Micro-Channel Plate Photon Detectors

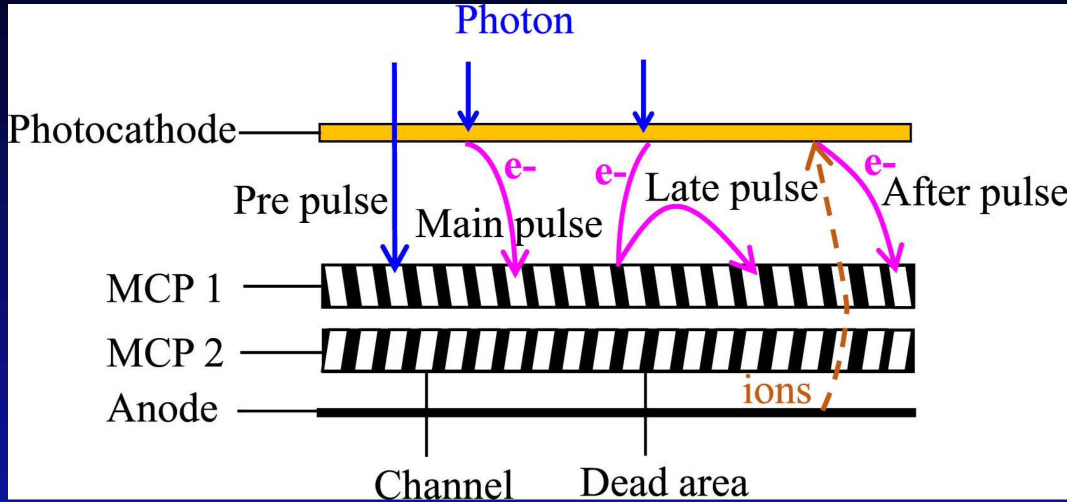
Thierry Gys
(CERN/PH-DT)

Outline

- Previous seminar given on 7th February 2014
  - https://indico.cern.ch/event/288433/
  - History – From large-size single channels to micro-channel plates – Gen II image intensifiers – Applications in scintillating fibre tracker detectors
- Today's seminar
  - Basic principles of operation
    - Re-discovering the MCP-PMT for fast timing
    - Specific features and effects
  - Applications in time-of-flight and particle identification detectors
  - Various layouts
  - Related recent developments and improvements
    - Lifetime
    - Collection efficiency
    - Surface coverage
    - Rate capability
  - MCP detectors in multi-photon regime
    - For time-of-flight and time reference detectors
- Conclusions and perspectives
- This overview is not exhaustive, many other activities are on-going !!!

Micro-channel plate photon detectors – Basic principle of operation

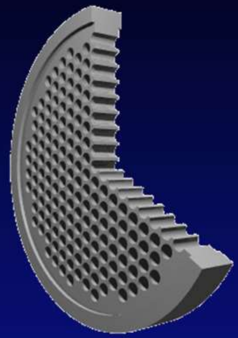
- Vacuum photon detector
  - Optical input window
  - Photocathode
  - Pair of micro-channel plates
    - Bulk material: Pb glass
      - Resistivity: bias supply
      - Secondary Emission (SE): continuous amplification
    - Gain per plate: typ. 10^3
    - Chevron configuration
      - Reduce Ion Feed-Back (IFB)
  - Anode
    - Various segmentations and types
    - AC/DC coupling



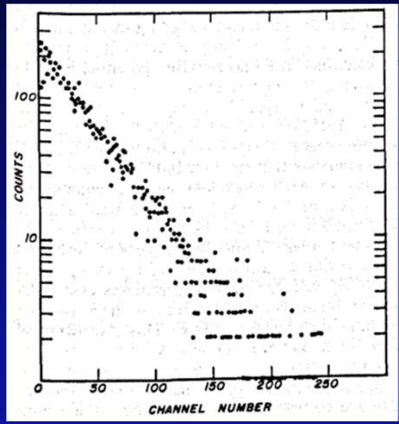
NIMA 912 (2018) 112-114

- Contributions to signal
  - Pre-pulse: no photon conversion in photocathode, SE in micro-channel, lower amplitude
  - Main pulse: photon conversion in photocathode, SE in micro-channel, nominal amplitude
  - Late pulse: after photoelectron backscattering and re-entry in micro-channel, ~nom. amplitude
  - After pulse (Ion Feed-Back – IFB): desorption/ionization effects
    - Degradation of gain and quantum efficiency

- Geometry
  - Pore d: ~6-25µm
  - Channel L: ~400-1000µm
  - Aspect ratio α=L/d: ~40-100, defines gain
  - Open Area Ratio (OAR): ~55-65%

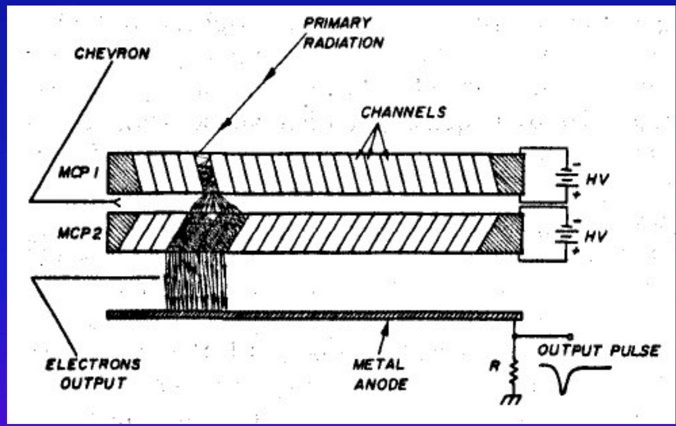


- Straight channel
  - Typical gain: 10^3-10^4
  - IFB limited
  - Negative exponential Pulse Height Spectrum (PHS)

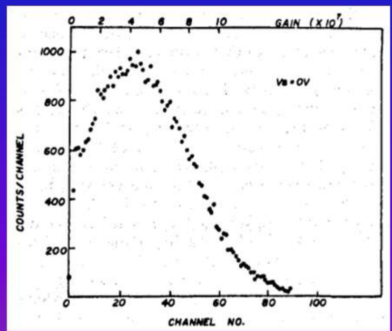


NIM 162 (1979) 587-601

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

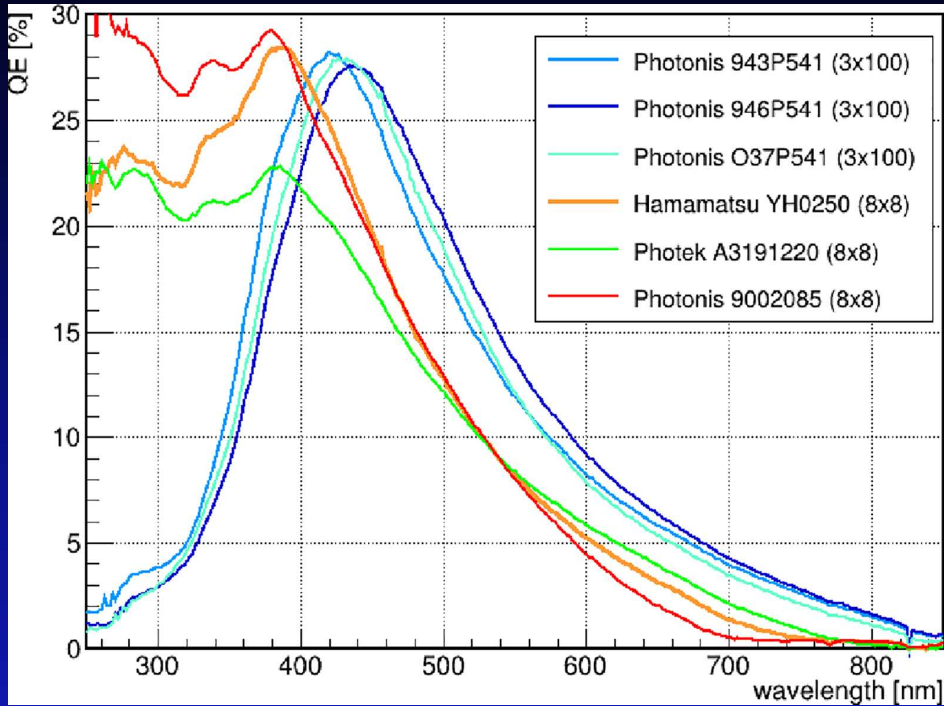


- Chevron configuration
  - Typical overall gain: 10^6-10^7
  - Gain ÷ d for fixed V/α
  - PHS
  - Gain fluctuations dominated by δ_1 (first impact)



Re-discovering the MCP-PMT for fast timing

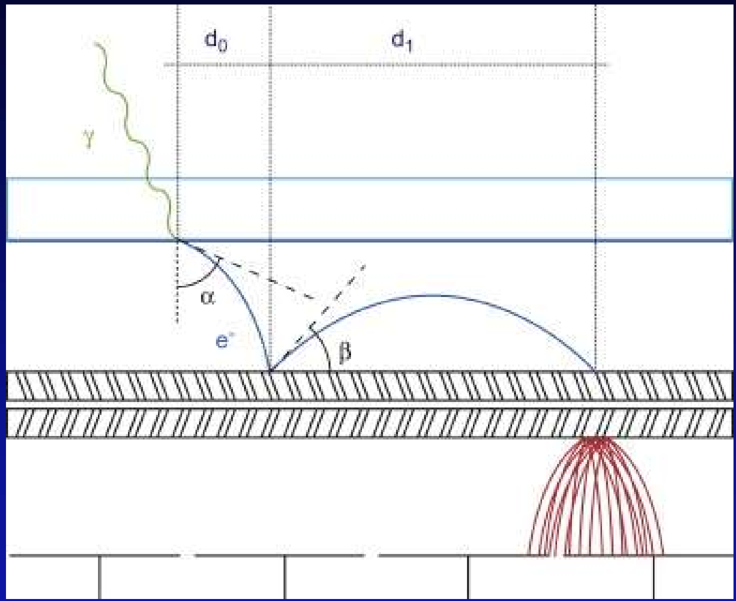
- Some interesting features
  - Square shapes
    - Better overall coverage
  - Single-photon sensitive
  - Low noise: DCR O(kHz/cm^2)
  - High gain: 10^6-10^7
  - Collection Efficiency (CE) ~60%
  - Compact, high E field
    - Works in large (axial) magnetic fields
  - Small Transit Time Spread (TTS): typ. 20-30ps (for Single Photo-Electron – SPE)
  - Good rate capability: up to 1MHz/cm^2 (the smaller d the better)
  - Position-sensitive
    - Appropriate anode segmentation



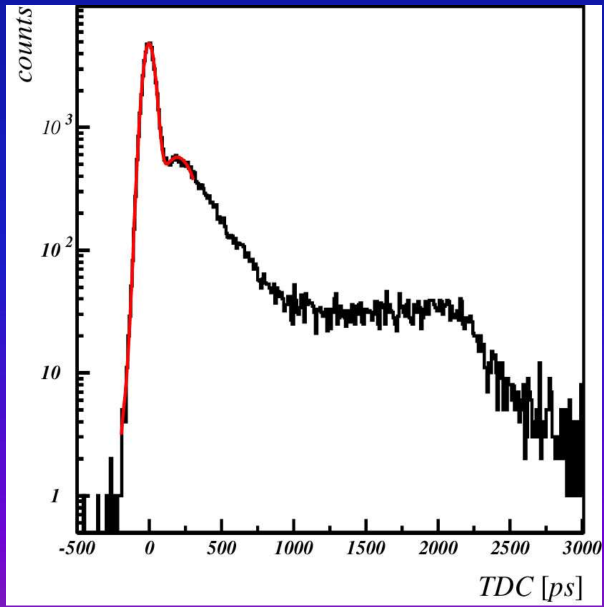
NIMA 1049
(2023) 168047

MCP-PMT spatial and timing effects

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

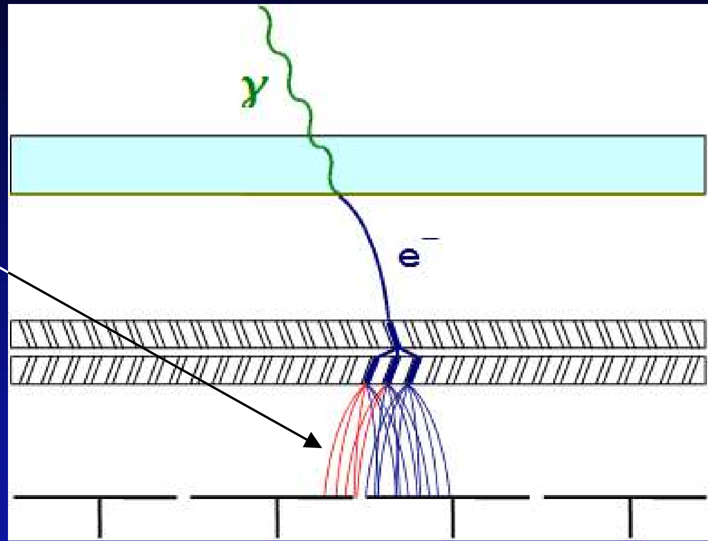


Typical single photon timing distribution with narrow main peak (σ ~ 40 ps) and contribution from photo-electron back-scattering.

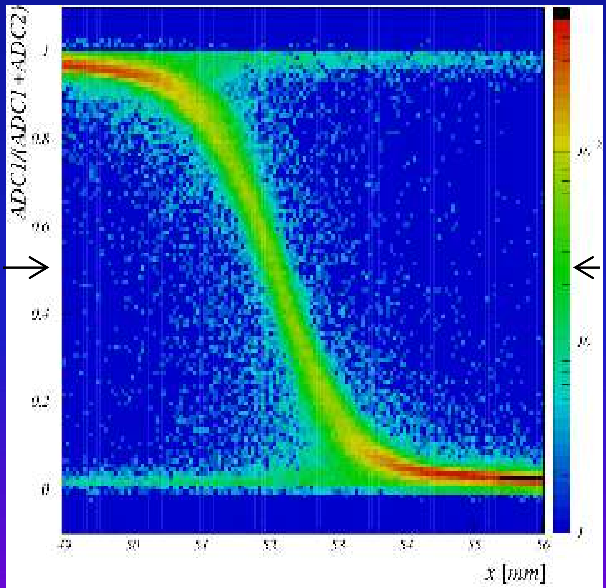


NIMA 595 (2008) 169-172

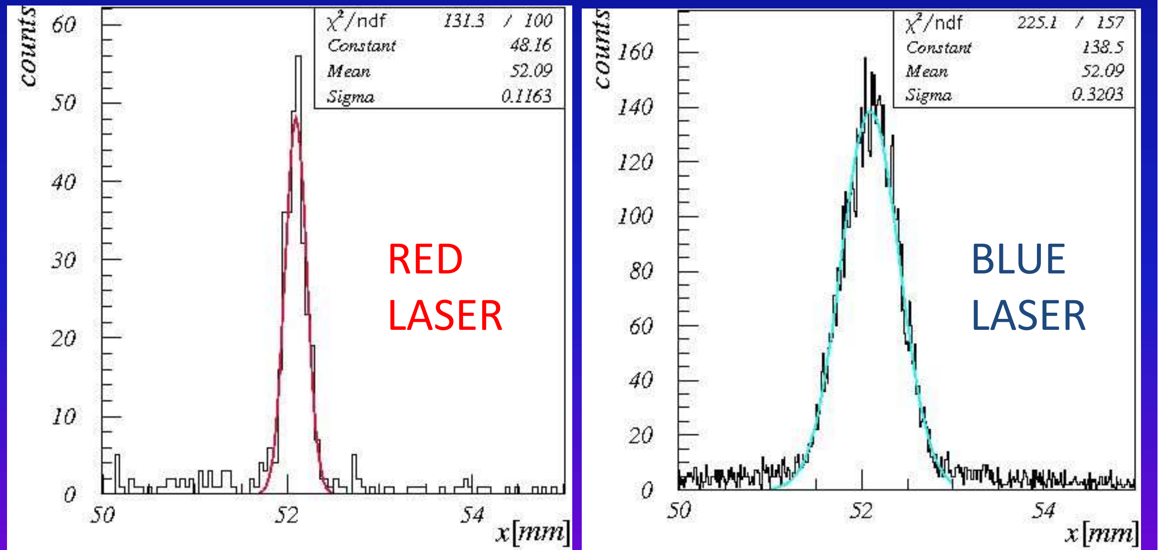
- Secondary electrons spread when traveling from MCPout to anode
- May hit more than one anode pad → Charge sharing
- May improve spatial resolution but degrade time resolution



NIMA 595 (2008) 169-172

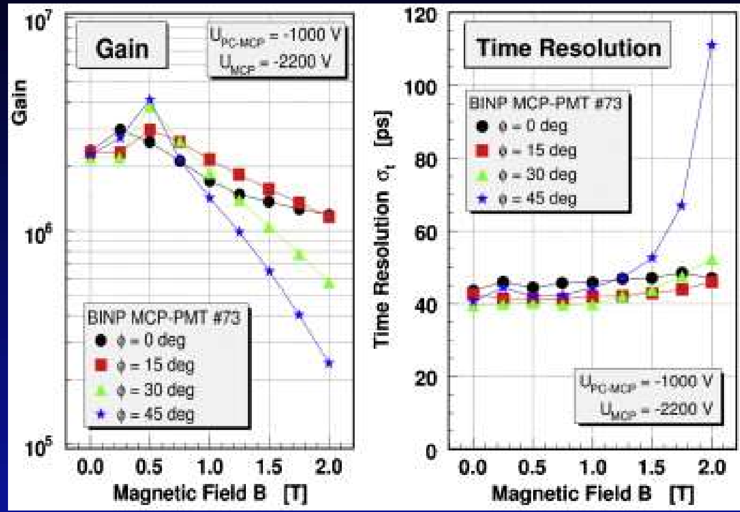


Fraction of the charge detected by left pad as a function of light spot position (red laser)

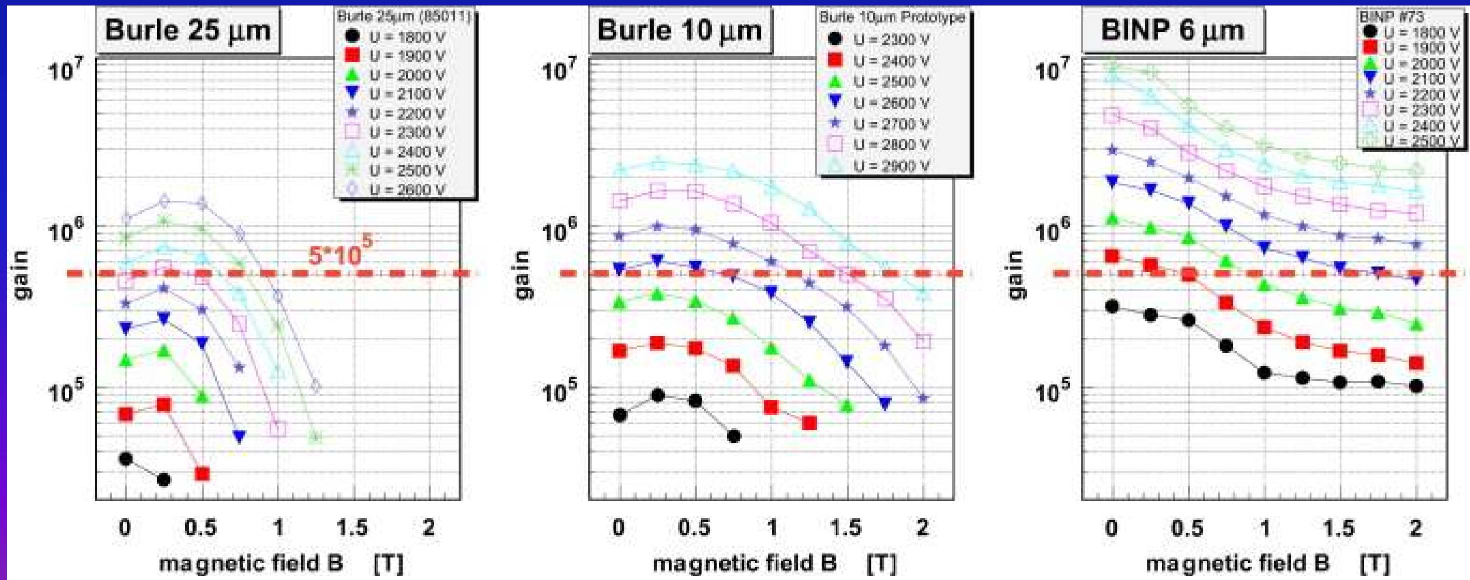


Slices at equal charge sharing for red and blue laser at pad boundary
Resolution limited by photoelectron energy

- 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

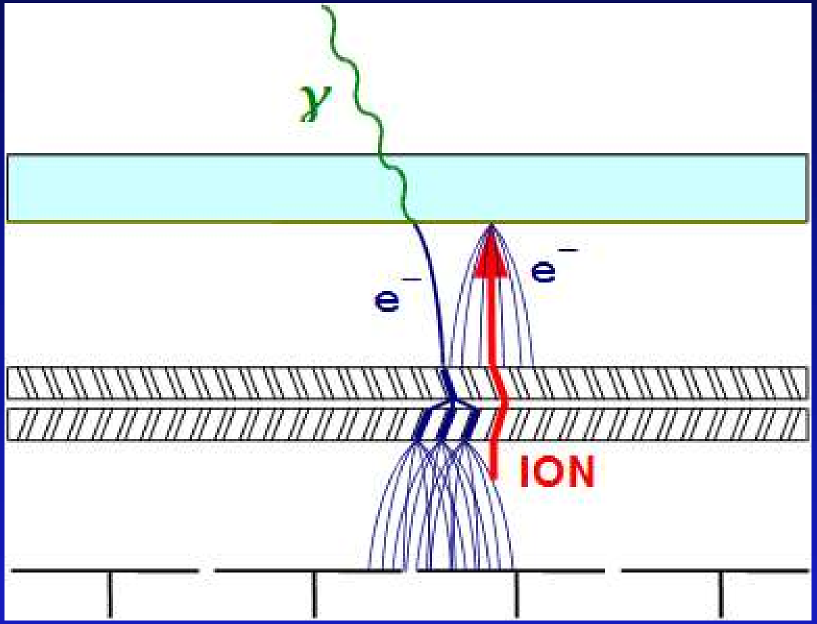


NIMA 595
(2008) 173-176



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

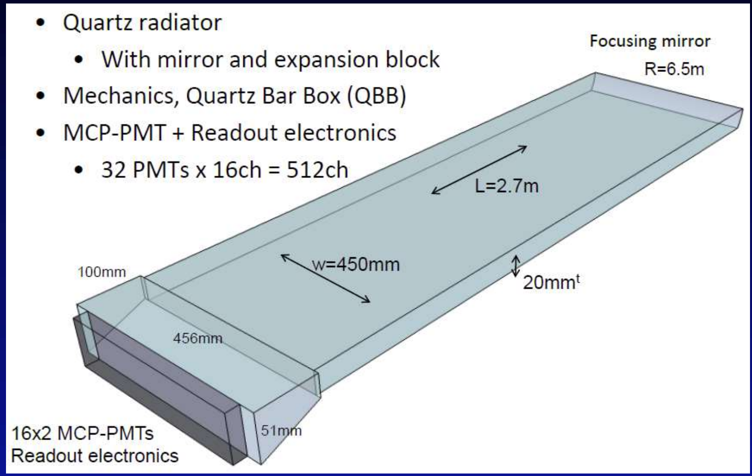


MCP-PMT ion feedback and ageing - possible strategies

- Conventional MCP-PMTs
  - Degradation observed @ a few 100mC/cm^2

- Possible strategies
  - Improve vacuum quality
  - Improve MCP scrubbing
  - Make more robust photocathodes
  - Implement ion barrier film
    - 5-10nm Al_2O_3
    - On 1st MCPin with 40% reduction of collection efficiency
    - Between MCPs to recover initial collection efficiency
  - Seal anode region from PC region
  - Investigate alternative MCP materials
  - Borosilicate, Alumina, Silicon
  - Investigate new thin-film technologies
    - Atomic Layer Deposition (ALD)

- TOP (Time-Of-Propagation)
  - Counter based on DIRC concept (BaBar)
  - 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



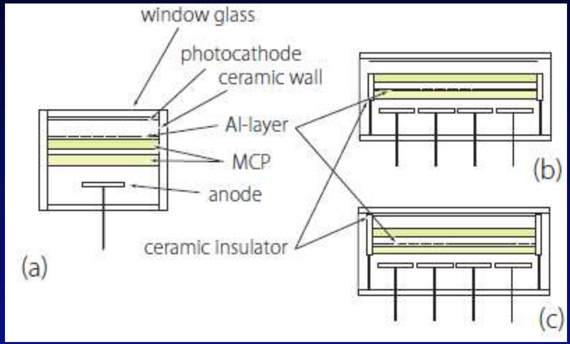
NIMA 766 (2014) 5-8

R. Okubo RICH 2022

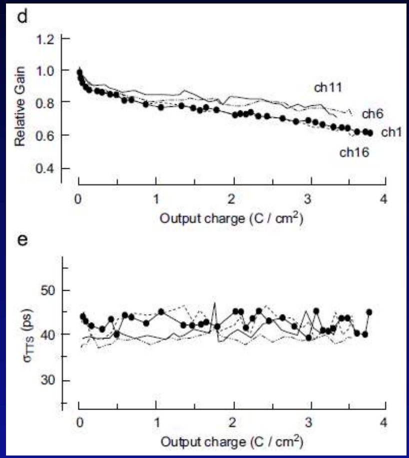
Belle II iTOP – photon detectors

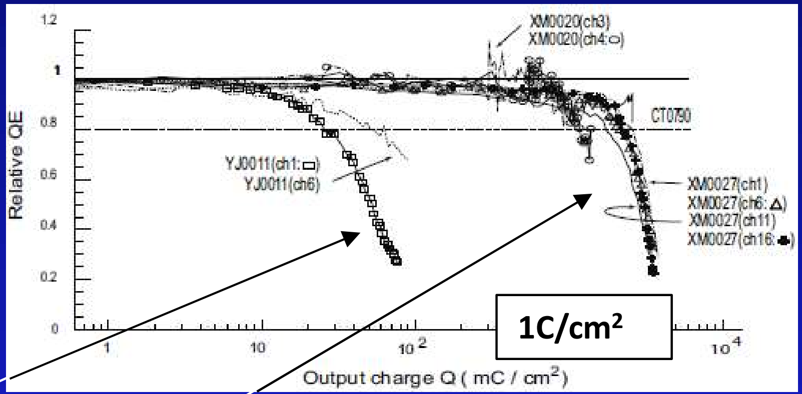
- Requirements
  - Integrated Anode Charge (IAC): 1.2-2.4C/cm²/50ab⁻¹ (5×10⁵ gain)
    - Lifetime: 0.8QE
    - Enhanced multi-alkali (>28% QE at peak)
  - TTS: <50ps for TOP
- Specifications
  - Pore Ø: 10µm
  - Bias angle: 13°
  - Thickness: 400µm
  - Layers: 2
  - Al protection layer on 2nd MCP
    + ceramic insulator (2011)
    + ALD (2013)
    + life-extended ALD (2015)
  - Anode channels: 4×4
  - Active area: 64%

Physics Procedia 37 (2012) 683



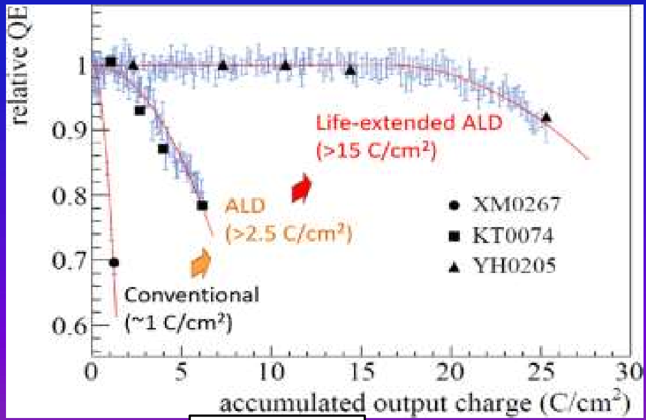
NIMA 629 (2011) 111-117





1C/cm²

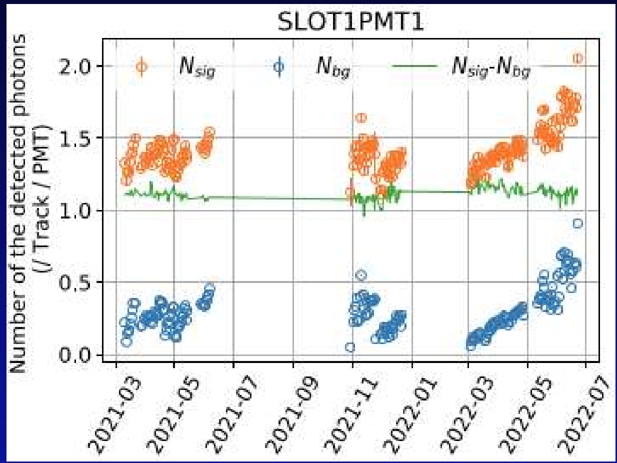
NIMA 936 (2019) 556–557

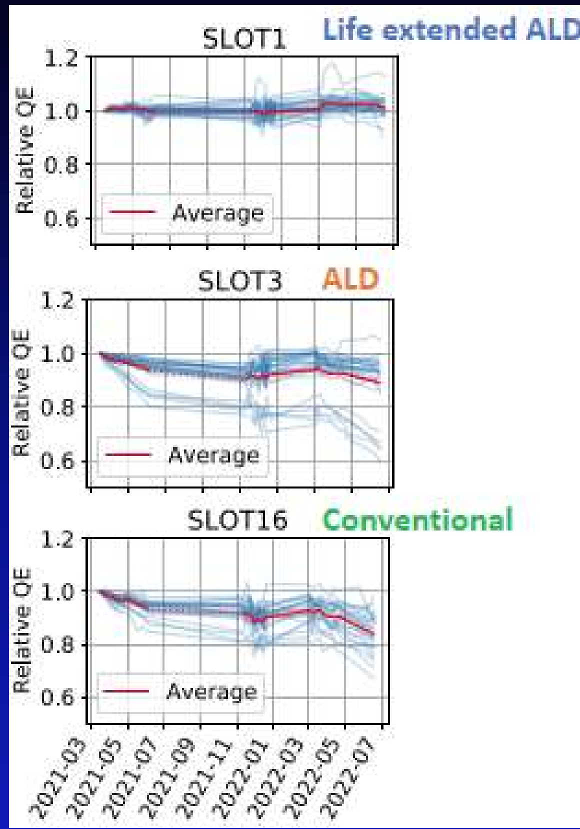


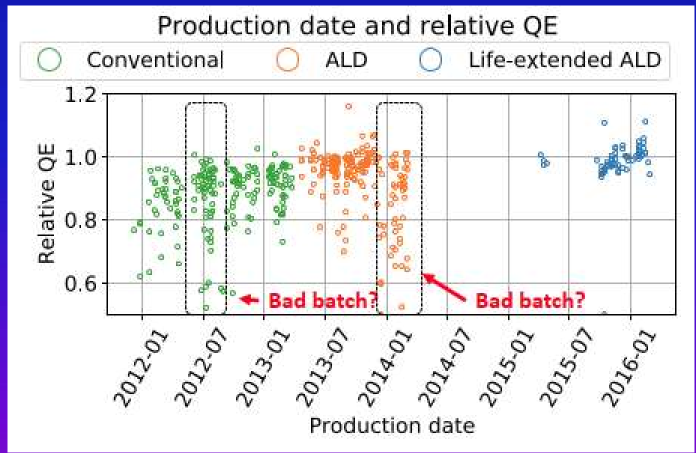
10C/cm²

Belle II MCPs – QE monitoring during first operation

- Time period
  - Mar 2021 – Jun 2022
  - Rate/PMT: 2->5MHz
  - IAC: 0.20-0.35C/cm^2
- QE estimate
  - Signal: isolated muon track
  - Bkd: no muon track
- Possible QE degradation ?
  - Production batch
  - Background rejection
  - Gain drop vs efficiency
  - Noise
  - T







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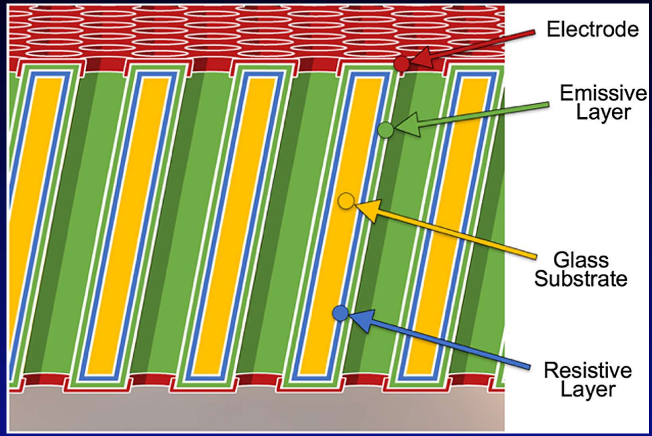
Atomic layer deposition (ALD)

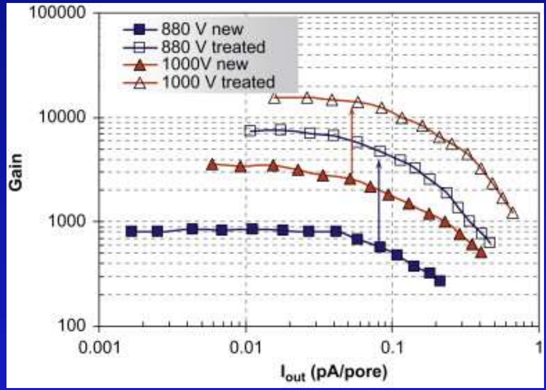
- Initiated by the LAPPD Collaboration
- Three-step deposition process
  - Resistive layer
    - Al_2O_3:Mo, Al_2O_3:W (50nm)
    - R typ. 10 to 120 MΩ
      - Too low R → thermal runaway
  - Emissive layer
    - Al_2O_3, MgO (10nm)
    - Secondary Electron Yield (SEY) 1-6, 3-7 resp. (SEY 2.5-3.5 for Pb glass)
  - Electrode
    - NiCr 80/20 (200nm)
- Optimization of MCP resistance and SEY
  - For a given gain, lower operating voltage
- Allow use of insulating materials other than Pb glass
  - Glass micro-capillary arrays

NIMA 912 (2018) 75–77

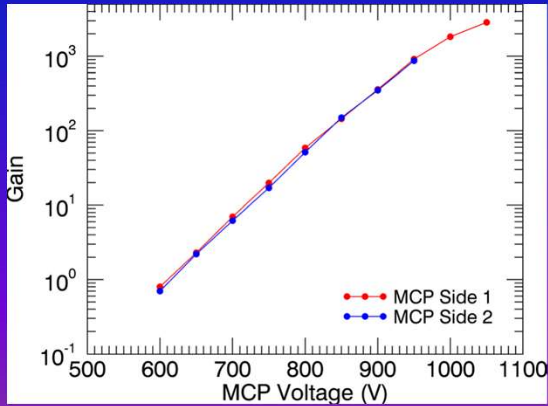


J. Vac. Sci. Technol. A 34, 01A128 (2016)

NIMA 607 (2009) 81–84

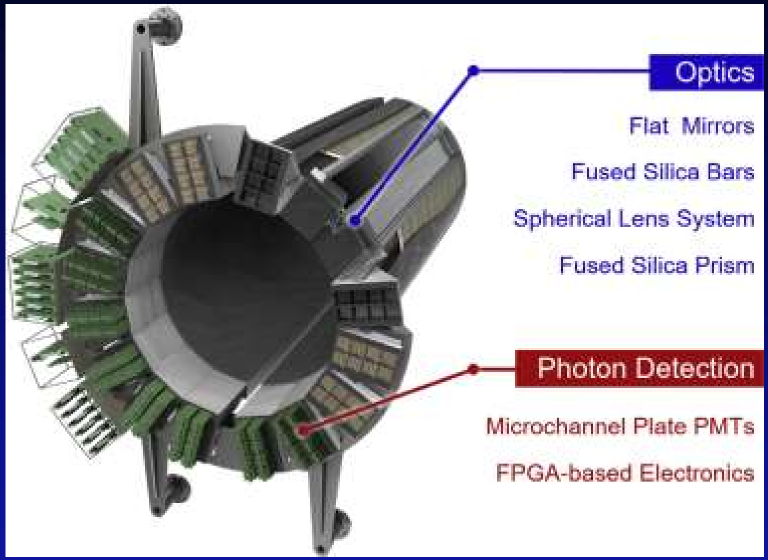


J. Vac. Sci. Technol. A 34, 01A128 (2016)



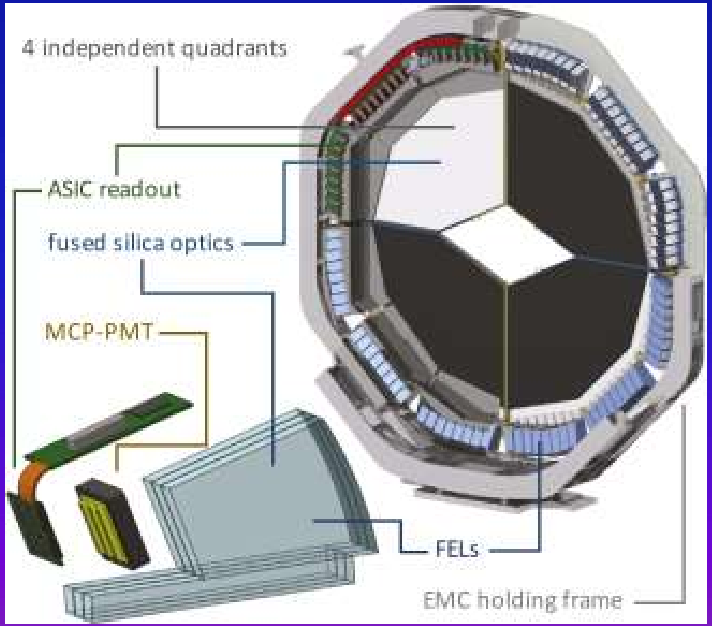
PANDA Barrel and Endcap Disc DIRC counters – MCP requirements

- Barrel DIRC
  - Integrated charge ~ 5C/cm^2 (10^6 gain)
  - Pixel rate ~ 200kHz (~ 600kHz/cm^2)
  - B field up to 1.5T
  - Segmentation 8×8 on 2" sq. tube
  - Time resolution ~ 100ps
  - 1 MeV n-equivalent fluence >2×10^{11} neq/cm^2



NIMA 952 (2020) 161790

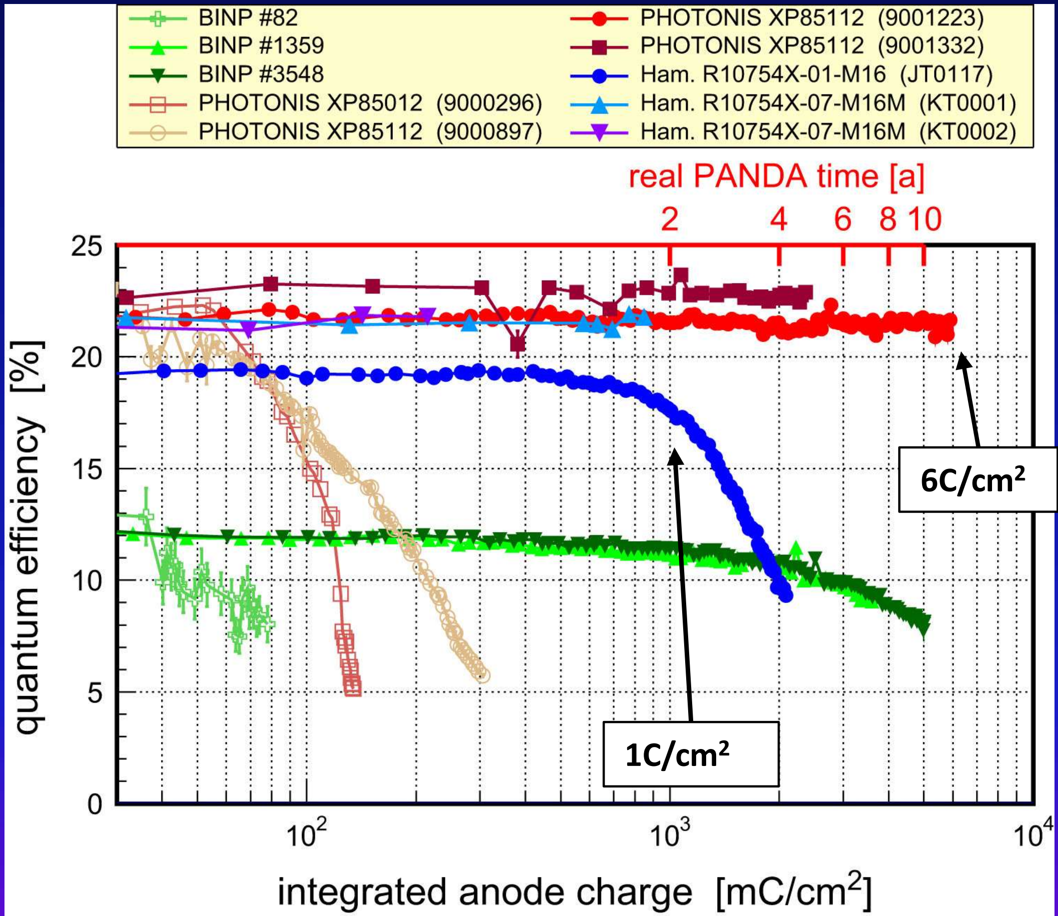
- Endcap Disc DIRC
  - Integrated charge ~ 7-8C/cm^2 (10^6 gain)
  - Rate ~ 2MHz/cm^2
  - B field up to 1.0T
  - Segmentation 3×100 on 2" sq. tube
  - Time resolution ~ 100ps
  - 1 MeV n-equivalent fluence >2·10^{11} neq/cm^2



Panda photon detectors R&D – evolution of lifetime

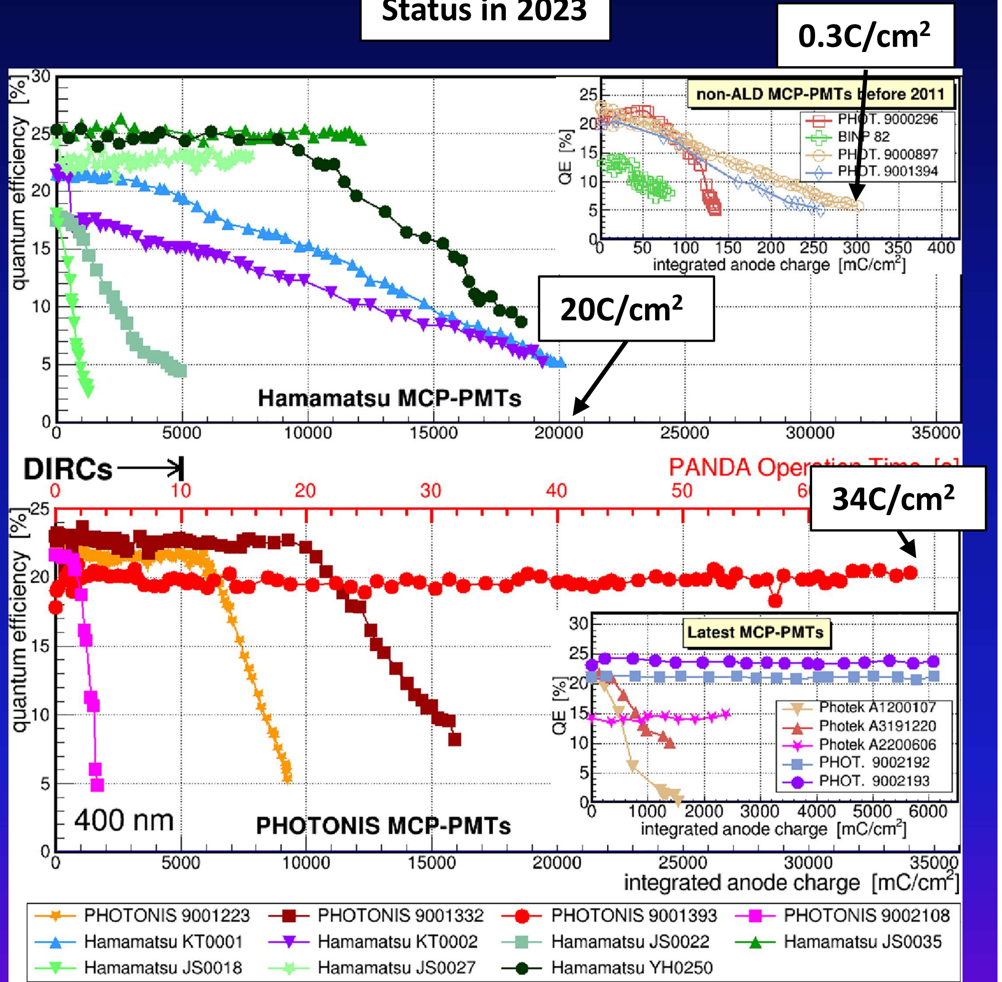
- Significant improvement for ALD-processed MCPs
  - Best devices now reach 35C/cm^2

Status in 2014



NIMA 766 (2014) 138–144

Status in 2023

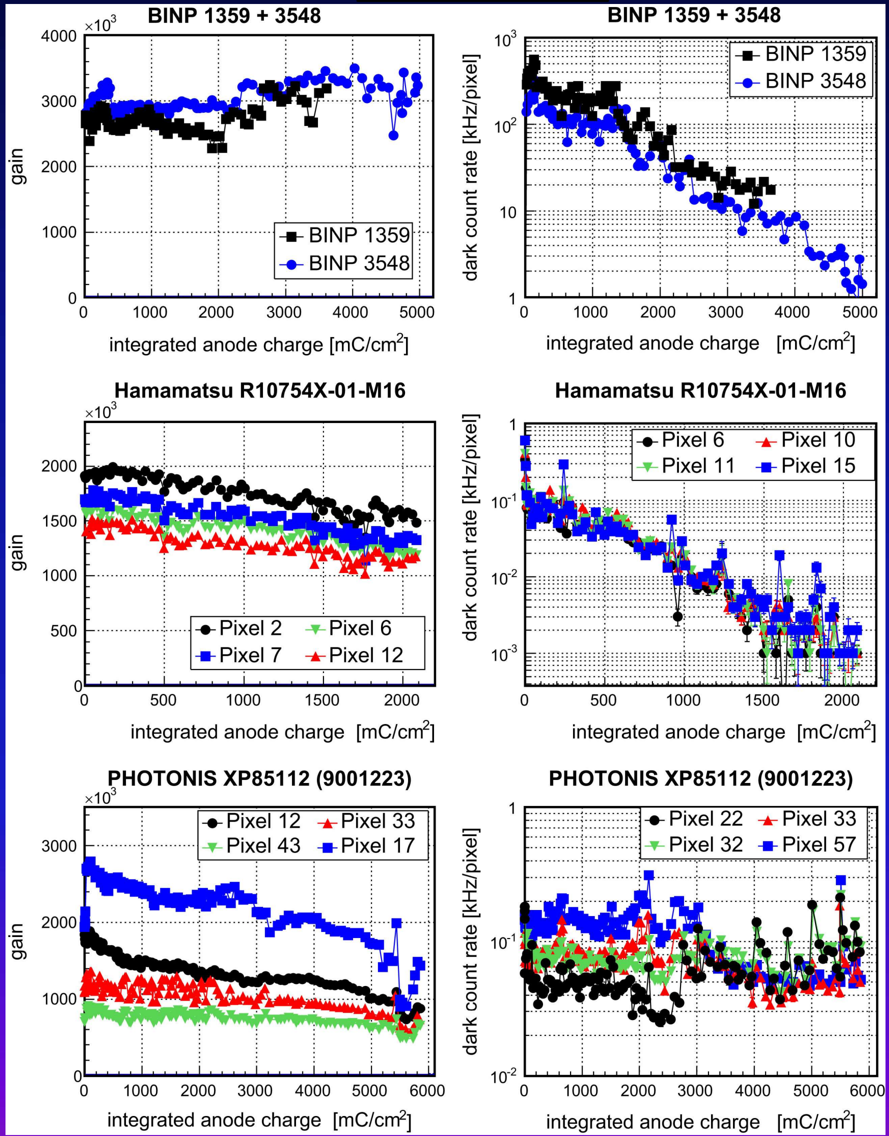


NIMA 1049 (2023) 168047

Panda photon detectors R&D – evolution of gain and DCR

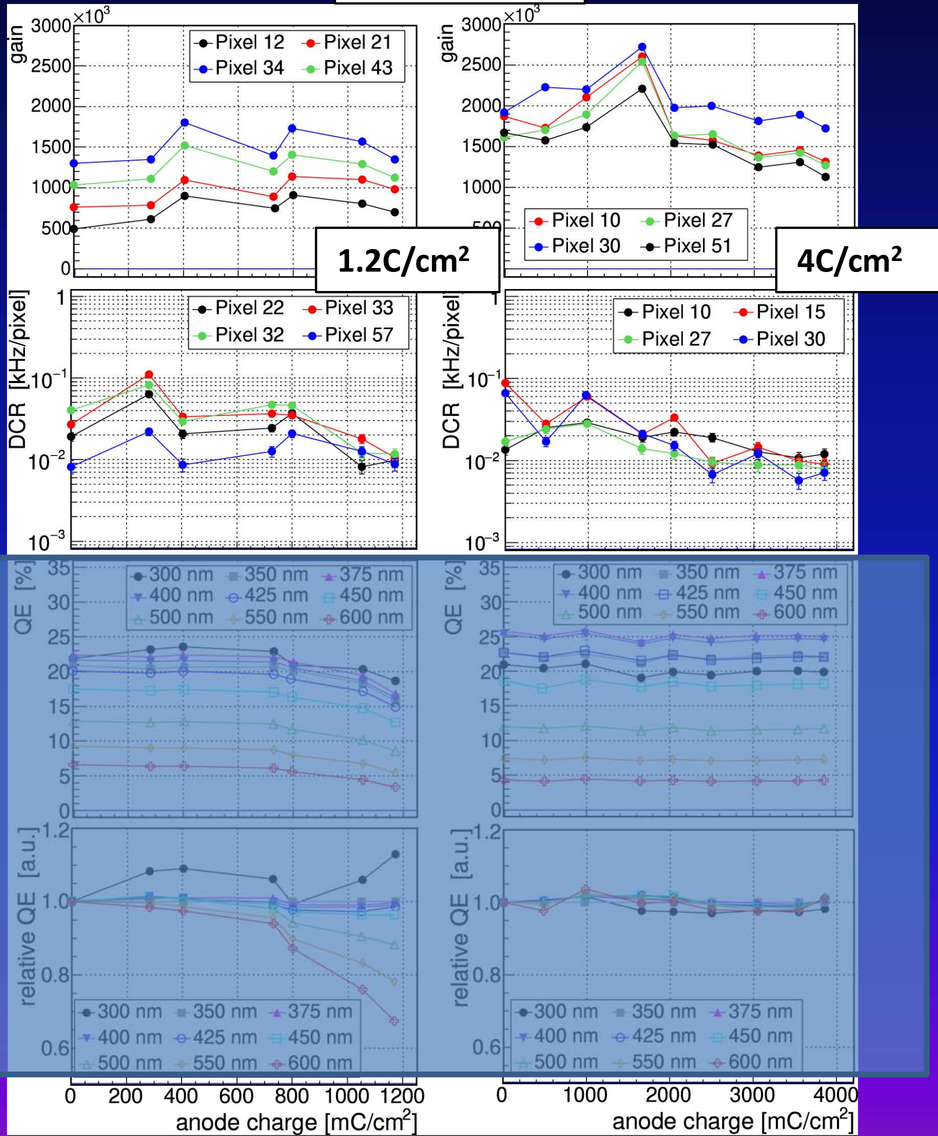
- Moderate gain changes and decrease of DCR

Status in 2014



NIMA 766 (2014) 138–144

Photonis **Status in 2020** Hamamatsu

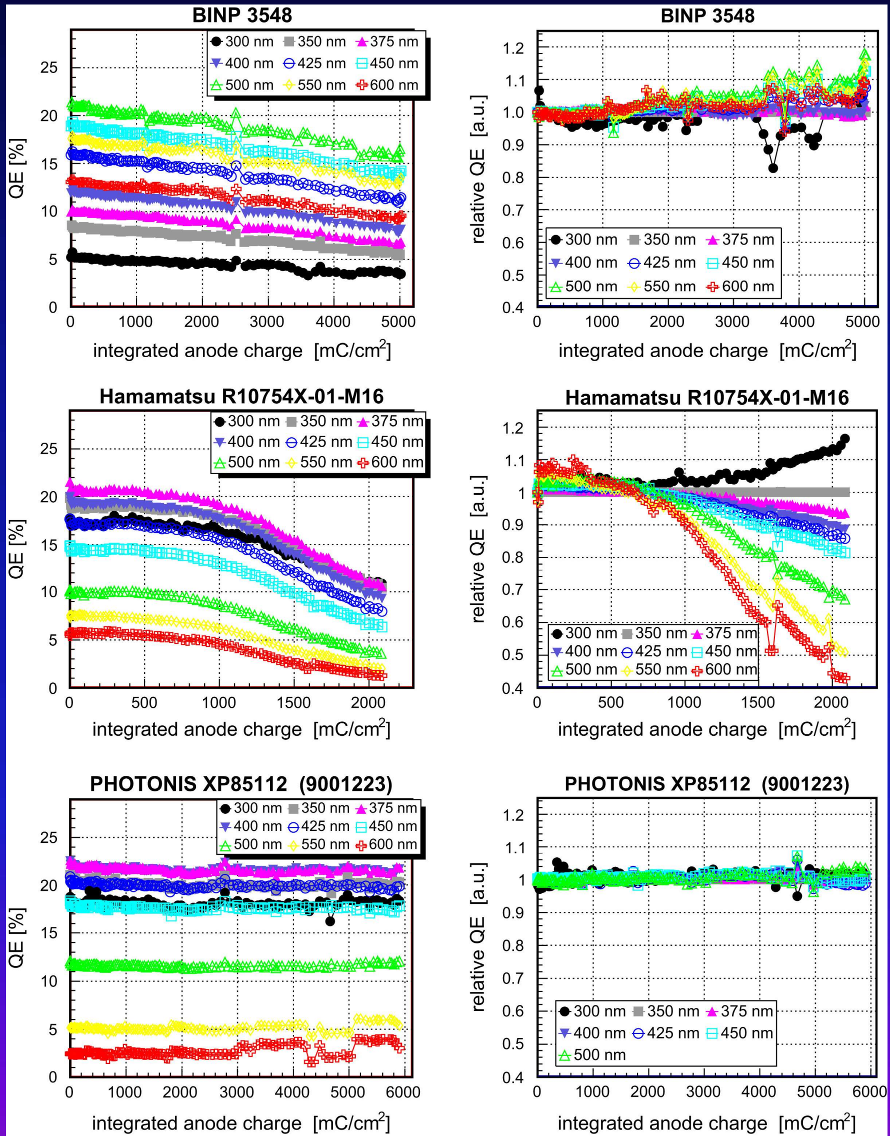


NIMA 958 (2020) 162357

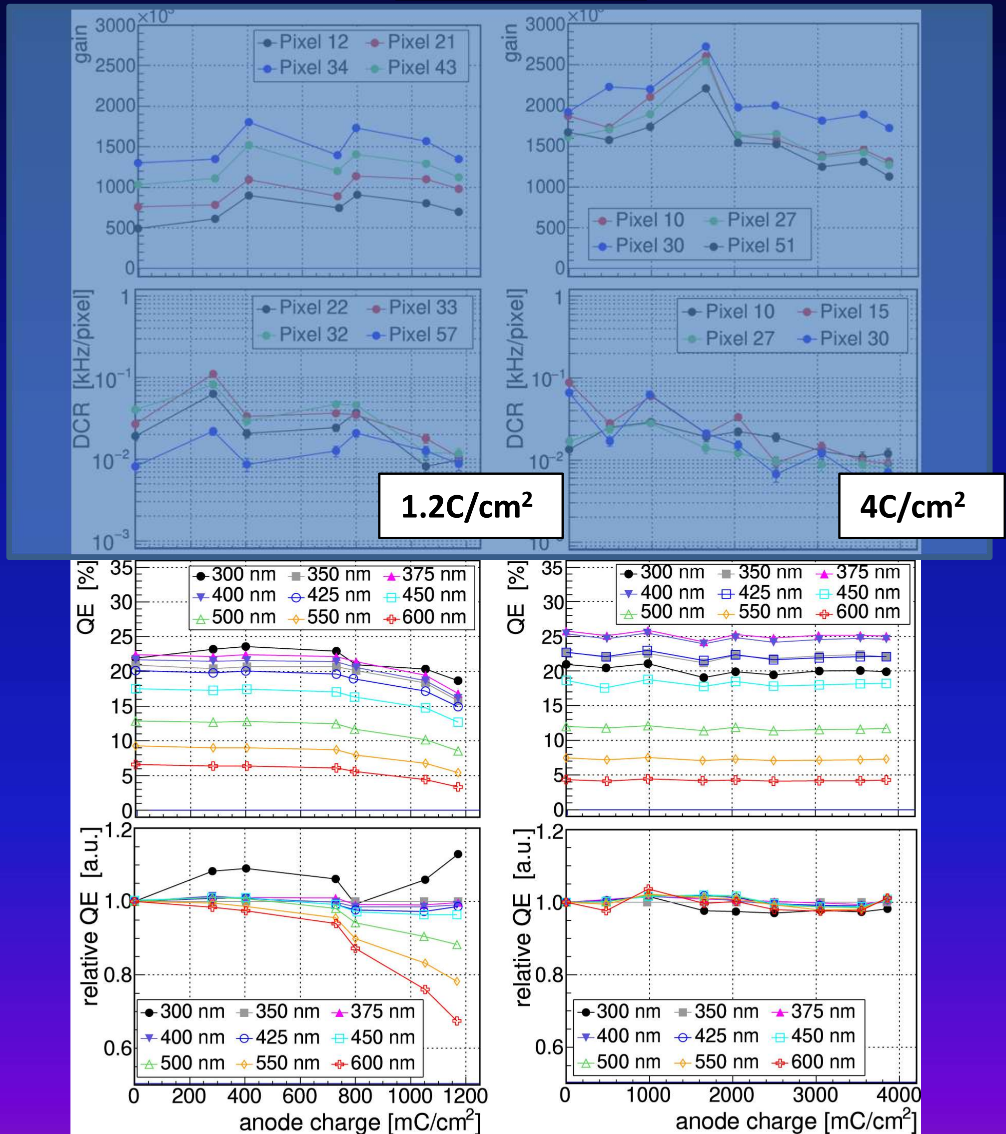
Panda photon detectors R&D – evolution of QE

- Improved trends

Status in 2014



Photonis **Status in 2020** Hamamatsu



NIMA 766 (2014) 138–144

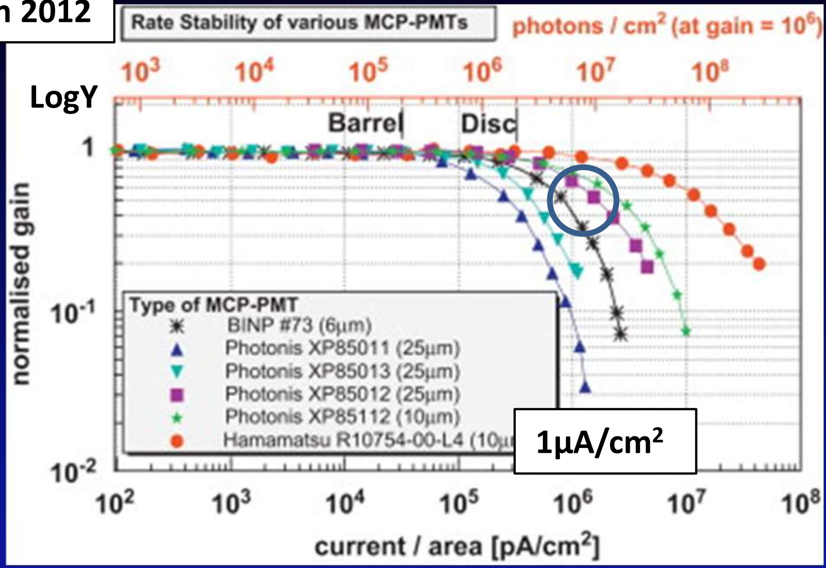
NIMA 958 (2020) 162357

Panda photon detectors R&D – evolution of rate capability

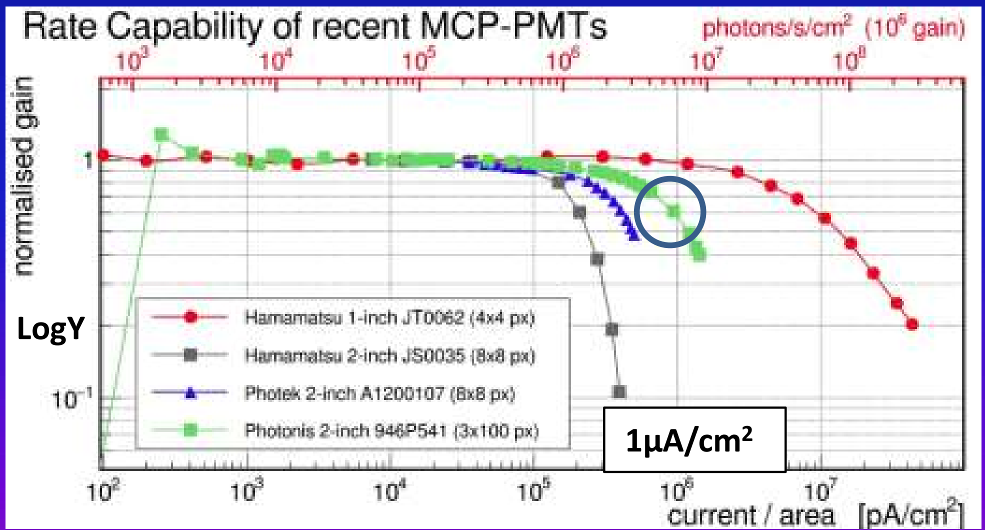
- Key parameters
  - Charge replenishment related to MCP R and C
  - Maximum anode current ≤10% strip current
    - 10MHz/cm^2 ≈ 2µA/cm^2 @ G=10^6
      → The lower G the better
  - Latest results
    - Recently observed "escalation effect" in ALD-processed tubes
      - Light emission
        - » From SEE layer ?
        - » Also observed in "standard" PMTs

NIMA 695 (2012) 68-70

Status in 2012



Status in 2023



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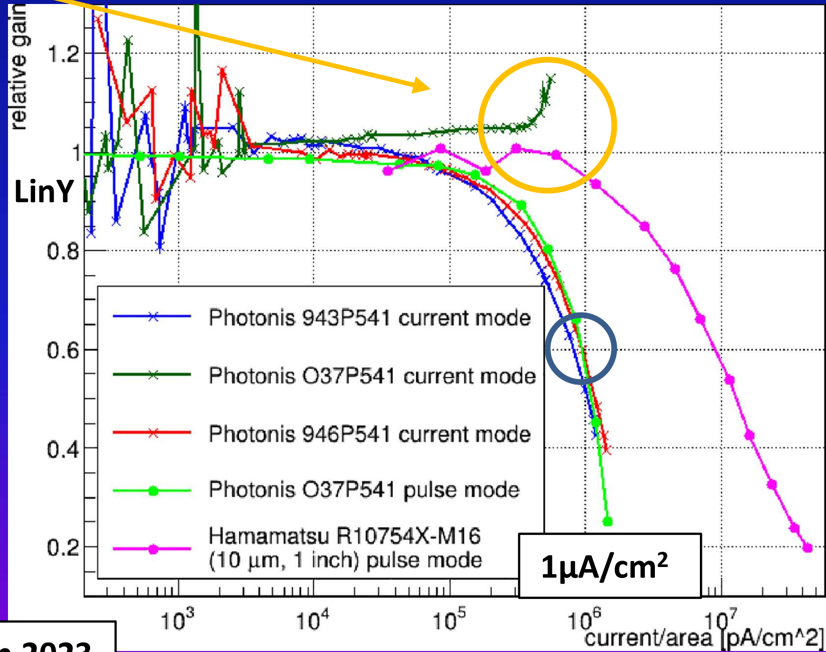
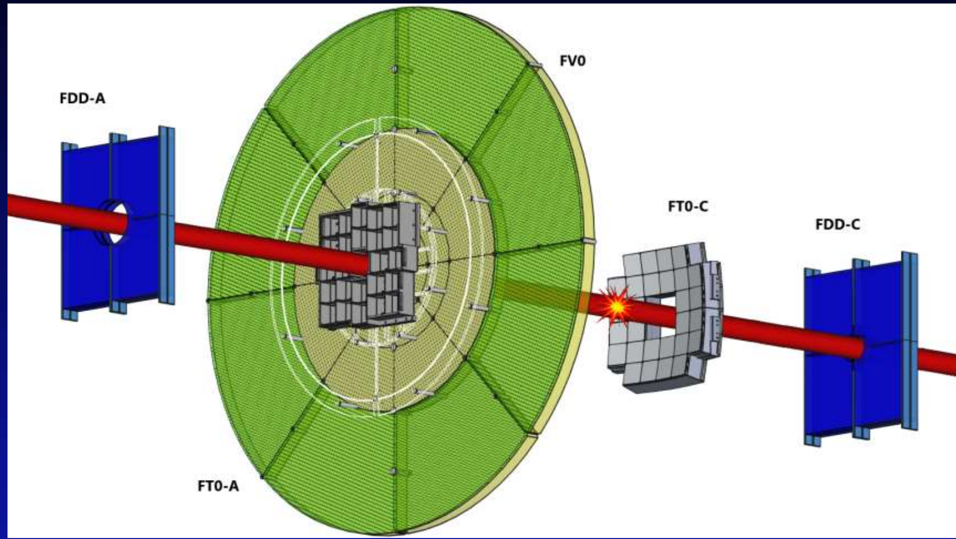


Status in 2023

NIMA 1049 (2023) 168047

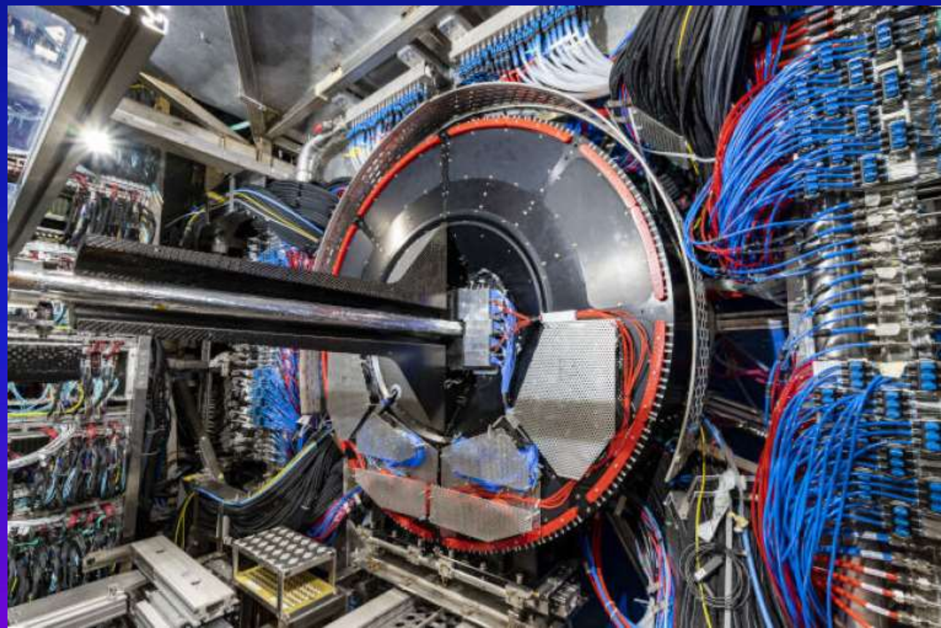
- Consists of 3 detectors
  - Fast Cherenkov arrays FT0-A and FT0-C
    - 208 optically-separated quartz radiators
    - Expected time resolution
      for high-multiplicity heavy-ion collisions
      ~ 7 ps
  - Scintillator disk FV0
  - Forward Diffractive Detectors FDD

PoS(ICHEP2020)779,814



- Purpose
  - Luminosity monitoring
  - Trigger generator
  - Online vertex determination
  - Collision time measurement
    needed for PID
  - Forward multiplicity counter

- Installed in June 2021

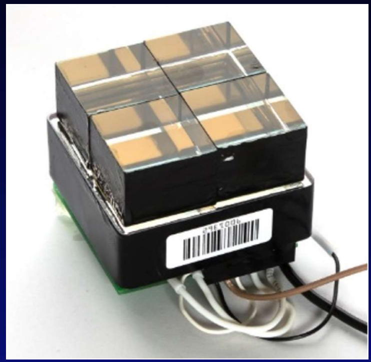


https://ep-news.web.cern.ch/content/new-alice-fast-interaction-trigger

ALICE Fast Interaction Trigger – Photosensors

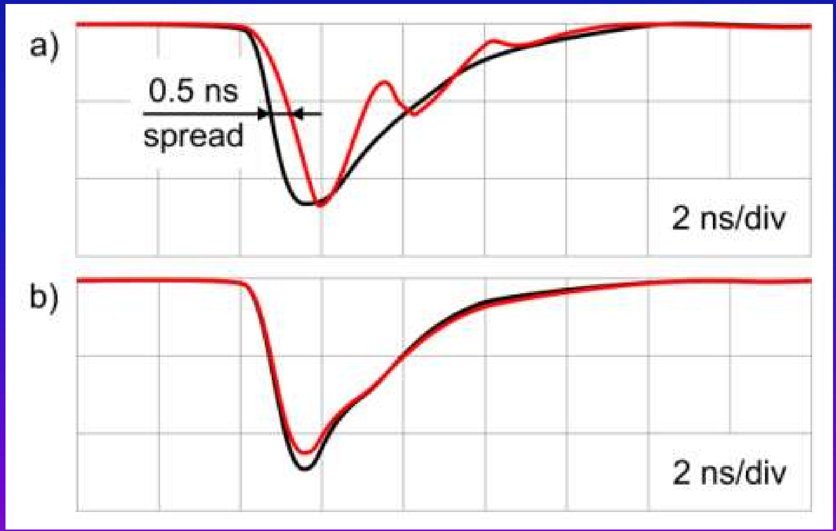
- FT0 sensors
  - 24(A) and 28(C) 8x8 2" Planacon MCP-PMTs
    - Each sensor coupled to 4 quartz radiators
    - Anode pads grouped in 4 sectors
  - IAC: >0.6C/cm^2
  - Average Anode Current (AAC): up to 250nA/cm^2 (7µA for 2" PMTs)
    - Equivalent illumination rate: up to ~100MHz/cm^2 @ G=1.5×10^4
  - B field: up to 0.5T
  - Custom back plane
    - No common connection at the MCP output
    - Reduced cross-talk
    - Increased dynamic range
  - Low operating gain 1.5×10^4
  - Achieved intrinsic time resolution: 13ps/quadrant
  - Low R devices preferred
    - Improve rate capability
    - Over-linearity
    - Heat dissipation

NIMA 952 (2020) 161920

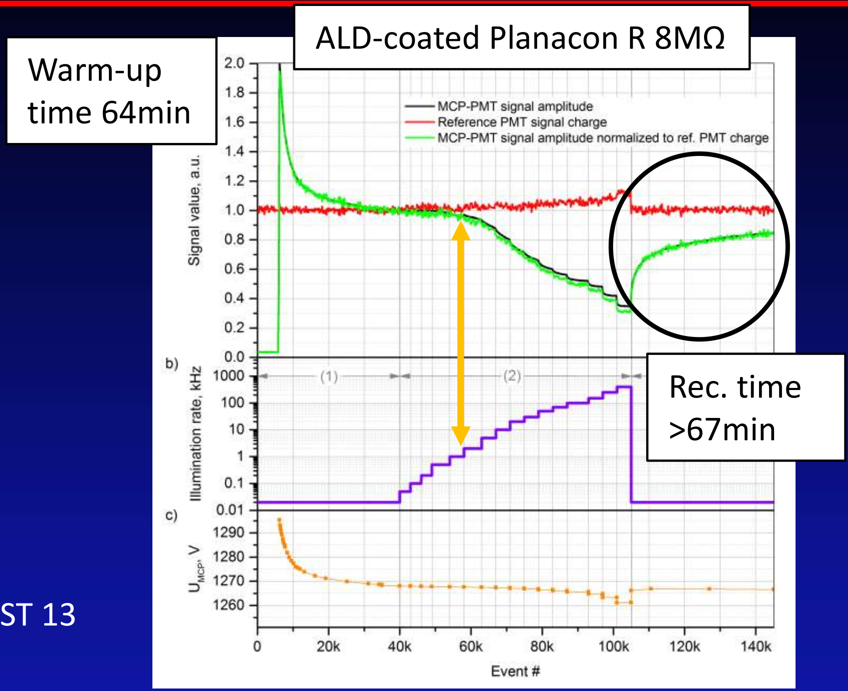


2021 JINST 16 P12032

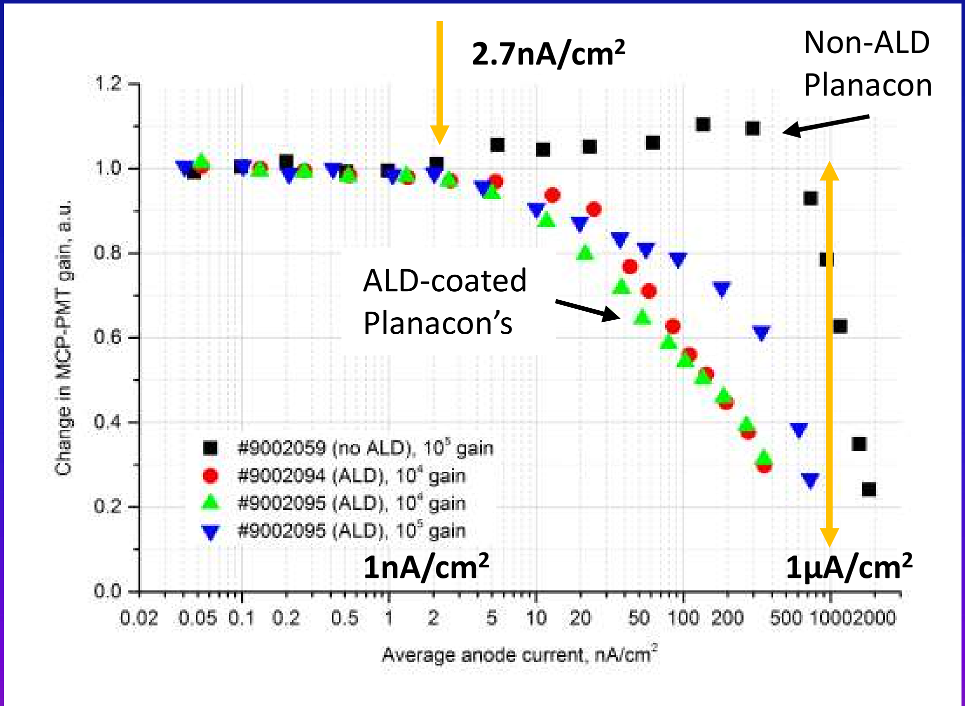
J. Phys. Conf. Ser. 798 (2017) 012168

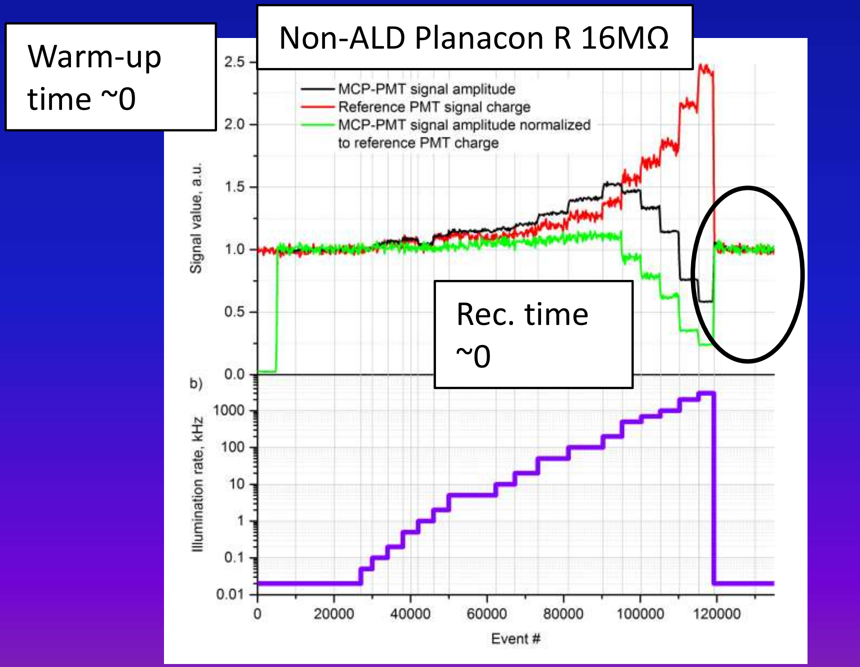


- Previously-developed ALD-coated MCPs exhibit
  - Lower saturation current levels
  - Longer gain recovery times
  - Gain decrease
    - Already seen @ 1kHz illumination rate ≡ 2.7nA/cm² (400kHz illumination rate ≡ 1.1μA/cm²)
    - Strip current ~6.6μA/cm²
      - Expected gain saturation to start @ 10%×6.6μA/cm² = 660nA/cm²



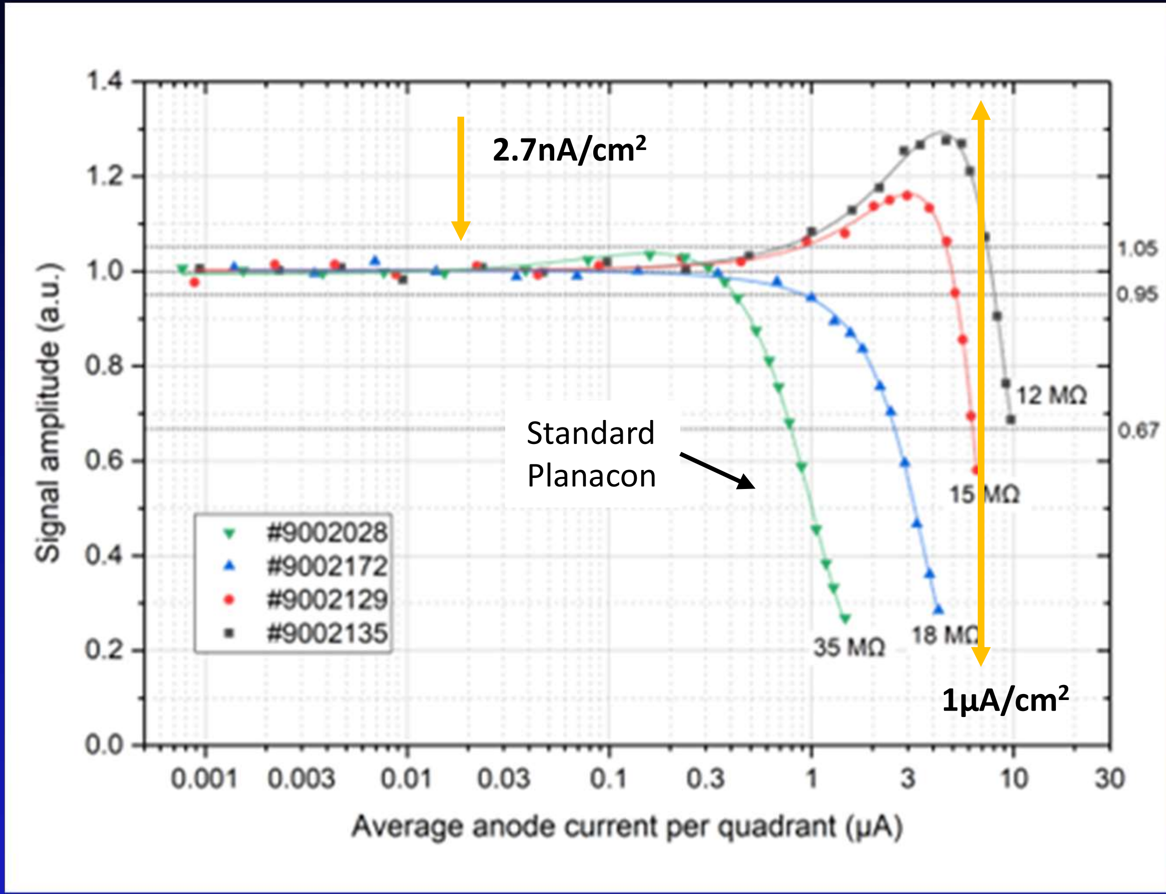
2018 JINST 13 T09001





ALICE Fast Interaction Trigger – Improving tube rate capability

- Standard tubes:
  - MCP R: 30-70MΩ
  - Nominal AAC limit: 3µA
- Customized tubes:
  - MCP R: 12-22MΩ
    - Increased AAC limit: 10µA
  - Non-ALD
  - Specific back-plane wiring
- Lower R devices:
  - Improved rate capability
  - Over-linearity
  - Heat dissipation
  - For tube w. R~12MΩ:
    - AAC limits
      - +5%: ~0.6µA/quadrant
      - +29%: ~4.2µA/quadrant
      - (-33%): ~9.9µA/quadrant
    - Strip (stack) current: ~80µA
    - P ≈ 75mW

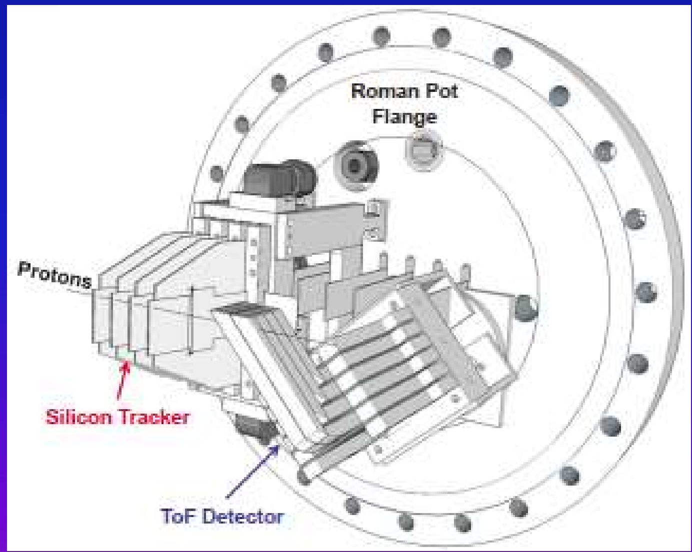


2021 JINST 16 P12032

- Stations
  - Located ~ 200m from IP1
  - Distant 2mm from LHC beam
  - Si pixel tracking planes (in two stations)
  - ToF quartz Cherenkov detectors (in far station only)
    - 16 L-shaped bars
    - Coupled to "out-of-vacuum" newly-developed MCP sensors through optical window
      - Easier environment for AFP operation
      - Easier access to electronics

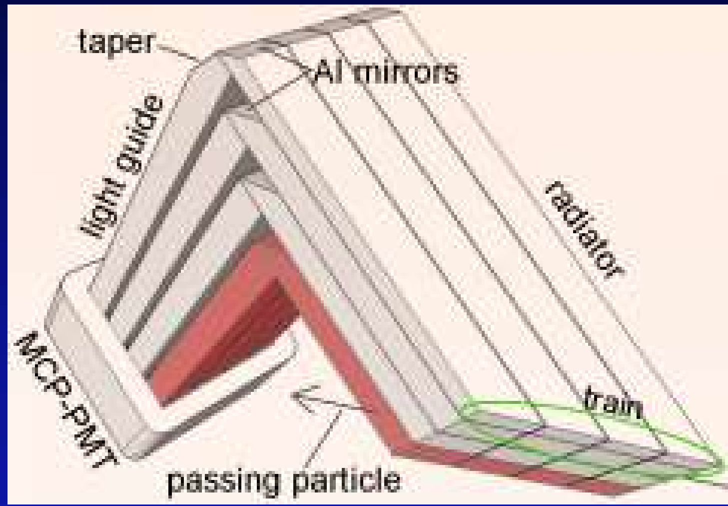
https://cds.cern.ch/record/2755104/files/ATL-FWD-SLIDE-2021-046.pdf

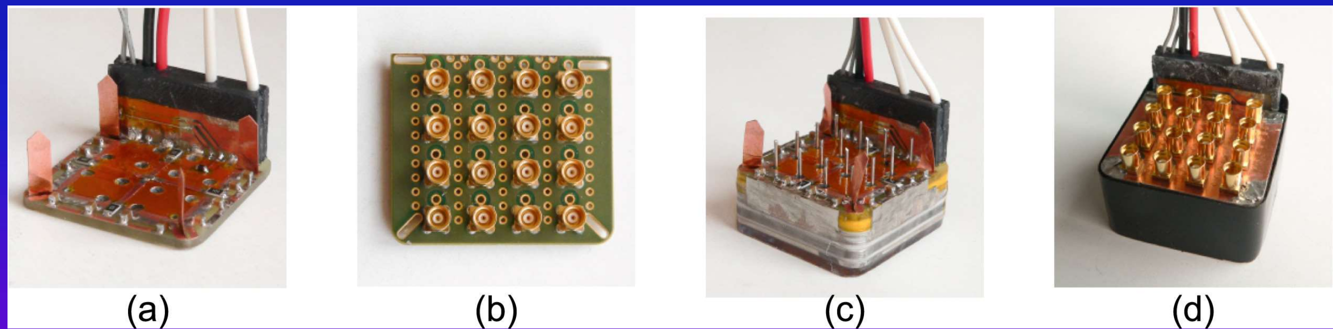
- Purpose
  - Assign protons detected by AFP to individual collisions in IP1
    - Precise timing measurement determines vertex position to match
  - Reduces background in high pileup situations
  - Expected performance O(10ps)



- AFP sensors
  - 4×4 1” Mini-Planacon MCP-PMTs
    - Each sensor pixel coupled to one quartz radiator bar
    - 4 bars form a “train”
  - IAC: 10C/cm^2
  - Rate: 20MHz per bar train
  - Reduced MCP R
  - Low operating gain ~ 2×10^3
    - Expected light yield: 25pe/bar
    - MCP anode current density ~ 1µA/cm^2
    - Additional amplification required
  - Custom back plane
    - HF connectors
    - Reduced cross-talk

https://cds.cern.ch/record/2755104/files/ATL-FWD-SLIDE-2021-046.pdf

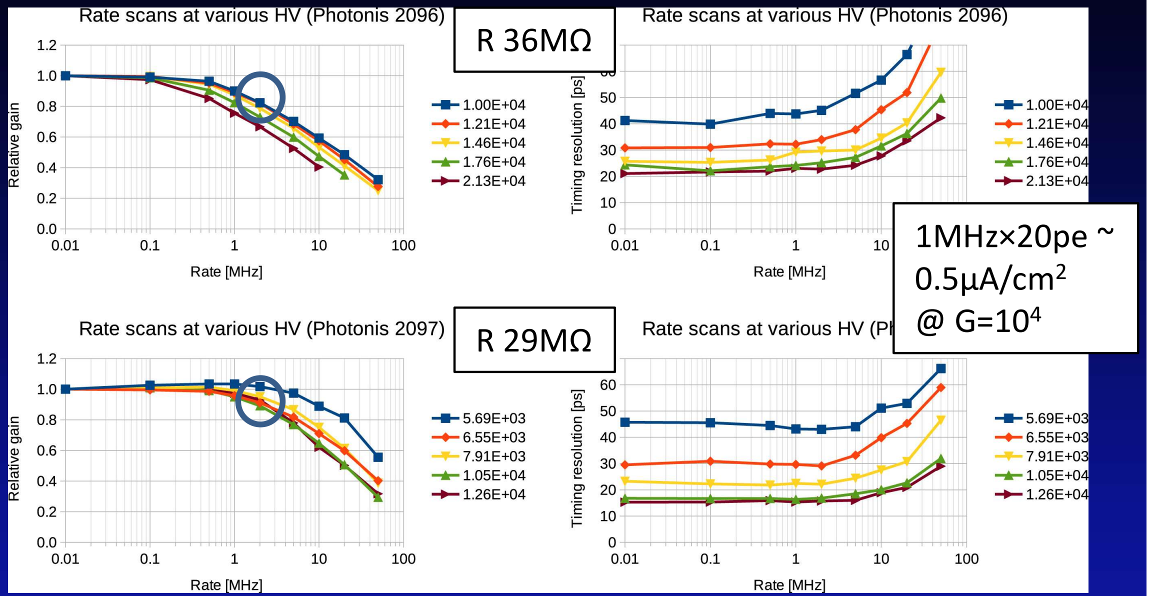




NIMA 1041 (2022) 167330

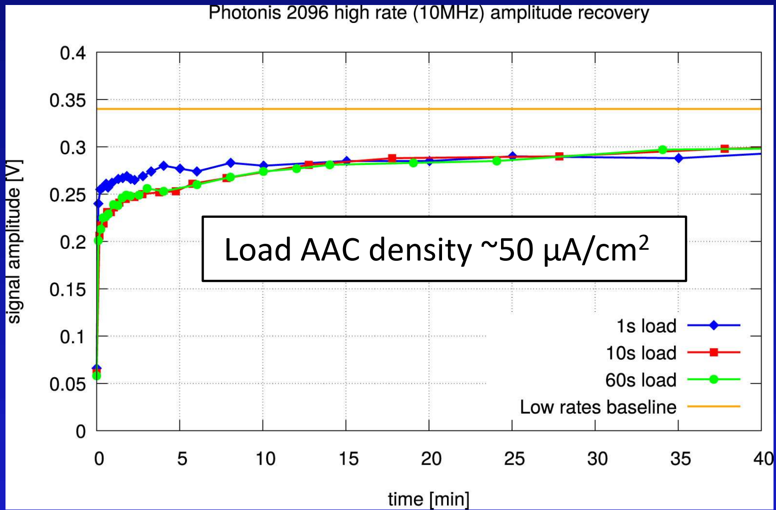
ATLAS Forward Proton detectors – Photosensors – Previous models

- Achieved rate capability
  - Low R
    - → better max. rate
    - → increased "super-linearity"
    - Gain (current mode): 10^4

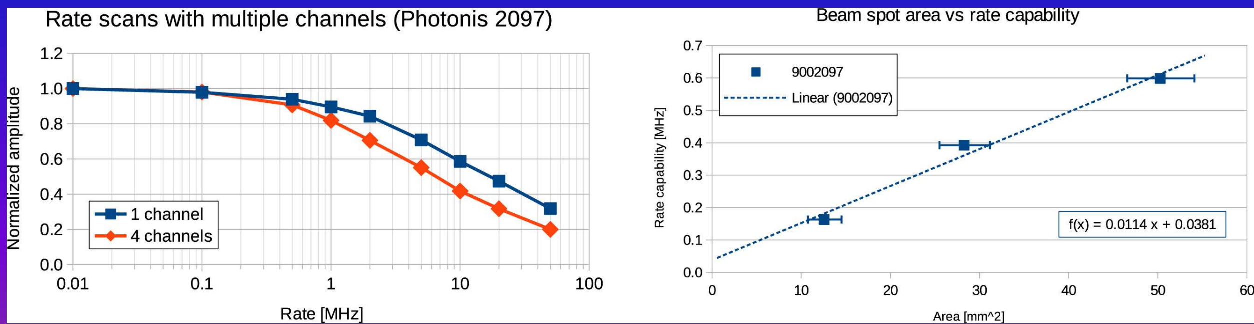


NIMA 985 (2021) 164705

- Saturation and recovery

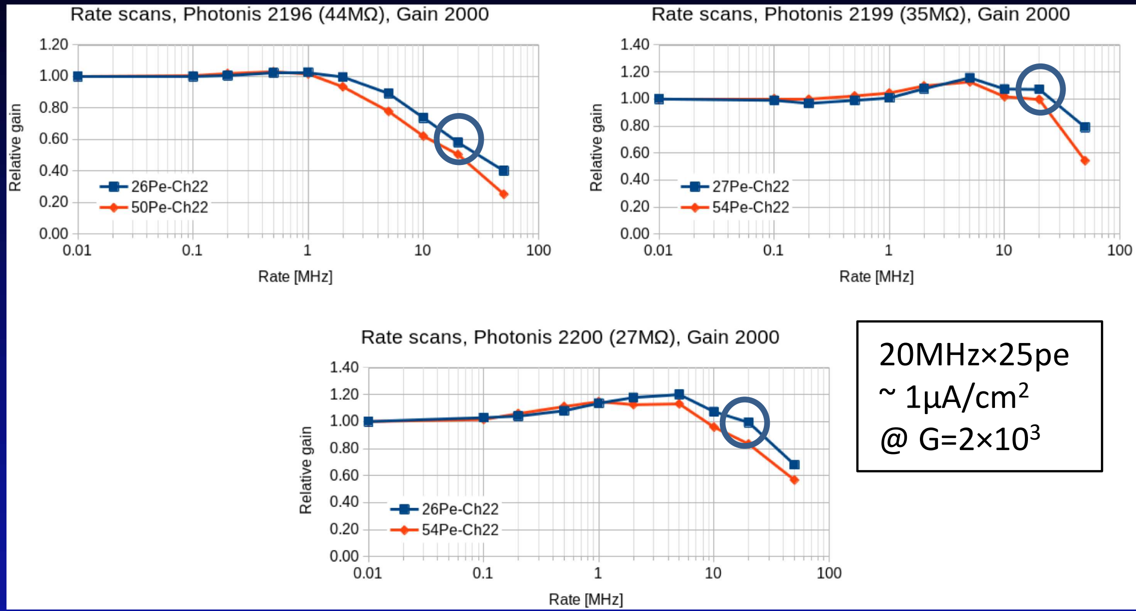


- Local vs global effects
  - Illumination conditions
    - 4 ch. vs 1 ch. at constant rate
    - Spot vs rate

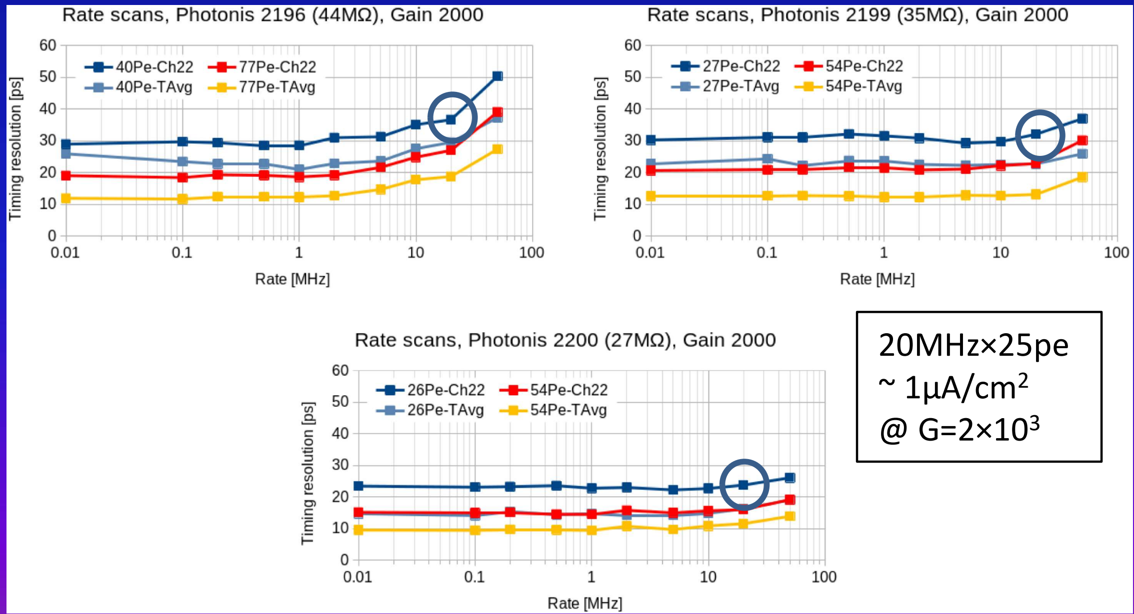


ATLAS Forward Proton detectors – Photosensors – Latest models

- Achieved rate capability
  - Low R
    - → better max. rate
    - → increased "super-linearity"
    - Gain (current mode): 2×10^3
- Recovery now ~OK
  - Double ALD layer
  - Larger gain after saturation
    - +20% levelling off to +10%
    - Full recovery with HV off
- Achieved intrinsic time resolution
  - Recent lab measurements
    - Typ. 15-30ps/train
  - From previous beam tests
    - Raw signal
      - 20ps single channel
      - 14ps train combination
    - HPTDC
      - 20ps train combination

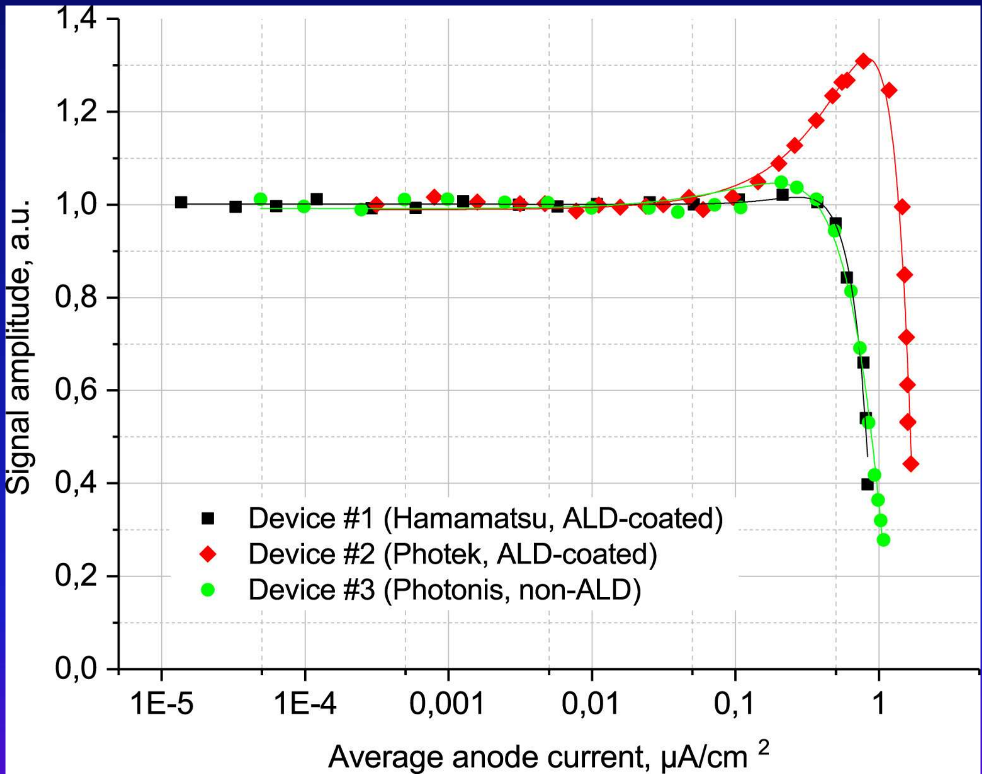


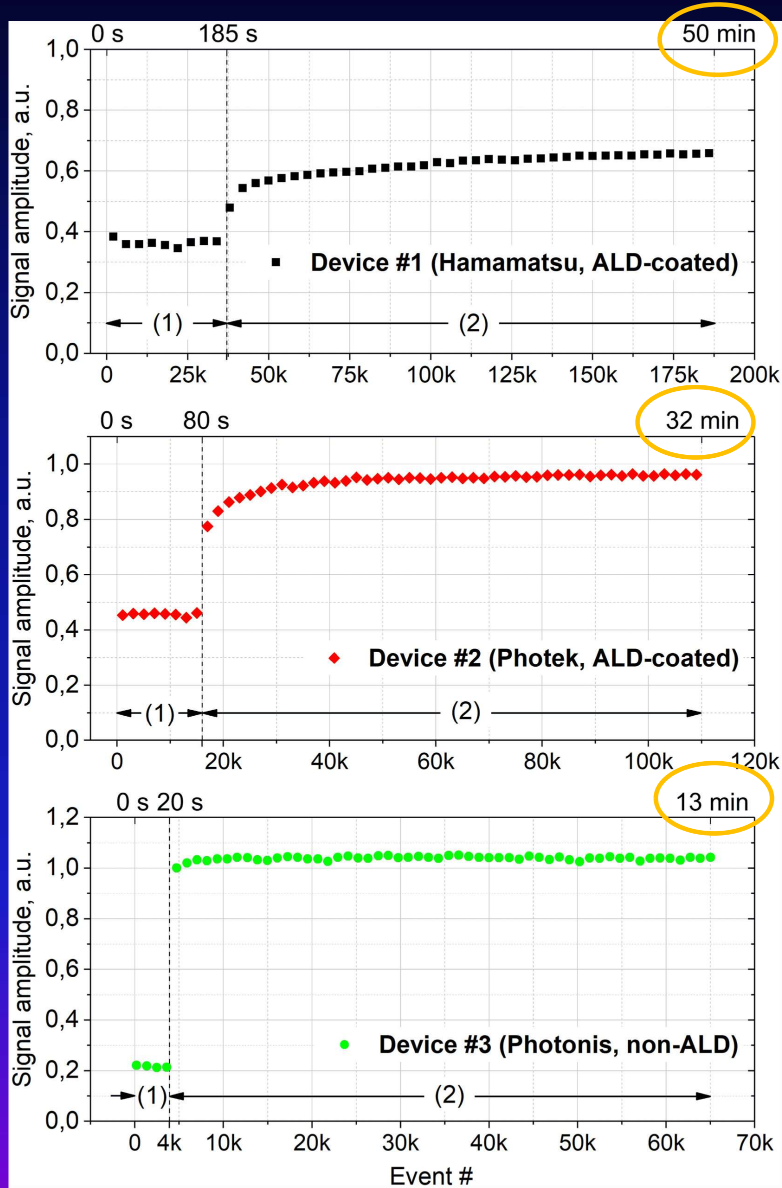
NIMA 1041 (2022) 167330



FIT/AFP – Photosensors – Saturation and recovery

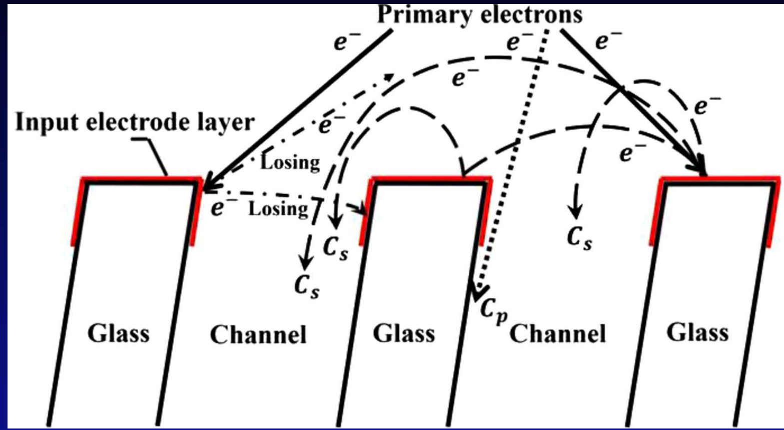
- ALD-coated MCPs exhibit
  - Lower saturation current levels
  - Longer gain recovery times
  - Saturation currents improved wrt previous FIT tests





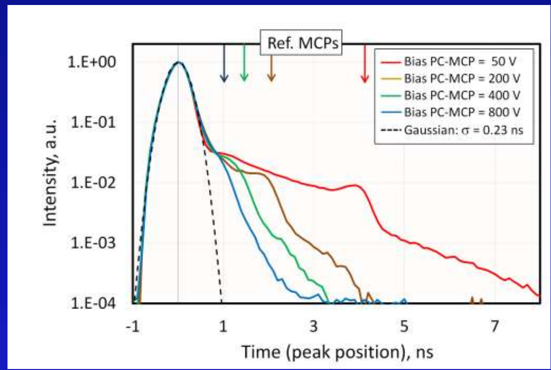
NIMA 949 (2020) 162854

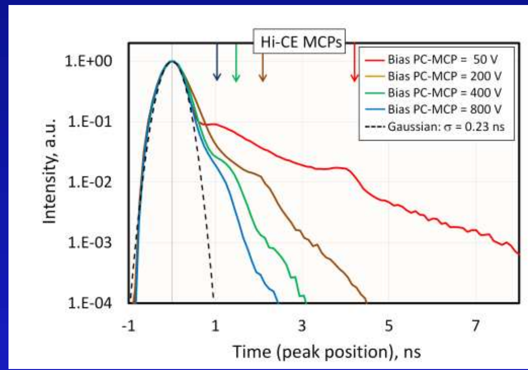
- Conventional CE
  - Primary pes entering micro-channel ~ 55%
    - Non scattered pe
    - Main pulse in time distribution
  - Primary pes hitting Ni-Cr electrode ~ 45%
    - A fraction backscattered
    - ~ 10% re-entering (another) micro-channel
    - Late pulse (tail) in time distribution



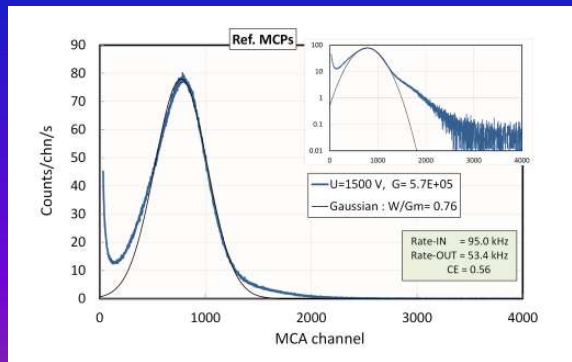
NIMA 827 (2016) 124-130

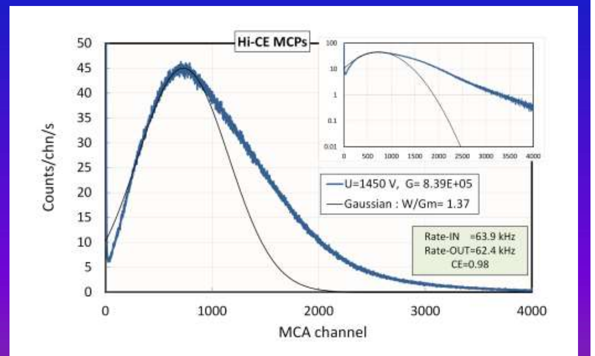
- Improved CE
  - Deposit SE layer on top electrode
    - Resulting CE reaching 90-100%
    - → Broadening of PHD
    - → Increased contribution of late pulse
  - Overall time resolution (partially) regained by increasing V between PC and first MCP
    - → Change voltage divider ratio





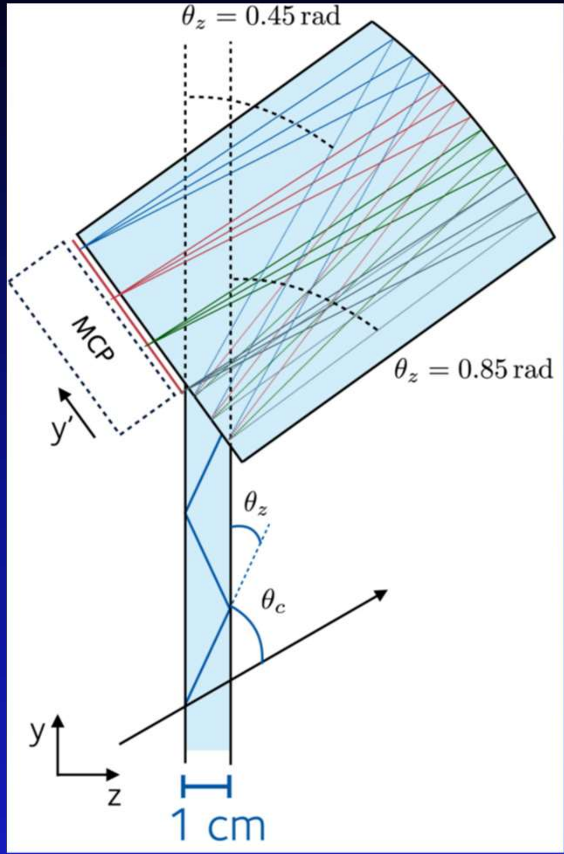
2018 JINST 13 C01047





- TORCH is a time-of-flight detector proposed for low-p particle ID in LHCb Upgrade 2

- MCP requirements
  - Segmentation 128x8 (~0.4mmx6.4mm for a 2” tube)
    - For reconstruction of photon angle propagation with ~1mrad resolution
  - Typical gain 100fC (6×10^5)
    - To extend lifetime and rate capability
  - TTS 50ps for single photons (including electronics)
  - Rate capability: ≥ 10MHz/cm^2
  - Lifetime: ≥ 10C/cm^2 per year

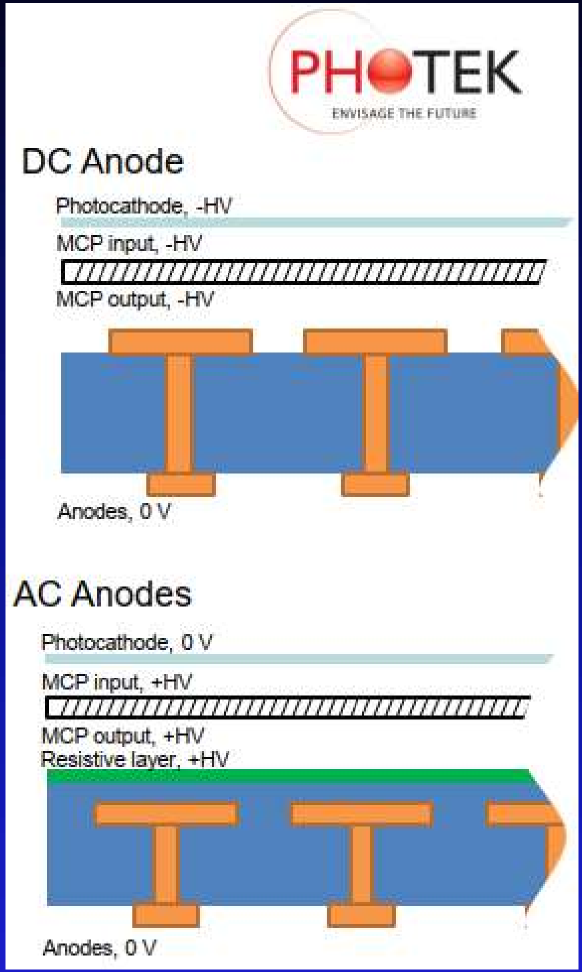


NIMA 1050 (2023) 168181

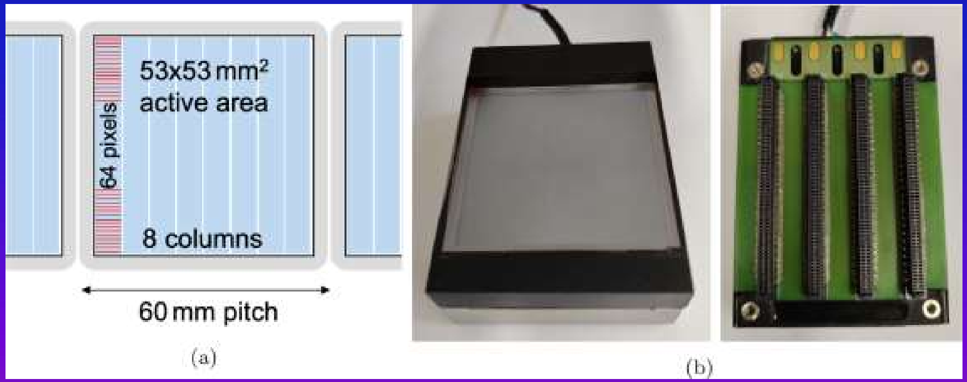
TORCH MCP R&D – Fine segmentation

- Anode fine segmentation
  - DC coupling
    - Standard layout
  - AC coupling
    - Thin dielectric between charge collection and readout
    - Induced image charge footprint with tuneable size
    - Use charge sharing and centroiding to reconstruct photon position, recovering initially required segmentation
    - Photocathode operated at 0 V, no charge-up on input window
    - Reduced electronic channel count
    - Increased channel occupancy
    - Photek TORCH prototypes model PMT253
      - Segmentation: 64×8

→ this AC coupling initially preferred

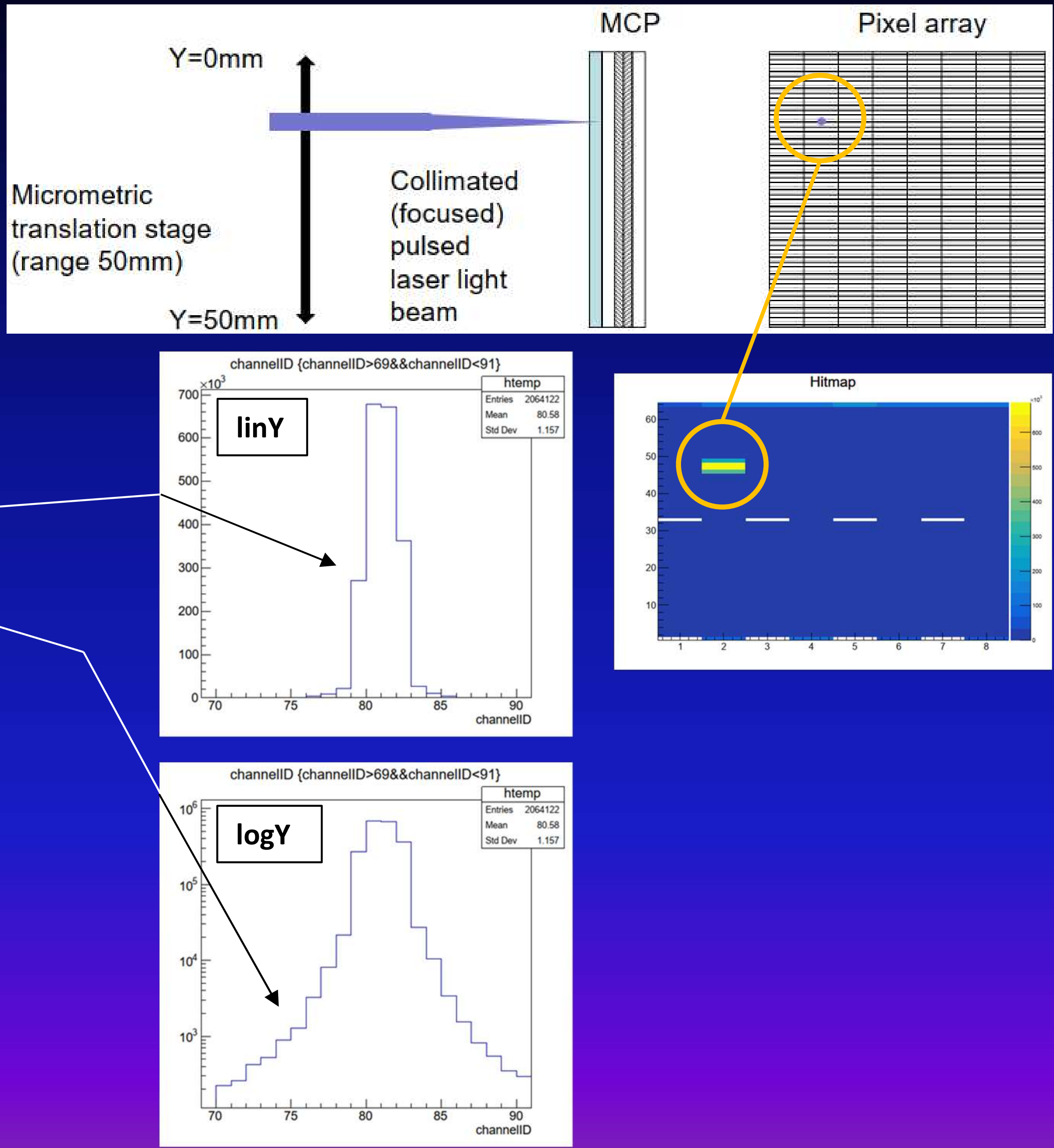


T. Conneely
DIRC 2017

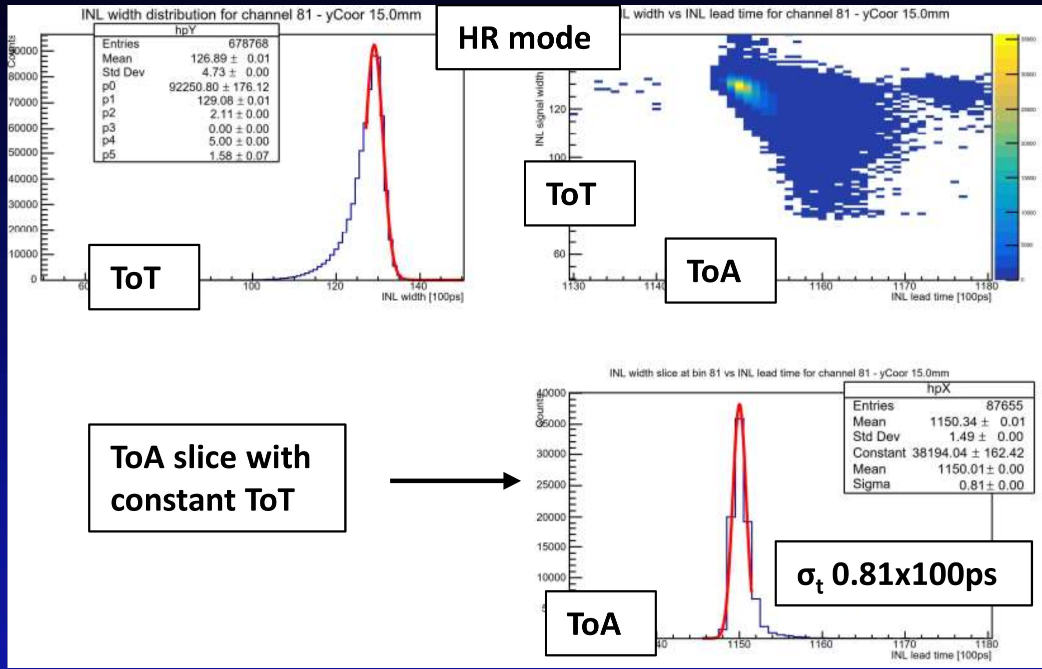


NIMA 1050 (2023) 168181

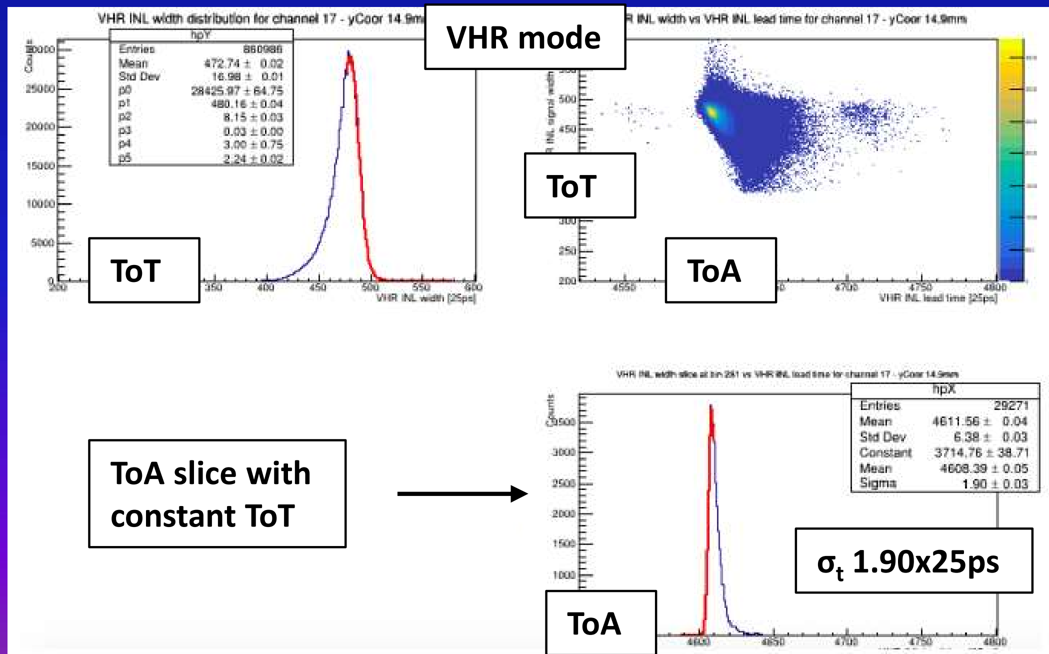
- Pulsed laser light spot
  - Time width: 20ps FWHM
  - Spot size: ~20µm
  - Low intensity: < 0.1pe/trigger
    - Use digital attenuator
    - Minimize ≥pes events
- Output charge cluster
  - σ(PSF): ~0.8mm
  - Typical cluster size: 3-4 pixels
  - Back-scattering "halo"
- Front-end electronics
  - NINO: 32 channel version
    - Single-level discrimination, ~30fC threshold
    - Time-over-threshold
  - HPTDC
    - HR Mode: 100ps time bin
    - VHR Mode: 25ps time bin



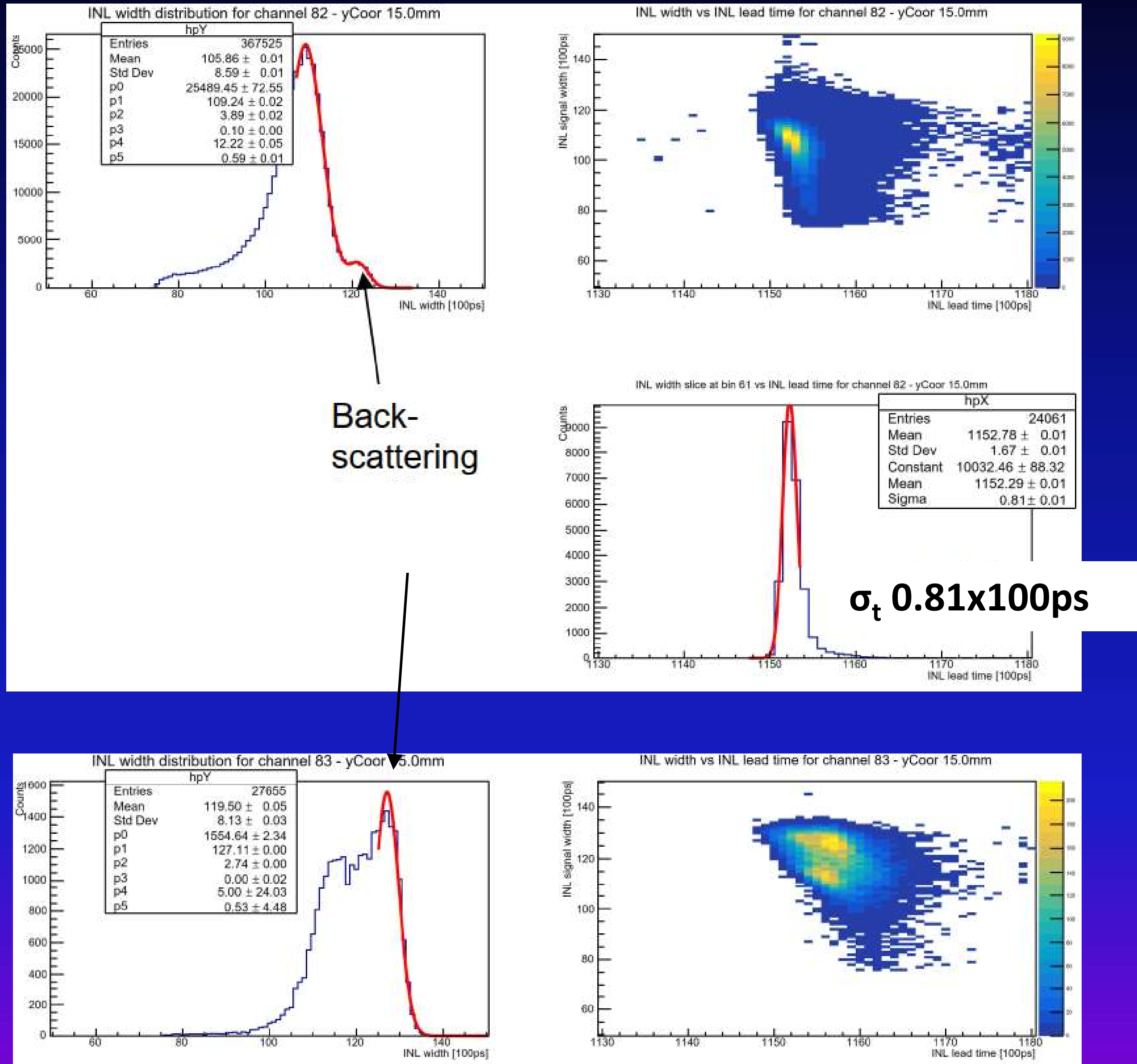
- Central pixel
  - Achieved time resolution *per pixel*
    - σ_t ~80ps
    - HPTDC
      in High Resolution (HR) mode
    - Constant Time-over-Threshold (ToT), time-walk corrected



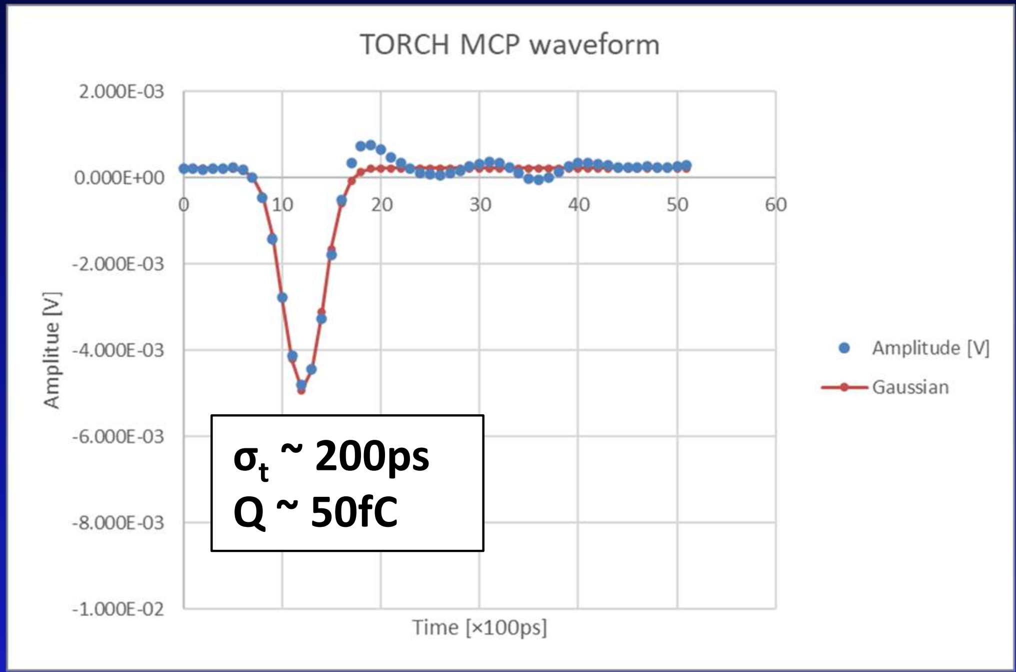
-
    - σ_t ~50ps
    - HPTDC
      in Very High Resolution (VHR) mode
    - Constant Time-over-Threshold (ToT), time-walk corrected



- Peripheral pixel
  - Not scattered pe
    - Lower charge
    - Larger time walk
    - σt ~80ps (constant ampl.)
  - Back-scattered pe
    - Larger charge
    - Small time walk
    - Delayed in time
- Most peripheral pixel
  - Not scattered pe
    - Even lower charge
    - Even larger time walk
  - Back-scattered pe
    - Larger charge
    - Small time walk
    - Delayed in time

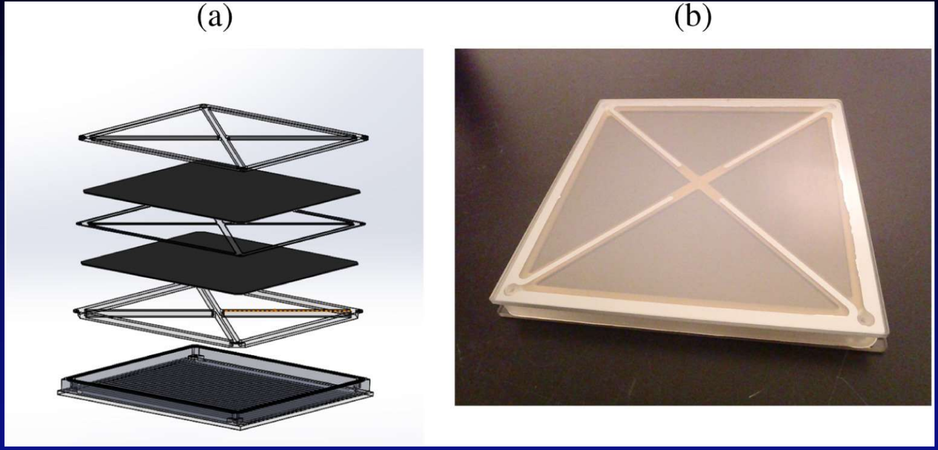


- Coping with high occupancies
  - DC coupling
    - Reduced PSF and cluster size: ≥1 pixel
  - Anode finer segmentation
    - Reduce pixel size in both dimensions → Increased channel count and density to preserve required spatial resolution
    - Segmentation R&D: 96x16
    - Illumination rate unchanged !
  - Smaller gain
    - G ~ 100fC (6×10^5) already achieved with similar performance
    - Further reduction possible
  - Example of typical pulse (AC coupling)
    - In central pixel of a cluster
    - σ_t(pixel) ~ 200ps
    - Q(pixel) ~ 50fC
    - Max current 100µA, compatible with FastIC/FastRICH specs:
      - Dynamic range: 5 µA to 5 mA (timing performance achieved for pulses >50 µA)
      - Noise: <2 µA r.m.s.
      - CFD residual spread: ~ 114ps for 30µA-2mA current pulses



Large Area Picosecond Photo-Detector – LAPPD ©

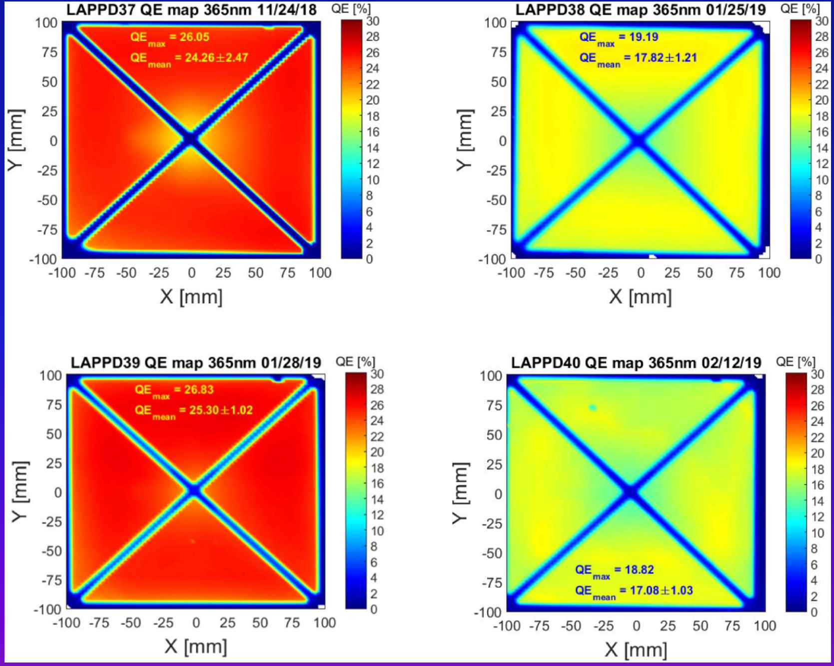
- Design
  - Input window
    - Borosilicate or fused silica
  - Enclosure and spacers
    - Borosilicate glass
  - Chevron pair of MCPs
    - Glass microcapillary array with ALD
  - Internal microstrip anode
  - 20×20cm^2 overall size !
  - Cost effective



NIMA 958 (2020) 162834

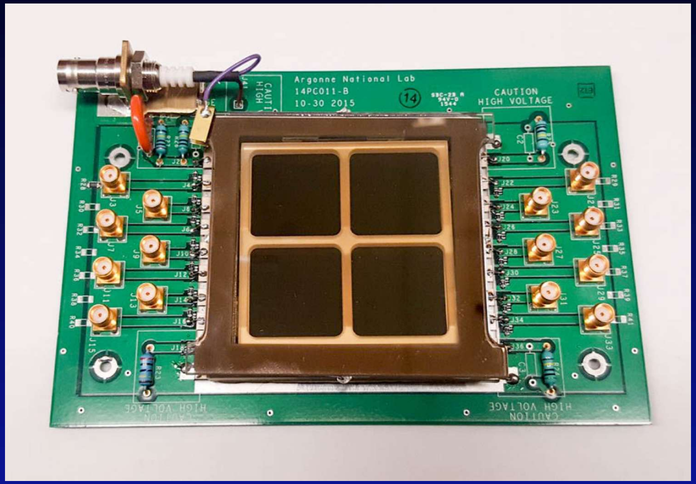
- Performance
  - Gain: up to 10^7
  - Dark count rate: 0.1-1kHz/cm^2 @ 6×10^6 gain
  - QE: up to 25% (365nm)
  - TTS: ~ 50ps
  - Spatial resolution O(mm)

} electronics limited

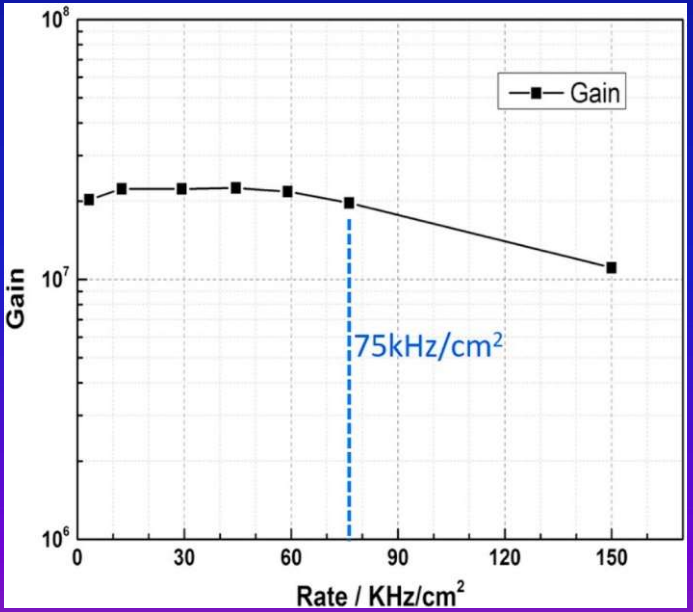


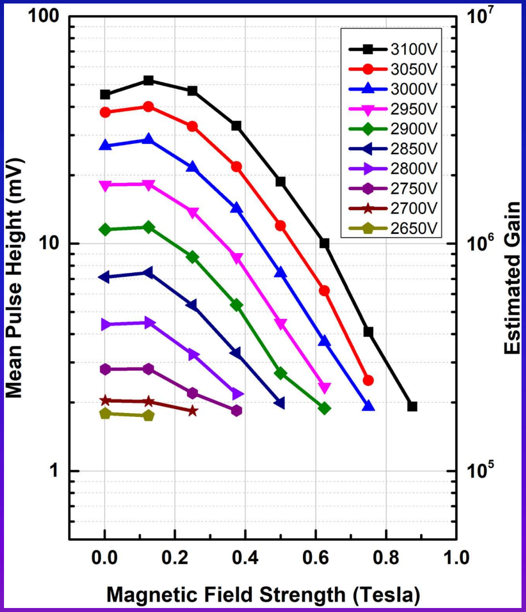
LAPPD – Other configuration studies for EIC

- Scale-model LAPPD
  - Motivation:
    - hpDIRC – small-pixel MCPs or HRPPD
    - pfRICH (aerogel radiator) – HRPPD
    - dRICH (aerogel + gas radiators) – SiPMs (high $B_\perp$ field)
  - 6×6cm^2 overall size
  - Rate capability
    - 120 GeV/c proton beam exposure
      - Expect ~100pes/p through 3mm-thick glass window
    - Gain >10^7 up to 150kHz/cm^2 beam flux
  - B field tests
- Next steps
  - HRPPD anode layouts:
    - AC: 24×24 pads
    - DC: 32×32 pads



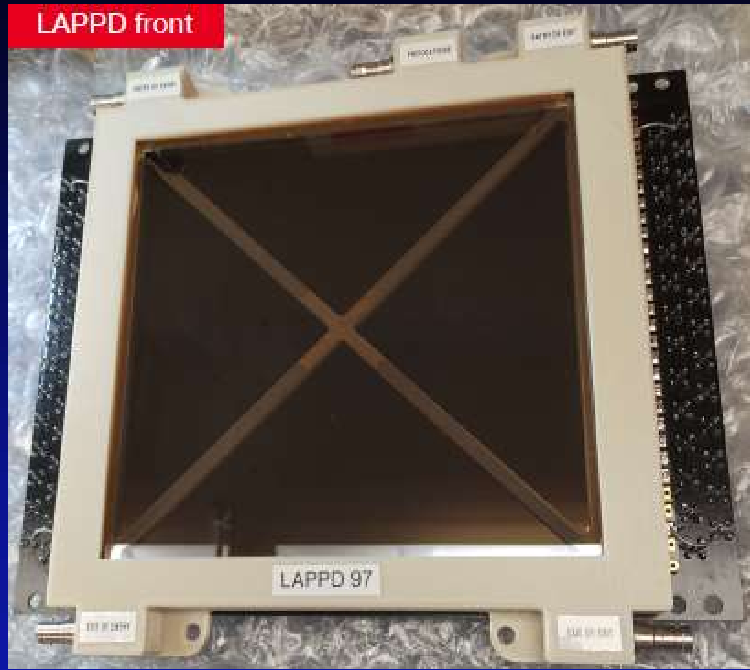
NIMA A 912 (2018) 85–89



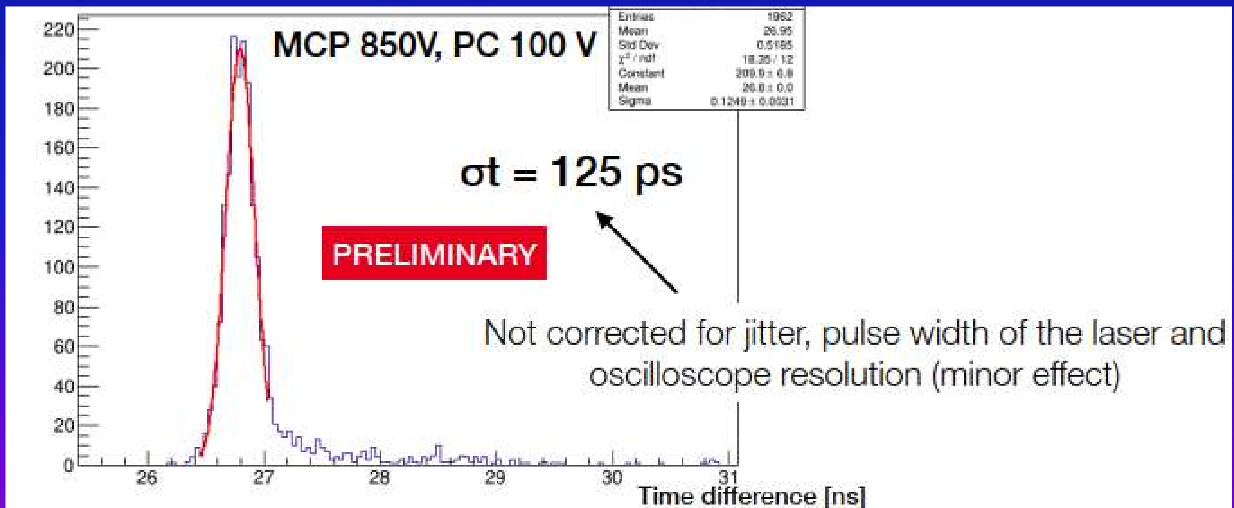


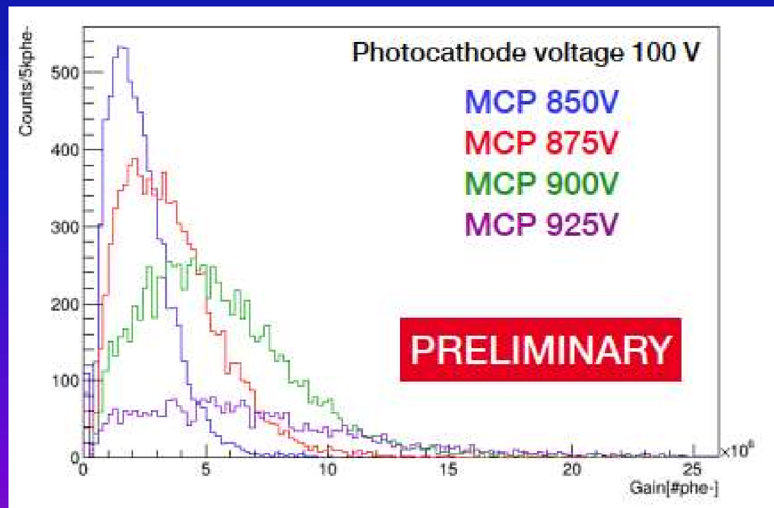
LAPPD – New generation II

- Design
  - Internal resistive layer anode
  - External 2D segmentation through AC coupling
  - Customizable anode pattern
    - Currently available
      - External pad segmentation: 8×8
      - Pad size/pitch: 24/25mm
  - Similar performance as in Gen I
  - Finer pad/pixel segmentation under development



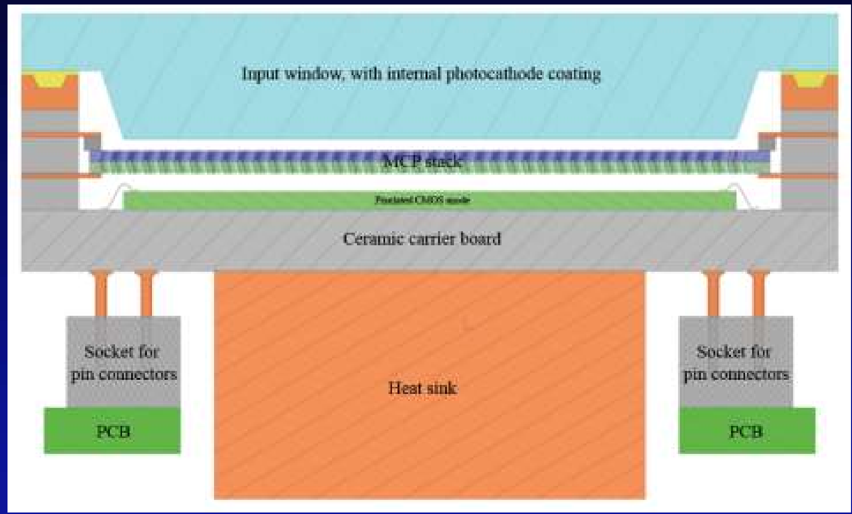
F. Oliva RICH 2022





Hybrid MCP with encapsulated ASIC

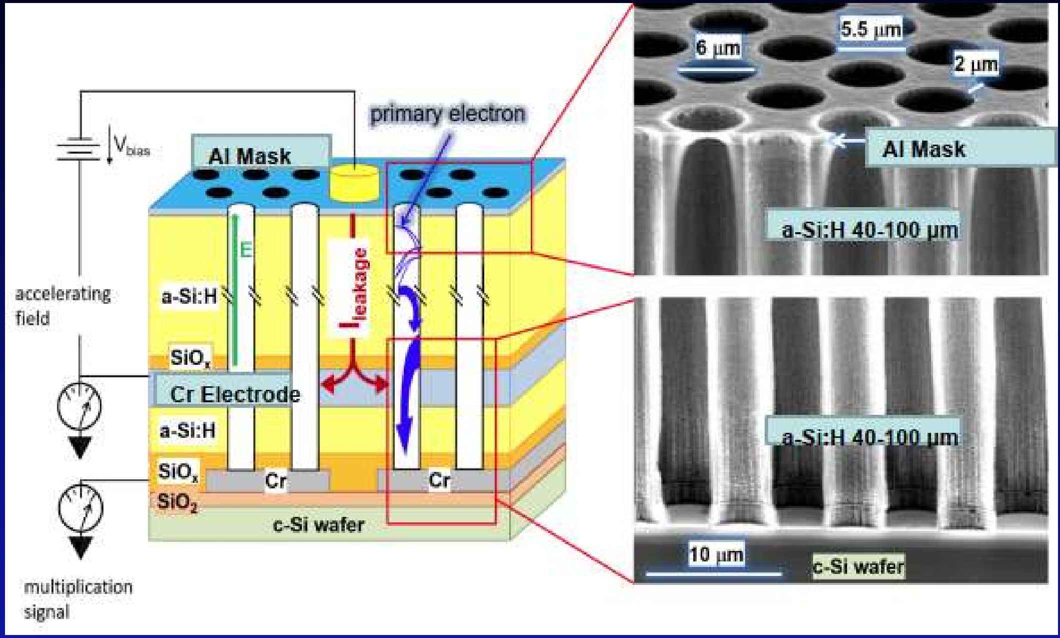
- Design
  - Pixel readout ASIC encapsulated in vacuum
  - No bump-bonded pixel detector
    - Use input bump-bond pad of FE channels
  - High channel count
  - Reduced number of output lines
  - Compatibility with vacuum tube technology
  - Heat dissipation
- Expected performance
  - Mostly defined from ASIC
  - Concept already demonstrated (Medipix2 2008, quad Timepix 2014)
  - Timepix4 specs (4DPhoton Project)
    - 448×512 square pixels (total area ~ 7cm2)
    - Pixel size: 55µm
    - Pixel ENC: 50-70e- rms
    - Discrimination level: 500-700e-
      → Low gain: typ. 10^4 → Increased MCP tube rate capability and lifetime
    - TDC bin: 195ps
    - Power: ~5W
- Many achievements (see eg in Rad. Meas. 130 (2020) 106228)



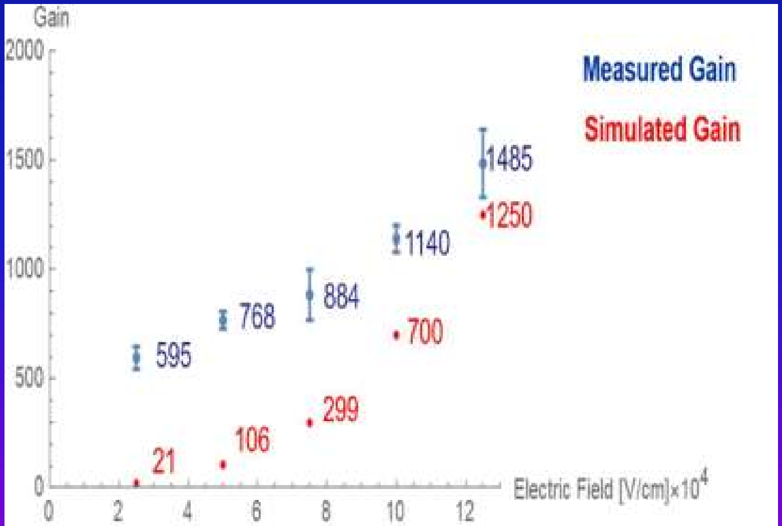
Journal of Physics: Conference Series 2374 (2022) 012129

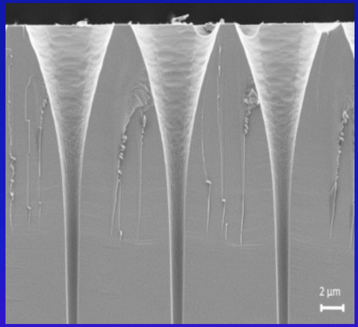
MCP based on amorphous silicon

- Design aspects
  - Vertical integration on readout electronics
  - Usage of c-Si microelectronics processes (cheap and flexible fabrication)
    - Funneled openings to increase CE
  - a-Si:H tunable resistivity (possibly faster charge replenishment)
  - Low Noise
  - High Spatial and Time Resolution
  - Radiation Hardness
  - Lower aspect ratio: 25-30
  - No channel tilt
  - No plate stacking
- Performance
  - Gain: up to 1500
  - σ_t: ~25ps (~7ps with amplifier)



S. Frey NDIP 2022





2021 NSS/MIC 1-3

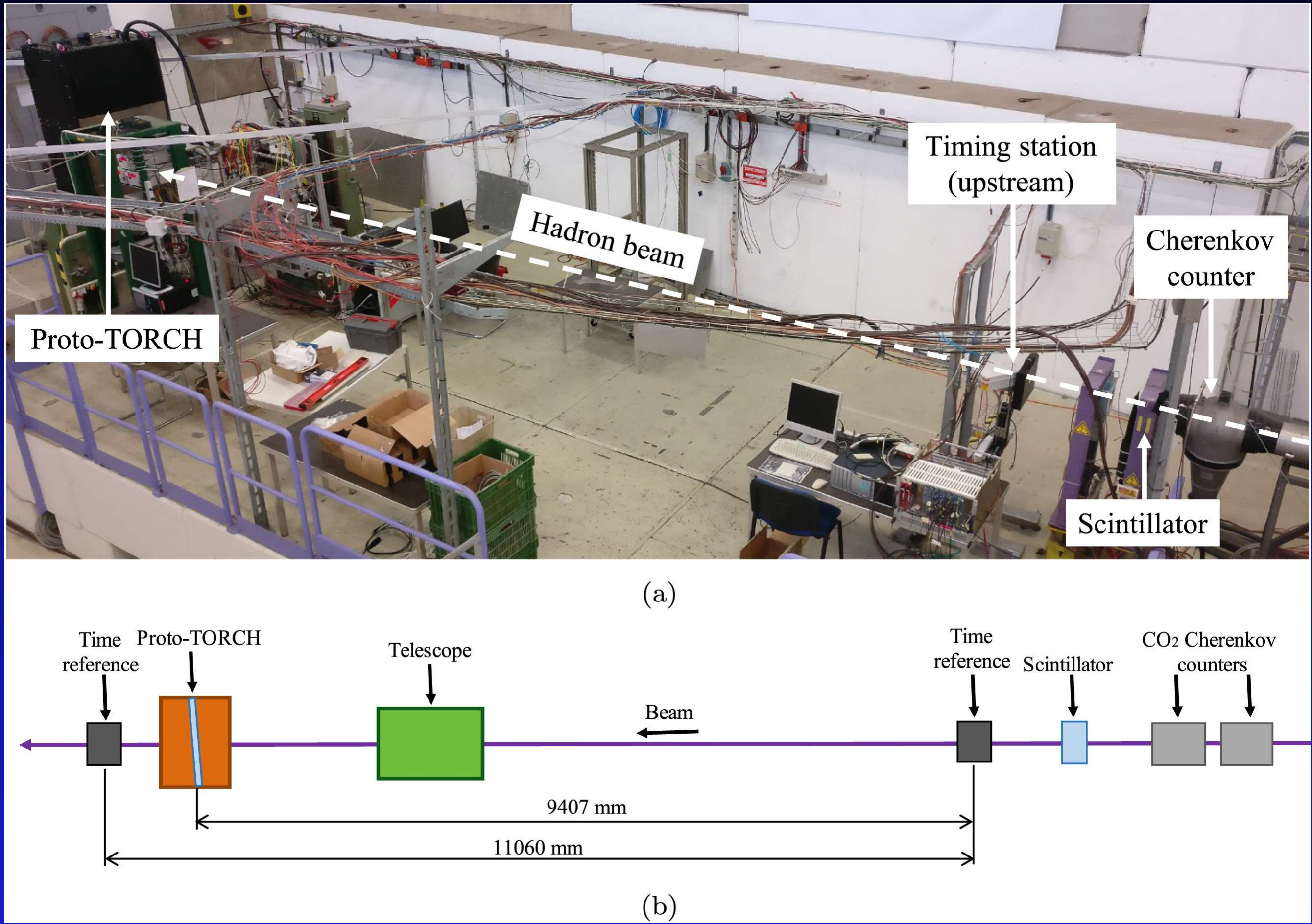
MCP detector in multi-photon regime

- Purpose
  - Precise time reference or time-of-flight

- Possible configurations
  - Cherenkov light generation in separate solid radiator
    - Minimize material in particle beam
    - Preserve MCP tube lifetime
  - Cherenkov light generation in optical entrance window of tube
    - Optimize light yield and coupling
    - Material in beam
    - Possibly affecting tube lifetime

TORCH R&D – T1 & T2 time references in beam tests

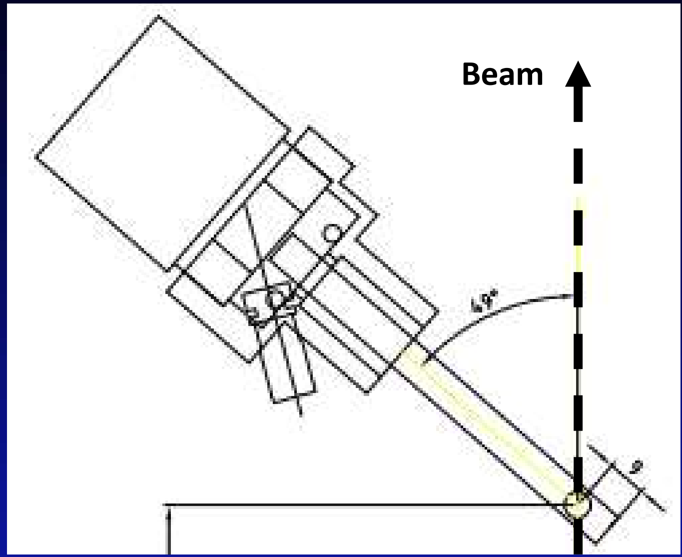
- Purpose
  - Provide upstream and downstream time references
  - Used with TORCH data for PID studies
    - Injected in HPTDC time reference channels
  - Used for beam momentum calibration
    - Injected in lab instrumentation modules
  - Re-used available material
    - MCP tubes
    - Glass radiators
    - Readout modules

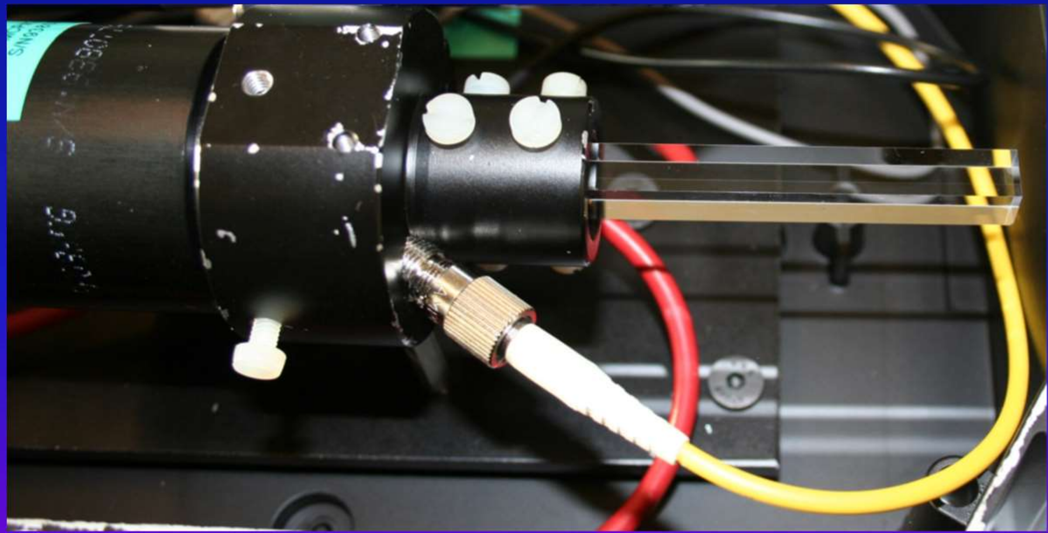


NIMA 1050 (2023) 168181

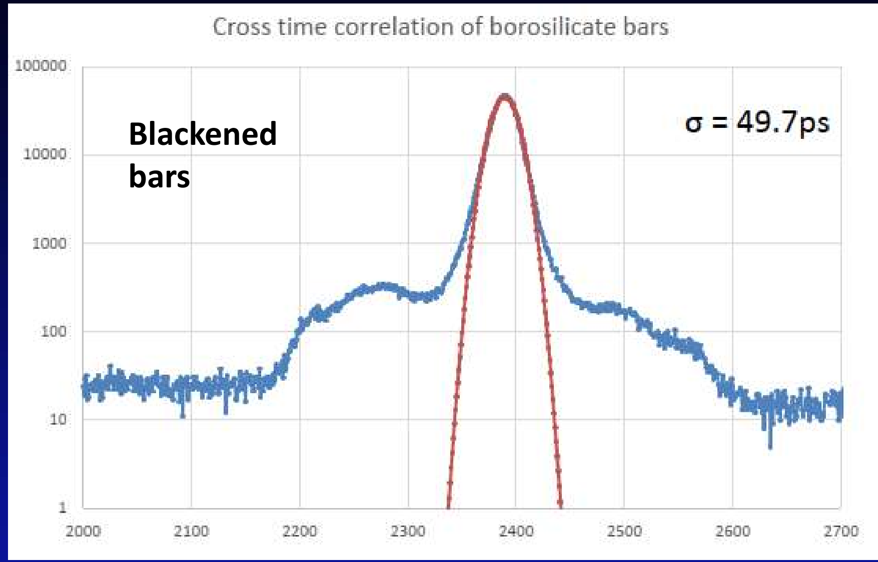
TORCH time reference system – layout

- Cherenkov radiator
  - Borosilicate bars: 8×8×100mm^3
    - Tilted wrt beam
    - ~12mm borosilicate: ~0.09X_0
  - Associated crossed scintillators: 8×8×5mm^3
    - Normal wrt beam
    - 5mm polystyrene: ~0.012X_0
  - No contact with MCP input window
- MCP tube
  - Photonis model PP0365G
  - PC-MCPin gap: 120µm
  - Active Ø: 18mm
  - Pore Ø: 6µm
  - Low gain: ~1-2×10^5
  - σ_t: ~ 30-40ps
  - Not ALD processed
- Readout electronics
  - ORTEC CFD model 9327
  - ORTEC TAC 566 and MCA 926 (~6.25ps time bin)

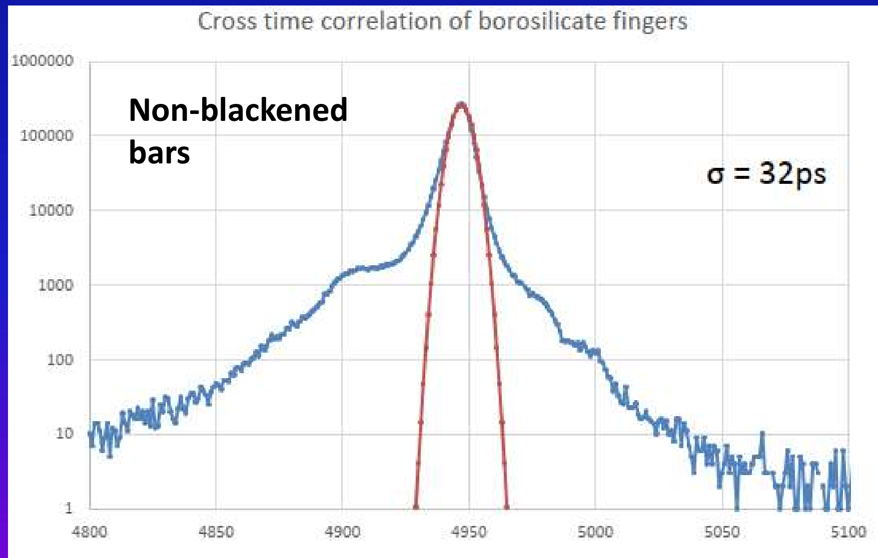


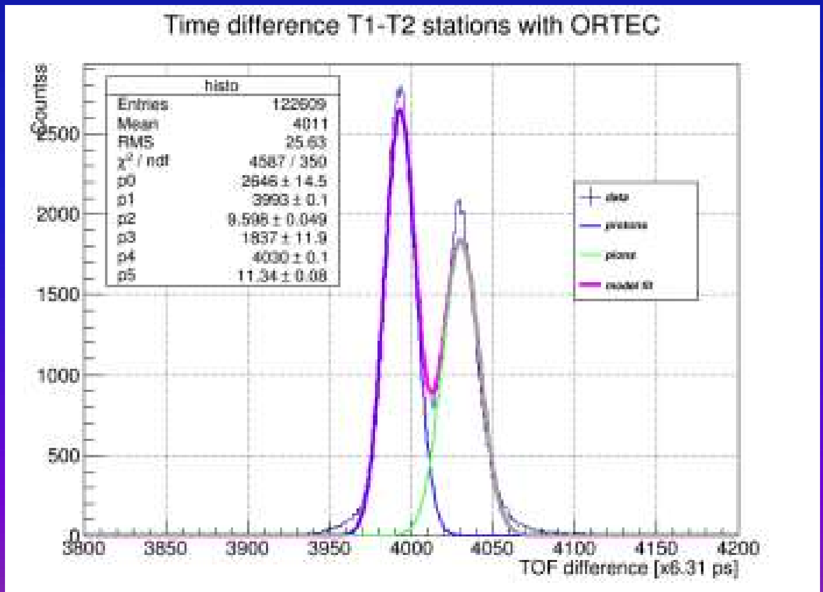


- Performance
  - SPS calibration tests
    - 180 Gev/ c charged hadrons
    - Low intensity
    - Blackened bars (no side reflections)
      - Light yield: 1.6-1.7 pe
      - σ_t: 49.7ps (individual)
    - Non-blackened bars (w. side reflections)
      - Light yield: 8.5-8.7 pe
      - σ_t: 32.0ps (individual)
  - PS time references and momentum calibration
    - 8GeV/c mixed p/pion beam



TORCH meeting 16.7.2015

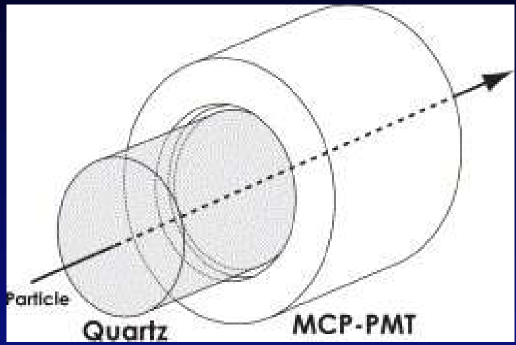




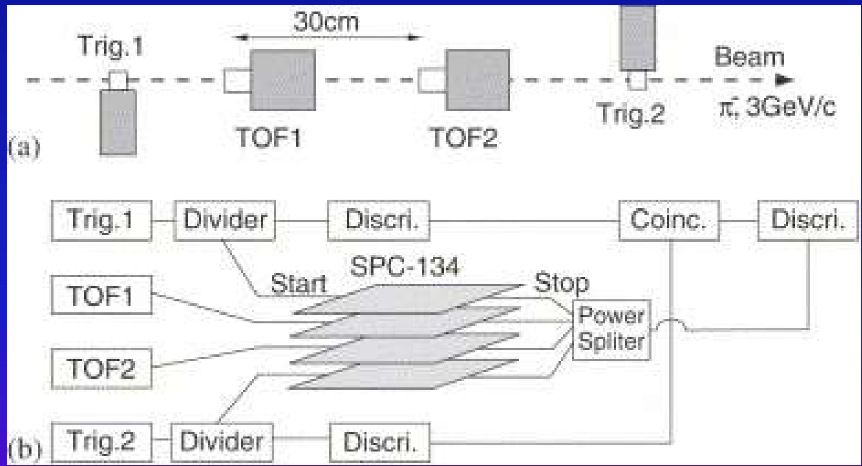
TORCH beam test status 1.9.2016

Time-of-flight counter with MCP-PMT for KEK B-factory experiments

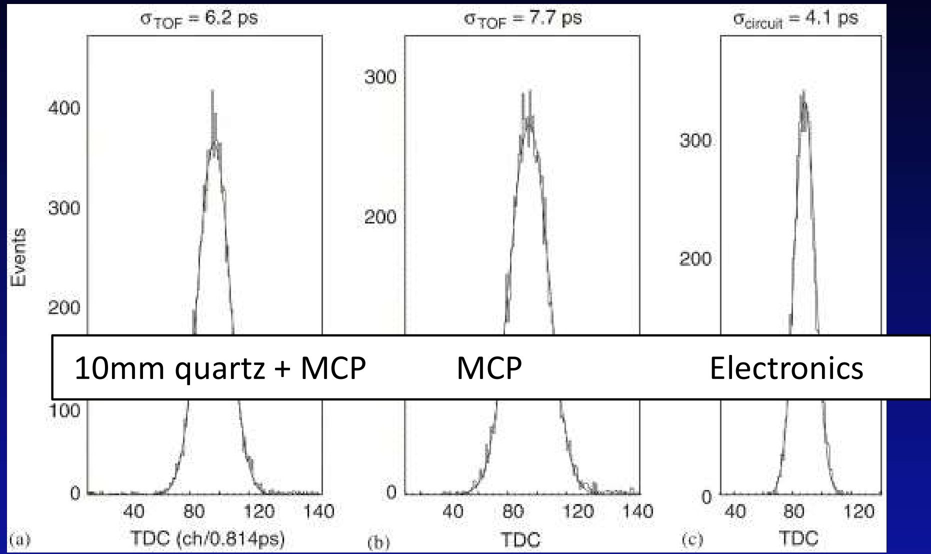
- Purpose
  - Time resolution studies of time-of-flight counters
- Test setup
  - Pion beam
    - p: 3GeV/c
    - Size: a few cm^2
    - Intensity: ~ 10Hz
  - Scintillators
    - 5×5×10mm^3
    - PMT readout
    - Trigger
  - 2 MCP-PMTs (+ Quartz rods)
- Readout
  - Time-correlated counting module
    - Channel resolution: 813fs
    - Time resolution: 4ps rms
    - Rep. rate: up to 200MHz



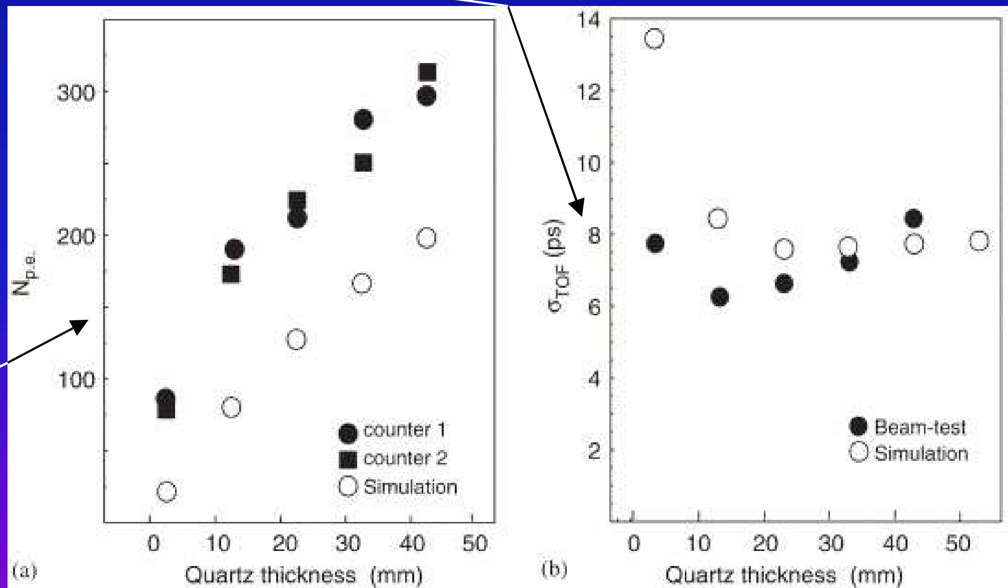
NIMA 560 (2006) 303-308



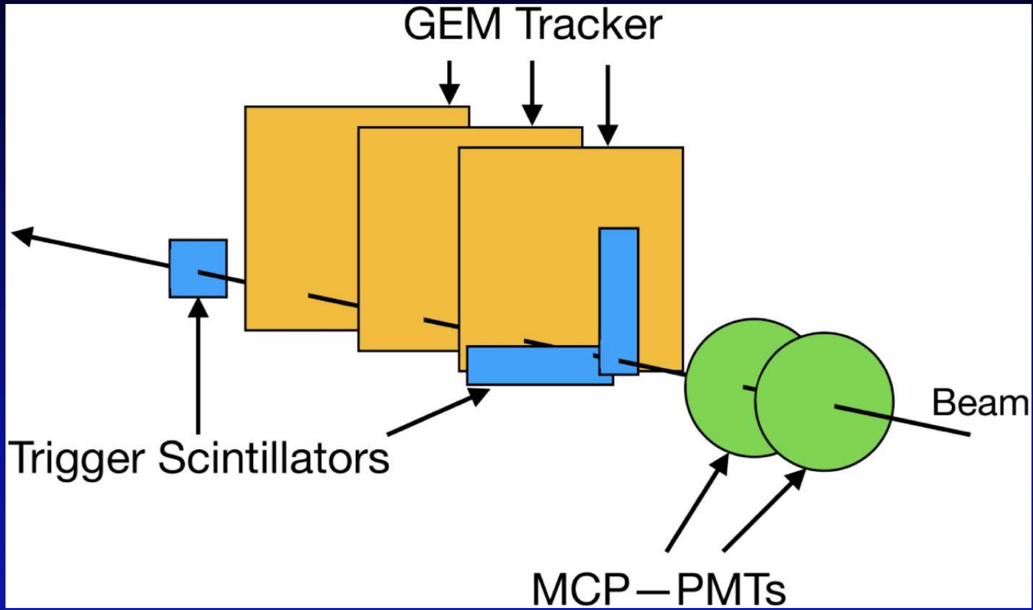
- Cherenkov radiator
  - Quartz rod
    - Variable thickness: 10-20-30-40mm
  - Quartz input window
    - Thickness: 3.0mm (?)
- MCP-PMTs
  - Hamamatsu model R3809U-50-11X
  - Active Ø: 11mm
  - Pore Ø: 6µm
  - Operating gain: ~ 1×10^6
  - σ_t: ~ 30ps (single photons $G\geq10^6$)
  - Not ALD processed
- Performance
  - σ_t: ~ 6.5ps (combined)
    - Without quartz radiator
    - Corrected for electronics σ_t
  - Discrepancy on N not understood



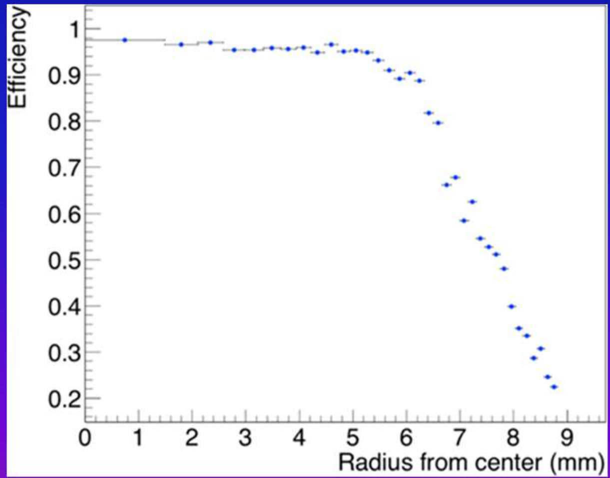
NIMA 560 (2006) 303-308

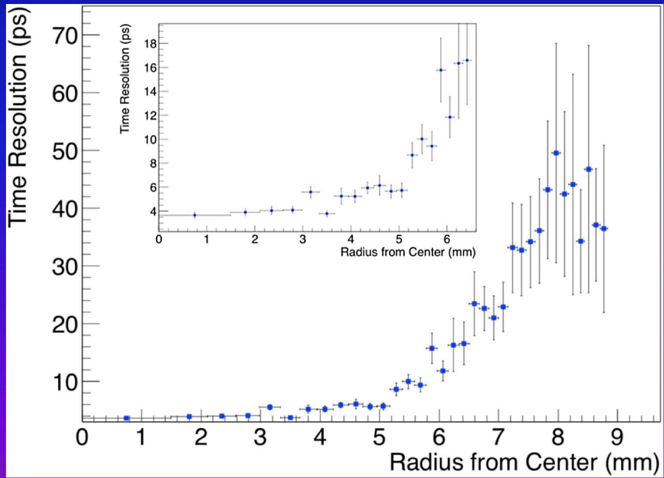


- Purpose
  - Provide ultra-precise T_0 for time resolution studies of PICOSEC Micromegas detectors
- Test setup
  - SPS-H4 muon beam, up to 180GeV/c
    - Rate: a few 10^5 per spill on scintillators (max. beam rate ~ 1kHz on MCP)
  - Tracking devices
    - Triple GEM
    - Extrapolated track precision: 40µm
  - Scintillators
    - PMT readout
    - Trigger
  - 2 MCP-PMTs
    - Time references
  - DUTs
    - PICOSEC Micromegas
  - Readout
    - Sampling oscilloscopes

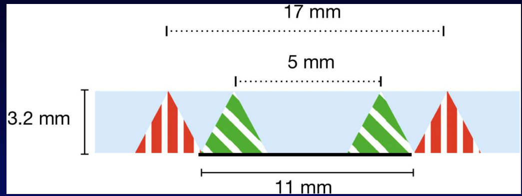


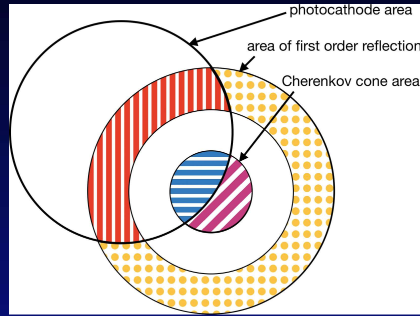
NIMA 936 (2019) 583-585



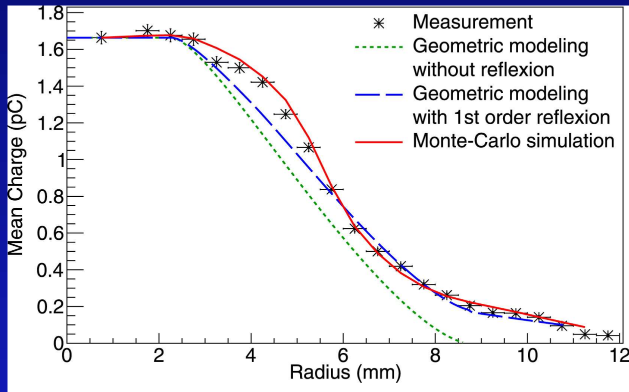


- Cherenkov radiator
  - Quartz input window
    - Thickness: 3.2mm ~ $0.03X_0$
- MCP-PMTs
  - Hamamatsu model R3809U-50
  - Active Ø: 11mm
  - Pore Ø: 6µm
  - Operating gain: ~ 8×10^4
  - σ_t: ~ 25ps
  - ALD processed
- Performance
  - σ_t: ~ 7.2ps (combined)
  - Illum. rate in spill: ~100kHz/cm^2
  - 2 spills of ~5s per min.
  - IAC
    - Q(MIP) ~ 1.4pC
    - Per spill: ~ 7nC/cm^2
    - Per 12 days of continuous beam tests: ~ 240µC/cm^2

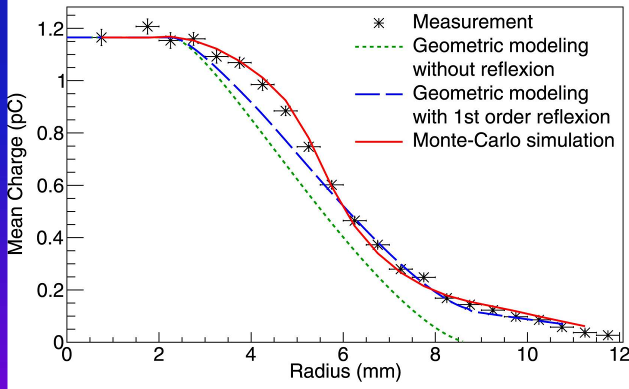




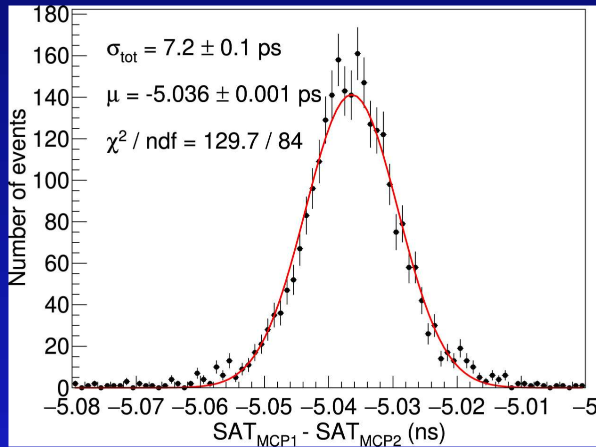
NIMA 960 (2020) 583-585

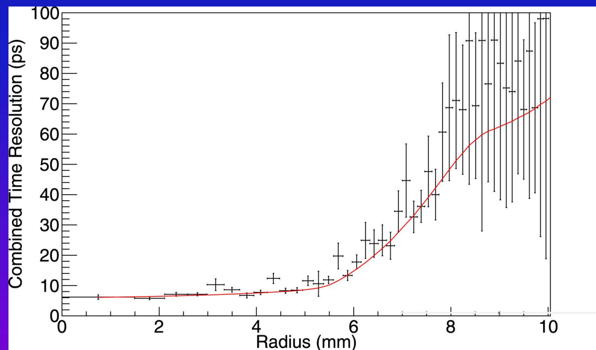


(a) MCP-PMT 1



(b) MCP-PMT 2





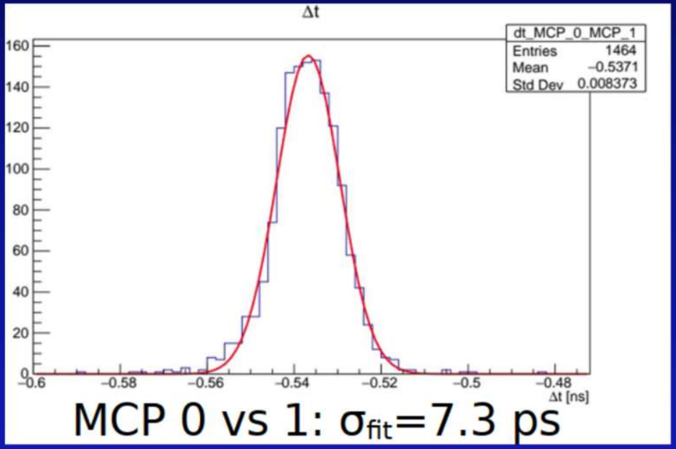
ATLAS HGTD and FASTPIX R&D – T_0 time reference from MCP-PMT

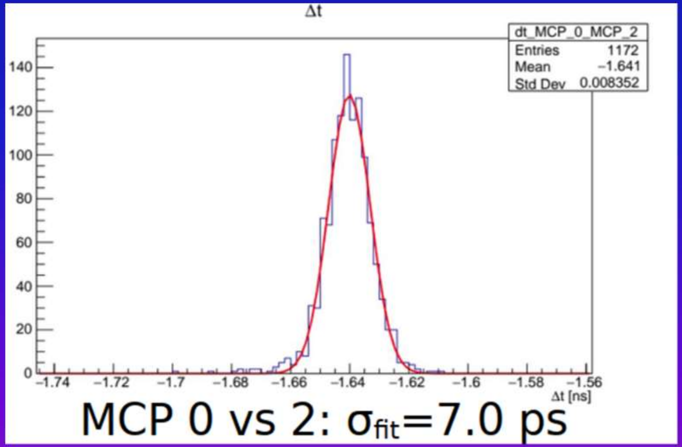
- Purpose
  - Provide ultra-precise T_0 for time resolution studies of HGTD LGAD and FASTPIX detectors

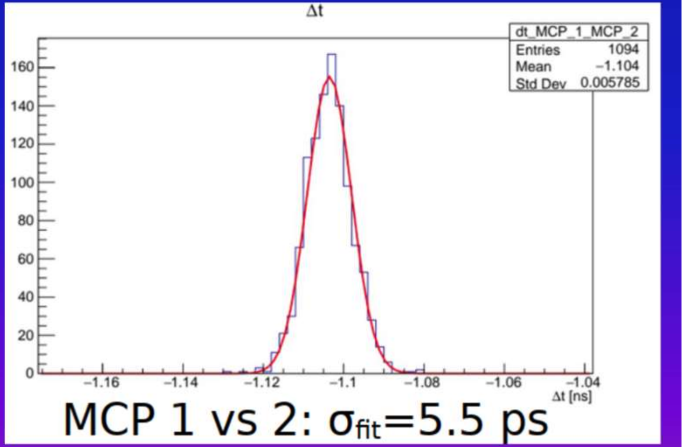
- Test setup
  - SPS-H6 pion beam, 120GeV/c
    - Rate: a few 10^6 per spill on scintillators (max. beam rate ~ 250kHz on MCP)
  - Tracking devices
    - Timepix3 telescope
  - Scintillators
    - PMT readout
    - Trigger
  - 3 MCP-PMTs
    - Time references and trigger
  - DUTs
    - LGAD/FASTPIX structures (fast OR trigger)
  - Readout
    - Sampling oscilloscopes

J. Braach et al., private comm.

- Cherenkov radiator
  - MCP-PMT input windows
    - Thickness: 3.2mm (HPK)
    - Thickness: 9.0mm (Photek)
- MCP-PMTs
  - MCP0/MCP1 HPK model R3809U-50
    - Operating gain: ~1×10^6
  - MCP2 Photek model PMT240
    - Active Ø: 40mm
    - Pore Ø: 10µm
    - Operating gain: ~3×10^5
    - σ_t: ~ 25ps
    - ALD processed
- Performance
  - σ_t:
    - MCP 0 (1742): 6.0ps
    - MCP 1 (1499): 4.2ps
    - MCP 2 (Photek): 3.6ps







D. Dannheim et al., private comm.

- Performance (cont'd)
  - Illumination rate in spill:
    - ~ 25MHz/cm^2 (G~1×10^6) MCP0/MCP1
    - ~ 75MHz/cm^2 (G~3×10^5) MCP2
  - 2 spills of ~5s per min.
  - IAC
    - Q(MIP) ~12-14pC
    - Per spill: ~ 16µC/cm^2
    - Per 12 days of continuous beam tests: ~ 0.55C/cm^2
- Note
  - Similar implementation of MCP-PMTs for high-precision T_0 under development for LHCb beam tests
    - Readout based on CFD and picoTDC

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
- Very high rate capability is a challenge
  - Mitigated with lower gain
- Instrumentation is a challenge too
  - High channel number and density
  - High speed
  - High SNR