Picosecond timing detectors and applications

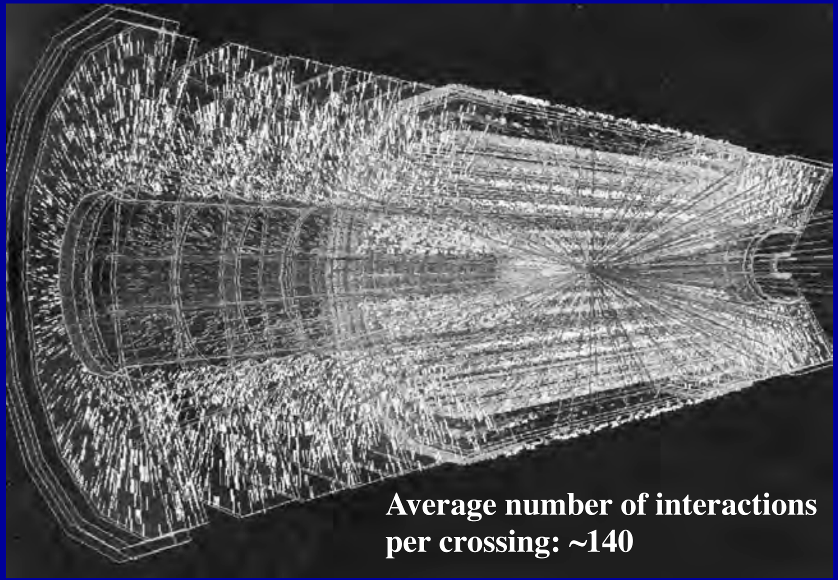
J. Va'vra, SLAC

Content

- **Detector examples discussed:**
  - MRPCs,
  - MCP-PMTs,
  - Diamond detectors,
  - SiPMTs,
  - Low and high gain Avalanche diodes (LGADs)
  - Micromegas
- **Issues:**
  - Single pixel vs. multi-pixel tests
  - Small test vs. large physics system results
  - Hidden problems people usually do not want to talk about…

New conditions drive timing developments

ATLAS event after high luminosity upgrade:

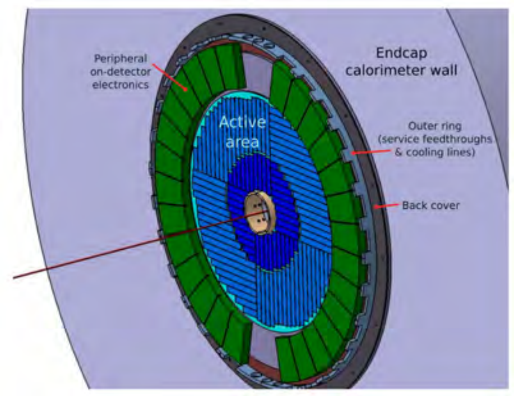


Average number of interactions per crossing: ~140

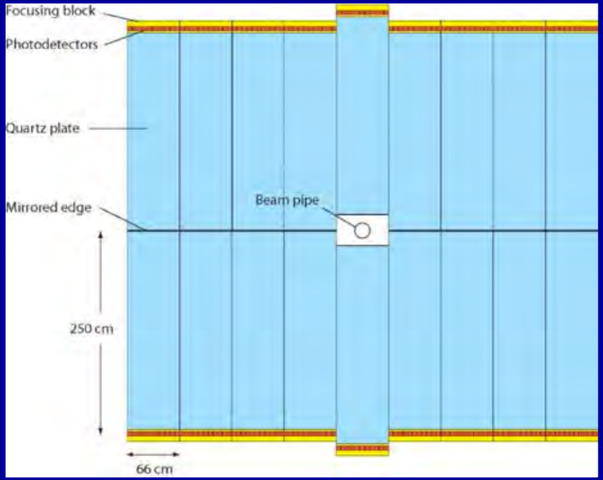
- **There is a general push for higher luminosity not only at LHC but also at Belle-II, Panda, Electron-ion collider, etc. Timing is more and more important.**
- **ATLAS: One needs to connect charged tracks to the correct production vertices, using position resolution and timing resolution (people argue for ~30ps/MIP).**
- **New DIRC applications aim for resolution at a level of ~70-120 ps/photon.**

A few applications of high resolution timing at a level of ~30 ps for MIPs, and 70-120ps for single photons

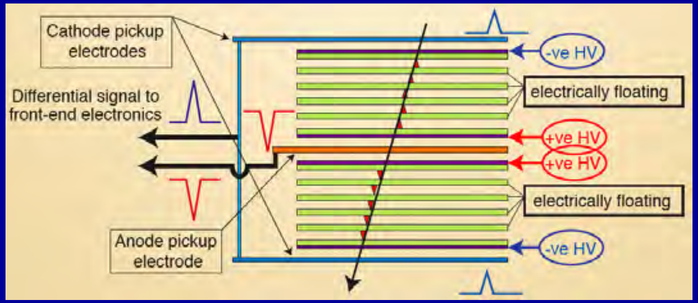
ATLAS High-Granularity Timing Detector (HGTD) with Low Gain Avalanche Diodes (LGAD):



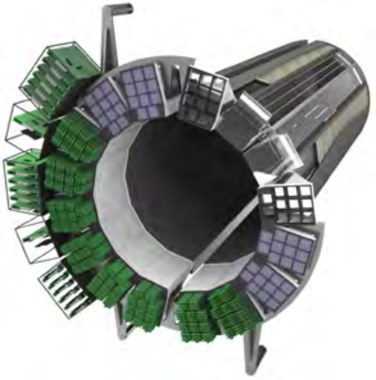
TORCH DIRC at LHCb:



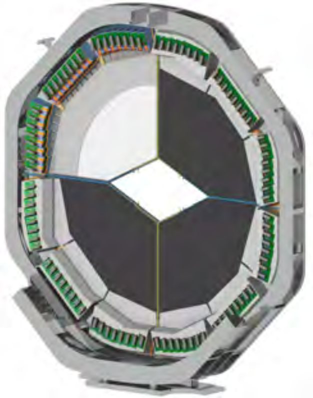
ALICE MRPC TOF counters:



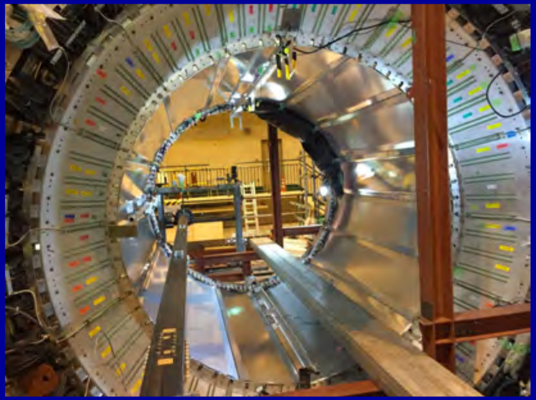
Panda Barrel DIRC:



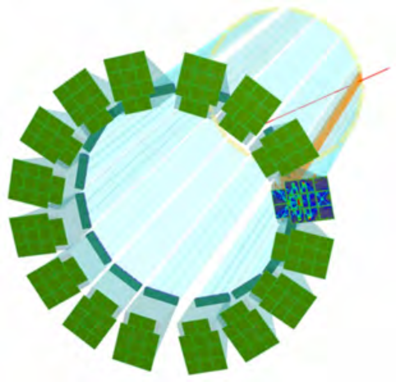
Panda Endcap DIRC:



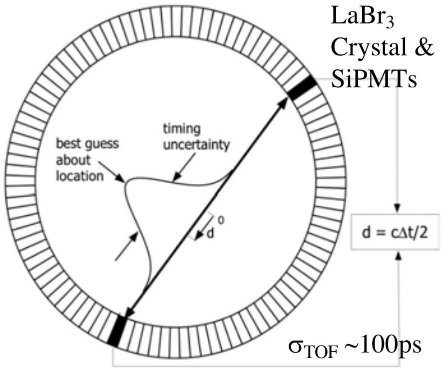
Belle-II iTOP DIRC:



EIC DIRC in USA:



TOF PET:



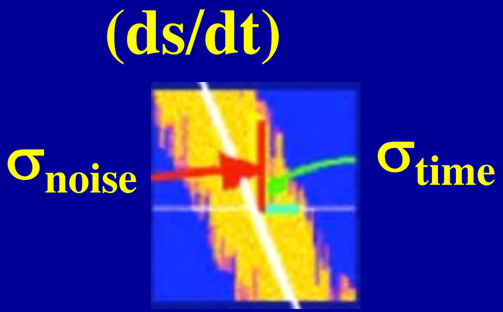
…etc.

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

- **I say: "Show me your pulses and noise level, and I will estimate your resolution".**
- **For MCP-PMT with $t_{rise\text{-}time}$ ~200 ps, one needs S/N ~20 to get to a ~10 ps regime.**
- **For Si-detector with $t_{rise\text{-}time}$ ~ 400ps, 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 = f(detector)

Example of contributions to the timing resolution:

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

$\sigma_{Electronics}$ - 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:

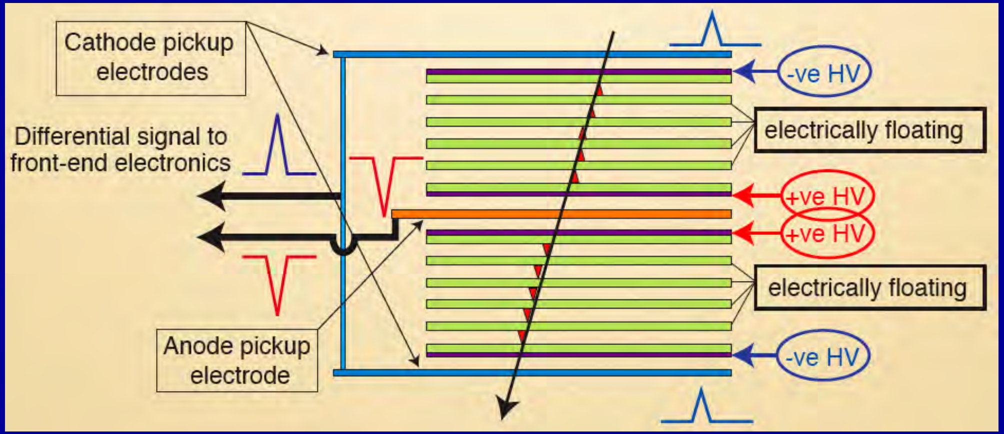
- clock distribution throughout the system
- cross-talk effects in multi-pixel detectors
- baseline oscillation or other instability instability in multi-pixel detectors
- charge sharing in multi-pixel detectors
- chromatic effects
- Charge tails
- Calibration
- etc.

MRPC

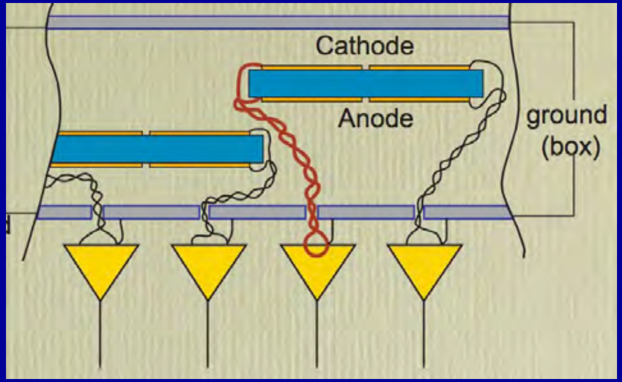
ALICE MRPC TOF detector

C. Williams, private communication, March 2019

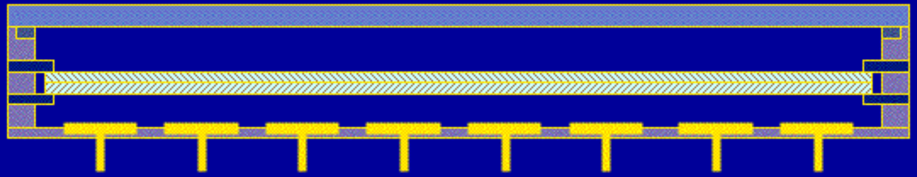
ALICE MRPCs:



Differential input to amplifier:



- **ALICE TOF system is delivering ~60 ps resolution presently.**
- **Crispin Williams told me that is proud that he pushed differential input and differential design throughout to minimize pick-up, cross-talk, etc.**
- NINO chip with time-over-threshold (TOT) pulse height correction; low power (40 mW/channel); Fast 1ns-peaking time.
- I was not able to obtain raw detector pulses from Crispin.
- **Plan is to develop a new detector with lower resistivity 400 μm-thick glass, allowing to build 20-gap MRPC capable of rate up to ~50 kHz/cm^2 with aim for ~20 ps resolution per MIP.**



MCP-PMTs

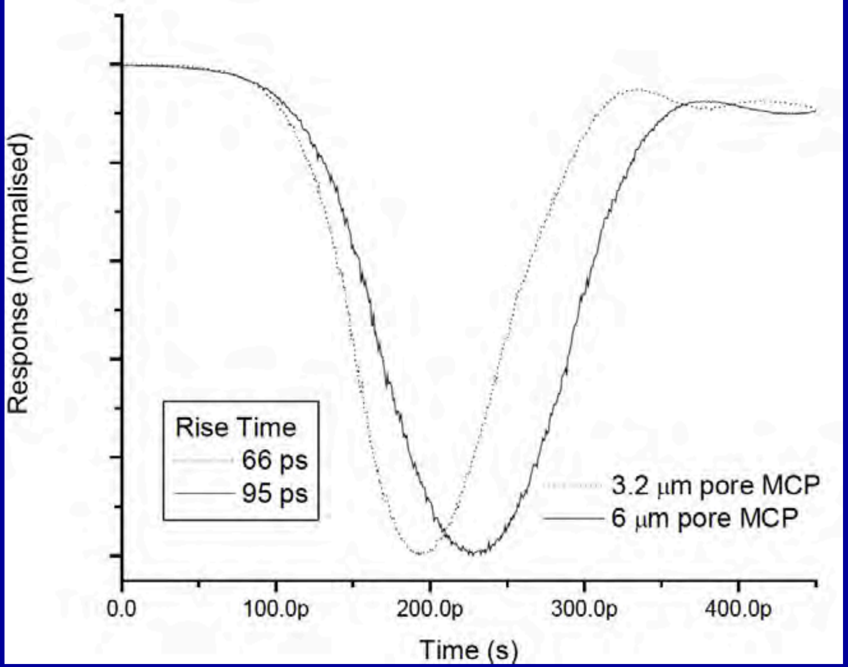
- **Great potential, but also many intricacies.**

Single-pixel MCP-PMTs

When I saw this picture I was very excited about MCP concept

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

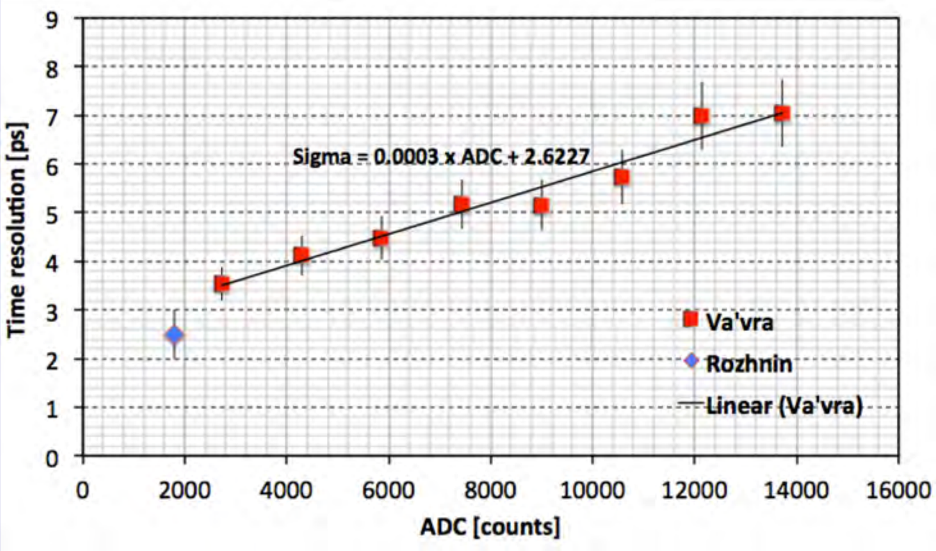
Photek MCP 110:
- single photons
- no amplifier



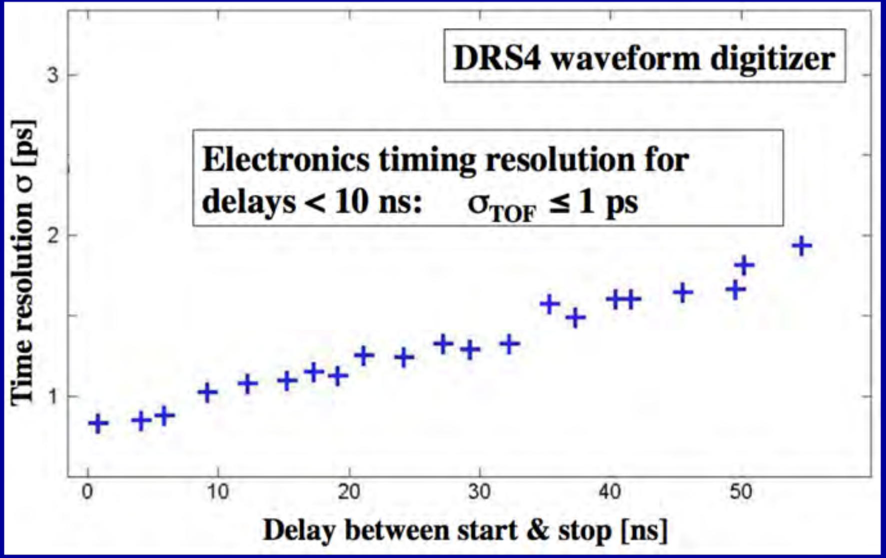
Using a simple formula:
If we assume S/N ~ 20
$t_{\text{rise time}}$ ~66 ps
$\sigma_{\text{time}} \sim t_{\text{rise time}}/(S/N)$ ~3 ps

A few examples of good electronics for good timing

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



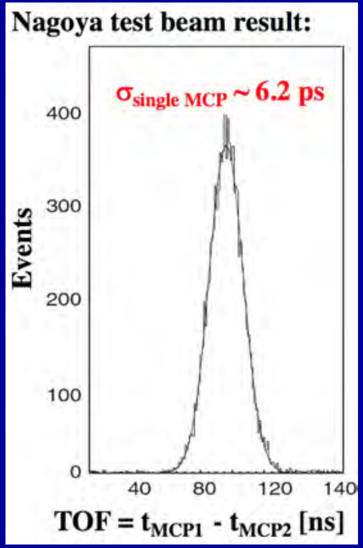
- **Jeff Peck, Ortec designer engineer: 9327 Amp/CFD can reach $\sigma_{Electronics}$ ~2ps resolution, if one avoids the TAC 566.**
- **DRS4: S. Ritt measured < 1ps for very small delay between start & stop.**
- **If you can afford it, you can also digitize pulses with a 20 GSa/s scope.**
- **Typically, if your electronics contributes ~2 ps, you are doing very well.**

Single-pixel TOF counter, no amplifier, large Npe

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

Two Hamamatsu R3809U-59-11 MCPs:

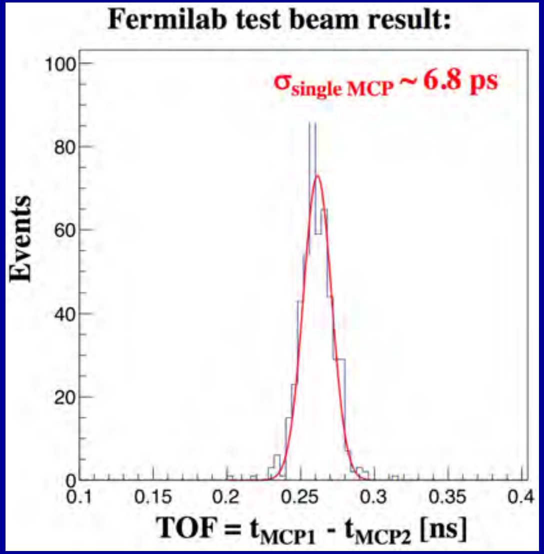
- 6 microns MCP hole sizes
- Fused silica radiator:10+3 mm
- Single pixel
- **MCP Gain ~2x10^6**
- **SPC-134, Becker & Hickl GmbH**
- **Electronics resolution: 4.1 ps**
- **Npe ~ 70**
- **Total anode charge: 1.4x10^8 !!!**



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

Two back-to-back Photek 240 MCPs:

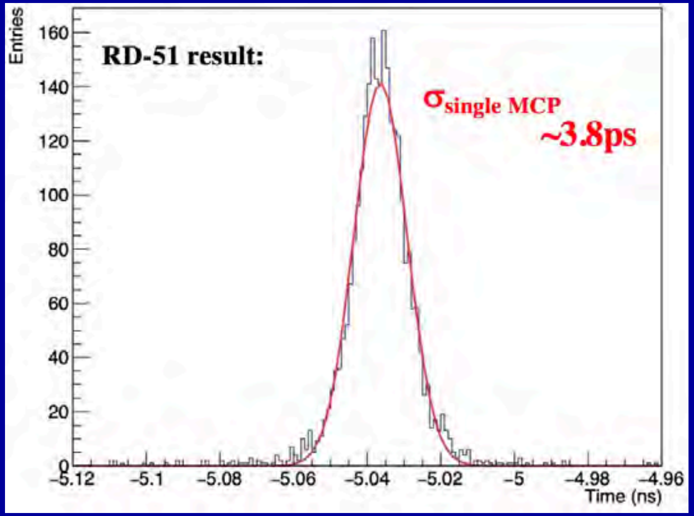
- 6 microns MCP hole sizes
- Fused silica window: 8 mm
- Single pixel
- **MCP Gain ~10^6**
- **DRS4 waveform digitizer**
- **Electronics resolution: 2.0 ps**
- **Npe ~ 80**
- **Total anode charge: 8x10^7 !!!**



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 !**

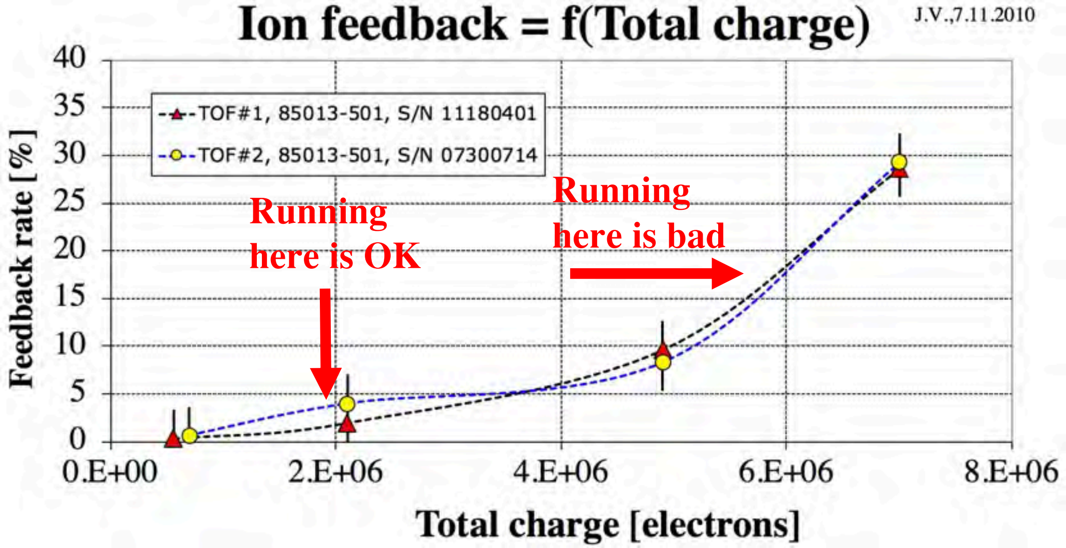


- **Excellent resolution can be achieved with a single-pixel MCP for MIP signal.**
- **<u>However, one has to be careful running large anode charges</u> – see next slide.**

Why do I want limit total charge on MCP in a TOF counter ?

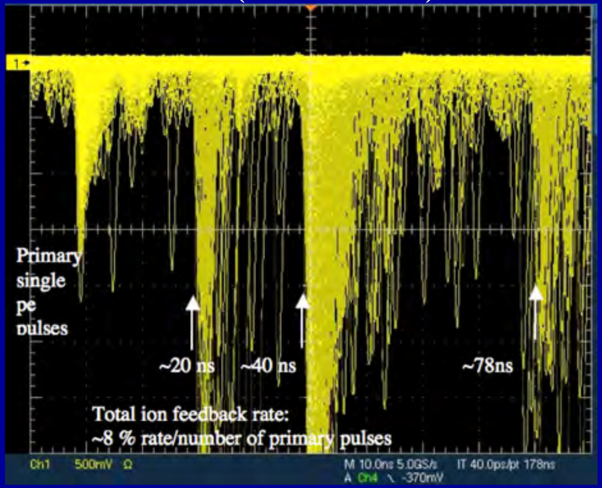
J. Va'vra, MCP logbook #6, page 122, 2010.

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⁺…) **:**

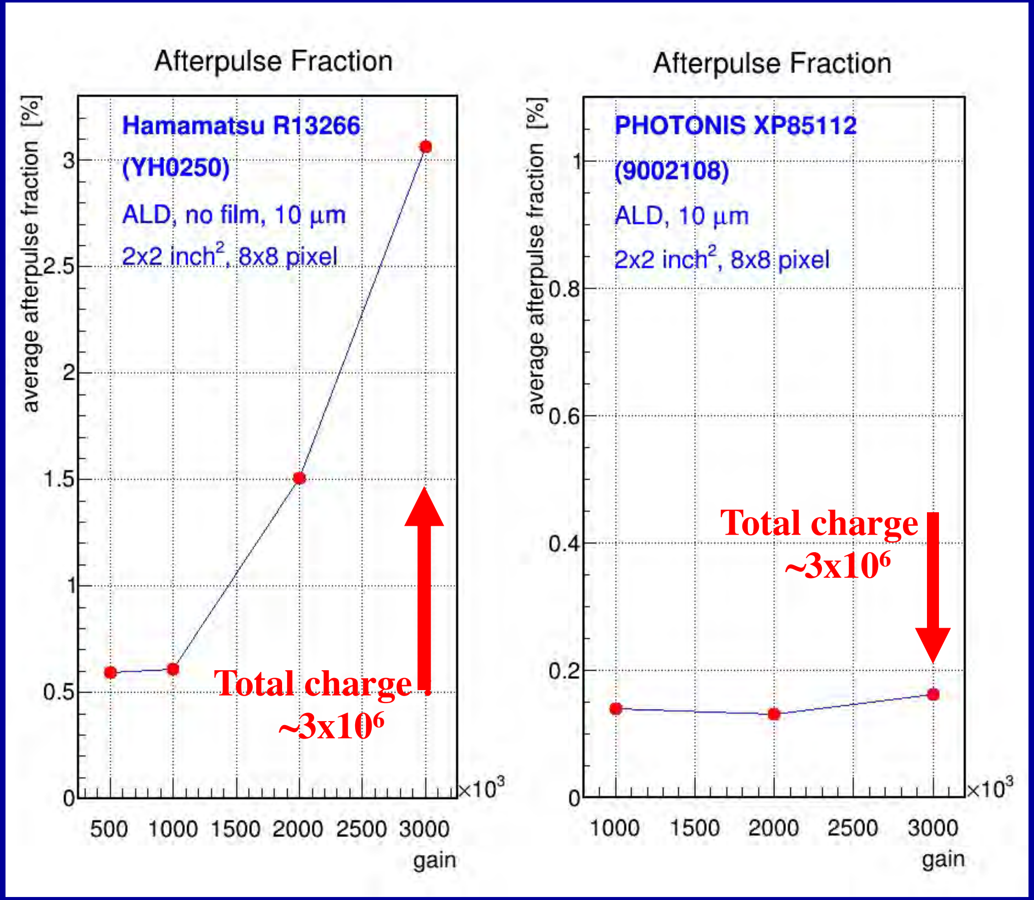


- **Old Burle Planacon MCP.**
- **One should limit total charge to ~2-3x10^6.**
- **Are the new MCPs with ALD coating behaving better ? – see next slide.**

Ion feedback in new MCPs, ALD-coated, Npe=1

A. Lehmann, private communication, April 22, 2018

ALD coated MCPs:

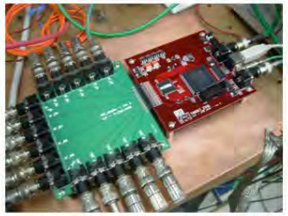


- **Photonis XP85112 MCP-PMT performs well at a total charge of ~3x10^6**
- **Hamamatsu R13266 sees an increase in the rate already at a total charge of ~1.5x10^6.**

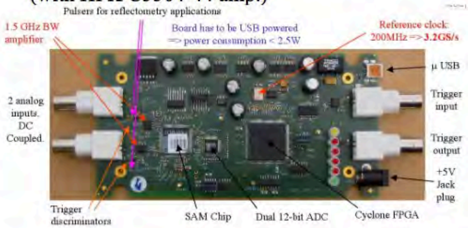
Timing at low total charge, with amplifier, large Npe

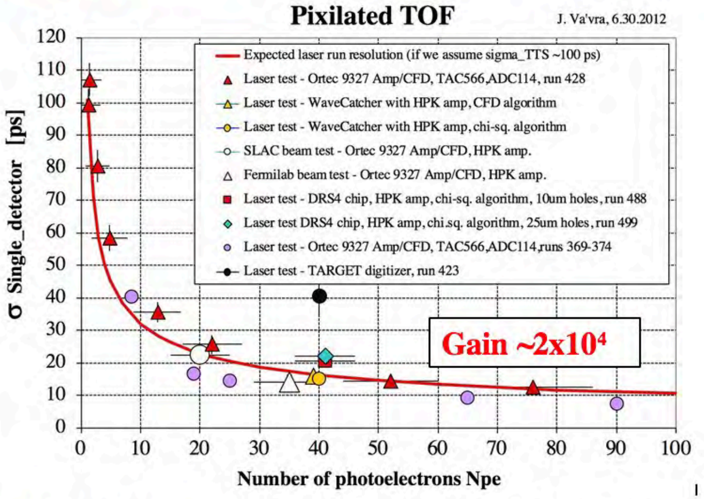
J. Va’vra, log book #7, 2012, NIMA 629 (2011)123, and NIMA 606 (2009) 404

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

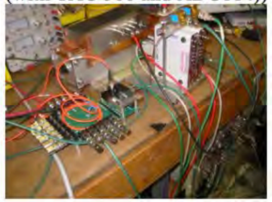


WaveCatcher v.5 (Dominique Breton):
(with HPK C5504-44 amp.)

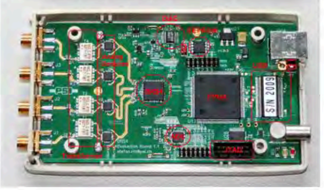




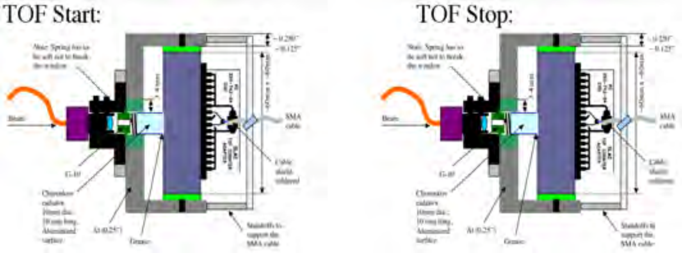
Ortec 9327 amp/CFD electronics:
(with TAC 566 and ADC114))



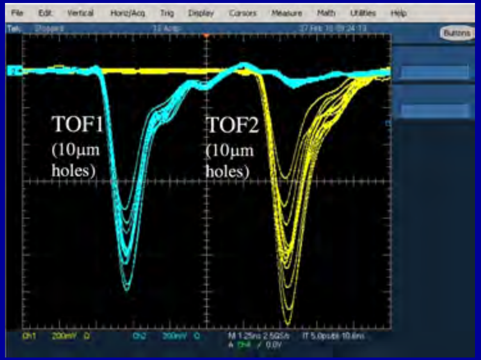
DRS4 (Stefan Ritt):
(with HPK C5504-44 amp.)



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.

- For TOF application, one can reach a good resolution even at low gain if Npe ~40-80.

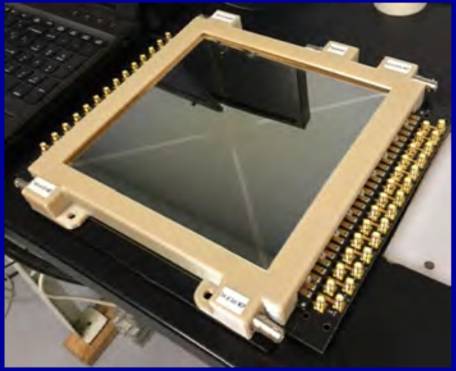
LAPPD development

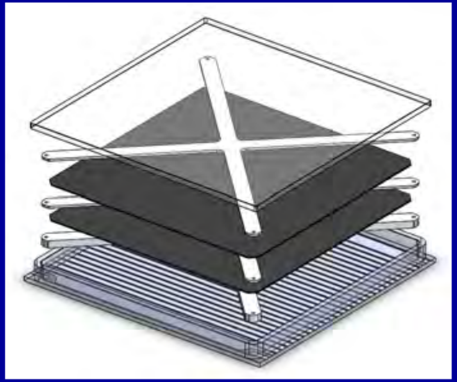
- **Strip readout.**
- **Pixel readout.**

LAPPD 8”x8” MCP detectors with strip readout

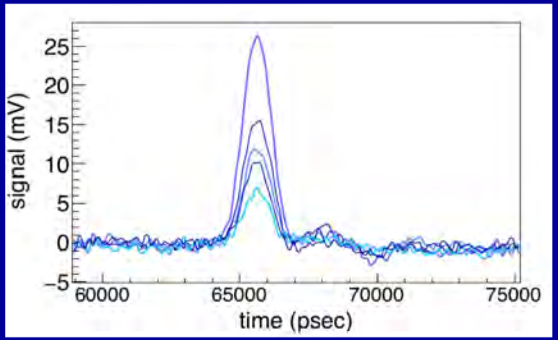
M.J. Minot et al., http://www.incomusa.com/mcp-and-lappd-documents/, 2/6/2019

LAPPD detector with strips:

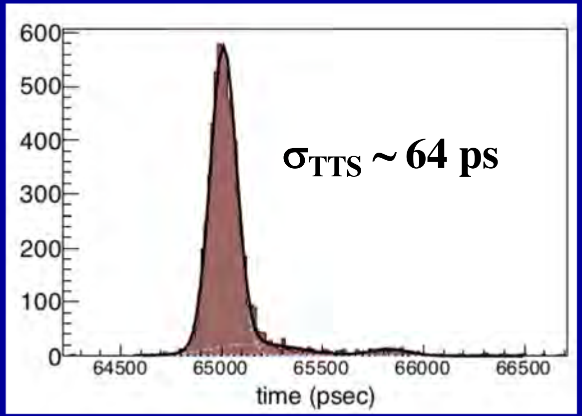




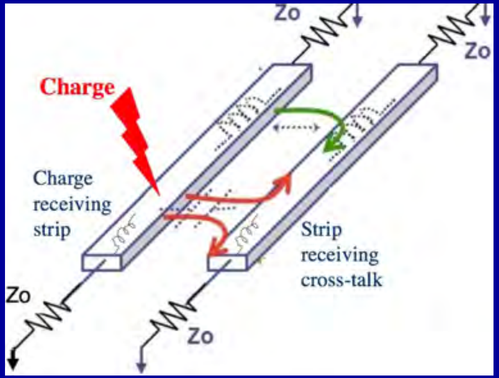
Strips: Single pe pulses (LAPPD #25):



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

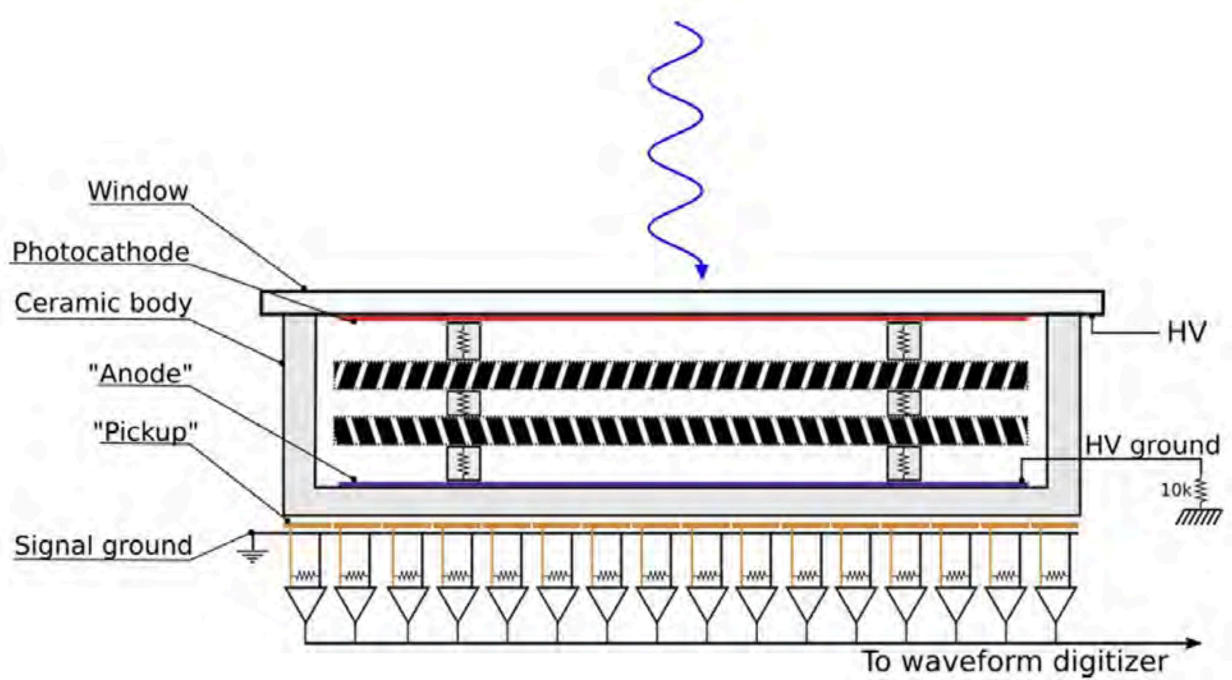
$\sigma_{\text{time}} \sim t_{\text{rise time}} /(S/N)$ ~60 ps

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

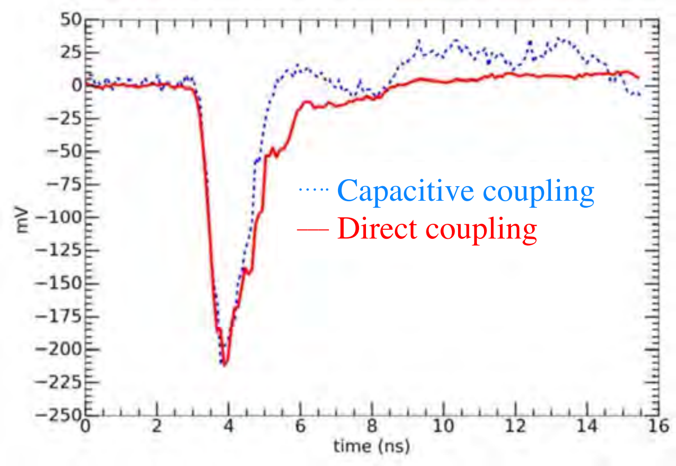
LAPPD 8”x8” MCP detectors with pixel readout

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.**

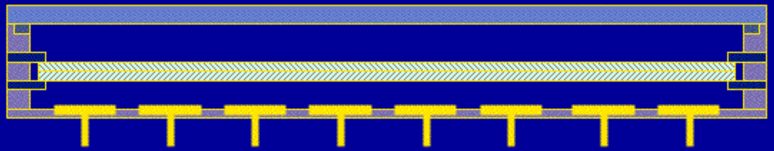
Challenges of multi-pixel MCPs

- **Cross-talk.**
- **Charge sharing.**
- **Pulse ringing in high background, causing fake hits.**

How to connect to Planacon MCP-PMT ?

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

In principle, a simple device:



The issue issue to connect to it ? Various schemes which were tried to connect to a 64 pixel Planacon:

Early Burle Planacon:

SLAC amplifier:

TOP counter:

Saclay test:

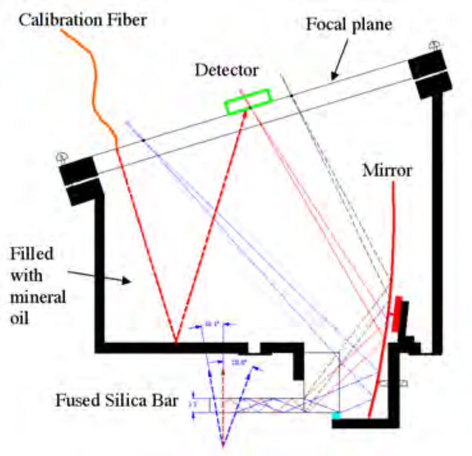
…etc.

- **MCP is inherently a single-ended device, which invites a possible pick-up problems. One needs a good RF-shielded box around the device.**
- **Early models had unwanted capacitances, inductances, ground return issues, which contributed to cross-talk, pulse shape distortions, ringing, fake hits, etc.**
- **Good news: There is a progress. New Photonis Planacons are better.**

Focusing DIRC (FDIRC) development at SLAC

SLAC effort: NIMA 553 (2005) 96, NIMA 595 (2008) 104 and NIMA 775 (2015) 112

The 1-st FDIRC prototype with SLAC electronics – see details appendix, slide 55:

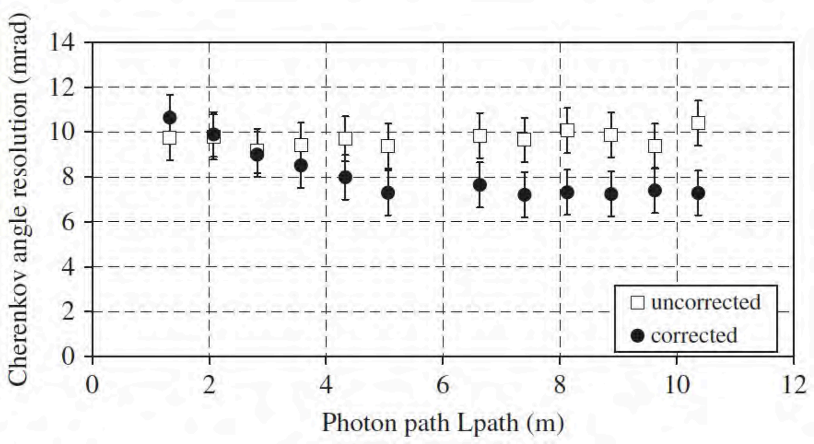


5 MCPs, 64 pixels each, 320 pixels:

Significance of this R&D:

- **The FDIRC prototype had a largest number of MCP pixels up to that point (320 pixels). It used early 64-pixel Planacon MCPs made by Burle.**
- **A very successful device. This prototype was the first RICH detector to correct the chromatic error by timing.**
- **Single photon timing resolution was 70-100 ps per pixel on a large scale – see appendix, slide 55.**

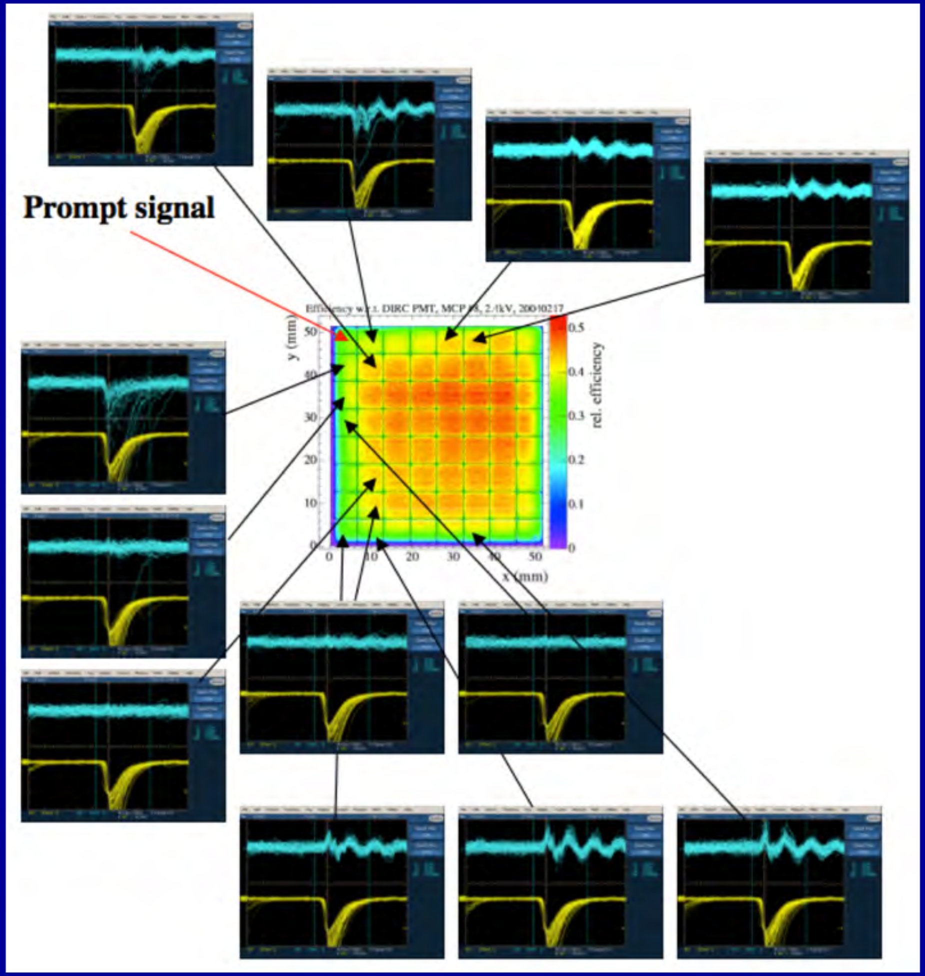
Cherenkov angle resolution (Chromatic correction by timing):



Cross-talk in early version of Planacon MCP

J.Va'vra, MCP-PMT log book #1, p.18, 2005, and FDIRC#1 beam test log book #3, p. 34, 2005

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

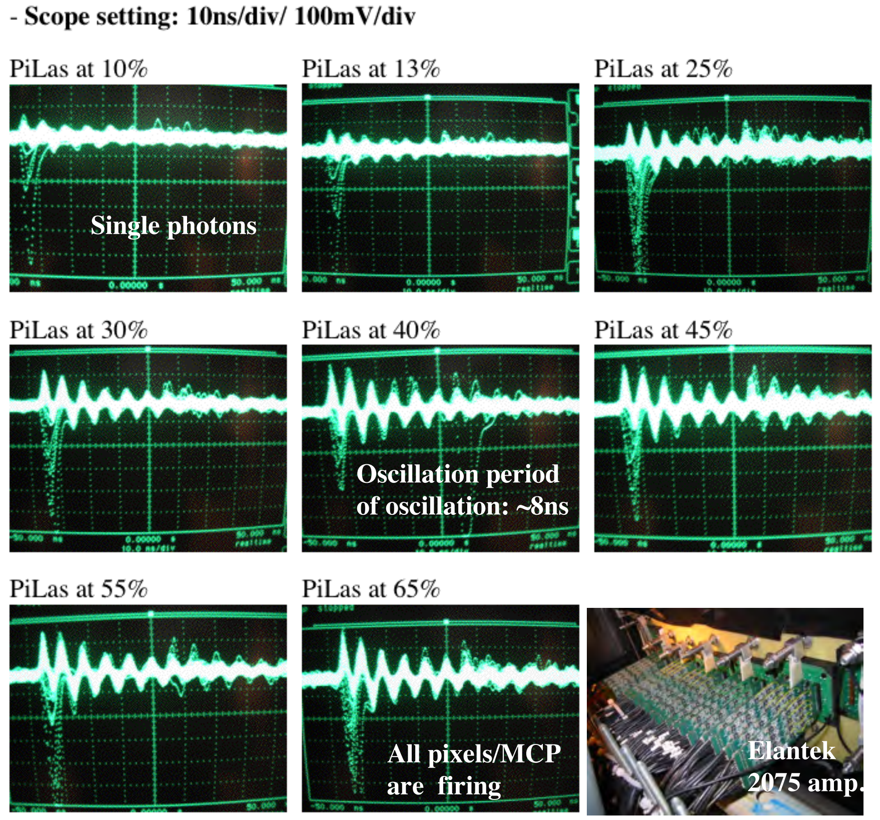


- **The cross-talk was very complicated.**

Ringing in early version of Planacon MCP vs. MaPMT

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

Early version of Planacon MCP-PMT:



- 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%

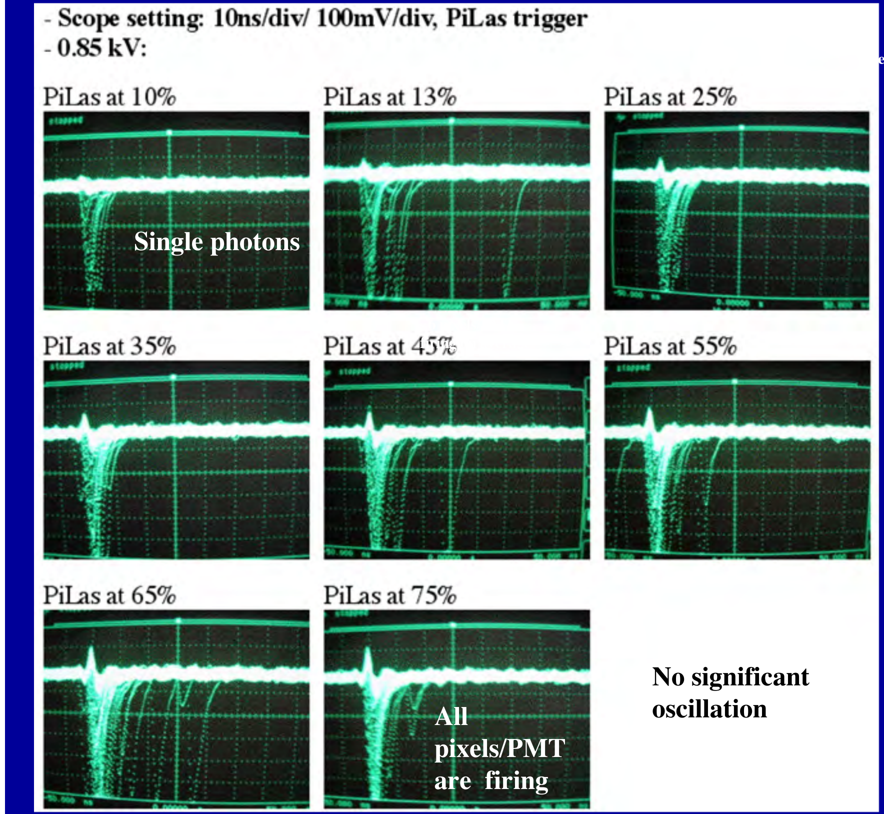
PiLas at 55%

PiLas at 65%

All pixels/MCP are firing

Elantek 2075 amp.

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

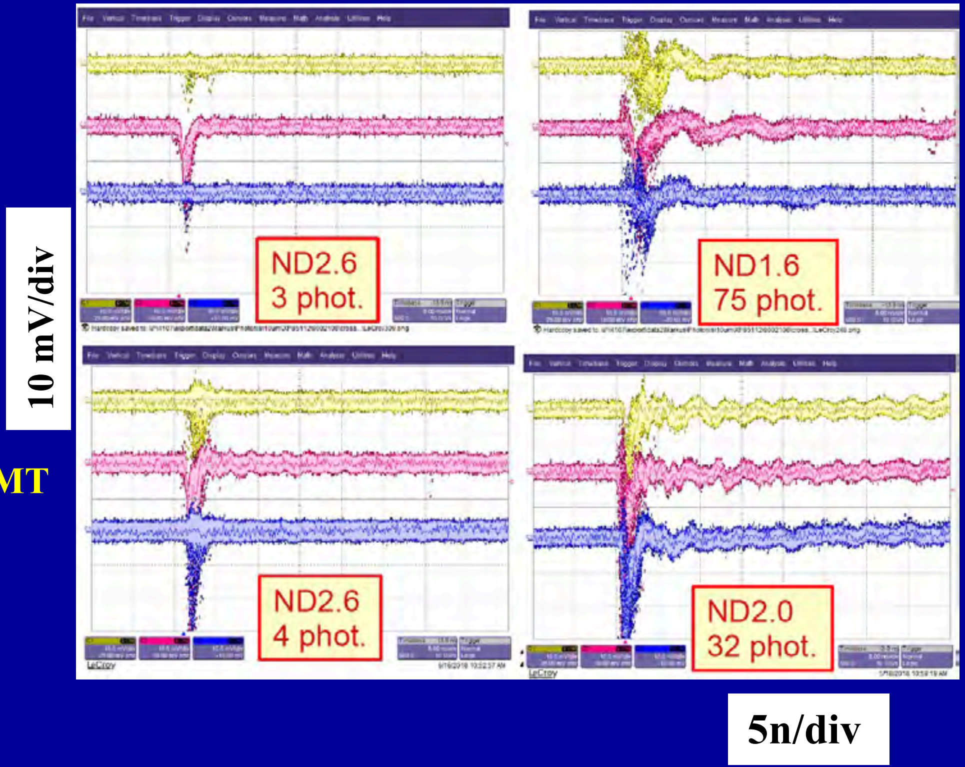
- **Amplitude of ringing increases with number of photons hitting MCP, which means a higher thershold.**
- **H-8500 MaPMT with the same electronics was OK.**

Panda: Ringing in new MCPs

Albert Lehman, PANDA, RICH 2018, Moscow, and private communication from last week

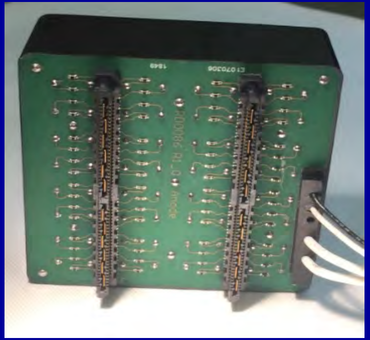
Photonis Planacon 64-pixel MCP-PMT (XP85112-Q-HA)**:**

Hamamatsu MCP-PMT 64-pixel (R13266-07-M64M)**:**



- No amplifier used
- Illuminate the entire photocathode

Latest Planacon, 2019:



- New connector
- Smaller anode-ground capacitance
- Better ground return, etc.

- **3-4 photons/MCP: very small effect.**
- **>10 photons/MCP: the cross-talk is observed.**
- **Last week's update from Albert: Latest Photonis MCP (#9002150) is better !**

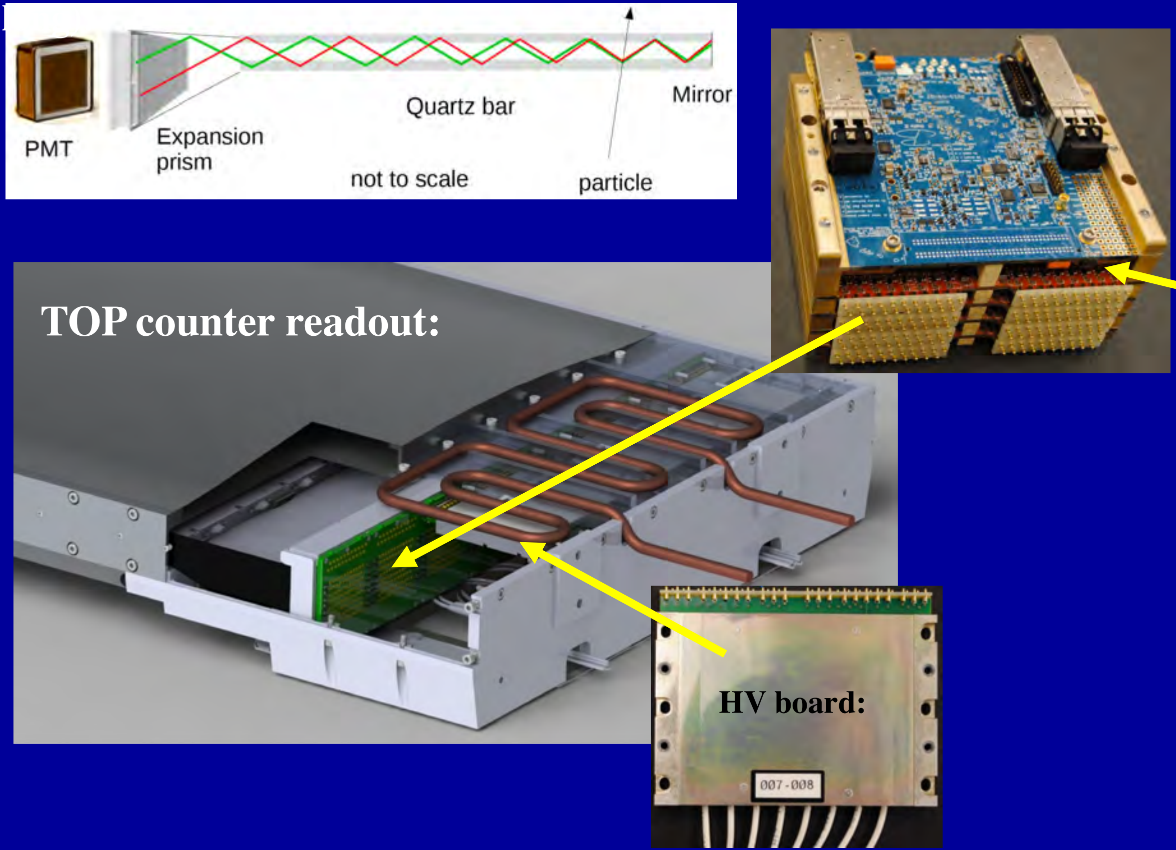
Several large physics applications with MCP-PMTs

- **Belle-II TOP DIRC.**
- **LHCb TORCH DIRC.**
- **Panda Barrel DIRC.**
- **Panda Endcap DIRC.**

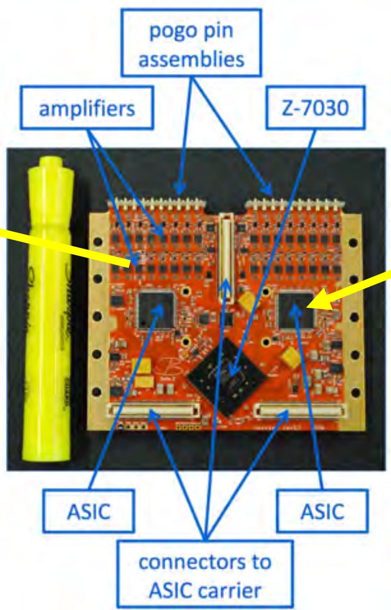
Belle-II: TOP DIRC counter waveform digitizing electronics

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

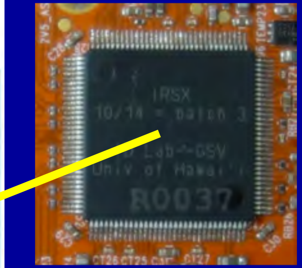
DIRC TOP counter principle (450mm wide x 2600 mm



Amplifier & ASIC:



IRSX ASIC:

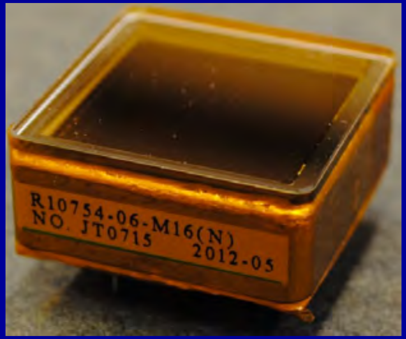


- **IRSX waveform digitizer: 2.7 GSa/sec.**
- **Amplifier gain: ~120x. They had to slow BW down to have 2 samples on leading edge.**

Belle-II: TOP counter present results

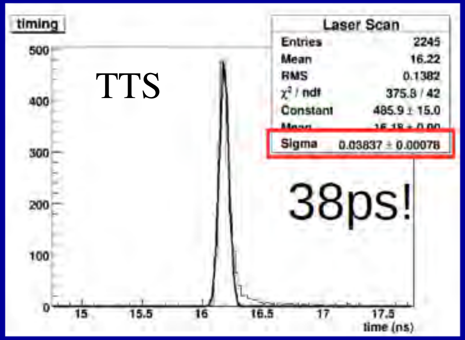
M. Bessner et al., Submitted to NIMA, 2019 and D. Kotchetkov et al., ArXiv:1804.10782, 2018

HPK 16 pixel MCP :

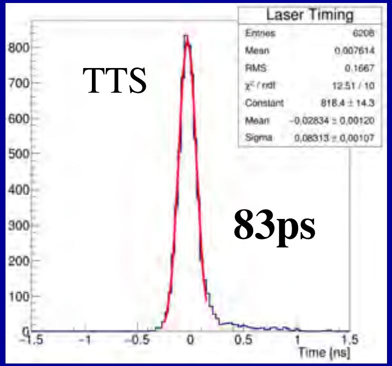


- 16 pixels (4 x 4)
- 5.3mm x 5.3mm pixel size

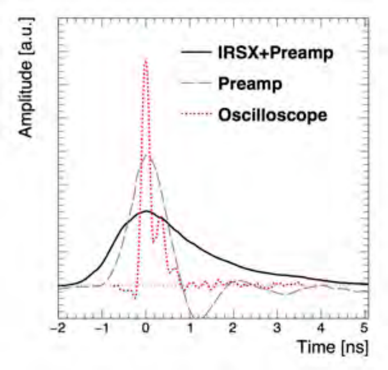
MCP is capable of excellent TTS resolution:



Bench test TTS resolution with final the IRSX electronics:



This may explain why IRSX timing resolution is worse:



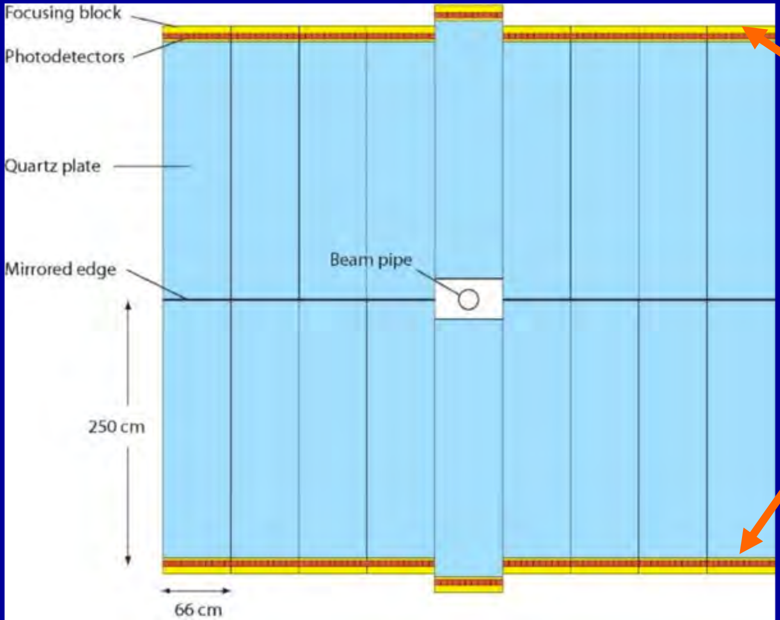
<u>Using a simple formula</u>:
Assuming S/N ~ 10
$t_{\text{rise time}}$ ~1 ns
$\sigma_{\text{time}} \sim t_{\text{rise time}} /(S/N) \sim 100$ ps

- **TOP counter is running and doing physics. Although, a lot to be done yet.**
- **Because of background, MCP gain was lowered to ~3×10^5. As a result of this and other effects, the resolution in Belle-II is presently: 80-120ps. Photon rate is kept < 4 MHz/MCP.**
- **Some non-ALD coated MCPs will have to be replaced in 2020.**

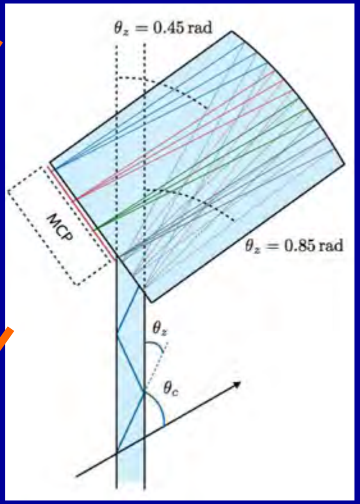
LHCb: TORCH DIRC R&D

N. Harnew, RICH 2018, Moscow, and T.M. Conneely et al., JINST, May 2015

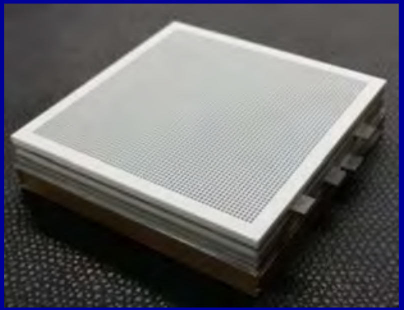
TORCH DIRC concept:



Focusing optics:



Photek MCP:



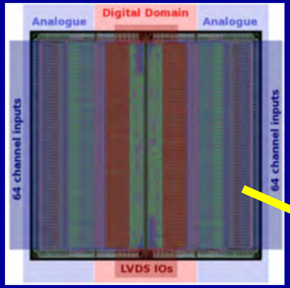
- **8 × 128 pixel readout**
- **53 × 53 mm^2**
- **anode pitch 0.414 mm**

- **Expected rates at LHCb: 10-40 MHz/cm^2, and anode charge doses up to ~5C/cm^2.**
- **Prototype has the NINO charge amplifier/discriminator ASIC with time-over-threshold (TOT) pulse height correction, coupled to HPTDC.**
- **Initial tests indicate a resolution of 80-100 ps/photon at a gain of ~10^6.**
- Aging tests with Phase-I MCP: good up to ~3C/cm^2 only at present time.
- Was not able to obtain raw pulses.

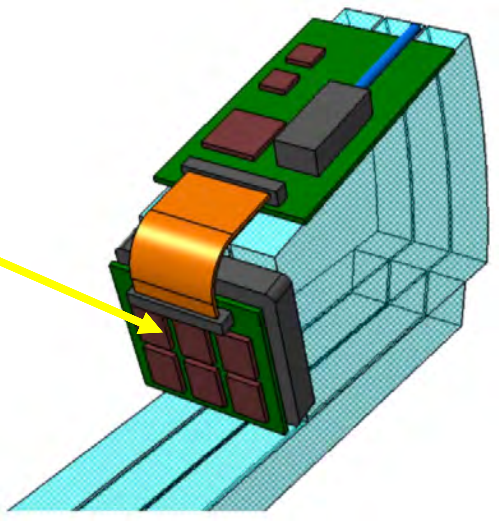
Endcap Panda: TOFPET electronics

Panda Endcup DIRC TDR, 2019

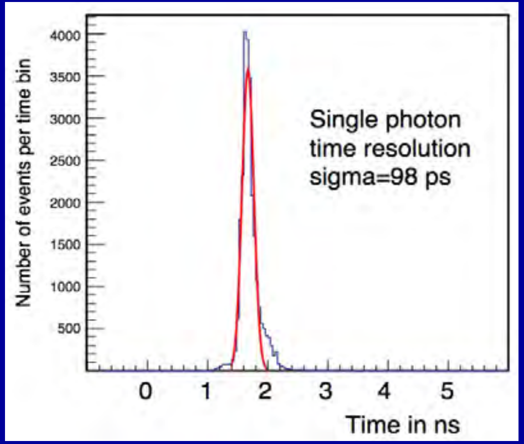
TOPFET ASIC:



Panda Endcap DIRC readout:



TTS resolution with SiPMT and TOPFET was ~100 ps:

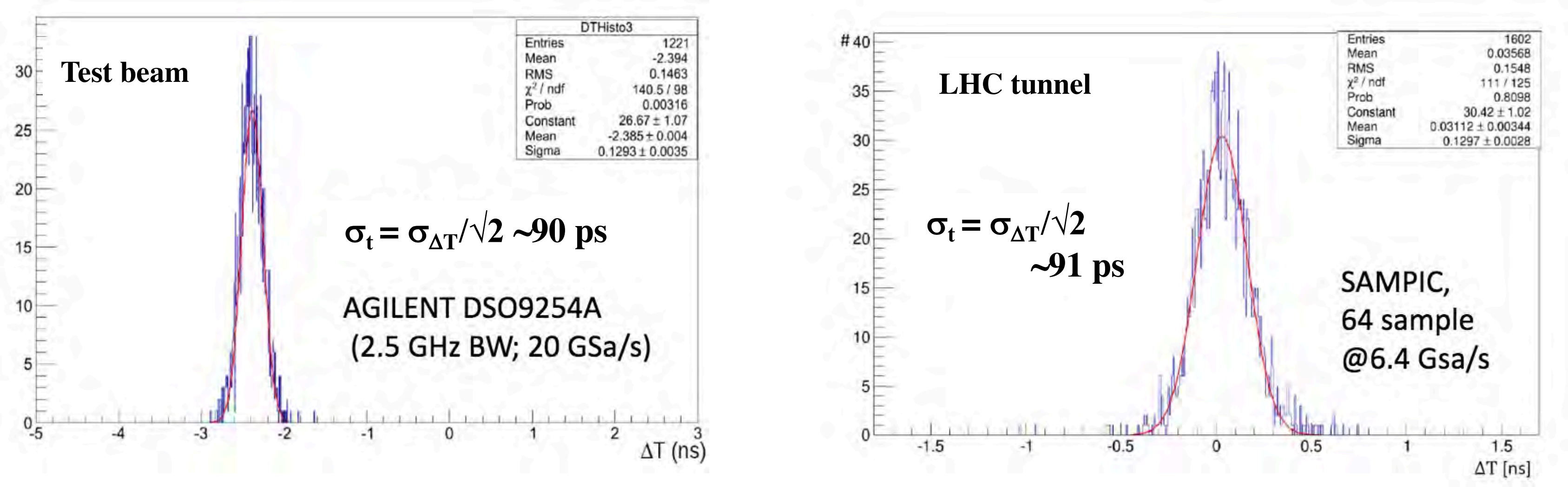


- **TOFPET ASIC was developed for Time-of-Flight Positron-Electron Tomography.**
- Intrinsic resolution is ~25 ps; ASIC allows time-over-threshold correction (TOT).
- TTS resolution of ~100ps was achieved with SiPMTs (Hamamatsu S13361). However, with the MCP they got a resolution of ~320 ps so far. Work is in progress.
- Maximum channel (pixel) hit rate is ~160 kHz.
- **This ASICS is radiation hard.**
- Was not able to obtain raw pulses.

Diamond detectors

TOTEM: Diamond detectors

E. Bossini, TOTEM collab., Instruments, Oct. 2018
G. Antchev et al., TOTEM collab., JINST 12 P03007, 2017



Test beam

$\sigma_t = \sigma_{\Delta T}/\sqrt{2}$ ~90 ps

AGILENT DSO9254A
(2.5 GHz BW; 20 GSa/s)

LHC tunnel

$\sigma_t = \sigma_{\Delta T}/\sqrt{2}$
~91 ps

SAMPIC,
64 sample
@6.4 Gsa/s

$\Delta T = T_{diamond\_1} - T_{diamond\_2}$ [ns]

- **Signal is only ~1.2x10^4 el. per 500μm thickness, so the S/N ratio is an issue. Sensor low capacitance and low noise electronics are essential.** Good results with fast low noise charge amplifier (10ns shaper); 2 GHz BW amplifier gave worse resolution**.**
- **For the LHC pp-diffraction scattering application, they would use ~4-6 layers in tandem, therefore they could reach ~40 ps resolution.**
- **The technology is radiation hard; the test achieved rate of ~3 MHz/cm^2.**

Si detectors

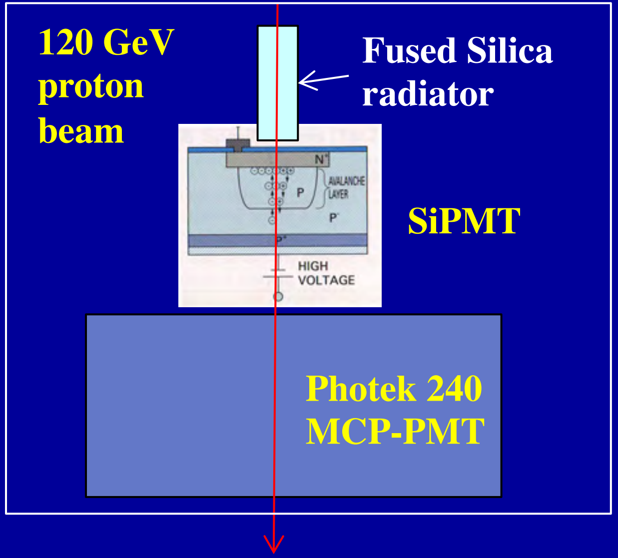
Si detectors: High gain SiPMTs

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
- **3cm-long Fused silica radiator**
- No extra radiator used on MCP, only 8mm-thick window
- Fast amplifier on SiPMT
- DRS4 digitizer

RF-shielded box:



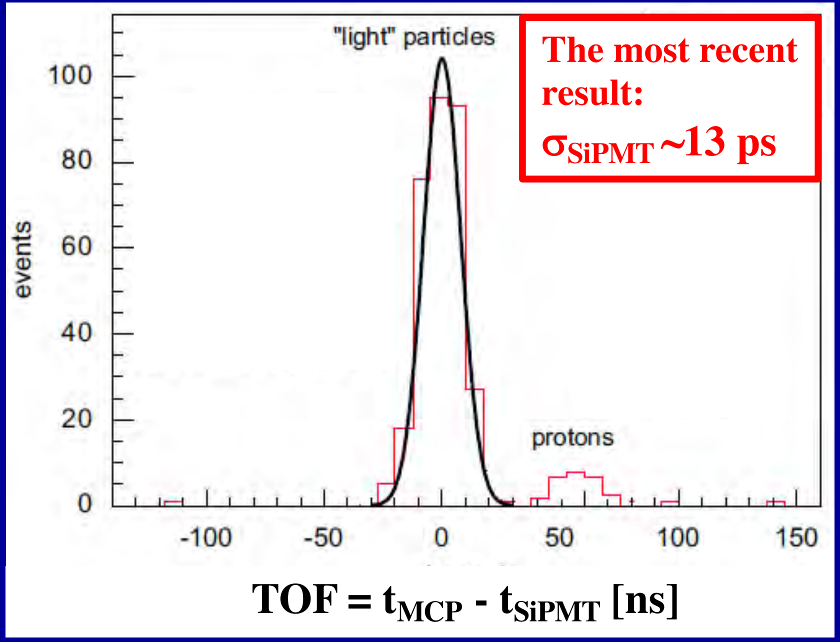
120 GeV proton beam

Fused Silica radiator

SiPMT

Photek 240 MCP-PMT

8 GeV/c e$^-$ beam (distance between two detectors: 7.12 meters)



The most recent result:

σ_{SiPMT} ~13 ps

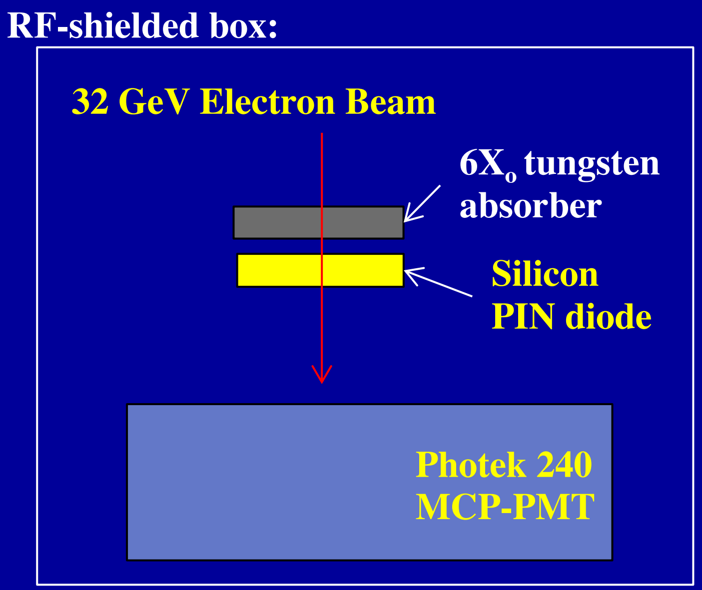
- **Test achieved σ_{SiPMT} ~ 13 ps resolution per MIP.**

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



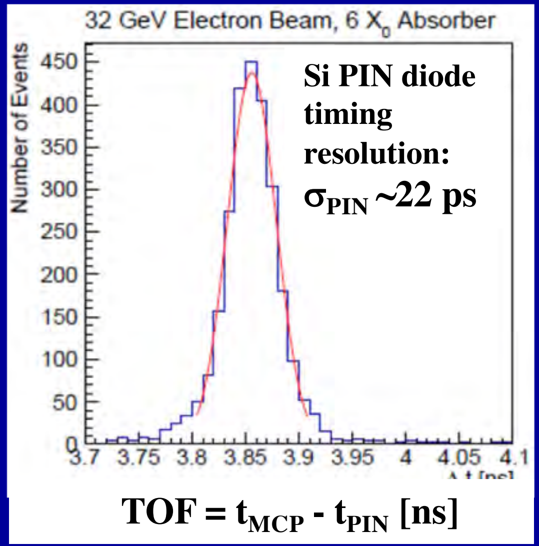
RF-shielded box:

32 GeV Electron Beam

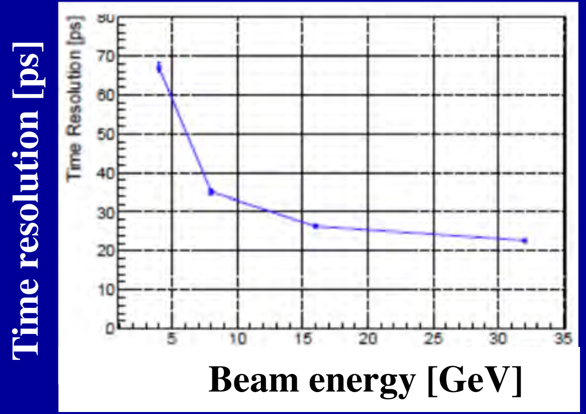
$6X_o$ tungsten absorber

Silicon PIN diode

Photek 240 MCP-PMT



Si PIN diode timing resolution: σ_{PIN} ~22 ps

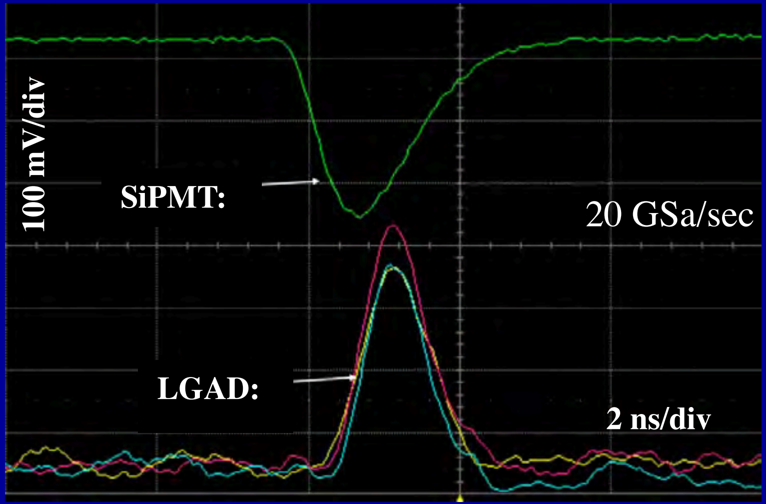


- **Si-PIN diode can achieve pretty good timing resolution in a calorimeter application.**

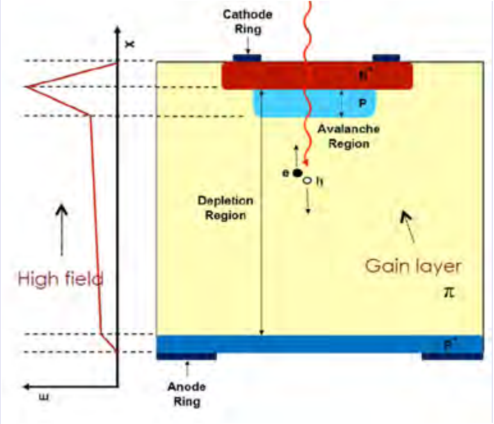
ATLAS: Low Gain Avalanche Diodes in test beam

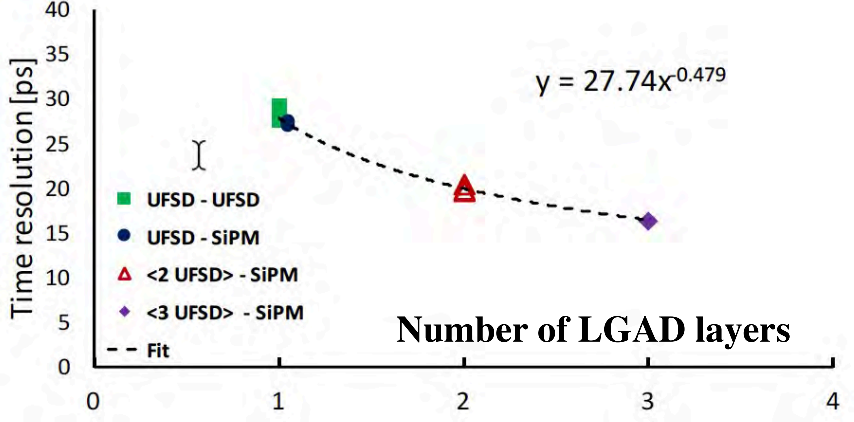
Cartiglia et al., ArXiv:1608.08681, 2017

- **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

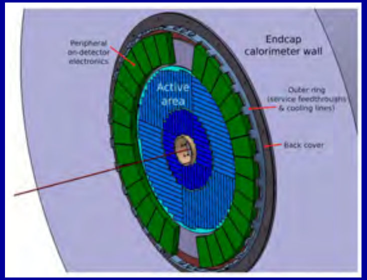
$\sigma_{\text{time}} \sim t_{\text{rise time}} /(S/N) \sim 20$ ps

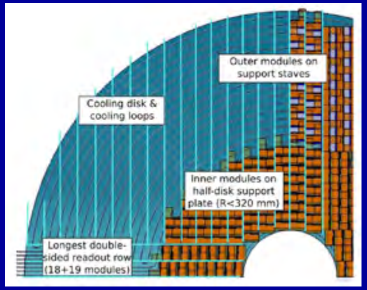
- **Test beam achieved: σ_{time} ~34 for a single sensor, and ~16 ps with a tandem of 3 sensors.**

ATLAS Endcap plan: Low Gain Avalanche Diodes

ATLAS technical proposal, 2019

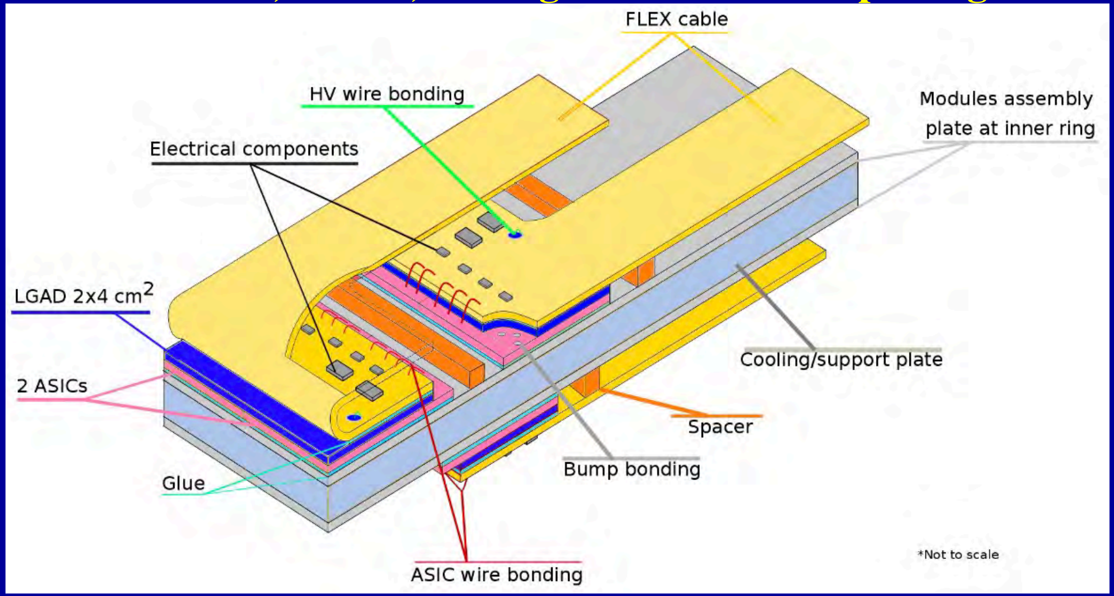
ATLAS Endcap:





12 cm < r < 60cm
7888 sensor modules

LGAD sensors, ASICs, cooling and connection package:



- **Radiation doses up to ~4 × 10^{15} n_{eq}/cm^2 and 4.1 MGy are extremely challenging.**
  (1 MGy = 100 Mrads !! I have tested BaBar DIRC optical components up to ~10 krads only !!).
- **Every component of the detectors will have to be tested, including glues, cables, etc.**
- **TDR has been delayed by ~1 year until the radiation effects are better understood.**
- **However, if they succeed, it would be a great detector development achievement.**

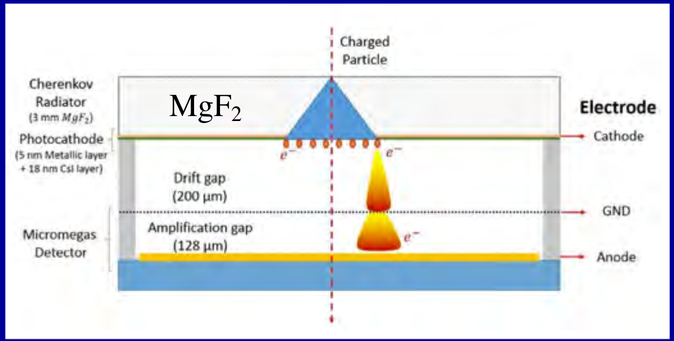
Gaseous detectors

Timing with Micromegas gas detector

Xu Wang, On behalf of the PICOSEC collaboration, presented at this conference

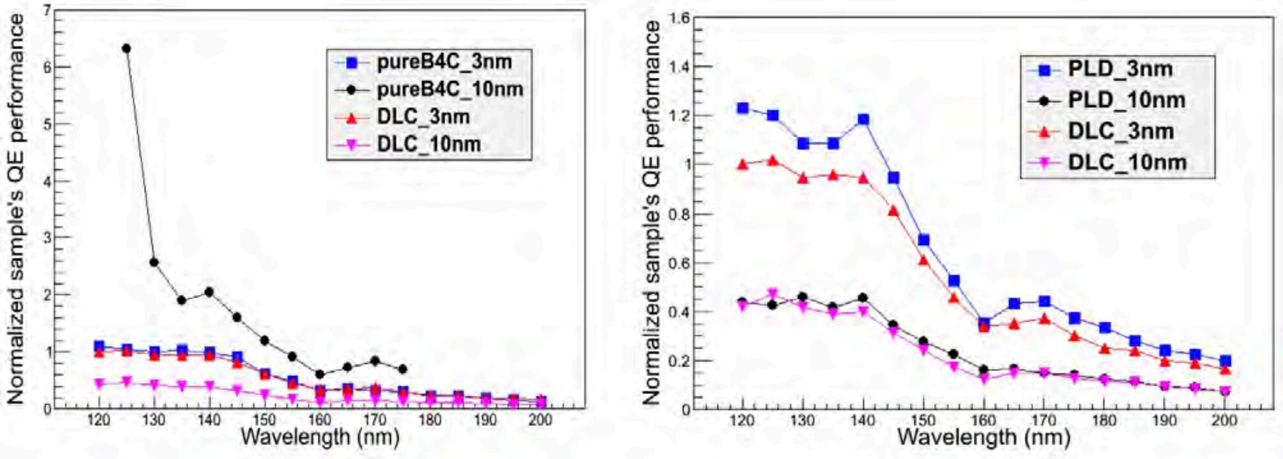
- Pixel size: ~1cm^2 area
- Photocathodes: CsI and DLC
- Gas: 80% Ne+10% CF_4+10% C_2H_6
- 3 mm MgF_2 window/radiator
- Cividec amp 1-2 GHz BW
- SAMPIC waveform digitizer
and 20 GSa/s LeCroy scope

Detector principle:



Preliminary:
New Diamond-Like Carbon (DLC) photocathodes →

Relative QE



- **Time resolution: ~24 ps for 150 GeV/c muons, ~76 ps for single photoelectrons !!**
- **Mean number of photoelectrons: ~10 per/MIP with CsI photocathode.**
- **New photocathodes (DLC): ~40 ps/MIP with 97% detection efficiency.**

Maximum rate and charge dose capability

MRPC (ALICE): MIP resolution of **~60 ps/MIP** and rate capability of **~500 Hz/cm^2** achieved.
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.
Needs to be cooled for single photon detection.

LGADs (ATLAS):
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 !!!! R&D in progress.

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

Conclusions

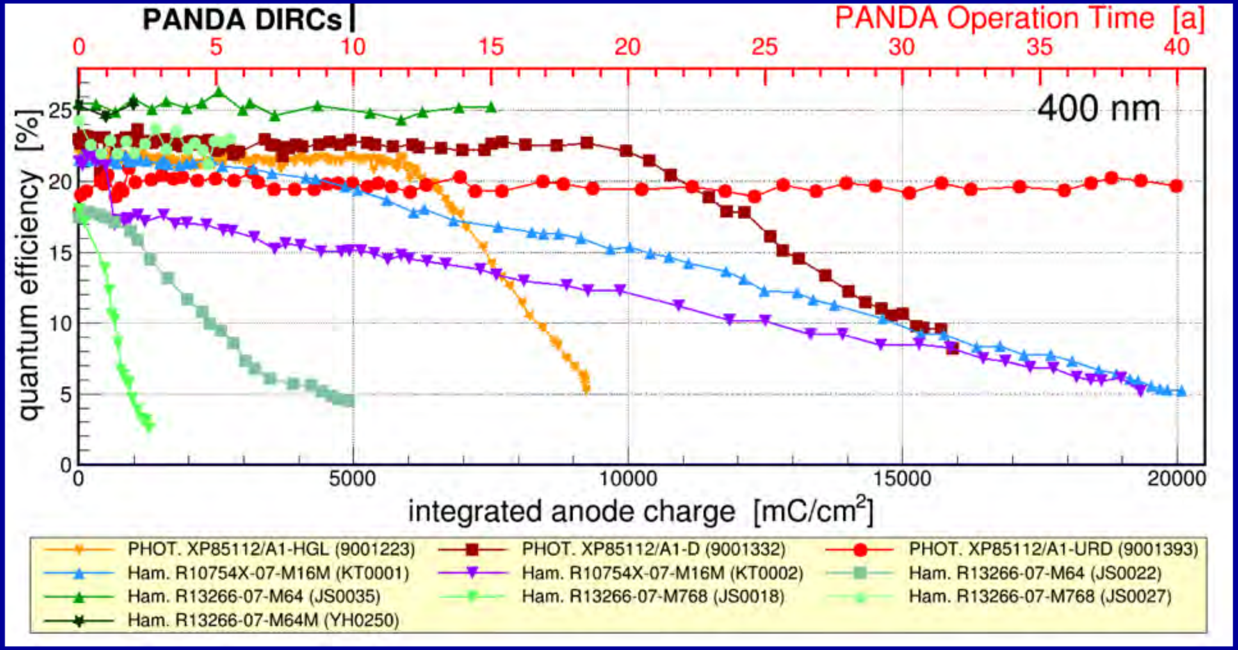
- **New MRPC R&D is aiming for ~20 ps resolution/MIP.**
- **There is a steady progress in the MCP detector technology to improve their lifetime and performance:**
  - **Single-pixel MCP can now achieve <10 ps resolution for MIPs.**
  - **There is a number of new large DIRC detectors aiming for a single photons resolution of 70-120 ps.**
- **ATLAS: There is a large effort to develop LGAD detectors aiming for a timing resolution of ~30ps. However, there are huge challenges due to high background rates at LHC.**
- **Micromegas gaseous detectors can reach timing resolution of ~25ps per MIP. This effort will benefit from a development of new radiation-resistant carbon-based photocathodes.**

Appendix

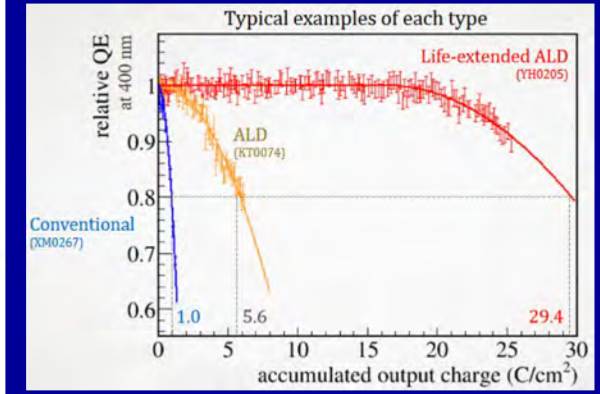
MCP-PMTs in high rate environment

MCP-PMT QE aging

PANDA: Albert Lehman, RICH 2018:



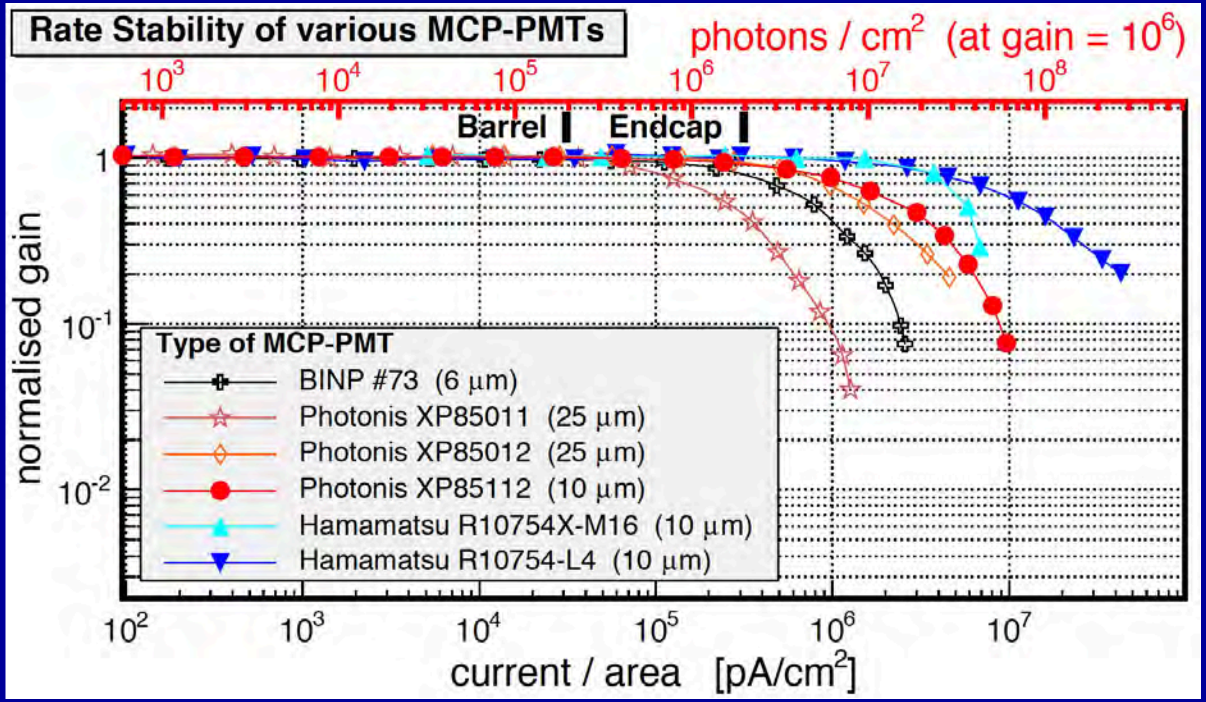
Belle-II: K.Matsuaoka, TIPP 2017:



- **New ALD-based treatment has improved the QE lifetime significantly.**
- Photonis MCP XP85112 (90011393) and a new Hamamatsu tube YH0205 are the best at present.
- **Not yet tested in a large system. Belle-II and Panda will do that.**

MCP-PMT rate capability

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

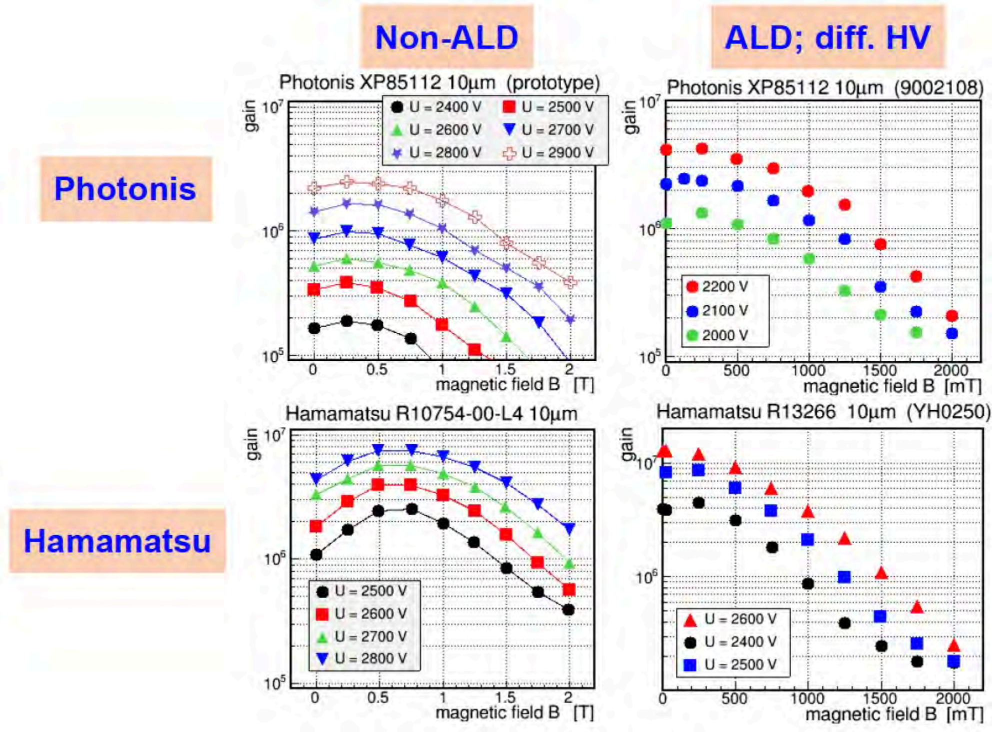


- **Most of the older MCP-PMTs show stable operation to ~200-300 kHz/cm^2 of single photons at gain of 10^6.**
- **Some latest MCP-PMTs could push rate up to ~10 MHz/cm^2.**
- **It is yet to be proven if this is sustainable in a large system for ~10 years !**

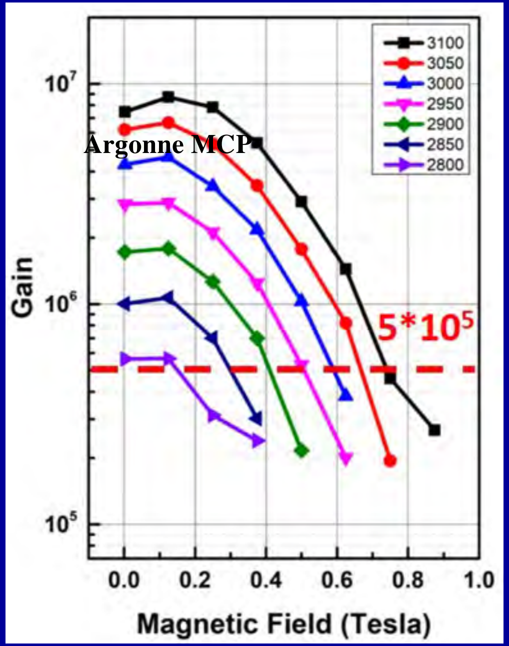
MCPs in magnetic field

MCP gain in magnetic field

A. Lehman, RICH 2018, Moscow:



Xie et al., submitted to NIMA:



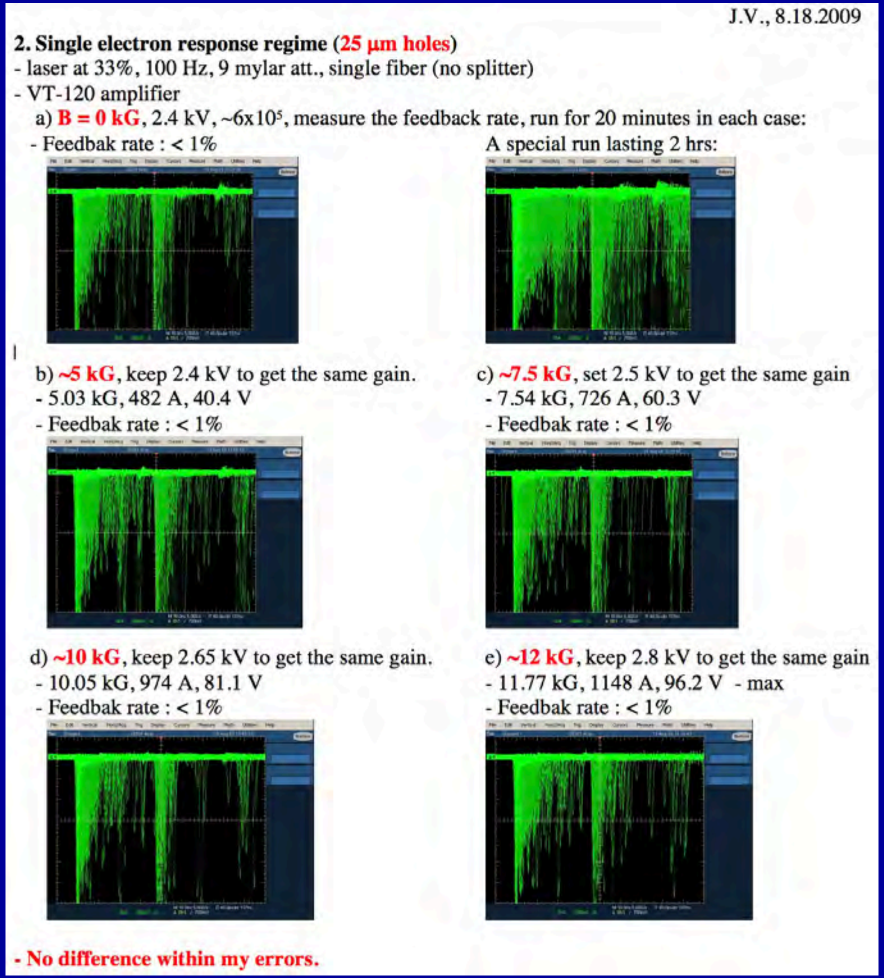
- **ALD tubes seem to show faster gain drop in B-fields than non-ALD tubes !**
- Photonis 9002108: gain drop by a factor of 2 at 1 Tesla, at 0 deg.
- Hamamatsu YH0250: gain drop by a factor of 4 at 1 Tesla, at 0 deg.
- Argonne MCP: gain drop by a factor of more than 10 at 1 Tesla, at 0 deg.

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%

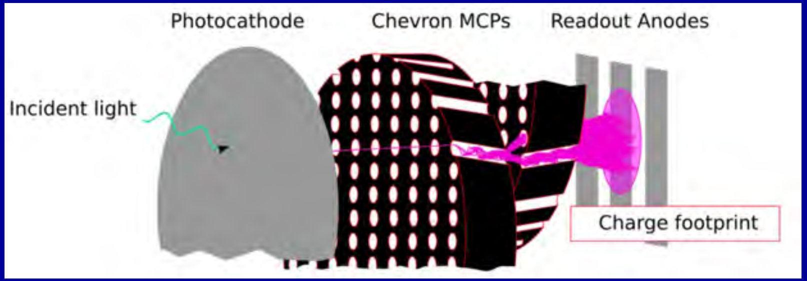
- No difference within my errors.

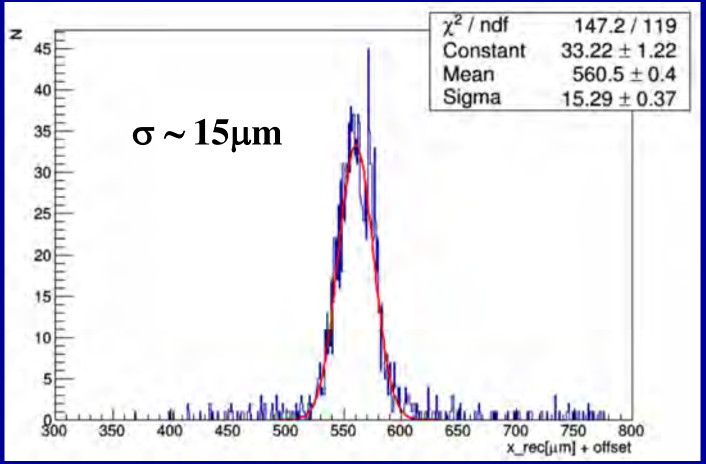
- **No increase in the ion feedback within my errors.**

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

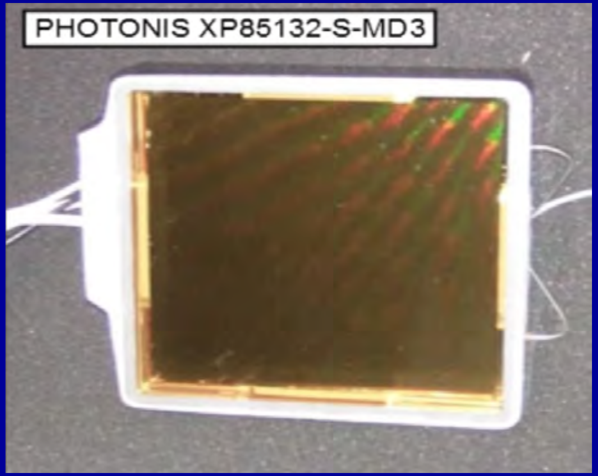
J. Rieke et al, JINST 11, 2016, and Panda Endcup DIRC TDR, 2019

Anode charge footprint:





New Photonis MCP for Endcap Panda:



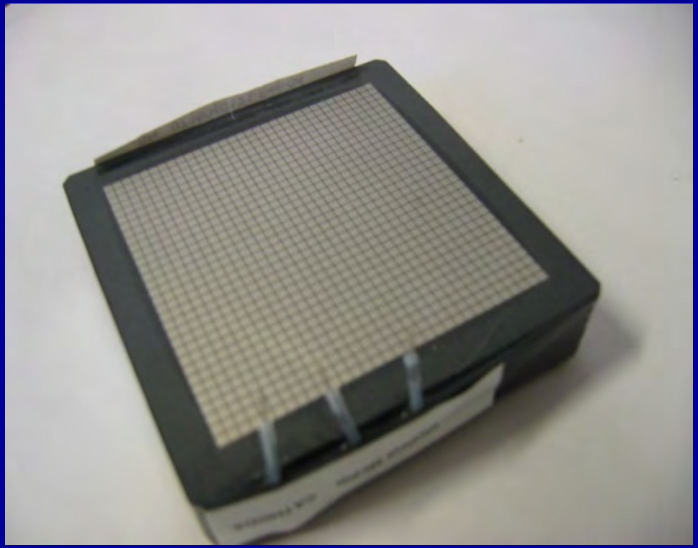
- MCP has 0.4 mm x 17 mm anode pads.
- 3 rows x 100 strip configuration.
- MCP-Anode gap = 0.625 mm
- tube does not have a ground plane

- This is a very significant measurement !! A magnetic field of only ~0.1 T will reduce the charge footprint to ~15µm !!

FDIRC development at SLAC

MCP-PMT is a simple device, in principle

Example: Bare Burle Planacon (available already in 2005 !!)
(Anode plane with 1024 pixels)



- **Small pixels would allow any configuration of final pixel sizes.**
- **Status of MCP understanding in our group by 2005, when I gave a talk at Hamamatsu Co.:** http://www.slac.stanford.edu/~jjv/activity/Vavra_Photon_detector_studies.pdf and NIMA 553 (2005) 96.

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>:

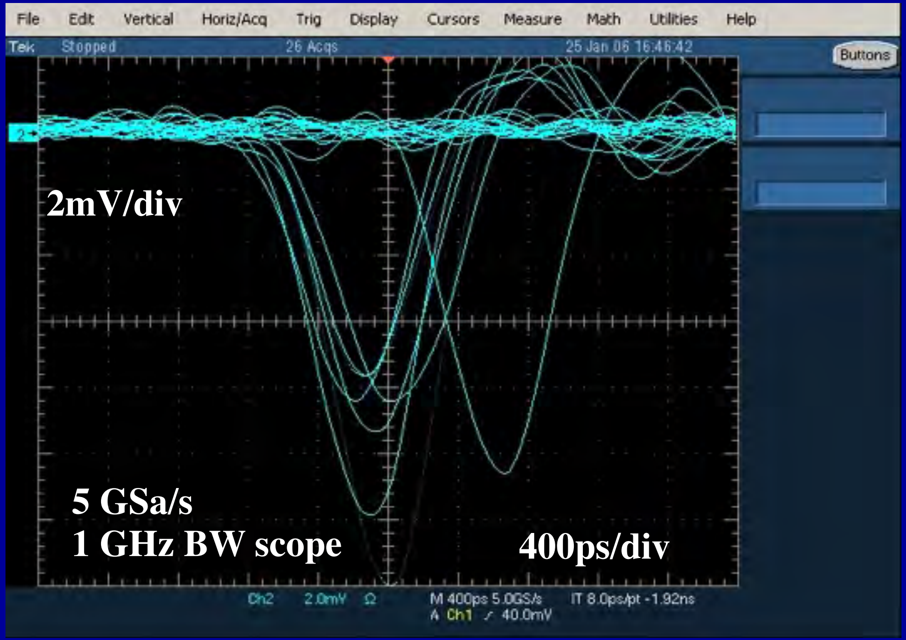
$\sigma_{noise} \sim 0.4$ mV

S ~ 8 mV

S/N ~ 8/0.4 ~ 20

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

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

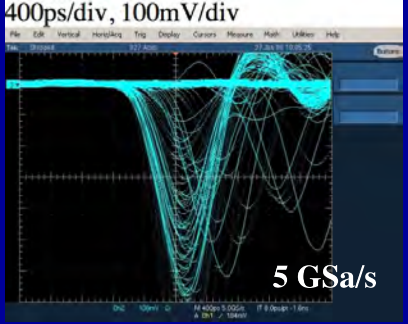


- **That told me that one can reach a very good resolution with this MCP**

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

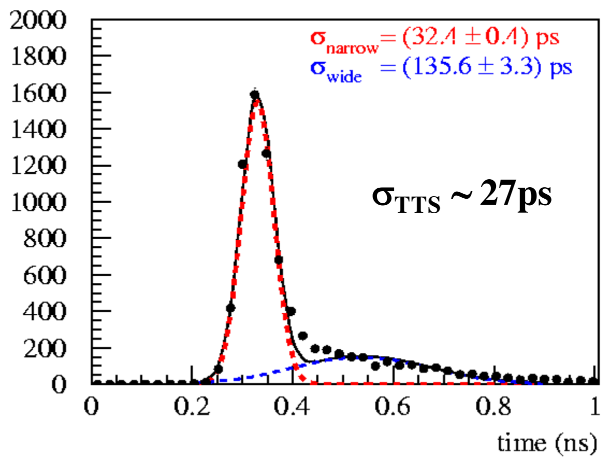
Planacon 85013-501 single electron pulses with Hamamastu 63x amplifier C5504-44 :



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

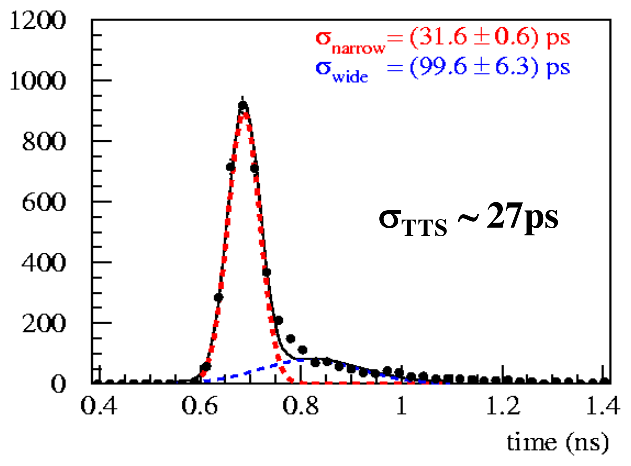
Hamamatsu C5594-44 amplifier

1.5 GHz BW, 63x gain, 2.8kV



Ortec VT120A amplifier

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

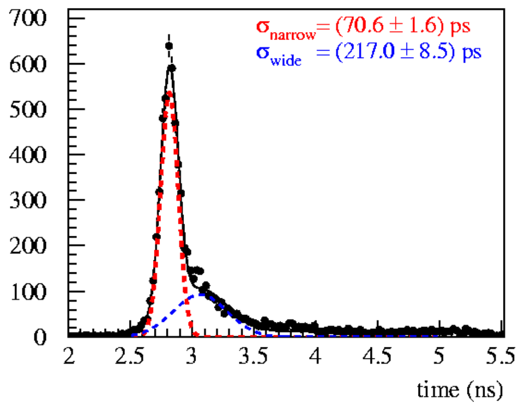


- **One can obtain a good TTS resolution even with a slower amplifier, if one has a good S/N ratio, and one tunes CFD discrimination carefully.**

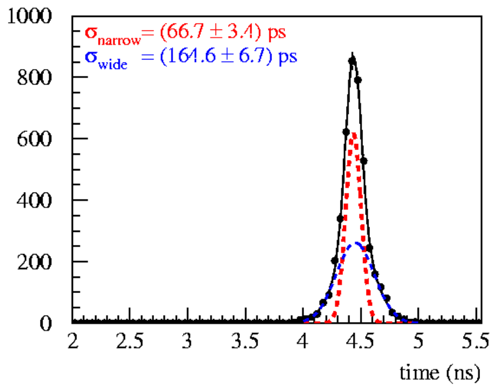
MCP-to-cathode distance - a way to eliminate tail

SLAC effort: NIMA553(2005)96

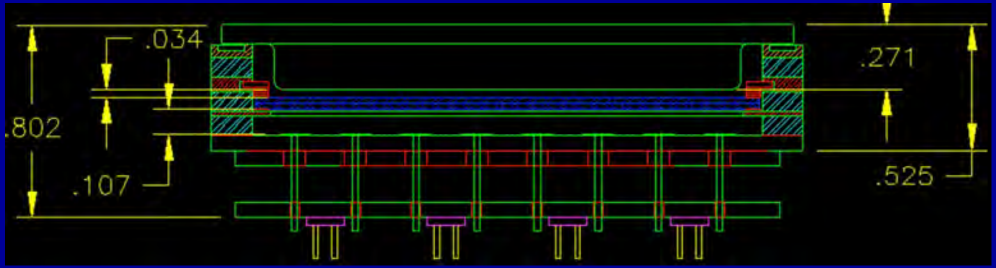
MCP-to-Cathode distance = 6 mm
85011-501 Nominal design:

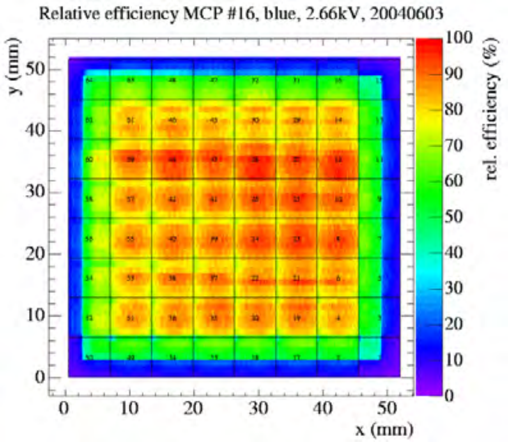


MCP-to-Cathode distance ~0.85 mm
85014-430 Drop Faceplate:



Planacon stepped face MCP (85014):





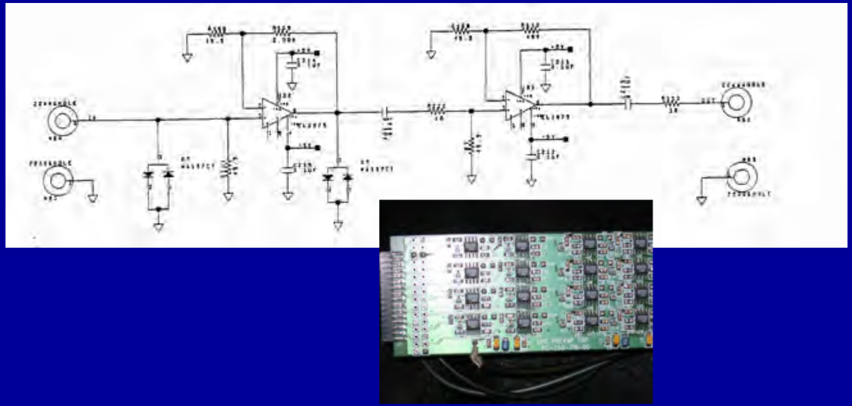
- **Penalty: the efficiency drops to zero half way through all edge pads.**

SLAC FDIRC prototype with 320-pixels in MCPs

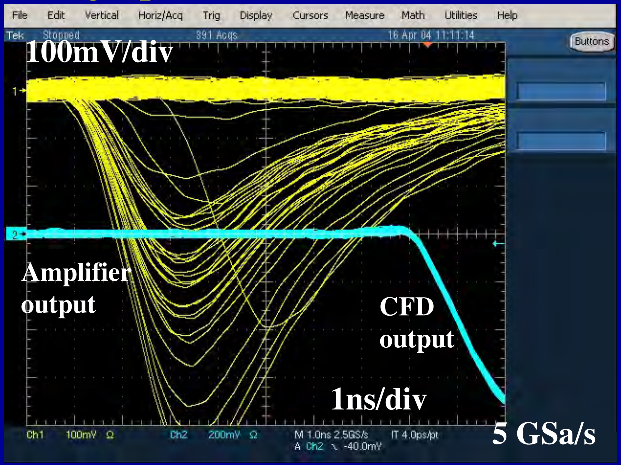
SLAC effort: NIMA 553 (2005) 96

SLAC Amplifier based on Elantek 2075:

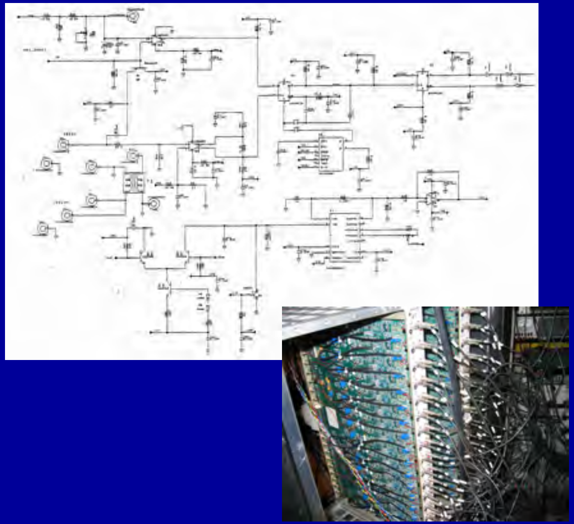
Voltage gain of ~130x, and a rise time of ~1.5ns.



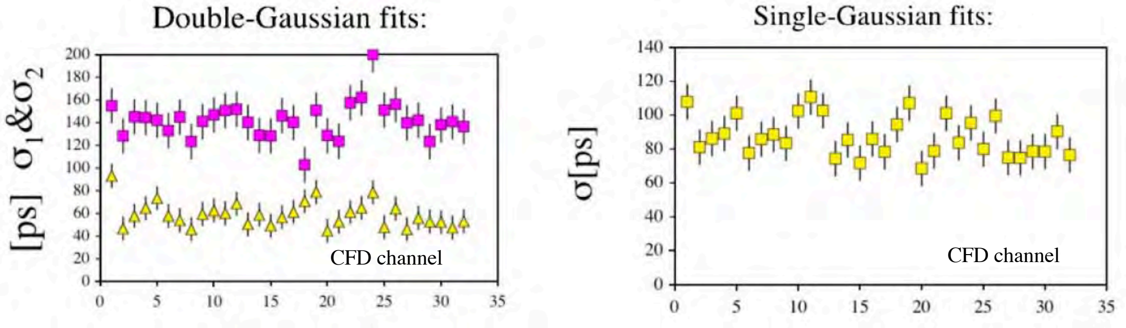
Single photons from Laser:



SLAC CFD (32 ch./board):



Single pixel timing resolutions with Planacon MCP:

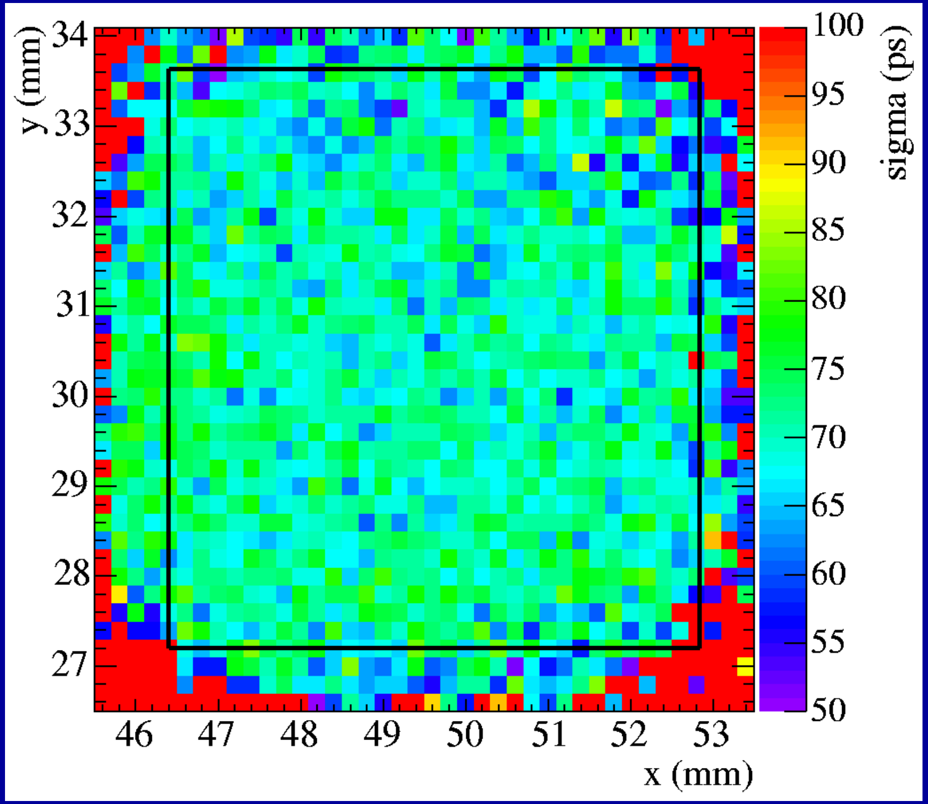


- **This was still one of the best timing performance of any large RICH detector system with MCPs.**

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.**