Lecture II:
SuperB Particle Identification systems - <u>Photodetectors</u>

J. Va'vra, SLAC

Content of these lectures

- **Lecture I: Basic Design Concepts**
  - Basic PID concepts: Cherenkov detectors, dE/dx, TOF
  - Photocathodes and Photon detection efficiency (PDE)
  - Photon propagation in dispersive media: transmission, chromaticity, internal reflection, etc.
  - DIRC-like detectors, 1-st DIRC-like detector: BaBar DIRC
- **Lecture II: Photon detectors**
  - MaPMTs, MCP-PMTs, GAPDs or SiPMTs, HAPDs, APDs
  - Timing performance, quantum efficiency
  - Aging, rate capability, effects of magnetic field
  - Readout schemes: pixels, strip lines, charge sharing
  - New ideas
- **Lecture III: Detector systems for SuperB and Belle 2**
  - Focusing DIRC (FDIRC) concept,
  - TOP counters
  - Aerogel RICH,
  - TOF detectors
  - Comparison of various methods.

Conditions at SuperB and Belle 2

$$L \sim 10^{36}\ cm^{-2}\ sec^{-1}$$

Total neutron doses: ~10^{12} /cm^2

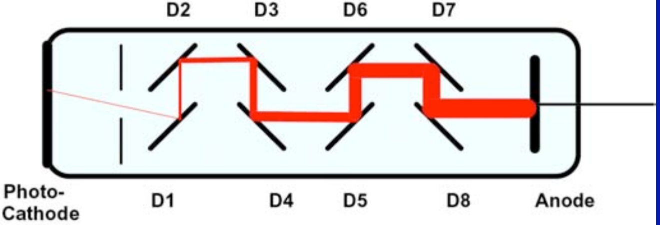
Total Gamma doses : ~$5x10^{11}$ /cm^2

Total charged particle doses : ~$5x10^{11}$ /cm^2

Bhabha rate in forward region: ~2 kHz/cm^2

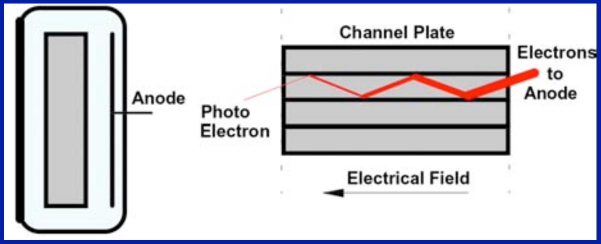
Photon detectors capable of detecting single photons

Conventional PMT:



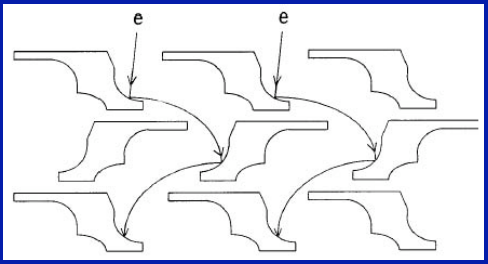
G ~ 10^7

Microchannel PMT:



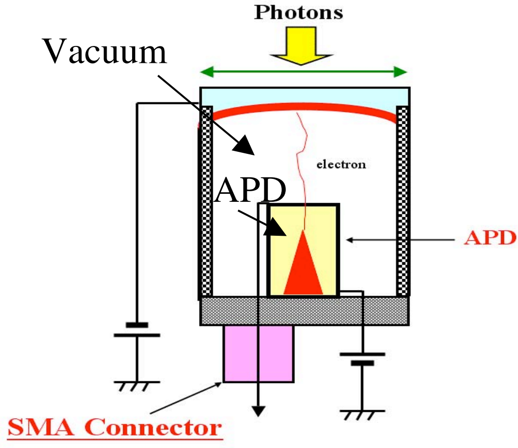
G ~ $5x10^5$

MaPMT:



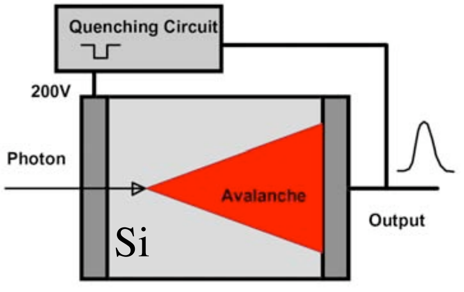
G ~ 10^6

HAPD:



G ~ $2x10^5$

Geiger mode APD = G-APD:



G ~ $2x10^6$

Also called SPAD

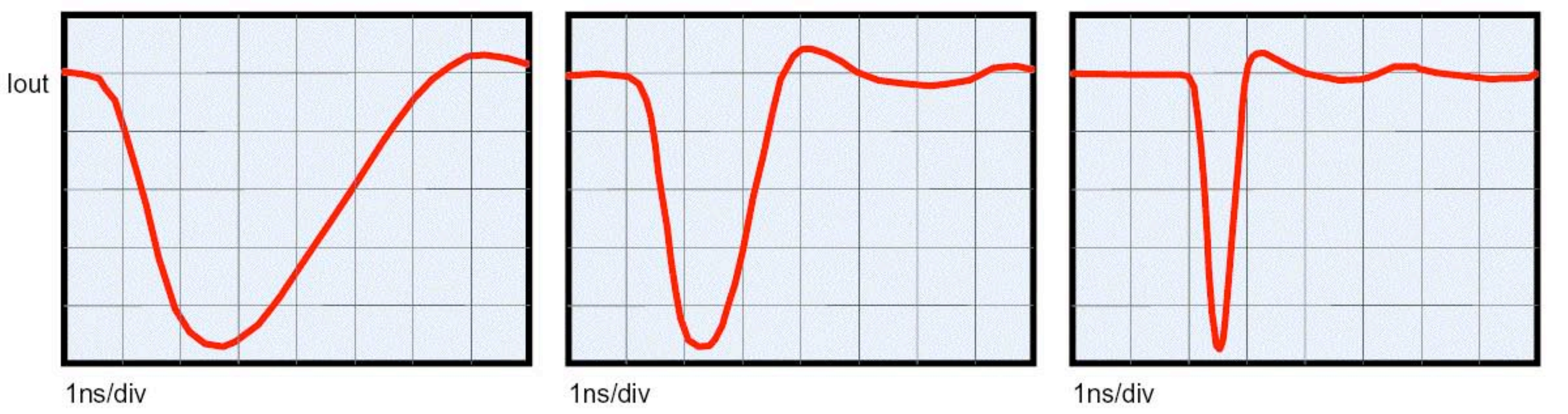
(single photon Avalanche Diode)

SiPMT = array of G-APDs

- **A crucial characteristics for good timing is the Transit Time Spread (TTS), defined only for the single photoelectrons.**
- Other crucial parameters are aging, rate capability, magnetic field sensitivity, etc.

Relative comparison of pulses

Standard PMT: **MaPMT:** **MCP-PMT:**



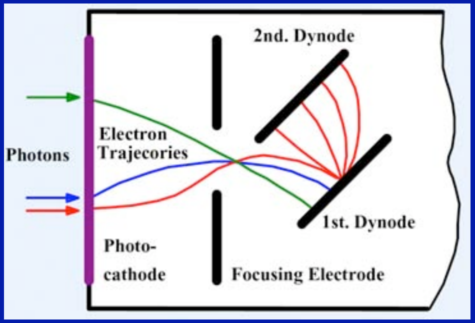
PMT	Gain	Pulse FWHM	$I_{Single\ el.\ pulse}$	$V_{Single\ el.\ pulse}(50\Omega)$
Standard	$\sim 10^7$	~ 3.5 ns	~ 460 µA	~ 175 mV
MaPMT	$\sim 10^6$	~ 1.5 ns	~ 100 µA	~ 75 mV
MCP-PMT	$\sim 10^5$	~ 400 ps	~ 40 µA	~20 mV

$I_{single\ el.\ pule}$ ~ Gain x electron/FWHM(pulse width), $V_{single\ el.\ pule}$ ~ $I_{single\ el.\ pule}$ x 50 Ω

- **PMT has a sufficient gain and usually does not need an amplifier.**
- **MCP-PMT has lower gain, very narrow pulses, needs a fast amplifier.**
- **MaPMT has higher gain, it is slower, and needs also an amplifier.**

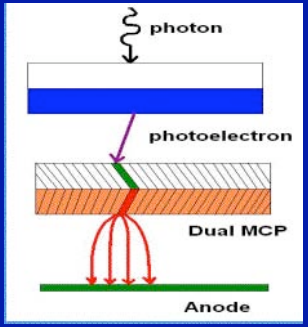
Single electron transit time spread - TTS

Standard PMT:



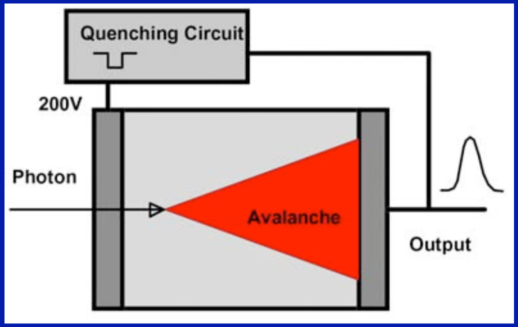
σ_{TTS}(best) ~ 150 ps

MCP-PMT:



σ_{TTS}(best) ~ 11 ps

Single G-APD (=SPAD):



σ_{TTS}(best) ~ 17 ps

Contributions to TTS:

Standard PMT & MCP-PMT:

- Emission at the photocathode = f(λ).
- Cathode-to-dynode transit (or 1-st MCP)
- Multiplication process.
- Emission at MCP exit towards anode.
- Light source jitter
  (usually one is trying to subtract this)
- Timing jitter of subsequent electronics
  (usually one is trying to subtract this)

G-APD:

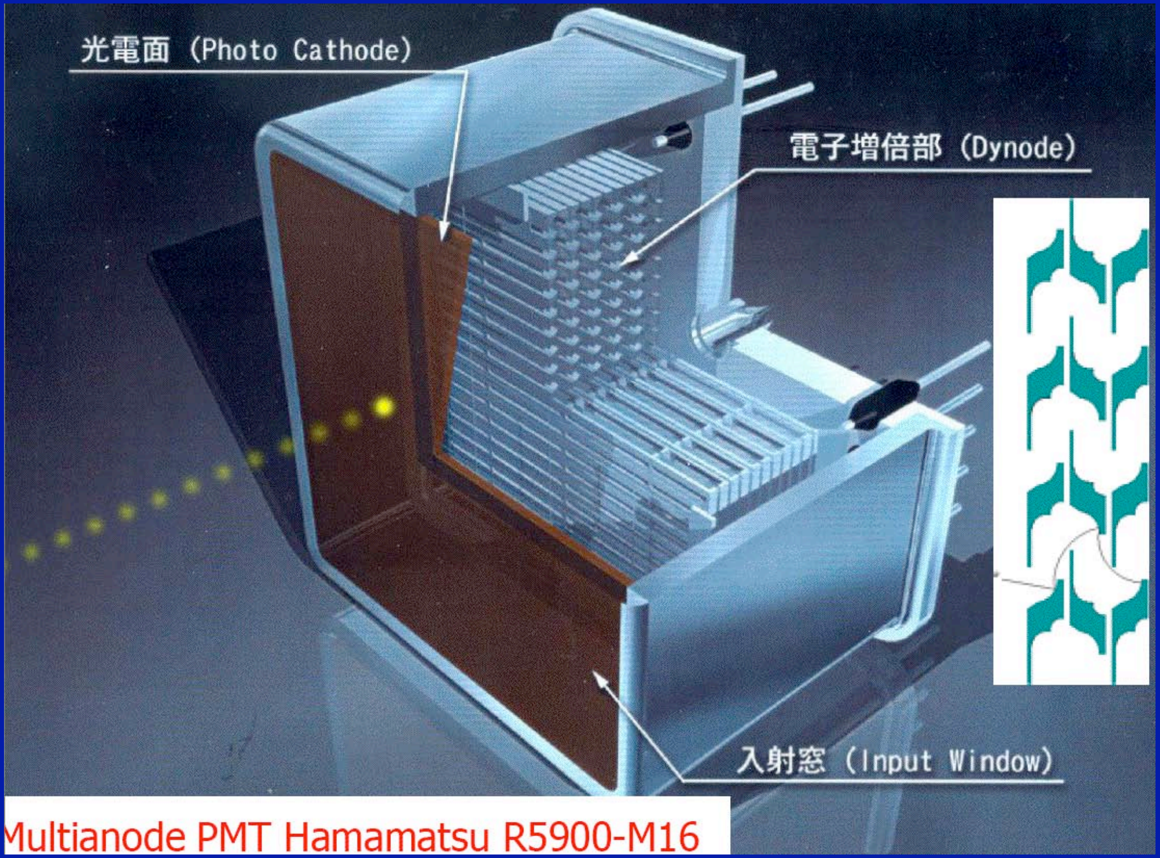
- Different depth of photon conversion = f(λ).
- Multiplication process.
- Sensitivity to passive quenching circuit.
- Light source jitter
  (usually one is trying to subtract this)
- Timing jitter of subsequent electronics
  (usually one is trying to subtract this)

Multi-anode PMTs (MaPMTs)

- Gain
- Timing properties
- Magnetic field sensitivity
- Aging

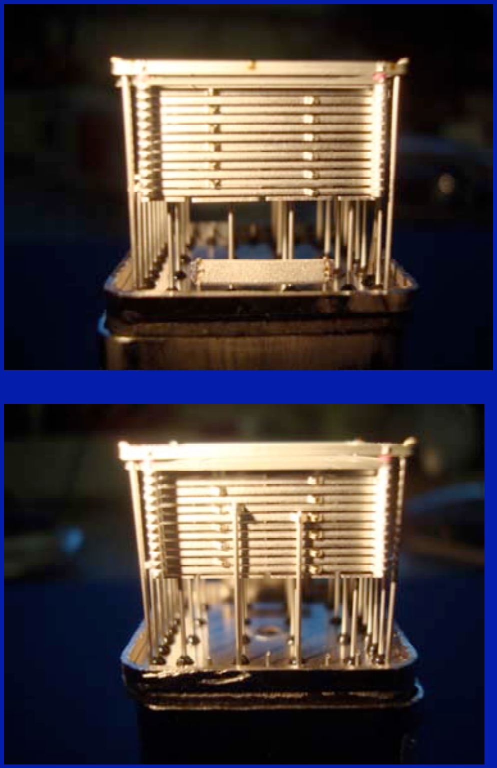
Multi-anode PMT (MaPMT)

Hamamatsu Co.



Multianode PMT Hamamatsu R5900-M16

R5900-M16



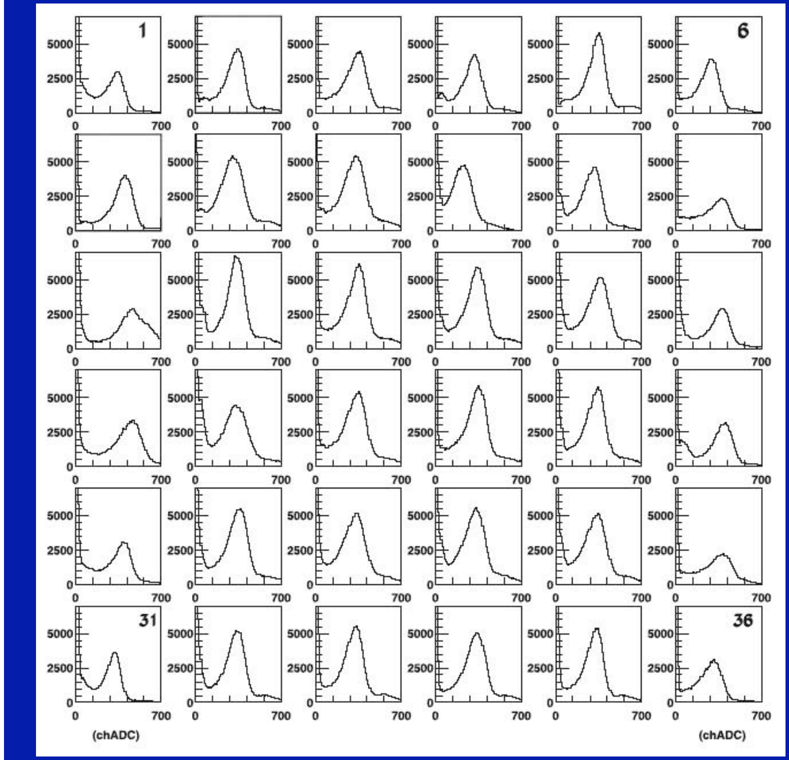
- **This particular tube was used very successfully in the HERA-B experiment, and proved to operate reliably at very high rates.**

R8900 MaPMT: Single pe response, DE and CE

(similar to R5900)

Y.Kawasaki et al., Nucl. Instr. & Meth., A564(2006)378

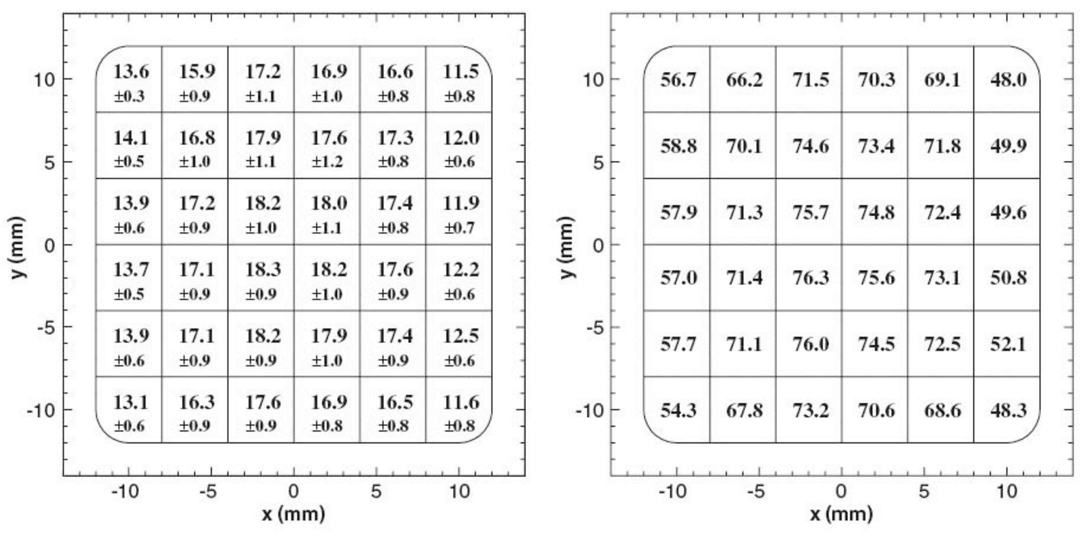
Single pe spectra at a gain of 5x10^6:



Detection efficiency (PDE) and collection efficiency (CE):

PDE:

CE:



PDE:

13.6 ±0.3	15.9 ±0.9	17.2 ±1.1	16.9 ±1.0	16.6 ±0.8	11.5 ±0.8
14.1 ±0.5	16.8 ±1.0	17.9 ±1.1	17.6 ±1.2	17.3 ±0.8	12.0 ±0.6
13.9 ±0.6	17.2 ±0.9	18.2 ±1.0	18.0 ±1.1	17.4 ±0.8	11.9 ±0.7
13.7 ±0.5	17.1 ±0.9	18.3 ±0.9	18.2 ±1.0	17.6 ±0.9	12.2 ±0.6
13.9 ±0.6	17.1 ±0.9	18.2 ±0.9	17.9 ±1.0	17.4 ±0.9	12.5 ±0.6
13.1 ±0.6	16.3 ±0.9	17.6 ±0.9	16.9 ±0.8	16.5 ±0.8	11.6 ±0.8

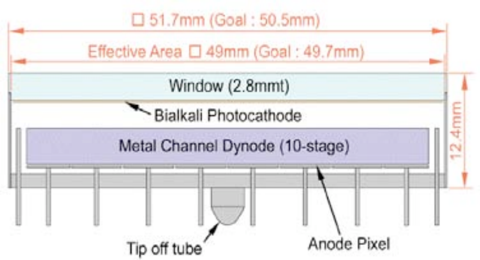
CE:

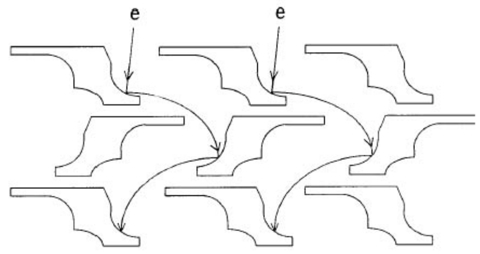
56.7	66.2	71.5	70.3	69.1	48.0
58.8	70.1	74.6	73.4	71.8	49.9
57.9	71.3	75.7	74.8	72.4	49.6
57.0	71.4	76.3	75.6	73.1	50.8
57.7	71.1	76.0	74.5	72.5	52.1
54.3	67.8	73.2	70.6	68.6	48.3

- **PDE = QE * CE, where PDE is detection efficiency, QE is quantum efficiency and CE is collection efficiency**

Hamamatsu H-8500 & H9500 Flat panel MaPMTs

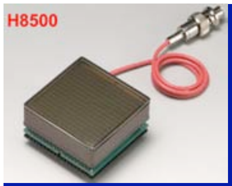
Based on Hamamatsu data





Parameter	Value
Photocathode: Bi-alkali QE at 420nm	20 %*
Geometrical collection efficiency CE of the 1-st dynode	75%*
Geometrical packing efficiency (dead space around boundary)	89%
PDE = Total fraction of “in time” photoelectrons detected	~ 13%*
Photocathode uniformity	1:1.5 to 1:2.5
Number of dynodes	12
Total average gain @ -1kV	$\sim 10^6$
Fraction of photoelectrons arriving “in time”	~95%
σ_{TTS} - single electron transit time spread	~ 140-150 ps
Matrix of pixels (H8500 & H9500)	8 x 8 & 16 x 16
Number of pixels (H8500 & H9500)	64 & 256
Pixel size (H8500 & H9500)	5.8 x 5.8 & 2.9 x 2.9 $[mm^2]$

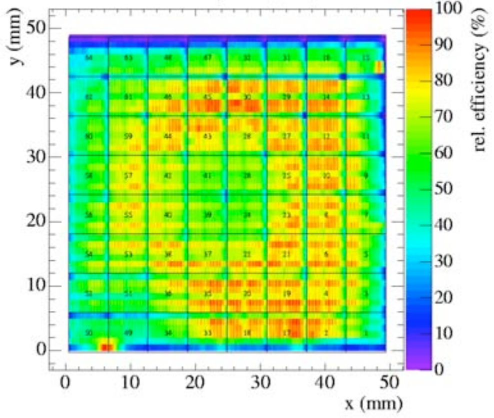
* - now available with a Super QE and better collection efficiency



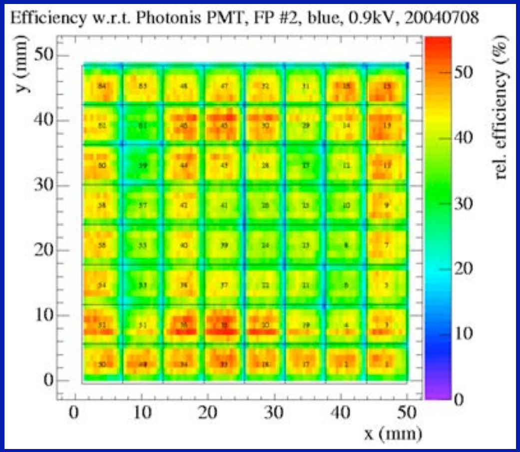
Single pe response of H-8500 MaPMT

C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va'vra,
Nucl.Instr. & Meth., A553(2005)96-106

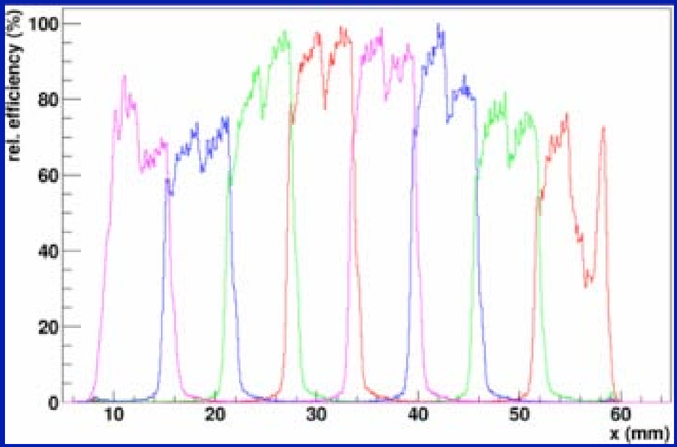
Single pe scan at 635nm:



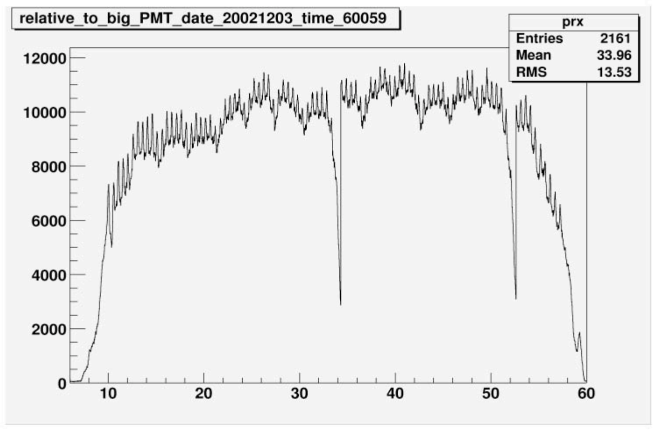
Single pe scan at 407nm:



Projection:



Micro-structure of the dynode electrodes:



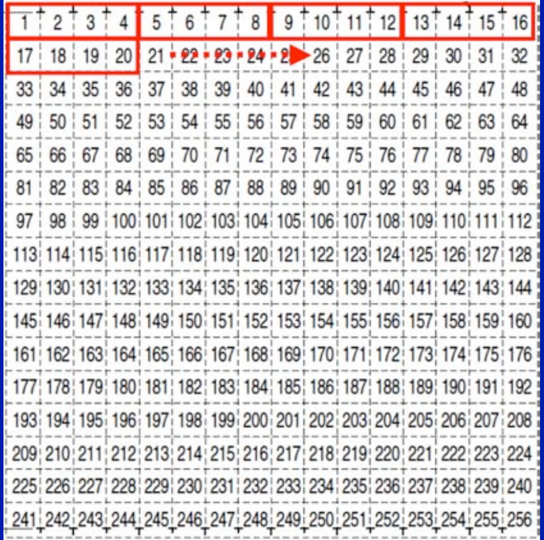
- **To get into the single pe sensitivity one runs a gain of 10^6 with a 40x amplifier.**
- **H-8500 MaPMT uniformity in single photoelectron sensitivity is between ~1:1.5 and ~1:2.5.**
- **Its relative efficiency is 50-70% of the Photonis Quntacon XP 2262B PMT at 407nm. The efficiency drops to 30-50% around the edges.**
- **If one wants to build a large system one will have to make a scan of each detector, and build a data base.**

Single pe response of H-9500 MaPMT

J. Va'vra et al., SLAC-PUB-12236, 2007

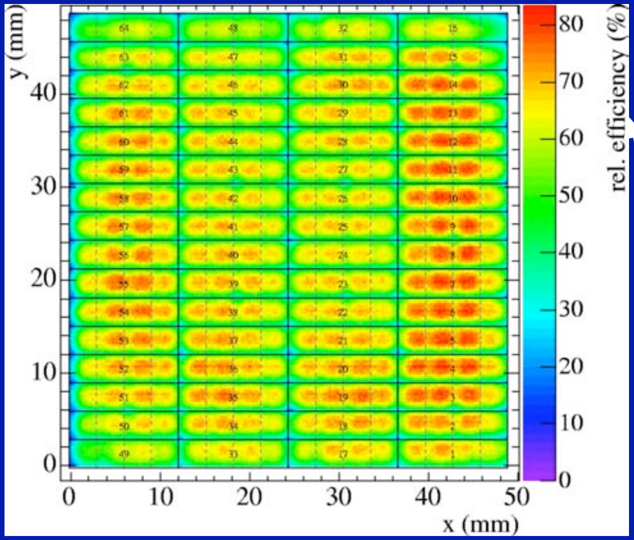
H-9500
has
256 pixels:

Short groups of four pixels:



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176
177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192
193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208
209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224
225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240
241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256

Single-pe scan at 407nm:



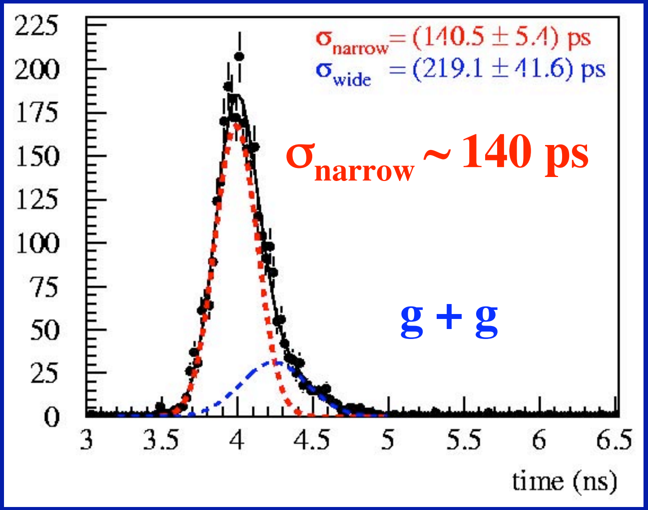
(Measured with a 407 nm PiLas laser)

- Small pixels of H-9500 allow to create special pixel sizes.
- For example, we want 3 mm x 12 mm for FDIRC at SuperB.
- The relative efficiency, normalized to Photonis XP 2262B PMT, is 50-70%.
- Not available with super QE at present.

Single electron timing response

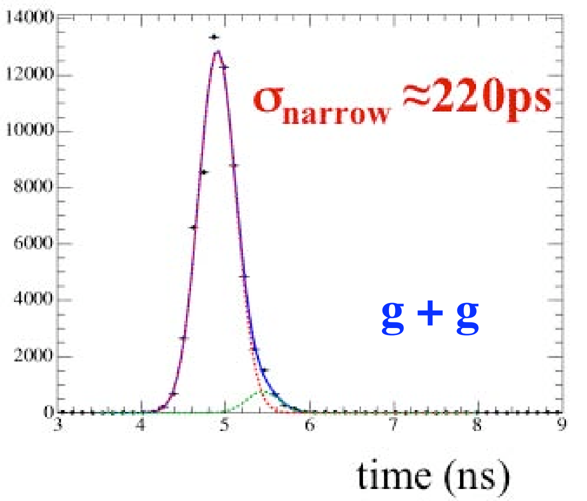
J. Va'vra et al., SLAC-PUB-12236, 2007

H-8500 TTS distribution:



(Measured with a 635 nm PiLas laser)

H-9500 TTS distribution:



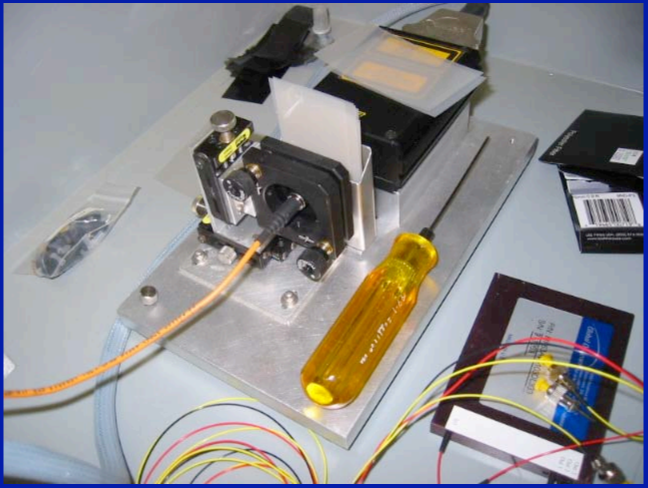
(Measured with a 407 nm PiLas laser)

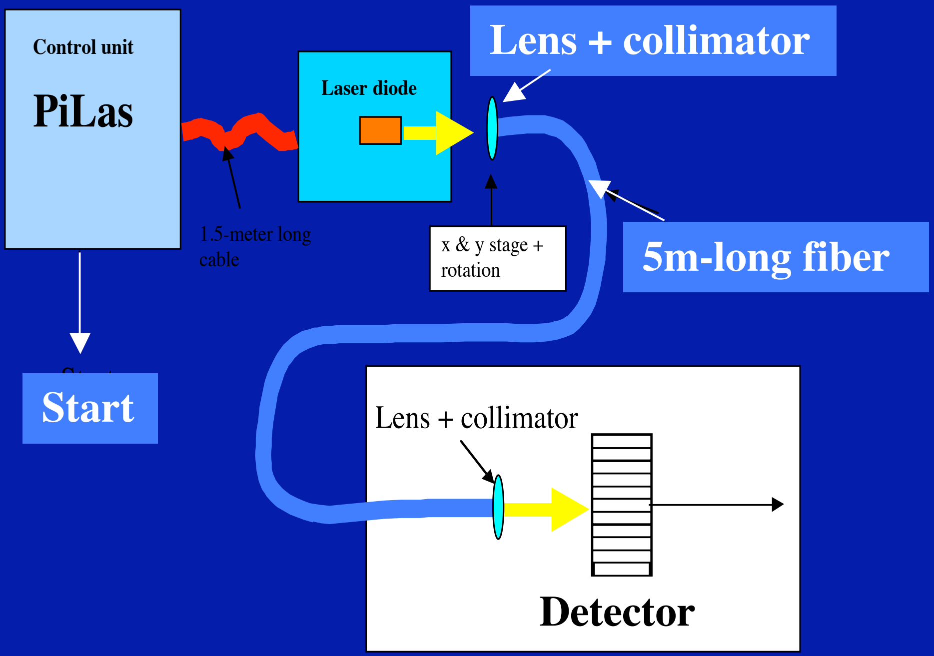
- **H-8500 has a slightly better TTS resolution than H-9500.**
- **MaPMTs have smaller timing tail compared to MCP-PMTs.**
- **This resolution is good enough to do the chromatic corrections, but not good enough to do a TOF detector.**

Example of a TTS measurement

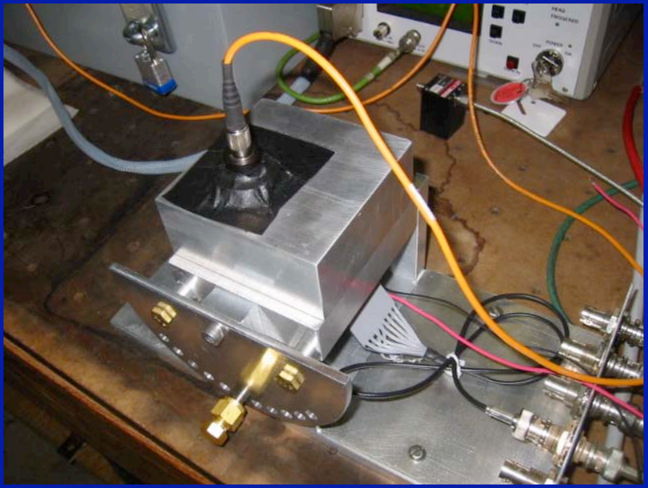
J.Va'vra, log book

PiLas laser head:



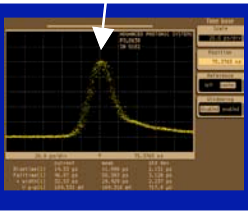


Calibration of a fast detector:



Parameter	SLAC tests
Laser diode source	PiLas
Wavelength	**635 nm**
TTS light spread (FWHM)	**~ 30 ps**
Fiber size	62.5 μm

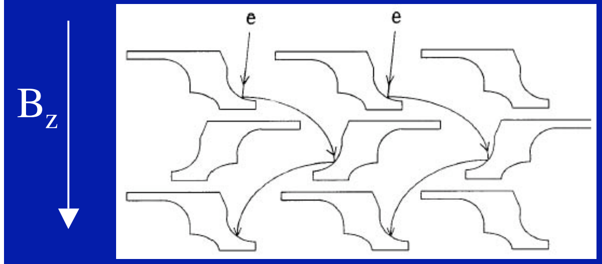
Ultra-fast Si Detector:
(can use also a Streak camera)



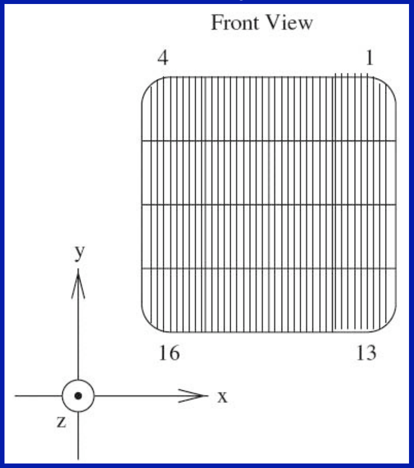
MaPMT in magnetic field

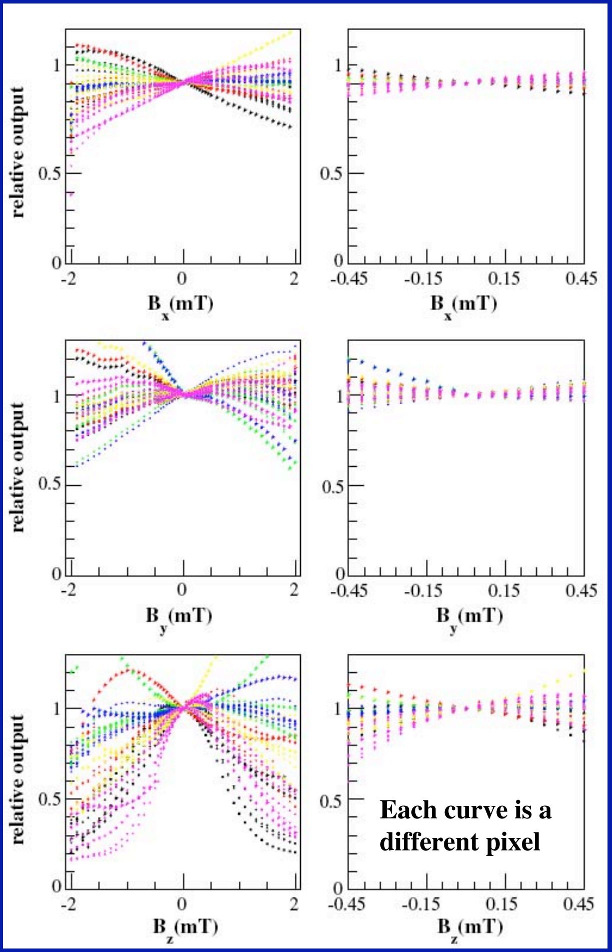
Y.Kawasaki et al., Nucl. Instr. & Meth., A564(2006)378, and Hamamatsu data

R8900 MaPMT:



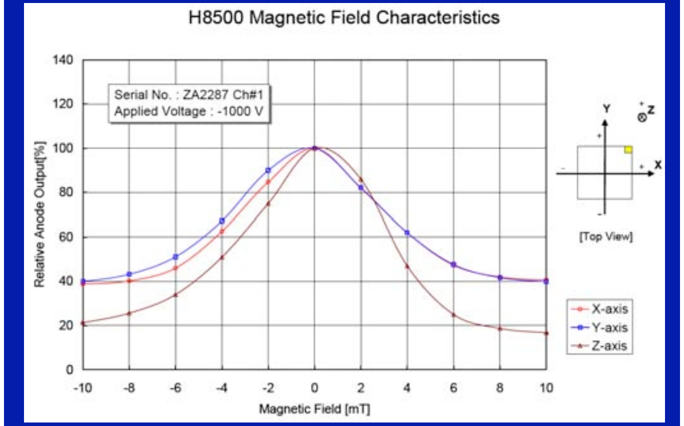
Coordinate system:





Each curve is a different pixel

H-8500 MaPMT:



- **H-8500: No pixel shows a variation higher than 10% for $|B_{x,y,z}| < 100$ Gauss.**
- **H-8500 is a bit more sensitive than R8900 MaPMT.**
- **DIRC PMT, for comparison, is sensitive to already 2-3 Gauss !!!**

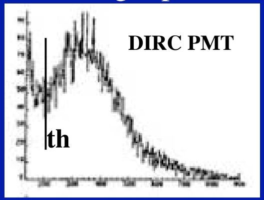
What is expected MaPMT aging rate ?

One expects that it is similar to the aging rate of normal PMTs.

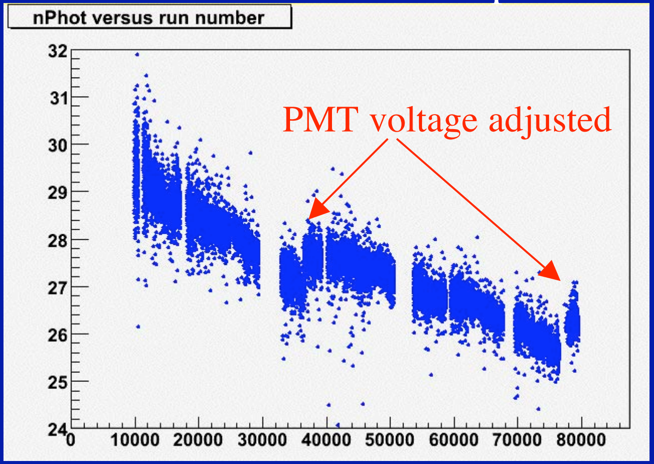
(a) QE aging rate, so called cathode aging.

(b) Dynode aging, which affects the gain.

Single pe's:



BaBar DIRC: rate of lost of photons:



Several effects involved in this curve:

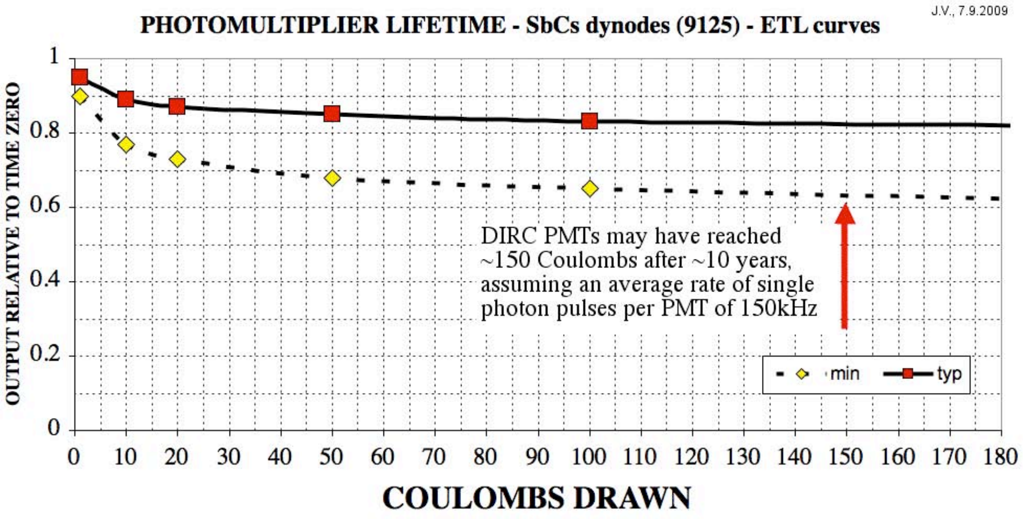
(a) PMT glass corrosion in water

(b) Cathode aging

(c) Dynode aging - probably dominant factor

(d) Glue yellowing

Expected gain loss - Electron Tube Ltd. (ETL) data.



DIRC PMTs may have reached ~150 Coulombs after ~10 years, assuming an average rate of single photon pulses per PMT of 150kHz

DIRC PMT: EMI 9125FLB17, 1" dia.

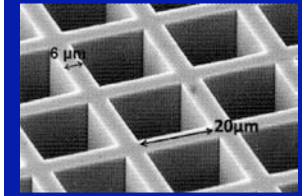
- **MaPMTs are expected to have a similar loss of photons as a normal PMT.**
- **DIRC PMT dynode structure may have lost this fraction of the total gain: ~20-40% loss after ~150 Coulombs of charge.**

Micro-channel PMTs (MCP-PMTs)

- Gain
- Timing properties
- Magnetic field sensitivity
- Aging

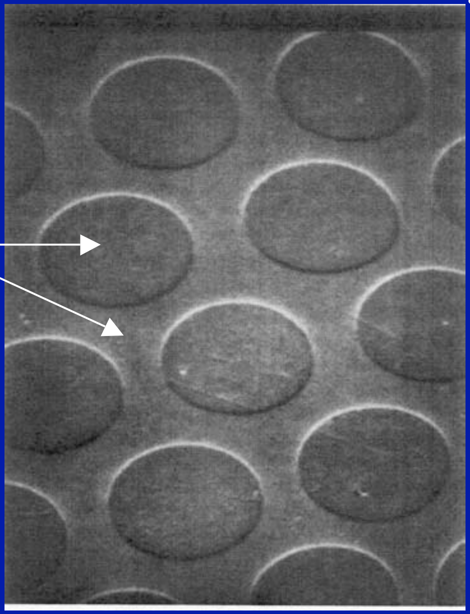
MCP structure

J. L. Wiza, Nucl. Instr. & Meth. 162(1979)587-601



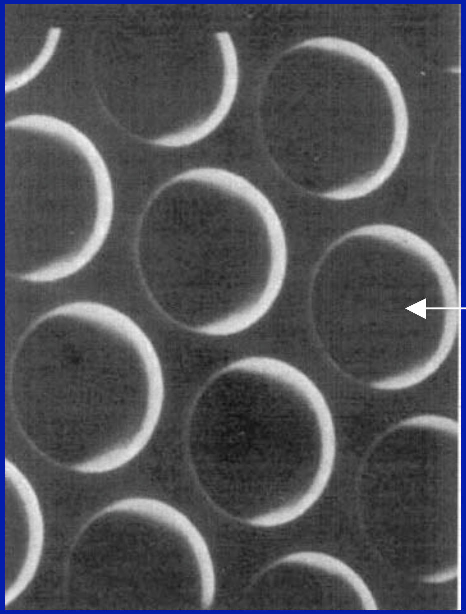
Square holes for Imaging (Photonis)

Glass matrix before etching:

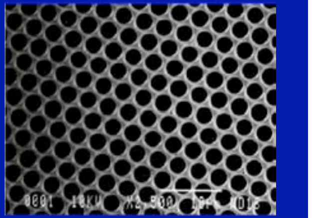


Two types of glass

Glass with holes after etching:



Core is etched away

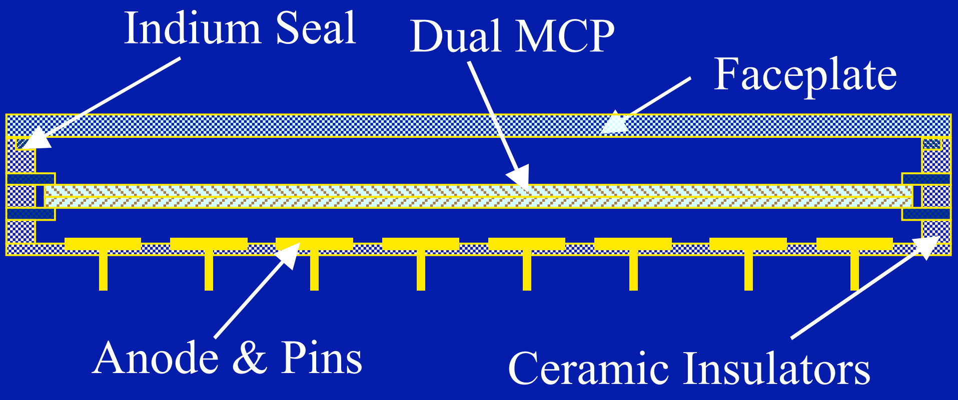


Smallest MCP hole ever: 2µm hole dia. (Photonis)

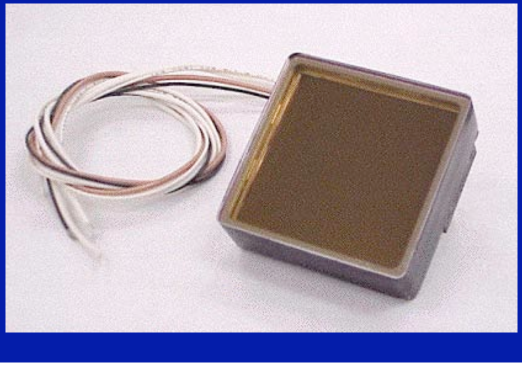
- **Present manufacturers of MCP use <u>lead glass</u> to manufacture the MCP plates. It gives sufficiently low resistivity to prevent charging, but high enough resistivity to pervent overheating. For example, a pure quartz without any coating would not work because of charging.**
- **A word MCP has two enemies of high vacuum: <u>micro & channel</u>,which complicates building of these types of detectors for small pore size.**

Photonis MCP-PMT with 10 μm holes

Photonis information with SLAC TTS data (J.V.)



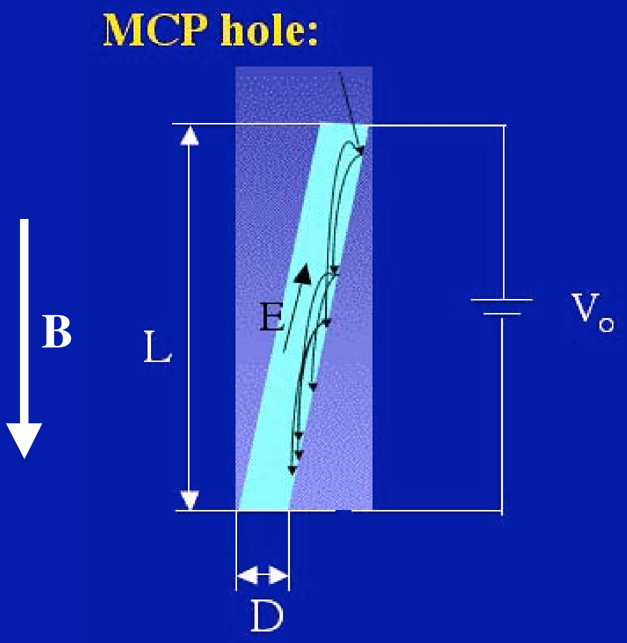
Photonis Planacon:



Parameter	Value
Photocathode: Bi-alkali QE at 420nm	22 %
Geometrical collection efficiency CE of the 1-st MCP (in-time photoelectrons)	70 %
Geometrical overall packing efficiency (dead space around boundary)	85 %
PDE = Total fraction of "in time" photons detected	~ 13 % @ 420 nm
Photocathode uniformity	1:1.5
Number of MCPs	2
Total average gain @ -2.4kV & B = 0 kG	~ 5 x 10^5
MCP hole diameter & hole angle & MCP thickness & L/D	10 μm & 8^o & ~ 600 μm & 60:1
σ_{TTS} - single electron transit time spread (for 10 μm dia. pores)	~ 30 ps
Photocathode-MCP gap & MCP-Anode gap & MCP -MCP gap	~ 6 mm & ~ 5 mm & 0 mm
Number of pixels & Pixel size	64 & (5.94 mm x 5.94 mm)

Amplification in MCP hole

J. Adams and B.W. Manley, IEEE Trans.Nucl.Sci.Instr. NS-13(1966)88, and & A. Frazer, Univ. of Leicester (wrote many papers), J. L. Wiza, Nucl. Instr. & Meth. 162(1979)587-601, and M. Akatsu et al., Nucl. Instr .& Meth. A528(2004)763-775



For typical lead glass used in the present MCPs, the electric field is close to be aligned along the hole axis

- **Gain at B = 0:**

  $G_n = \delta^n = (KV_o/\kappa)^\kappa$

  $\kappa = 4\ V\ \alpha^2/V_o$

- δ secondary emission rate (typ. 2-3)
- $G_1 = \delta$ for one strike, $G_2 = \delta^2$ for two,…
- $G_n = \delta^n$ for n strikes
- **To get a gain of 10^6, one needs n ~ 15**
- V_o is the total channel voltage
- $\alpha = L/D$, or length to diameter ratio
- $\delta = KV_c$, where K is a constant and $E_c = eV_c$ is a collision energy: $V_c = V_o/\kappa$
- E = eV is the initial kinetic electron energy emitted from the MCP wall (typ. ~ 1 eV)

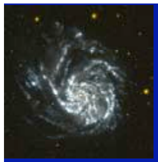
- **Gain at B ≠ 0:**

  $G_n = \delta^n = (KV_o/\kappa)^{\kappa\ \cos\text{^}2\ \phi}$

  $\kappa = (e/2m_e)\ (L^2/V_o)\ (B/\theta)^2$

  $\cos\theta = \rho / \sqrt{}\ [\rho^2+(D/2)^2]$

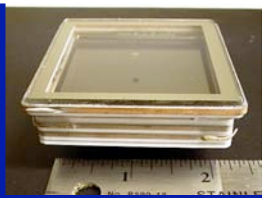
- ρ electron Larmor radius
- φ tilt angle between E and B
- θ electron turn angle



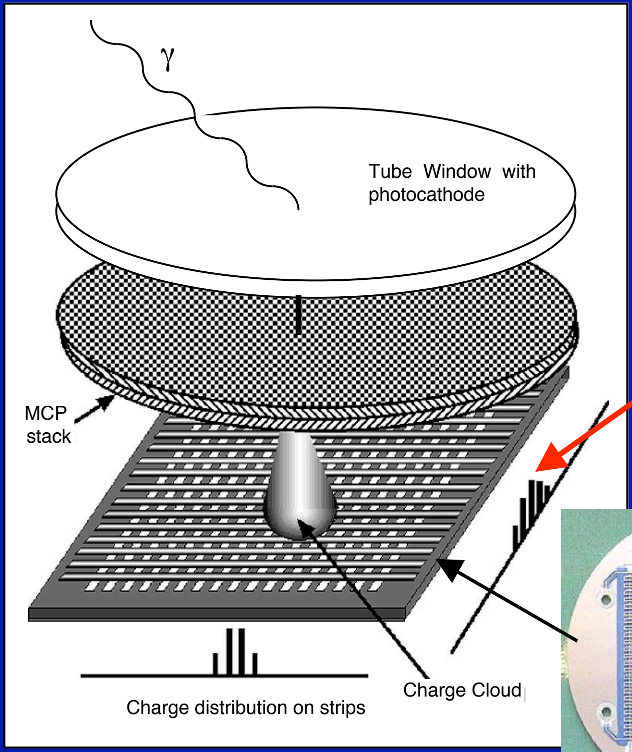
GALEX satellite

MCP-PMT detector

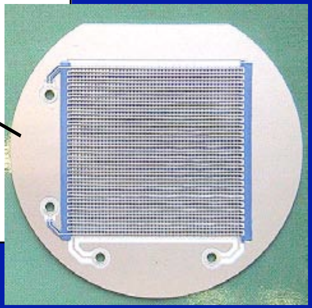
O. Siegmund, Space Science Lab, Berkeley, CA



1-st Planacon

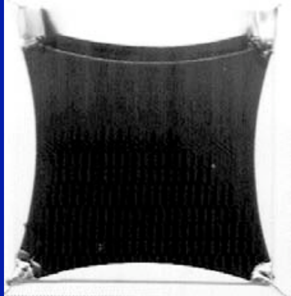


Cross-strip line readout

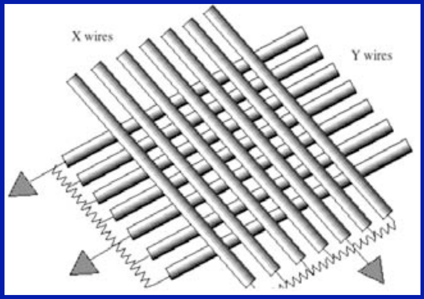


~ 30 µm resolution

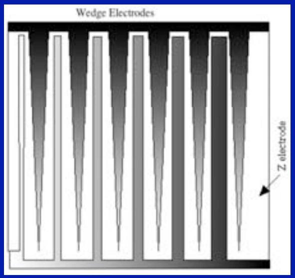
Charge division:



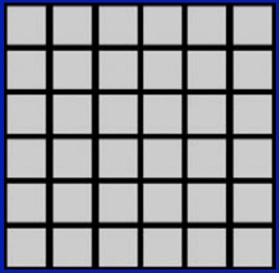
Wires with resistive division:



Wedge strips:



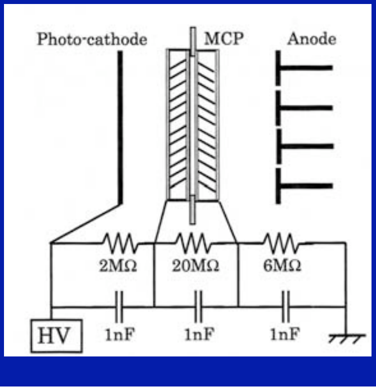
Pads:

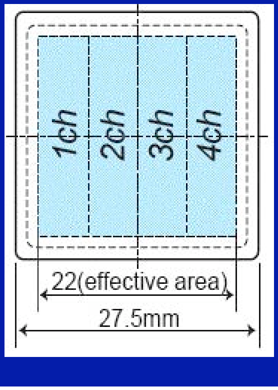


- Typically, two micro-channel plates.
- Anode plane to localize the charge: (a) pads, (b) strip lines, (c) wedge strips, (d) charge division, etc. For high rate applications one needs a pad readout.

Hamamatsu SL-10 MCP-PMT with 10 μm holes

Hamamatsu with some Nagoya University data (Inami)





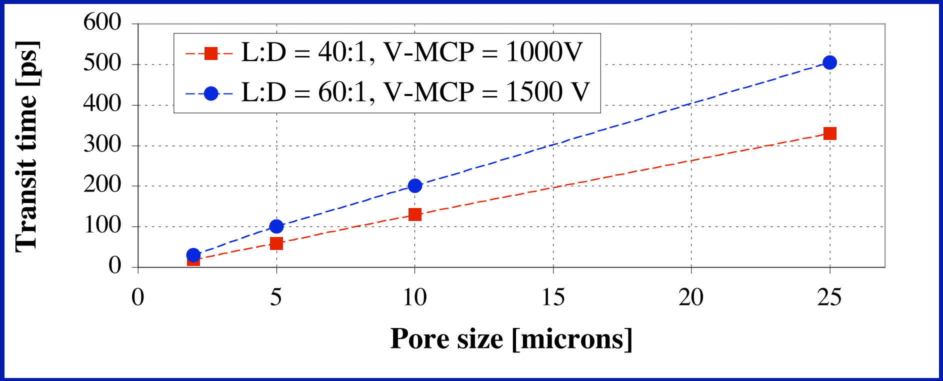
SL-10:

Parameter	Value
Photocathode: Multi-alkali QE at 350nm	20 %
Geometrical collection efficiency CE of the 1-st MCP (in-time photoelectrons)	70 %
Geometrical packing efficiency (dead space around boundary)	65 %
PDE = Total fraction of "in time" photons detected	~9% @ 350 nm
Photocathode uniformity	1:1.5
Number of MCPs	2
Total average gain @ -3.5kV & B = 0 kG	~2 x 10^6
MCP hole diameter & hole angle & MCP thickness & L/D	10 μm & 13° & 800 μm & 80:1
σ_{TTS} - single electron transit time spread (for 10 μm dia. pores)	~30 ps
Photocathode-MCP gap & MCP-Anode gap & MCP-MCP gap	2 mm & 1 mm & ? 0.03 mm
Number of pixels & Pixel size	4 & (22 mm x 5.3 mm)

Rise time = f(MCP pore size)

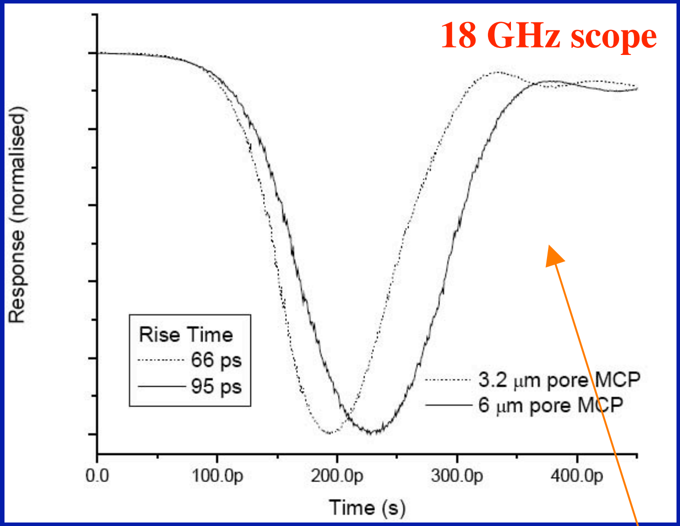
Photek Ltd. & Burle/Photonis information

Transit time in a MCP hole (from Burle):



Smaller pore size, smaller the transit time.

Rise time =f(pore size) in MCP (Photek):



Smaller MCP pore size, faster rise time.

Note:

If you want to see a rise time of MCP detector you better have a fast scope

Rise time (ps) = 350/BW (GHz) => 18 GHz scope has Rise time (scope) ~ 19ps

(Cost to buy of ~20 GHz scope: ~$140k. Cost to rent: ~$5k/month).

Typically, rise times shown in this lecture are limited by a scope, except a few exceptions like this.

Burle/Photonis MCP-PMT TTS measurement

J.Va'vra, MCP log book #3, pages 27-40

MCP-PMT 85012-501:

- **10 μm MCP hole diameter**
- **High gain:** 2.8 kV, B = 0 kG, **to get the best σ_{TTS}**
- **PiLas red laser diode operating in the single photoelectron mode (635 nm):**

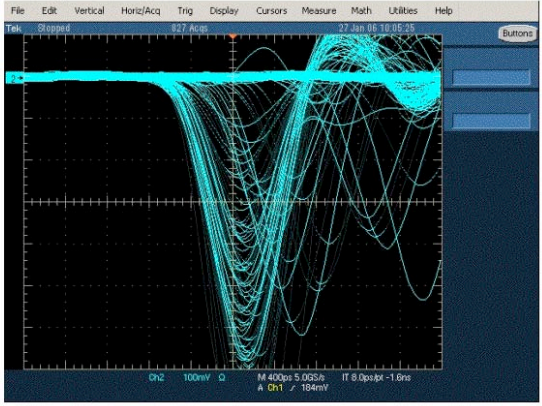
$$\sigma_{TTS} < \sqrt{(32^2 - 13^2 - 11^2)} = 27 \text{ ps}$$

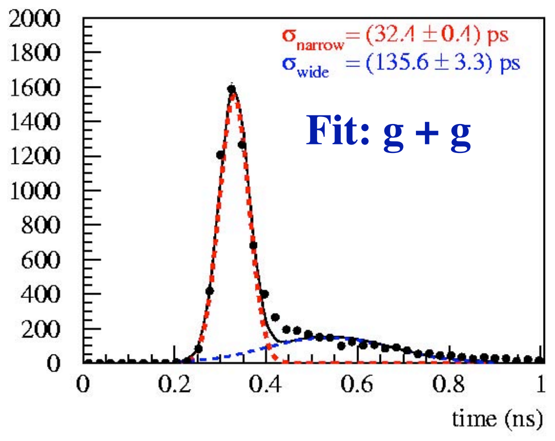
PiLas laser diode Electronics

a) Fast amplifier + CFD/TAC:

Hamamatsu C5594-44 amplifier

1.5 GHz BW amp (63x gain), 1GHz BW scope

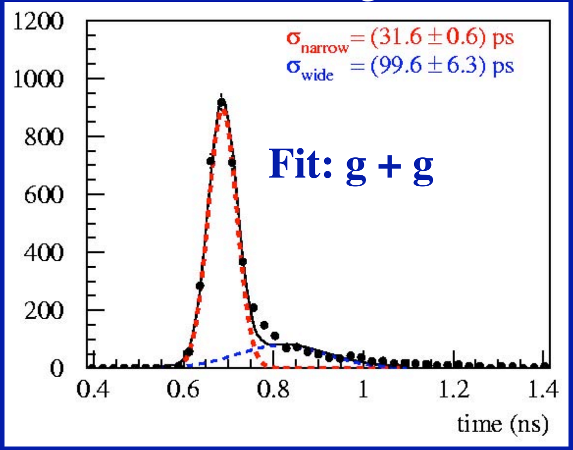




b) Slow amplifier + CFD/TAC:

Ortec VT120A amplifier

~0.4 GHz BW, 200x gain + 6dB



Hamamatsu R3809U-50 MCP-PMT TTS measurement

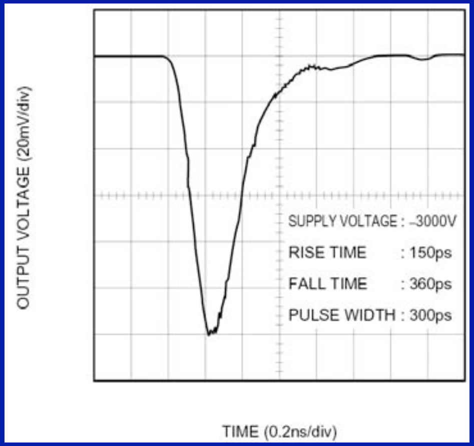
Hamamatsu data sheets

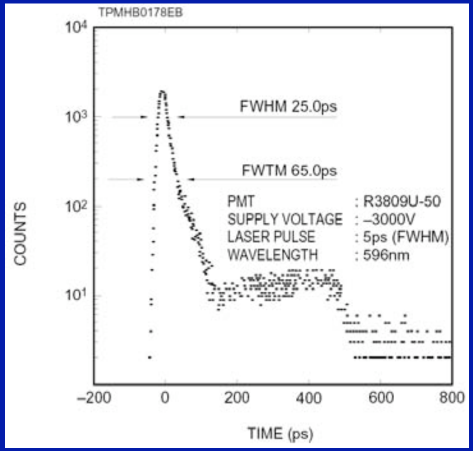
MCP-PMT R3809U-50:

- **6 μm MCP hole diameter**
- Useful photocathode dia.: 11 mm
- Rise time: **~150 ps**.
- Single pixel device.
- MCP-to-anode capacitance: **~3pF**
- **σ_{TTS} ~ 11 ps** ← **! ! !**
- Nd-YAG laser light source jitter: ~ 5 ps (FWHM)
- Red wavelength: 596 nm

Hamamatsu C5594-44 amplifier

1.5 GHz BW, 63x gain



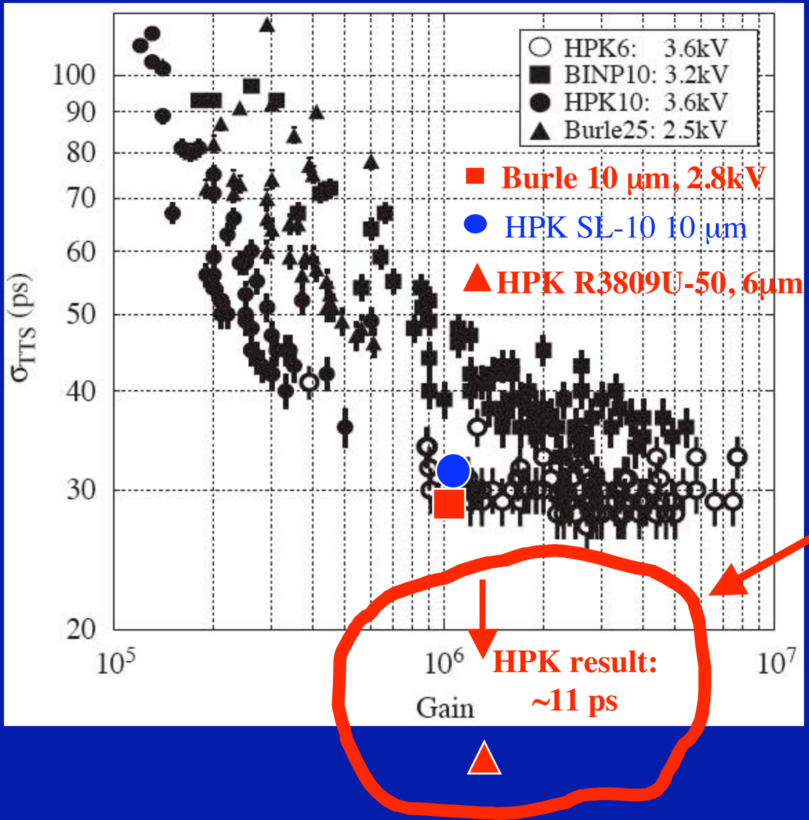


The best TTS measurement result I know about.

TTS distribution = f(gain)

M. Akatsu et al., Nucl.Instr .& Meth. A528(2004)763-775, and J. Va'vra, MCP-PMT log book #3, page 27,
K. Inami et al., Nucl.Instr .& Meth, A592(2008)247-253, and Hamamatsu data sheets

B = 0 kG



HPK result:
~11 ps

Point is way down there
(see the scale)

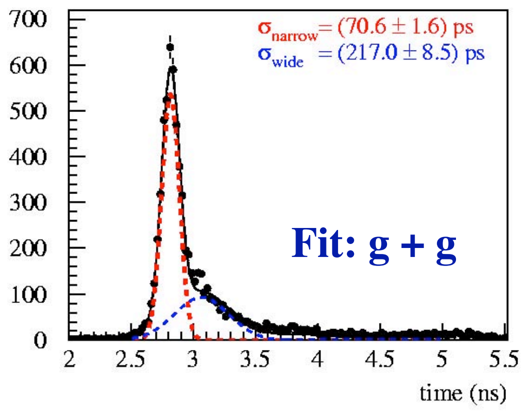
- **To get σ_{TTS} ~ 30 - 40ps, one needs a gain of ≥10^6.**

Factors influencing PDE: tail and dead space

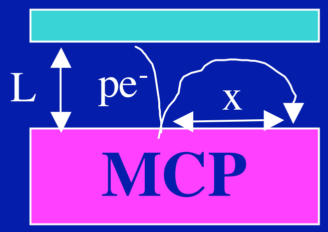
C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va'vra, **SLAC**
RICH 2004, Cancun, Mexico, Nucl.Instr. & Meth., A553(2005)96-106

MCP-to-Cathode distance ~ 6 mm

Burle 85011-501 Nominal design:

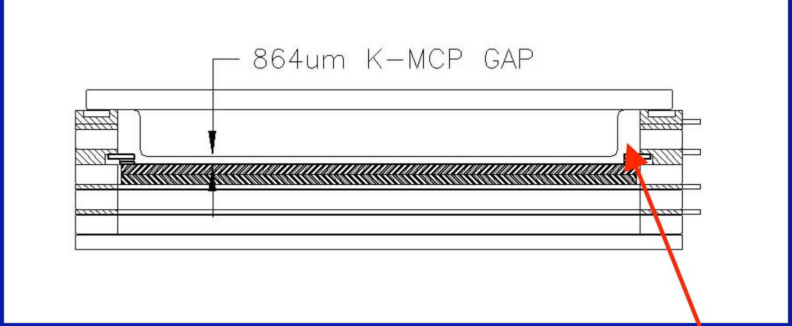


L should be small:

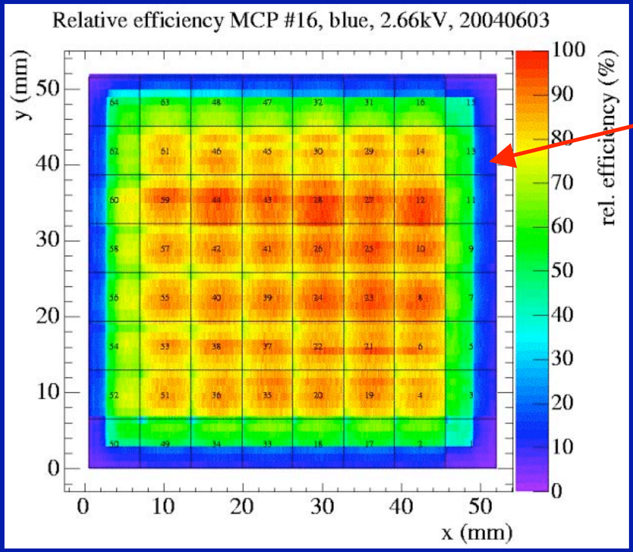


x ≤ 2 L

So called "stepped face" MCP-PMT

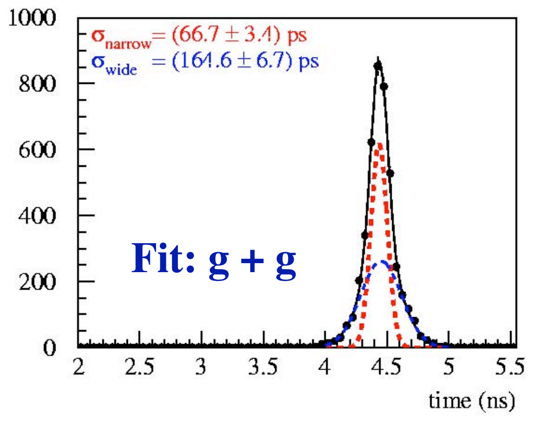


Penalty of this design:
the efficiency drops to zero near edges.



MCP-to-Cathode distance ~0.85 mm

Burle 85011 430 Drop Faceplate design:

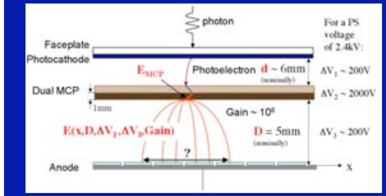


Charge sharing range - compare H-8500 MaPMT and Photonis MCP-PMT

J.Va'vra, Scanning setup log book, page 49, 2003, J. Schwiening analysis of data

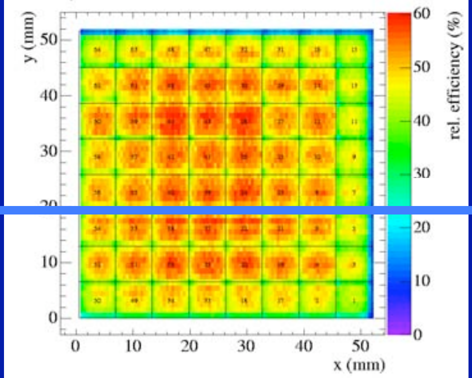
Laser scan

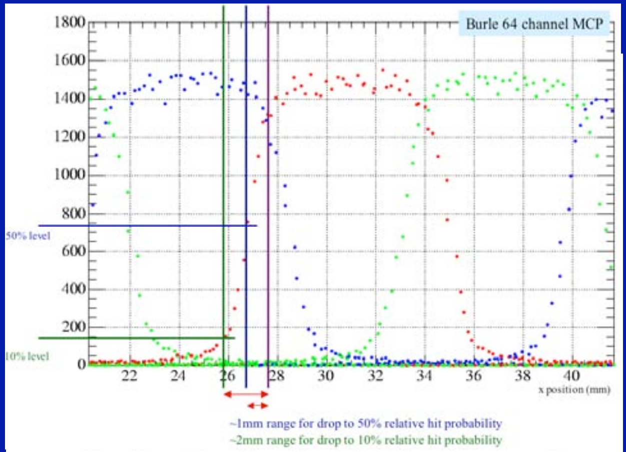
MCP-PMT:



Our experience:
MCP-PMTs tend to be
more uniform than MaPMTs.

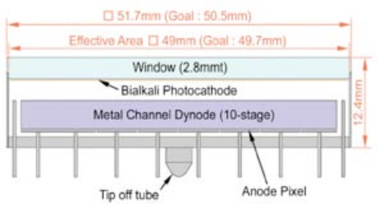
430 nm 85011 MCP-PMT


Efficiency w.r.t. Photonis PMT, MCP #15, blue, 2.4kV, 20040607

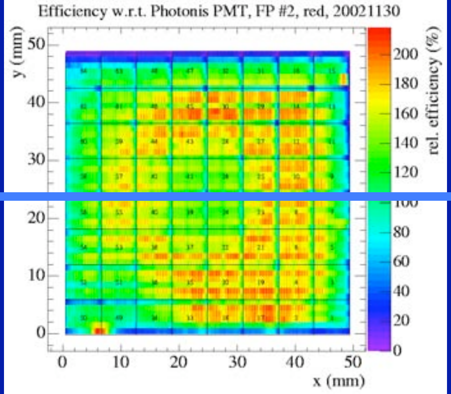


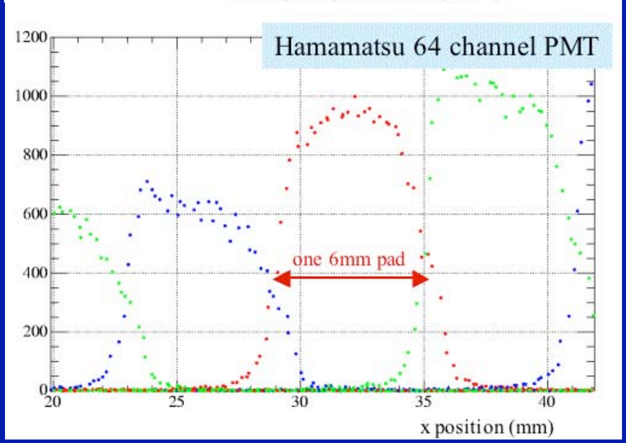
~1mm range for drop to 50% relative hit probability
~2mm range for drop to 10% relative hit probability

MaPMT:



430 nm H-8500 MaPMT


Efficiency w.r.t. Photonis PMT, FP #2, red, 20021130

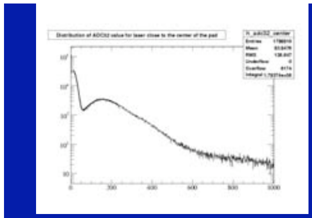


one 6mm pad

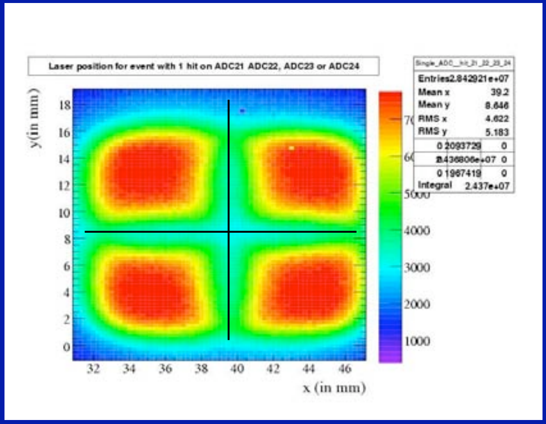
- **A useful range is ~2 mm from a pad boundary, if one implements ADC readout.**

Charge sharing with a MCP-PMT

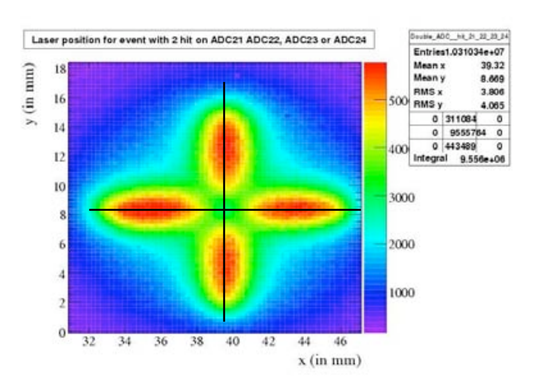
FDIRC R&D (data analysis by a summer student M. Bethermin)


Single photoelectron spectrum

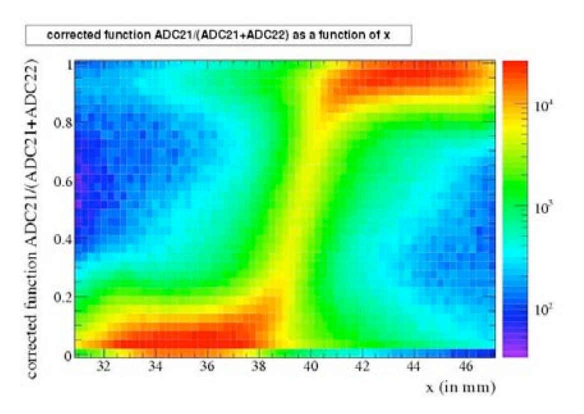
Position of laser with **single** ADC/ev:



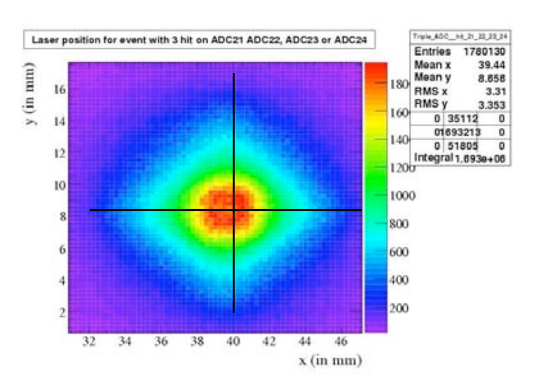
Position of laser with **two** ADCs/ev:



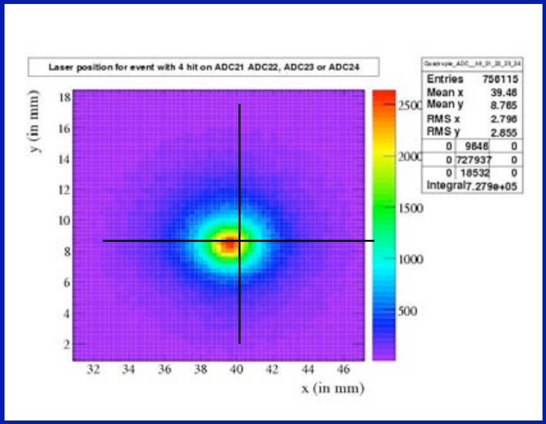
$ADC_i / (ADC_k + ADC_i) = f(x)$



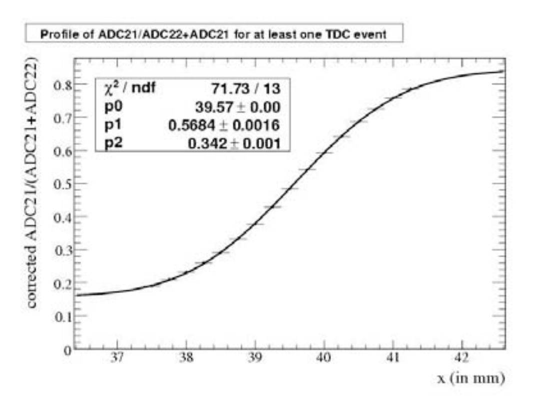
Position of laser with **three** ADCs/ev:



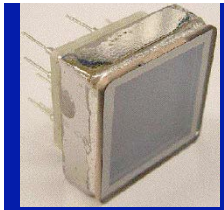
Position of laser with **four** ADCs/ev:



Fitted with $y = 0.5 + p2*erf(p1.(x-p0))$



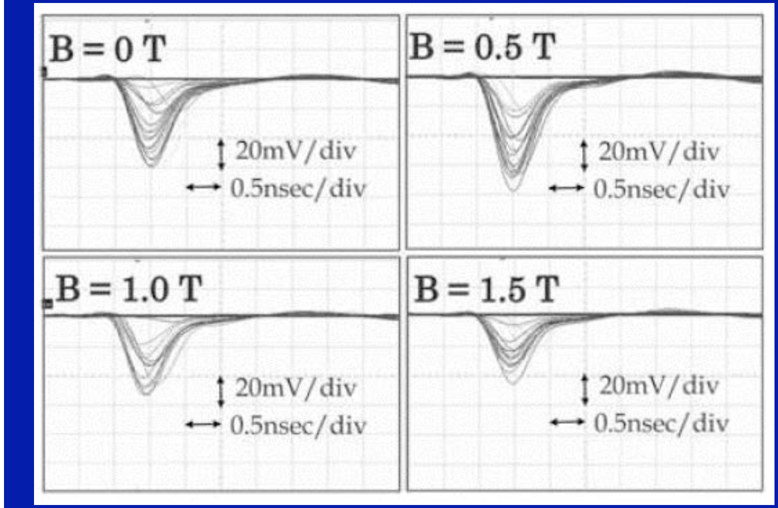
Magnetic field



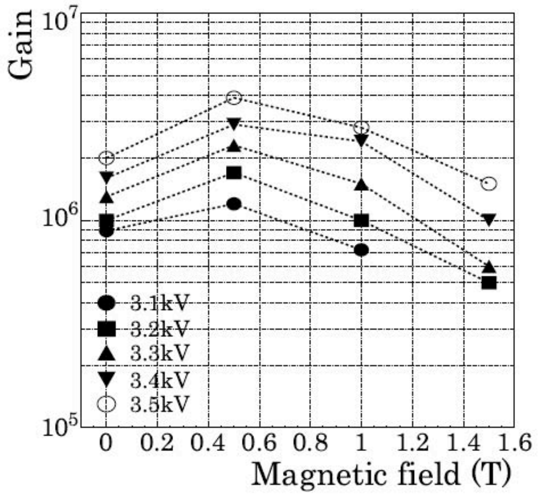
HPK SL-10 in the magnetic field

K. Inami et al., Nucl.Instr .& Meth, A592(2008)247-253

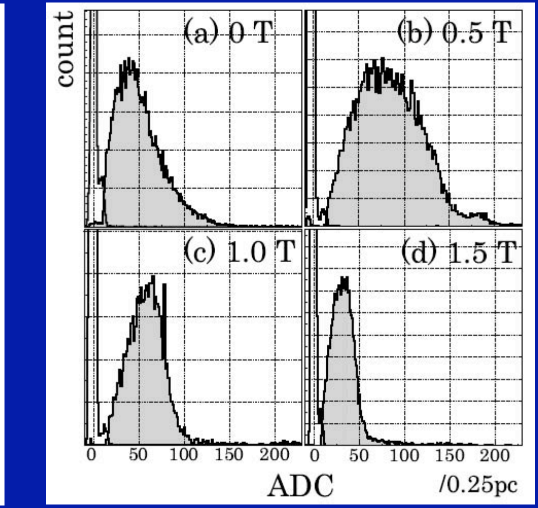
Single pe pulses = f(B)



Gain = f(B)



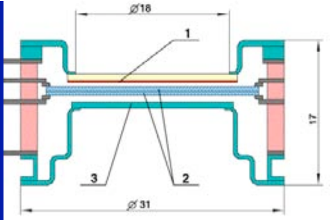
Single pe PH spectra = f(B)



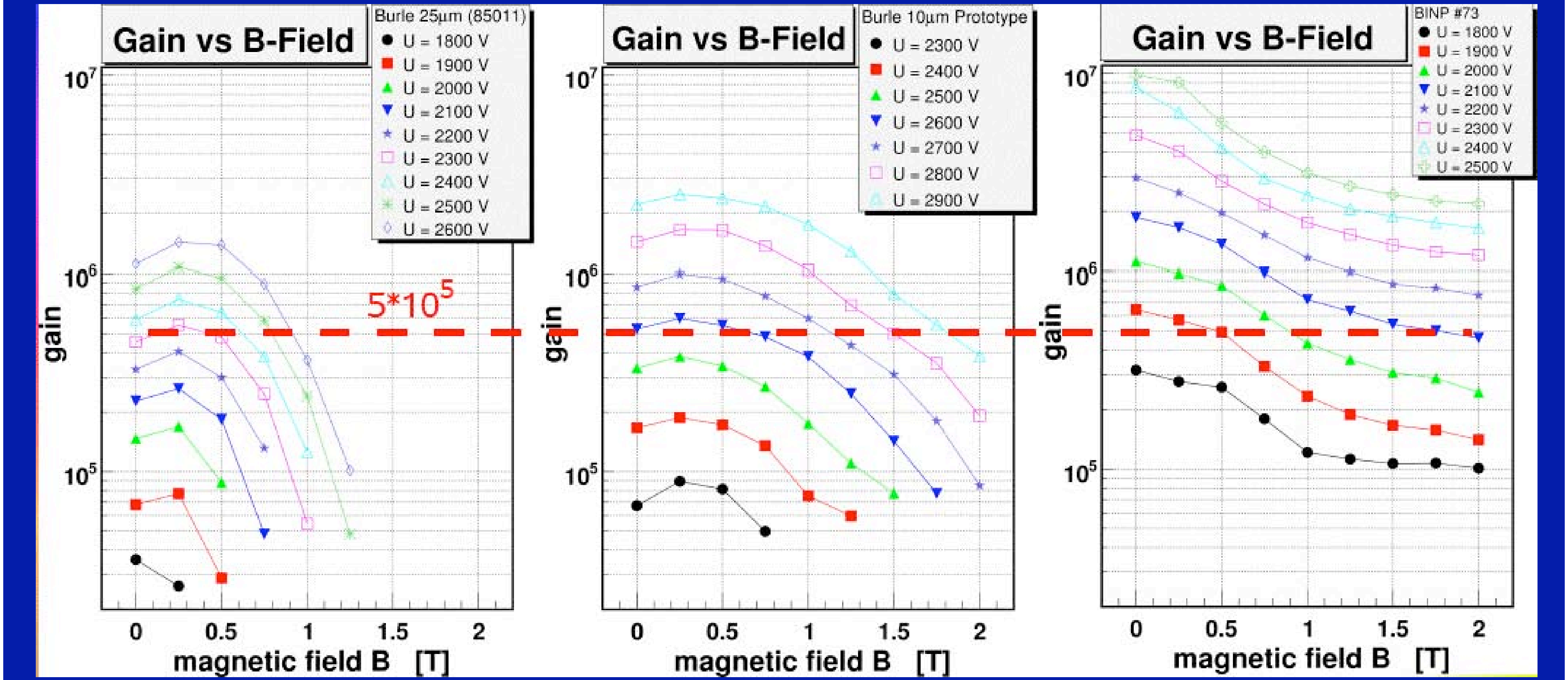
- **This tube will be used in the TOP counter.**
- **To run it successfully as a single photoelectron detector at 1.5 T, it needs to run at a gain of ~2x10^6 @ 3.5 kV.**

Magnetic field and gain

Lehmann et al., Nucl.Instr .& Meth. A595(2008)173



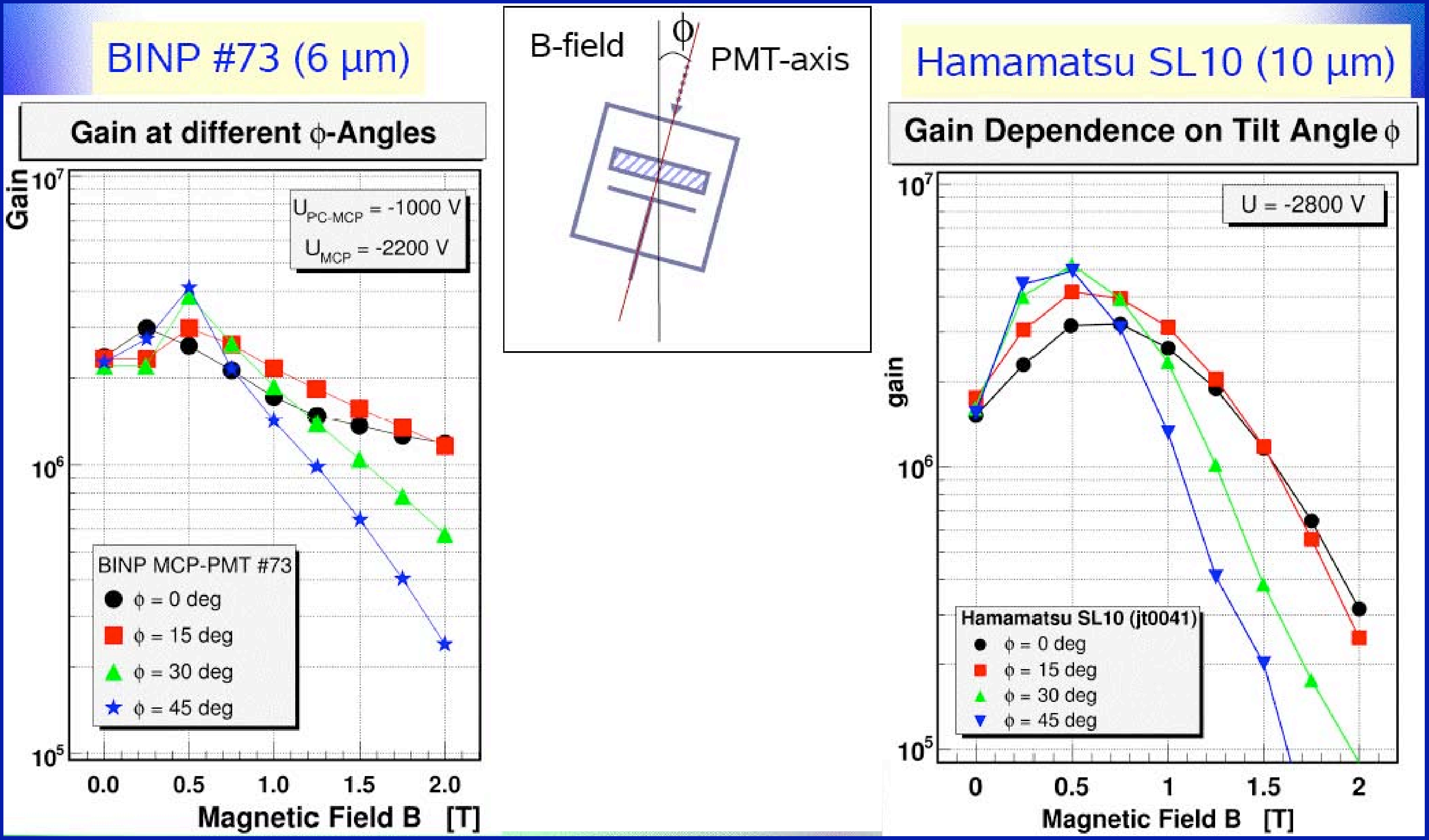
Photonis Planacon (25 µm) **Photonis Planacon (10 µm)** **BINP #73 (6 µm)**



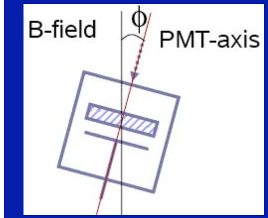
- **MCP gain for a given voltage is different at 0 kG and 16 kG.**

Gain = f(ϕ) at large B

Lehmann et al, Nucl.Instr .& Meth. A595(2008)173

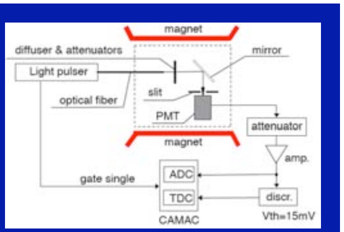


- **Gain is very sensitive to ϕ at large values of B.**



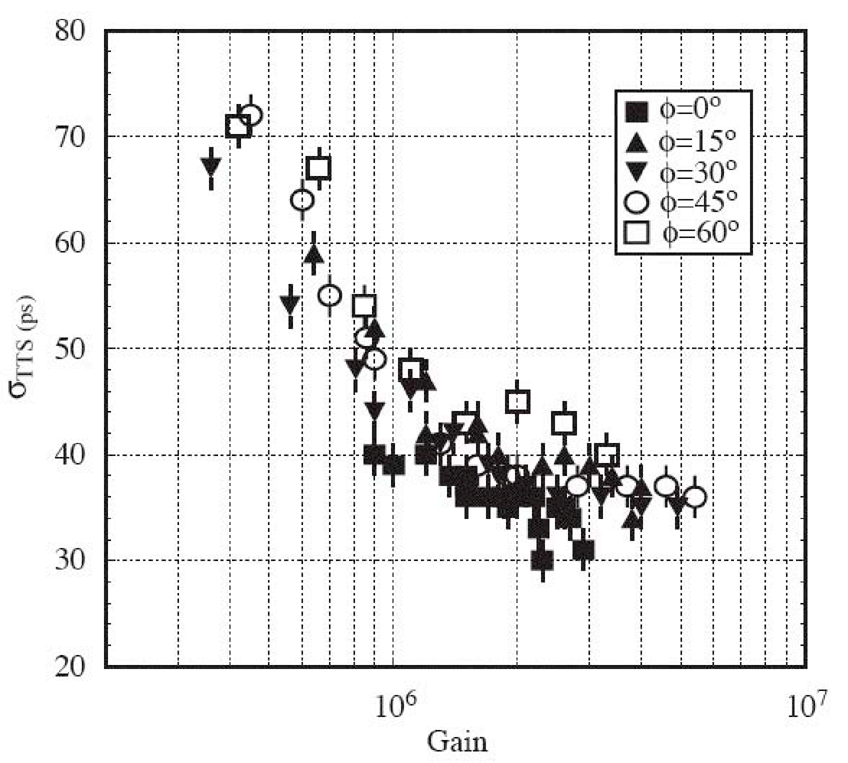
σ_{TTS} and PH = f(ϕ) at B = 1.5 T

M. Akatsu et al., Nucl.Instr .& Meth. A528(2004)763-775

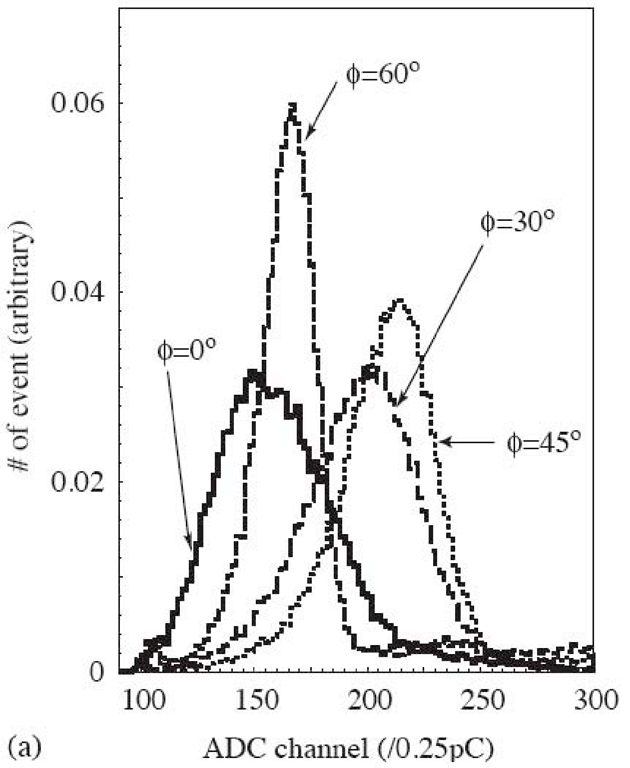


Phi vary, B = 1.5 T

σ_{TTS}



Phi vary, B = 1.5 T



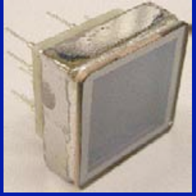
- σ_{TTS} is relatively insensitive to ϕ, even though the pulse heights vary quite a bit.

Aging and rate capability of MCP-PMTs

- QE
- Gain
- TTS
- Ion feedback rate

Note: Many variables enter the aging equation, for example, hole angle, how many MCPs the tube has, vacuum quality, gain, magnetic field,etc. Not easy to disentangle all this experimentally.

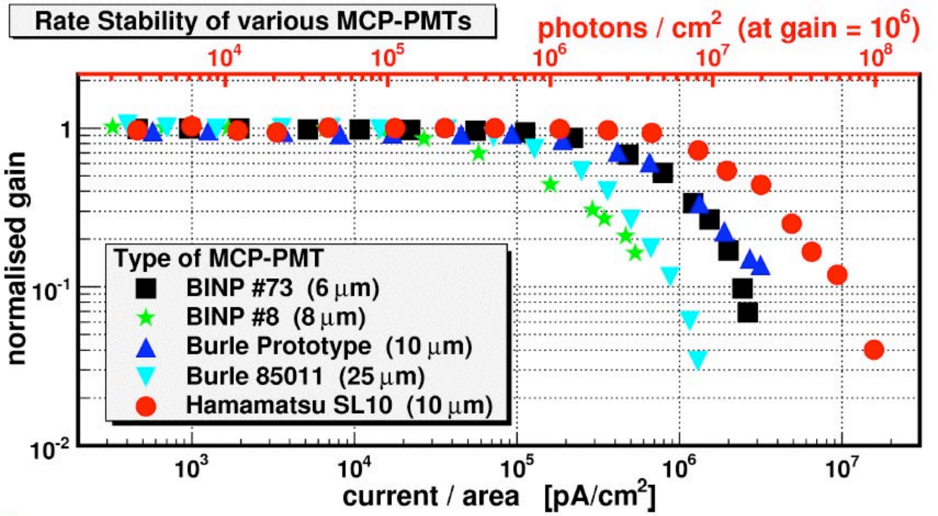
Hamamatsu SL-10:



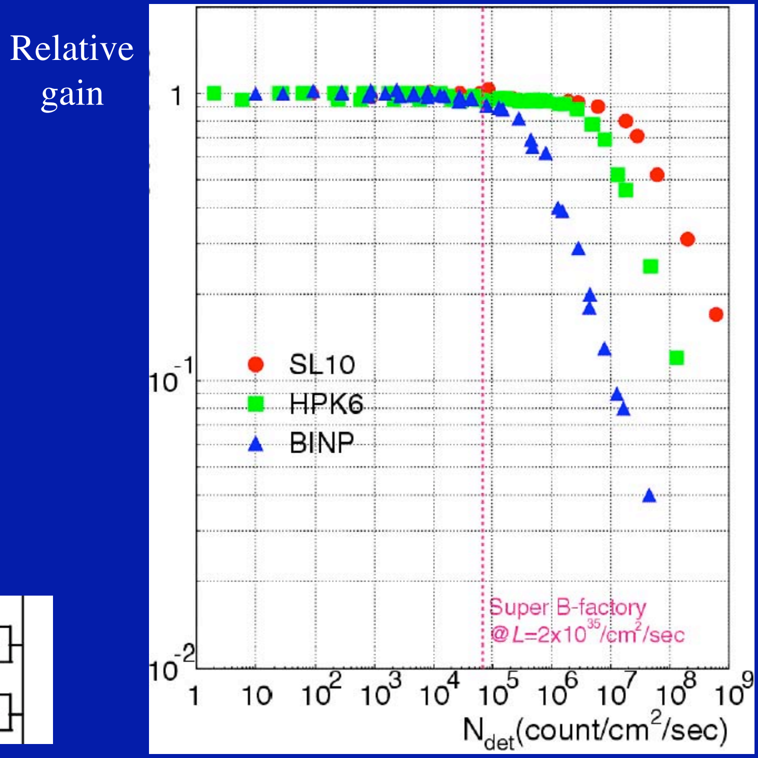
Rate capability at high gain of MCP-PMTs

K. Inami, RICH workshop, Giessen, May 2009, and Lehmann, RICH workshop, Giessen, May 2009

Lehmann:

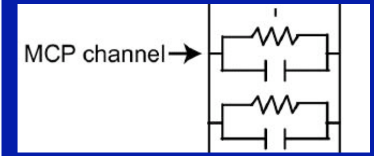


Inami:



Inami:

	SL10	HPK6	BINP
MCP resistance (MΩ cm²)	96	143	380~1000
MCP capacitance (pF/cm²)	16	31	24~39

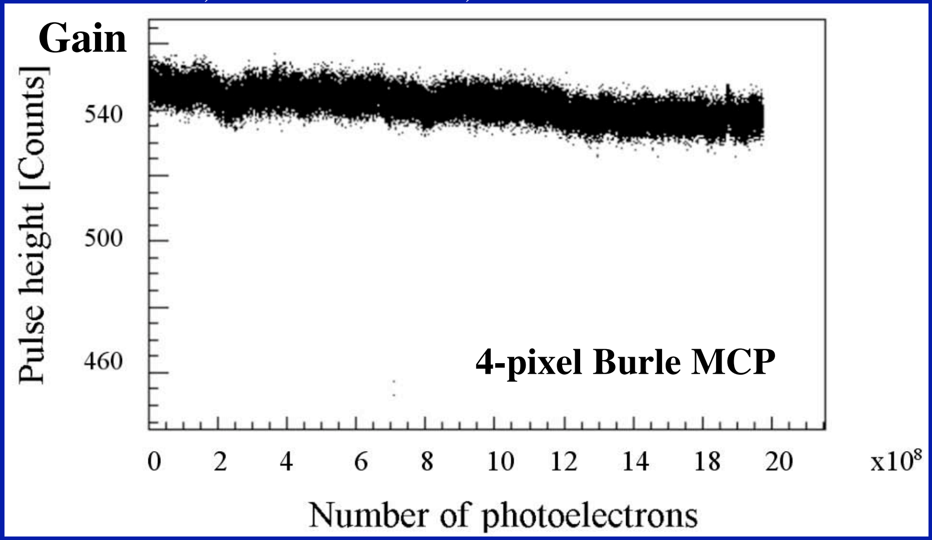


- **SL-10 stable up to ~5-7x10^6/cm^2/sec, Photonis 10 μm tube up to ~ 2x10^6/cm^2/sec.**
- **Why SL-10 is the best ? It has smallest MCP channel resistance and capacitance.**
- **According to Belle 2 people estimates, they expect a highest rate below 10^5/cm^2/sec.**
- **One serious consequence of high rate: possible heating of the surface => outgasing !!!**

Two scary examples of MCP-PMT aging

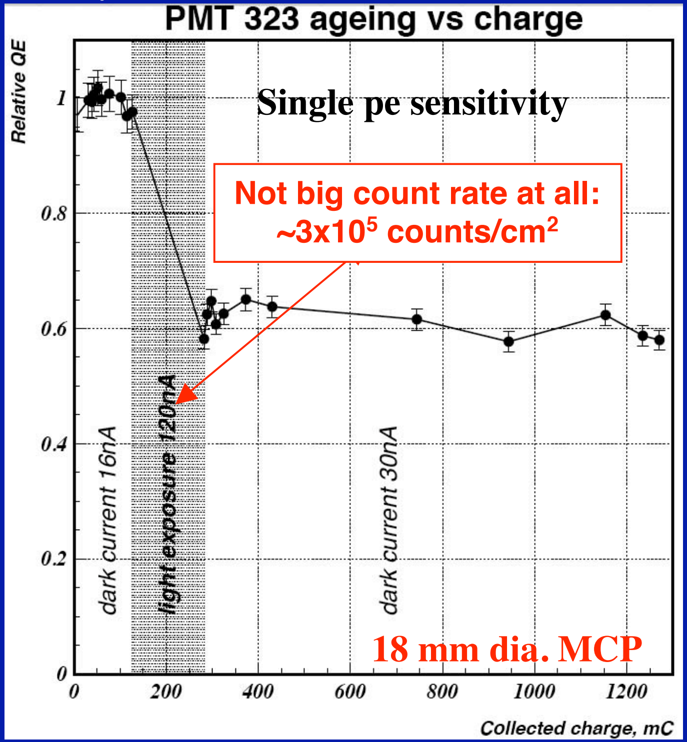
Aging observed just doing a calibration of the start counter:

C. Field et al., SLAC-PUB-11107, 2004



Rate can affect the speed of QE aging !!

Y. Banyakov et al., Nucl.Instr.&Meth. A567(2006)17



Single pe sensitivity

Not big count rate at all: ~3×10^5 counts/cm^2

18 mm dia. MCP

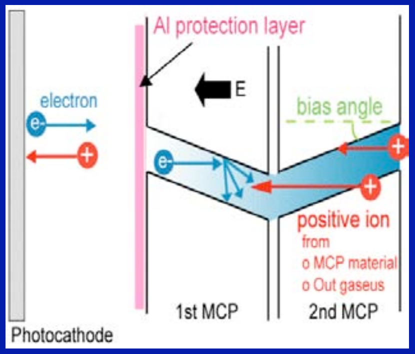
- **Just a calibration with laser diode has caused aging of Burle MCP-PMT in the FDIRC prototype in the test beam, consistent with a 50% drop after ~250mC/cm^2.**
- **Barnyakov has shown that the rate is important factor in aging. This is because it causes a local surface heating, which in turn causes outgassing, which then creates ions by electron bombardment in the avalanches.**

How to suppress MCP-PMT aging ?

Foil protection method

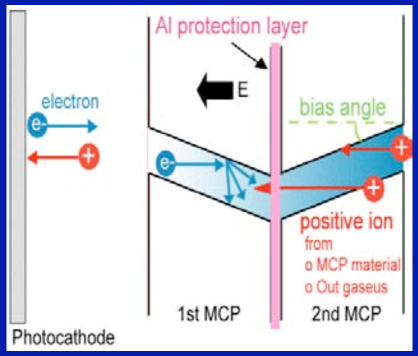
(K. Inami, RICH workshop, Giessen, May 2009)

a) Foil on top MCP



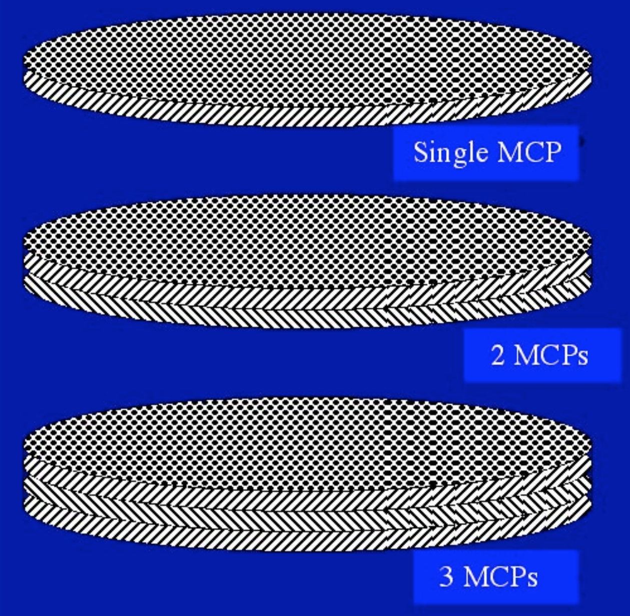
Problem with this scheme:
- foil absorbs almost half of single photoelectrons

b) Foil in between two MCPs



Putting a foil in between two MCPs solves this problem

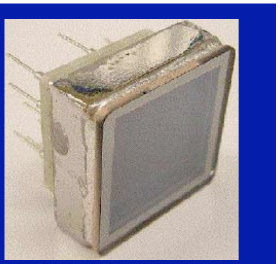
Inclined holes & multiple MCP



- Outgassing, created either by either manufacturing process or an excessive rates, creates ions by electron bombardment in the avalanche.
- Ions go back to photocathode and affect the electron emission (work function).
- Ions can also extract the secondary electrons, creating after pulses.
- **Aging remedy: (a) incline holes with as large angle as possible, (b) improve vacuum, (c) use a protection foil, (d) and use multiple MCPs in the stack.**

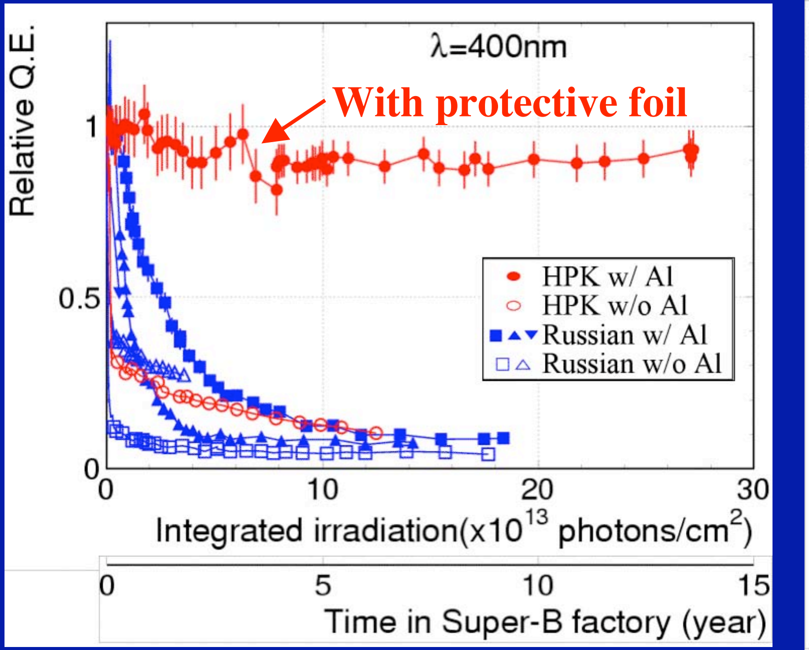
QE aging of SL-10 MCP-PMT

N. Kishimoto et al., Nucl.Instr .& Meth. A564(2006)204-211

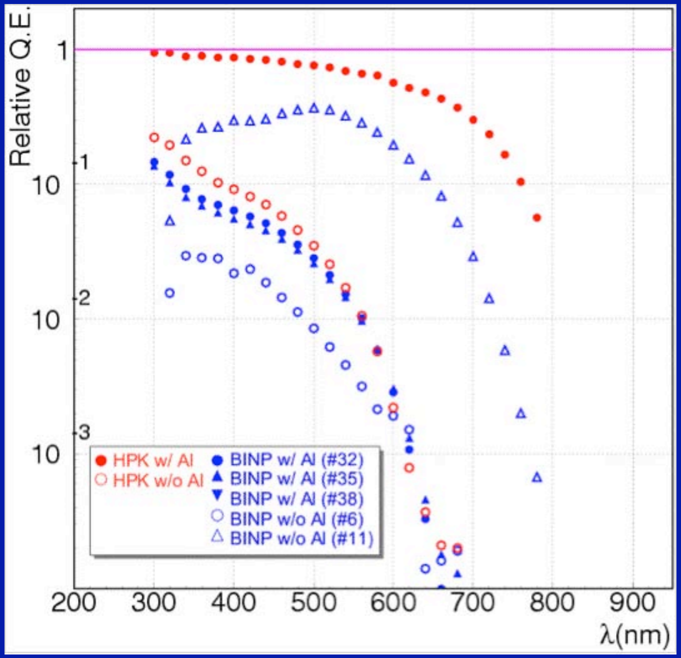


SL-10

QE aging at 400 nm

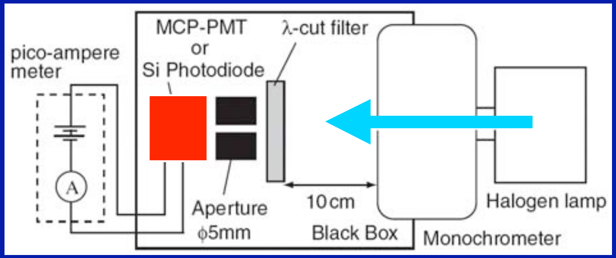


QE aging = f(wavelength)



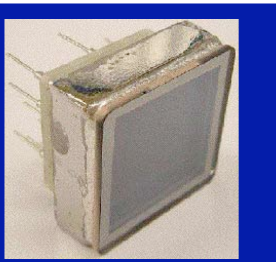
- Foil added between two MCPs
- Adding a foil solves the QE aging problem
- QE sensitivity to red wavelengths suffer first

Aging setup:

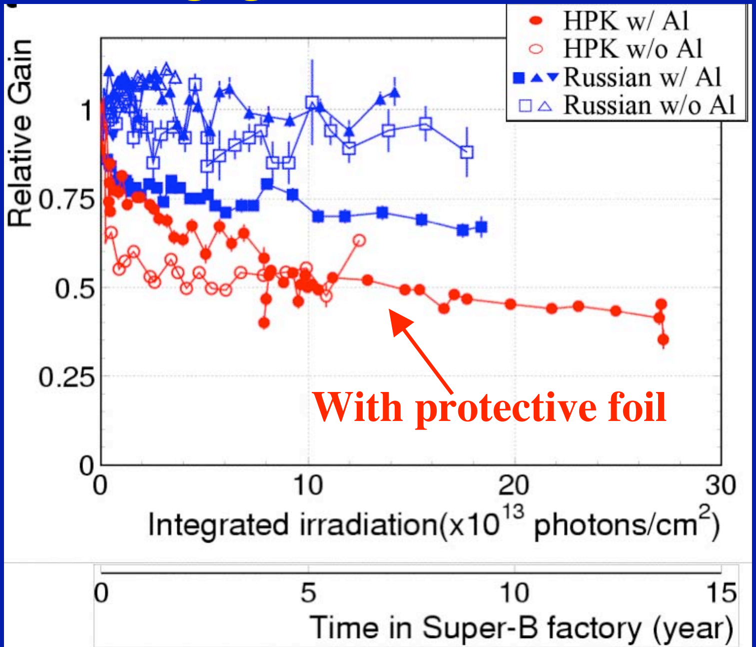


Aging of gain and TTS

N. Kishimoto et al., Nucl.Instr .& Meth. A564(2006)204-211

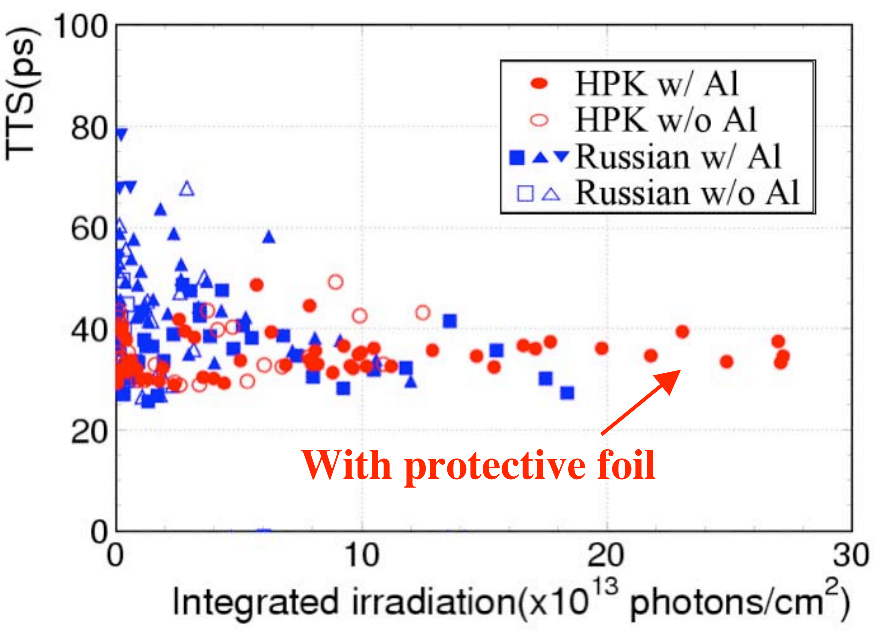


Gain aging at 400 nm



With protective foil

TTS aging

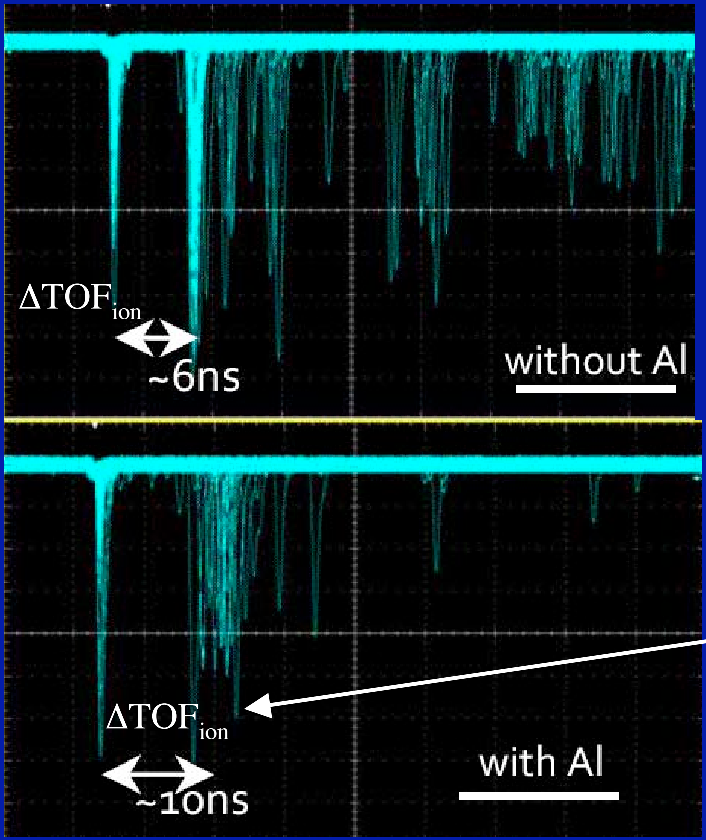


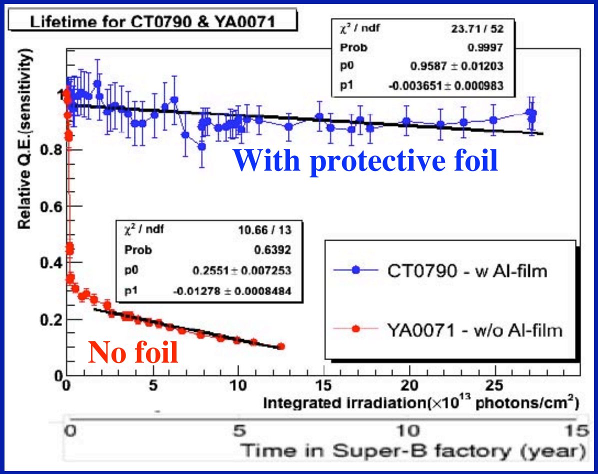
With protective foil

- **Some small gain drop - can be corrected by HV; foil does not help here.**
- **TTS seems to be insensitive to aging; foil does not help here.**

Positive ions and aging

K. Inami, “ps workshop”, Lyon, 2008 & N. Kishimoto et al., Nucl.Instr .& Meth. A564(2006)204-211





- 10 micron holes
- 13^o angle
- 11mm active dia.
- 5 mm dia. aging spot
- aging done with LED

- $\Delta TOF_{ion} = L \sqrt{(2m/eV)}$
  - m is mass of the ion (H^+, H_2^+ or He^+)
  - V is the voltage applied over distance L

		HPK without Al	HPK with Al
ΔT(calc.)	H^+	5.4ns	10.7ns
	H_2^+, He^{2+}	7.2ns	15ns
ΔT(data)		~6ns	~10ns

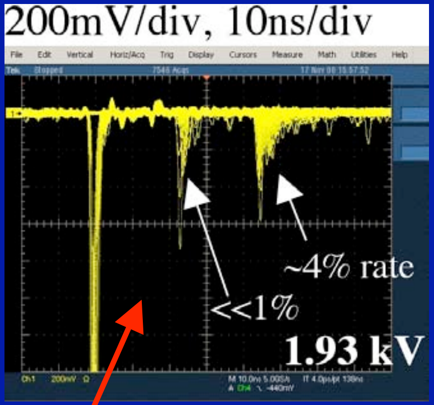
Observe mainly H+ ions from the surface.

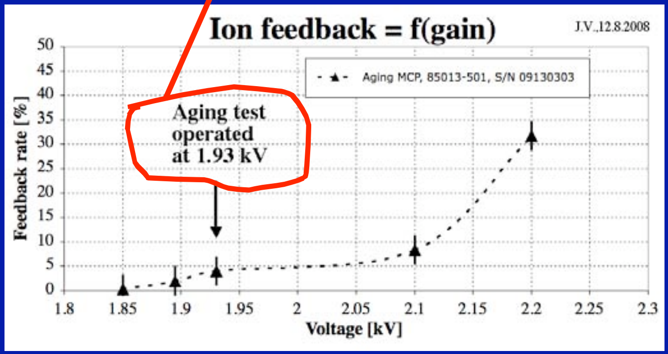
- **Single pe sensitivity => high gain ~ $2x10^6$.**
- **Foil reduces the ion feedback**
- **No aging on MCP-PMT with the foil**
- **Rate of ion feedback correlates with aging**

Aging - will running at low gain help ?

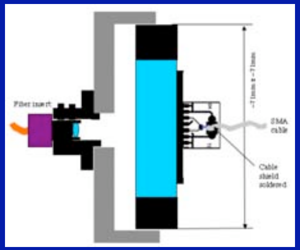
J. Va'vra, log book #6, page 56, SLAC, 2008

Ion feedback at low gain with Npe = 30-40:



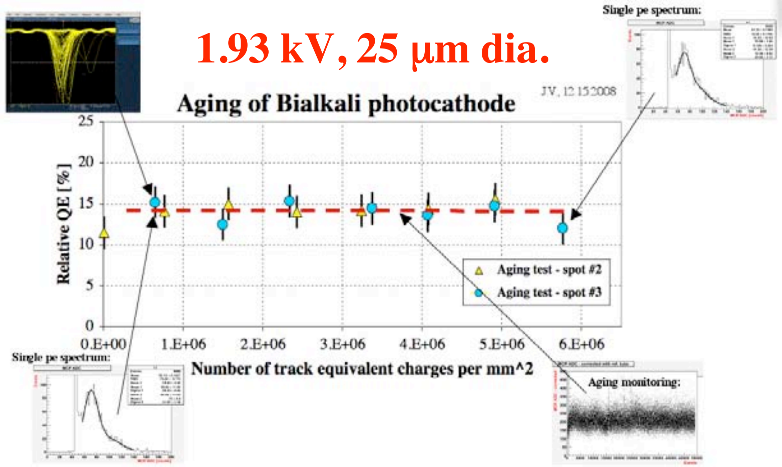


Aging setup:



- Photonis Planacon
- 25 micron holes
- 16° hole angle
- 2 mm dia. aging spot
- aging done with a laser

Example of the aging run:



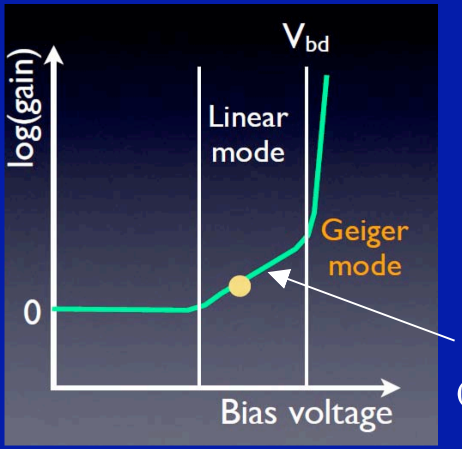
- **Npe ~ 30-40, Gain ~ 2x10^4 => total charge ~ 6-8x10^5. It does not see single pe's.**
- **Ion feedback ~ 4% when running the MCP-PMT with this condition.**
- **No aging observed for a limit equivalent to ~5x number of expected SuperB tracks.**
- **However, Photonis Planacon with 10 micron hole dia. has a hole angle only 8° !!!**

Hybrid APD
(HAPD)

A combination of vacuum tube and APD

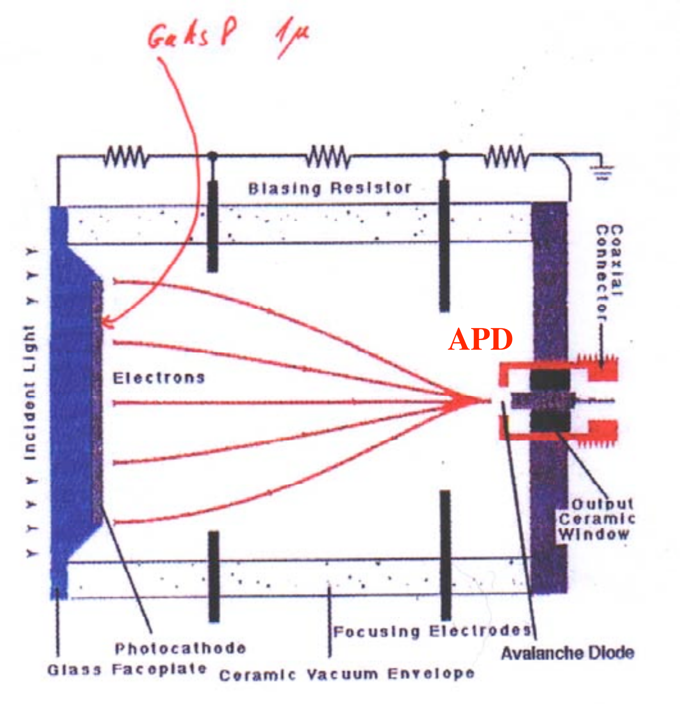
The first HAPD

R&D development in 1995 by INTERVAC Co., USA

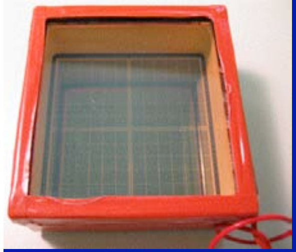


APD

(G<150)

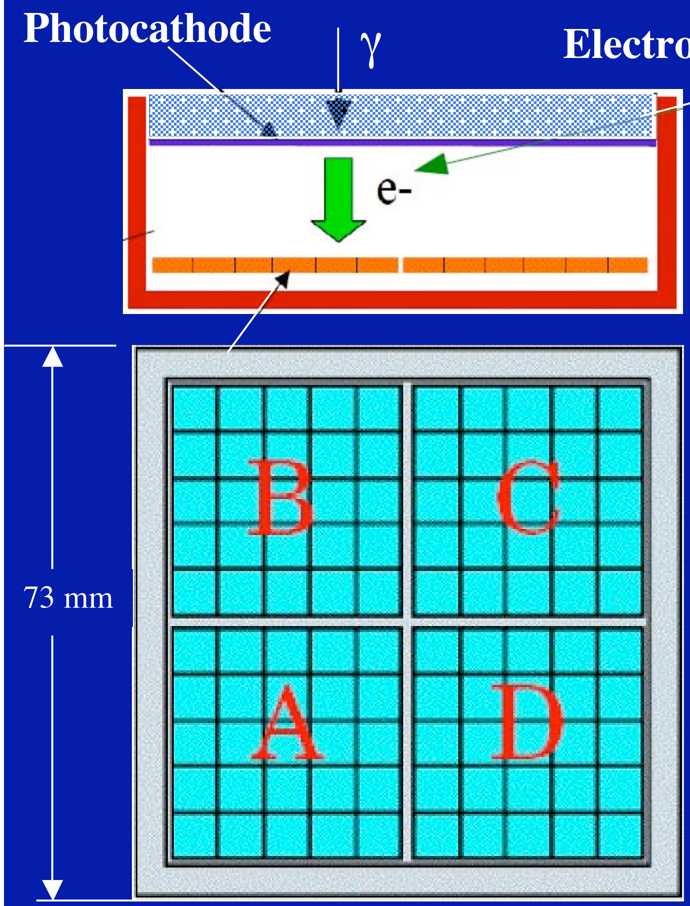


Photocathode	**GaAsP**
Accelerating medium	vacuum
Max. recommended value of $V_{photocathode}$	**< 10 kV**
Pixel capacitance	**~ 40 pF**



Hamamatsu HAPD

I. Adachi, R. Dolenec, K. Hara, T. Iijima, H. Ikeda,Y. Ishii, H. Kawai, S. Korpar, Y. Kozakai, P. Krizan,
T.Kumita, E. Kuroda, Y. Miyazawa, S. Nishida,I. Nishizawa, S. Ogawa, R. Pestotnik, N.Sawafuji,
S. Shiizuka, T. Sumiyoshi, M. Tabata, Y.Ueki, and Hamamastu Co.



4 APD chips/tube

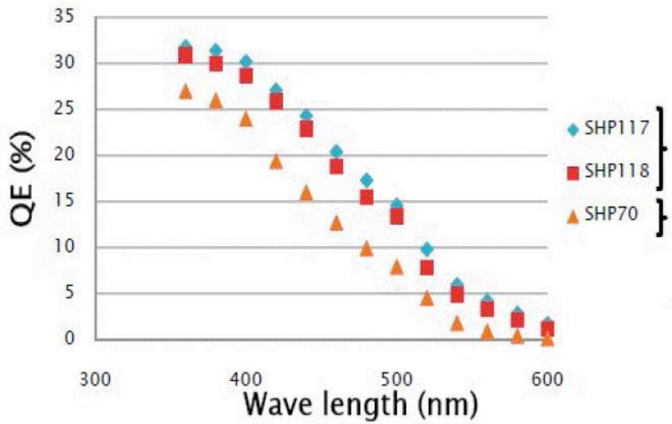
QE at 350nm (Bialkali)	25%
Geometrical pixel efficiency (pixel active area)	59 %
Geometrical oveall packing efficiency	77 %
PDE = Total fraction of detected photons	~ 11% @ 350 nm
$V_{photocathode}$ & APD diode bias voltage V_{APD}	~ 8-9 kV & ~300 V
Total number of channels & number of chips	144 & 4
APD pixel matrix & Pixel size	5x 5 & 4.9 x 4.9 mm^2
Overall size & Sensitive size	73 mm & 64 mm
HPD gain @ -8kV & APD gain @ 300 V	~ 1000x & ~10x
Total Gain	10^4 - 10^5
Transit time spread σ_{TTS}	< 100 ps

- Proximity focusing design => works in 16 kG field
- Relatively small gain => need an amplifier (>100x)
- PDE comparable to MCP-PMTs at present

Hamamatsu HAPD

K. Inami, November 2009

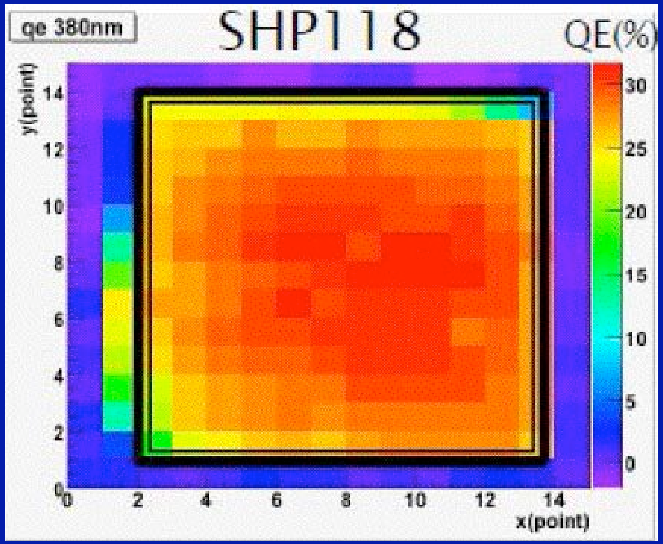
Super Bialkali QE:



} New

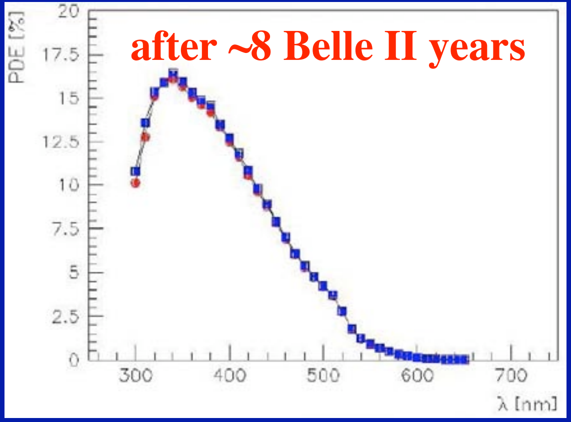
\- Old

Uniformity test of QE:

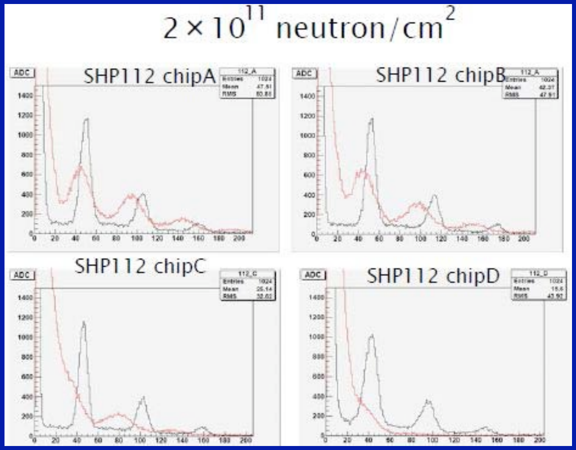


Aging of PDE with light from LED:

Almost no change in PDE after the light exposure



Aging with neutron flux: 2 x 10^{11}/cm^2



Clearly, observe an increase in leakage Current; different from chip to chip

Geiger mode APD
(G-APD)

- **Single-pixel Geiger mode APD's** were developed long time ago !!!! They were called SPAD. *(for* example: *R. Haitz et al, J.Appl.Phys. (1963-1965)).*
- **Multi-pixel Geiger mode APD's** were first developed ~10 years ago by Dolgoshein et.al., Nucl. Instr. & Meth., A442(2000)18. They called them SiPMT.

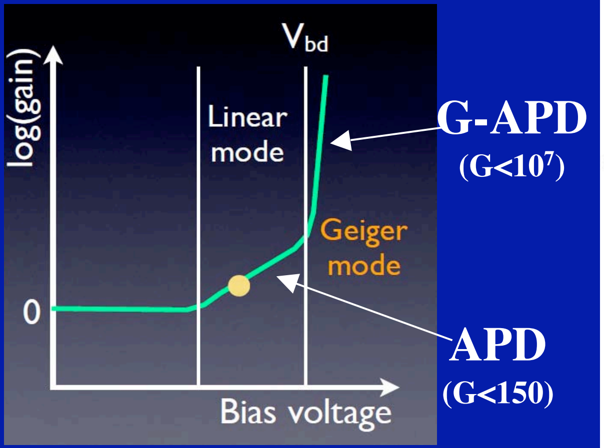
- **Explosion of names:** SPAD, SiPM, SiPMT, MGPD, MRS-APD, PSiPs, SPM,MPPC, G-APD…
- I prefer to call them simply either "single-pixel" or "multi-pixel" G-APD.

Many sources: CPTA/Photonique (Moscow/Geneva), MEPhI/Pulsar (Moscow, Russia), Amplification Technologies (Orlando, USA),
Hamamatsu Photonics (Hamamatsu, Japan), SensL (Cork, Ireland), RMD (Boston, USA),
MPI Semiconductor Lab. (Munich, Germany), FBK-irst (Trento, Italy), STMicroelectronics (Catania, Italy),
FBK, Zecotek, (Singapore), and Z. Sadygov (JINR, Dubna, Russia)

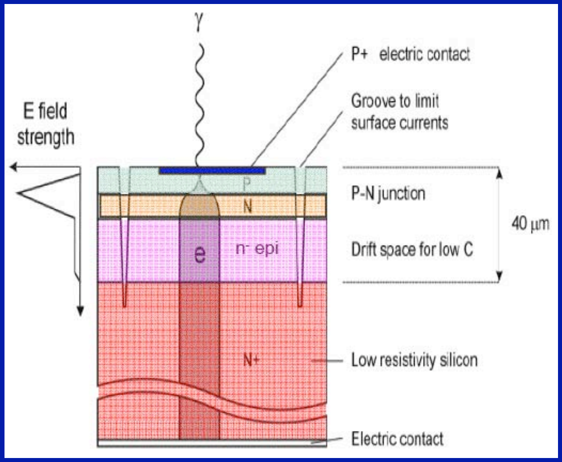
G-APD

I benefited from a talk of D. Renker at RICH Giessen workshop, 2009
https://indico.gsi.de/getFile.py/access?contribId=1&sessionId=1&resId=0&materialId=slides&confId=529

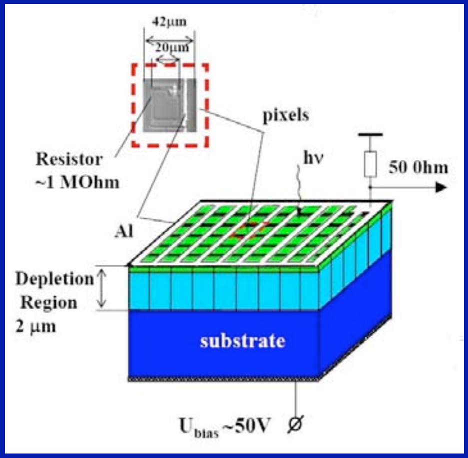
I-V dependence:



Typical APD/G-APD design:

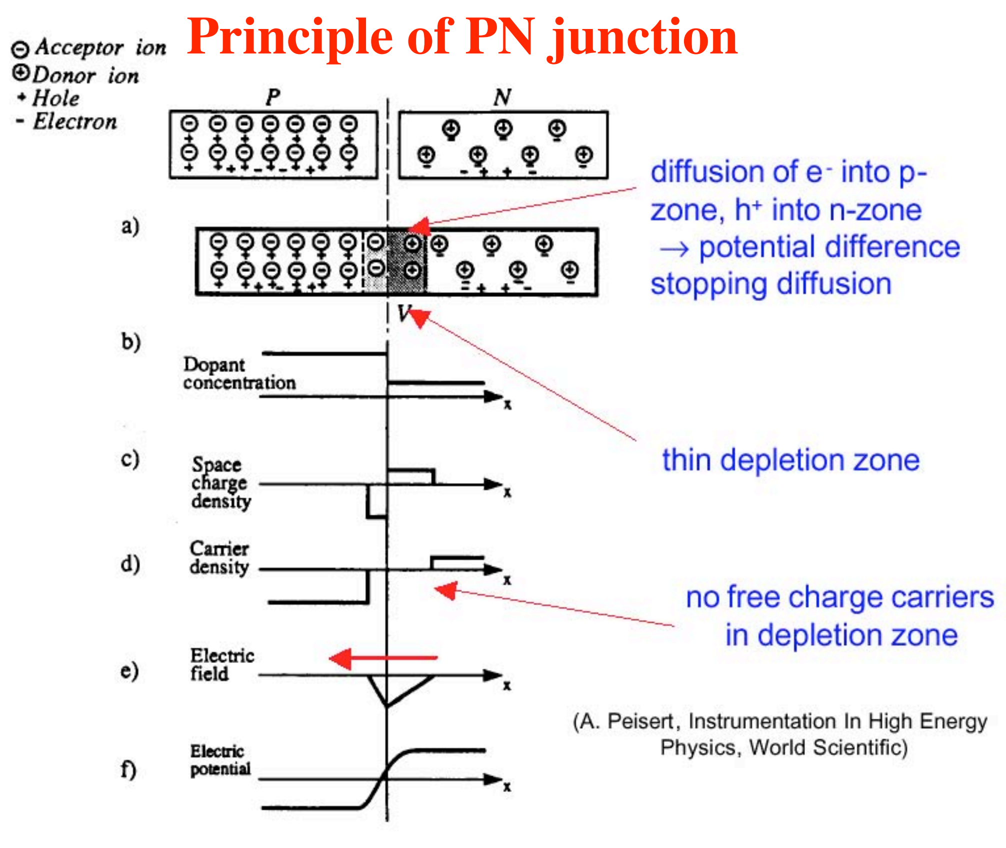


G-APD array:



- **APD gain is typically limited to 10-150 x.**
- **G-APD electric field reaches values of ~ 3-5 x 10^5 V/cm, and gain of ~ 10^7.**
- **The trick, to survive the breakdown, is to use a limiting resistor on every G-APD.**
- **Trenches are used to reduce the optical cross-talk.**
- **A crucial trick, to be able to operate a larger area APD in the Geiger mode, was a subdivision into many tiny independent cell - credit goes to V. Golovin and Z. Sadygov.**

High field in pn junction



Principle of PN junction

diffusion of e^- into p-zone, h^+ into n-zone → potential difference stopping diffusion

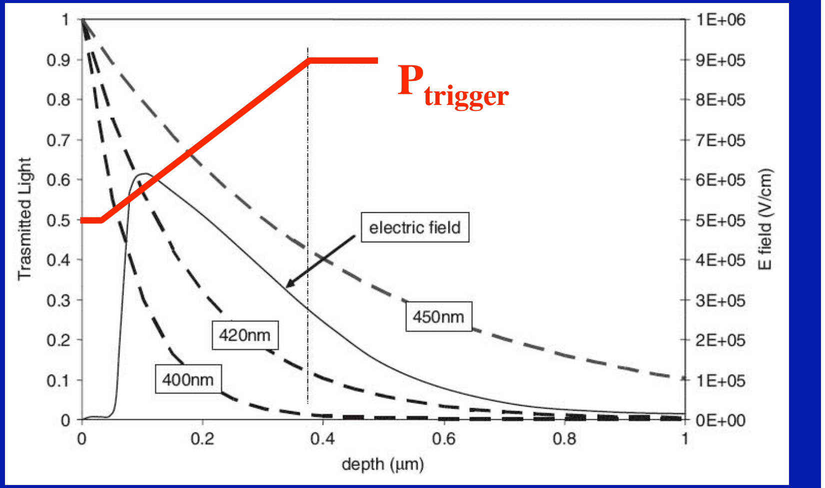
thin depletion zone

no free charge carriers in depletion zone

(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

Simulation of electric field,
light absorption and triggering probability Pt

C. Piemonte, Nucl. Inst. & Meth., A568(2006)224



(~90% of photons absorbed before reaching Pt-max.)

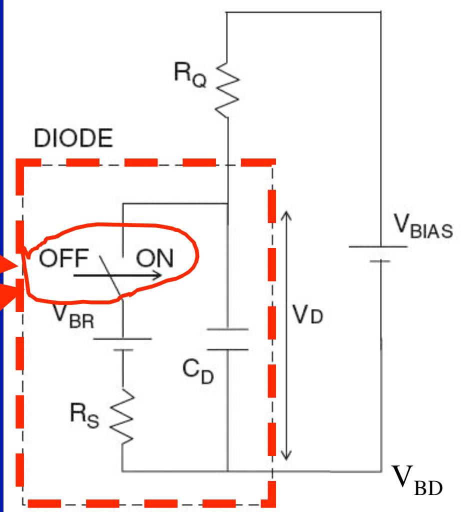
- One has to "tune" the light absorption and the electric field profile to absorb as many photons as possible before reaching a maximum triggering probability.

Equivalent electrical circuit of G-APD

C. Piemonte, Nucl. Inst. & Meth., A568(2006)224

- **Ready state:**
  - C_D is charged to V_{BIAS}
- **Photon triggers avalanche**
  - Switch turned on
  - C_D is discharged to V_{BD} ($\tau = R_S C_D$)
- **Recharge C_D:**
  - Switch turned off
  - C_D is recharges from V_{BD} to V_{BIAS} ($\tau = R_Q C_D$)
- **Ready again for next photon**

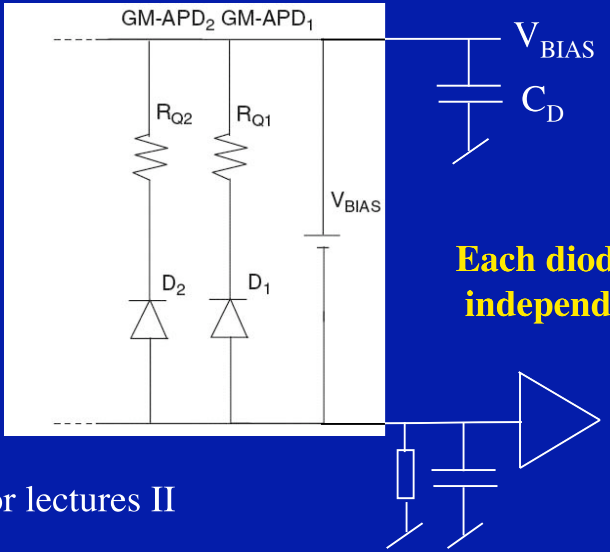
Single G-APD - equiv. model:



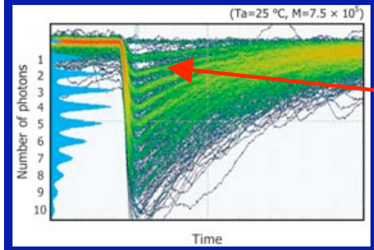
R_Q - quench resistor
(typ. 100-200 kΩ)
C_D - junction capacitance
V_{BIAS} - PS voltage
(typ. ~70 V)
V_{BR} - breakdown voltage
(typ. A few V < V_{BIAS})
R_S - silicon resistance
(typ. ~1kΩ)

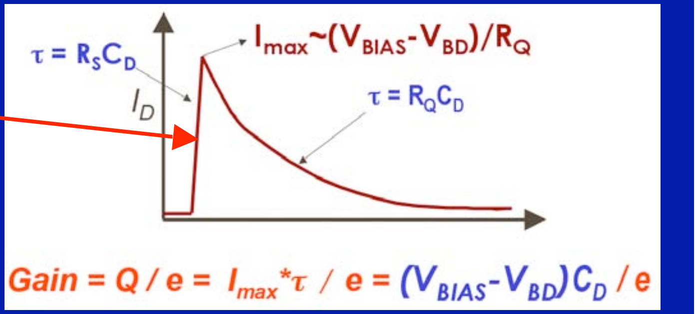
V_{BD}

G-APD array:



Each diode acts independently



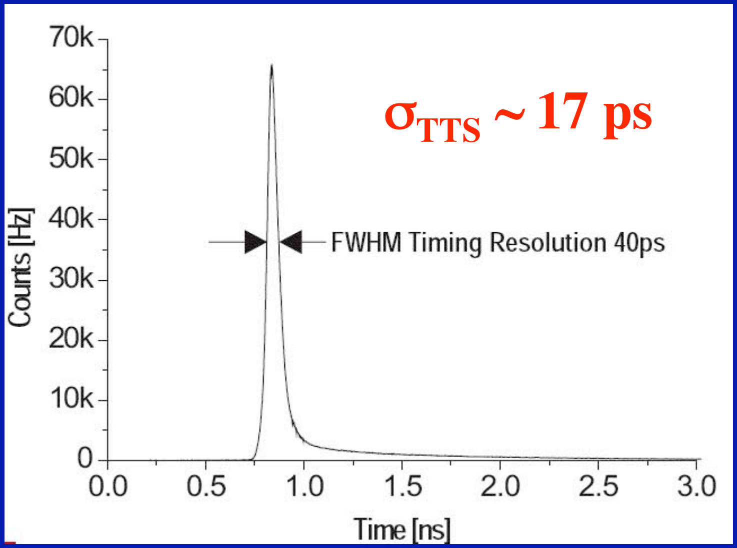


$$Gain = Q / e = I_{max} {}^{*}\tau \;/\; e = (V_{BIAS}-V_{BD}) C_D / e$$

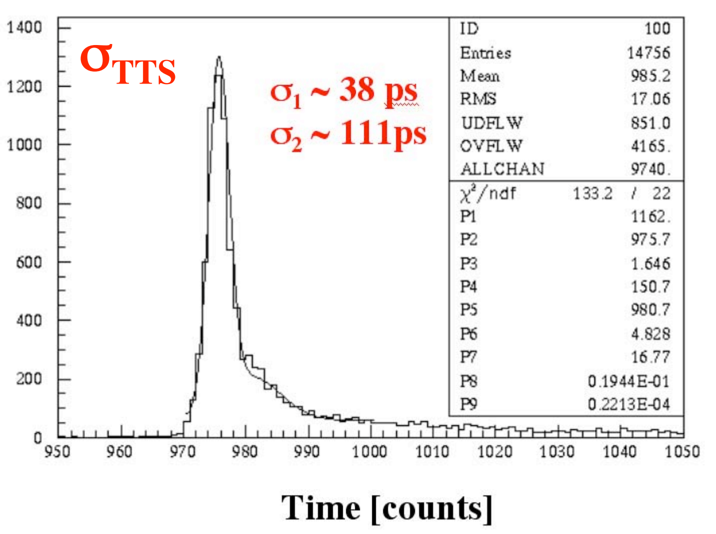
Timing resolution of single G-APD

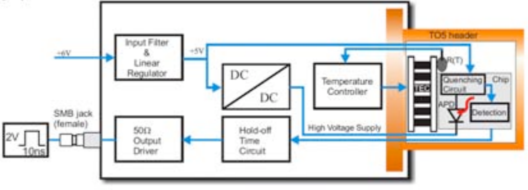
id-100 made by Quantique Co., Switzerland, and J.Va'vra, MCP-PMT log book 1, page 79 (G-APD from Sopko, Active quenching from Prochazka, CVUT Prague)

id-100 (company's data)



My measurement with Sopko's diode, λ = 635nm

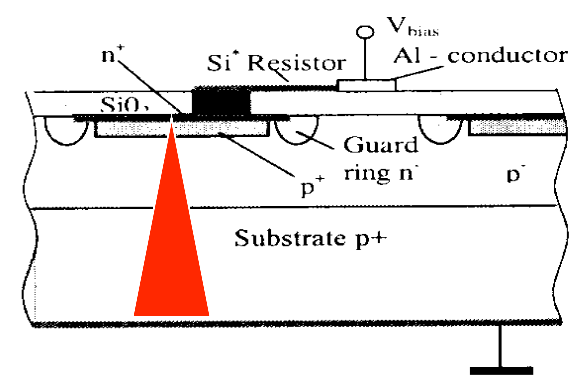




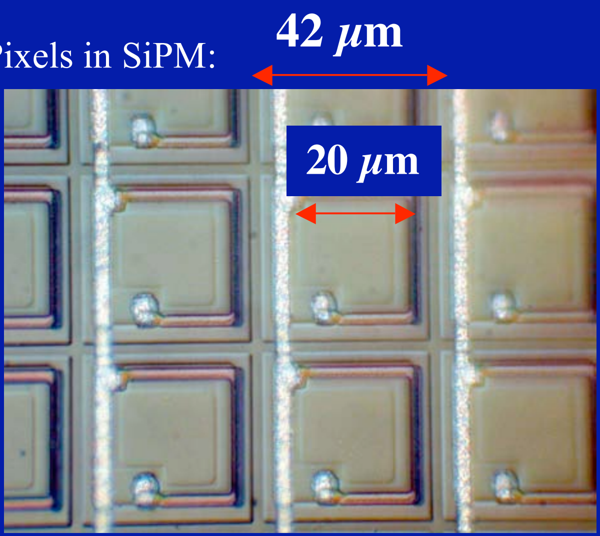
- **id-100: The best TTS measurement made by any G-APD, to my knowledge.**
  Its other parameters: <u>noise < 20Hz</u>, spectral range of 350-900nm, after pulsing probability < 3%, dead time of 50ns, maximum rate of 20 MHz, active area of 50 μm.

The 1-st G-APD array

B. Dolgoshein et al., Nucl. Instr. & Meth., A442(2000)18 - they called them SiPMTs

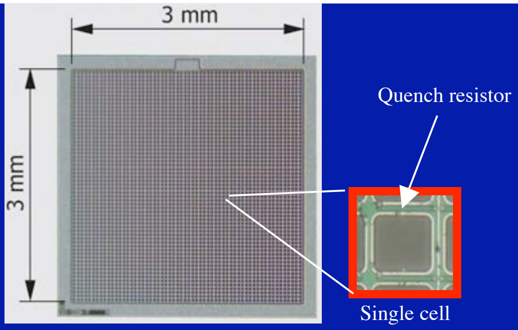


Pixels in SiPM:



Photocathode	**Silicon**
Accelerating medium	**Si**
Operating voltage	**24-25V**
Geometrical packing efficiency	**~44%**
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 (τ ~ C_{pixel} x R_{pixel}~30ns)	**~100ns**
σ_{TTS} Timing resolution per single photon	**σ_{TTS} ~ 60ps** ←

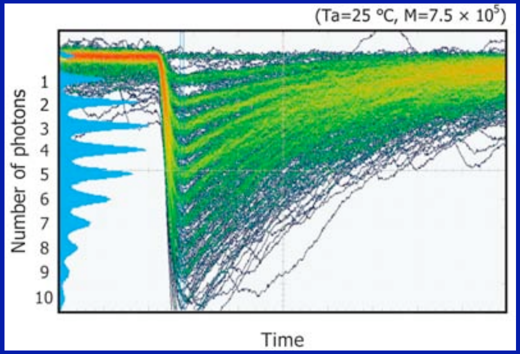
Each pixel = binary device → SiPM = analogue detector



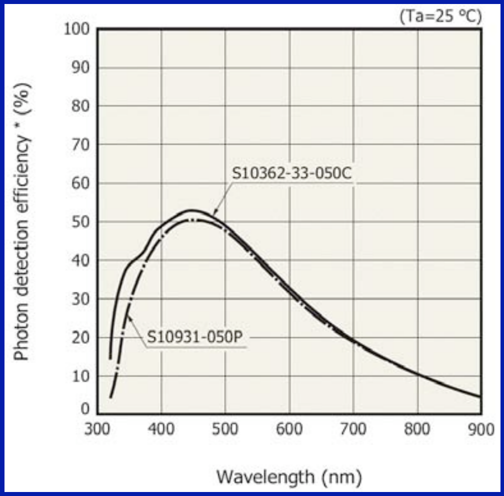
G-APD array

Hamamatsu data sheet

Pulses and PH spectra:



PDE (HPK info):



S10362-33 -059C MPPC

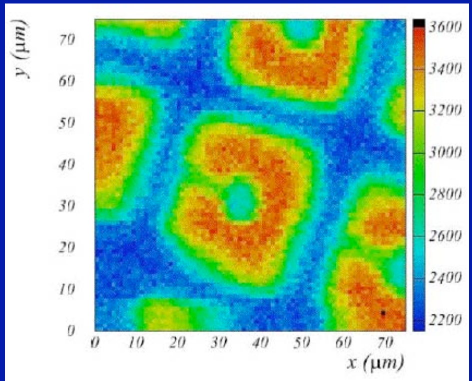
QE at 440nm (Silicone)	> 60 %
$P_{trigger}$ - trigger probability	80 - 90 %
Geometrical fill factor	78.5 %
PDE = Total fraction of detected photons (includes after-pulses & cross-talk !!!) *	~ 52 % @ 440 nm (HPK quote)
After-pulsing total rate	~ 20%
Operating voltage	70 ± 10 V
Terminal capacitance	320 pF
Pixel size	100 µm x 100 µm
Overall size & Sensitive size	~ 3.85 mm x 4.35 mm & 3 mm^2
Total Gain	~ 2.4 x 10^6
Noise rate (Single photoelectron threshold) *	~ 8 MHz
Transit time spread σ_{TTS}	< 100 ps

- **PDE includes the after-pulses & cross-talk, which could reduces PDE by as much as ~ 30 % !!!!**
- **The single pe noise rate is presently rather high, but it is only a factor in the single pe detection, and, its effect can be reduced in the triggered applications.**

PDE

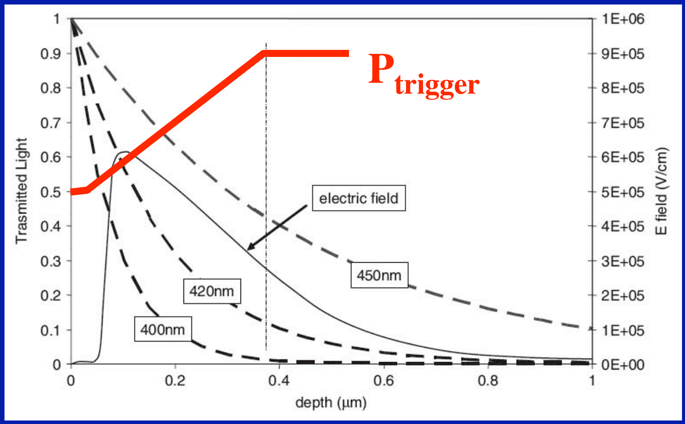
$$PDE = QE \times P_{\text{trigger probability}} \times \varepsilon_{\text{packing geometry}}$$

$\varepsilon_{\text{packing geometry}}$



P. Križan, Light07

$P_{\text{trigger probability}}$



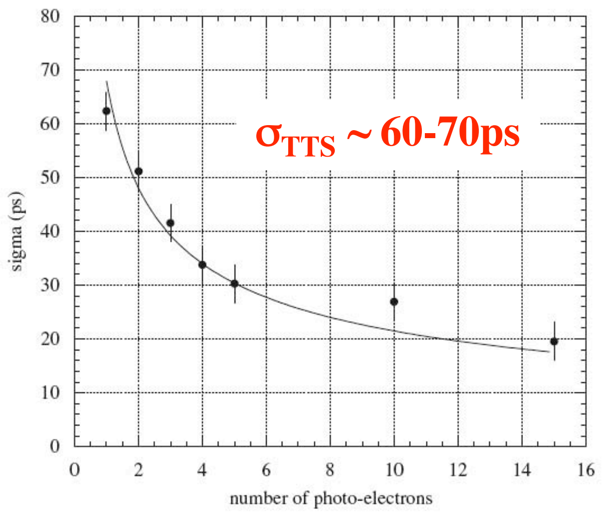
C. Piemonte

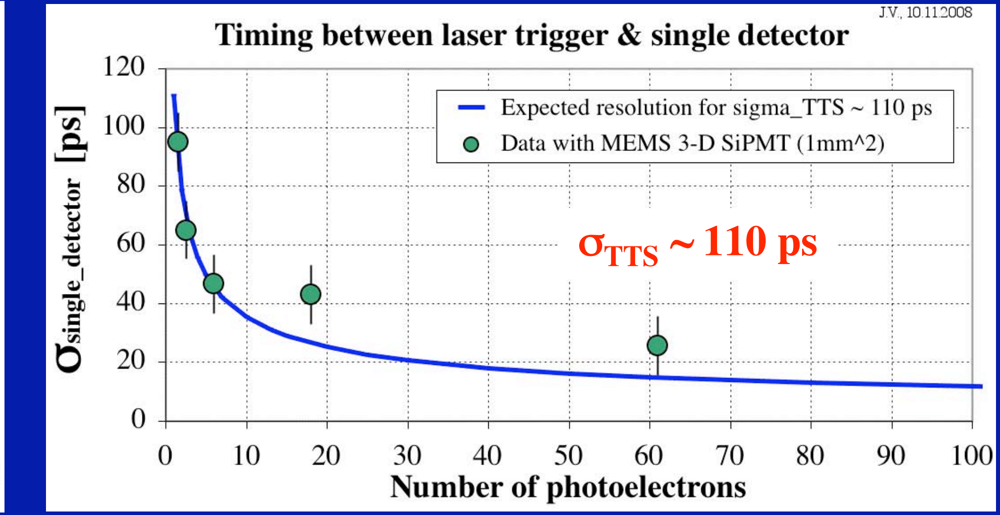
- **QE is 80-90% depending on wavelength.**
- $\varepsilon_{\text{packing geometry}}$ is typically 70-80%
- **P_{trigger} depends where electron is created and it is a function of overvoltage. It is not quoted by manufacturers. It can be anywhere between 50-90%**
- **PDE in the range of 30-40% is a realistic number to expect at present.**

Timing with G-APD arrays

Colazuol et al, Nucl. Instr & Meth., A581(2007)461, and J. Va'vra, MCP-PMT log book 6, page 97, 2008

σ [ps]





Npe

Npe

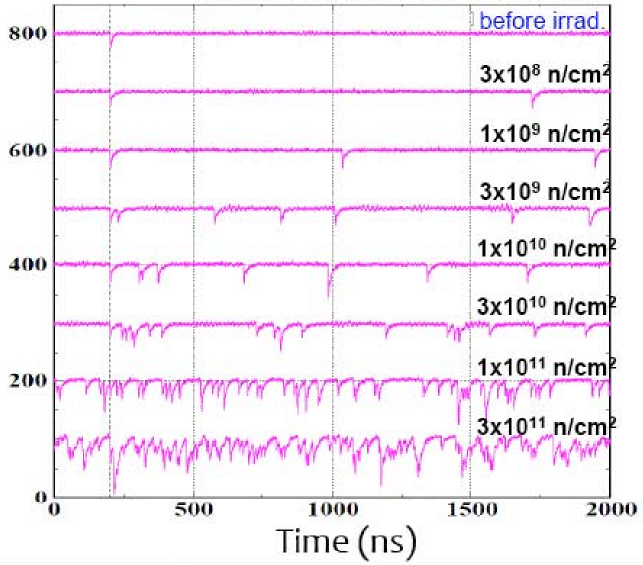
- σ_{TTS} ~ 70 - 120 ps presently.
- It is possible to achieve σ ~ 20 ps presently, if one has Npe ~ 20-30.
- A record with a single G-APD is σ_{TTS} ~ 17 ps (id-100).

Aging of G-APD: damage by neutrons & protons

T. Matsumura, IEEE, Dresden, 2008

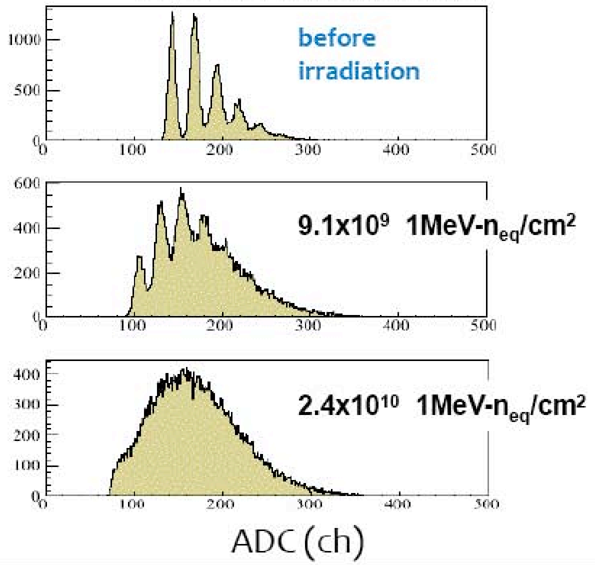
Typical waveform of dark pulses
(after neutron irradiation)

I.Nakamura, JPS meeting, Sep. 2008



ADC distributions (proton irrad.)

T.M. *et al*, PoS (PD07)033, 2007



lost of photon counting capability
due to baseline fluctuation and noise pile-up

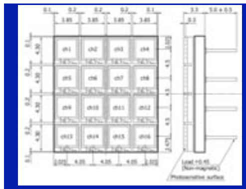
~ 10^{10} 1MeV-n_{eq}/cm^2

in both cases of the proton/neutron irrad.

Damage effects caused by proton and by neutron irradiation are almost scaled by NIEL.

→ **Bulk damage is dominating for the proton irradiation**

- **Presently, one cannot think about G-APD application for single pe detection at SuperB factory.**



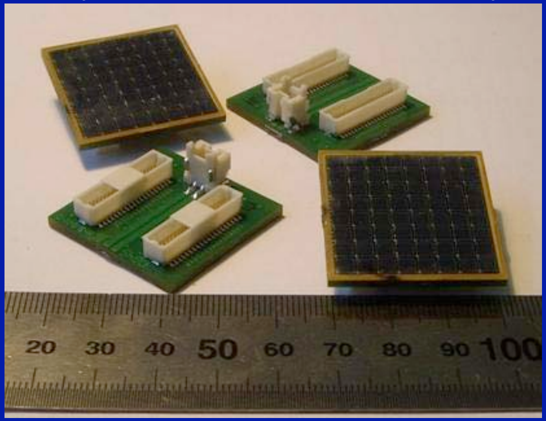
HPK S11064
4 x 4 array of 3mm^2 G-APD

What to expect next in SiPMTs ?

Taken from a talk of D. Renker at RICH Giessen workshop, 2009
https://indico.gsi.de/getFile.py/access?contribId=1&sessionId=1&resId=0&materialId=slides&confId=529

8 inch wafer produced by Zecotek:

8x8 arrays of 3 mm^2 G-APDs by Zecotek:



Present:

- PDE ~15-40% for 350-650 nm
- Dark count rate ~ 300 kHz/mm^2 at room temperature
- Optical crosstalk < 1-3%
- Active area > 100mm^2
- Fast timing ~ 50 ps (RMS) for single photons (all)
- Large dynamic range with 15 000 –40 000 pixels/mm2(Zecotek)
- Large area of 3x3 mm2
- Low temperature coefficient of ~0.3%/C
- production cost >10 \$/mm^2 (too expensive)

Future (a few years from now):

- PDE > 50-60% for 350-650 nm
- Dark count rate < 100 kHz/mm^2 at room temperature
- Optical crosstalk < 1%
- Active area > 100mm^2
- G-APD arrays: 6 x 6, 8 x 8 ...
- Radiation hard G-APDs -up to 10^{14} - 10^{15} n/cm^2 !!!???
  (new materials: diamond, GaAs, SiC, GaN, BD (carborane) ???)
- Production cost < 1\$/mm^2

!?

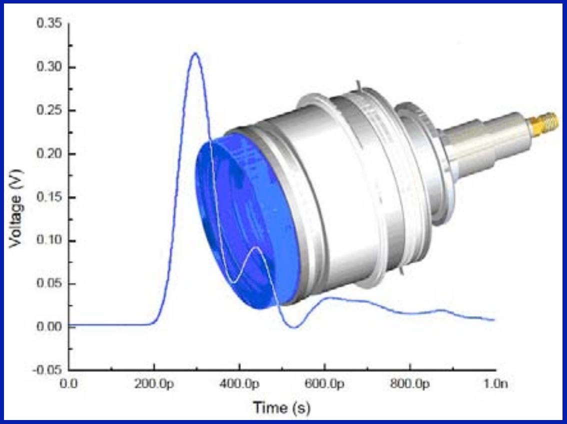
- **If this happens, I say: good buy all vacuum devices**

Ultimate fast detector: diamond films ?

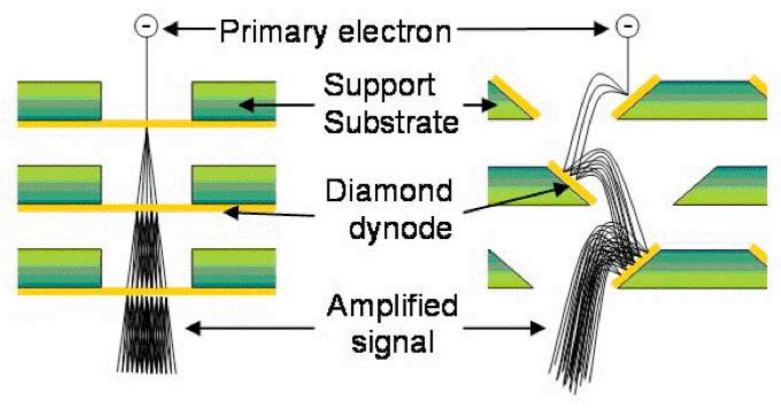
J. S. Lapington, P.W. May, N. A. Fox, J. Howorth, J. Milnes, http://www.laserfocusworld.com/articles/336816

Photek diamond film triode: world's fastest detector

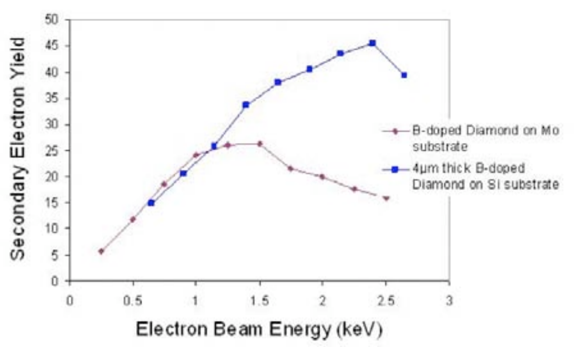
Rise time: 55ps
FWHM: 88ps



Possible diomond film application in dynode structures

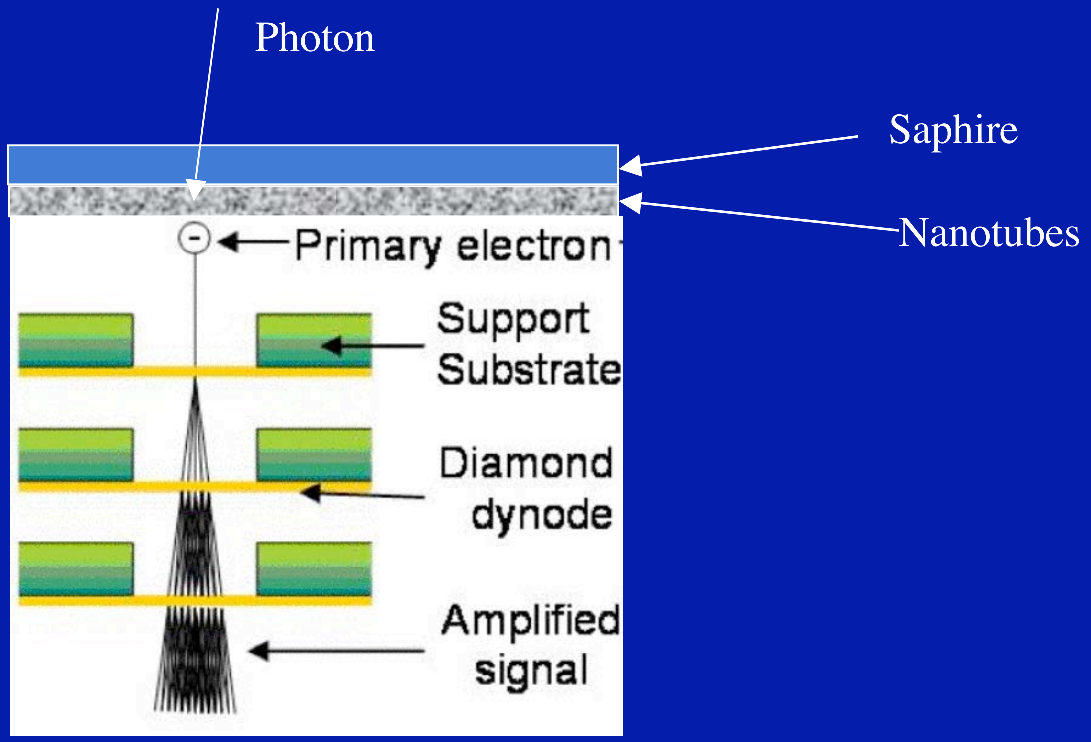


Secondary electron yield in diamond films



- **Diamond can be deposited using chemical-vapor deposition (CVD) coating techniques.**
- **Diamond is very suitable for a dynode structure because it is very electronegative, radiation hard, and can be deposited as a film.**
- **Detectors with a sub-10ps timing resolution are anticipated.**

Concluding slide & a suggestion for new R&D



- **One could combine Dr. Ambrosio's nanotubes, which I saw in his lab demonstration yesterday, with diamond films. Tube would have to have a decent vacuum, but not an ultra-vacuum.**