Novel Photon Detectors for RICH applications

J. Va'vra

Content

- **Multi-anode PMTs**
- **Microchannel plates**
- **HPDs**
- **HAPDs**
- **APDs operating in a Geiger mode**
- **Gaseous Detectors**

Aim of this talk

- **Discuss devices detecting photons.**
- **Discuss only examples, which are "possibly" relevant to the RICH.**
- **New ideas are fragile. Initially, we do not know if any one will be either fruitful or useless.**
- **In this talk, I will try to give the "fragile" ideas equal chance.**

RICH detector interests:

- **Rate capability.**
- **High "effective" efficiency.**
- **Aging issues.**
- **Reliability.**
- **Timing resolution (aim for σ ~100 ps).**

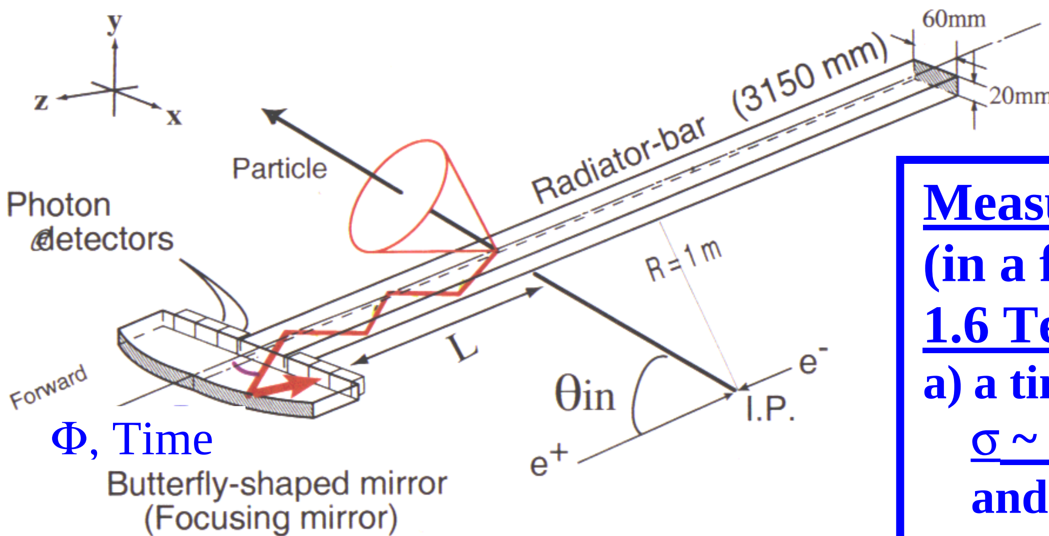
Why a timing resolution of σ ~ 100ps?

- All this is driven by a success of DIRC in BaBar, and a desire to develop this concept further both at BaBar and Belle B-factories. DIRC with such a timing resolution can correct the chromatic error out. This goal drives the present DIRC R&D program.
- Other possible applications: Aqua RICH and cosmic ray telescopes.
- One should say that the LHC RICH detectors would not benefit from it.

Examples of the "DIRC-like" R&D:

1) "Time-of-Propagation ≡ TOP counter":

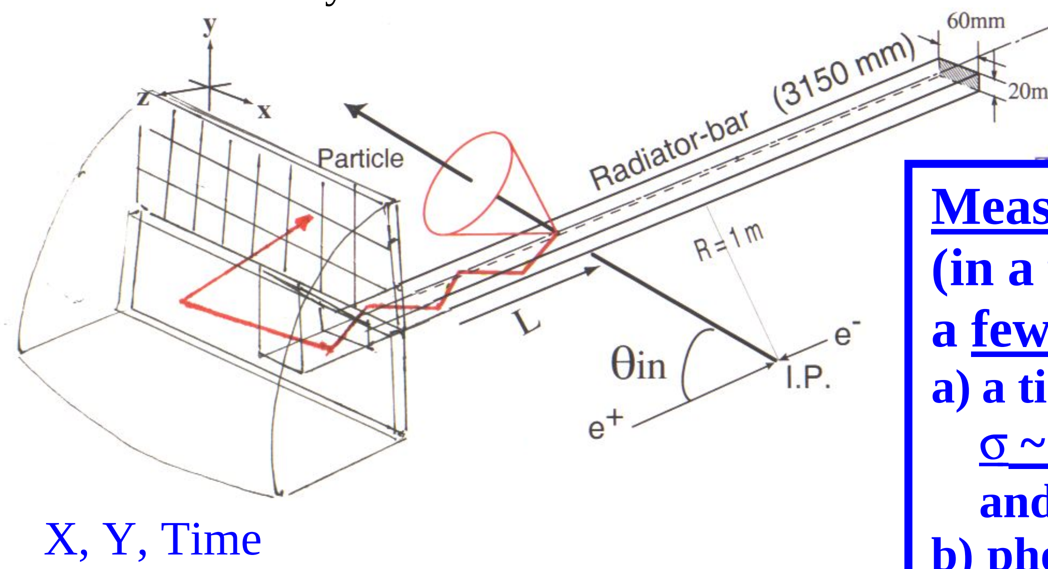
R&D at Nagoya University, Japan:



Measure (in a field of 1.6 Tesla):
a) a time to σ ~ 100ps, and
b) Φ angle.

2) "DIRC upgrade":

SLAC R&D activity:



(Focusing mirror, quartz matching fluid,
Flat panel H-8500 PMT detector)

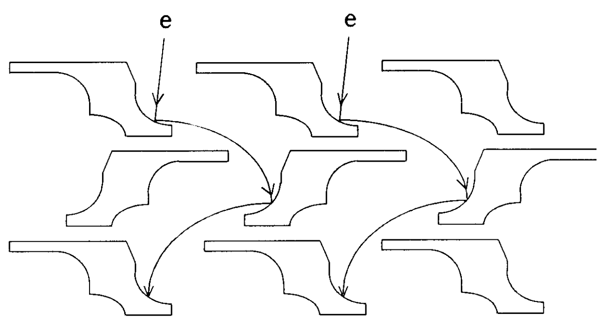
Measure (in a field of a few Gauss):
a) a time to σ ~ 100ps, and
b) photon position in both x & y.

What are the devices, which can deliver presently a single photon timing resolution of σ ~ 100 ps ?

Manufacturer	Name	PMT	Dia.	σ_{TTS}
Photonis	Quantacon	XP2020	2"	250 ps
Photonis	PMT	XP2020/UR	2"	150 ps
Photonis	PMT	XP2262B	2"	500 ps
Electron Tubes	PMT	9125B	1"	1500 ps
Electron Tubes	PMT	911B	1"	500 ps
Hamamatsu	Multianode	R-5900	-	70 ps
Hamamatsu	Flat panel	H-8500	-	80 ps
Hamamatsu	Multi-mesh	R-6135	-	80 ps
Dolgoshein et al.	Silicone PM	SiPM	-	60 ps
Photek, DEP, Burle, or Hamamatsu.	Micro channel plate	MCP	1"	60 ps

DIRC PMT ← (9125B)

. What is the right choice ?

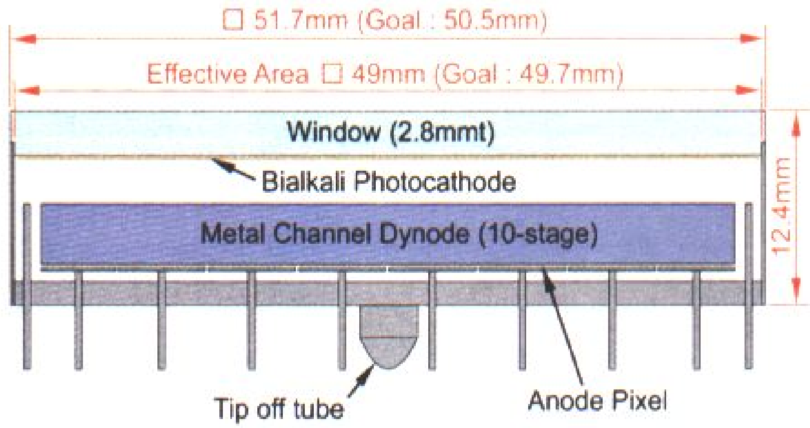


Multi-anode PMTs

- **Hamamatsu Flat Panel 64-pixel H-8500 (BaBar DIRC R&D upgrade).**
- **Hamamatsu Multi-anode 16-channel R-5900-U-L16 (Belle TOP counter).**
- **Hamamatsu Multi-anode Multi-mesh R-6135-L24-γ (Belle TOP counter).**

Hamamatsu Flat-Panel PMT H-8500:

DIRC R&D at SLAC:



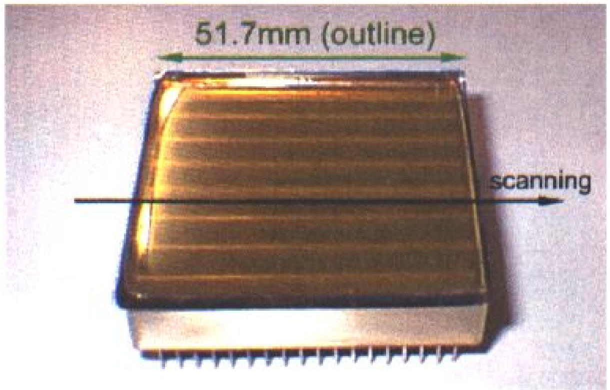
Photocathode	Bi-alkali (visible & UV)
Accelerating medium	vacuum
Geometrical packing efficiency	**~97%**
Collection efficiency of the dynode structure	**~70-80%**
Operating voltage (max.)	**-1 kV**
Pixel size	5mm x 5mm
Matrix	8 x 8
Number of pixels	64
Gain (Hamamatsu claim)	**$\sim 10^6$ @ –1 kV**
Type of amplifier (SLAC)	Elantec EL2075C
Amplifier BW (SLAC test)	2 GHz @ gain 1
Number of stages	**12**
Resistor chain (K - D1 - D2 - -> A)	**1-1-1-….-1-0.9-0.1**
Transit time distribution (Hamamatsu claim)	**σ ~80 ps + tail**
Timing resolution per single photon (SLAC)	**σ ~125 ps**

Low

- The tube has a low gain at present -> need an amplifier !!
- Good timing resolution, and an excellent packing efficiency.
- However, to achieve such a timing resolution, it is necessary to correct the timing for the pulse height variation.
  This means an additional considerable cost increase!!!

b) Relative uniformity response (Hamamatsu data):

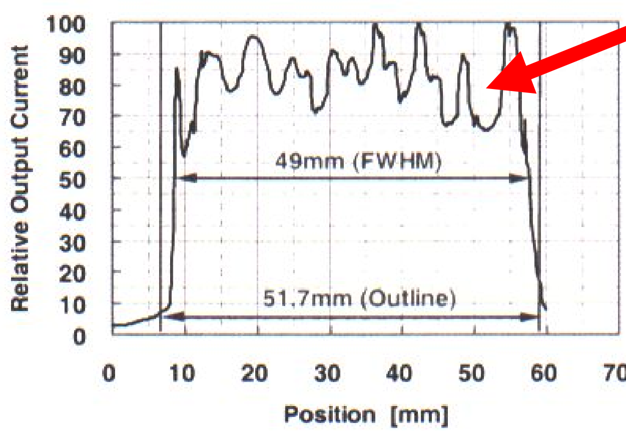
(measured with a 1mm dia. light spot using a current mode)



Effective loss of efficiency ~10-30%

Hamamatsu measures in the current mode:

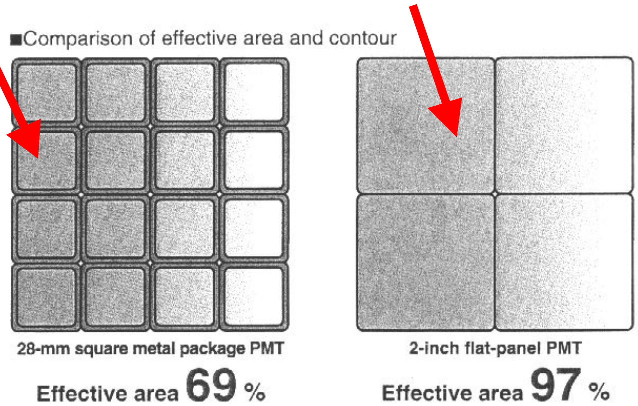
At SLAC we are preparing a setup operating in a single-photon mode, which will measure: (a) σ_T profile, (b) gain profile, and (c) collection effeciency profile.



- ~1.35 mm dead space at each edge.

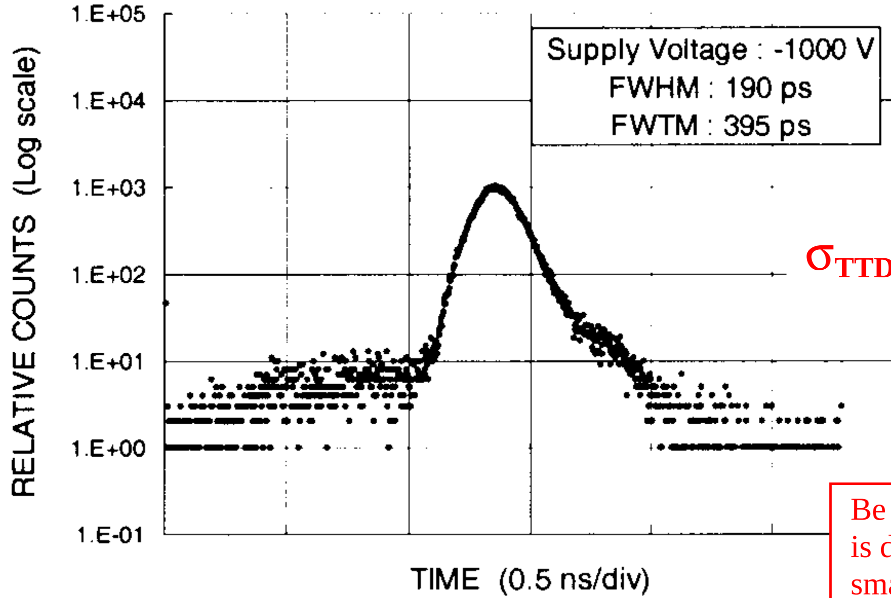
c) Effective are (Hamamatsu data):

HERA-B PMT vs. Flat Panel PMT:



On the other hand, a good packing efficiency

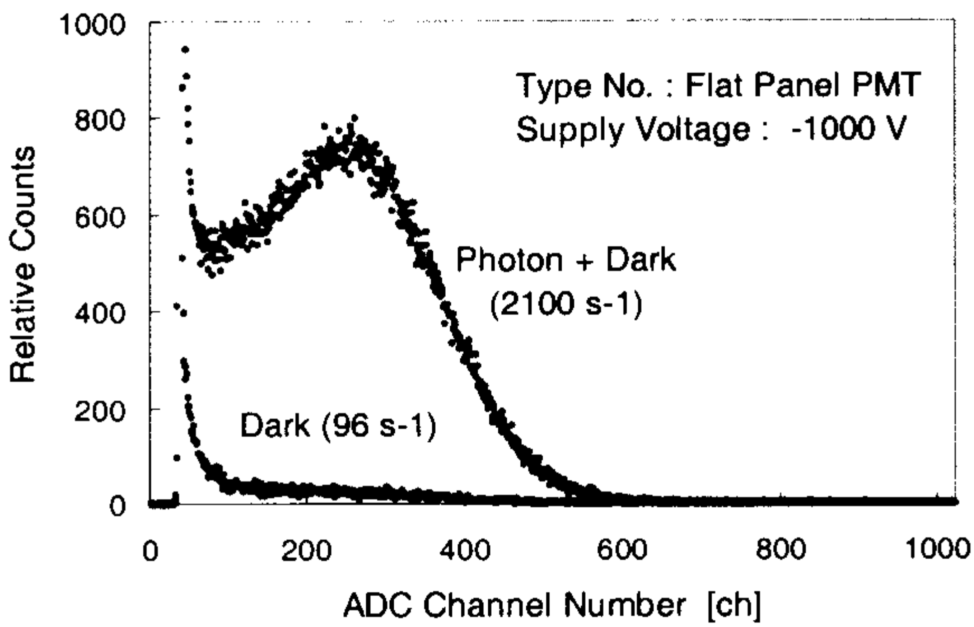
e) Transit time distribution (Hamamatsu data):



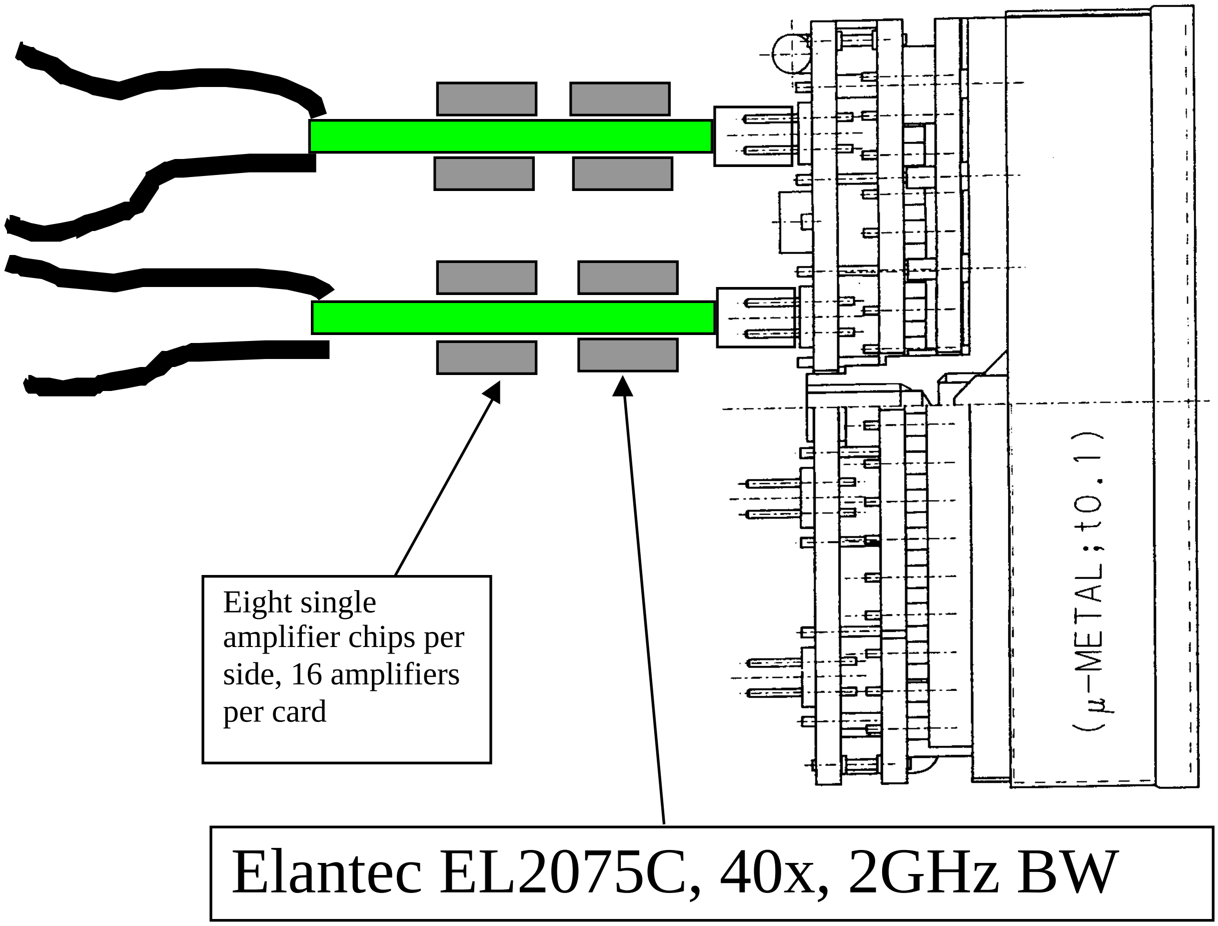
σ_{TTD} ~ 80ps

Be aware that Hamamatsu is de facto cutting away small pulse heights to measure this quantity !!!

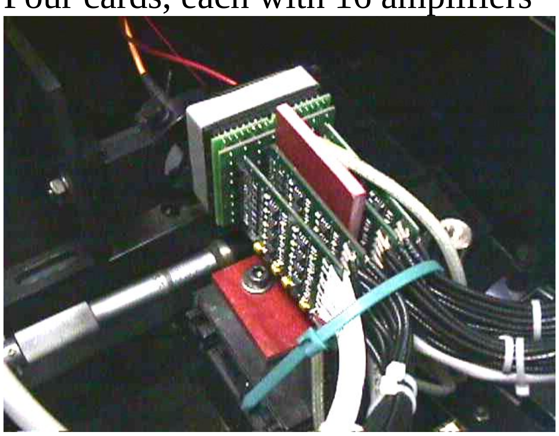
f) Single electron PH spectrum (Hamamatsu data):



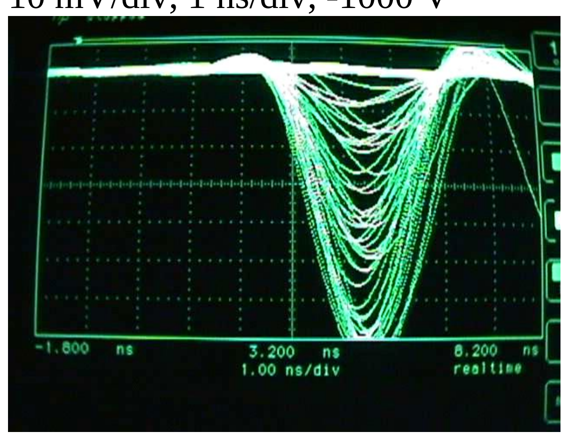
g) Amplifier (SLAC R&D program):



Four cards, each with 16 amplifiers



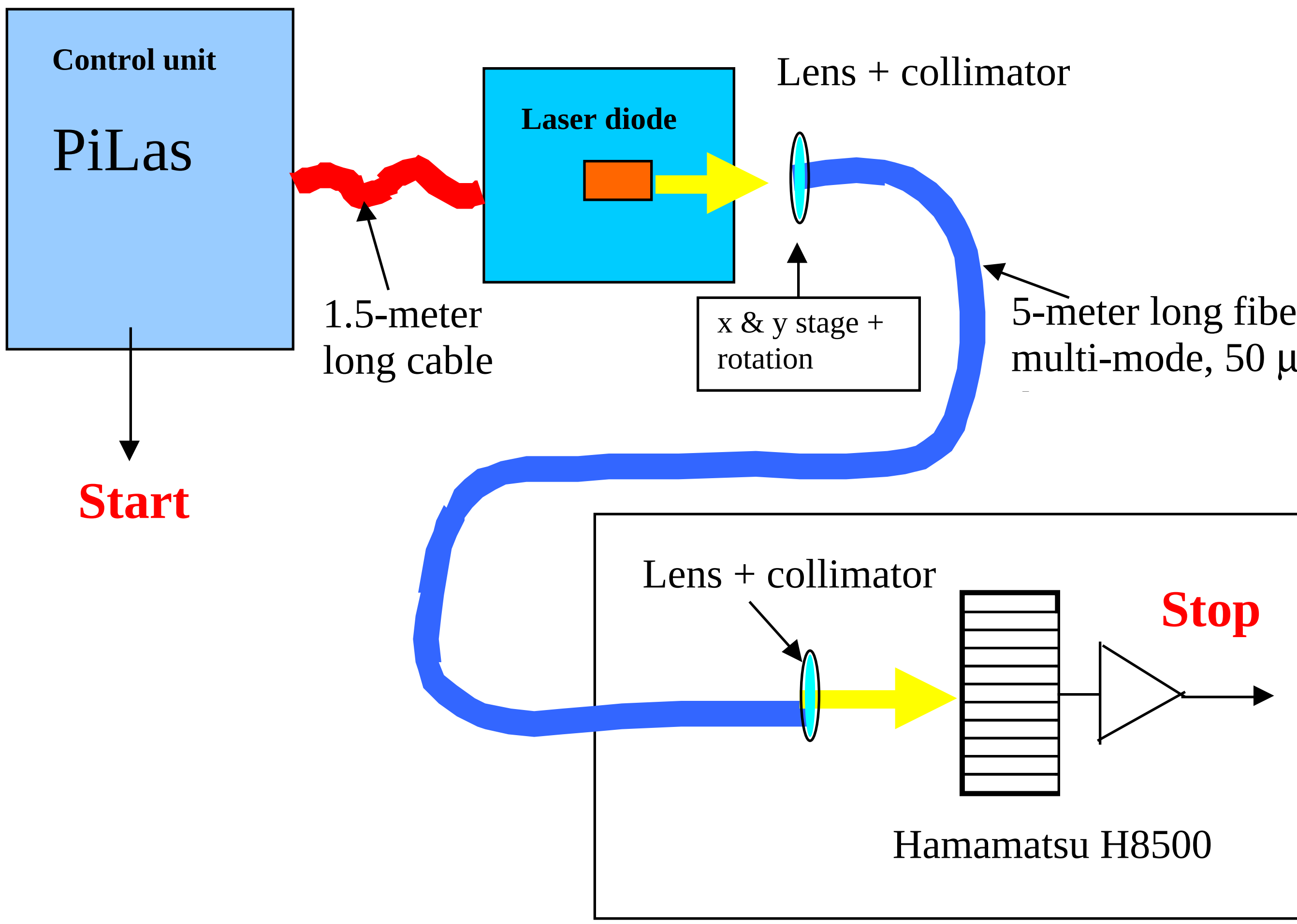
10 mV/div, 1 ns/div, -1000 V



Cross-talk: Worst neighbor ~3-4 %, typically <1%.

h) Timing resolution needs a sophisticated light pulser:

- In SLAC tests, we use the picosecond laser diode:

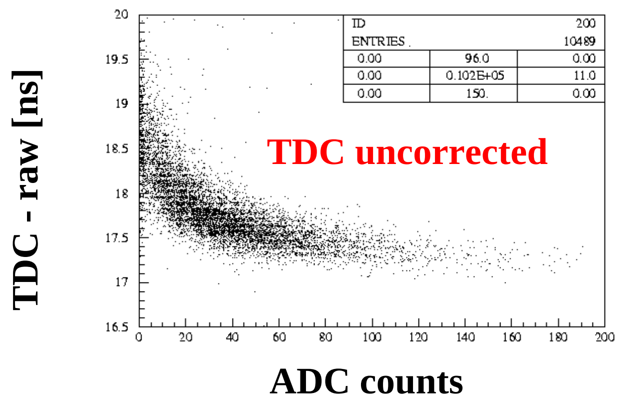


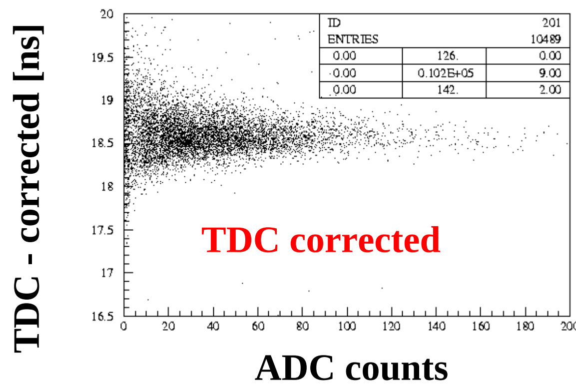
Parameter	SLAC tests	Nagoya tests
Laser diode source	**PiLas**	**Hamamatsu**
Wavelength	535 nm	394 nm
FWHM of light pulse spread	~35 ps*	34 ps
Light pulse jitter relative to trigger	~2 ps*	±10 ps
Fiber size	50 µm dia.	2 mm dia.
Fiber length	5 m	2 m
Diffuser	No	Yes

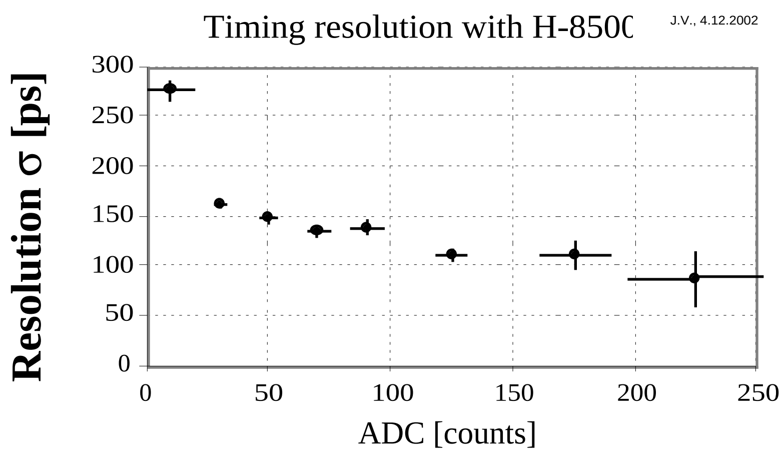
* Not yet directly confirmed directly by tests at SLAC.

Timing resolution study at SLAC (author's own data):

(a) Correct time walk with an ADC measurement:

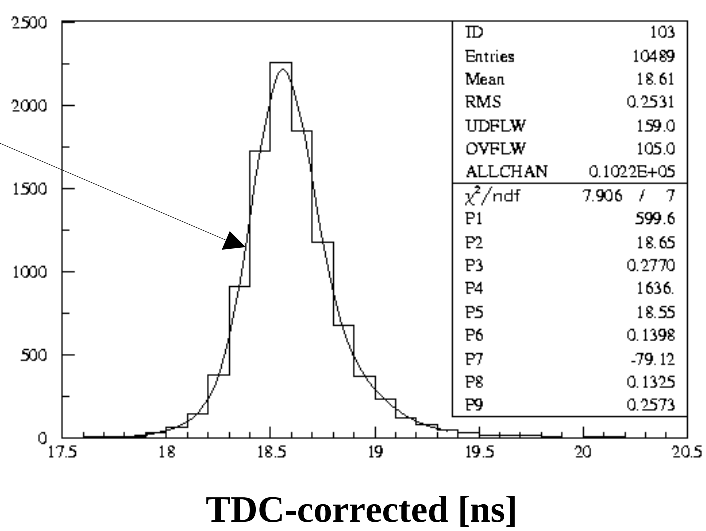






To do this, need an amplifier gain of ~100x, and PMT at –1.0kV.

σ ~ 140 ps
&
277 ps

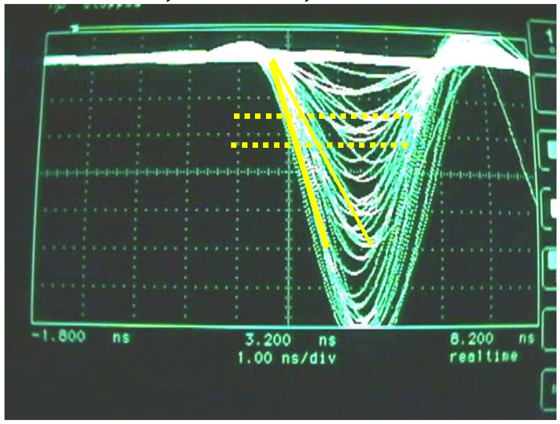


Fit:
G1+ G2+
$a+bx+cx^2$

- For all these tests run the PMT at –1.0 kV, and using a nominal resistor chain as recommended by Hamamatsu.

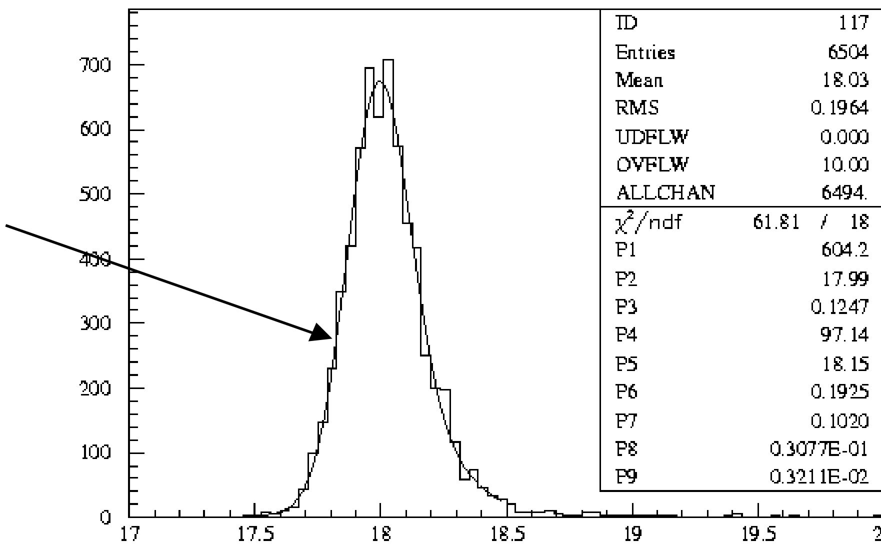
(b) Correct time walk with the two-threshold timing:

10 mV/div, 1 ns/div, -1000 V



σ ~ 125 ps
&
193 ps

Fit:
G1+ G2+
$a+bx+cx^2$



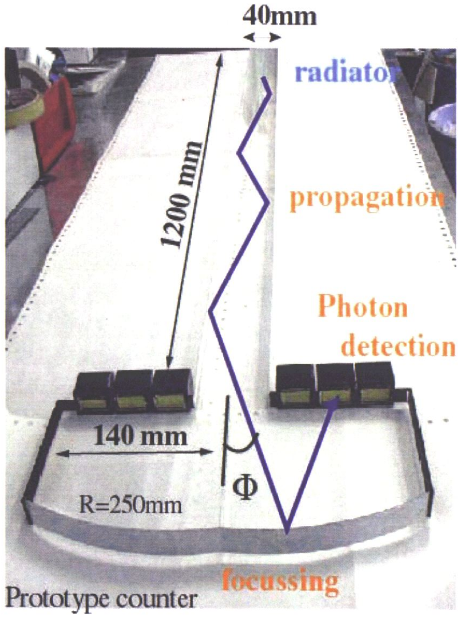
t_0–extrapolated [ns]

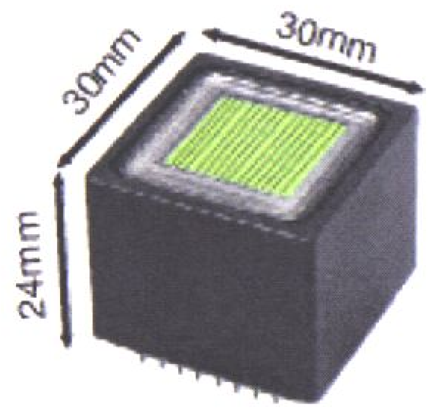
To do this, need an amplifier gain of ~40x, and PMT at –1.0kV.

- t_0-extrapolated is a time extrapolated to the base line using the TDC_1,TDC_2, $Threhold_1$, $Threshold_2$ and a known pulse shape.
- Each imaging pixel needs:
  - a) a fast amplifier, and
  - b) either TDC & ADC, or two TDCs (!!!..)
  - c) in a long run, need a cheap constant-fraction discriminators.

Hamamatsu Multi-anode PMT R-5900-U-L16:

TOP Counter R&D at Nagoya University, Japan:

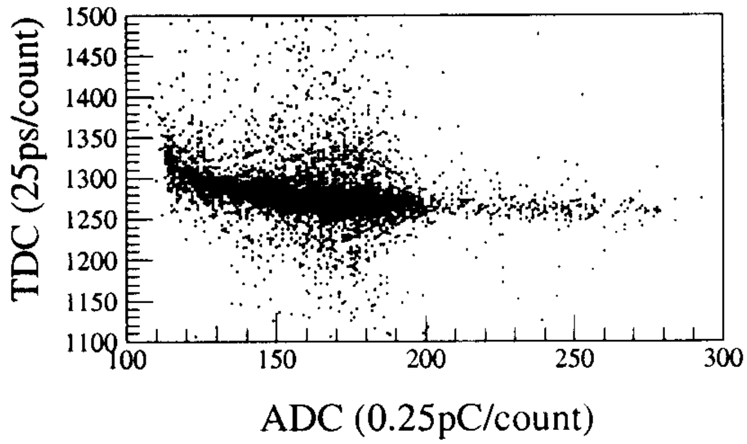




Photocathode	Bi-alkali (visible & UV)
Geometrical packing efficiency	**~40%**
Collection efficiency of the dynode structure	**~50%**
Anode-to-anode pitch	1 mm
Maximum recommended voltage (Hamamatsu)	**-900 V**
Pixel size	16 mm x 0.8 mm
Number of pixels	16
Number of stages	10
Gain (Hamamatsu)	**$\sim 10^7$ @ –900 V**
Typical cross-talk	~1-3%
Number of stages	**12**
Resistor chain (K - D1 - D2 - -> - D10 - A)	**2-1-1-….-1-1**
PMT rise-time	**~0.6 ns**
Transit time distribution (Hamamatsu)	**σ ~70 ps**
Timing resolution per single photon (Nagoya)	**σ ~83 ps @ –1000 V**

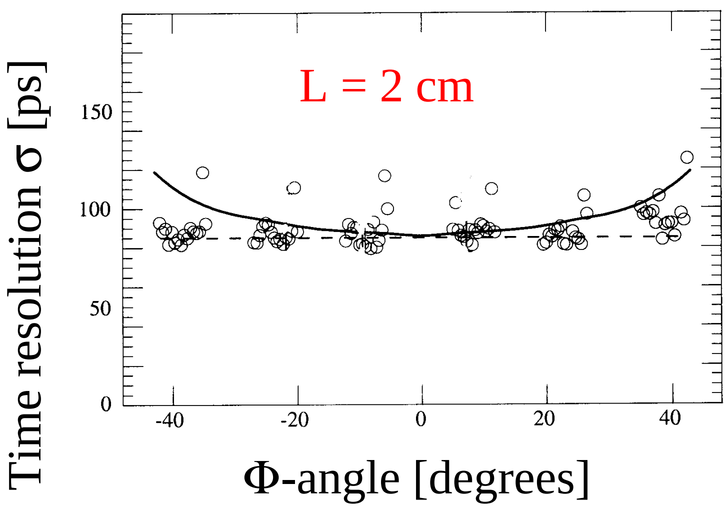
- This PMT has ~10x higher gain than H-8500 at nominal voltages.
- Does not work in a high magnetic field, and has a poor efficiency.

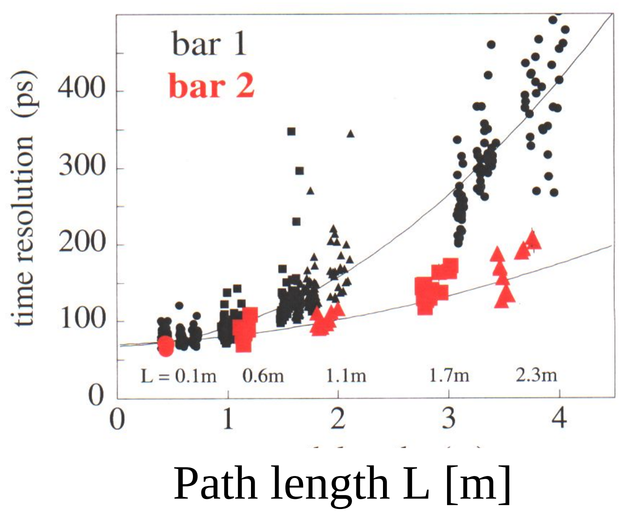
a) Beam test - a time-walk correction with an ADC:



b) Beam test with 96 anodes:

T. Ohshima, ICFA Instr. Bulletin, ICFA-J-20, Spring 2000:

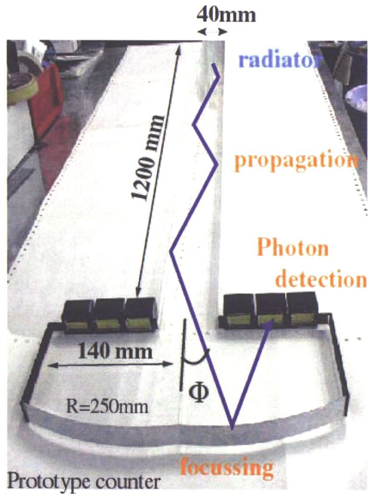


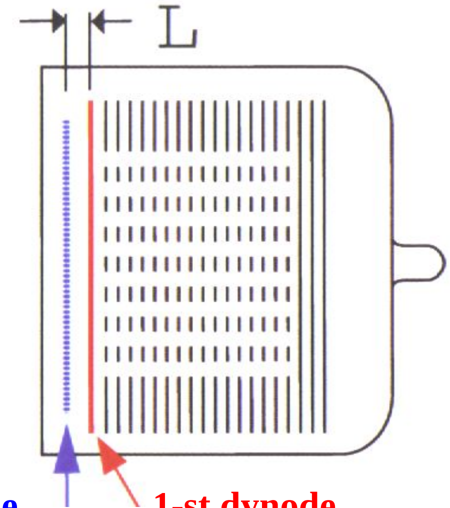


- A timing resolution of ~80 ps achieved by a combination of:
  - (a) running with a gain of ~2 x 10^7 at 1000V (!!!),
  - (b) a modification of the resistor chain (2-1-1-1-…-1),
  - (c) applying an ADC correction.
  - (d) split the signal actively, i.e., do not loose an amplitude.
- Time resolution grows as a function of path length due to (a) bar quality and (b) chromatic error.

Hamamatsu Multi-anode Fine-mesh PMT R-6135-L24-α,β,γ:

Hamamatsu&Nagoya R&D: M. Hirose et al., NIM A460(2001)326:

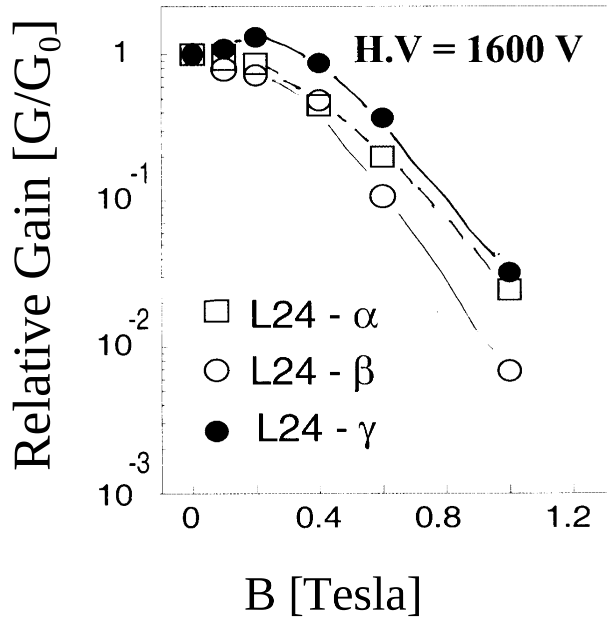




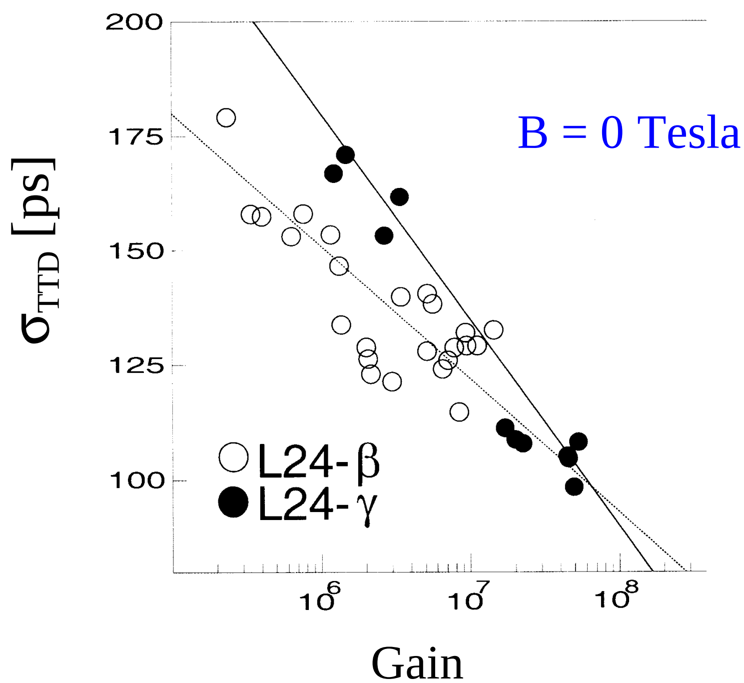
Photocathode	Bi-alkali (visible & UV)
Maximum magnetic field	1.5 Tesla
Geometrical packing efficiency	**~90%**
Collection efficiency of the dynode structure	**52%(α) & 63%(β) & 85% (γ)**
Cathode-the 1-st dynode distance = L	2.5-3 (α) and 1 (β,γ) mm
Mesh design (lines/inch)	2000 (α,β) 2500 (γ) lines/inch
Mesh design (pitch)	9 (γ) &12.5 (β) μm
Operating voltage (B=1.5 Tesla)	**-3.4 kV (γ)**
Pixel size	26.5 mm x 0.8 mm
Number of pixels	24
Gain in 1.5 Tesla	**~5x10^{6} @ –3.4 kV (γ)**
Number of stages	24 (α) 19 (β,γ)
Resistor chain (K - D1 - D2 - -> A)	**1-1-….-1 (α) & 2-1-….-1 (β,γ)**
PMT rise-time	**~1.0 ns**
Timing resolution per single photon (Nagoya)	**σ ~100 ps at B < 1Tesla**
Timing resolution per single photon (Nagoya)	**σ ~150 ps at B ~ 1.5Tesla**

- This PMT has a good single photon pulse height distribution.
- It can operate at 1.5 Tesla magnetic field.

b) Relative gain = f(Magnetic field):



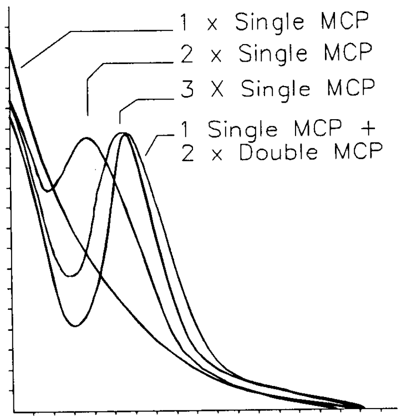
a) Transit time distribution = f(Gain):

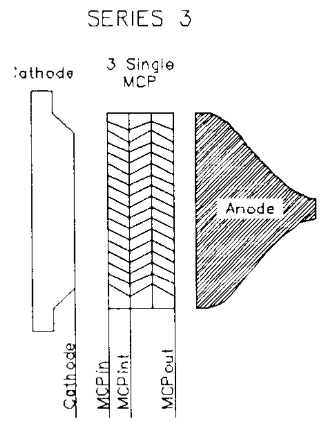


- Conclusion of the test:
  - To reach σ~100ps, one needs a gain of 3-5x10^7 at 1.5 Tesla, and an ADC corrected timing.

Multi-anode Microchannel Plates ? Example: Photek MCP 340:

Photek Ltd., U.K. (Note: other companies make similar devices):



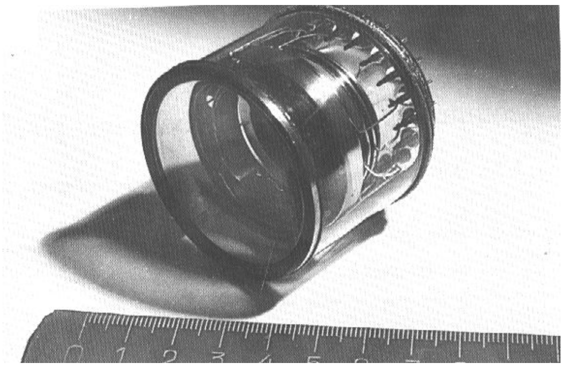


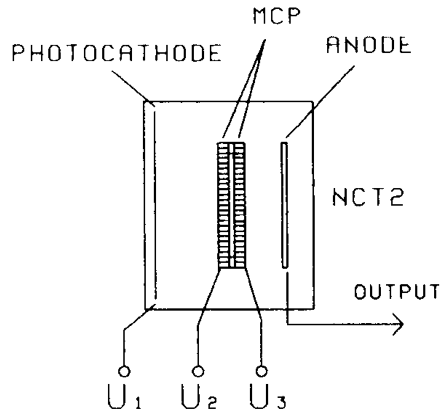
Photocathode	Bi-alkali
Accelerating medium	vacuum
Detector	Microchannel plate
Max. recommended value of $V_{photocathode}$	**-2.15 kV**
Max. voltage per one microchannel plate	~850 Volts
Sensitive area	40 mm dia.
Multi-anode arrangement	8x8 matrix
Geometrical packing efficiency	~20 %
Gain	**~ 10^7**
Rise time	**~0.5 ns**
Transit Time Distribution	**$\sigma \sim 55$ ps**
Magnetic field	1.5 Tesla possible

- Good single electron pulse height spectrum.
- Two MCPs would deliver a sufficient gain.
- Why don't we all use it? (assuming that money does not matter)
  The answer: A significant aging is observed.

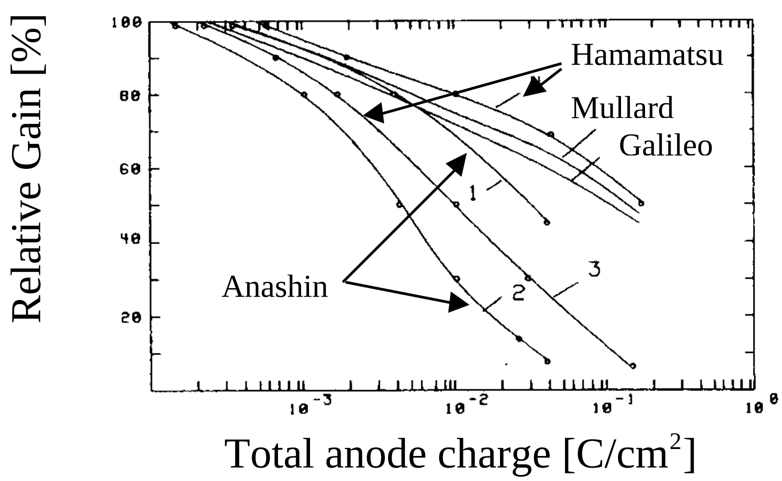
Aging with Microchannel plates:

V.V. Anashin et al., Nucl. Instr. & Meth., A357(1995)103:





Photocathode	Bi-alkali
Maximum magnetic field	1.5 Tesla
Operating voltage	**1.5 kV**
Number of Microchannel plates	2
Gain	**$\sim 10^7$**
Significant gain reduction after anode charge	**10-20 mC/cm^2**
Dead time per MCP channel	**a few ms**



- Significant aging of the <u>gain and QE</u> by an ion bombardment (authors did not separate the two contributions, unfortunately).
- DIRC, with such a detector, would not live even a year.

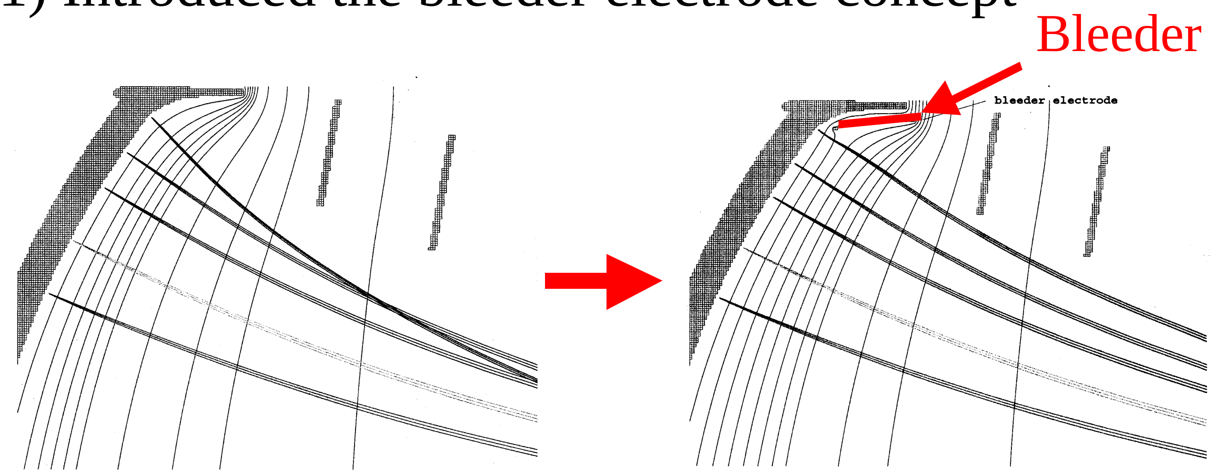
HPD

- **CERN HPD development.**
- **DEP HPD development for LHC-b.**
- **A sub-nanosecond timing resolution with an ordinary HPD ?**

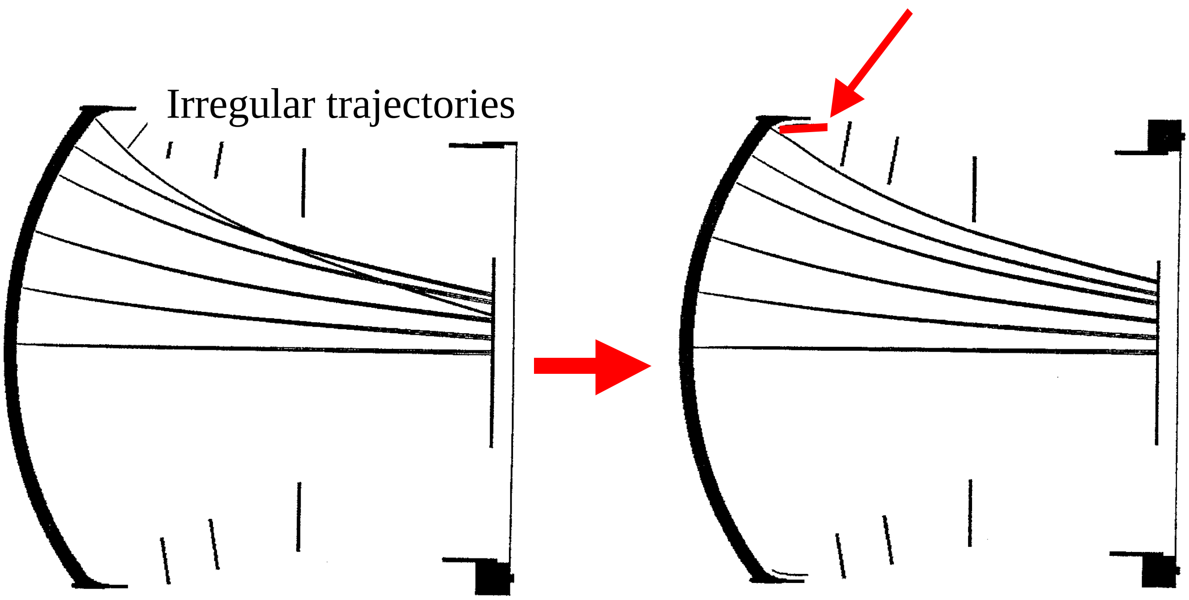
Electrostatics of the HPDs:

D. Ferenc, Nucl. Instr. & Meth., A431(1999)460:

1) Introduced the bleeder electrode concept:



a) No bleeder electrode b) With the bleeder electrode

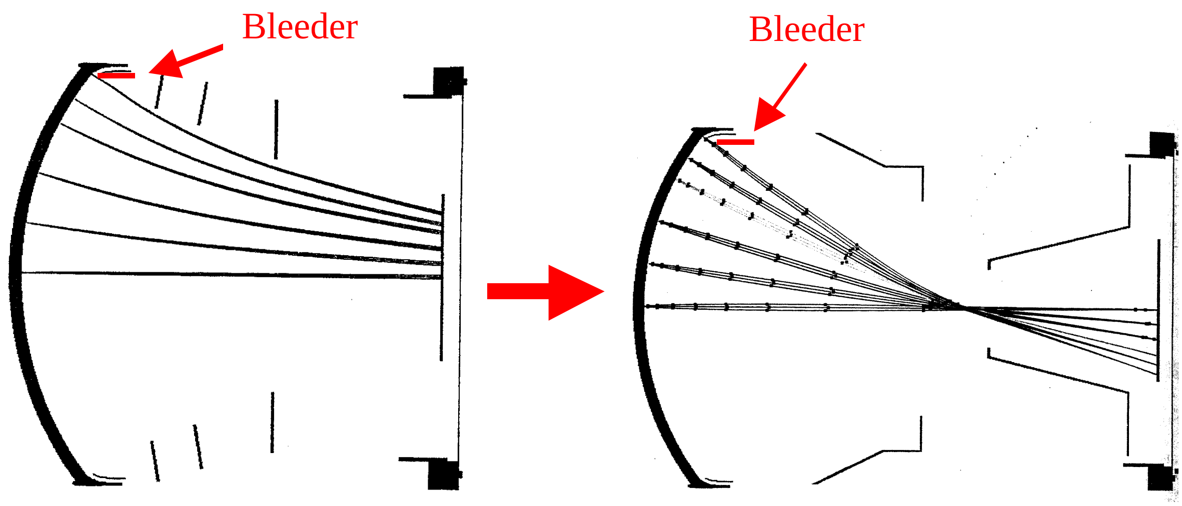


- The bleeder electrode is essential to define unique mapping.

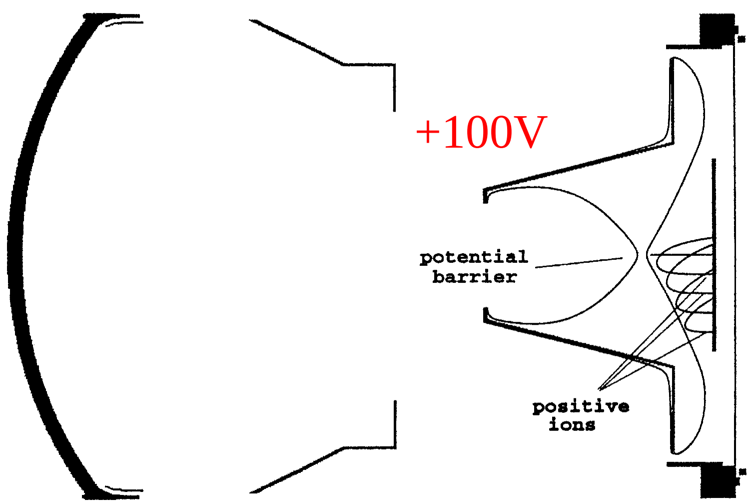
2) Cross-focussing optics allows a positive ion barrier:

D. Ferenc, Nucl. Instr. & Meth., A431(1999)460,
D. Ferenc, D. Hrupec and E. Lorentz, NIM, A427(1999)518:

a) Fountain-focussing: b) Cross-focussing



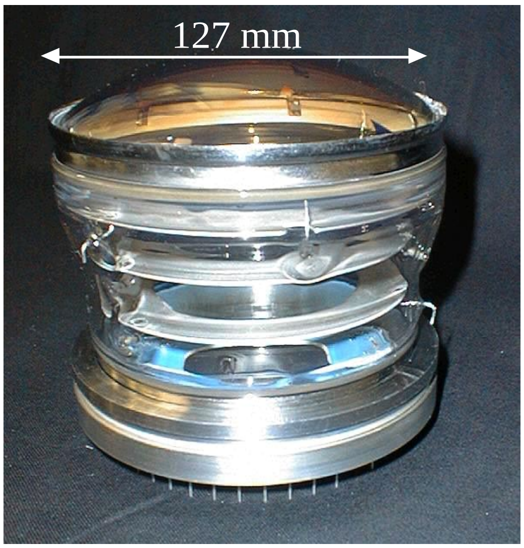
c) Positive ions are trapped by a +100 Volts bias:

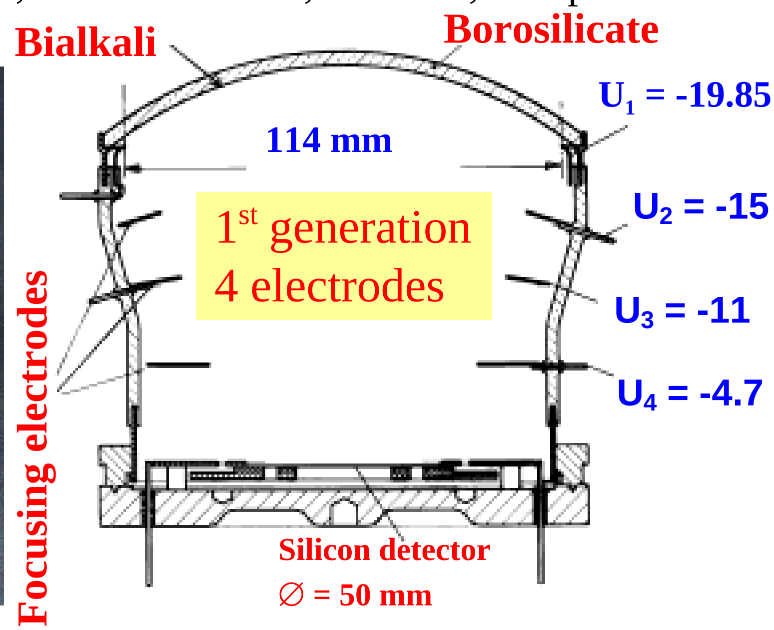


- Simulation software used: SIMION 3D
  (D.A.Dahl,43-rd ASMS Conf. on Mass Spectrocopy and Applied topics, Atlanta, 1995).

CERN/LHCb 5" Pad HPD:

J. Sequinot, C. Joram, A. Bream, P. Wielhammer, E. Chesi, T. Ypsilantis:

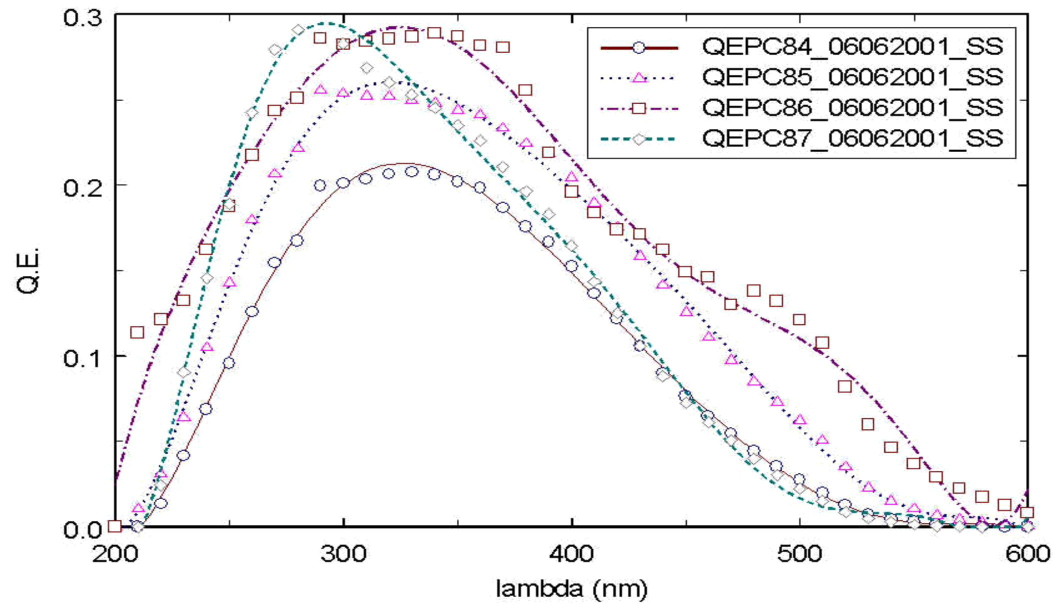




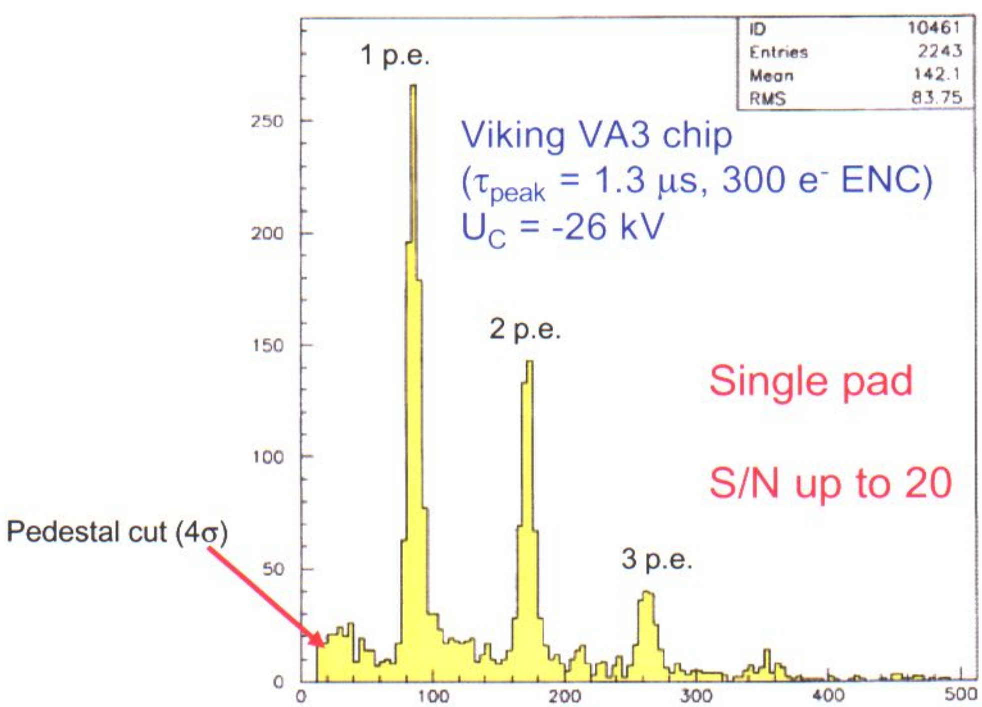
Photocathode	Bi-alkali
Accelerating medium	vacuum
Operating voltage	**-20 kV**
Detector	Pixel Silicon PIN diode
Pixel size	1mm x 1mm
Matrix	16 x 128
Number of pixels	2048
Pixel size (granularity at the photo-cathode plane)	**1 mm x 1 mm**
Electron optics	Fountain focusing
Demagnification	4
Photo-electron transit time distribution σ_{TTD}	<100 ps
Hole transit time distribution σ_{TTD}	**~3-4ns**
PIN diode signal formed from:	Motion of holes
Gain ~$(V-V_{th})\, q_e$ / 3.62 eV, V_{th} ~2.1kV	**~5000 @ –20kV**
Measured electronics noise	**~400 electrons**
Random noise per pad at 20 kV	5.6×10^{-4}
Type of amplifier	Viking VA3
Shaping time	**1.3 µs**

- Internal electronics: Viking VA3.

Measured Quantum efficiency = f(E_{photon}):

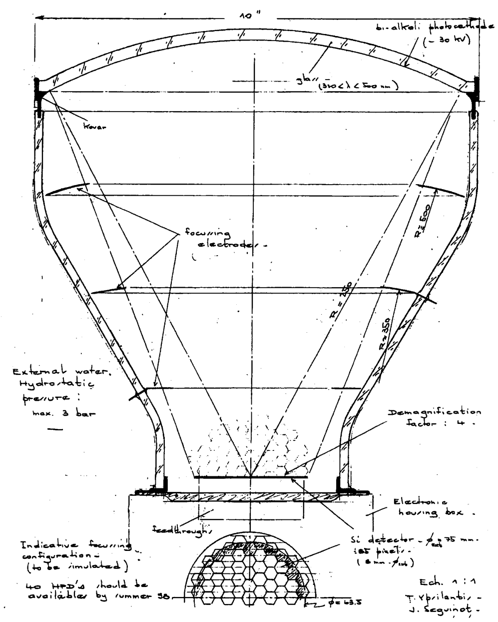


Pulse height spectrum:



CERN 10" Pad HPD:

J. Sequinot, Ch. Joram, P. Wielhamer, E. Chesi, M. Alemi, D. Ferenc, etc.: CLUE cosmic ray experiment, La palma, Canary Islands.

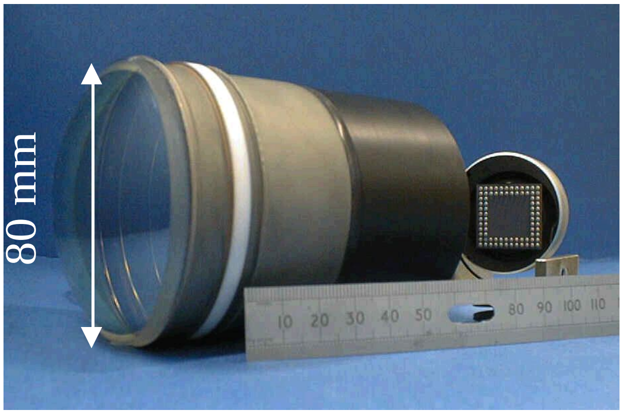


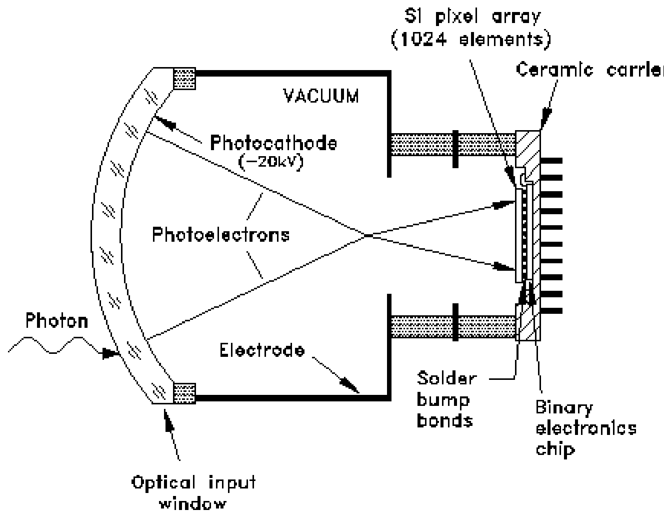
Photocathode	Bi-alkali
Accelerating medium	vacuum
Operating voltage	**Up to -30 kV**
Detector	Pixel Silicon PIN diode
Pixel size	8mm diameter
Number of pixels	85
Pixel size (granularity at the photo-cathode plane)	**32 mm diameter**
Electron optics	Fountain focusing
Demagnification	4
PIN diode signal formed from:	Motion of holes
Gain ~$(V-V_{th})q_e$/3.62 eV, V_{th} ~2.1kV	**~8000 @ –30kV**

- The device will use an external electronics.

LHCb – HPD made by DEP:

Thierry Gys, LHC-b R&D:

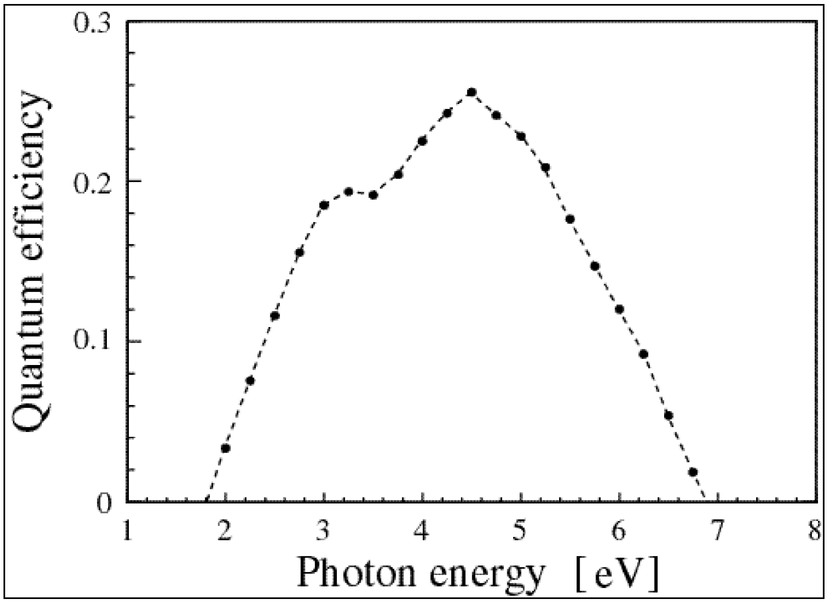




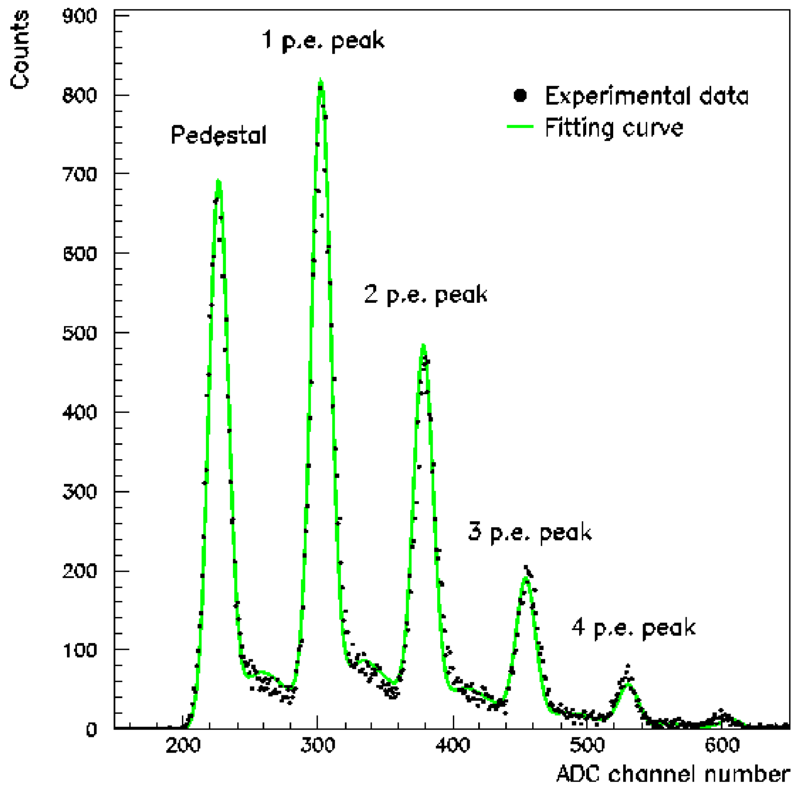
Photocathode	Bi-alkali (K_2CsSb)
Accelerating medium	vacuum
Operating voltage	**-20 kV**
Geometrical packing efficiency	**~81%**
Detector	Canberra PIN diode
Pixel size	50μm x 500 μm
Pixel capacitance	~4pF
Matrix	320 x 32
Number of pixels	1024
Pixel size (granularity at the photo-cathode plane)	**2.5 mm x 2.5 mm**
Electron optics and demagnification	Cross-focussed and 5
PIN diode silicon volume resistivity	~5 kΩ.cm
Photo-electron transit time distribution	<100 ps
Hole collection time spread	**~3-4ns**
PIN diode signal formed from:	Motion of holes
Gain ~$(V-V_{th})q_e/3.62$ eV, V_{th} ~2.1kV	**~5000 @ –20kV**
Electronics noise (plan for LHCb)	**~250 electrons**
Type of amplifier	New development
Shaping time (plan for LHCb)	**~25 ns**

- Internal electronics.

Measured Quantum Efficiency = f(E_{photon}):

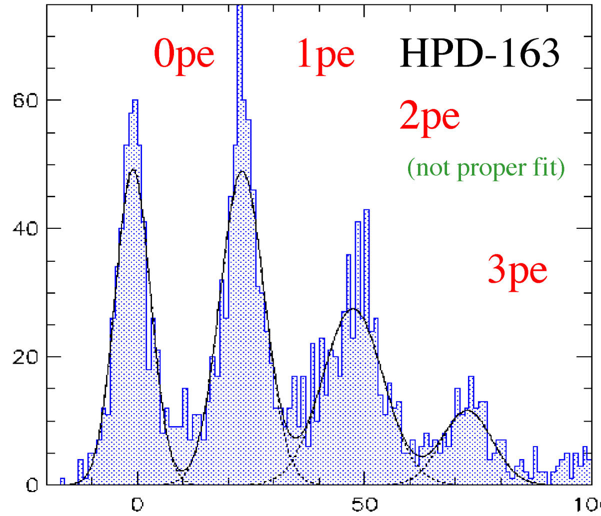


Pulse Height Spectrum:



BTEV – HPD made by DEP:

Ray Mountain, Syracuse University:



Photocathode	Bi-alkali (K_2CsSb)
Accelerating medium	vacuum
Operating voltage	**-20 kV**
Geometrical packing efficiency	**81%**
Detector	Canberra PIN diode
Pixel size	1.4 mm flat-to-flat, hex.
Pixel capacitance	~10pF
Number of pixels	163
Pixel size (granularity at the photo-cathode plane)	**6.5 mm flat-to-flat, hex.**
Electron optics and demagnification	Cross-focussed and 4.1
PIN diode silicon volume resistivity	~5 kΩ.cm
Photo-electron transit time distribution	~100 ps
Hole collection time spread	**~3-4ns**
PIN diode signal formed from:	Motion of holes
Gain ~$(V-V_{th})q_e/3.62$ eV, V_{th} ~2.1kV	**~5000 @ –20kV**
Electronics noise	**~500 electrons**
Type of amplifier	VA-2 type of amplifier
Shaping time during the initial tests	**~2 μs**

- External electronics.

Electronics for HPDs:

1) CERN HPD Development

a) VA2 / VA3 (presently used): τ_{peak} = 1.3 μs, Noise ≈ 400 e^-

b) VA1-PRIME: τ_{peak} = 0.35 - 2 μs.

c) SCTA 128: τ_{peak} = 20 ns, Noise 450 e^-+35 e^-/pF.

d) VATAGP 128: τ_{peak} = 3 μs, Self-triggering "slow" chip.

2) LHC-b HPD Development

τ_{peak} ~25 ns, Noise ~250e.

Other variables:

Discriminator threshold:	2000e
Power consumption of chip:	~ 0.5 W
Radiation dose over 10 years:	30 kRad
Level-0 trigger:	1 MHz, 4 μs latency
Process:	0.25 um CMOS

3) BTEV HPD Development

a) VA2 - CLEO III (present tests): τ_{peak} = 2 μs, Noise ≈ 500 e^-

b) VA-32/75 (BTEV experiment): τ_{peak} = 75 ns.

Can one achieve a good timing resolution with an HPD ?

- The last time I spoke with Tom Ypsilantis was about this subject. Tom was very optimistic that one can achieve a 100ps resolution with CERN-style HPD with PIN diode, I was rather skeptical. Two years later, what is my opinion ?

Expected timing resolution:

For Si detectors, followed by charge sensitive amplifier, the timing resolution is typically determined by a ratio of the amplifier noise and the slope of the pulse at the threshold V_0.

$$\sigma_t = \sigma_{AMP} / (dV/dt \,|_{\text{at threshold } Vo}) \sim$$

$$\sim \sigma_{AMP} * Tr / Vpeak$$

where σ_{AMP} [mV] is amplifier noise, Tr is the pulse rise time, and V_{peak} [mV] is the peak amplitude of the HPD signal.

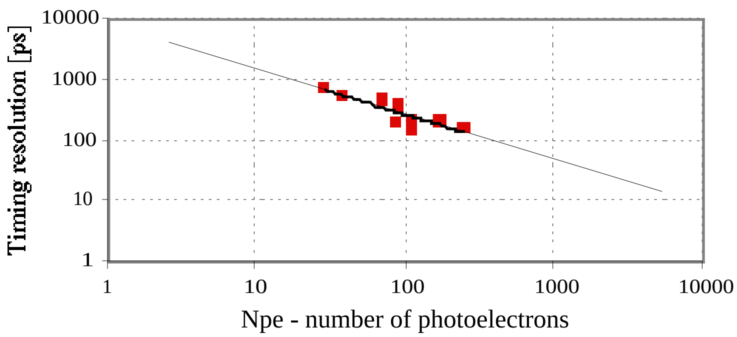
- Tr should be small (small capacitance/pixel, large PIN diode bias voltage, use APDs, drift electrons instead of holes in silicone, etc).
- V_{peak} should be large (high HPD gain, use APDs).
- σ_{AMP} should be small.
- Want to trigger where pulses dV/dt is max.

The timing formula correct within ~10%.

R. DeSalvo et al., Nucl. Instr. & Meth., A367(1995)384:

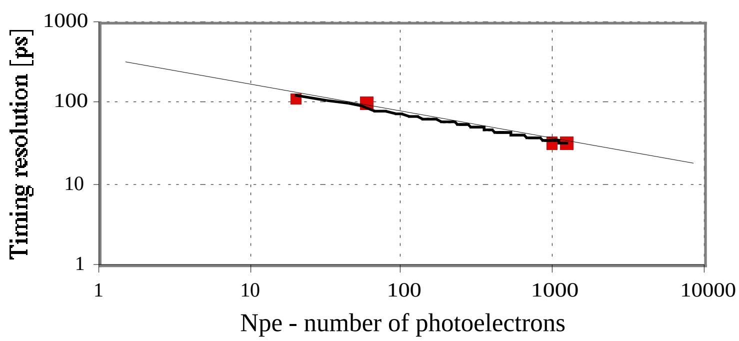
Tested by varying:
- HPD gain,
- HPD rise time by varying the PIN diode bias voltage,
- the preamplifier input impedance,
- the preamplifier noise.

DeSalvo's measurement: $\sigma = f(N_{pe})$



HPD DEP-P-25:
PIN diode,
Proximity focussed,
-15kV,
Gain ~3500,
Amp:~2ns risetime,
(home made)
V_b ~200-300 V,
300µm thick Si,
270pF capacitance!

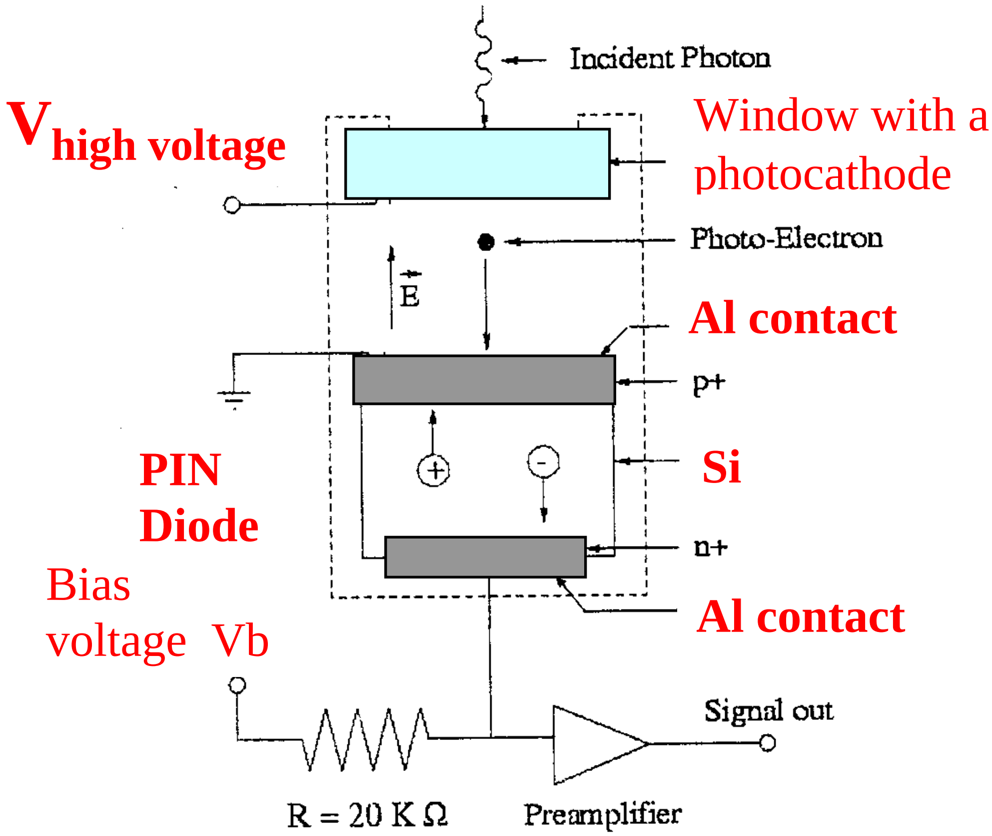
A.H. Heering - DEP internal memo: $\sigma = f(N_{pe})$



HPD DEP-E18:
PIN diode,
Electrostatically focusing,
-15kV,
Gain ~3500,
Ortec 142A amplifier,
<5ns risetime,

- σ ~100-200ps is definitely achievable for N_{pe} ~ 100.
- However, for N_{pe} ~1 not clear (can we extrapolate like this?).

Equivalent circuit:



1) Gain:

$$\text{Gain} \sim (V_{\text{high voltage}} - V_{\text{threshold}})\, q_e / 3.62 \text{ eV}$$

where $V_{\text{threshold}}$ ~ -2.1 kV typically, is energy loss in the aluminum contact layer, q_e is the electron charge.

2) HPD rise time Tr is a convolution of:

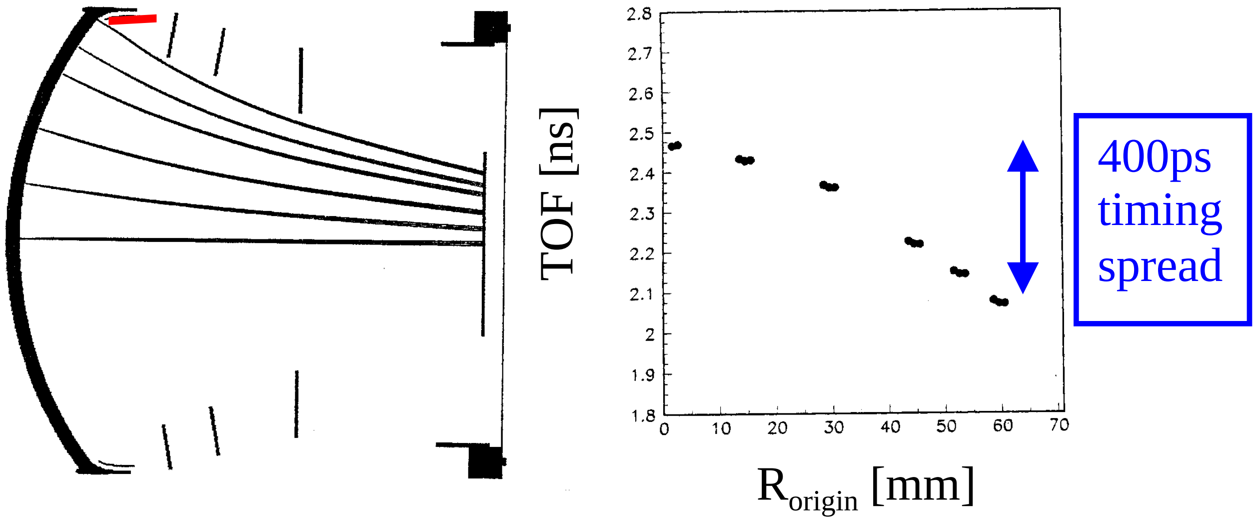
Amp $_{\text{rise time}}$ ⊗ Electron drift distr. ⊗ Hole drift distr.

~2-3 ns ⊗ ~100ps ⊗ 3-4ns.

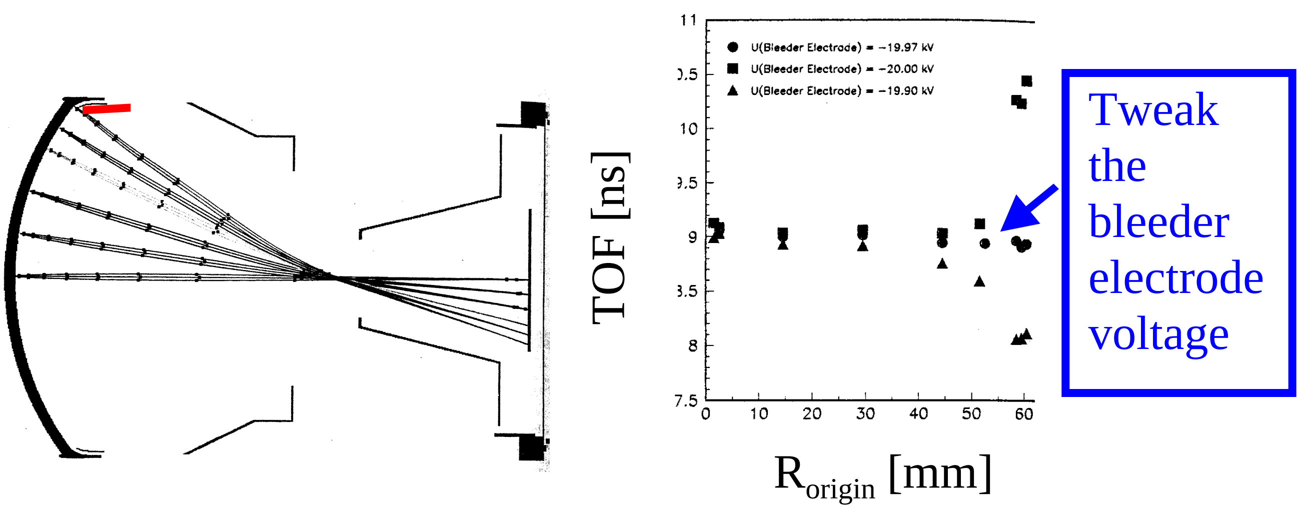
Electron drift distribution (σ_{TTD}):

D. Ferenc, Nucl. Instr. & Meth., A431(1999)460:

a) Fountain-focussing optics with the bleeder electrode:



b) Cross-focussing optics with the bleeder electrode:



- The cross-focussing optics has more uniform timing spread if the bleeder electrode voltage is properly tweaked.
- σ_{TTD} ~ 100-200psec for electron appears possible.

Hole drift distribution (σ_{TTD}):

P.B. Cushman and A. Heering, IEEE, San Diego, CA, 2001.

Current pulse:

$$I(t) = e^{(\frac{2\mu V_d}{d^2})\, t}\, N q \mu (V_b - V_d)/d^2$$

and its width:

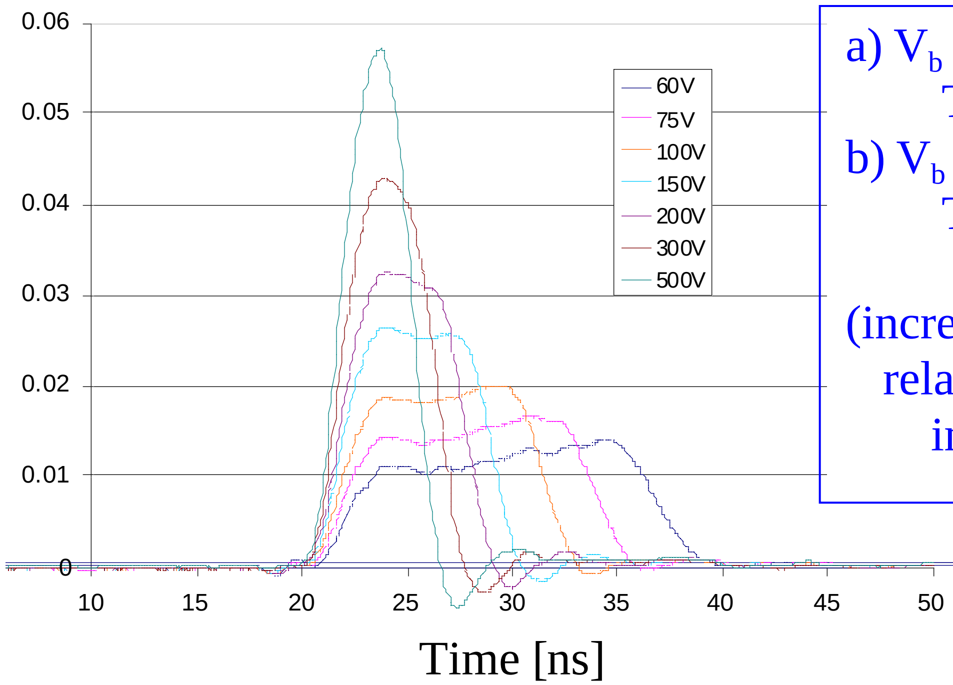
$$\Delta(ns) = d^2 \ln\left(\frac{\sqrt{V_b + V_d}}{\sqrt{V_b - V_d}}\right)/\mu V_d \approx d^2/\mu V_b \,(\text{for } V_d \text{ small})$$

where Nq is total charge, V_b is bias voltage, V_d is depletion voltage, d is depletion depth, and μ is hole mobility.

To minimize Δ(ns), d should be small, V_b large, and V_d small, which corresponds to a high Si resistivity.

Smaller Δ(ns) yields smaller risetime of the HPD pulse.

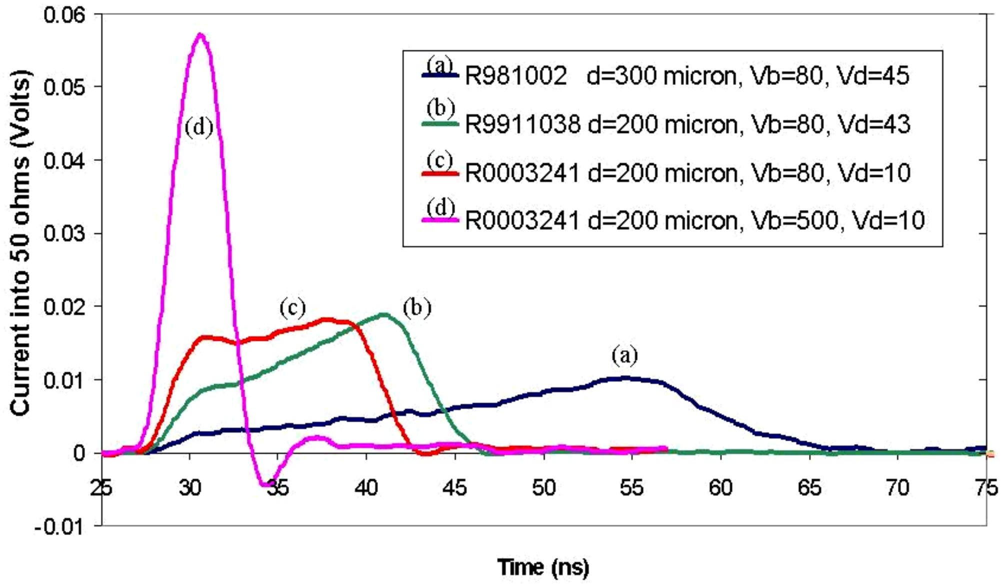
(a) Tune bias voltage V_b (d = 200μm, V_d small)



a) V_b ~ 60 Volts:
Tr ~ 4 ns
b) V_b ~ 500 Volts:
Tr ~ 2-3 ns

(increasing V_b is a relatively slow improvement)

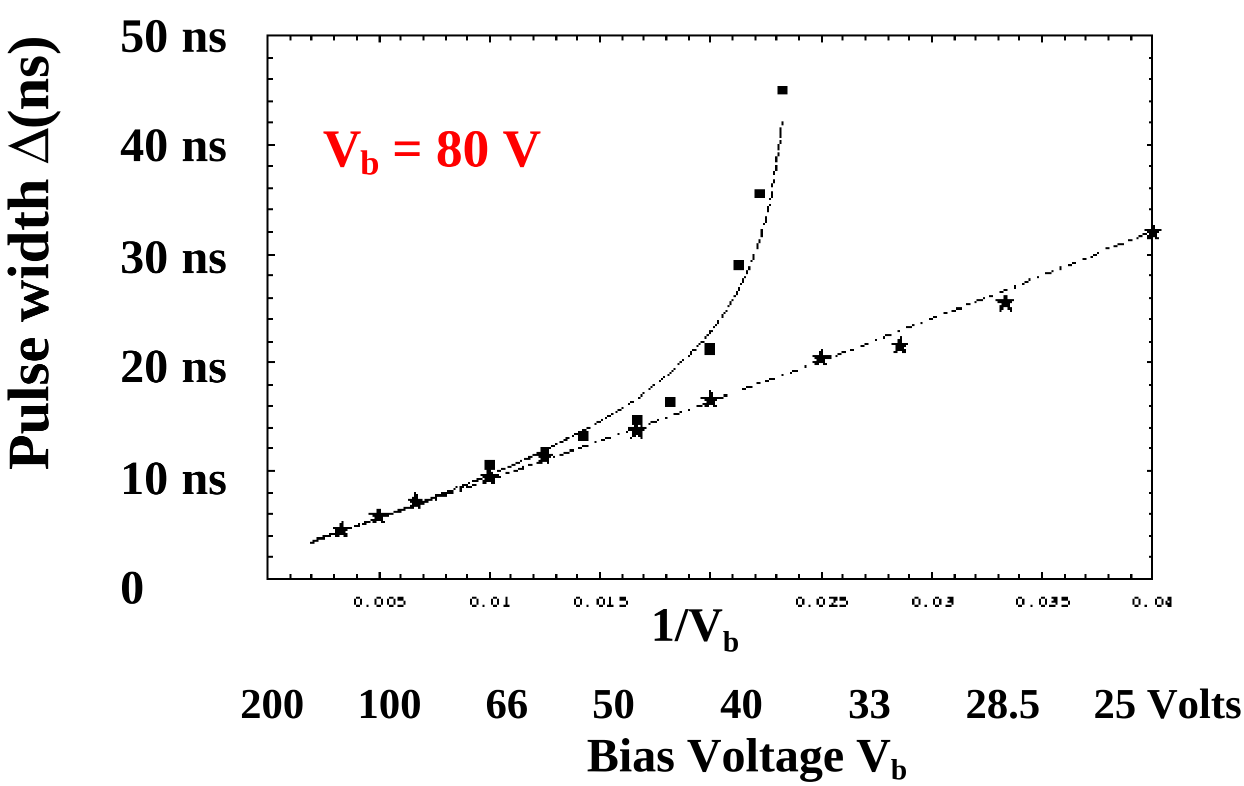
(b) Tune Si thickness (thinner means more noise !!!):



(c) Tune Si resistance, i.e. depletion depth:

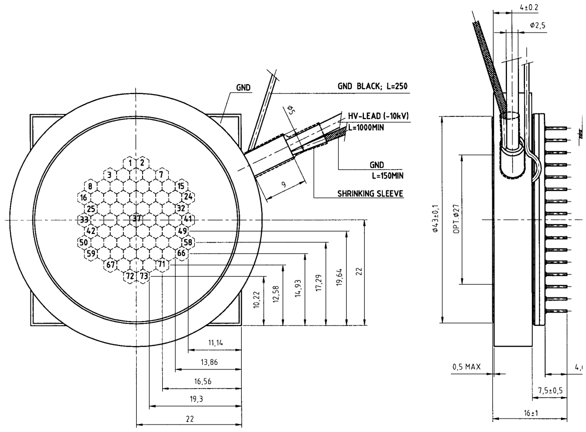
- For higher depletion (lower Ohmic silicon) V_b-V_d ~ V_b is not true.

n - 3 kΩ-cm diodes, H - 12 kΩ-cm diodes



DEP Proximity Focussing HPD (0380AJ):

Used in P.B. Cushman's tests:

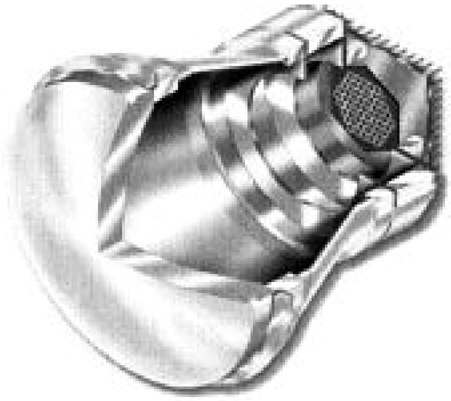


Photocathode	Bi-alkali
Accelerating medium	vacuum
Operating voltage	**-12 kV**
Geometrical packing efficiency	**~63%**
Detector	Canberra PIN diode
Overall uniformity	~98%
Cross-talk from pixel-to-pixel	<2%
Pixel capacitance	~5pF
Number of pixels	73
PIN diode bias voltage	60-100 Volts
Pixel size (granularity at the photo-cathode plane)	**2.5 mm flat-to-flat**
Electron optics and demagnification	Proximity focussed and 1
PIN diode silicon volume resistivity	~5 kΩ.cm
Photo-electron transit time distribution	<100 ps
Hole collection time spread	**~3-4ns**
PIN diode signal formed from:	Motion of holes
Gain ~$(V-V_{th})q_e/3.62$ eV, V_{th} ~2.1kV	**~3000 @ –12kV**
Required electronics noise	**~400-600 electrons**
Type of amplifier	Charge integrating
Expected timing resolution per single photon	Possibly a sub-ns

- Can operate in a 4 Tesla magnetic field.

DEP Electrostatically Focussing HPD (PP0380AU):

DIRC R&D at SLAC:



Photocathode	Bi-alkali (visible & UV)
Accelerating medium	vacuum
Operating voltage	**-20 kV**
Geometrical packing efficiency	**~81%**
Detector	Canberra PIN diode
Overall uniformity	>80%
Cross-talk from pixel-to-pixel	<2%
Pixel capacitance	~4pF
Number of pixels	61
PIN diode bias voltage	60-100 Volts
Pixel size (granularity at the photo-cathode plane)	**2.5 mm flat-to-flat**
Electron optics and demagnification	Proximity focussed and 5
PIN diode silicon volume resistivity	~5 kΩ.cm
Photo-electron transit time distribution	<100 ps
Hole collection time spread	**~3-4ns**
PIN diode signal formed from:	Motion of holes
Gain ~$(V-V_{th})q_e/3.62$ eV, V_{th} ~2.1kV	**~5000 @ –20kV**
Required electronics noise	**~400-600 electrons**
Type of preamplifier & amplifier	**ORTEC 142A + 9302**
Combined max. charge gain of the system	**~32 µV / e-h pair**
Amplifier rise time (both together)	**~5 ns**
Expected timing resolution per single photon	Possibly a sub-ns

- Timing tests are in progress at SLAC.

What do we expect ?

Parameters of our test:

- ORTEC 142A amplifier + ORTEC-9302 (200x),
- Gain ~ 0.16 μV/e-h pair,
- Q_{in} ~ 5000 electrons @ 20kV (HPD gain),
- σ_{AMP} ~ 500 electrons @ 5pF (amplifier noise),
- V_{peak} ~ 0.8 mV x 200 = 160 mV,
- V_{noise} ~ 0.08 mV x 200 = 16 mV,
- Tr (142A preamplifier) ~ 5-6 ns @ 5-10pF,
- Tr (9302 amplifier) ~ 3 ns,
- Tr (PIN diode) ~ 3-4 ns (DEP information),
- **σ_t ~ 4 ns * (500/5000) ~ 400 psec, or worse.**

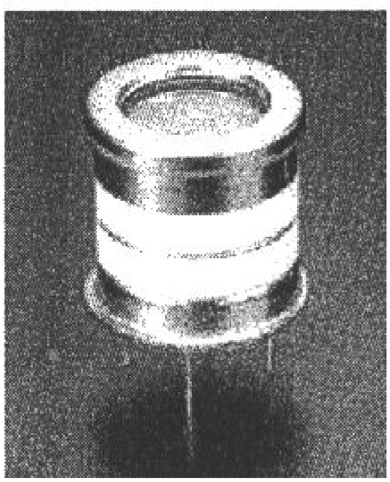
4) What to do next?

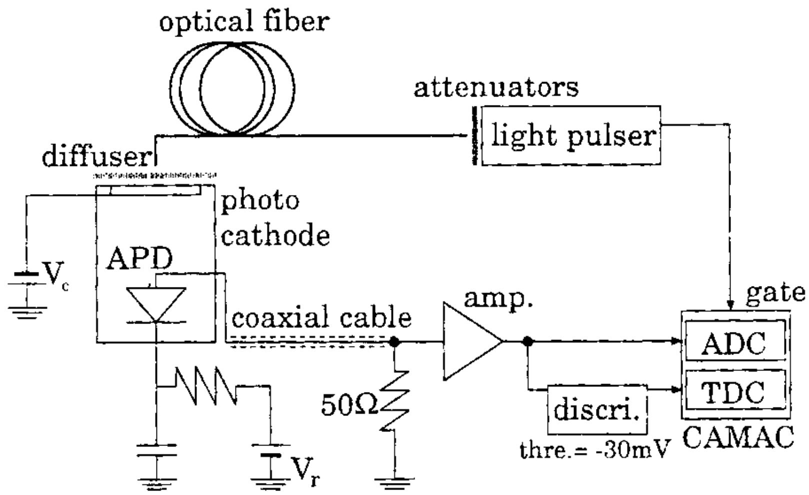
Discussions with DEP/Canberra, P. Cushman, R. DeSalvo, V. Radeka, D. Gedcke:

- Drift electrons. Unfortunately, Canberra does not plan to do this in the near future.
- Make silicon thinner (means more noise), of higher resistance, and run a large bias voltage.
- Run higher HPD voltage to get more signal.
- Can we gain from a multiple sampling of the waveform ? V. Radeka (BNL) or D. Gedcke (ORTEC) argue that this works only in a noise-free limit, and not in the practical systems.
- Use APD for the detector instead of PIN diode.

Hamamatsu HAPD R7110U-07:

S. Matsui et al., NIM A463(2001)220, Belle Detector R&D in Nagoya:



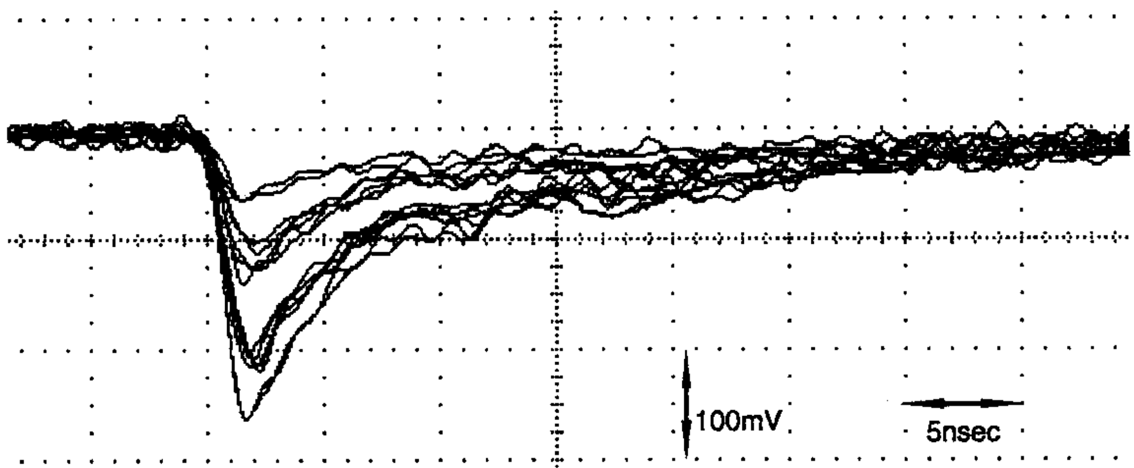


Photocathode	Multi-alkali
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	**-8.5 kV**
APD diode bias voltage V_{APD}	~155 Volts
Avalanche Photodiode Detector diameter	3mm dia.
Sensitive area	8 mm dia.
Pixel capacitance	**120 pF**
Geometrical packing efficiency	16 %
Gain @ $V_{photocathode}$ = -9 kV and V_{APD} ~160 V	**~1.5 x 10^5**
Type of amplifier	MITEQ, 60dB,300MHz BW
Rise time	**~1.1 ns**
Fall time	**~14.8 ns**
Pulse width	**~4.9 ns**
Timing resolution per single photon	**σ ~ 150 ps**
Planned operating magnetic field	**1.5 Tesla**

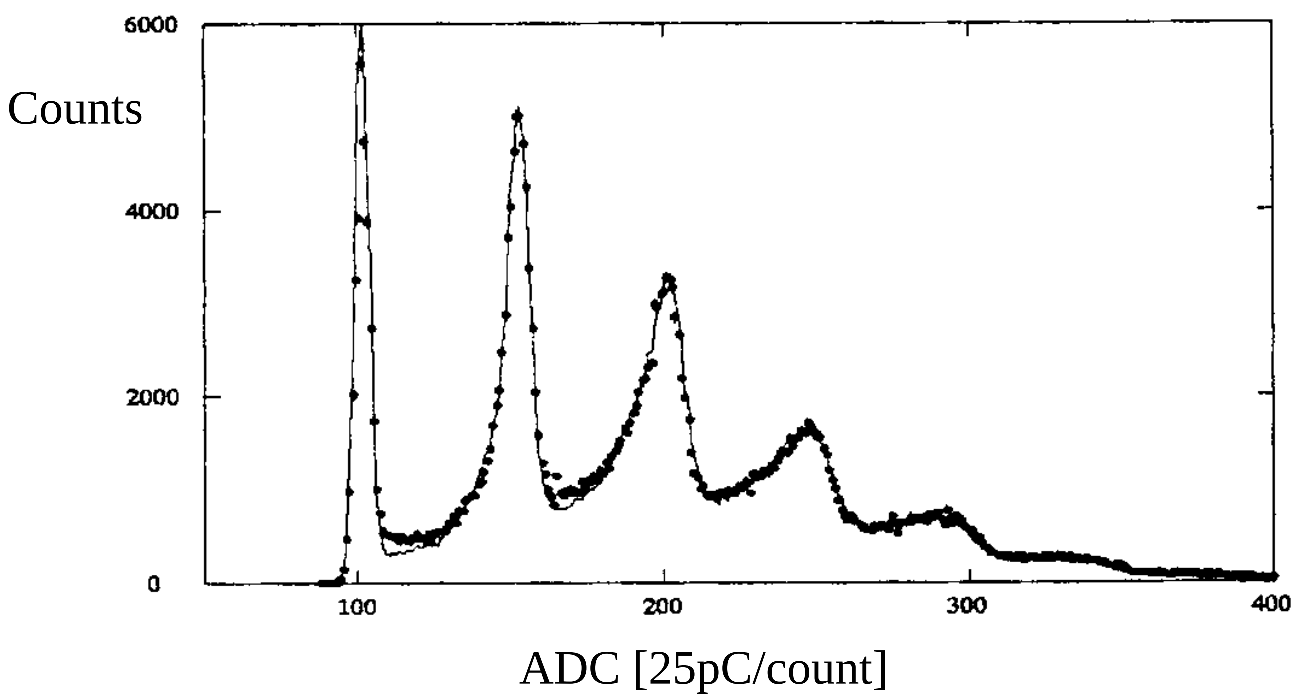
- They reached σ~150ps at a total HAPD gain of ~1.5x10^5, by correcting the time walk with an ADC.
- To reach σ~100ps, they conclude that they would need a total HAPD gain of ~4x10^5.

a) HAPD pulses with 60dB, 300MHz BW amplifier:

100mV/div, 5 ns/div

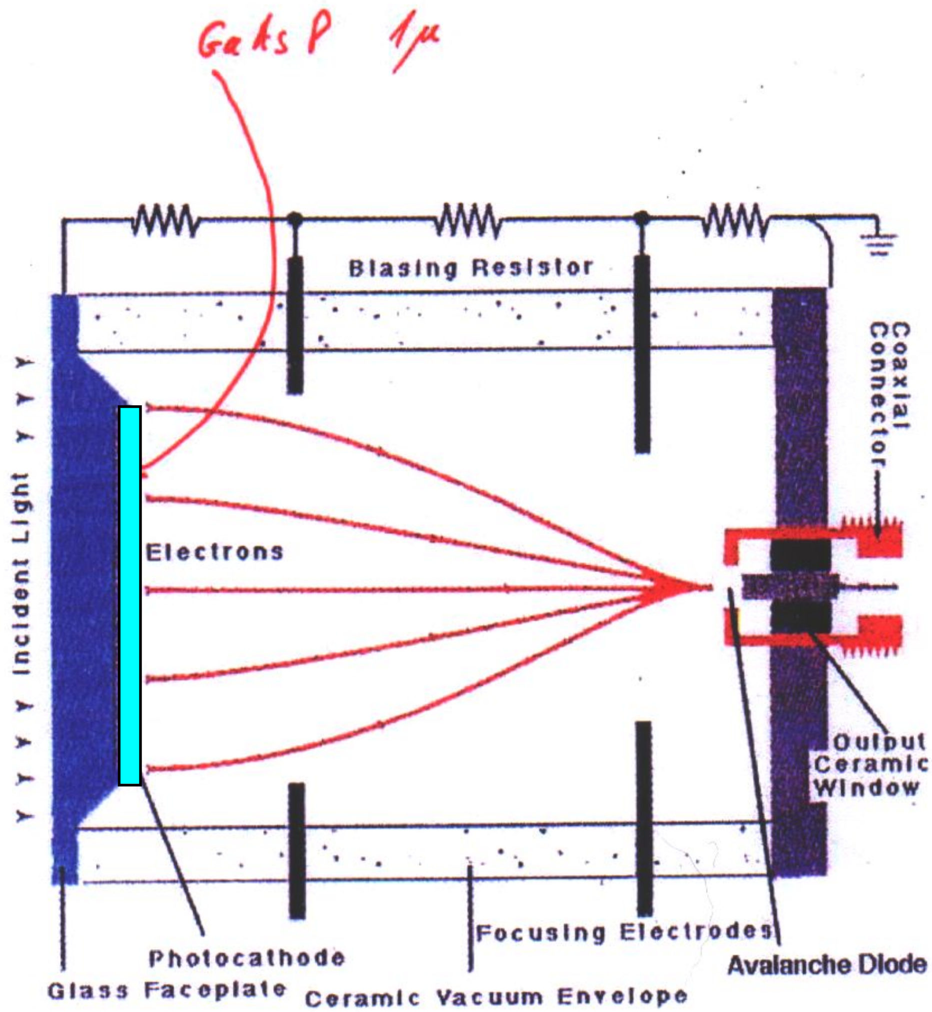


b) HAPD pulse height distribution:



Hamamatsu HAPD R7110U-07 is a derivative from an old INTERVAC tube:

E. Lorenz, private communication:



Photocathode	GaAs
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	**<10 kV**
Pixel capacitance	**40 pF**

- The INTERVAC tube developed in 1995.

R7110U-01MOD – a new development of high Q.E. (>45%), red extended, and very fast HAPD:

E. Lorenz, private communication (MPI/Hamamatsu joint development):

Goal:

- For harsh background from night sky or moonlight (3-10 GHz).
- Single electron sensitivity.
- Expect to reach time resolution of ~100ps.
- 18 mm diameter.
- Limit voltage to <10kV.

Solution:

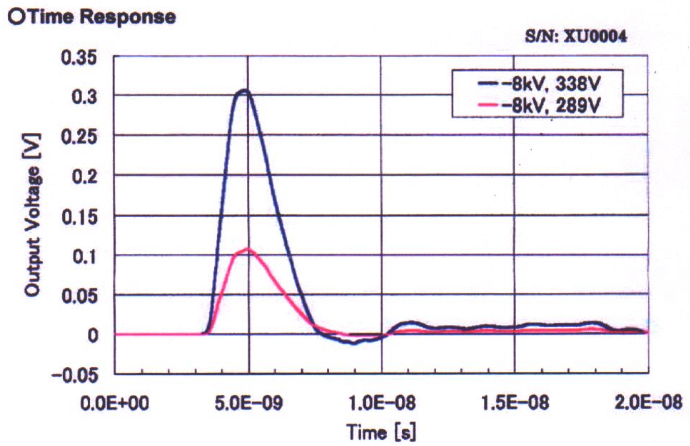
- HPD with GaAsP photocathode and low capacitance APD.

Present status:

Photocathode	GaAsP
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	**-8 kV**
APD diode bias voltage V_{APD}	~338 Volts
Sensitive area	18 mm dia.
Pixel capacitance	**24 pF**
Total Gain (APD gain alone is ~30x)	**~5 x 10^4**
Rise time	**~0.8 ns**
Fall time	**~1.9 ns**
Pulse width	**~2.1 ns**

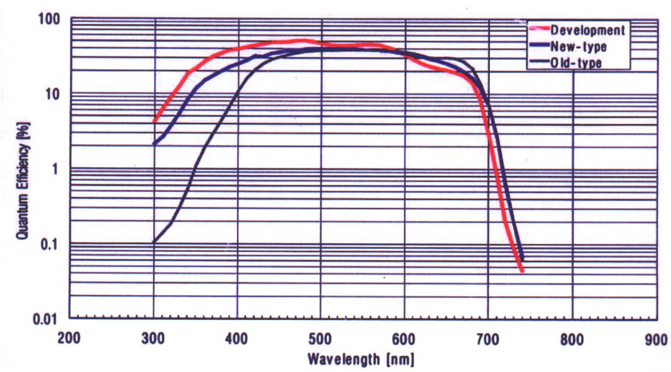
Pulses:

(Light source: FWHM ~ 35ps, 780nm; Photocathode voltage: -8kV; Load: 50Ω)



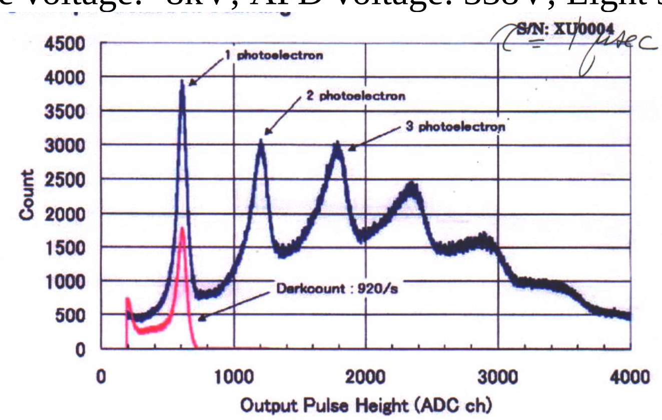
Q.E. of GaAsP photocathode:

(A further improvement at small wavelengths with a wavelength shifter)



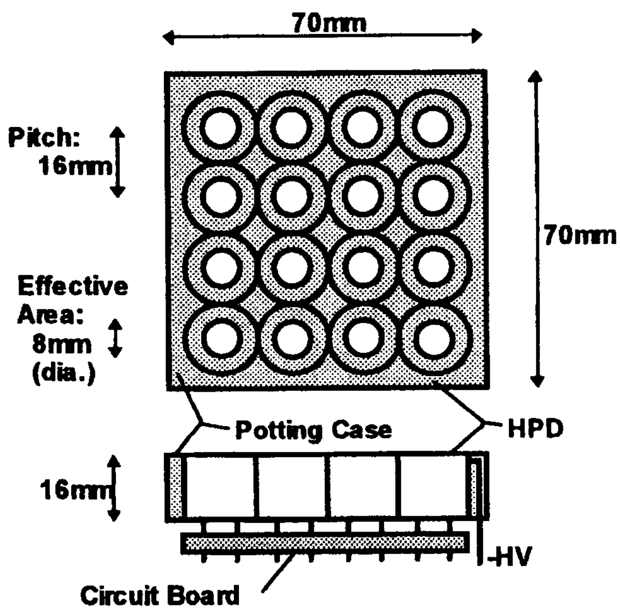
Pulse height spectrum with slower charge integrating amplifier:

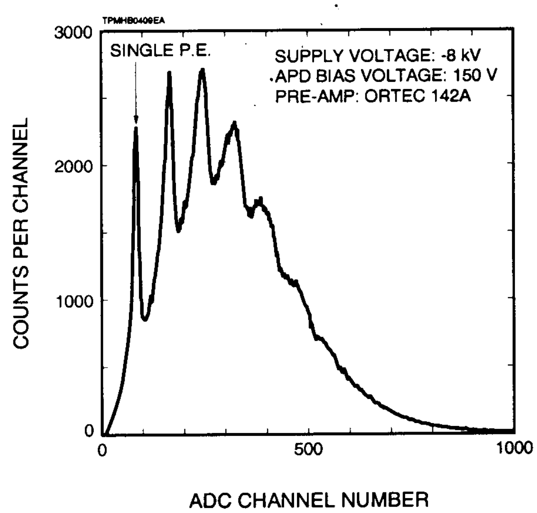
(Photocathode voltage: -8kV; APD voltage: 338V; Light source: 650nm)



Hamamatsu offers "multi-pixel" 4x4 array R7110U-01 HPDs:

Hamamatsu information:



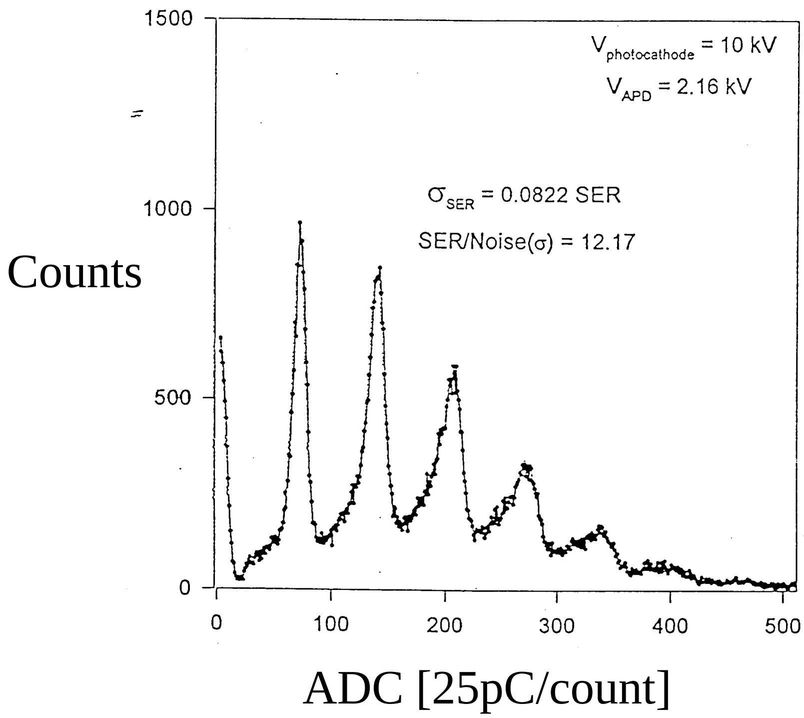


Photocathode	Multi-alkali
Detector	3mm dia. Avalanche Photodiode
Sensitive area	7 mm dia.
Amplifier	Ortec 142A
Planned operating magnetic field	**1.5 Tesla**

- It can work in a strong magnetic field (1.5 T).

Advanced Photonics VAPD:

M. Szawlowski, Advanced Photonics, Internal note, 1995:

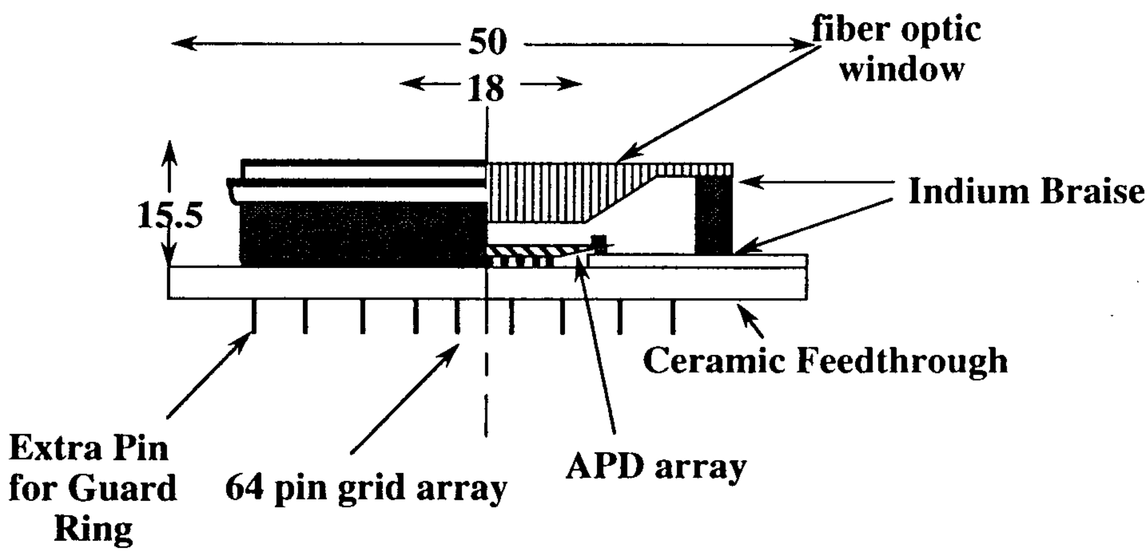


Photocathode	Multi-alkali
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	**-10 kV**
APD diode bias voltage V_{APD}	~2.2 kV
Detector	Aalanche Photodiode
APD size	16 mm dia.
Gain @ $V_{photocathode}$ = -10 kV and V_{APD} ~2.2 kV	**up to ~10^6**
Rise time	**~2-5 ns**

- It was not tested for timing since they did not have a ps pulser at that time.
- The device was called VAPD.

64-channel APD-HPD:

P. Cushman, R. Rusack and V. Singh, Nucl. Physics B, 44 (1995) 35:

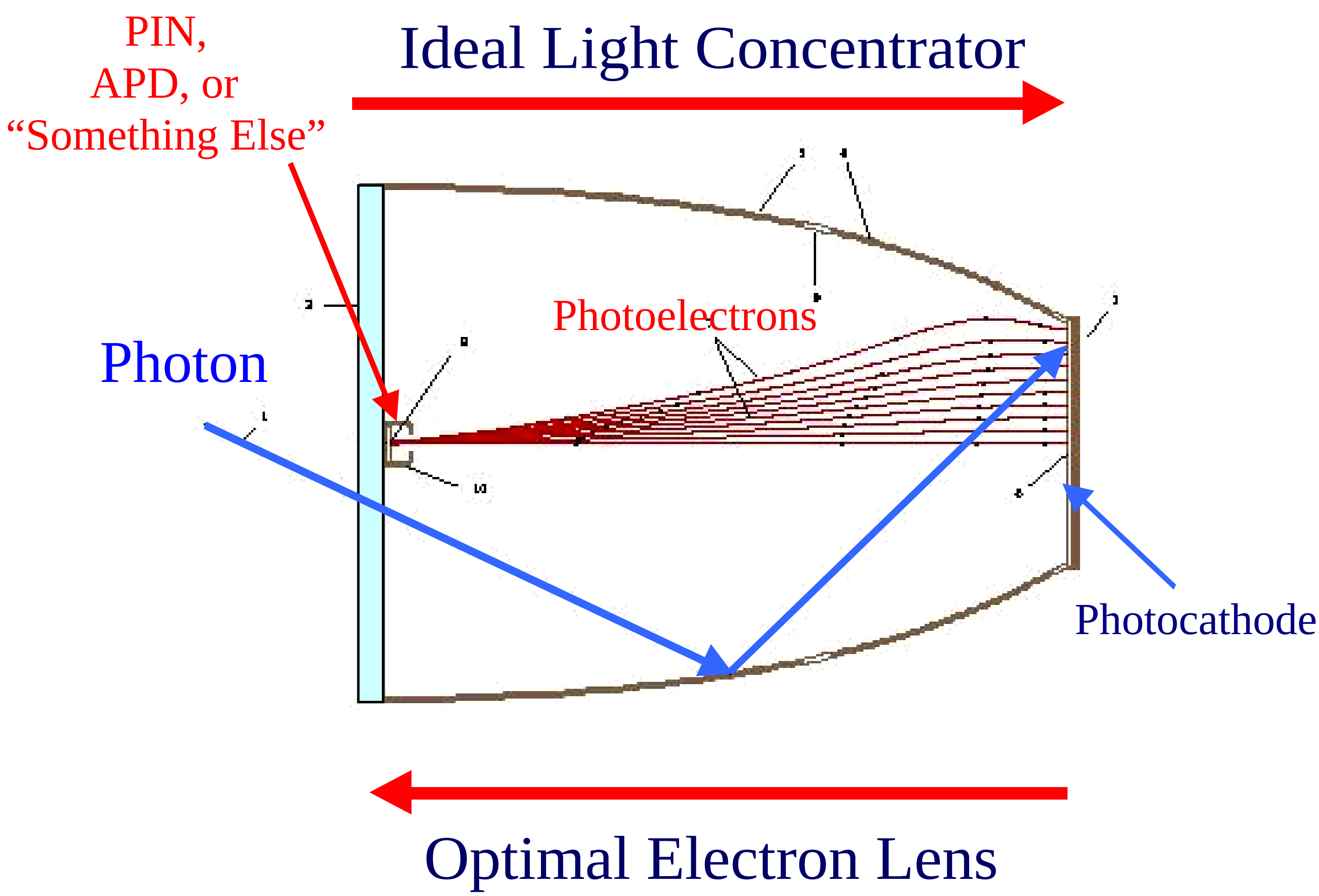


Photocathode	S-20
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	**-10 kV**
APD diode bias voltage V_{APD}	~2.0 kV
Detector	Aalanche Photodiode
APD array	8 x 8
APD Gain @ V_{APD} ~2.0 kV	**~1000**
Total Gain @ $V_{photocathode}$ = -10 kV & V_{APD} ~2 kV	**up to ~10^6**
Rise time	**2-5 ns**

- The APD array was manufactured by Advanced Photonics Inc.
- The HPD was manufactured by Litton Electron Devices.
- This was another casualty of the SSC death….

ReFerence Photosensor:

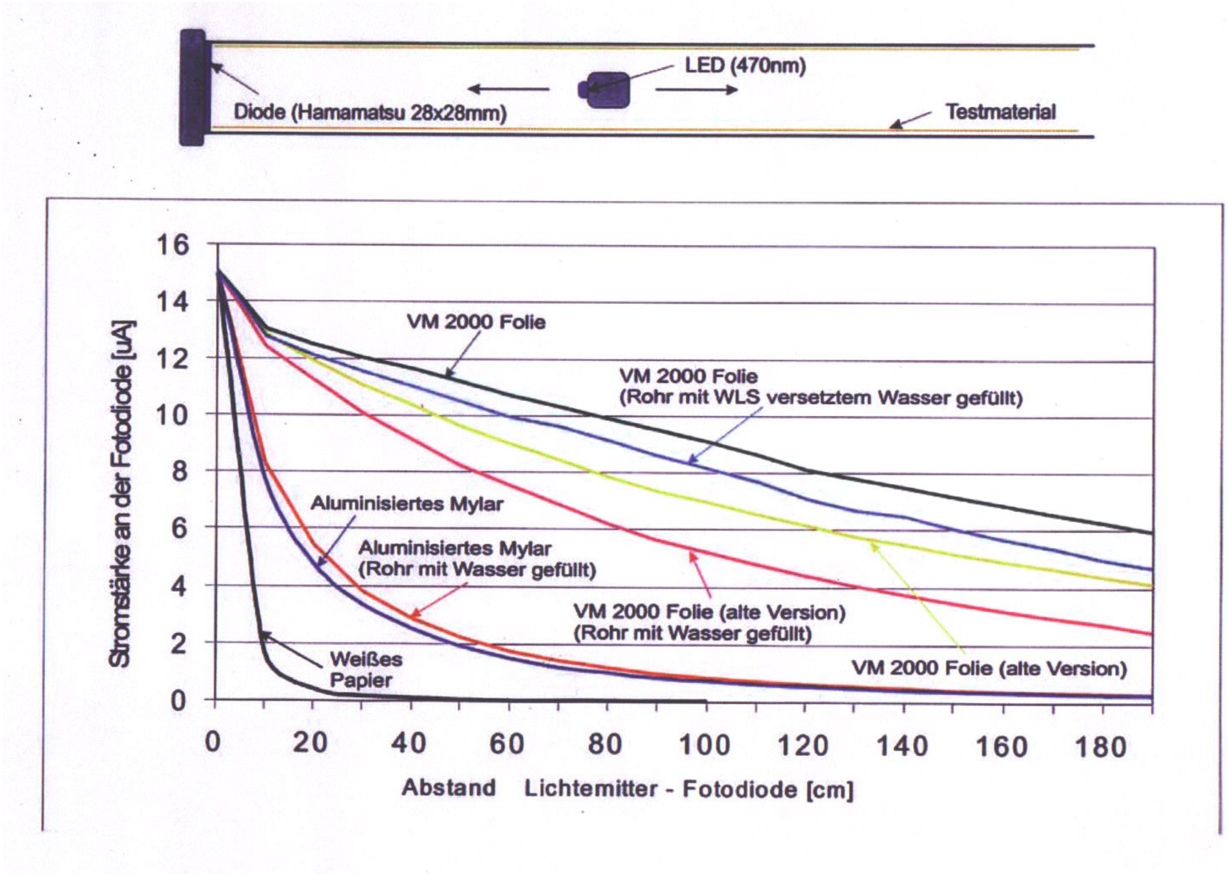
D. Ferenz, IEEE, Lyon, France, 2001, and private communication:

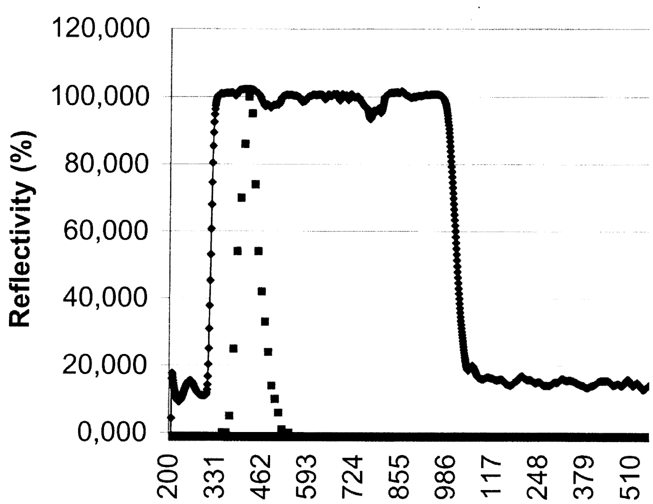


- Optimal usage of photocathode surface.
- Excellent Time-Resolution, although flat photocathode.
- Higher Quantum Efficiency in reflection mode.
- Efficient magnetic shielding.
- Many permutations of this idea possible.
- The first fully functional sealed prototype from ITT Night Vision will be soon available for evaluation.
- Use of very reflective film.

A very transparent foil:

E. Lorenz, private communication (3M product):





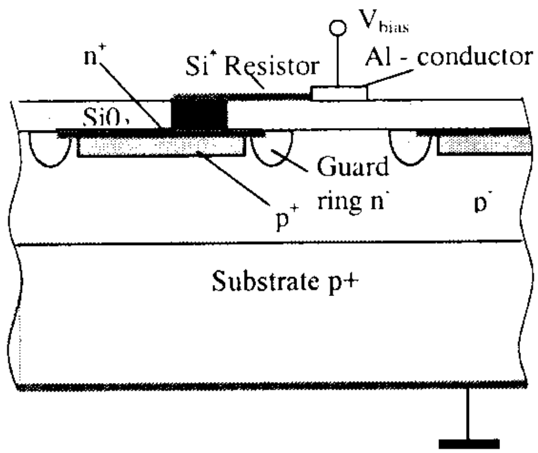
- Reflectivity of the film can be selected.

APD silicone arrays operating in a Geiger mode

- **Silicon PMT - SiPM.**

Silicon Photomultiplier - SiPM:

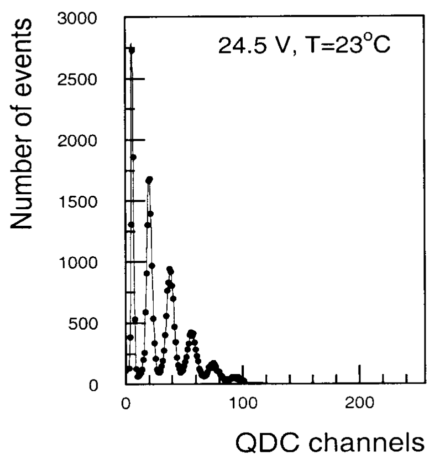
P. Buzhan, B. Dolgoshein et al., ICFA Instr. Bulletin, Fall 2001 issue
G. Bondarenko et al., Nucl. Instr. & Meth., A442(2000)187:



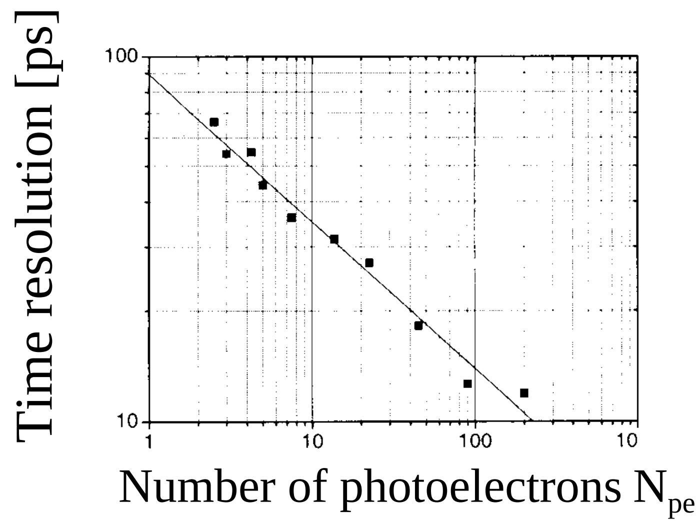
Photocathode	Silicon
Accelerating medium	Si
Operating voltage	**24-25V**
Geometrical packing efficiency	**~44%**
Detector (possible range: 15-70 µm)	Pixel Silicon PIN diode
Pixel size	42 µm x 42 µm
Pixel capacitance	~100 fF
Protecting resistor on each pixel	~100-200 kΩ
V_{bias} - $V_{breakdown}$ (Geiger condition: $V_{bias}>V_{breakdown}$)	A few Volts
Number of pixels (possible limit ~4000/mm^2)	**~576 / mm^2**
Electric field in the silicon	(3-5) x 10^5 V/cm
Dark noise rate (at room temperature)	**A few MHz/mm^2**
Gain	**1.5x10^6 @ 24.5V**
Gain uniformity	~10%
Typical rise time	~1ns
Typical fall time ($\tau \sim C_{pixel}$ x R_{pixel}~30ns)	~100ns
Measured timing resolution per single photon	**60ps**

- Insensitive to magnetic field, excellent timing and PH.
- In practice one would gang many pixel together to one channel.

Pulse height spectrum



Time resolution = f(n_{pe})



- **Actually σ** ~ 60ps per single photon was already achieved.
- To get σ ~ 60 ps one does not need ADC or double threshold timing corrections because the pulse height is so uniform.
- One needs a lens to correct for a large geometrical inefficiency.

- A US company, called RMD, is offering 16 pixel arrays.

  - Gain ~10^8 achieved.
  - QE: ~50% at 400nm, 75% at 532nm, and 20% at 1064nm.
  - 100kΩ resistor to protect the diode.
  - Active are of each diode 10-30μm.
  - Noise rate at room temperature: 0.01-1kHz.
  - However, presently a large dead spaces between diodes.

Comparison

Parameter	Flat-Panel Multi-anode H-8500 PMT	LHC-b Electrostat. Focus. HPD	R7110U-01MOD	SiPM
Company	Hamamatsu	DEP	Hamamatsu	Dolgoshein
Model	H-8500	PV0380AU	–	–
Q.E. blue	~20 %	~20 %	>45 %	~12 %
Mag. Field operation	Problematic	Problematic	OK	OK
Gain per pe^-	$\sim 10^6$ @ 1kV	~5000 @ 20kV	$\sim 5\times10^4$ @ 8kV	1.5×10^6 @ 25V
Pulse height spectrum	Poor	Superb	Good	Superb
Voltage	-1 kV	-20kV	-8kV	25 Volts
Timing resolution σ per photon	~100 ps	~500 ps (possibly)	~100 ps	60 ps
Noise rate	<1kHz/PMT @ 1kV	6×10^{-4}/pixel @ 20kV *	–	a few MHz/mm^2
Number of anode pads	64	61	1	Not defined yet

* Test performed with the CERN HPD actually

Gaseous Detectors

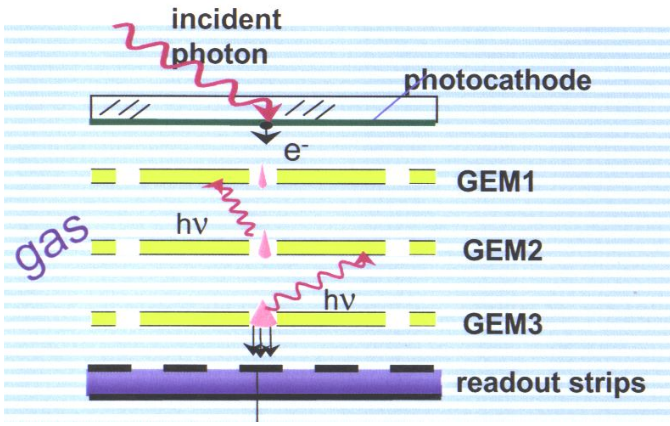
- **Multiple-GEM + Pads.**
- **Hadron-blind detector for RHIC.**
- **MICROMEGAS + single-GEM + Pads.**
- **Multiple-Capillary + Pads.**
- **MICROMEGAS + single-Capillary + Pads.**

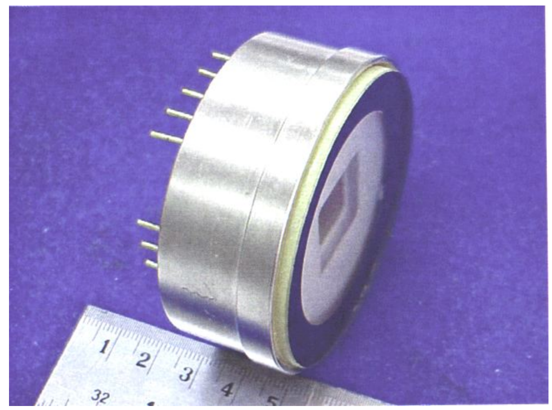
- Some think that gaseous photon detectors are dead. However, if one would give you a detector working at 4 Tesla, with visible photocathode, timing resolution of 1 ns, and your own geometry, wouldn't you take it ?

- All detectors mentioned in the following can work at 4 Tesla.

Tripple-GEM + Pads:

A. Breskin, R. Chechik et al., Nucl. Instr. & Meth., A478 (2002) 225.



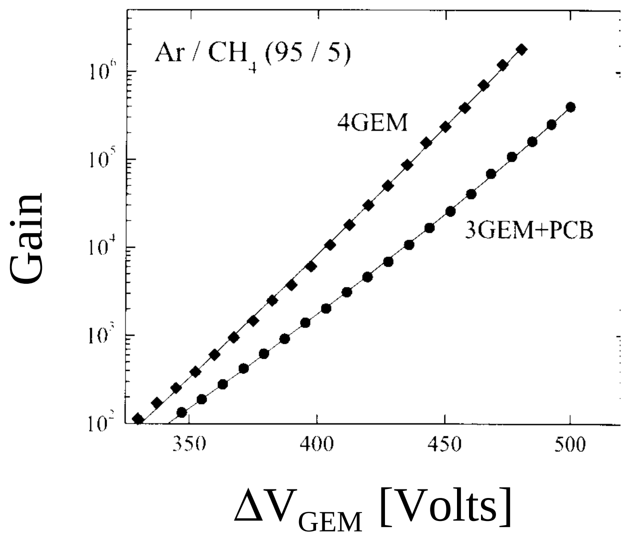


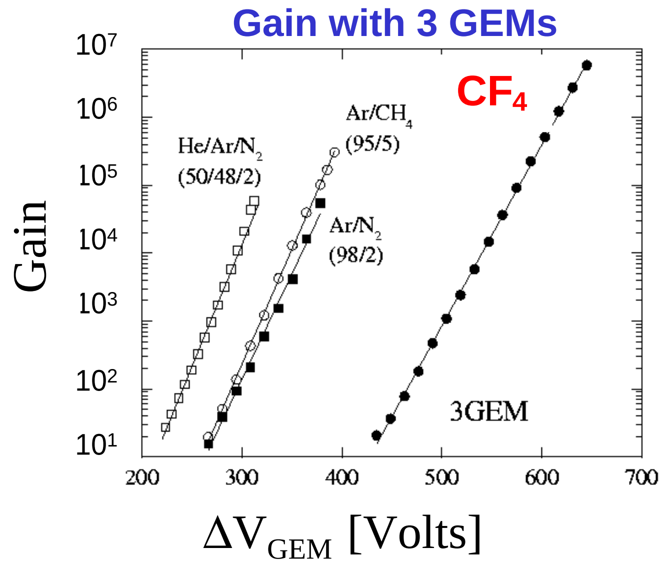
Photocathode	CsI
Method	Quartz/30Å Cr/150Å CsI
Carrier gas (1atm)	CF_4
Gas	Permanently sealed
Method of sealing	Indium seal
Baking procedure	200°C for a few days
GEM-to-GEM and GEM-to-Pad distance	1.2 mm
The 1-st GEM-to-photocathode distance	6.5 mm
Kapton and copper hole diameters	50 & 80 μm dia.
GEM hole pitch	140 μm
Max. achieved charge gain on single electron	**~3 x 10^6 (CF_4)**

- It can operate up to ~4 Tesla magnetic field.
- Can define your own geometry.
- Aging rate: a significant gain drop after ~10μC/mm^2; however, this rate is similar to that of the non-sealed detectors.

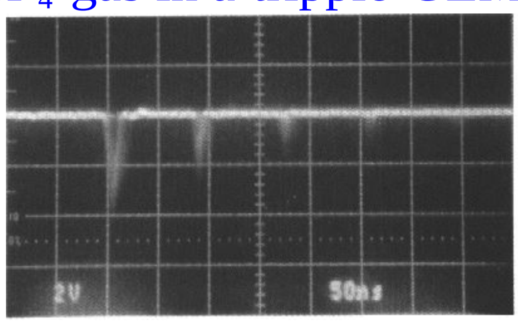
a) Gain in Quadruple and Tripple GEM in different gases:

A. Breskin, R. Chechik et al., Nucl. Instr. & Meth., A478 (2002) 225.

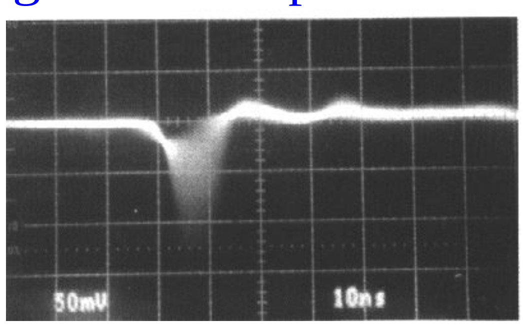




b) Secondary effects occur only at extremely large gain of ~6x10^6 in CF_4 gas in a tripple-GEM:



Fast amplifier single electron pulses at a gain of ~2.7x10^6:



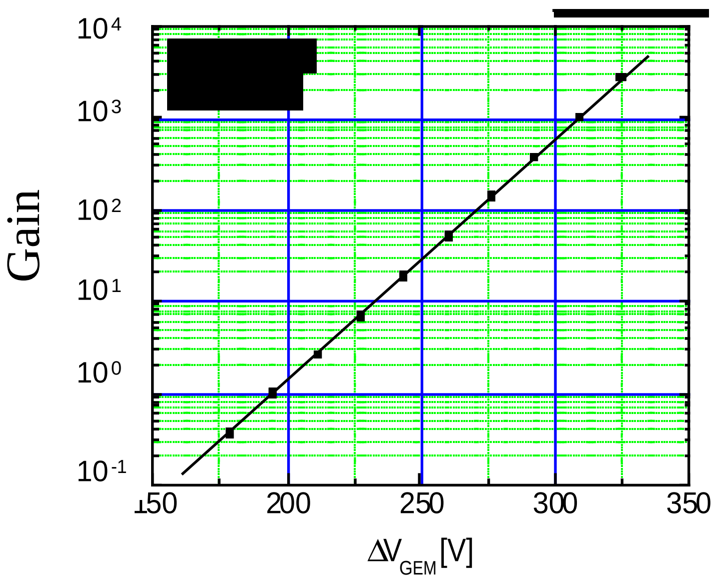
- Remarkable result!!! The GEM structure shields the scintillation photons very efficiently. Remember, CF_4 is a good scintillator !

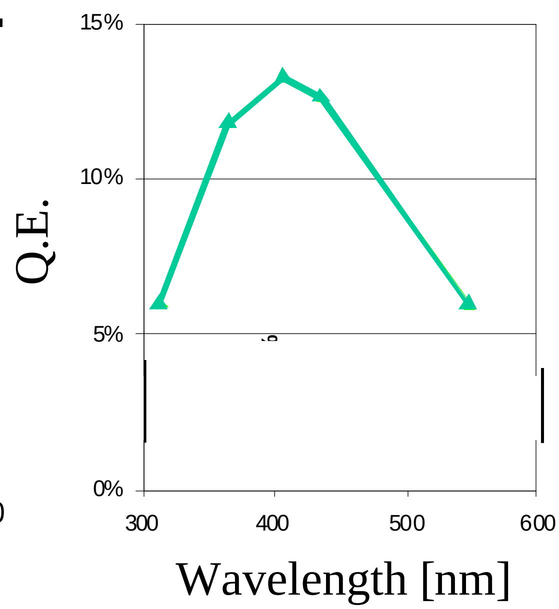
c) Aim: develop a device with a Bialkali photocathode

R. Chechik, talk at this conference.

Status:
Stable sealed Bialkali photocathodes for 6 months.

Total gain with double GEM operation



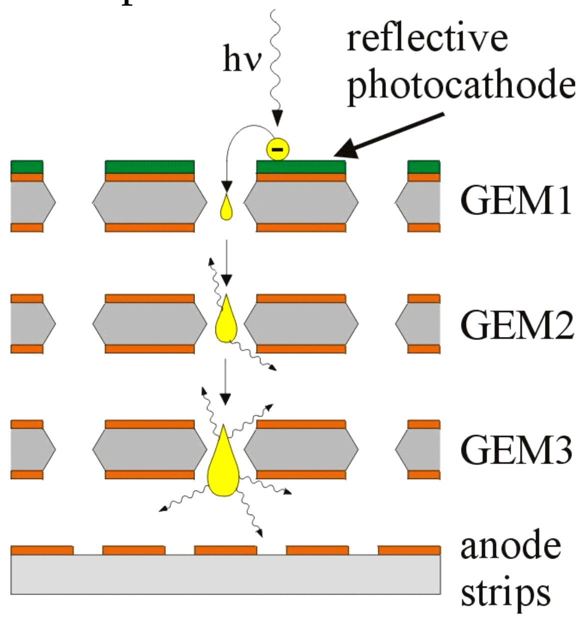


- Undergoing work: sealed multi-GEM PMT operating with 95/5% Ar/CH_4 at 1 bar. Obtained gain of 2000 with two GEMs with no secondary effects.
- Q.E. is stable 2 weeks presently with a gas at 1 bar.
- A remarkable result !!!

Hadron-blind GEM-based Detector:

I. Tserruya et al., Phenix proposal, RHIC, BNL.
Based on work D. Mormann et al., Nucl. Instr. & Meth., A478 (2002) 230.

CsI evaporated on top of the GEM foil:



Advantages:

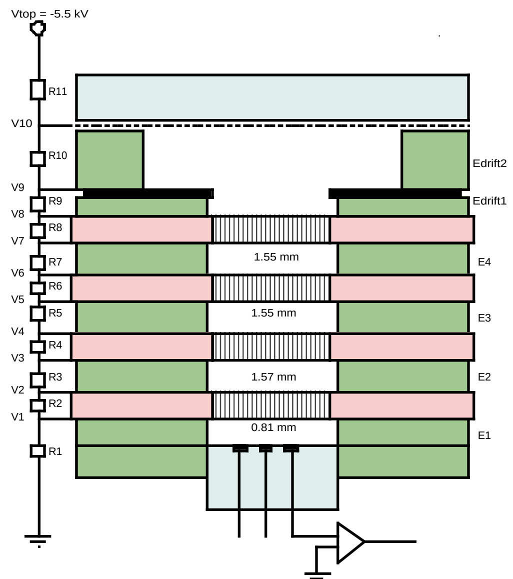
- Thick reflective photocathodes have superior QE.
- The detectors are almost free of the photon feedback.
- Detectors are fast (time resolution σ ~2.1ns in CF_4).
- High gain operation demonstrated (>10^5).
- Good 2D resolution (σ ~100µm).

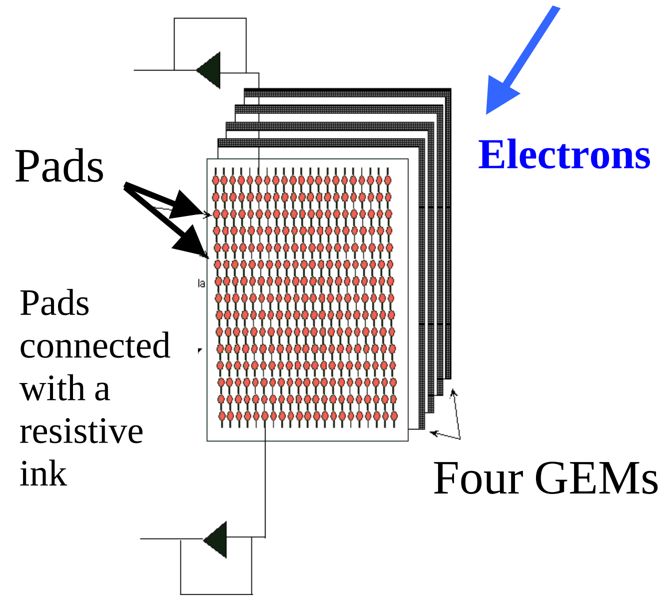
Possible difficulties:

- The CsI may end up in the GEM holes during evaporation.
- CF_4 gas can be corrosive.

Quadruple-GEM + Pads:

J. Va'vra and A. Sharma, Nucl. Instr.&Meth., A478(2002)235.



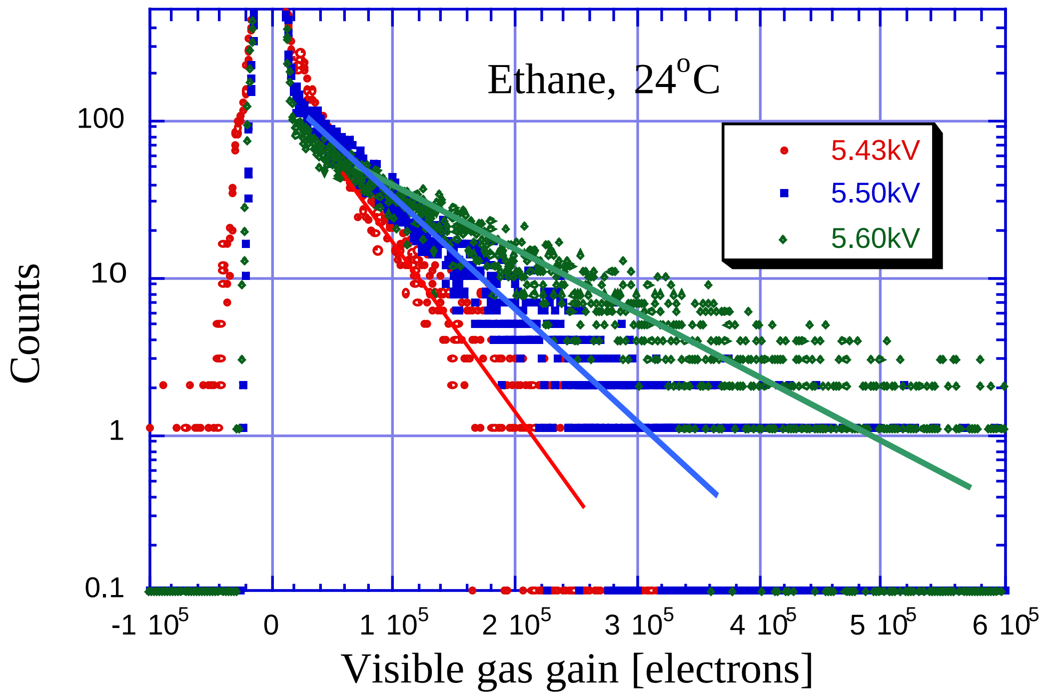


Photocathode	TMAE or s.s. mesh
Carrier gas (1atm)	C_2H_6
Pad size and pitch	1.25 mm dia. & 2.5 mm
Pad connected in y-direction via resistive ink	~40 kΩ/column of pads
GEM source	CERN (F. Sauli)
GEM-to-GEM distance	1.6 mm
GEM-to-Pad distance	0.8 mm
Kapton and copper hole diameters	40 & 80 μm dia.
GEM hole pitch	120 μm
GEM design	Conical hole
Amplifier gain (charge sensitive)	~ 2.7 μV/electron
Amplifier shaping time	~65ns
Max. achieved charge gain on single electron	**~10^6 in C_2H_6**

- Motivation: candidate for a possible last SLD runs in 1999. It would work well, if this run would happen.
- The reason for four GEMs: Reduce a load on any single GEM, & to reduce the TMAE photon feedback into the drift volume.

Single electron pulse height spectra:

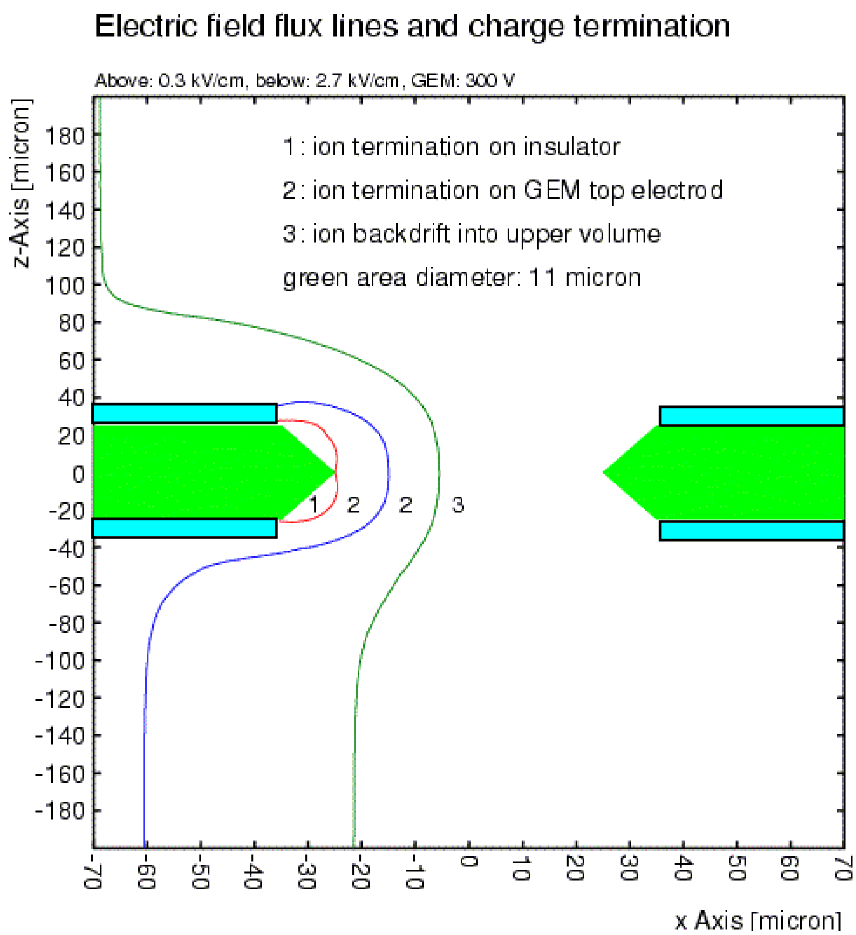
J. Va'vra and A. Sharma, Nucl. Instr.&Meth., A478(2002)235.



- All single electron spectra have an exponential shape. I have never seen a Polya distribution type of turnover with the GEM detectors.
- No sign of a poor quenching, which would show up as an excessive tail in the single electron spectrum.

Where does the charge go ?

J. Va'vra and A. Sharma, Nucl. Instr.&Meth., A478(2002)235.



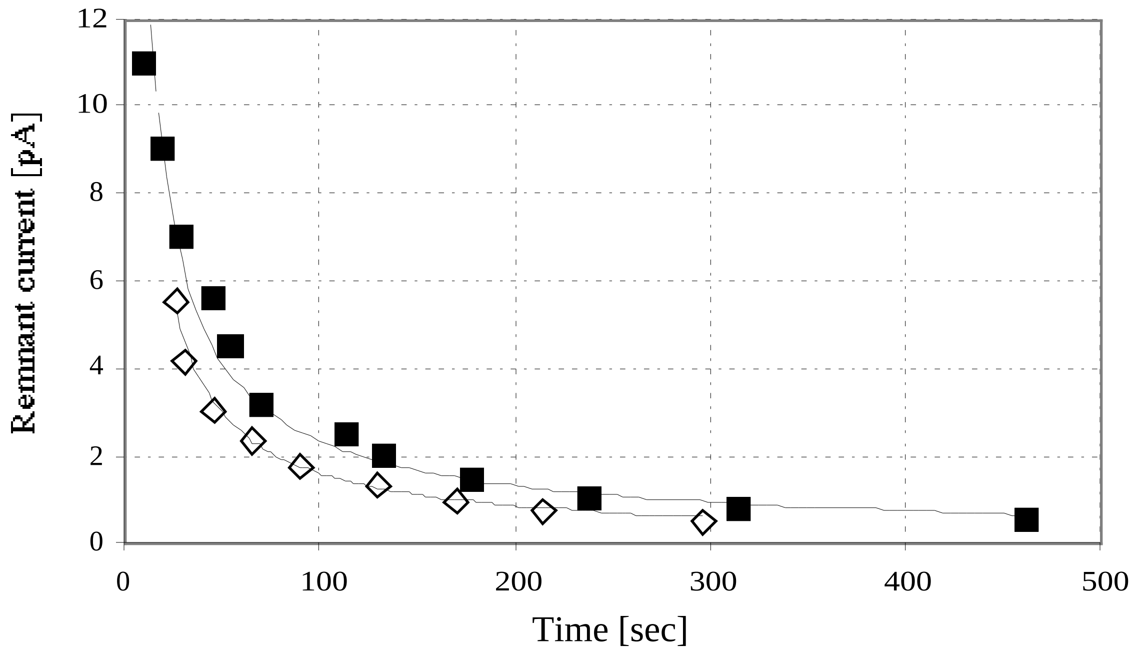
Charge losses [%]	GEM 1	GEM 2	GEM 3	GEM 4
Ions charge ending at the top GEM electrode	6	4	5	6
Ions charge ending on the Kapton insulator	2	3	3	6
Electron charge ending at the top GEM electrode	15	10	12	5
Electron charge ending on the Kapton insulator	1	3	5	15
Electron charge ending at the bottom GEM electrode	20	26	28	32
Transmitted electron charge	56	54	47	36

- The transmitted electron charge is only 36%, the ion deposition on the Kapton insulator in the last GEM is ~6%.

Charging effects:

J. Va'vra and A. Sharma, Nucl. Instr.&Meth., A478(2002)235.

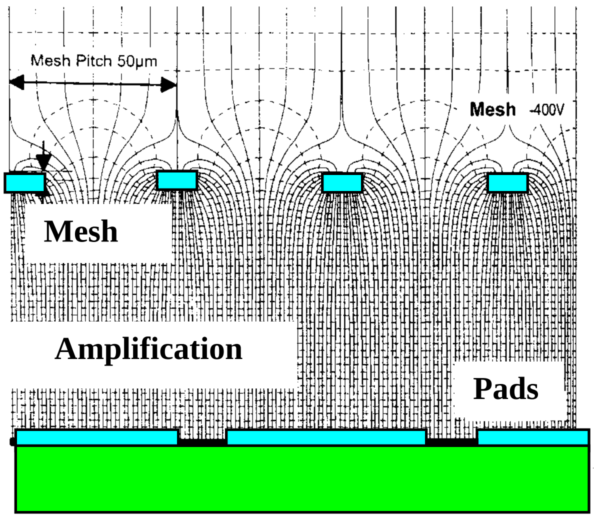
Response to switching the light off:

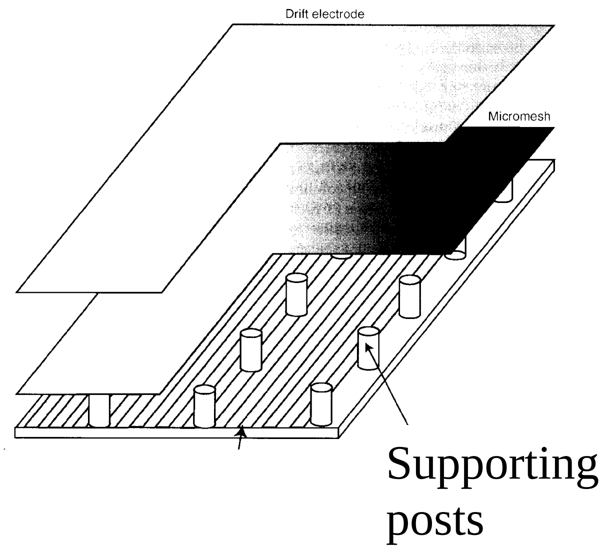


- The charging is related to the Kapton resistance. It takes minutes to discharge the Kapton.
- Does this matter ? It may in very high rate environment.

MICROMEGAS + Strips/Pads:

Y. Giomataris, Nucl. Instr. & Meth., A419 (1998) 239, and
G. Charpak et al., Nucl. Instr. & Meth., A478 (2002) 26.



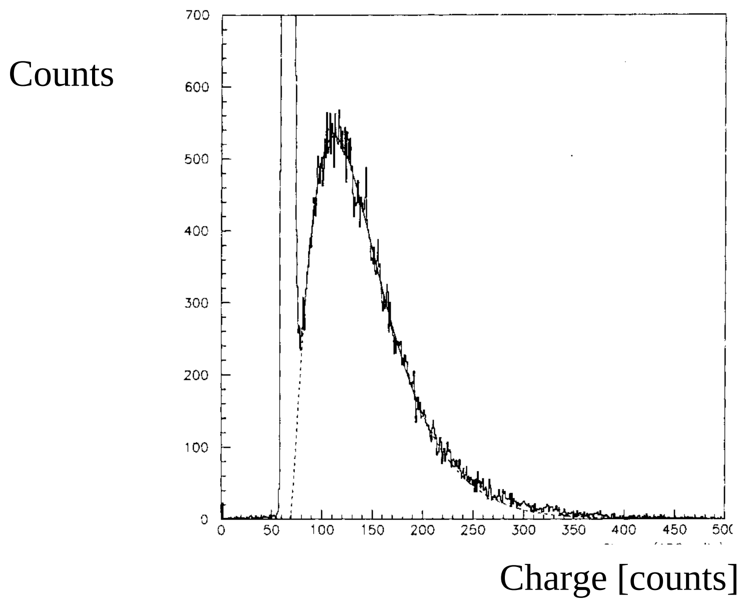


Photocathode	CsI
Method	CsI deposited in the mesh
Typical Gases used	Ar/10%C_4H_{10}, He/10%C_4H_{10}, Ne/5%C_4H_{10}, Ar/5%CF_4
Mesh type	s.s. electro-mesh
Mesh thickness	3 µm
Mesh pitch	**50 µm**
Mesh-to-pad distance	**50 µm or 100 µm**
Electric field in the amplifying gap	50-100 kV/cm
Max. achieved charge gain on single electron	**~10^6 (Ar /10%iC_4F_{10})**

- It can operate up to ~4 Tesla magnetic field.
- The proponents argue that it is a very resilient structure.

a) Single Electron Pulse Height Spectrum:

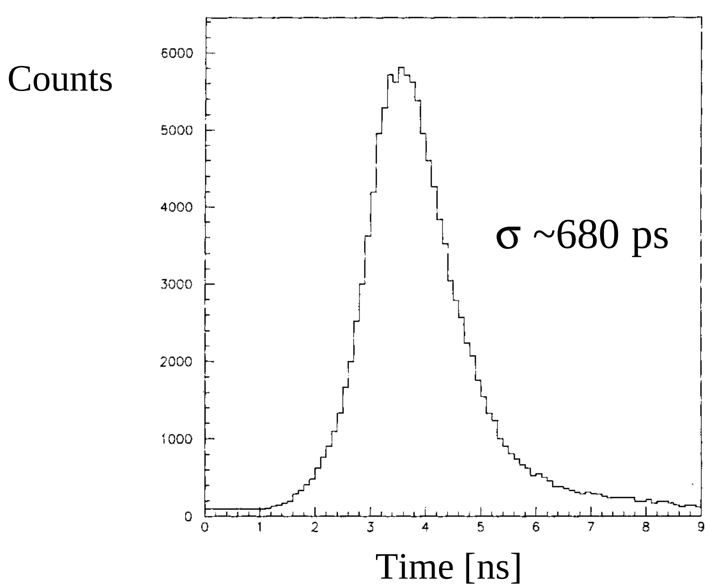
G. Charpak et al., Nucl. Instr. & Meth., A478 (2002) 26.



CsI is evaporated on the micromesh in this particular case

b) Timing Resolution with Single Electrons:

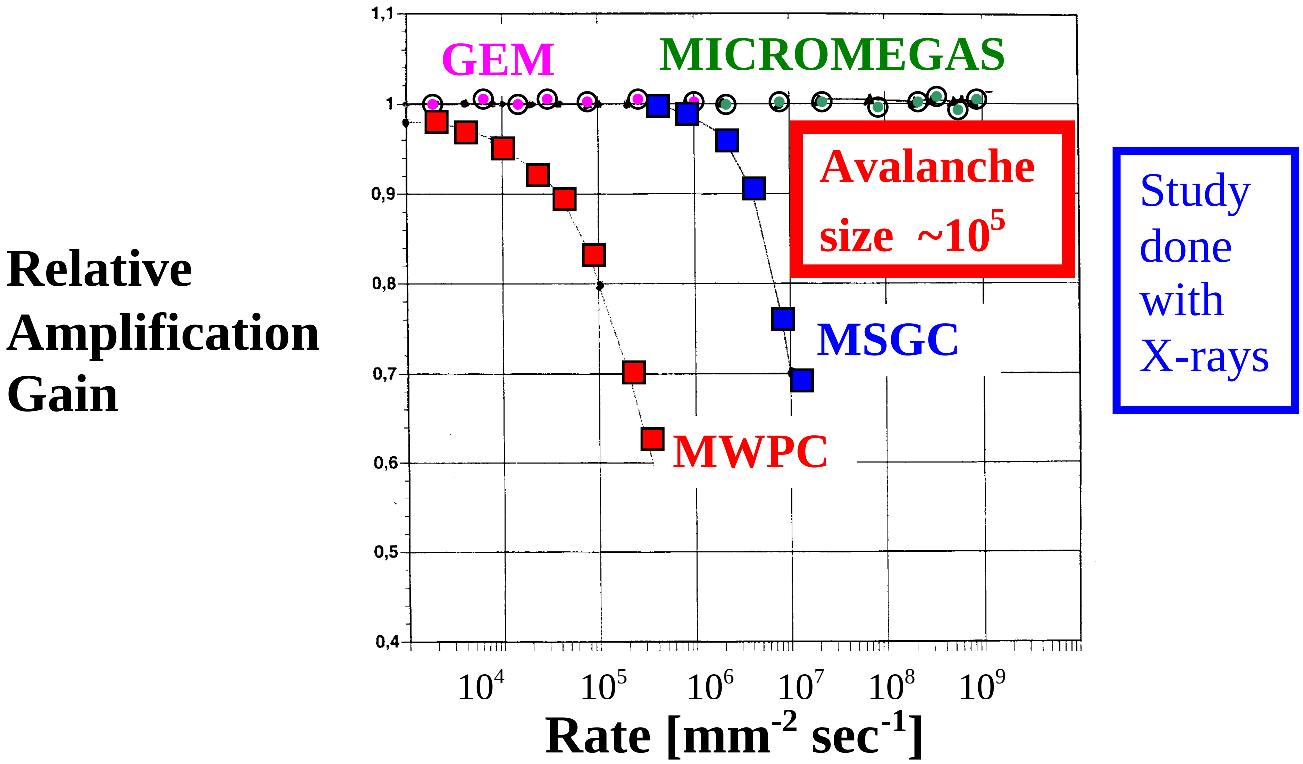
G. Charpak et al., Nucl. Instr. & Meth., A478 (2002) 26.



- This is a best timing resolution a gas detector ever achieved.

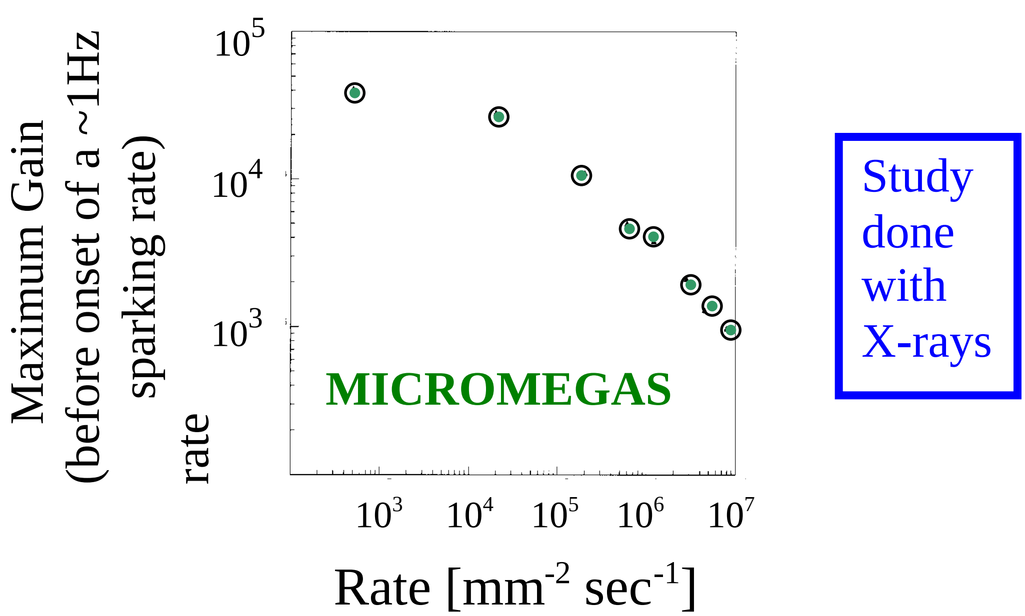
Rate capability of various gas detectors:

Y. Giomataris, Nucl. Instr. & Meth., A419 (1998) 239.



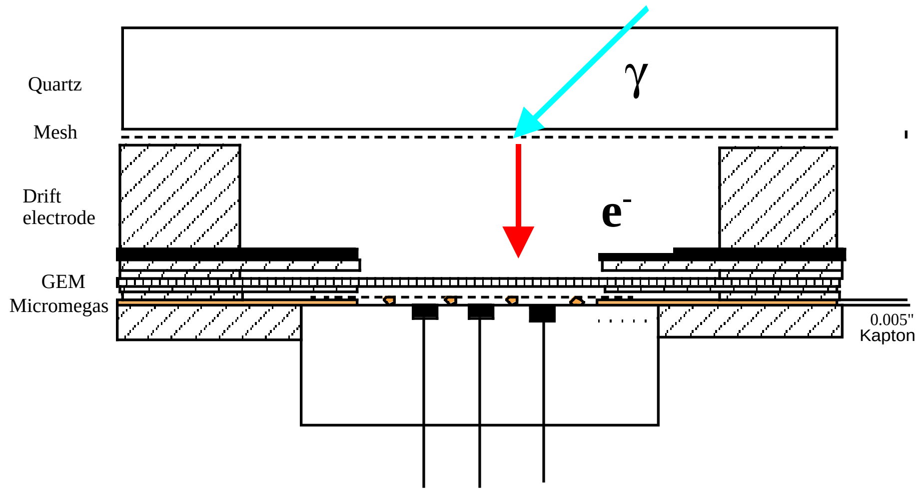
However, the maximum achieavable gain drops earlier, if we consider sparking as a limiting factor.

G. Charpak et al., Nucl. Instr. & Meth., A478 (2002) 26.



MICROMEGAS + single-GEM + Pads:

J. Va'vra, unpublished.

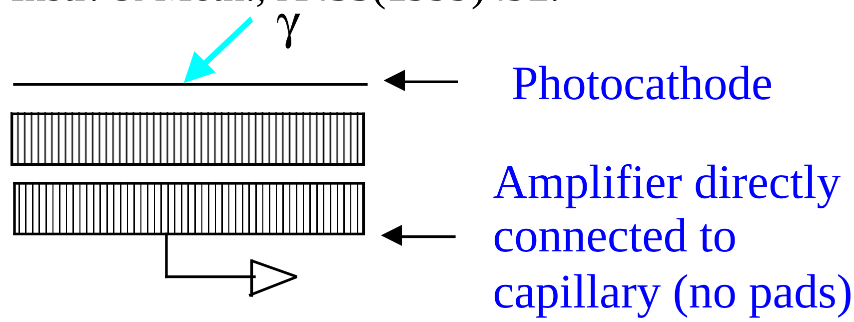


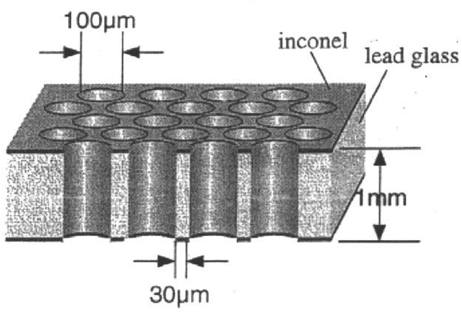
Photocathode	s.s. mesh
Carrier gas (1atm)	90%He+10%iC_4H_{10}
Pad size and pitch	1.25 mm dia. & 2.5 mm
GEM source	CERN (F. Sauli)
GEM-to-Mesh distance	1.24 mm
Kapton and copper hole diameters	40 & 80 μm dia.
GEM hole pitch	120 μm
GEM design	Conical hole
Mesh type	s.s. electro-mesh
Mesh thickness	3 μm
Mesh pitch	50 μm
Mesh-to-pad distance	100 μm
Amplifier gain (Elantec 2075C)	10x
Amplifier bandwidth	2GHz
Max. achieved charge gain on single electron	**$\sim 10^7$**

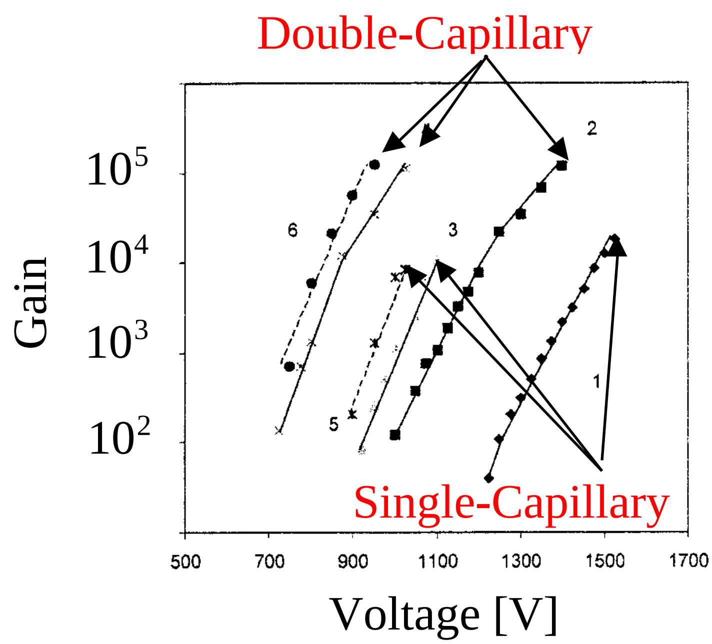
- A resistor chain used to avoid the damage of the GEM foil.
- A stable single electron operation at very large gain achieved. No tripping !!! The detector is quiet when triggering on itself.
- Too soon to claim anything. Needs much more study.

Double-Capillary (?):

V. Peskov et al, Nucl. Instr. & Meth., A433(1999)492.





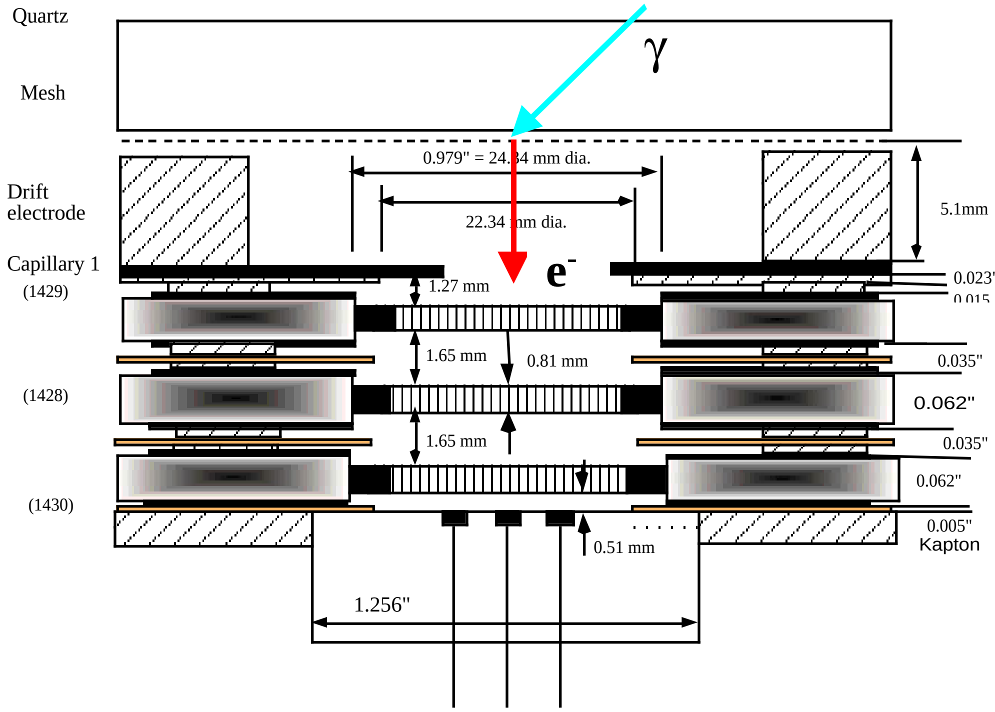


Photocathode	SbCs
Q.E. reached	A few %
Carrier gas (1atm)	95%Ar+5%CH_4
Lead Glass Capillary source	Hamamatsu
Capillary thickness	1 mm
Capillary hole diameter	100 μm dia.
Glass Capillary hole pitch	130 μm

- A gas gain of ~10^5 just about reached in 90%He+10%iC_4H_{10}.
- However, no convincing stable single electron mode operation proved at this point, i.e., not yet clear if this is a right avenue.

Tripple-Capillary + Pads:

J. Va'vra, T. Symioshi provided capillary plates made by Hamamatsu.



Photocathode	TMAE
Carrier gas (1atm)	C_2H_6
Lead Glass Capillary source	Hamamatsu
Measured capillary resistance	
Capillary thickness	1 mm
Capillary hole diameter	100 µm dia.
Glass Capillary hole pitch	130 µm
Max. achieved charge gain on single electron	**~10^4 (ethane)**

- Would barely support a gain of ~$2x10^4$ in C_2H_6.
- The reason for problems: capillary resistance too high, causing charging effects.
- V. Peskov: ~80% of microchannel plates fail his qualifying test.

Conclusions

- **HPD detectors have made a huge progress since the last RICH workshop.**

  - **The next challenge:** 100ps resolution.

- **The imaging with >10,000 PMTs has been a real success in DIRC.**

  - **The next challenge:** ~30,000 channels with σ~100ps.
  - Potential benefit: correction of the chromatic error.

- **Gaseous detectors are under pressure, but not dead yet for the RICH applications. From some reason, the ingenuity has no bounds here.**

  - **The next challenge:** operation in a high magnetic field with a Bialkali photo-cathode, and geometry "defined by us."

  My personal choice of amplifying structure:

  - The Triple or Quadruple-Gem structure + Pads.
  - Possibly, a Micromegas + Single-GEM + Pads, or Double-Cappilary + Pads.
    However, still needs much more study.