7th International Conference on
New Developments In Photodetection
Tours, France, June 30th to July 4th 2014
NDIP

Micro-Channel Plates And Vacuum Detectors

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(CERN/PH-DT)

Review disclaimer

- Much more has been and is taking place than what can be covered in 45 minutes!
- This (partially historical) review is actually a mix between an overview, a tutorial and a highlight from the viewpoint of a modest MCP user
- The selection criteria were a combination of
  - the speaker's past and current activities and interests
  - those MCP-related developments coming from relatively old, new and near-future R&D and experiment projects
  - topics which are generally covered in other oral or poster presentations during this Conference
  - topics the illustrations of which were easily accessible, directly via authors, publications and web sites

Outline

- History – the channel electron multiplier
- From large-size single channels to micro-channel plates
- Gen II image intensifiers
- Applications in scintillating fibre tracker detectors
- Re-discovering the MCP-PMT for fast timing
- Applications in time-of-flight and particle identification and related recent developments
- Conclusions and perspectives

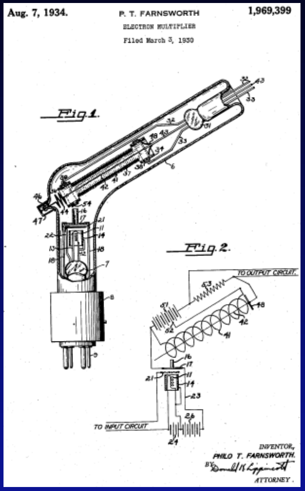
History – the channel electron multiplier (CEM)

- Combination of secondary emissive dynode and resistive chain

- First proposed in 1930 by Farnsworth
  - Modulated electron stream
  - Hollow resistor
  - Central electrode coated with Th (45eV/e-) or Ba (33eV/e-)
    - Evaporate on resistor
    - Increase e- v_t

  - Linear up to space charge effects

US Patent 1,969,399



Instr. and Exp. Tech. 4 (1960) 611

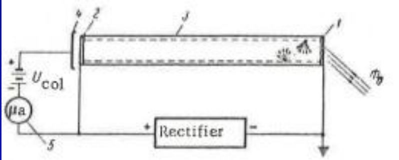
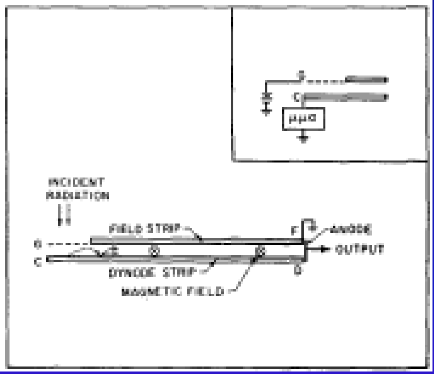
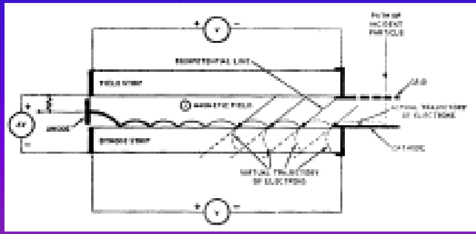


Fig. 1. Schematic of a continuous secondary electron multiplier. 1,2) Contact rings; 3) cylindrical channel; 4) electron collector; 5) instrument for recording the output current; Φ_0) primary radiation which produces electron emission from the internal surface.

- Further developed in 1960's
  - Oschepkov et al.
    - No central electrode
    - TiO_2+MgO
  - Heroux and Hinteregger
    - SnO+Sb-coated glass
  - Goodrich and Wiley
    - "They may either be made of a conducting coating on an insulating base or they may consist of the surface of a material with the proper volume resistivity for convenient operation"



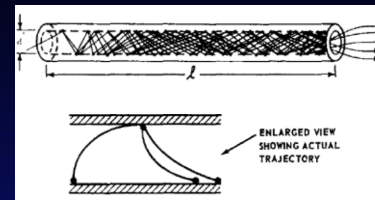
Rev. Sci. Instr. 31 (1960) 280



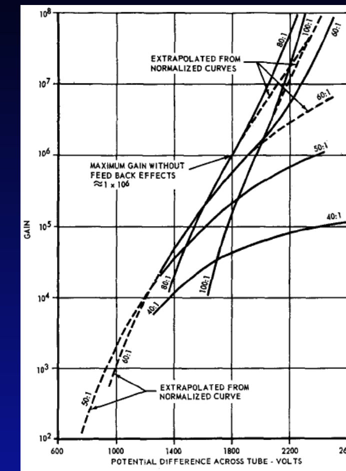
Rev. Sci. Instr. 32 (1961) 846

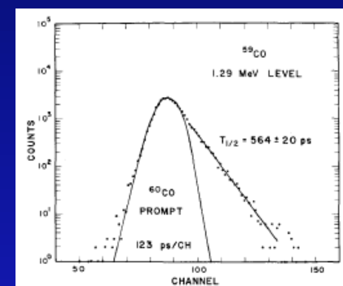
History – the CEM (2)

- Hollow tube replace strips, no B field
  - Parallel array possible
  - ø range 0.04-0.004”
- Typical secondary emitters
  - AgMgO (Cs) GaP(O) ε>10
  - Initial e- emission energy of a few eV
- Achieve high gains up to 10^8
- Ion feed-back limitations => curved channels
- Time resolution ~500ps
  - Measurement of short lifetimes of nuclear energy states
- Count rate up to 10^7
- Lifetime up to 5000GCounts

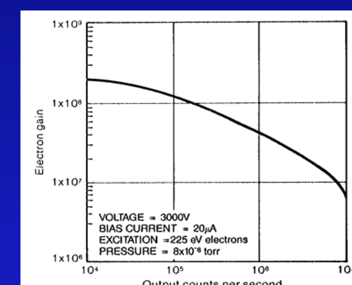


Rev. Sci. Instr. 33 (1962) 761

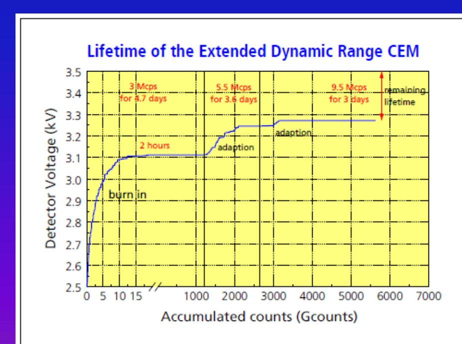




NIMA99 (1972) 445



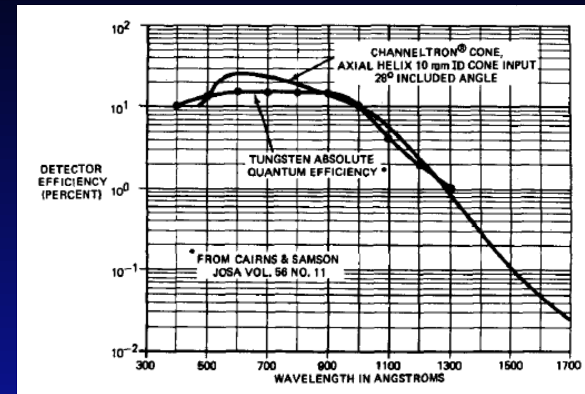
Channeltron (Burle)



SPECS GmbH

CEM applications and commercial products

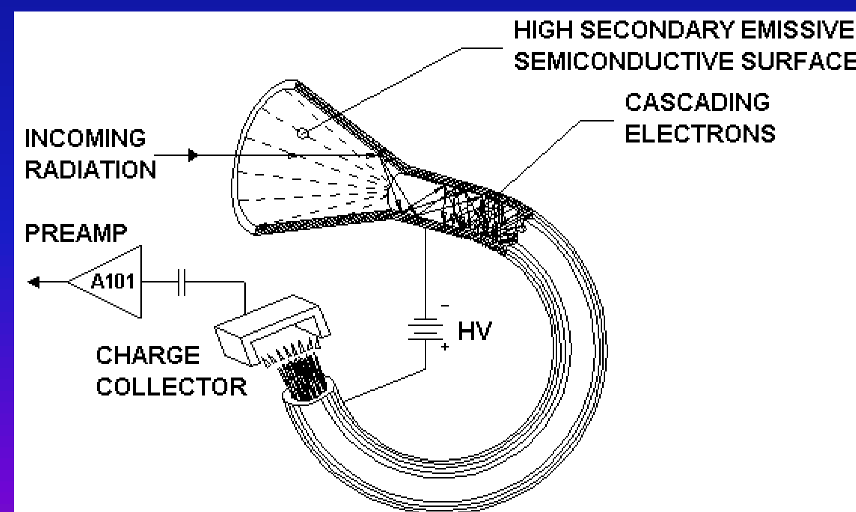
- Numerous applications in space, mass spectrometry, …
  - E.g "A secondary standard vacuum ultraviolet detector" by M.C. Johnson (Bendix)



Rev. Sci. Instr. 40,2 (1969) 311

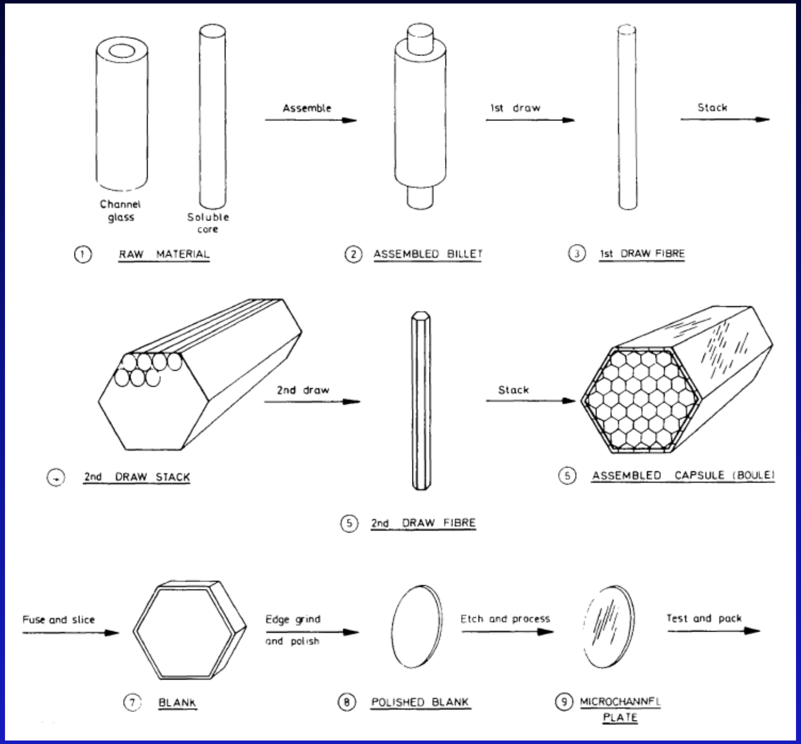
Channeltron (Burle)

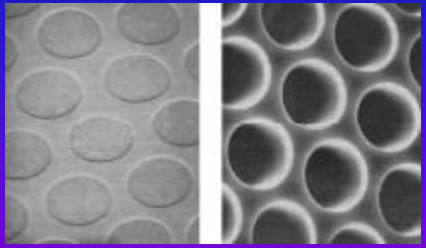
Amptektron (Amptek)



- Production of resistive surfaces in Pb-glass by high T reduction in hydrogen
  - See K. Blodgett J. Am. Ceram. Soc. 34,1 (1951) 14
- The same technology that produced optical fibres and fibre optic bundles, with a slight change in manufacturing, allowed the production of micro-channel plates
- Manufacturing steps
  - Hollow tube of non-etchable glass
  - Core of etchable glass
  - Heated and drawn (0.8mm ø)
  - Bundled to hexagon rod
  - Drawn again
  - Fused and sliced
  - Polished and etched
  - Heated under H_2 and "electroded" (NiCr)
  - Pre-conditioning through electron scrubbing
- Glass surface resistivities 10^7 to 10^{13} Ω/□

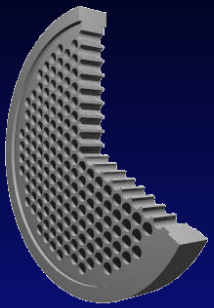
VALVO



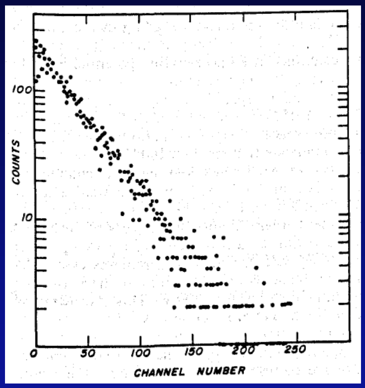


NIM162 (1979) 587

- Geometry
  - d~6-25μm
  - L~400-1000μm
  - α=L/d~40-100, defines gain
  - OAR~55-65%

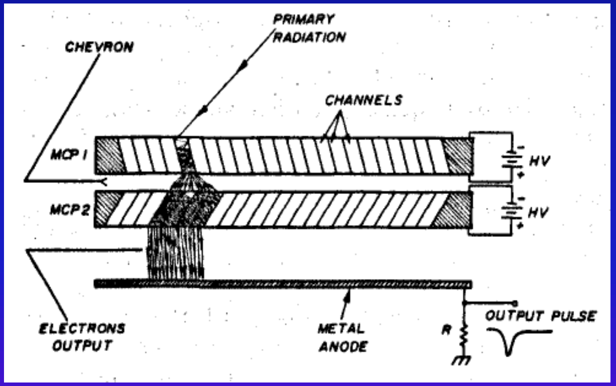


- Straight channel
  - Typical gain 10^3-10^4
  - IFB limited
  - Negative exponential PHS

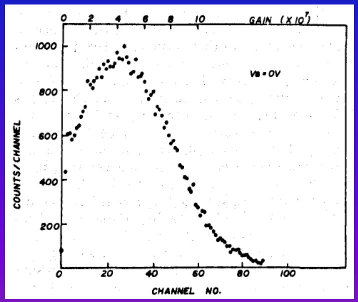


NIM162 (1979) 587

- Curved channel
  - Space-charge limited – dynamic equilibrium
  - Quasi Gaussian PHS
  - Difficult to bend if small-sized



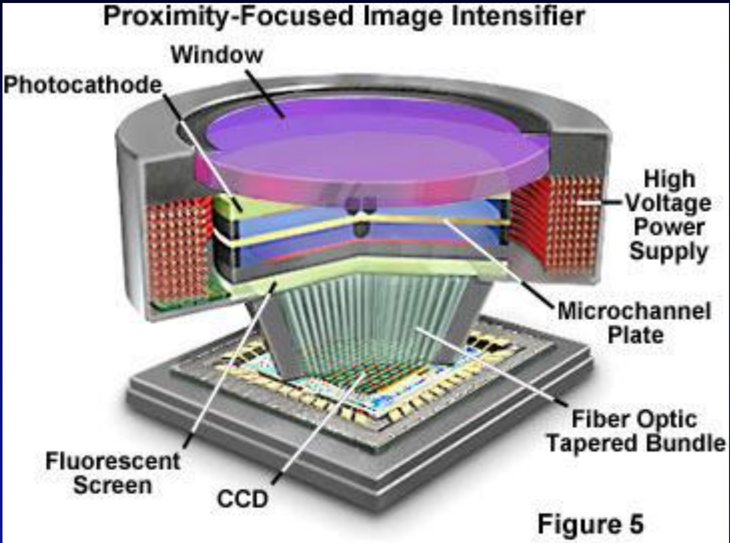
- Chevron
  - Typical gain 10^6-10^7
  - Gain ÷ d for fixed V/α
  - PHS

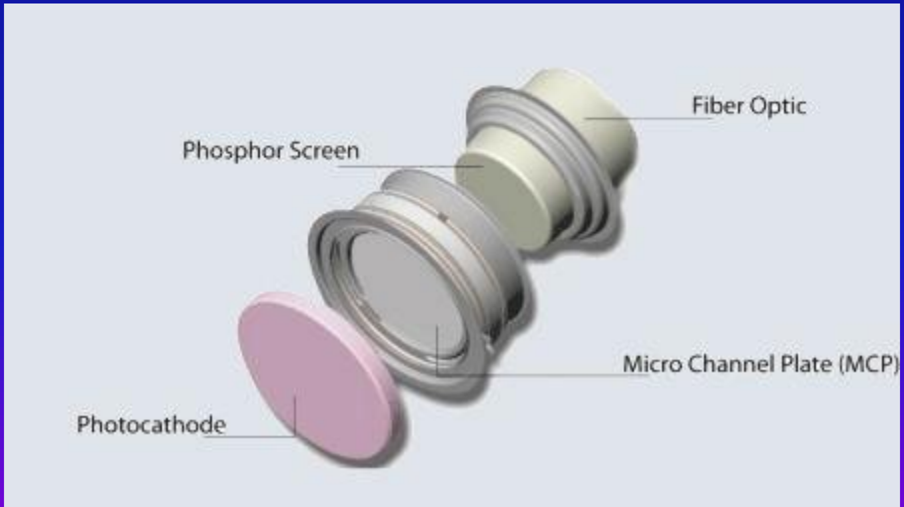


Generation II image intensifier tubes

- Driving market
  - Night vision
  - Military applications
- Typical structure
  - Optical input window
  - Photocathode
  - MCP (chevron)
  - Phosphor screen
  - Optical fibre bundle
  - CCD readout

http://www.microscopyu.com/print/articles/digitalimaging/digitalintro-print.html



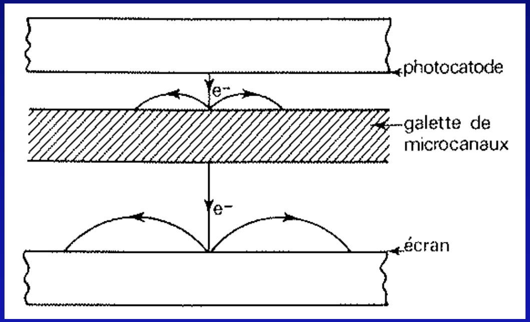


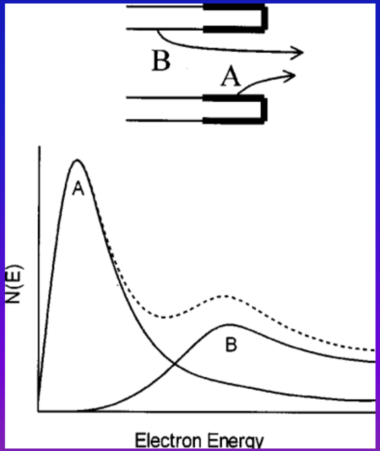
- Image features
  - High gain
  - No pin-cushion distortion (Gen I)
- Spatial resolution (and time)
  - Photon energy
  - Tube gaps
- Halos (and time tails)
  - Back-scattering
  - Tube gaps
    - PC-MCPin gap can be as small as 120µm
- End-spoiling
  - Increased spatial resolution
  - … to some extent (lens effect)
  - What about timing effects?

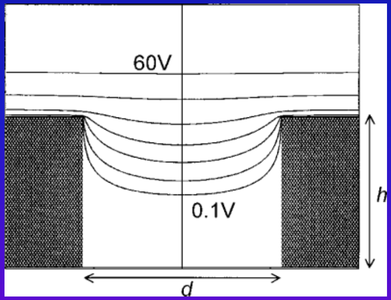
Gen I

Gen II

Acta Electronica 20,4 (1977) 369

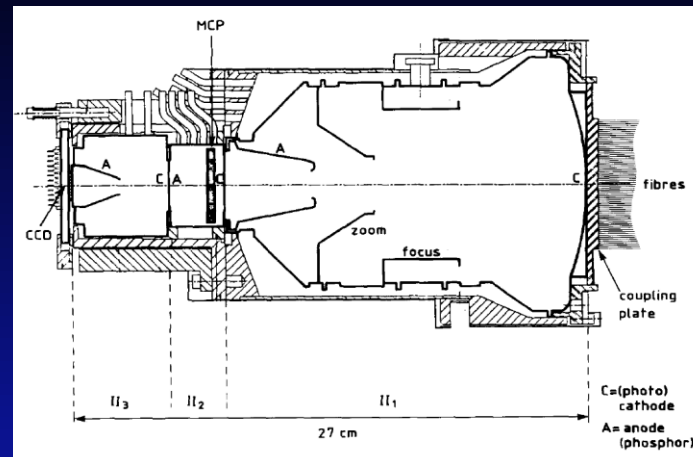


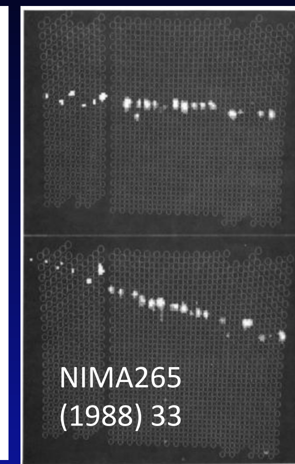




J. Vac. Sci. Tech. B 19 (2001) 843

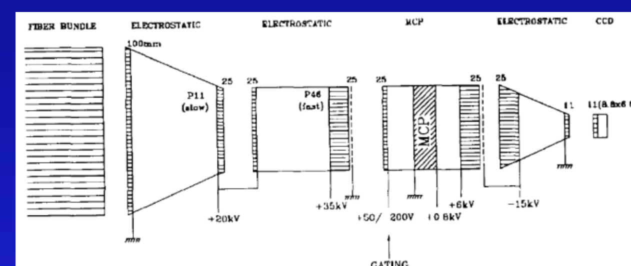
- UA2 tracker upgrade
  - Search of e- with p_T~10-30GeV/c as a signature for top quark production
  - Cascade of 3 image intensifiers
  - 1st stage is Gen I
    - Good coverage
    - De-magnification required to match Gen II size
  - 2nd stage is Gen II
    - High gain
  - 3rd stage is Gen I
    - De-magnification required to match CCD size





NIMA265 (1988) 33

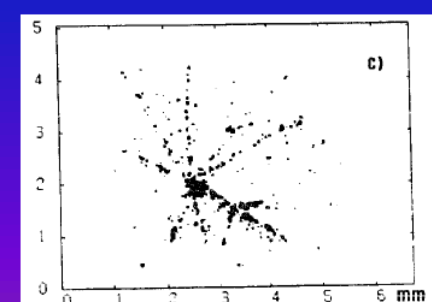
- CHORUS
  - Search for ν_μ-ν_τ oscillations
  - Fibre tracker restricts search for vertex location ν_τ,N -> τ-,X in bulk emulsion



NIMA344 (1994) 143

- WA84
  - Beauty search with scifi microvertex detector

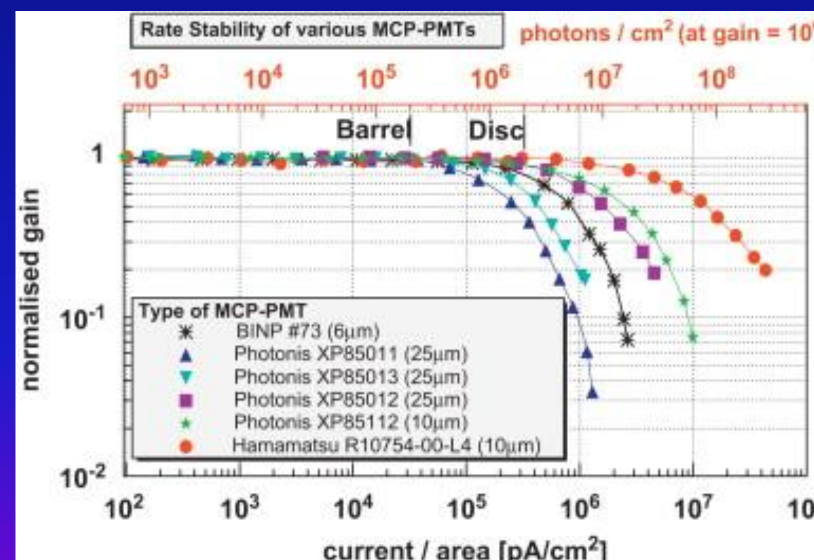
NIMA289 (1990) 342



- Some interesting features
  - Square shapes
    - Better overall coverage
  - Single-photon sensitive
  - High gain
  - Collection efficiency ~ 60%
  - Compact, high E field
    - Small TTS
    - Works in large (axial) magnetic fields
    - Good rate capability (the smaller d the better)
  - Position-sensitive
    - Appropriate anode segmentation

Photonis

Hamamatsu

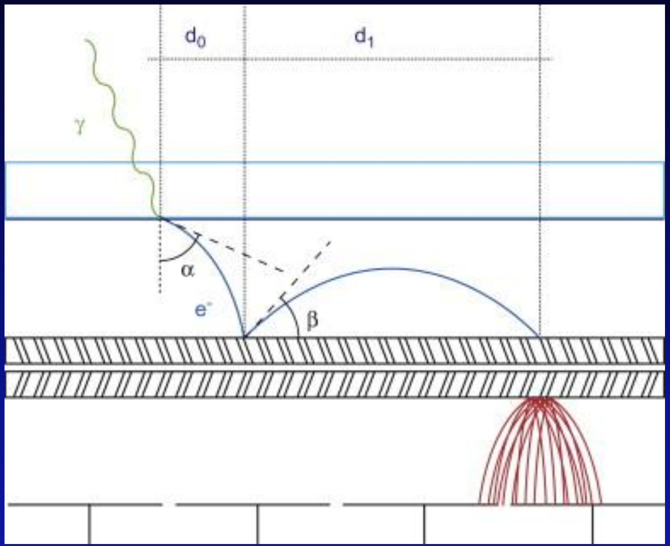


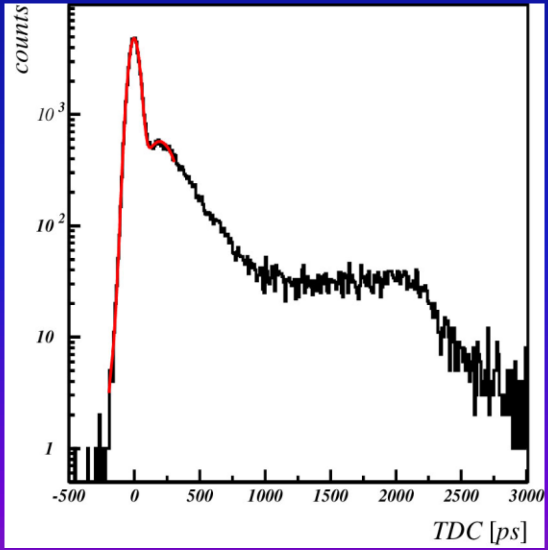
NIMA 695 (2012) 68

- Photo-electron back-scattering

Pulse height distribution

  - Tails in spatial and timing distributions
  - Spatially
    - Worst case: elastic scattering @ 45°
    - Range twice PC/MCPin gap
  - Timing
    - Worst case: elastic scattering @ 90°
    - Range twice transit time PC/MCPin



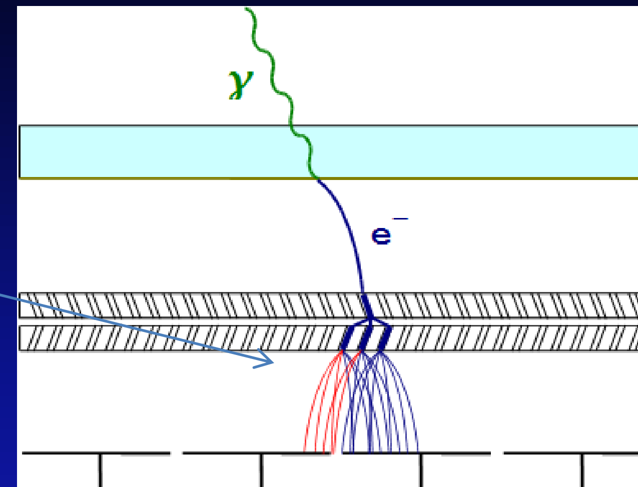


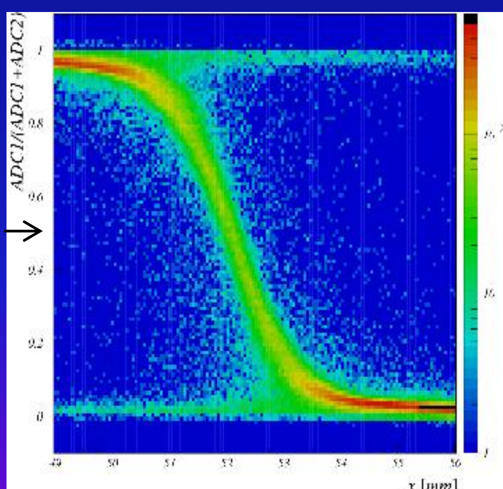
Typical single photon timing distribution with narrow main peak (σ ~ 40 ps) and contribution from photoelectron back-scattering.

NIMA595 (2008) 169

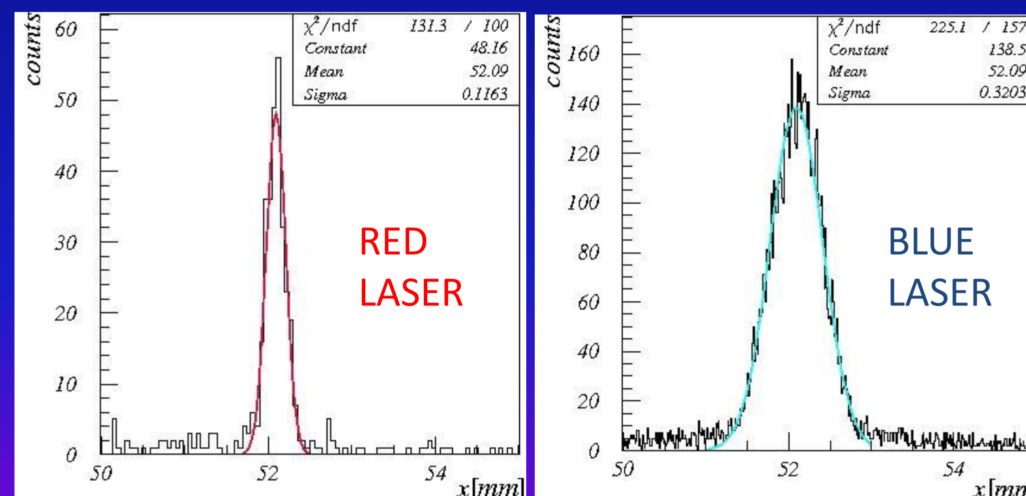
- Secondary electrons spread when traveling from MCPout to anode
- May hit more than one anode pad → Charge sharing
- May improve spatial resolution but degrade time resolution

NIMA595 (2008) 169





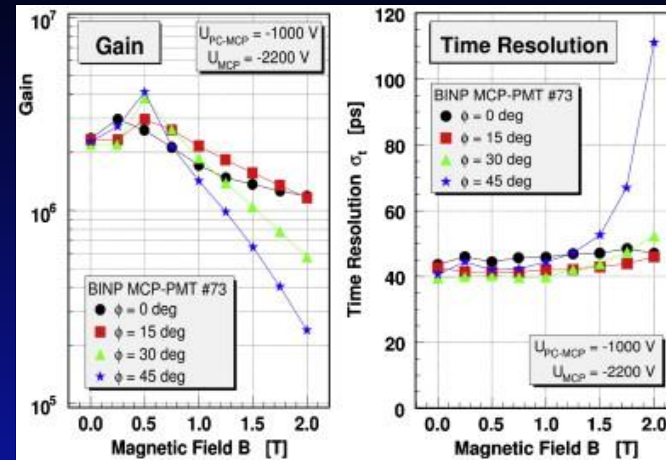
Fraction of the charge detected by left pad as a function of light spot position (red laser)



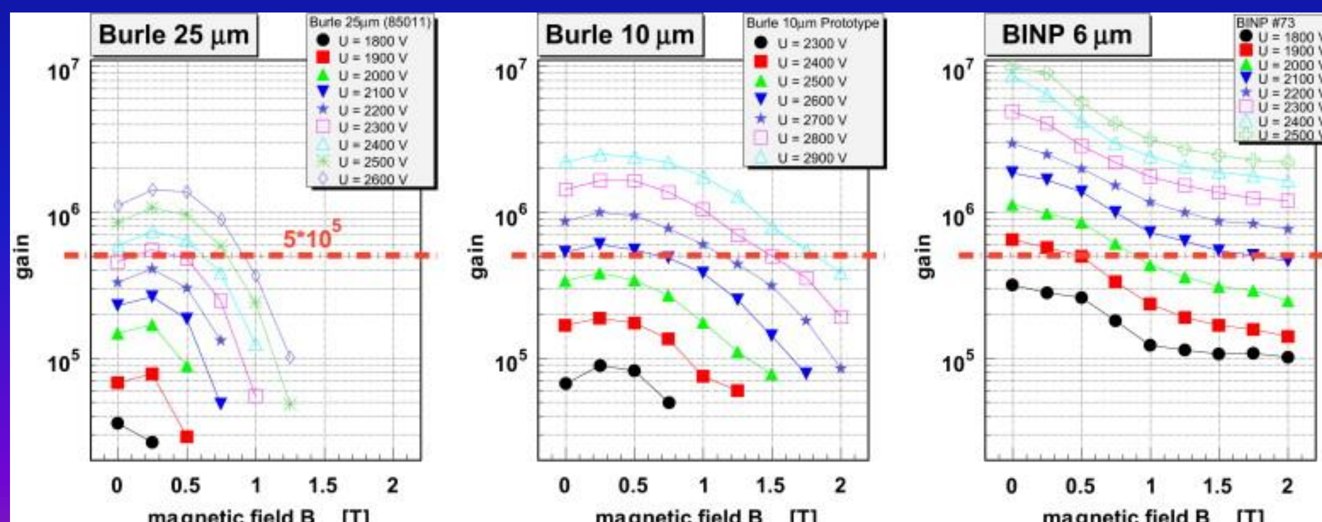
Slices at equal charge sharing for red and blue laser at pad boundary
Resolution limited by photoelectron energy.

MCP-PMT in large B fields

- Narrow amplification channel and proximity focusing electron optics allow operation in magnetic field (~axial direction)
- Amplification depends on magnetic field strength and direction
- Effects of charge sharing and photoelectron backscattering on position resolution are strongly reduced while effects on timing remain

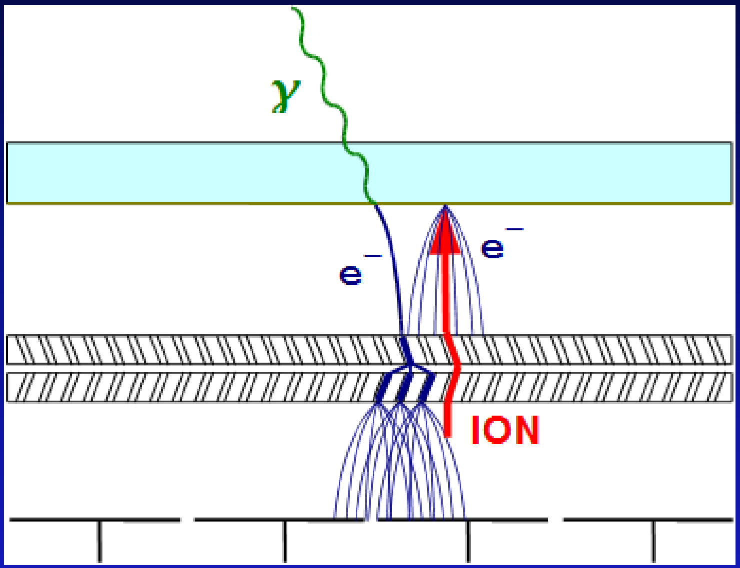


NIMA595 (2008) 173



MCP-PMT ion feedback and ageing

- During the amplification process
  - Atoms of residual gas get ionized and/or desorbed
  - Travel back towards the photocathode and produce secondary pulse
- Ion bombardment damages the photocathode reducing QE
- Atoms may react with and degrade the photocathode
- Overall gain reduction also seen

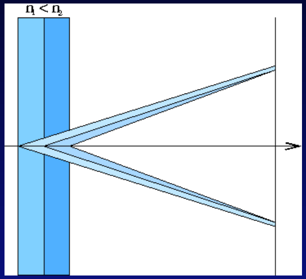


MCP-PMT ion feedback and ageing - possible strategies

- Improve vacuum quality
- Improve MCP scrubbing
- Make more robust photocathodes
- Investigate new thin-film technologies
- Investigate alternative MCP materials
  - Borosilicate, Alumina, Silicon
- Implement ion barrier film
  - 5-10nm Al_2O_3
  - On MCPin with 40% reduction of collection efficiency
  - Between MCPs
- Seal anode region from PC region

Robust photocathodes (combined with improved scrubbing)

- Developed @ BINP for FARICH concept
  - Possible applications
    - Super c-τ factory (Novosibirsk)
    - ALICE
    - PANDA forward RICH
- DCR ranges
  - $Na_2KSb(Cs)+Cs_3Sb$: 50-100 kHz/cm^2
  - $Na_2KSb(Cs)+Cs$: 5 kHz/cm^2
  - $Na_2KSb(Cs)$: 0.5 kHz/cm^2
  - Na_2KSb: <0.5 kHz/cm^2
- Test operating parameters
  - Counting rate 2-10MHz/cm^2
  - Gain 10^6
- Recoverable gain change



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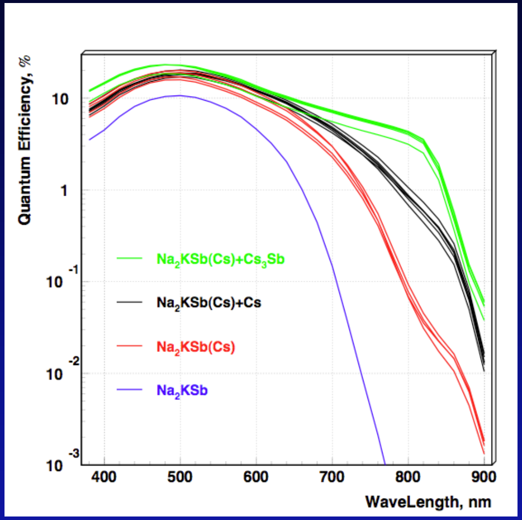
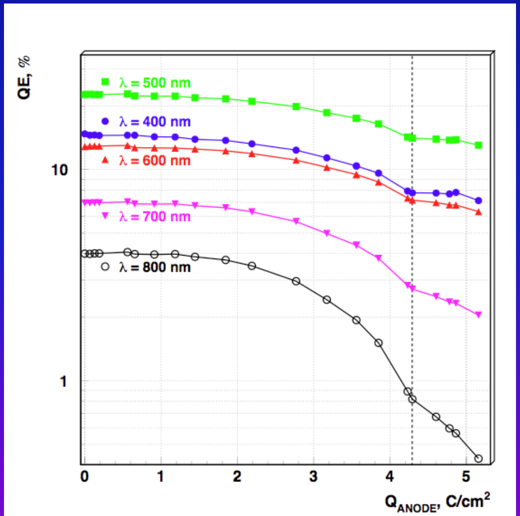
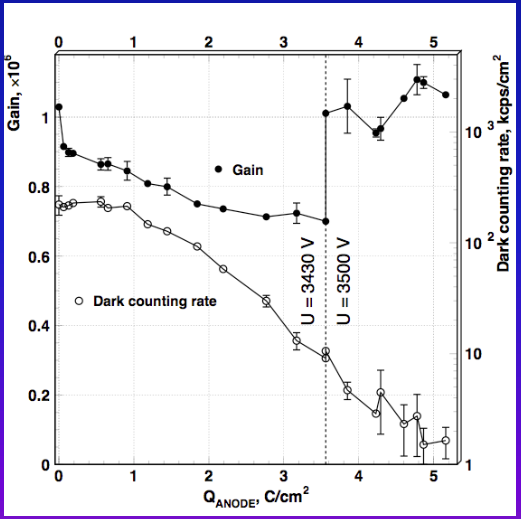
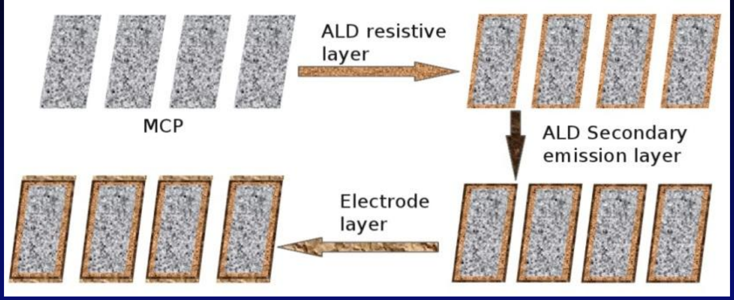






Atomic layer deposition (ALD)

See talk of O. Siegmund at this Conference



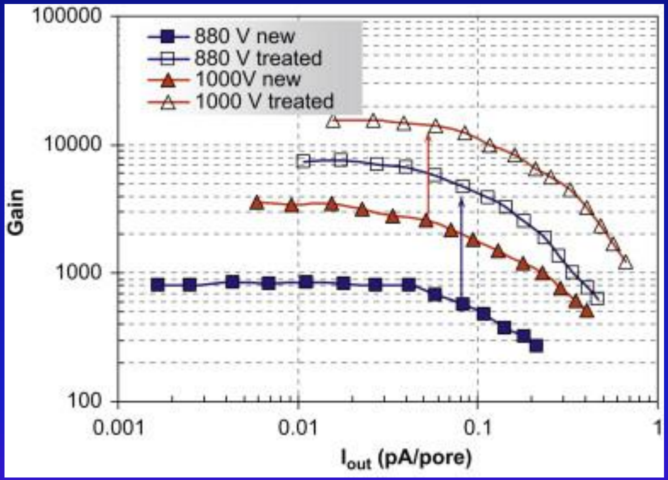
Arradiance

- Three-step deposition process
  - Resistive layer
  - Secondary emission layer
  - Electrode layer

- Optimization of MCP resistance and SEE
  - Independently for each film
  - For a given gain, lower operating voltage

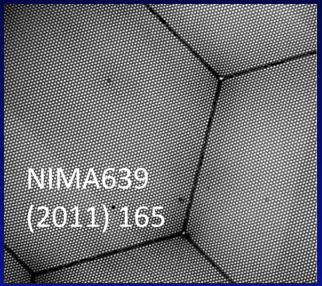
- Allow use of insulating materials other than Pb-glass

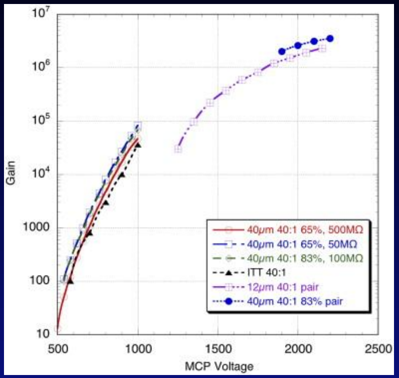
- Initiated by the LAPPD Collaboration

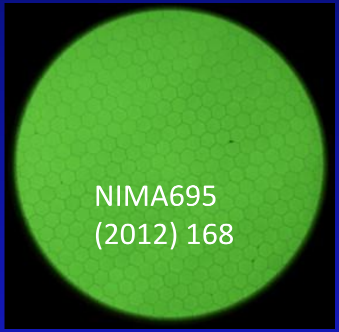


NIMA607 (2009) 81–84

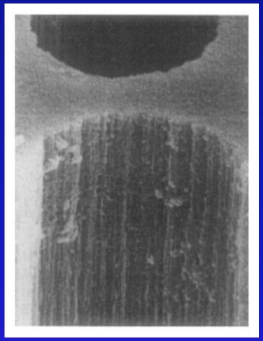
- Borosilicate → See talk of O. Siegmund at this Conference
  - In combination with ALD
  - “Micro capillary array”
  - Large area
  - Improved process







- Anodic alumina

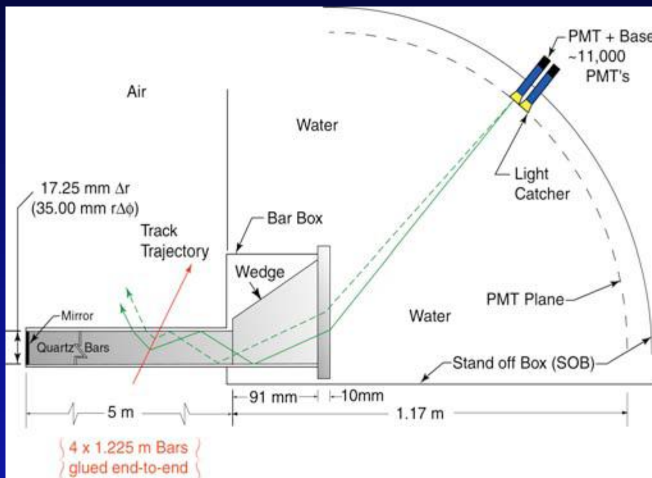


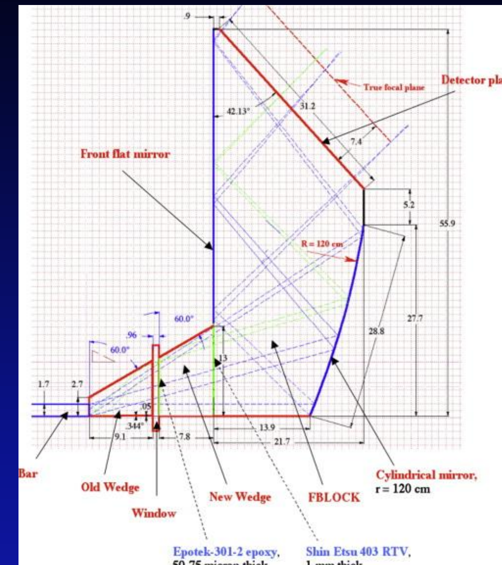
Nucl. Phys. B (Proc. Suppl.) 125 (2003) 394

NIMA567,1 (2006) 290

- Amorphous Si-based → See talk of F. Andrea at this Conference

DIRC concept (BaBar) – 2D imaging

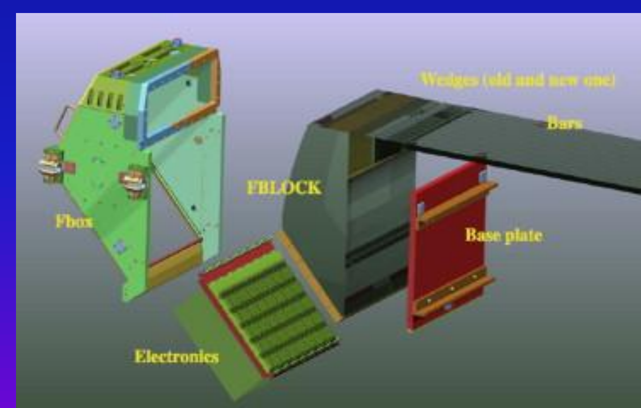




NIMA718 (2013)

Focusing DIRC with chromatic correction (SuperB) uses measured time of propagation to correct chromatic error

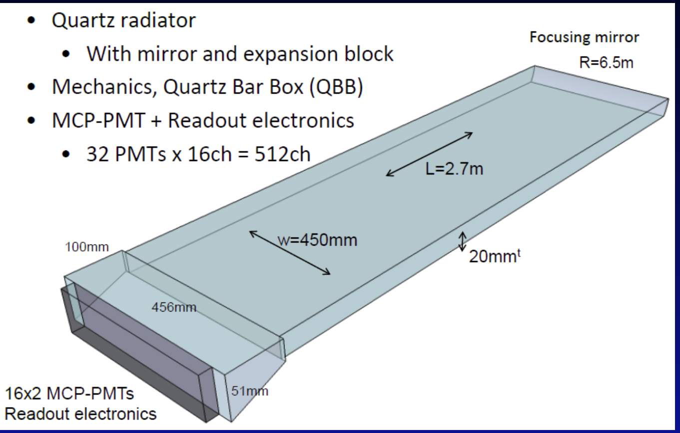
$$t_p = \frac{L_{path}}{v_g} \quad v_g = \frac{c}{n(\lambda) - \lambda \dfrac{dn}{d\lambda}} \quad \text{(group velocity)}$$



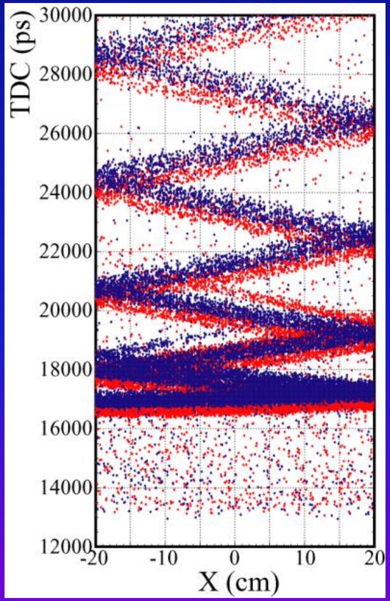
Required various MCP-related R&D

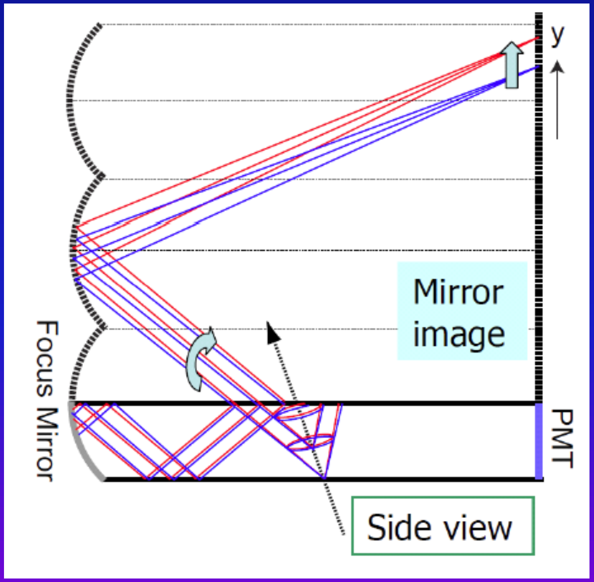
See talk of S. Hirose at this Conference

- Particle ID in Belle II
- TOP (Time-Of-Propagation)
  - Counter based on DIRC concept
  - Using linear array of MCP-PMTs to measure x coordinate and time of propagation (length of photon path)
  - Chromaticity dispersion 100ps
  - Evolved towards iTOP with focussing mirror and y coordinate



K. Inami RICH2013





Belle II iTOP photon detectors

- MCP-PMT requirements
  - Integrated charge
    - 1.2-2.4 C/cm^2/50 ab^{-1} (5x10^5 gain)
    - Lifetime 0.8QE
  - Enhanced multi-alkali (>28% QE at peak)
  - MCP
    - Channel ϕ 10µm
    - bias angle 13°
    - thickness 400µm
    - layers 2
  - Al protection layer on 2nd MCP + sealing + ALD
  - Anode channels 4×4
  - Sensitive region 64%
  - HV ~ 2500 – 3500 V
  - Readout: analogue sampling memory

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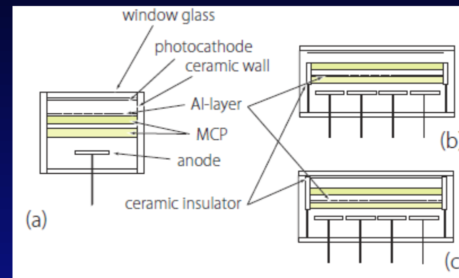

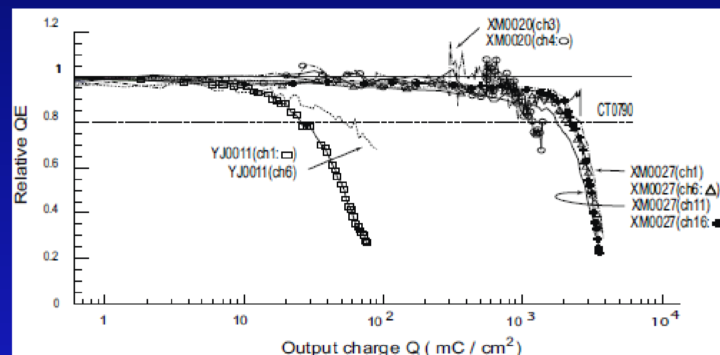

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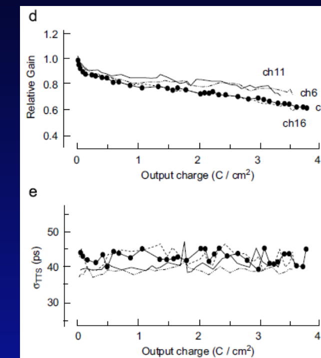
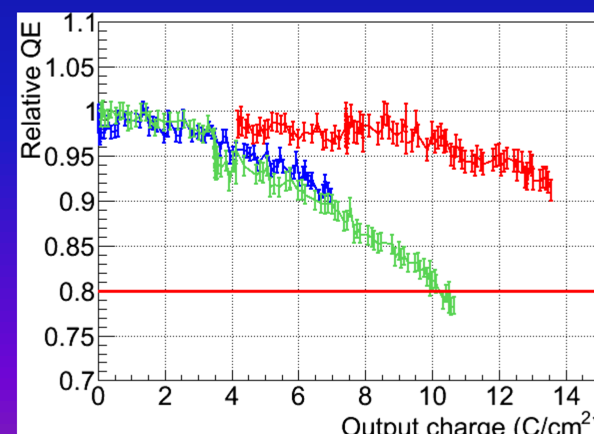
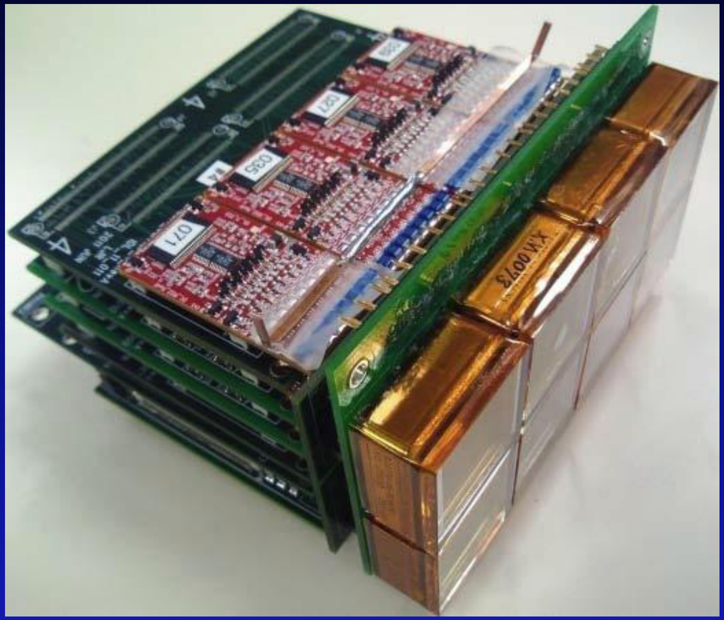
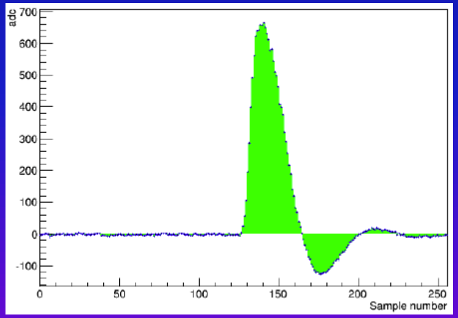


K. Matsuoka RICH2013



- Time resolution: acceptable up to 100 ps (rms)
- T_0 jitter: acceptable up to 50 ps (rms)
- MCP-PMT signal is read out by newly developed "IRS" (Ice Radio Sampler) series of ASICs
  - Waveform sampling
  - Clear signal read out by ASIC
  - High density, multi-hit buffering 512ch / module, 30kHz trigger rate
  - Clock jitter measured with test pulse is about 20ps.



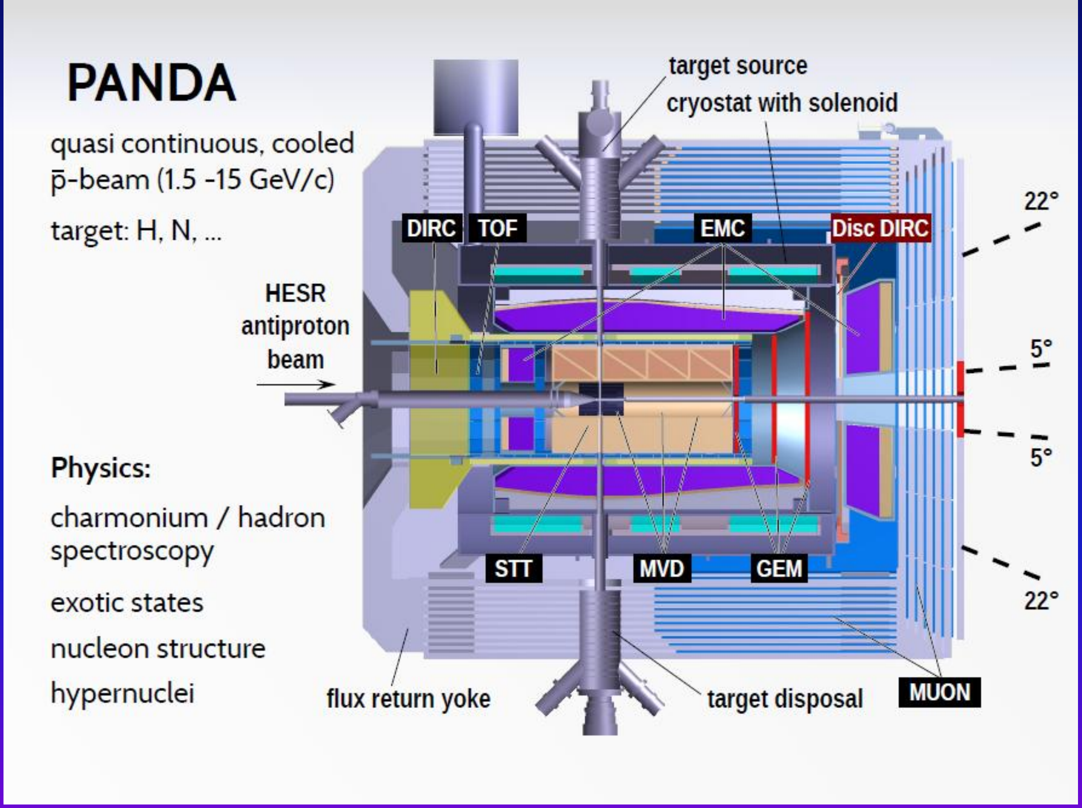


K. Inami RICH2013

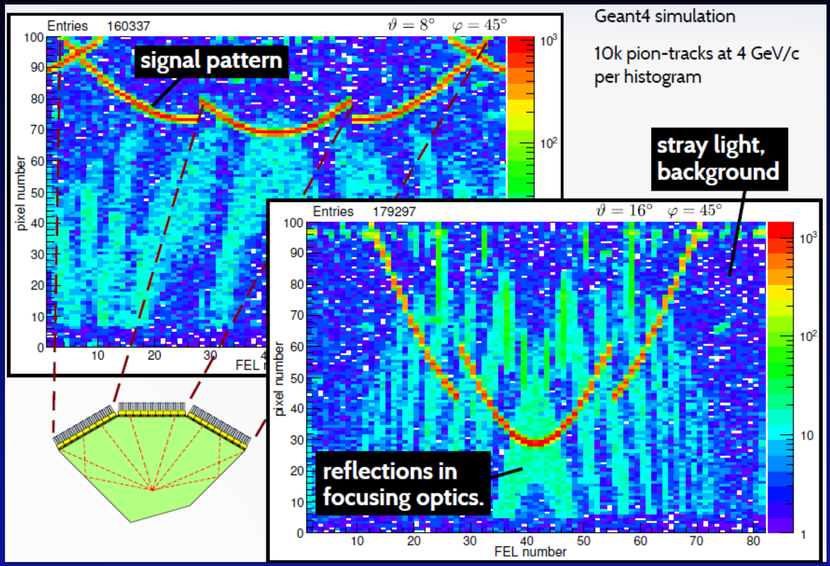
See talk of A. Lehmann at this Conference

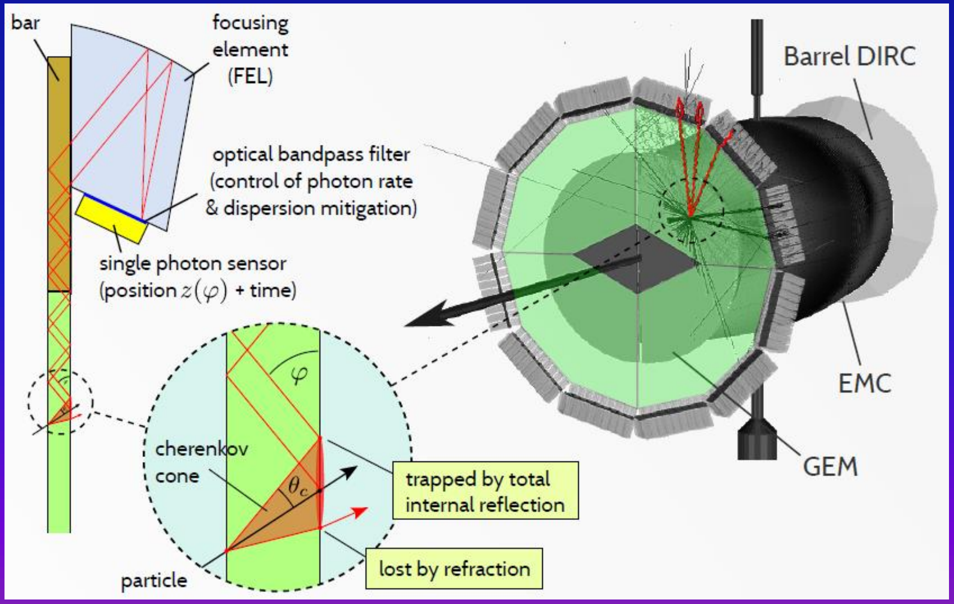
O. Merle RICH2013

- Interaction rate
  - cycle average: ~10 MHz
  - max. average: ~20 MHz
- Require K/π separation up to 4GeV/c
- Disc DIRC
  - Very limited space
  - B field 1-2T
  - ~ 3 "Cherenkov emitting" tracks per interaction
  - Triggerless operation
  - 1 MeV n-equivalent fluence $>2\cdot10^{11}$ neq/cm^2



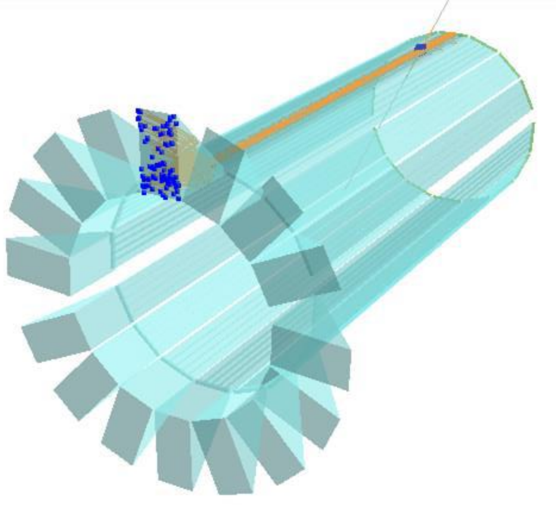
- MCP-PMT requirements
  - Integrated charge ~ 5.6C/cm^2
  - Rate ~ 225kHz/cm^2
  - Bfield 1-2T
  - Segmentation 3x100 on 2” sq. tube
- ASIC candidate
  - TOF-PET Rolo et al. 2013 JINST 8 C02050

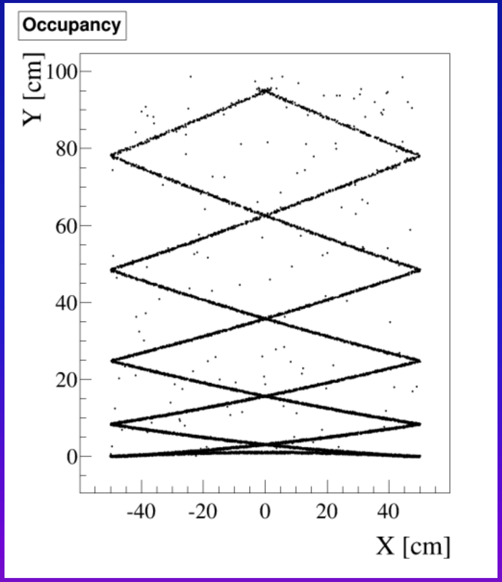




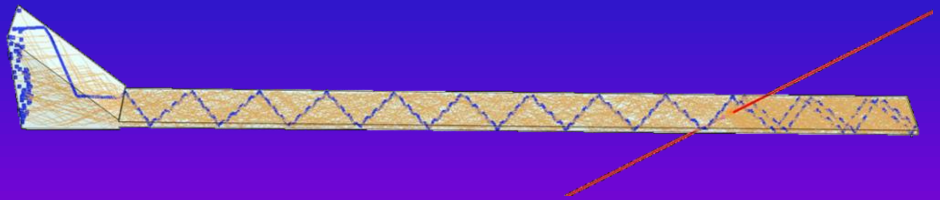
O. Merle RICH2013

- DIRC concept
- Design similar to BELLE II iTOP
- MCP-PMT requirements
  - Single photon detection
  - Spatial resolution ~ few mm
  - Fast rise time
  - Operation in 1 T field
  - High-rate capability ~0.2 MHz/cm^2
  - Long lifetime: 0.5 C/cm^2 per year at 10^6 gain
  - Photonis 8x8



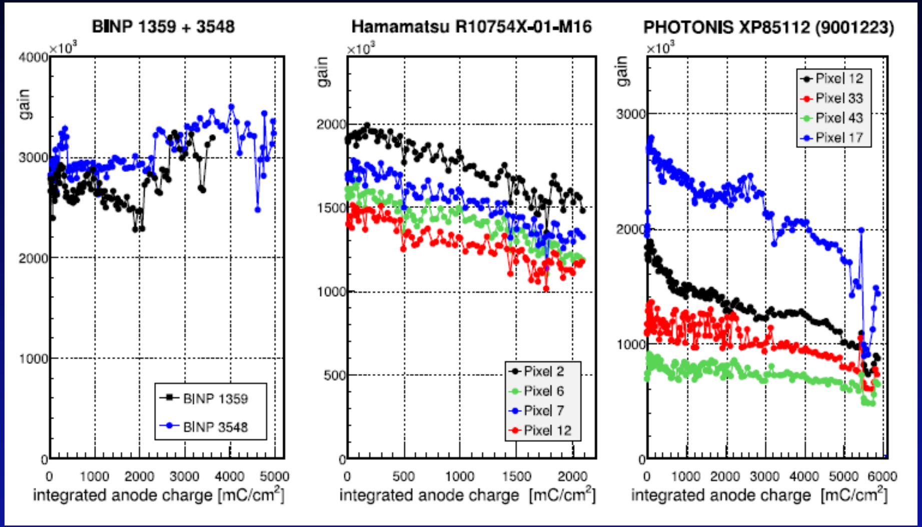


M. Hoek RICH2013

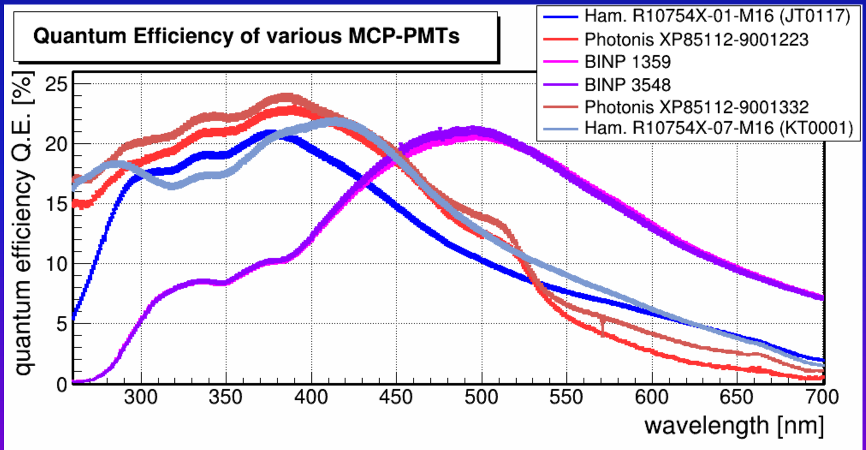


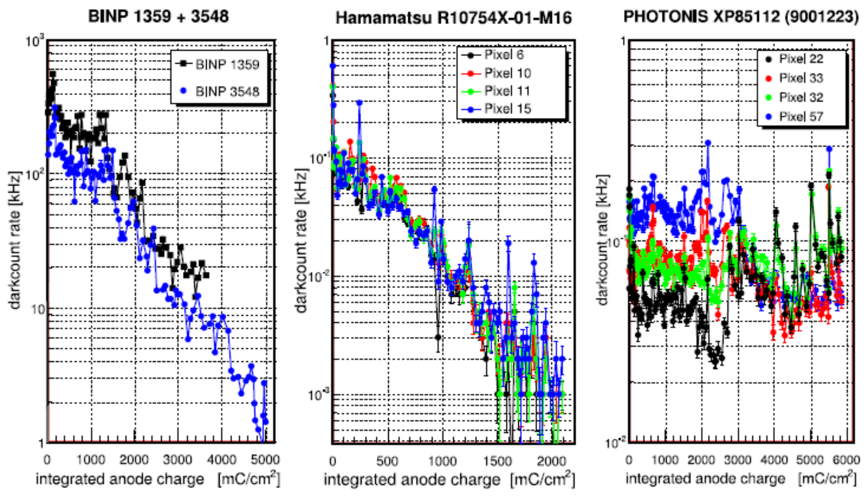
Panda photon detectors – evolution of lifetime

- Moderate MCP gain changes
- Decrease of DCR



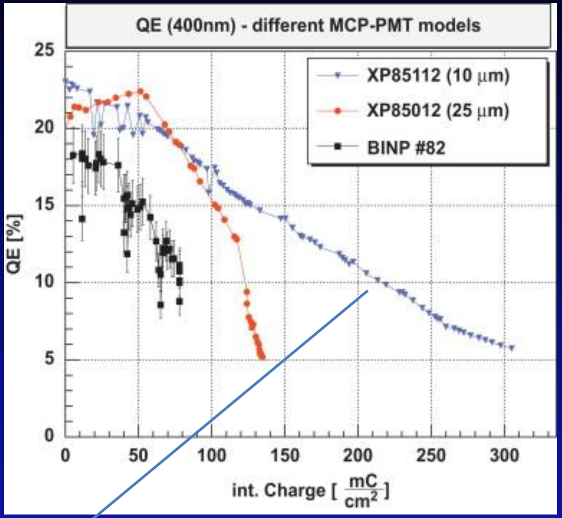
A. Lehmann RICH2013





Panda photon detectors – evolution of lifetime

- Big improvement for ALD-processed MCPs



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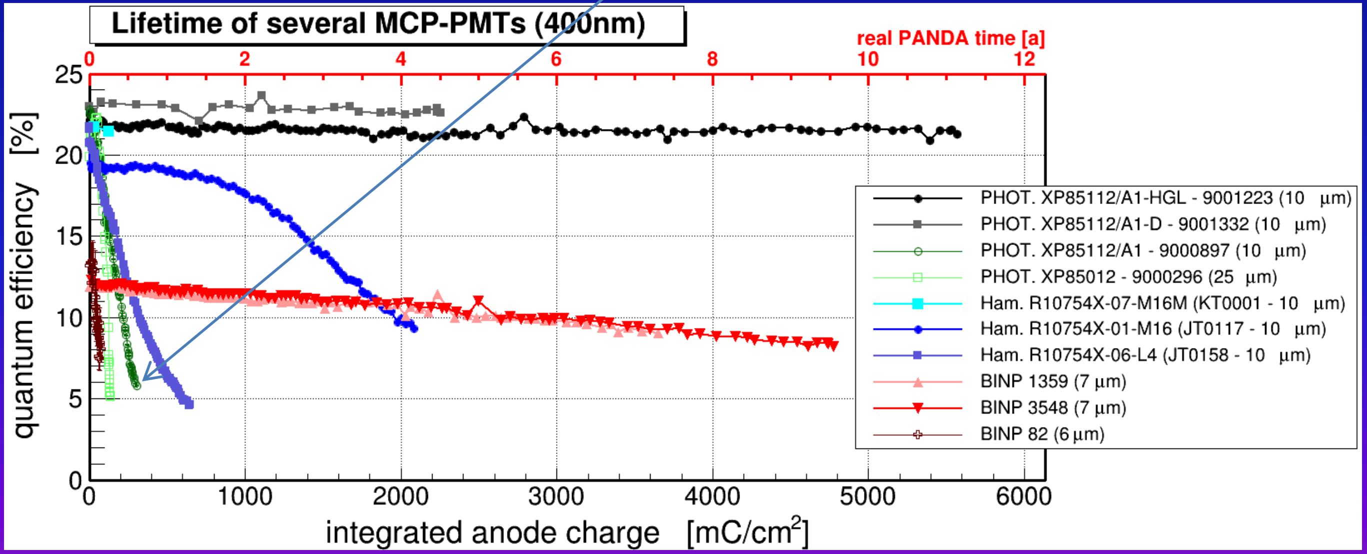

A. Lehmann RICH2013

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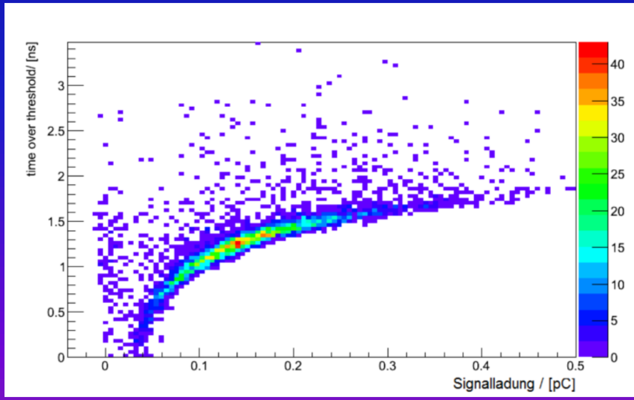
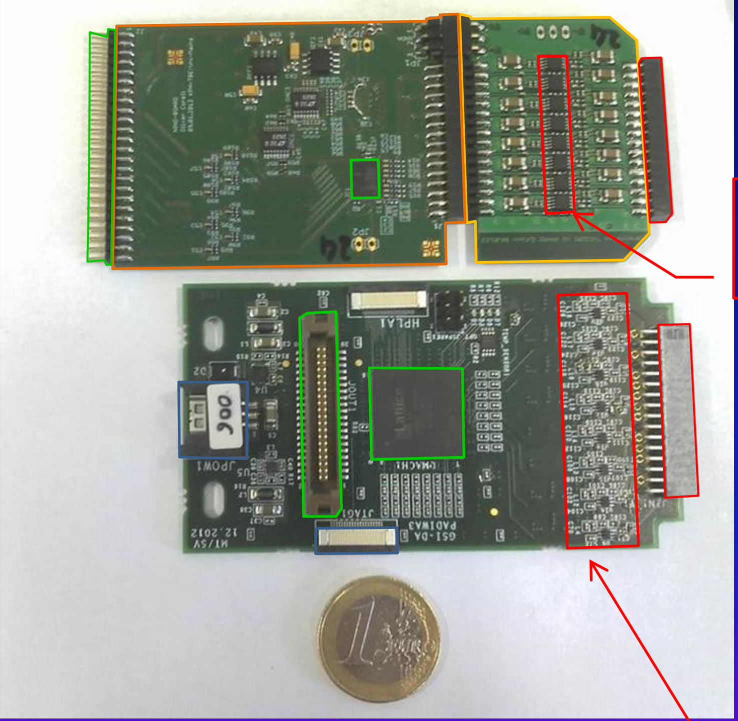
- DAQ system based on TRBv3 board (developed at GSI)
  - High-resolution TDC (<10 ps) based on FPGAs
  - LVDS input signals
  - Precise timing
  - Amplitude information (ToT)
- Compare different technologies
  - ASIC: NINO chip (ALICE TOF)
  - FPGA: PADIWA (GSI)
  - From beam tests TTS O(50ps) achieved

M. Hoek RICH2013





NINO

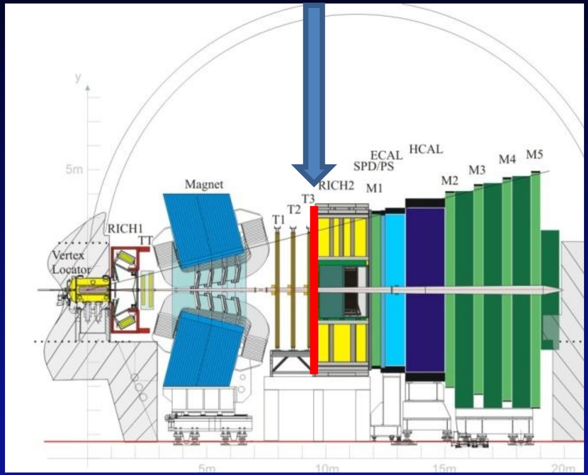
Current feedback amplifier (THS3201)

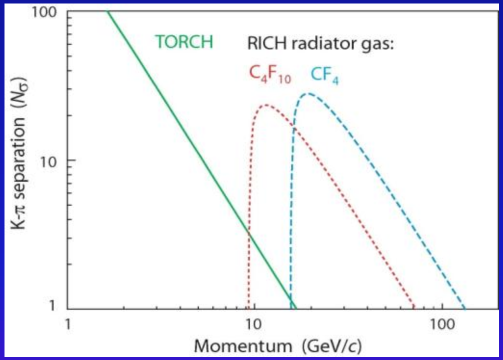
PADIWA

Pre-amplifier (MMIC)

See talk of L. Castillo García at this Conference

- TORCH (Time Of internally Reflected CHerenkov light) is a possible solution for low-momentum particle ID in LHCb
- Largely inspired by Babar DIRC and iTOP concepts of Belle II
- Want positive identification of kaons in region below their threshold for producing light in the C_4F_{10} gas of RICH-1, i.e. p < 10 GeV/c
- ΔTOF (π-K) = ~35 ps at 10 GeV/c over a distance of ~ 10 m → aim for ~15 ps resolution per track
- ERC-funded Project (ERC-2011-AdG, 291175-TORCH)





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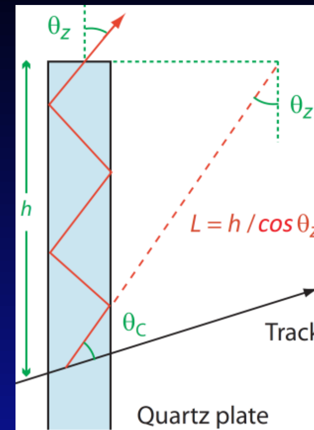
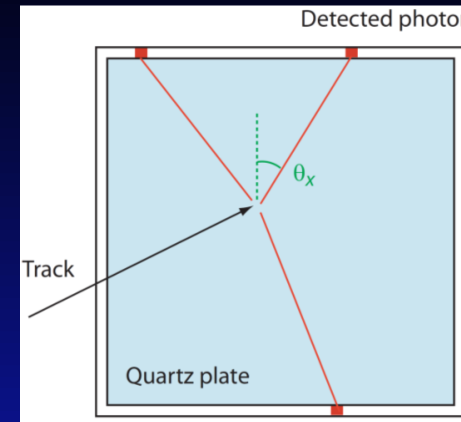
- Reconstruction
  - Measure angles θ_x, θ_z of photon trajectory with 1mrad precision to reconstruct photon path length
  - Require appropriate focussing optics at periphery and corresponding coarse (θ_x) and fine (θ_z) segmentation of photon detectors





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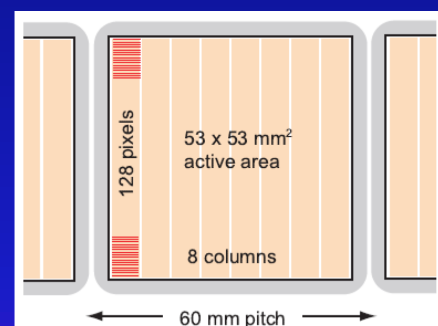
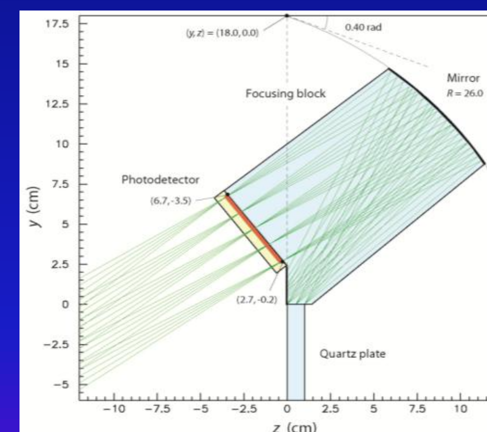
- MCP-PMT requirements
  - Segmentation 8x128 (~6.4mmx0.4mm for a 2” tube)
  - Typical gain 100fC (6×10^5)
  - TTS 50ps for single photons (including electronics)
  - 100 tracks per event, 30 detected photons per track every 25ns
    => 1-10MHz/cm^2 detected photon rate
    => 1-10C/cm^2 per year

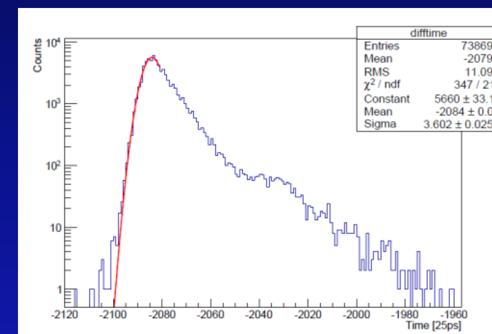




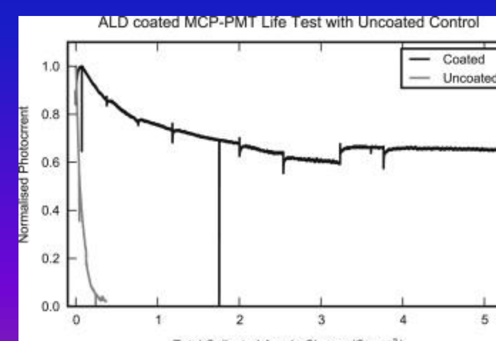
- Commercial MCP-PMTs
  - The closest candidates
    - Planacon 8x8 5.9 mm/6.5 mm in size/pitch
    - Planacon 32x32 1.1 mm/1.6 mm in size/pitch
  - Measured TTS for single photon
    - 38ps with single-channel electronics
    - ≤90ps with NINO/HPTDC (w/o time walk and non-linearity corrections)
  - Fine segmentation → not OK
- Custom MCP-PMTs
  - Dedicated R&D programme subdivided in three phases
    - Circular devices with extended lifetime
    - Circular devices with required segmentation
    - Square devices with extended lifetime and required

Photonis

L. Castillo García et al. ICATPP2013



Photek



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Conclusions and perspectives

- MCP concept is old but technology is still evolving and improving
- Most spectacular progress is on lifetime – to be confirmed long-term on large quantities
- Trend towards finer anode spatial segmentation
- Readout electronics is a challenge
  - High channel count rate
  - High speed
  - High SNR
- Cost aspects!
- Some design guidelines
  - Survey of existing technologies
  - Collaboration with industry: as much as possible, try to combine/match requirements with industrial standards
  - Development of new photon detectors and their associated readout (front-end) electronics should be carried out in parallel but not independently

Note: apologies for any omission!

- @ Session 6 – High Energy Physics
    - L. Burmistrov, “Cherenkov detector for proton Flux Measurement (CpFM)”
- @ Session 10 – Cherenkov Detectors
    - S. Hirose, “Development of the MCP-PMT for the Belle II TOP Counter”
    - L. Castillo García, “MCP photon detectors studies for the TORCH detector”
- @ Session 11 – Innovative Photodetectors
    - L. Hiirvonen, “Sub-exposure-time time resolution in wide-field time-correlated single photon counting imaging”

MCP-related talks at this Conference (2)

- @ Session 12 – MCPs
  - Q. Sen "The Status of MCP-PMT R&D in China"
  - O. Siegmund, "Application of Atomic Layer Deposited Microchannel Plates to Imaging Photodetectors with High Time Resolution"
  - F. Andrea et al., "Latest results about the performances of amorphous silicon-based microchannel plate"
  - A. Lehmann et al., "Breakthrough in the Lifetime of Microchannel-Plate PMTs"
  - V. Yurevich, "Development and study of picosecond start and trigger detector for high-energy heavy ion experiments"
- @ Session 16 – Readout Electronics
  - J. Lapington et al., "The capacitive division image readout; an imaging technique combining high time and spatial resolution"
  - M. Fiorini et al., "CLARO-CMOS: a fast, low power and radiation-hard front-end ASIC for single-photon counting in 0.35 micron CMOS technology"

MCP-related posters at this Conference

- @ Poster Session #2
  - M. Minot et al., “Pilot Production & Commercialization of LAPPD™”
  - L. Giudicotti, “Gain saturation in microchannel plate detectors”
  - A. Tremsin, “Optimization of High Count Rate Photon Counting Detector with Microchannel Plates and Quad Timepix readout”
- @ Poster Session #3
  - S. Leach et al., “Optimising image resolution for photon-counting detectors using adaptive pulse processing”

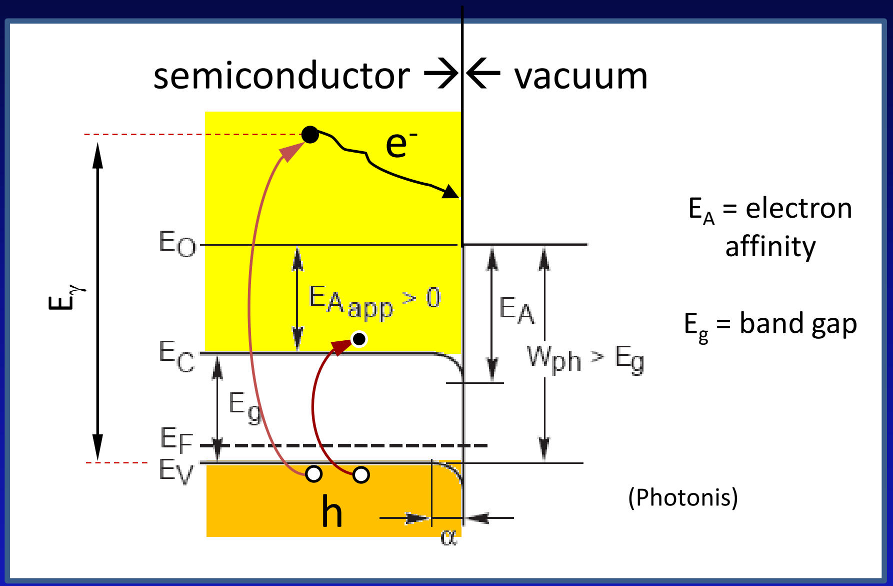
Spare slides

Photoelectric effect in a vacuum photocathode

Solid materials (usually semiconductors)

Multi-step process:

1. absorbed γ's impart energy to electrons (e) in the material; If $E_\gamma > E_g$, electrons are lifted to conductance band.
   → In a Si-photodiode, these electrons can create a photocurrent. → Photon detected by Internal Photoeffect.

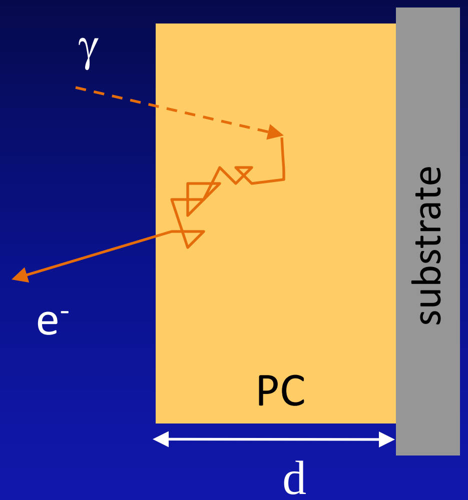


However, if the detection method requires extraction of the electron, 2 more steps must be accomplished:

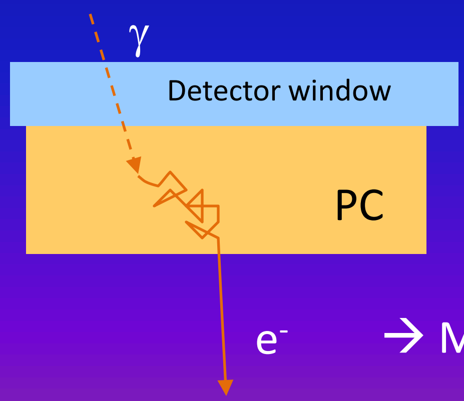
2. energized e's diffuse through the material, losing part of their energy (~random walk) due to electron-phonon scattering. $\Delta E \sim 0.05$ eV per collision. Free path between 2 collisions $\lambda_f \sim 2.5 - 5$ nm → escape depth $\lambda_e \sim$ some tens of nm.
3. only e's reaching the surface with sufficient excess energy escape from it
   → External Photoeffect

$$E_\gamma = h\nu > W_{ph} = E_G + E_A$$

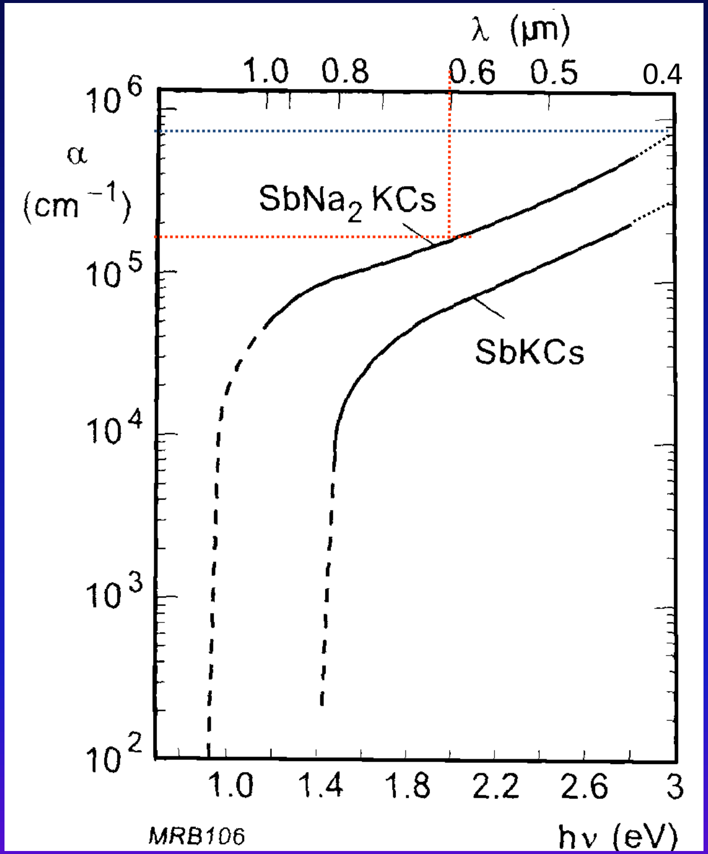
Opaque photocathode



Semitransparent photocathode



Light absorption in photocathode



$N = N_0 \cdot \exp(-\alpha d)$

$\lambda_A = 1/\alpha$

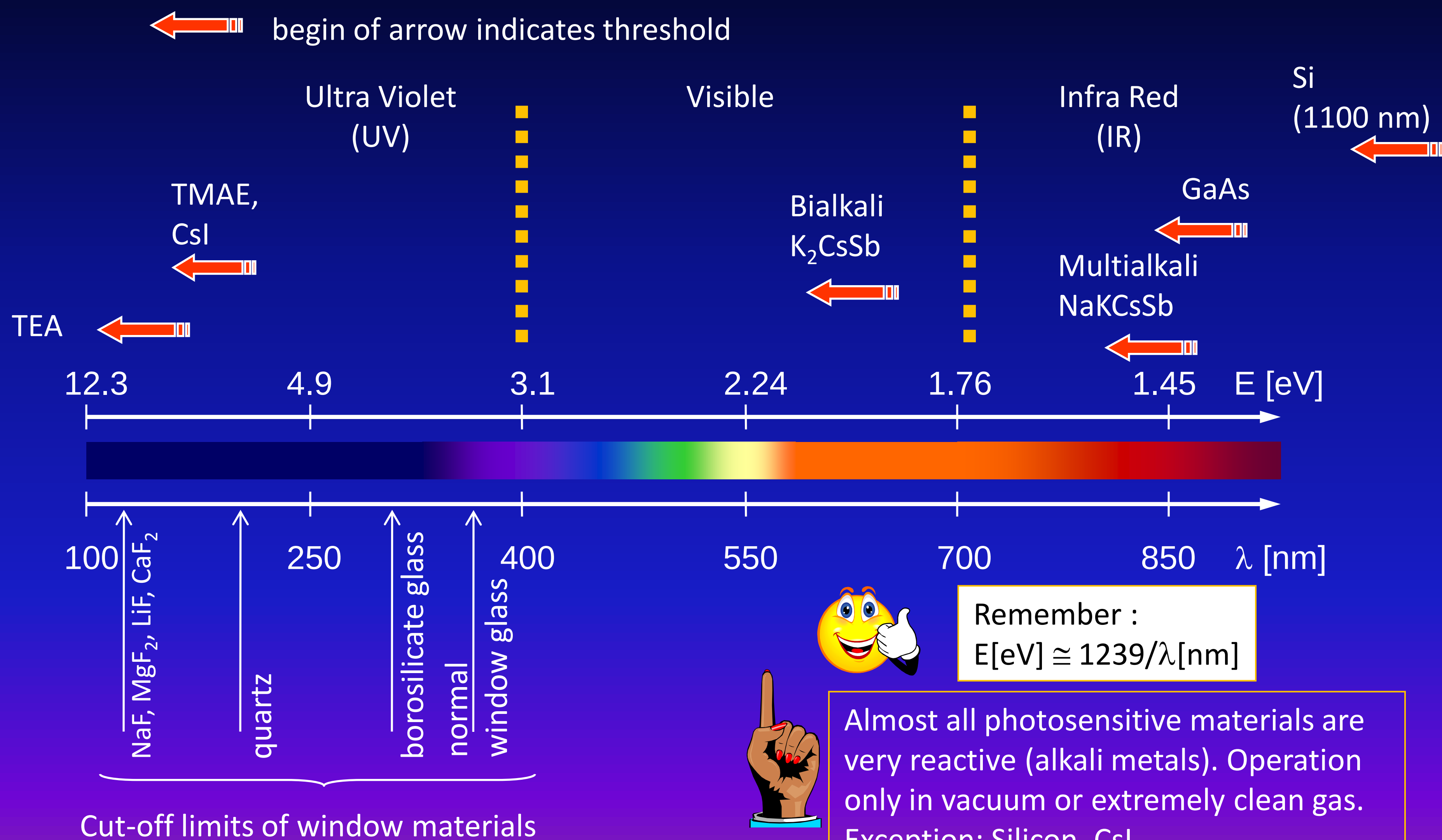
Red light ($\lambda \approx 600$ nm)
$\alpha \approx 1.5 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 60$ nm

Blue light ($\lambda \approx 400$ nm)
$\alpha \approx 7 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 15$ nm

Blue light is stronger absorbed than red light !

→ Make semitransparent photocathode just as thick as necessary!

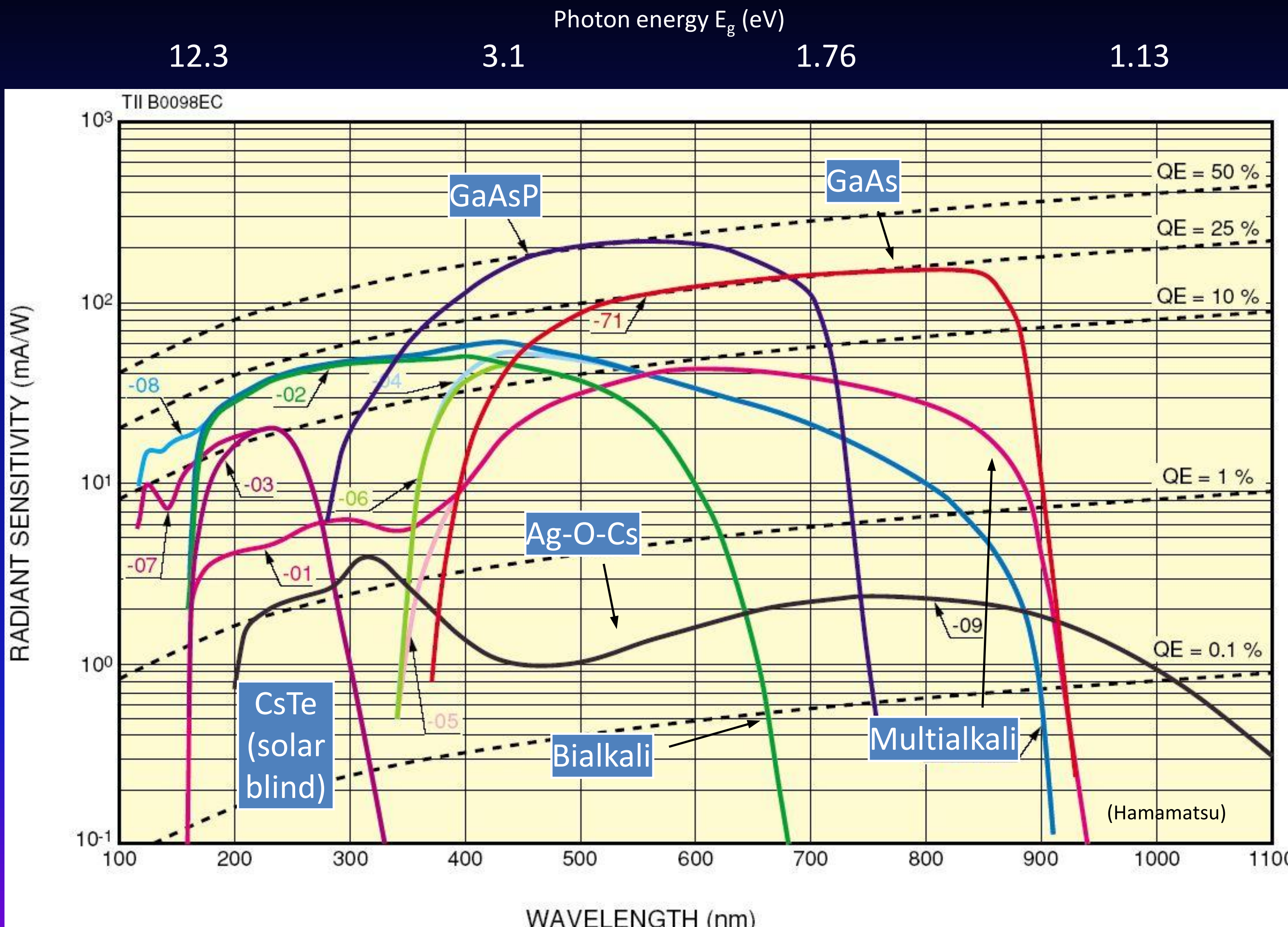
Frequently used photosensitive materials / photo-cathodes



Remember :
E[eV] ≅ 1239/λ[nm]

Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas. Exception: Silicon, CsI.

(External) QE of typical semitransparent photo-cathodes



Bialkali: SbKCs, SbRbCs Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

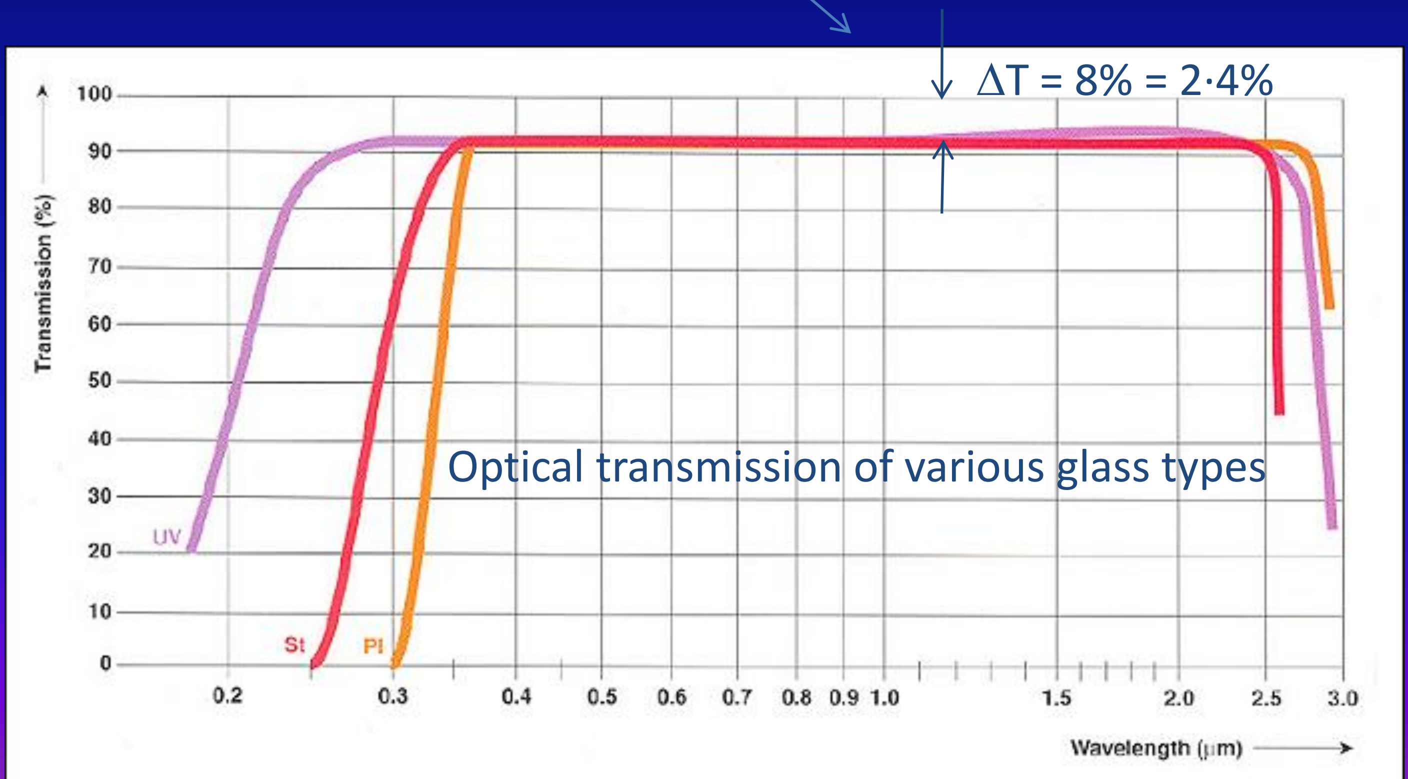
2 types of losses:

- Fresnel reflection at interface air/window and window/photocathode

  $R_{Fresnel} = (n-1)^2 / (n+1)^2$ n = refractive index (wavelength dependent!)

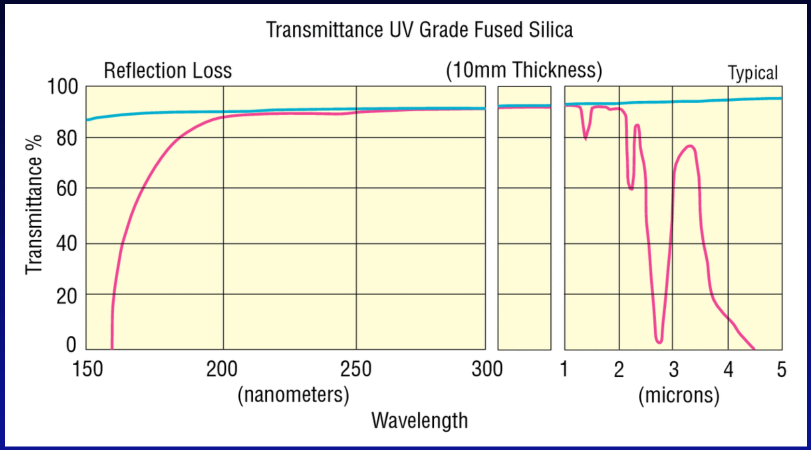
  $n_{glass} \sim 1.5$ $R_{Fresnel} = 0.04$ (per interface)

- Bulk absorption due to impurities or intrinsic cut-off limit. Absorption is proportional to window thickness



Schott

Optical transmission of typical window / substrate materials



Newport