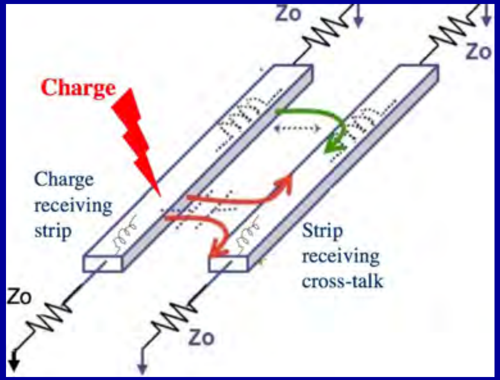
Strips: Single pe pulses (LAPPD #25):



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)



Using a simple formula:

S/N ~ 15

$t_{\text{rise time}}$ ~850 ps

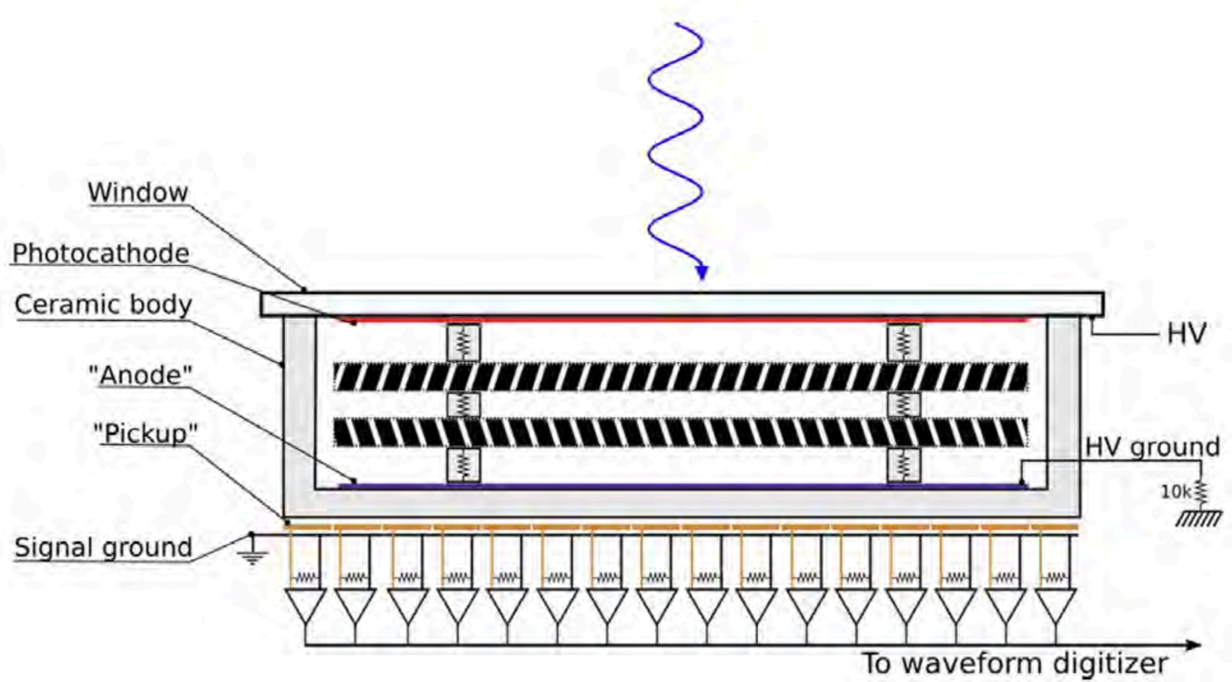
$\sigma_{\text{time}} \sim t_{\text{rise time}} /(S/N)$ ~60 ps

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

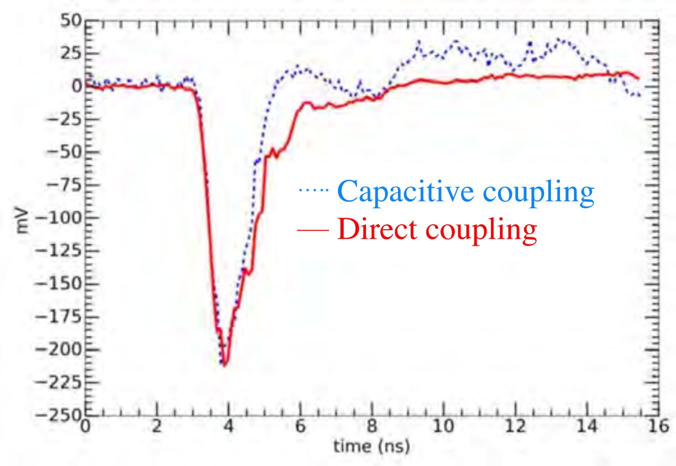
LAPPD 8”x8” MCP detectors with pixel readout

Angelico et al., NIMA 846 (2017) 75

LAPPD detector concept with capacitively coupled pixels:



Pixels: capacitive vs. direct coupling pulses:



- **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

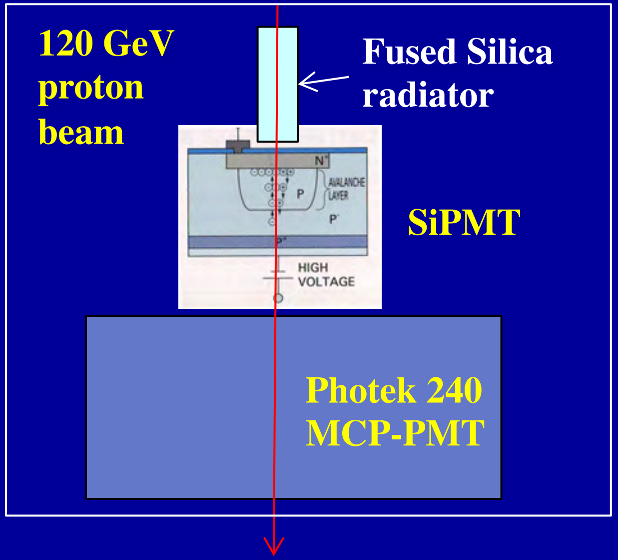
Si detectors: High gain SiPMTs

A. Rozhnin et al., Fermilab, Talk at Picosecond timing workshop, Arlington, Oct. 5-7, 2015

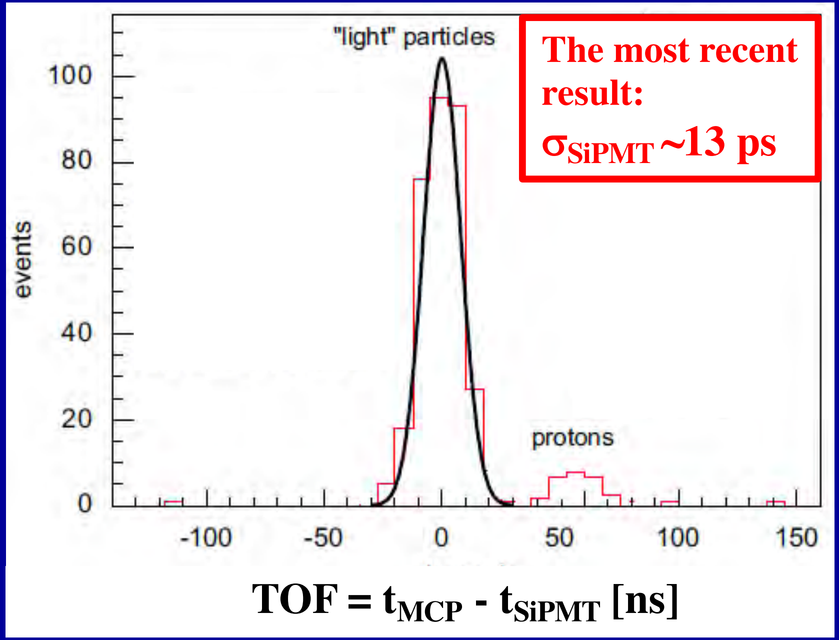
Start: SiPMT, Stop: Photek-240 MCP-PMT

- SiPMT: 3x3mm^2
- 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:

σ_{SiPMT} ~13 ps

TOF = t_{MCP} - t_{SiPMT} [ns]

- **Test achieved σ_{SiPMT} ~ 13 ps resolution per MIP.**

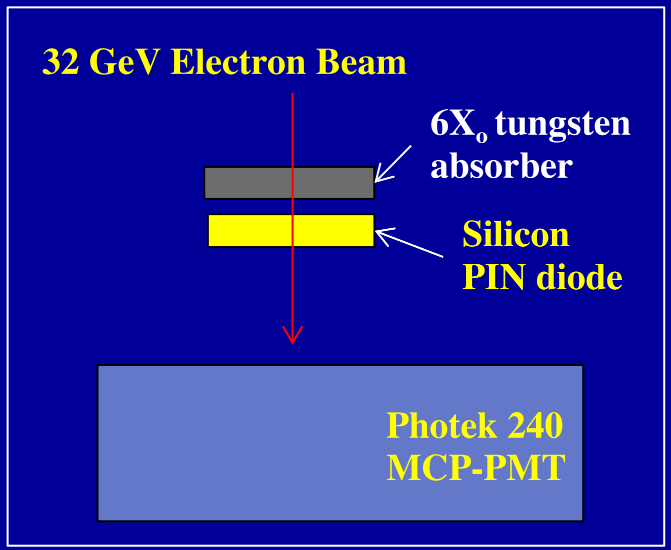
($\sigma_{SiPMT} \sim \sqrt{[14.5^2 - (8.3/\sqrt{2})^2]} \sim 13$ ps)

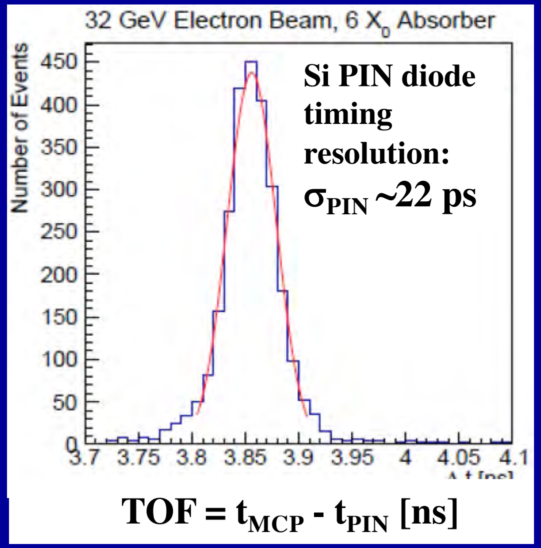
Timing + position + calorimeter + PIN diode

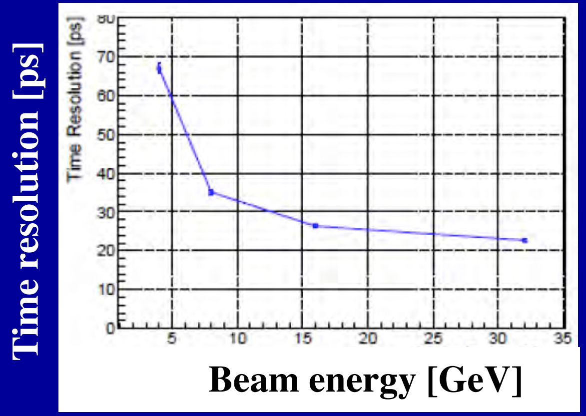
A. Ronzhin et al., Fermilab, SLAC talk, 2017

- **Start: Photek-240 MCP**
- **Stop: Hamamatsu Si PIN diode – zero gain**
- 6 x 6 mm^2 pad
- Absorber: Pb or W
- DRS4 digitizer

RF-shielded box:







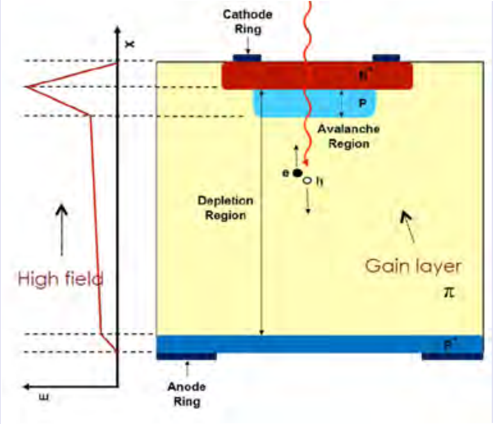
- **Si-PIN diode can achieve pretty good timing resolution in a calorimeter application.**

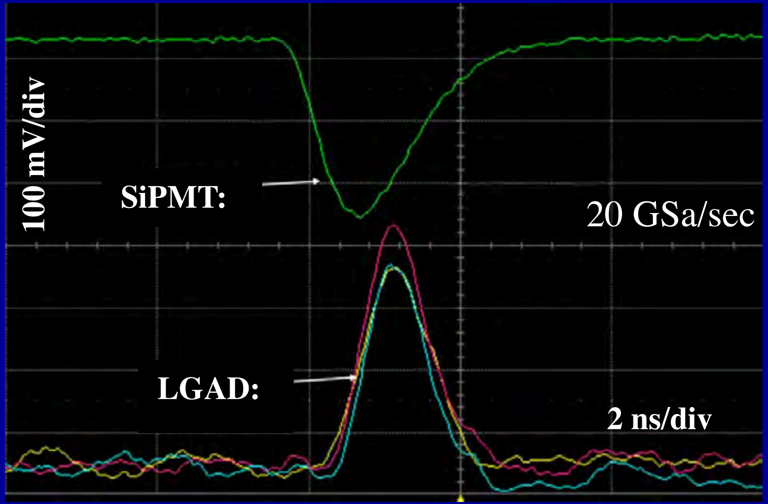
ATLAS: Low Gain Avalanche Diodes in test beam

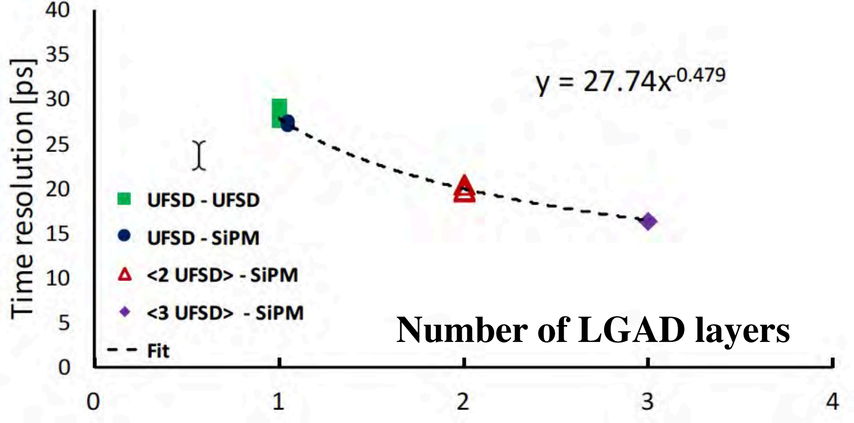
Cartiglia et al., ArXiv:1608.08681, 2017

- **Pixel size: 1.3mm x1.3mm 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 ~ 20

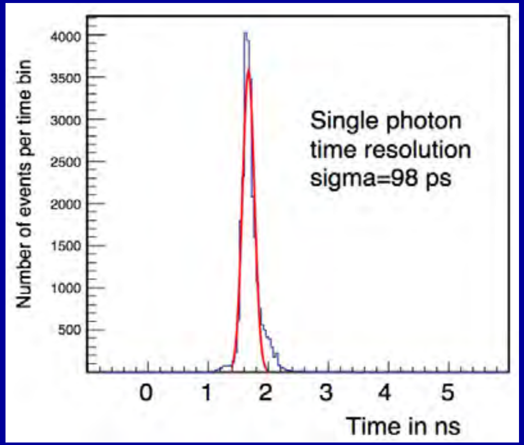
$\sigma_{\text{time}} \sim t_{\text{rise time}} /(S/N) \sim 20 \text{ ps}$

- **Test beam achieved: σ_{time} ~34 for a single sensor, and ~16 ps with a tandem of 3 sensors.**

SiPMTs for RICH detectors with TOPFET2 ASIC

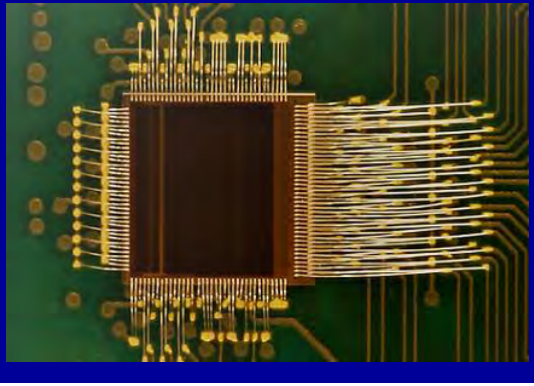
R. Bughalo et al., Talk at IEEE/NSF, Atlanta, 2017

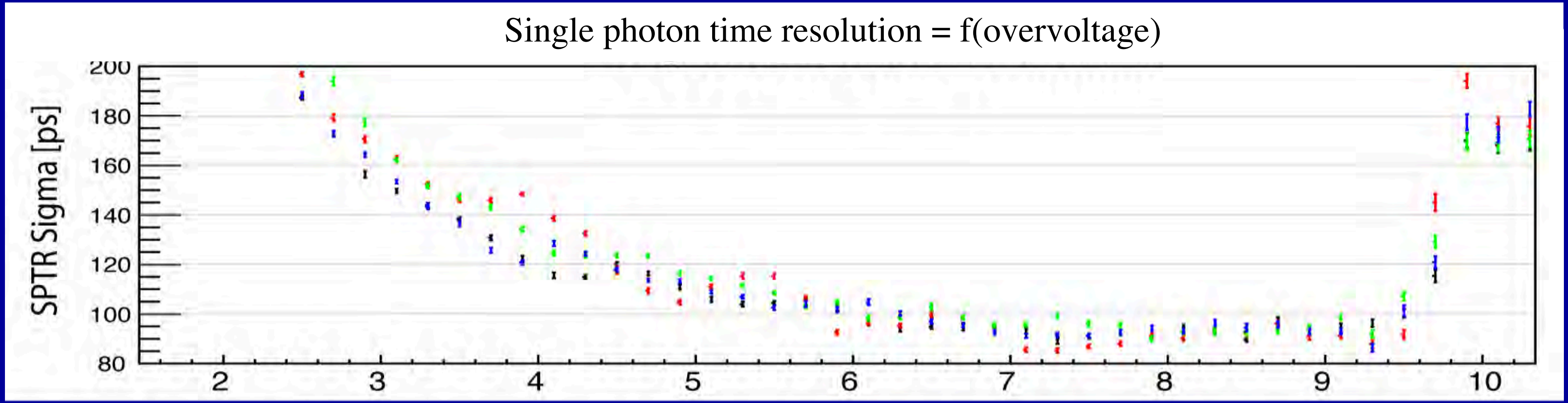
TTS resolution with SiPMT and TOPFET was ~100 ps:



- SiPMT: 5x5mm^2
- SiPMT: HPK S31361-3050
- 64 channel ASIC
- **Low power: 5-8 mW/ch**
- ps laser (405 nm)

TOPFET2 ASIC:

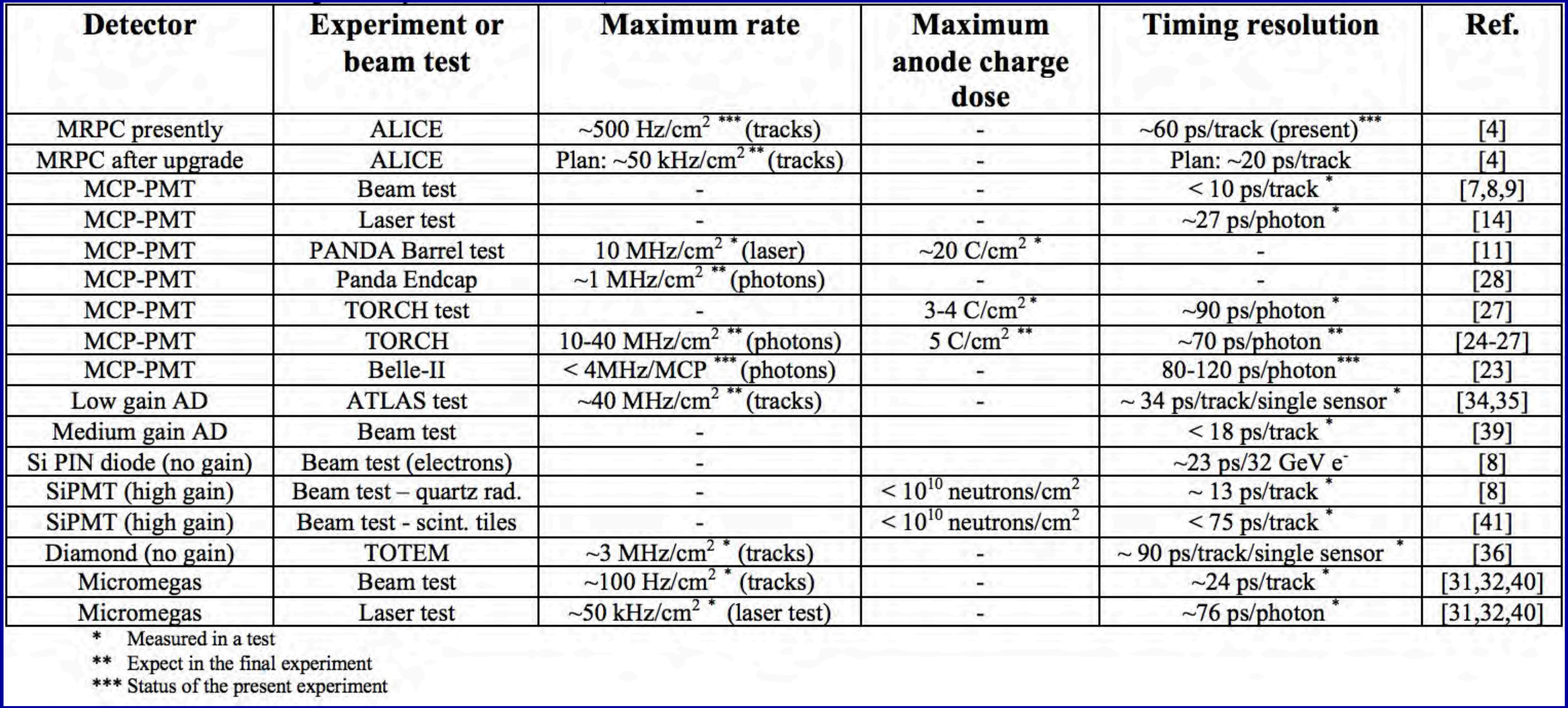




- **TOFPET ASIC was developed for Time-of-Flight Positron-Electron Tomography.**
- **Test achieved σ_{SiPMT} ~ 90-100 ps resolution per single photon at 7.5V overvoltage.**
- **Lesson #??: Lower power consumption (5-8 mW/ch.)**

Maximum rate and charge dose capability

J. Va'vra, https://www.slac.stanford.edu/~jjv/activity/Vavra_Invited_paper_La_Rochelle_2019.pdf



Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm^2 *** (tracks)	-	~60 ps/track (present)***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm^2 ** (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/cm^2 * (laser)	~20 C/cm^2 *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm^2 ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm^2 *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm^2 ** (photons)	5 C/cm^2 **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon***	[23]
Low gain AD	ATLAS test	~40 MHz/cm^2 ** (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/cm^2	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm^2	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm^2 * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm^2 * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm^2 * (laser test)	-	~76 ps/photon *	[31,32,40]

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