TOT/TOA timing for MCP-PMTs ?

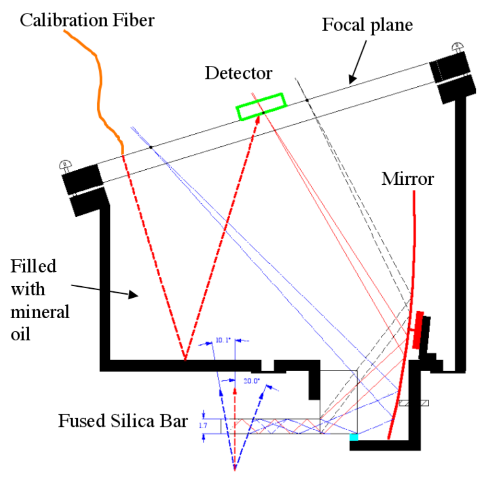
J. Va’vra, SLAC

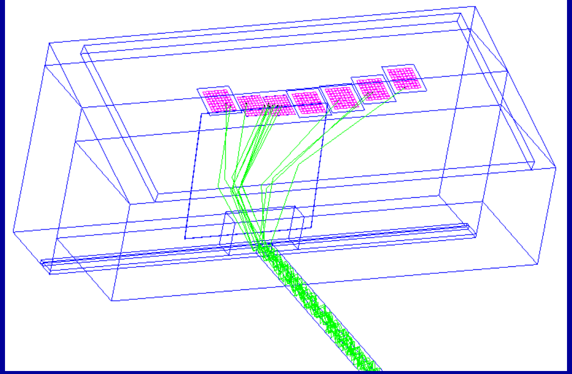
For more information: “Picosecond timing detectors and applications”, J. Phys.: Conf. Ser. 1498 (2020) 012013

Fast Detector R&D for SuperB

SuperB Detector TDR, INFN-13-01/PI, LAL-13-01, SLAC-R-1003, 2013

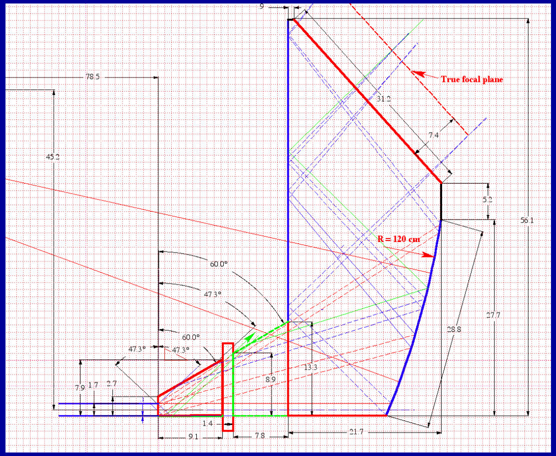
FDIRC prototype #1:

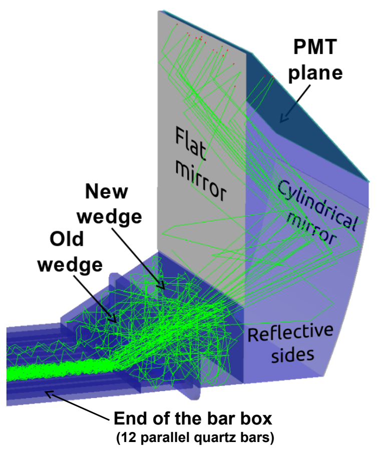




- Learn the FDIRC concept
- 5 MCP-PMTs + 2 H-8500 MaPMTs
- CFD electronics

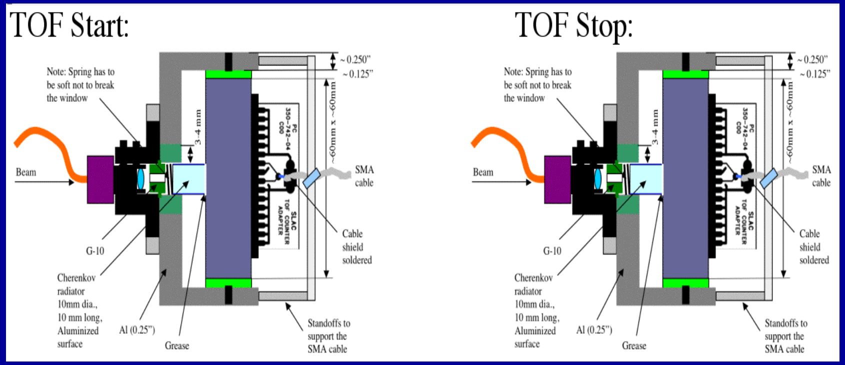
FDIRC prototype #2:





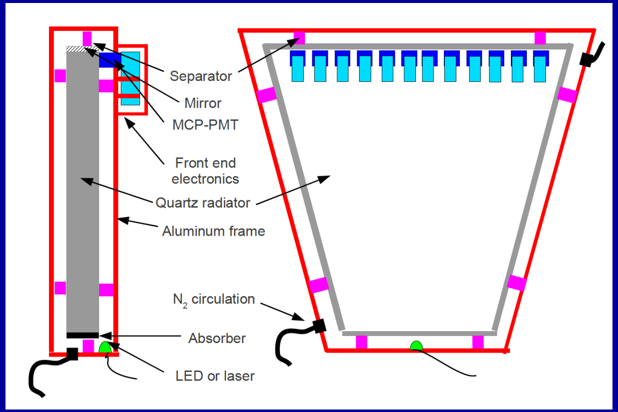
- 12 H-8500 MaPMTs
- IRS-2 waveform electronics

TOF prototypes:



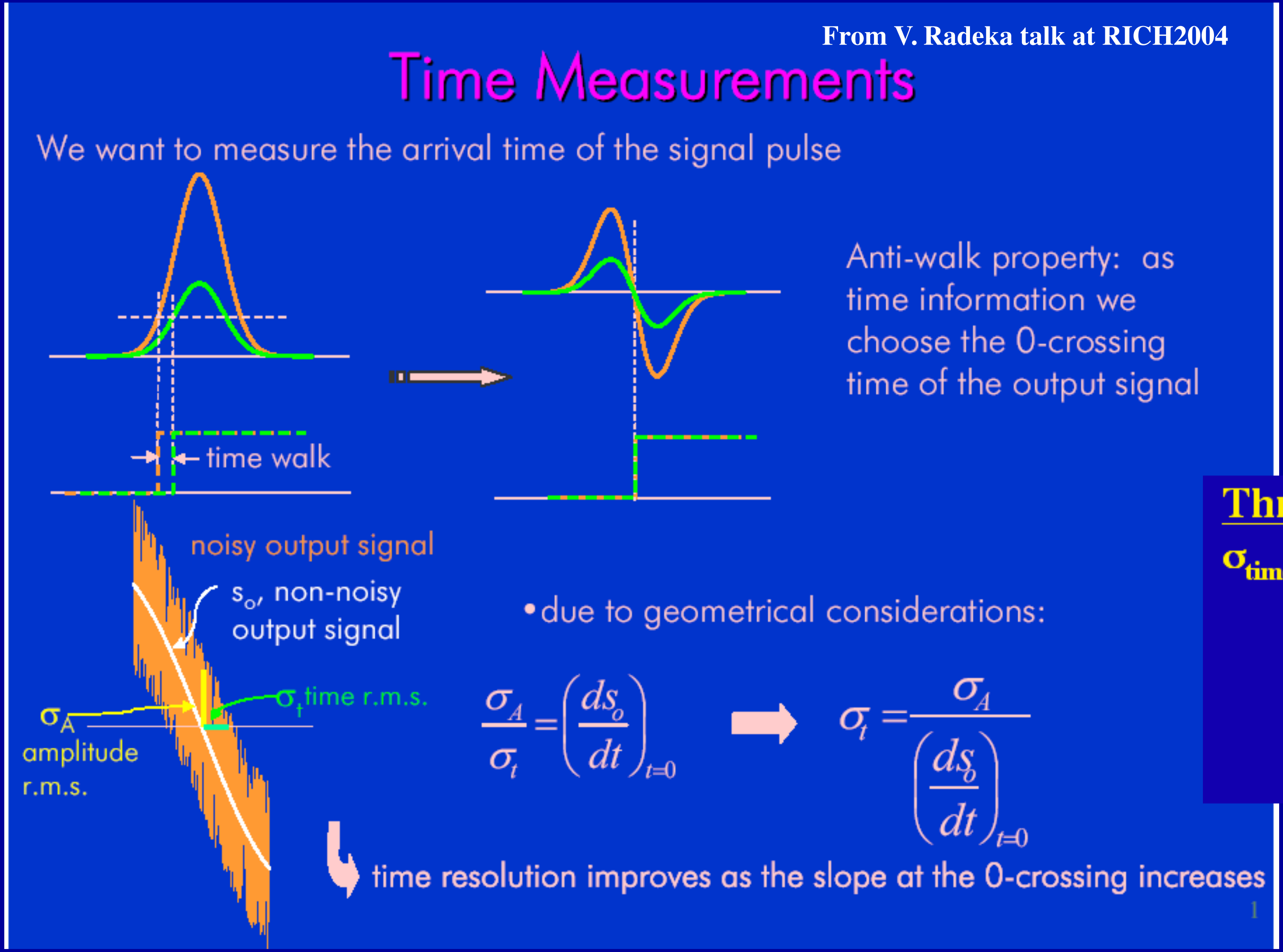
- MCP-PMTs
- Explore many timing techniques

FTOF concept:



- MCP-PMTs
- WaveCatcher waveform electronics

Constant fraction timing (CFD)



From V. Radeka talk at RICH2004

Time Measurements

We want to measure the arrival time of the signal pulse

Anti-walk property: as time information we choose the 0-crossing time of the output signal

- due to geometrical considerations:

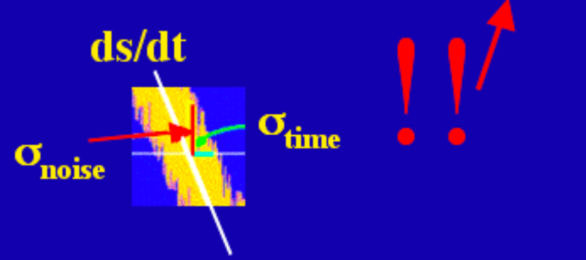
$$\frac{\sigma_A}{\sigma_t} = \left(\frac{ds_o}{dt}\right)_{t=0} \Rightarrow \sigma_t = \frac{\sigma_A}{\left(\frac{ds_o}{dt}\right)_{t=0}}$$

time resolution improves as the slope at the 0-crossing increases

I would add to it this:

Threshold timing:

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



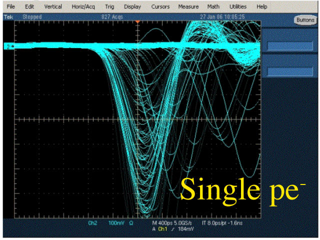
One can reduce rise-time if S/N increases correspondingly

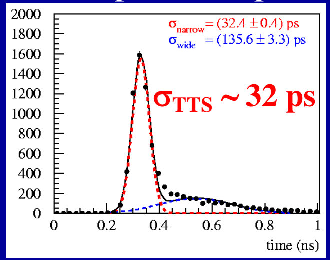
My best σ_{TTS} was achieved with slower electronics

J.Va'vra et al., Nucl.Instr.&Meth. A 572 (2007) 459–462, and my logbooks 3 & 6, 2006 & 2008

1) ~ 300 MHz BW electronics:

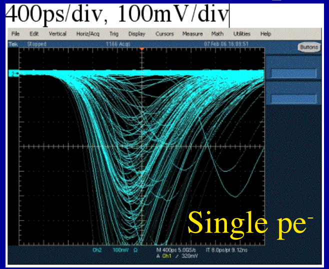
HPK C5594-44 (1.5 GHz BW amp.), Phillips 715 CFD, TDC 2248:

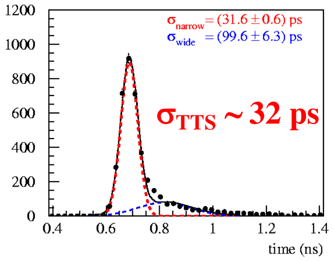



$\sigma_{narrow} = (32.4 \pm 0.4)$ ps
$\sigma_{wide} = (135.6 \pm 3.3)$ ps

σ_{TTS} ~ 32 ps

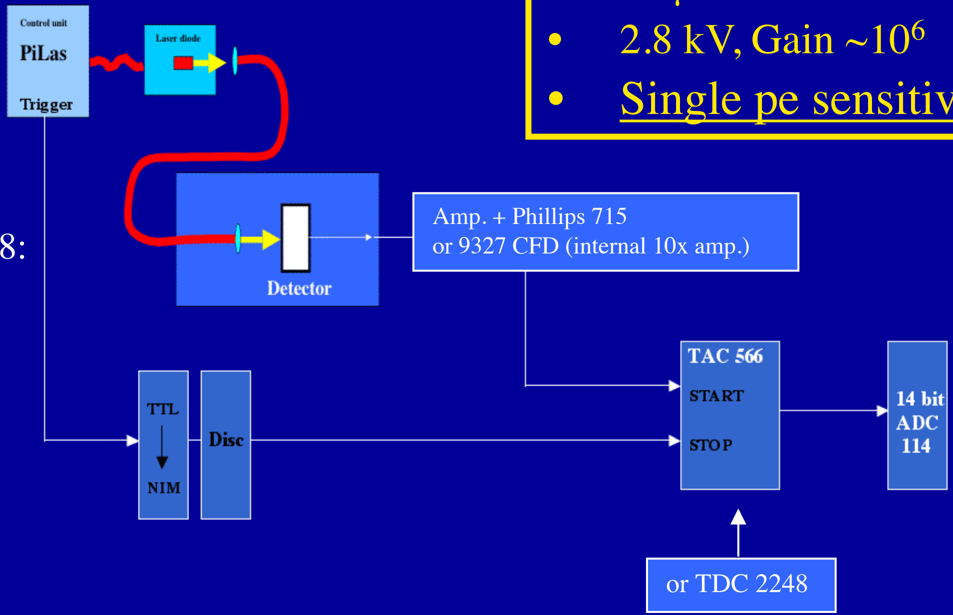
Ortec VT-120 amp. (0.4 GHz BW), Phillips 715 CFD, TDC 2248:




$\sigma_{narrow} = (31.6 \pm 0.6)$ ps
$\sigma_{wide} = (99.6 \pm 6.3)$ ps

σ_{TTS} ~ 32 ps

- Slow down amplifiers by a long cable between Amp & CFD (optimum was found to be ~20ns).

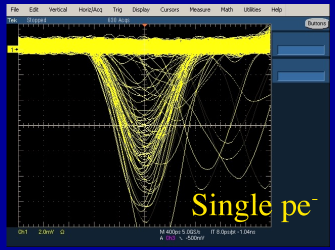


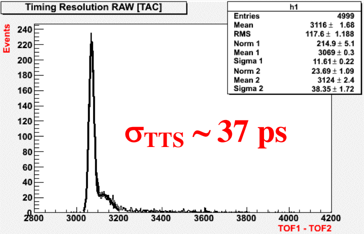
- Burle Planacon, S/N 11180401
- 10 μm MCP hole diameter
- 2.8 kV, Gain ~10^6
- Single pe sensitivity

2) ~ 1 GHz BW electronics:

Ortec 9327CFD, TAC566, ADC114:

CFD monitor output:



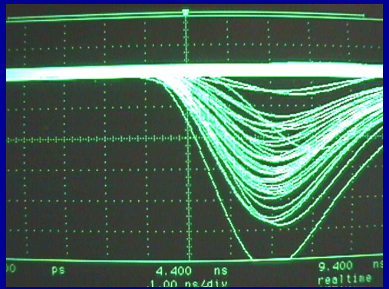

Timing Resolution RAW [TAC]

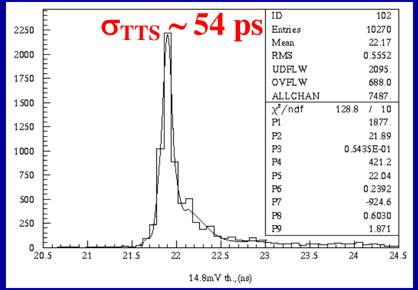
h1	
Entries	4999
Mean	3116 ± 1.68
RMS	117.6 ± 1.188
Norm 1	214.9 ± 5.1
Mean 1	3069 ± 0.3
Sigma 1	11.61 ± 0.22
Norm 2	23.69 ± 1.09
Mean 2	3124 ± 2.4
Sigma 2	38.35 ± 1.72

σ_{TTS} ~ 37 ps

3) ~ 300MHz BW electronics:

SLAC amplifiers: Tandem of two Elantek EL2075C chips, SLAC CFD:



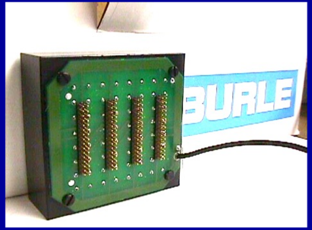

σ_{TTS} ~ 54 ps

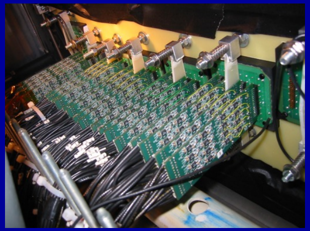
ID	102
Entries	10270
Mean	22.17
RMS	0.5552
UDFLW	2095.
OVFLW	688.0
ALLCHAN	7487.
χ^2/ndf	128.8 / 10
P1	1877.
P2	21.89
P3	0.5435E-01
P4	421.2
P5	22.04
P6	0.2392
P7	-924.6
P8	0.6030
P9	1.871

CFD timing in SLAC FDIRC prototype #1 with 320 MCP pixels

C. Field, T. Hadig, David W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, J. Va'vra, NIMA 553 (2005) 96

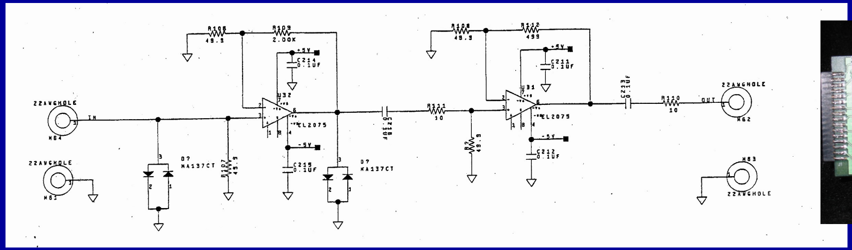
Old Burle Planacon:

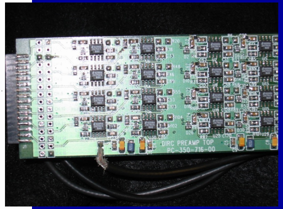




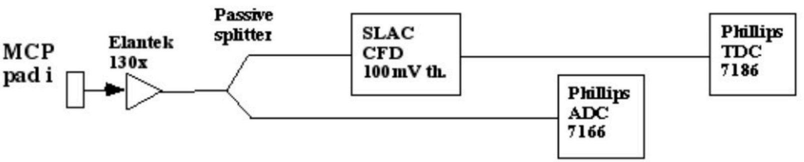
SLAC-made Amplifier based on Elantek 2075:

Voltage gain of ~130x, ~300 MHz BW.

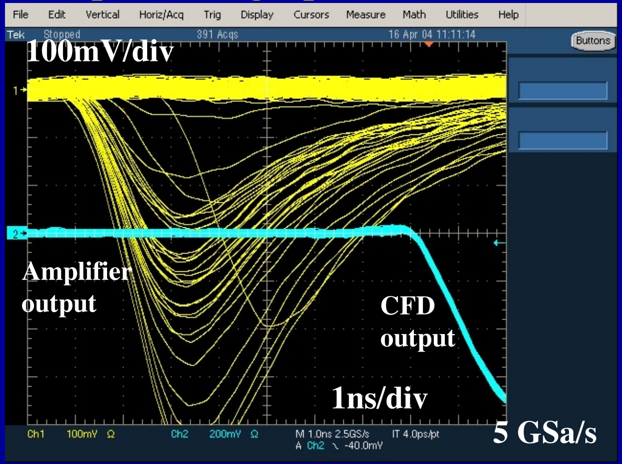




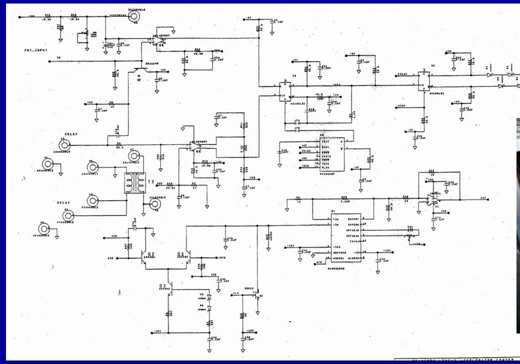
Simple electronics:

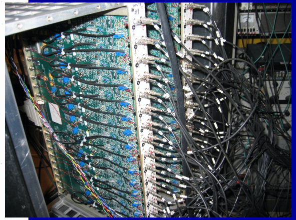


Amplified single photons - laser:



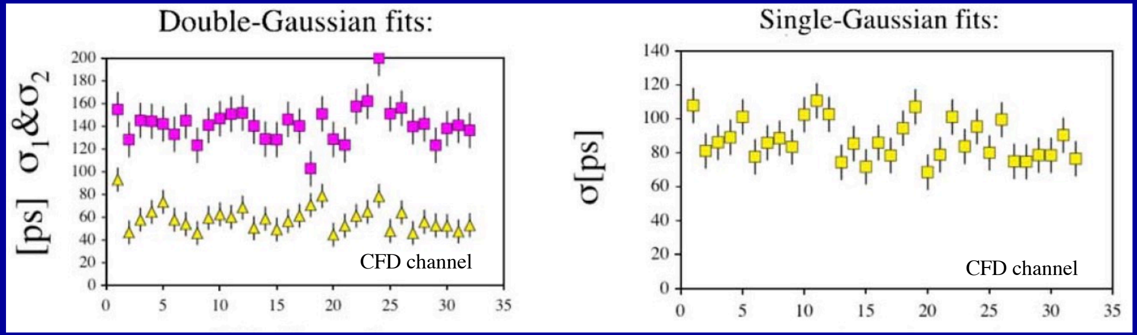
SLAC-made CFD (32 ch./board):





Single photo-electron timing resolutions with Planacon MCP:

(Burle Planacon MCP used in this test had 25 μm pores)



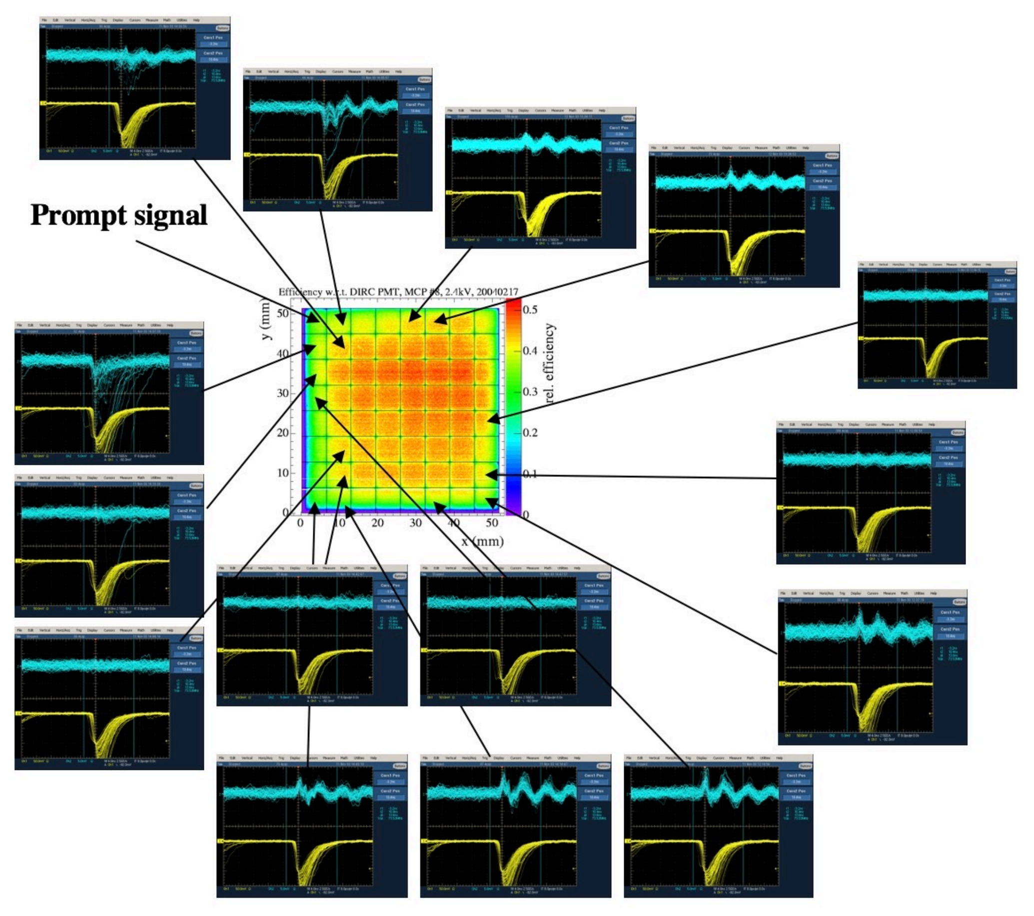
- **SLC CFD electronics worked very well.**

Cross-talk & ringing in early version of Planacon MCP-PMT

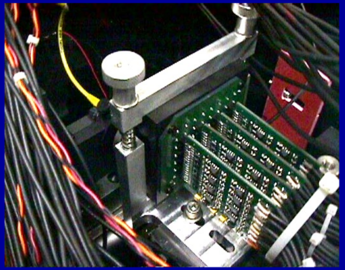
J.Va'vra, MCP-PMT logbook #1, p.81, 2005, and J Va'vra 2020 J. Phys.: Conf. Ser. 1498 012013

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

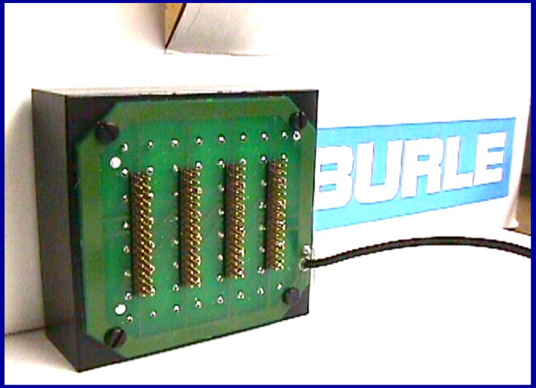
4 ns/div
&
50 mV/div
&
5 mV/div



Electronics used in this particular test:
Total voltage gain of 130x
Tandem of two Elantek 2075 amplifiers



All 64 pixel instrumented



- **Cross-talk was geometrically complicated in old Planacon 85011-501 (largest around boundaries).**

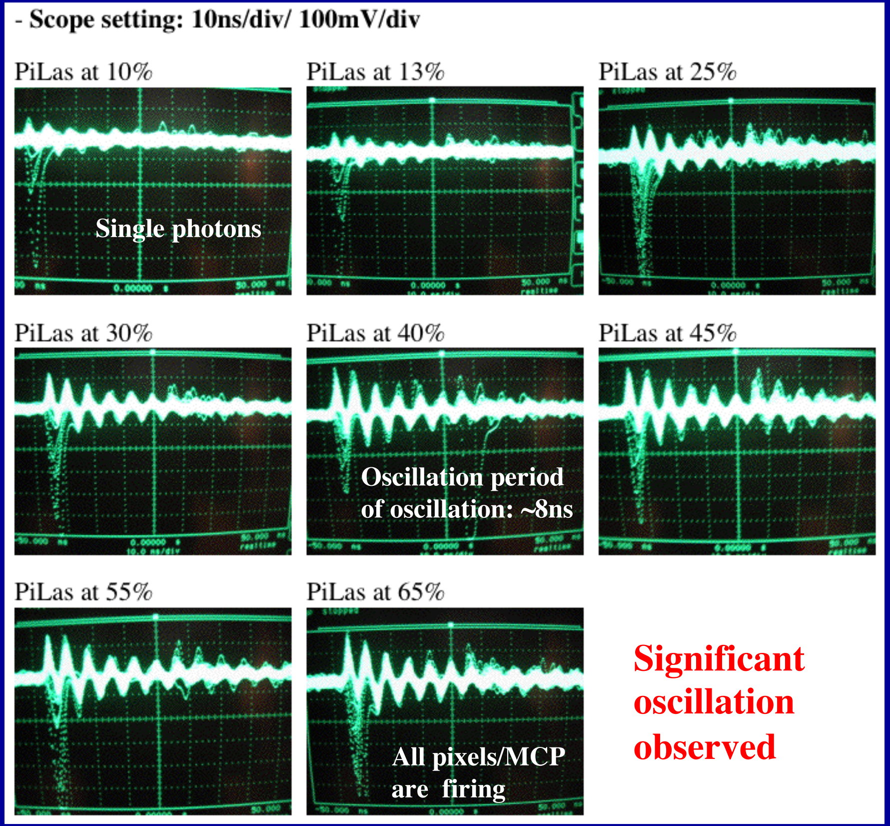
Ringing in early version of Planacon MCP vs. MaPMT

J. Va’vra, FDIRC logbook “Beam_test_Focusing_DIRC_3.pdf”, p.53, 2006, and J Va’vra 2020 J. Phys.: Conf. Ser. 1498 012013

Pilas laser

10ns/div
&
100mV/div

Planacon MCP-PMT 85011-501:



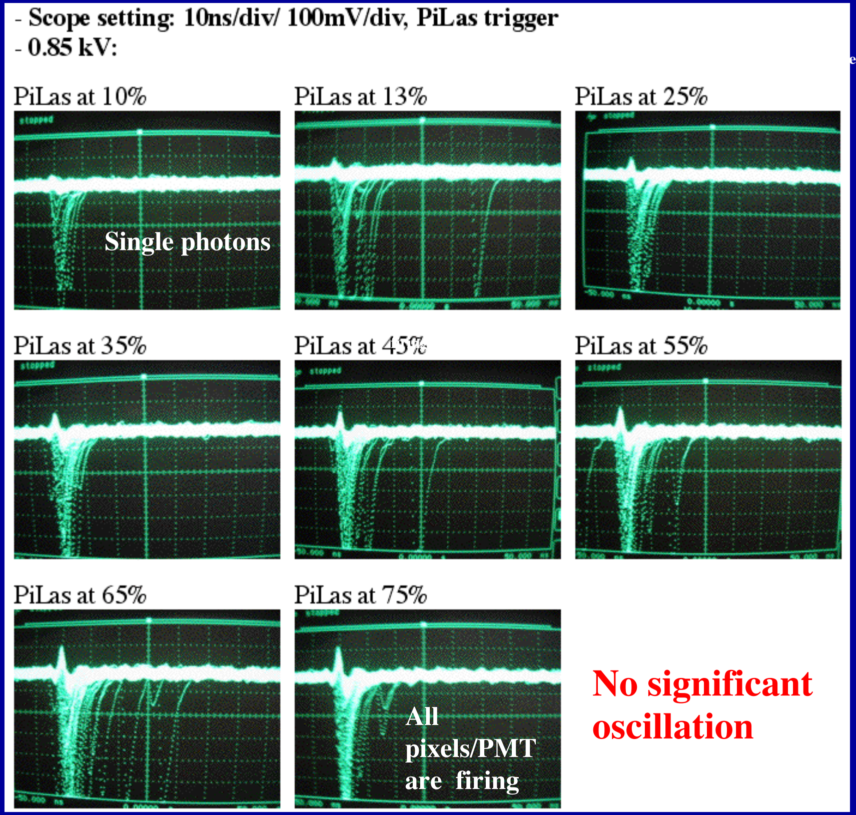
- Scope setting: 10ns/div/ 100mV/div

Oscillation period of oscillation: ~8ns

All pixels/MCP are firing

Significant oscillation observed

8500 MaPMT:



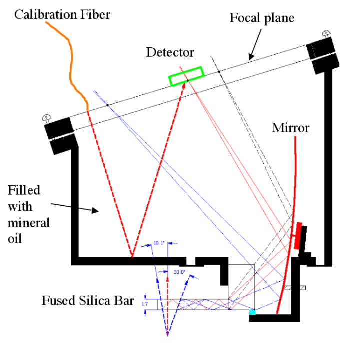
- Scope setting: 10ns/div/ 100mV/div, PiLas trigger
- 0.85 kV:

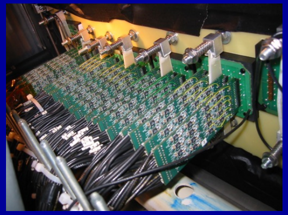
All pixels/PMT are firing

No significant oscillation

Scope trigger: Pilas laser

FDIRC #1

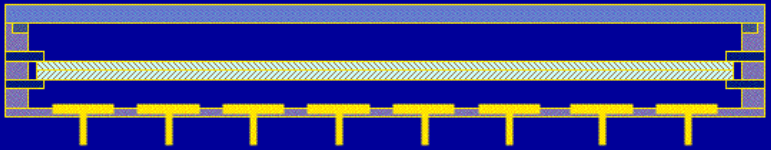




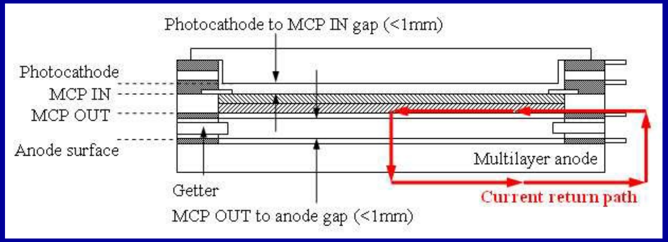
- Message: Amplitude of ringing increases with number of photons hitting MCP. Had to increase the discriminator threshold to avoid fake hits. H-8500 MaPMT with the same electronics was better.
- We provided all this information to Burle, i.e., to Jeff DeFazio, who now works for Photonis.

How to connect to Planacon MCP-PMT ? Many attempts…

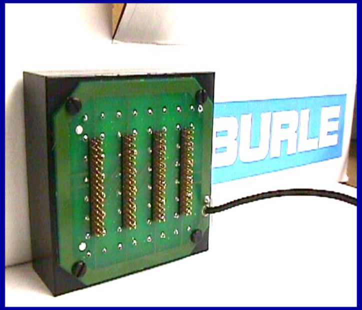
In principle, MCP is a simple device, but … :



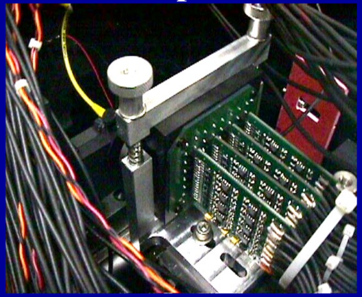
Ground return can be inductive:



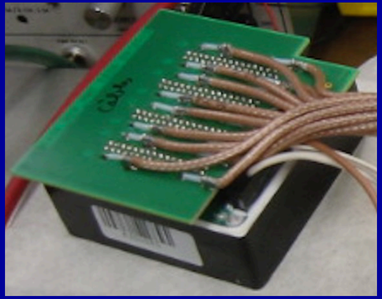
Old Burle Planacon:



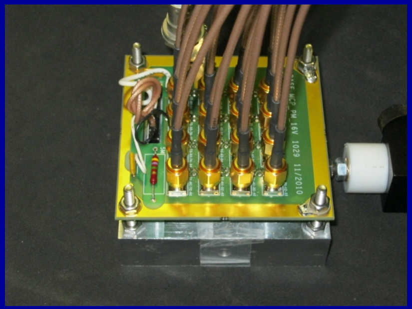
Old Planacon with SLAC amplifier:



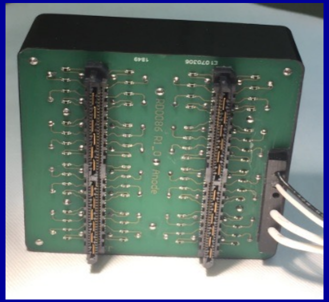
Old Planacon in FTOF counter:



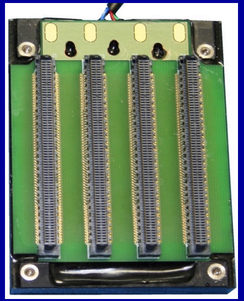
Old Planacon in Saclay bench test:



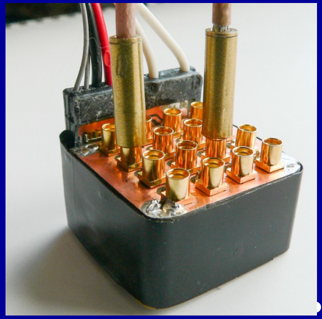
Latest Photonis Planacon:



Latest Photek:



New Mini-Planacon design for ATLAS:

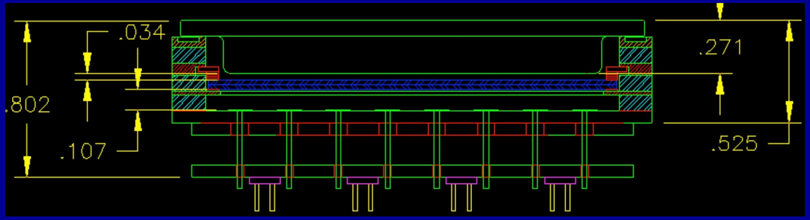


- MCP is <u>inherently a single-ended device</u>, which invites pick-up problems.
- Early Planacons had low-BW connectors, inductance in ground return, poor ground reference, cross-talk and ringing in far-away pixels creating wiggles in pulse shapes, etc.

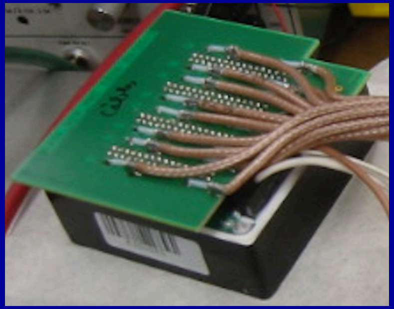
SLAC FTOF prototype for SuperB

J. Va’vra, Logbook #7, p.78, 2010, and FTOF results in L. Burmistrov et al., NIMA 695(2012)83 and his Ph.D. thesis

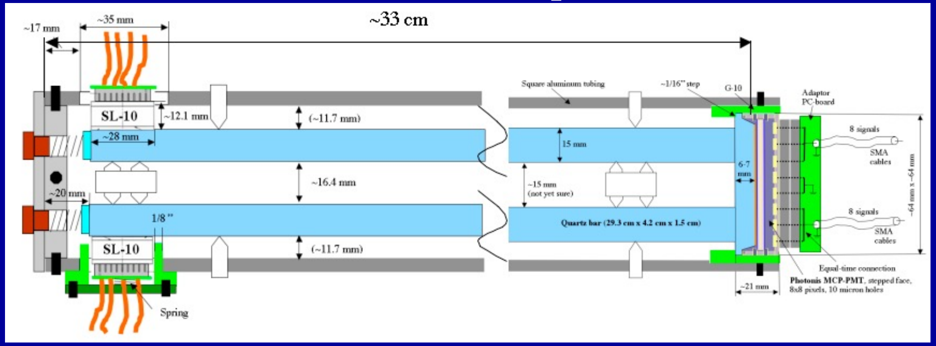
Stepped face Planacon MCP 85014:



Special PC board on MCP:

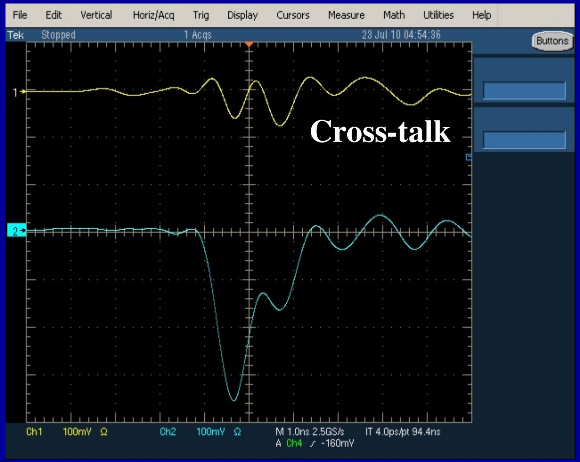


DIRC-like TOF counter with 2 quartz bars:



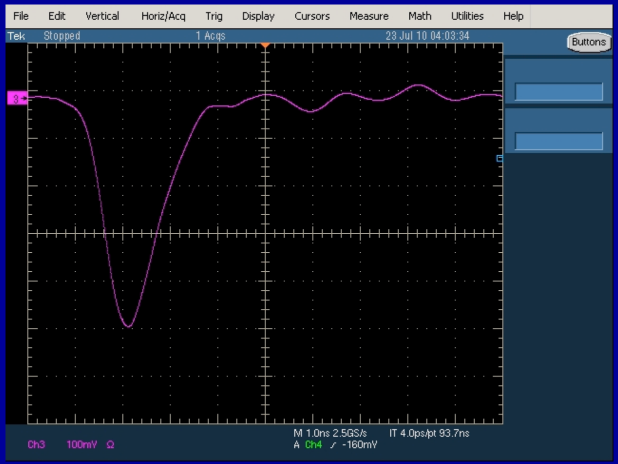
HPK C5594-44 amp., 1.5 GHz BW, 63x, no LP filter (MITEG amp. is similar):

Single photoelectrons at a gain of 5x10^5:



Cross-talk

VT-120 amp., 0.4 GHz BW, 63x, no LP filter:

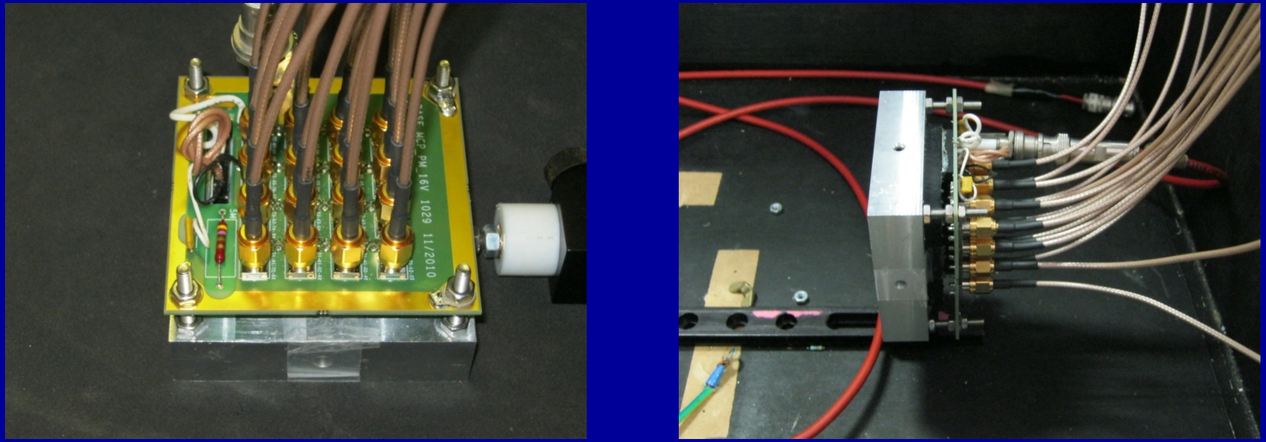


- **SLAC simulation by Tang shows that wiggles are caused by inductance; capacitance affects S/N ratio.**
- **Wiggles can be reduced by adding a low pass filter (~ 0.5 GHz BW), or slower amplifier, such as VT-120.**

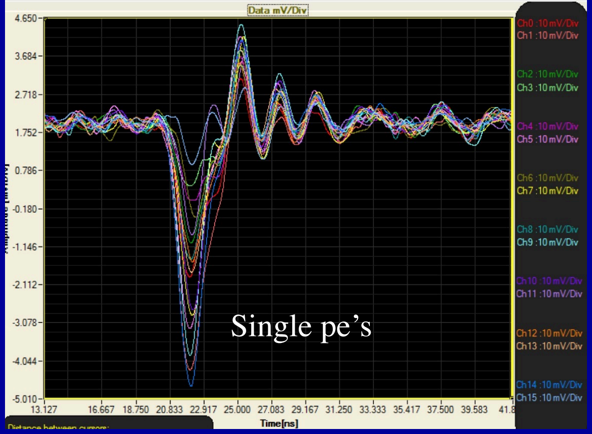
Ringing in Orsay Planacon MCP test for SuperB

D.Breton, L.Burmistov, J.Maalmi, V.Puill (LAL Orsay), 2010

Special PC board for Planacon MCP:



MITEG amp., 1.5 GHz BW, 63x, no LP filter:

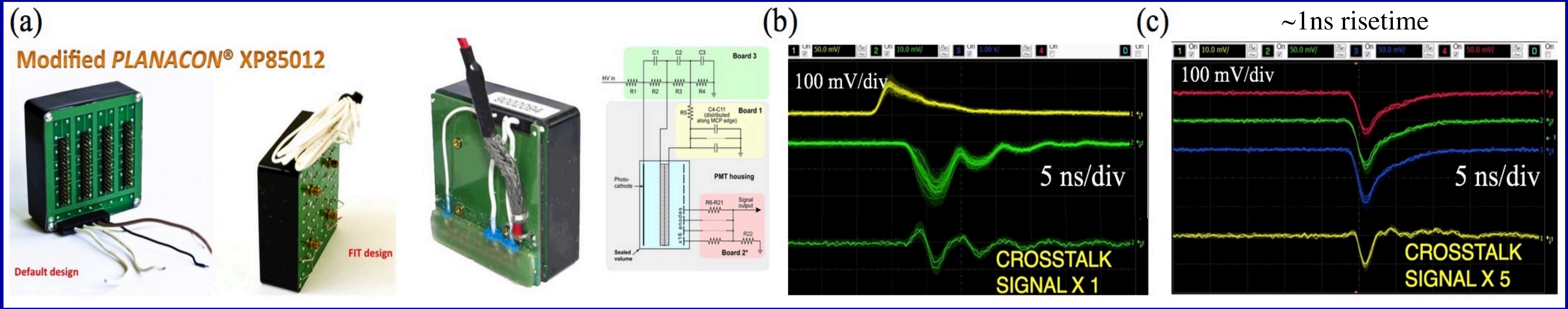


- **Planacon MCP-PMT 85012, 25µm holes & MITEG 1 GHz BW amp (gain ~ 63x).**
- **Special PC board: Group pixels into 16 groups of 4; equalize line lengths for each group of 4 pixels; output with SMA connectors and SMA cables to digitizers.**

ALICE FIT TOF detector: Modified Planacon MCP-PMT

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:**



- **A modification of 64-pixel Planacon XP85012 included:**
  - **(a)** reduced number of pixels from 64 to 4 (SMA connectors),
  - **(b) <u>improved the HV ground return</u>**
  - **(c) <u>increased a distributed capacitance along MCP edges</u>.**

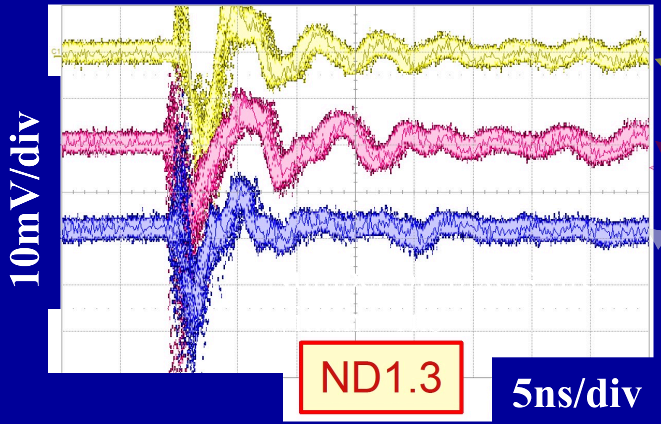
- **Cross-talk & ringing significantly improved, proving that it is MCP, which is causing problem.**

Cross-talk causing coherent excitations in new tubes

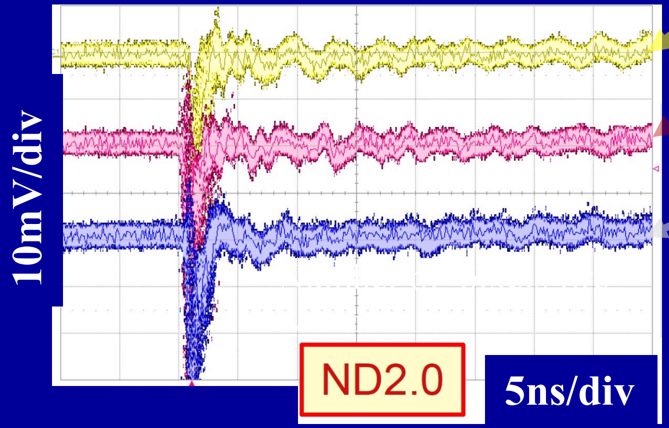
Albert Lehman, private communication before this talk, 5.20.2018

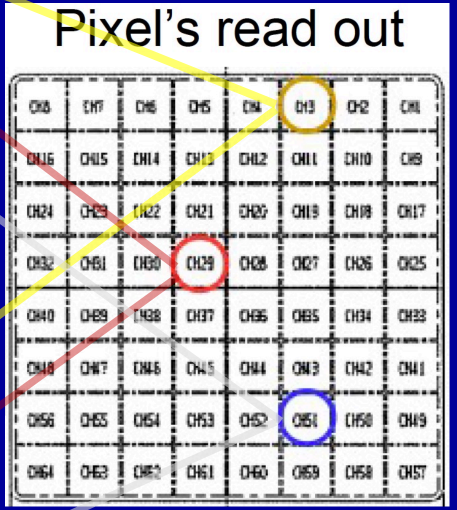
New Photonis Planacon 64-pixel MCP-PMT (XP85112-Q-HA)**:**

Illuminate the entire photocathode:



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





Pixel's read out

CH8	CH7	CH6	CH5	CH4	CH3	CH2	CH1
CH16	CH15	CH14	CH13	CH12	CH11	CH10	CH9
CH24	CH23	CH22	CH21	CH20	CH19	CH18	CH17
CH32	CH31	CH30	CH29	CH28	CH27	CH26	CH25
CH40	CH39	CH38	CH37	CH36	CH35	CH34	CH33
CH48	CH47	CH46	CH45	CH44	CH43	CH42	CH41
CH56	CH55	CH54	CH53	CH52	CH51	CH50	CH49
CH64	CH63	CH62	CH61	CH60	CH59	CH58	CH57

Scope trigger: ch.29

- **The cross-talk in the new Photonis Planacon MCP-PMT seems to be still there.**

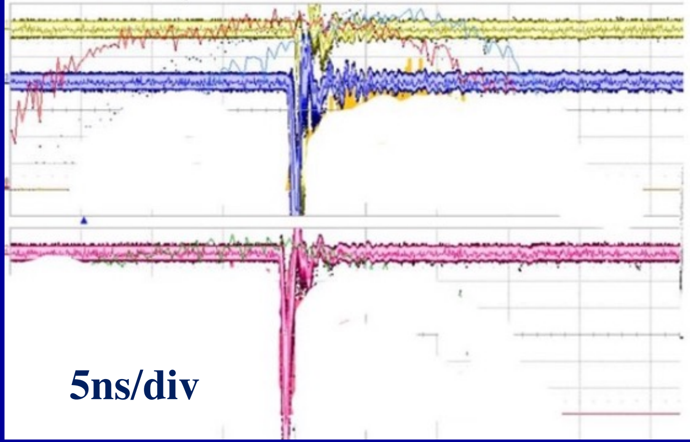
Panda R&D: Latest update on ringing of new 64-pixel Planacon

Albert Lehman, private communication, May 7, 2019, and Jeff DeFazio, private communication, and J Va'vra 2020 J. Phys.: Conf. Ser. 1498 012013

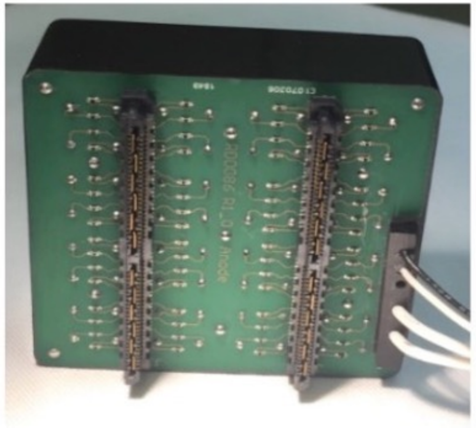
Latest Photonis Planacon, 2019:

All pixels fire at the same time:

Photonis (#9002150) - a latest model:



Latest Photonis Planacon:



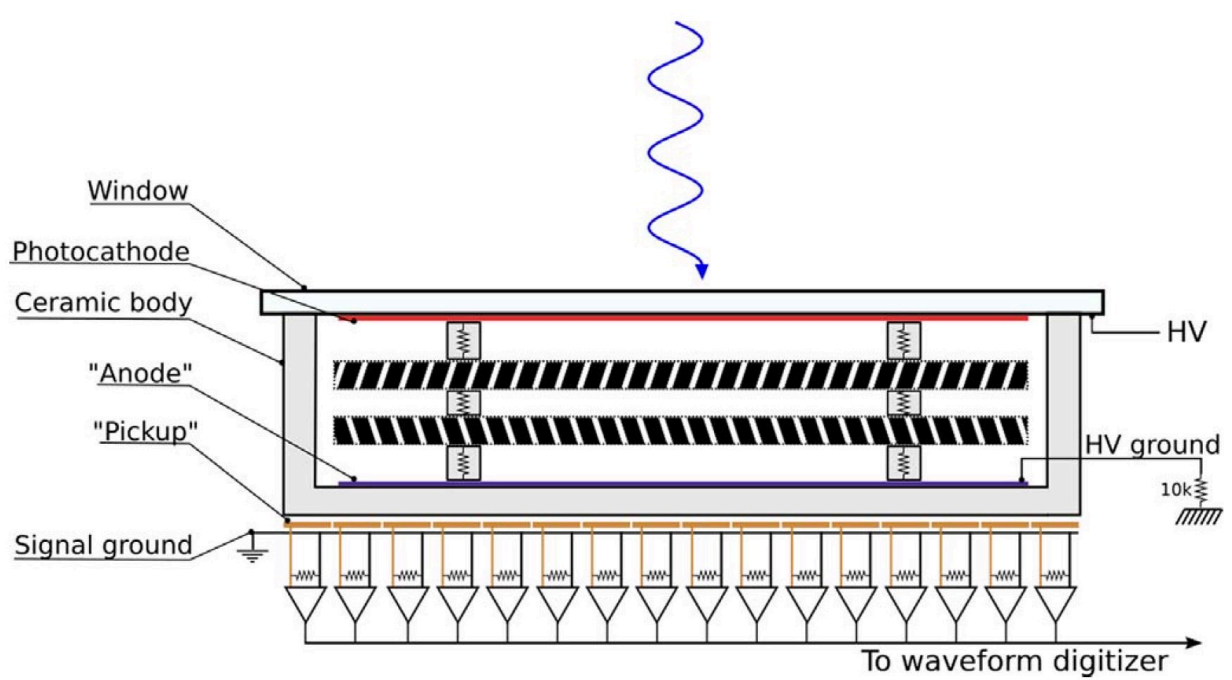
New features from Jeff DeFazio:
- New connector.
- Smaller anode-ground capacitance.
- Better ground return.
- Tube has the ground plane.
(Jeff thinks it helps to reduce ringing).

- **After ~15 years, the latest Photonis MCP (#9002150) has better ringing performance than old Planacon.**

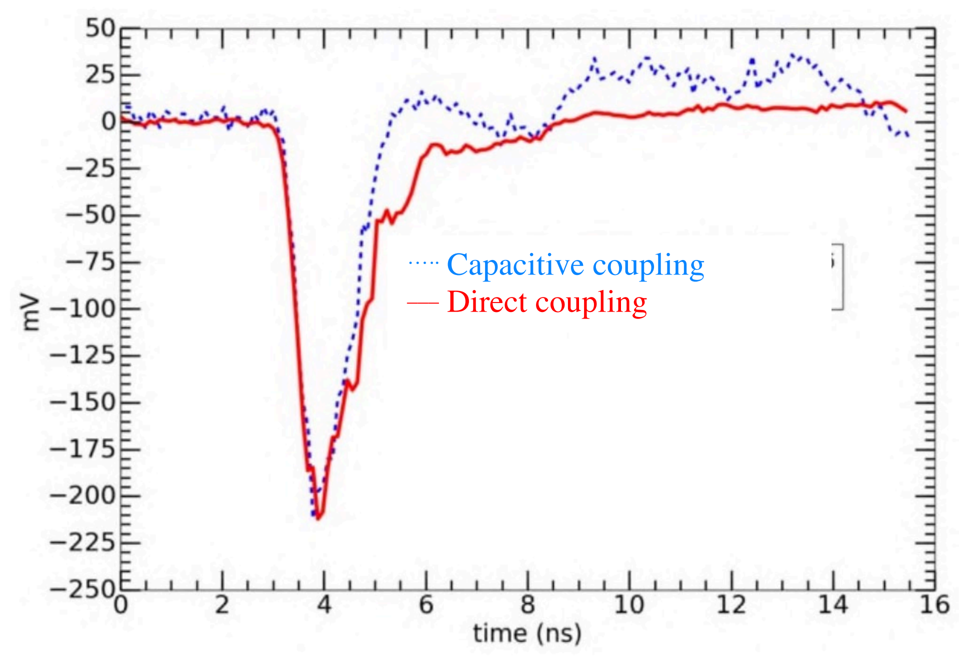
LAPPD 8”x8” MCP detectors with pixel readout

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.**

TOF detector R&D with various timing techniques, at low gain

Why do I want to limit the total charge on MCP-PMT ?

J. Va'vra, MCP logbook #6, page 122, 2010, and J Va'vra 2020 J. Phys.: Conf. Ser. 1498 012013

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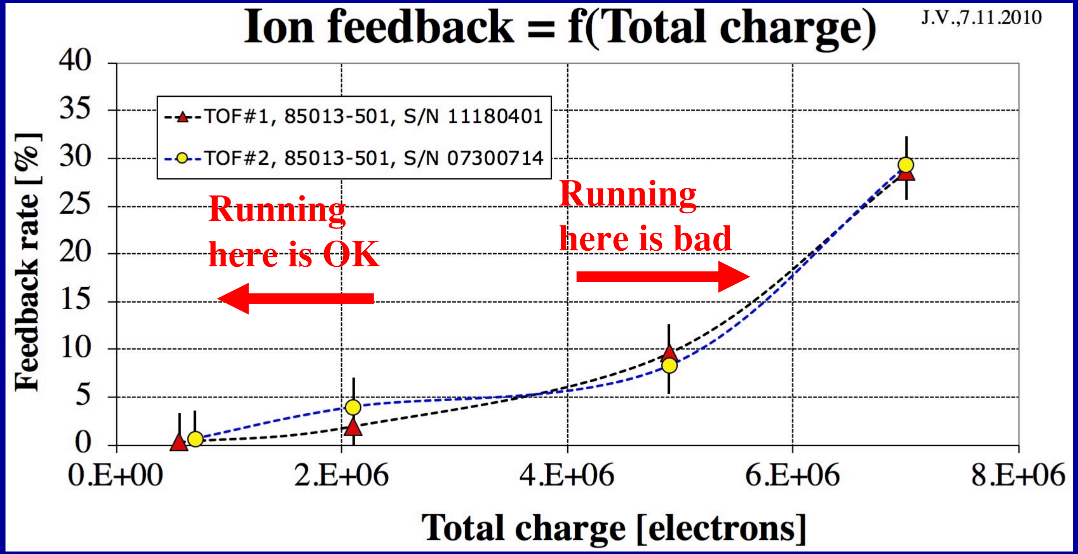
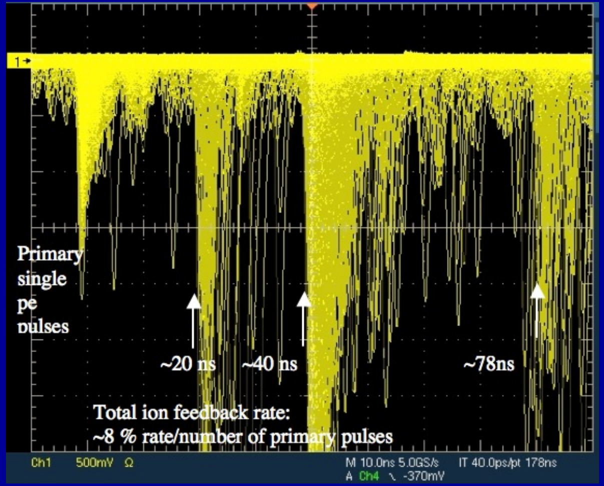
Ion feedback (after-pulse rate) with two old Burle Planacon tubes with 10 μm holes:



Old Burle Planacon MCP-PMT 85013-501:

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

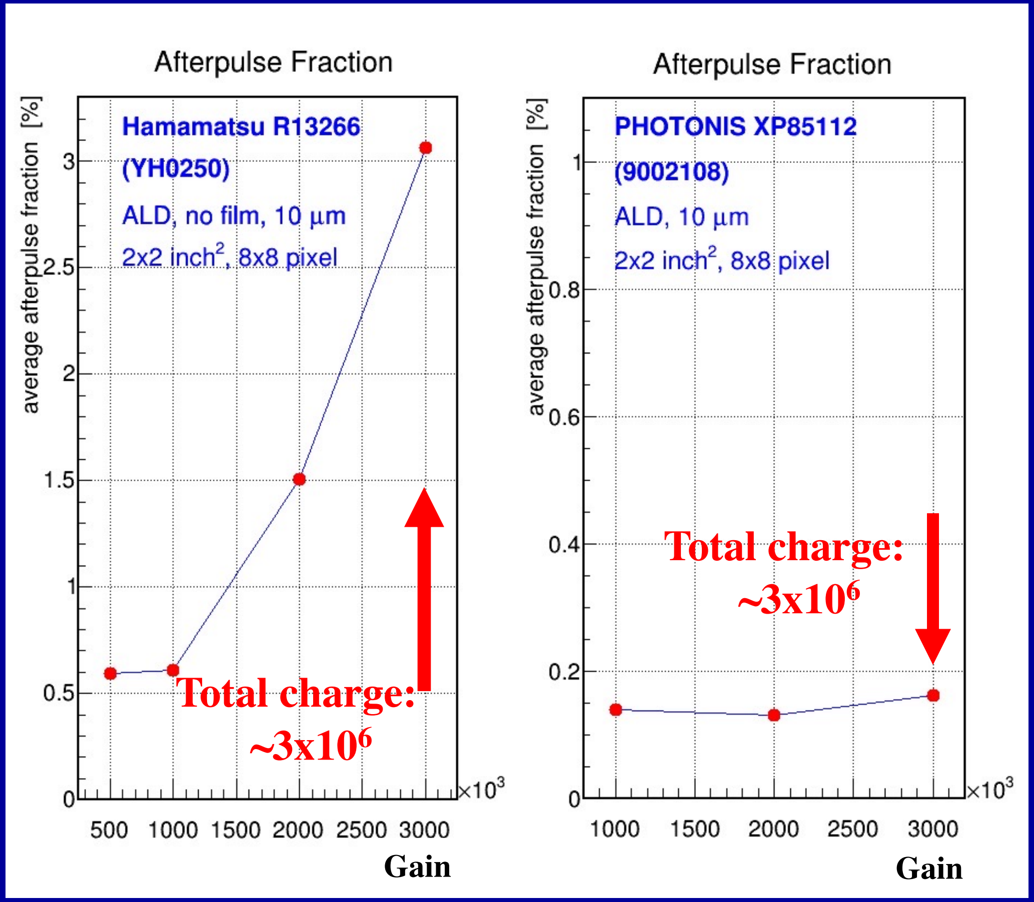


- **<u>Message:</u> One should limit total charge to ~2-3x10^6 to limit the after-pulsing rate.**
- **Are the latest MCPs behaving better ? <u>Some do and some don't</u>** – see Lehmann (appendix, page 34).
- You should check this for any MCP you are getting, and especially old ones.

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

A. Lehmann, private communication, April 22, 2018

Both are ALD-coated MCPs:



Total charge: ~3x10⁶

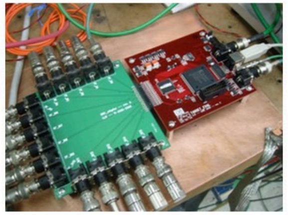
Total charge: ~3x10⁶

- **Photonis XP85112 MCP-PMT performs well at a total charge of ~3x10⁶**
- **Hamamatsu R13266 sees an increase in the rate already at a total charge of ~1.5x10⁶.**

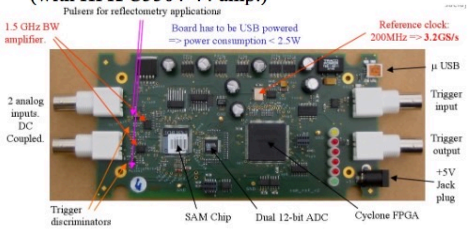
Can one do timing with low total charge ?

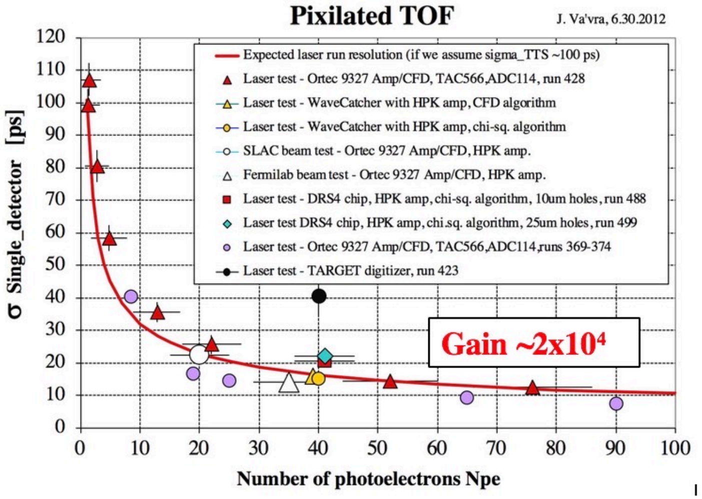
J. Va’vra, MCP logbook #7, 2012, NIMA 629 (2011)123, and NIMA 606 (2009) 404

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

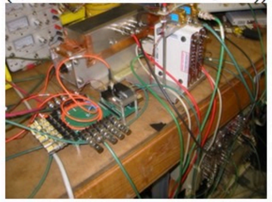


WaveCatcher v.5 (Dominique Breton):
(with HPK C5504-44 amp.)





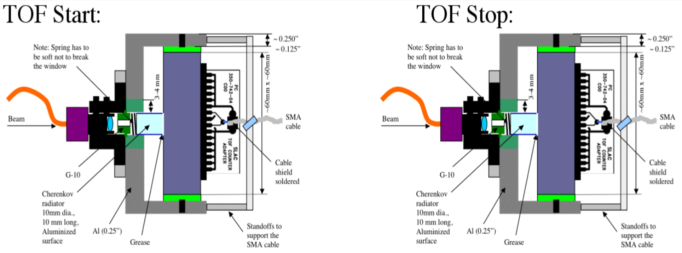
Ortec 9327 amp/CFD electronics:
(with TAC 566 and ADC114))



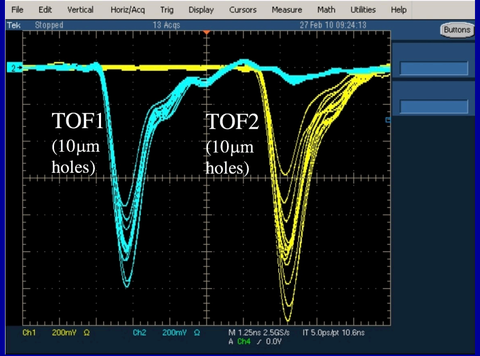
DRS4 (Stefan Ritt):
(with HPK C5504-44 amp.)

2 Burle 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 :

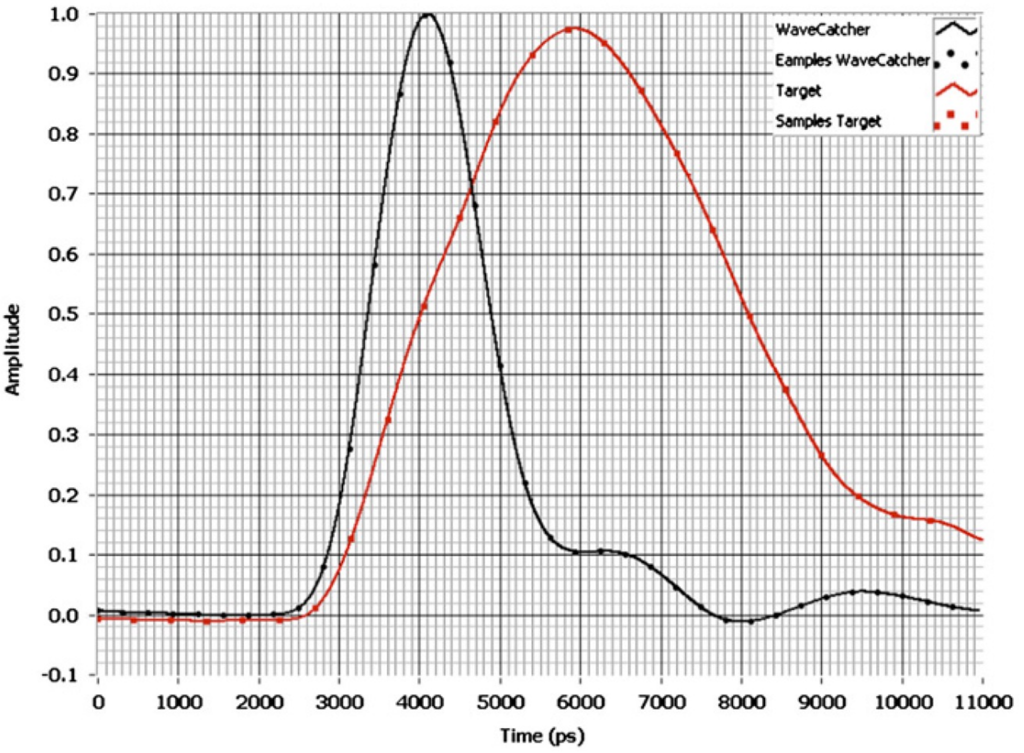


- Low gain ~2×10^4 , vary Npe (1-100)
- Total charge: ~8×10^5 for Npe ~40
- For Npe ~ 40 pe, we reached ~14 ps.
- For Npe ~80, one could reach ~10ps.

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

Why Target chip performance is worse than WaveCatcher ?

D. Breton, E. Delagnes, J. Maalmi, K. Nishimura, L.L. Ruckman, G. Varner, J. Va'vra, NIM A 629 (2011) 123



Two waveform digitizers:

- **WaveCatcher: 3.2 GSa/s**
- **TARGET: 2.5 GSa/s**
- **WaveCatcher front end has higher BW than TARGET's chip**

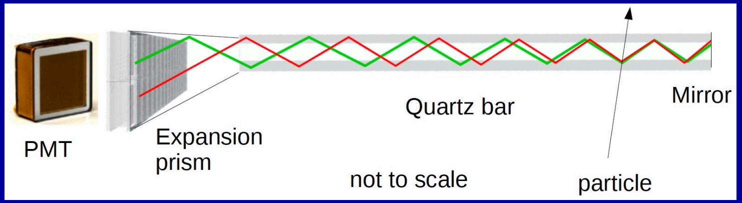
- **In both cases use HPK amplifier C5504-44, 1.5 GHz BW, 63x.**
- **Many methods tried: software CFD (best & fastest method), reference timing with χ^2-method, spline, etc.**
- **ASIC-based waveform digitizers, such as WaveCatcher or DRS4, can compete with commercially available 1 GHz BW CFD timing electronics, such as Ortec 9327 CFD/TAC. But did not do better than my best measurements – see slide 4.**

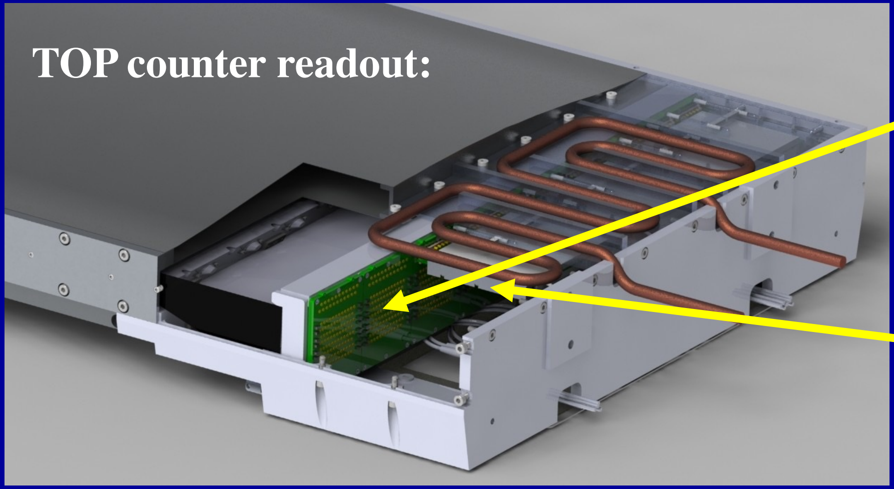
Several large-scale physics applications with MCP-PMTs

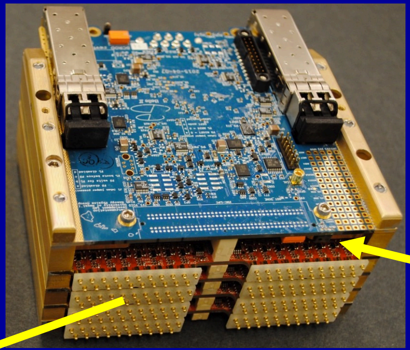
Belle-II TOP counter: waveform digitizing electronics

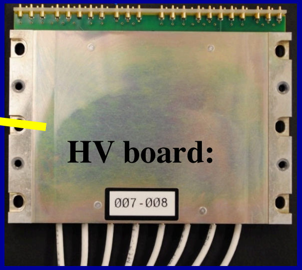
Work led by Gary Varner, Univ. of Hawaii, details in ArXiv:1804.10782, 2018

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

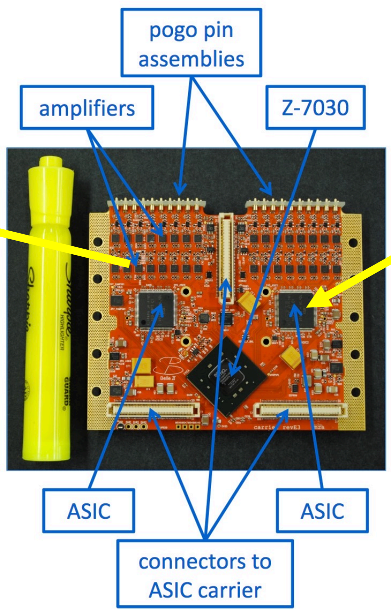



TOP counter readout:



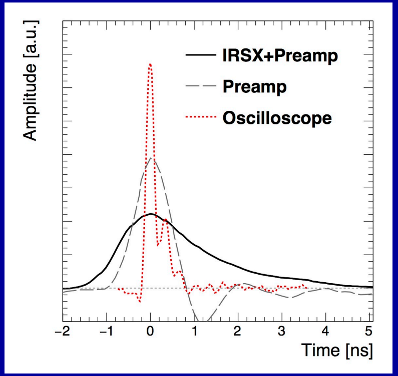

HV board:

Amplifier & ASIC:



IRSX ASIC:

Slow down risetime of preamp to have 2 samples on leading edge (single pe's):

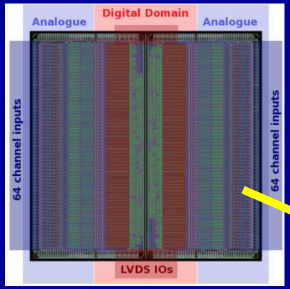


- **2.7 GSa/sec IRSX waveform digitizer, equivalent to a cheap scope on every pixel.**
- **They slowed down the risetime to have 2 samples on leading edge. Amplifier gain: ~120x.**
- **σ_{TTS} ~83 ps with a laser; σ ~80-120 ps at a gain of ~3x10^5 in Belle-II experiment.**
- **The total power consumption: ~570 mW/channel !!**

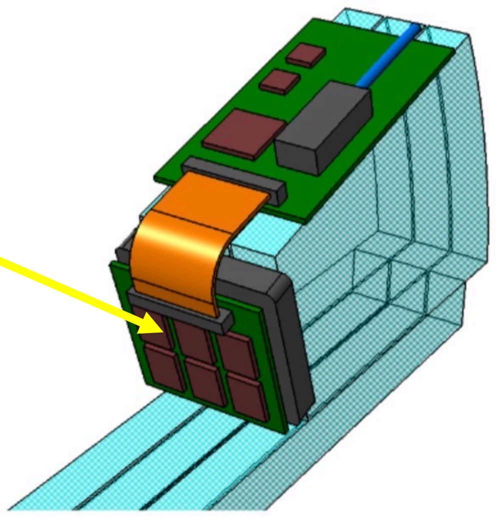
Endcap Panda DIRC: Photonis MCP with TOFPET electronics

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

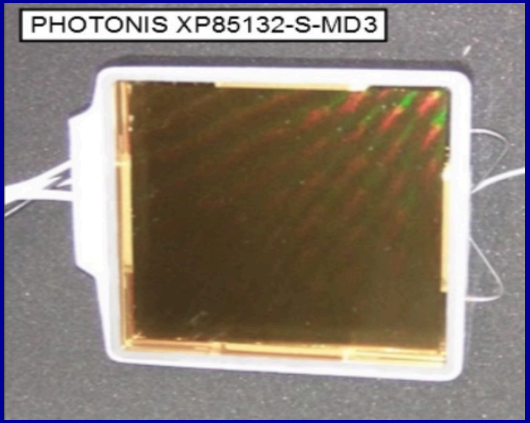
TOPFET ASIC:



Panda Endcap DIRC readout:

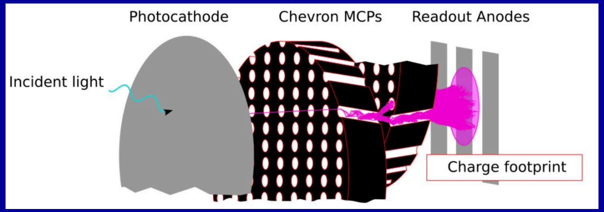


New Photonis MCP:

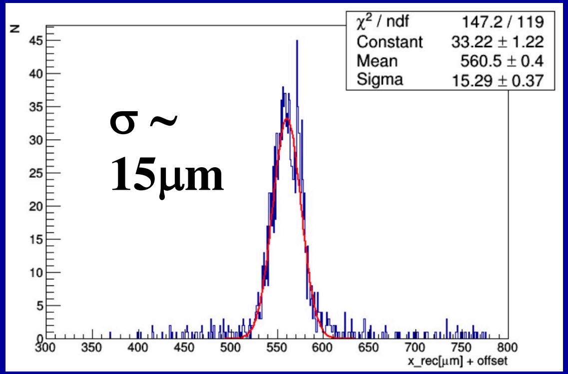


- **MCP has 0.4 mm x 17 mm anode pixels.**
- **3 rows x 100 strip configuration.**
- **MCP-Anode gap = 0.625 mm**
- **Anode strips are grounded by electronics.**
- **tube does not have a ground plane (Jeff DeFazio)**

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



Anode charge footprint with B~0.1T (single pe's):



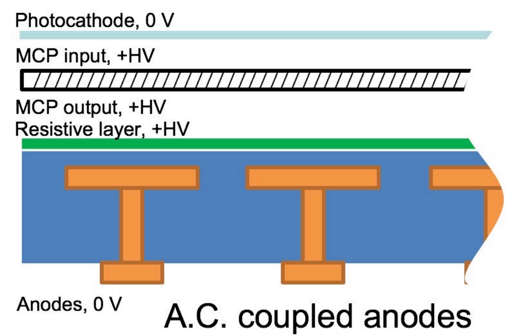
- **Goal: σ ~ 70-100 ps/single photo-electron.**
- **TOPFET2 ASICS is using time-over-threshold timing (TOT), it is cheap, electronics has low mass, it is radiation hard and has low power consumption (<10mW/ch). No amplifier is needed (??).**
- **A magnetic field of only ~0.1 T can reduce the charge footprint to ~15μm !!**

LHCb TORCH TOF: Photek MCP-PMTs with TOPFET

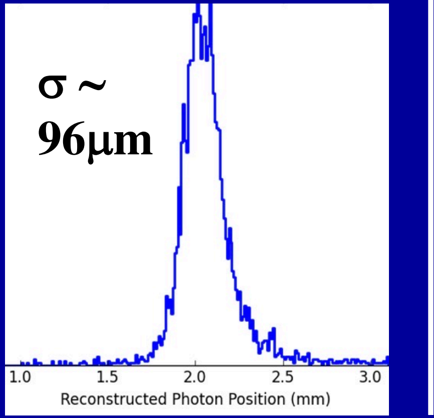
1) J. Milnes, Analysis of MCP253, Photek, 2020

2) T. M. Conneely, A. T. Duran, J. S. Milnes, P. Hink, Photek, IEEE poster, 2020

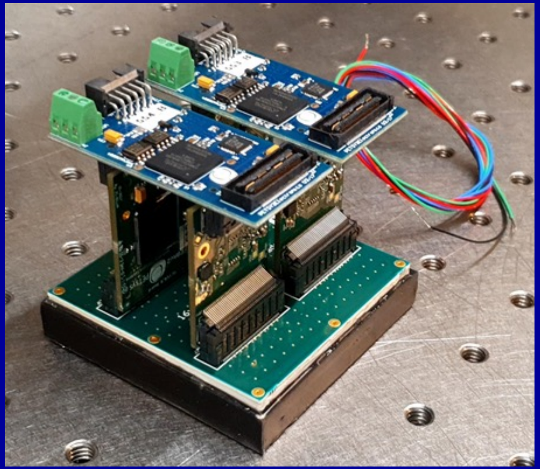
Study of <u>AC-coupled anodes</u>:



Position resolution for LHCb anode pad geometry (single pe's):

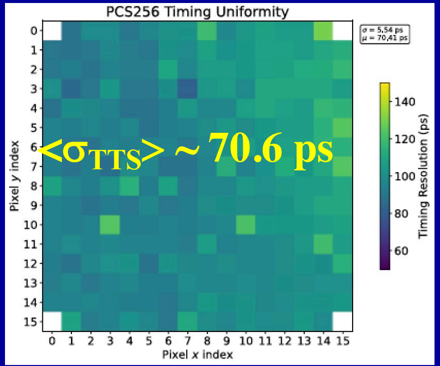


σ ~ 96µm



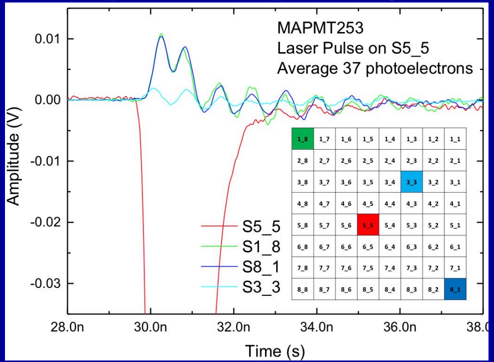
- 4 **TOFPET2d ASIC**s/MCP
- **TOT timing**
- **16 × 16 pixel layout of a 1024 = 32x32 pixel tube**
- **Active area: 53 × 53 mm²**
- **Gain ~2x10⁶ (too high !!!!)**
- **DC coupled anodes**
- **No amplifiers used !!!**
- **10 mW/ch. !!!**

2-D timing scan (single pe's):

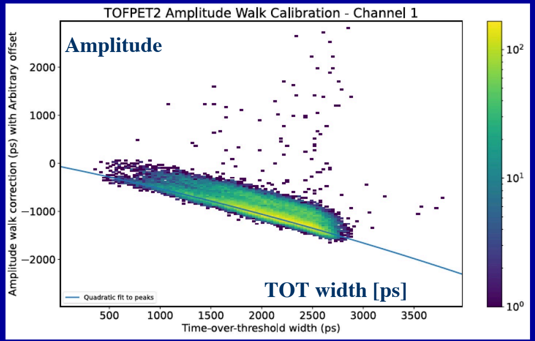


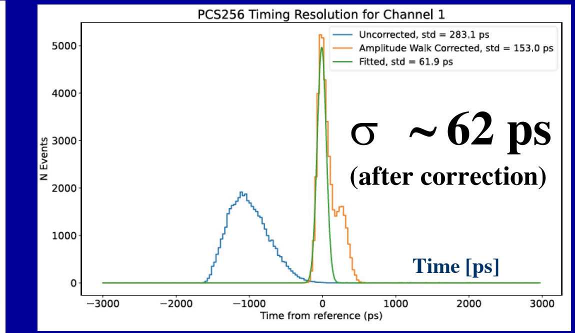
$\langle\sigma_{TTS}\rangle$ ~ 70.6 ps

Ringing in <u>boundary pads</u> (red pixel: 36 pe's signal):



Study with TOPFET2 ASIC using TOT (single pe's):





σ ~ 62 ps

(after correction)

- **Excellent single photo-electron position resolution with AC-coupled anodes.**
- **TOT correction with TOPFET2 ASIC works well: < σ_{TTS} > ~ 70 ps. <u>No amplifier !</u> Gain ~2x10⁶ !!**
- **Ringing around edges of MCP, which might be important at very high rates.**

Conclusion:

- TOT/TOA timing methods need to have good quality signals.
- Slower electronics with better S/N is a winner, based on my experience.
- Having electronics with no knowledge of raw signals deprives your understanding of MCP performance. This does not matter if things work, but badly needed when they don't. Perhaps, having one channel per MCP dedicated to waveform digitizing electronics might be a good choice ?
- Waveform digitizers take too much power.
- TOPFET2 with TOT, or its equivalent, seems to be a good direction. However, TOT is probably more sensitive to wiggles than TOA.