Light 2014, Ringberg castle,
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HAPD studies

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HAPD as the photo-sensor of the Belle II aerogel RICH

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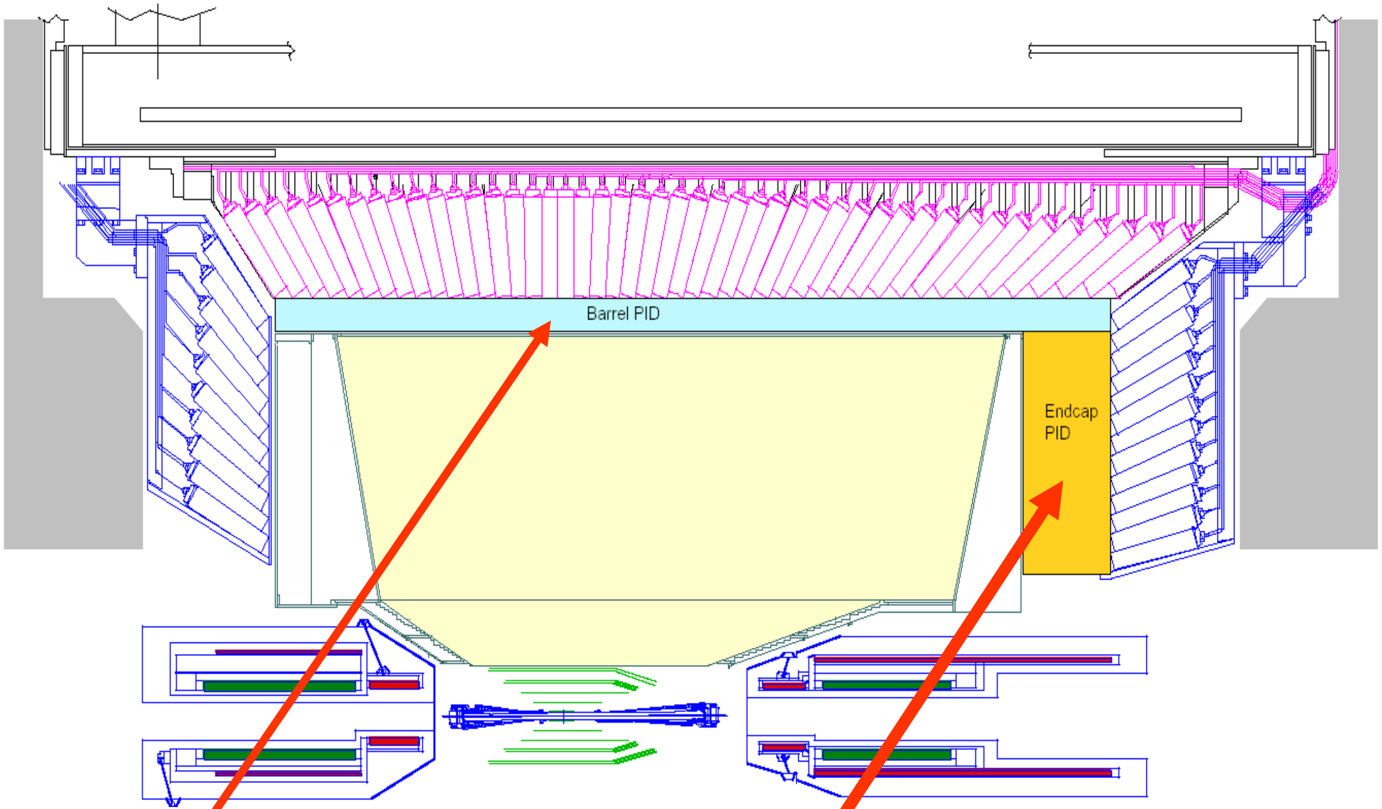
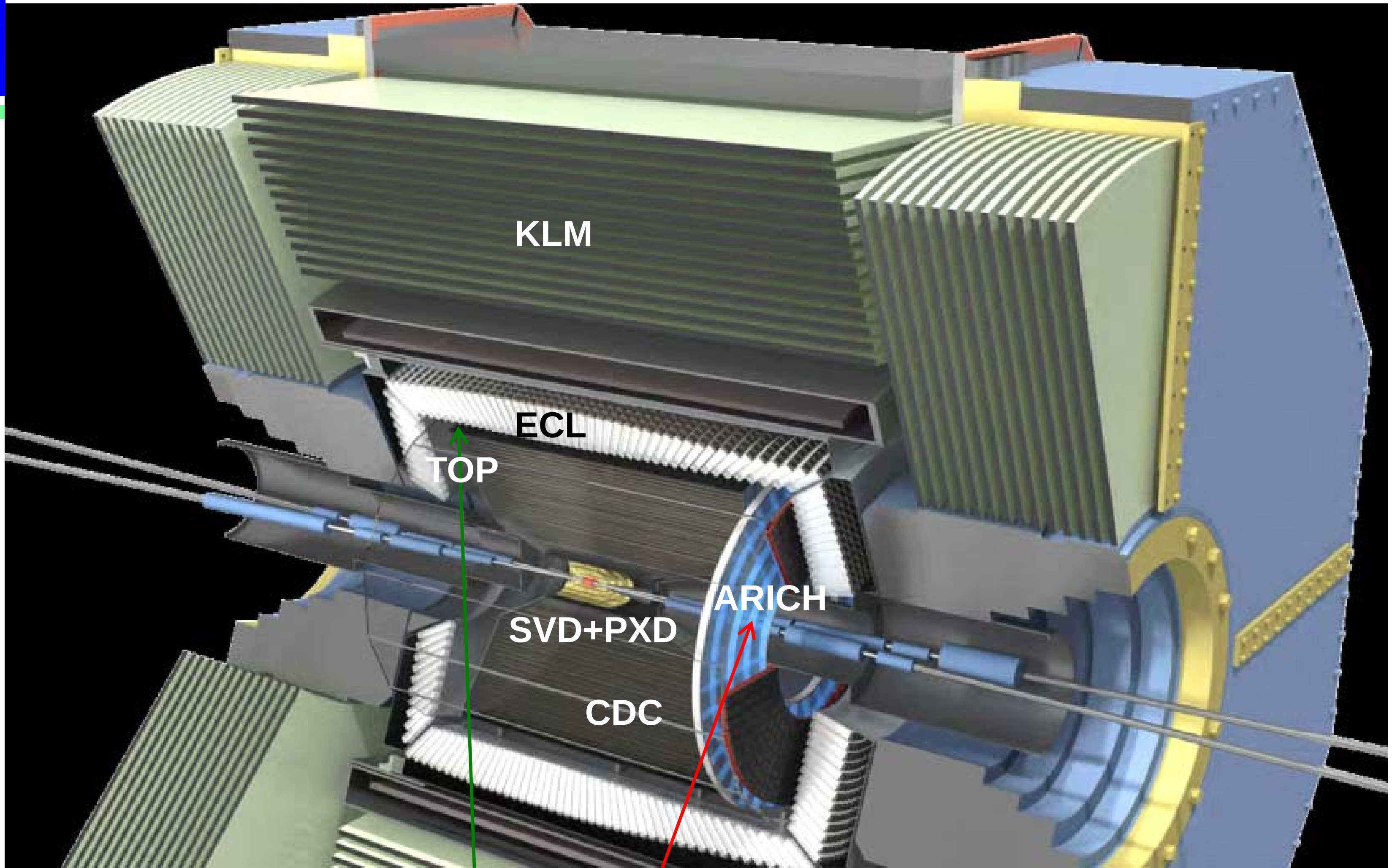


Two new particle ID devices, both RICHes:

Barrel: time-of-propagation (TOP) counter

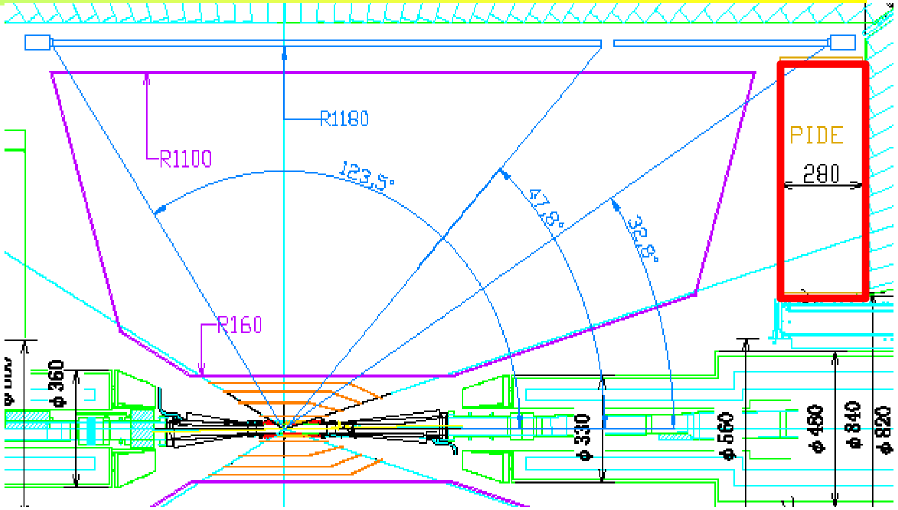
Endcap: proximity focusing RICH



Two dedicated particle ID devices - both RICHes –

- Barrel: Time-Of-Propagation (TOP)
- End-cap: focusing Aerogel RICH (ARICH)

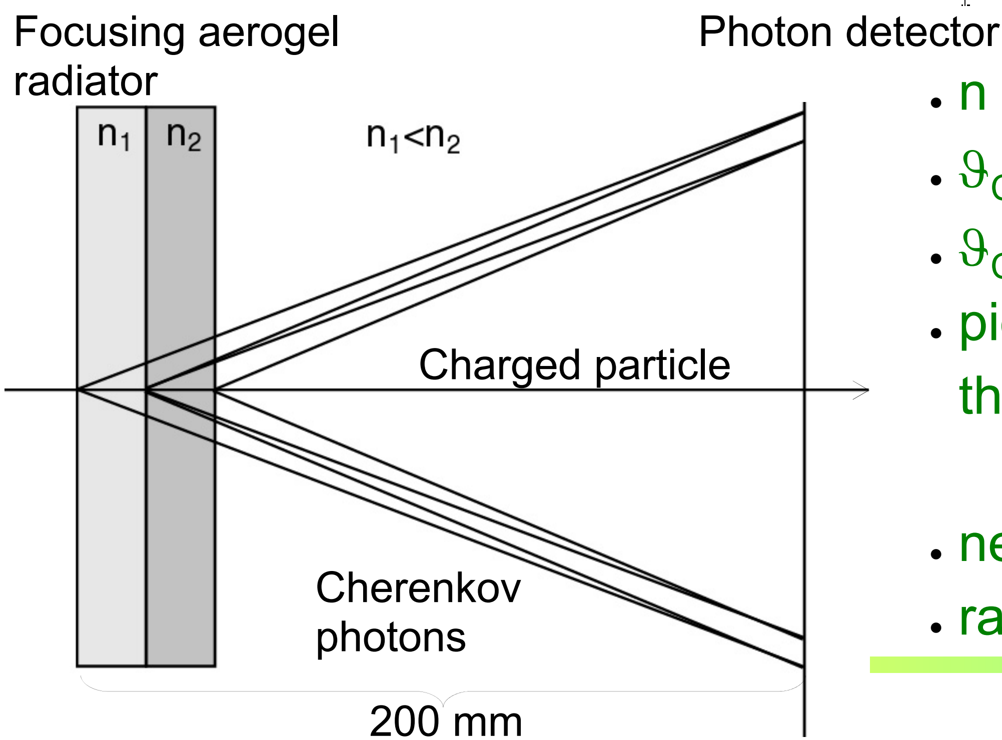
Focusing Aerogel RICH - ARICH



Goals and constraints:

- > 4 σ K/π separation @ 1-3.5 GeV/c
- limited available space ~280 mm
- operation in magnetic field 1.5 T
- radiation tolerance (n,γ)

Selected type: focusing aerogel RICH



- n ~ 1.05
- $\vartheta_C(\pi) \approx$ 307 mrad @ 3.5 GeV/c
- $\vartheta_C(\pi) - \vartheta_C(K)$ = 30 mrad @ 3.5 GeV/c
- pion threshold 0.44 GeV/c, kaon threshold 1.54 GeV/c

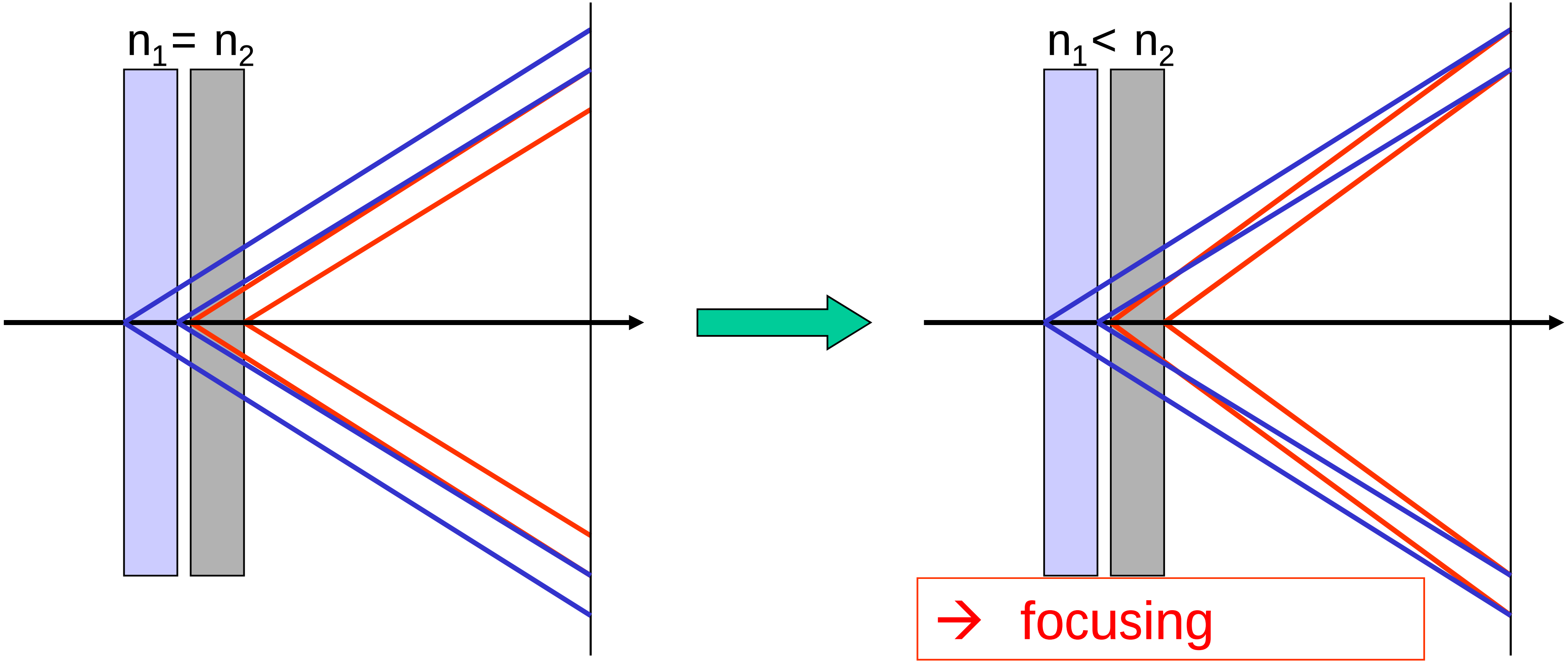
- neutron fluence: ~10^{12} n/cm^2
- radiation dose: up to 1000 Gy

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: "focusing" configuration

normal

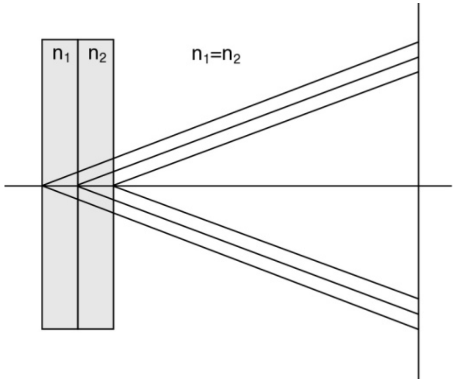


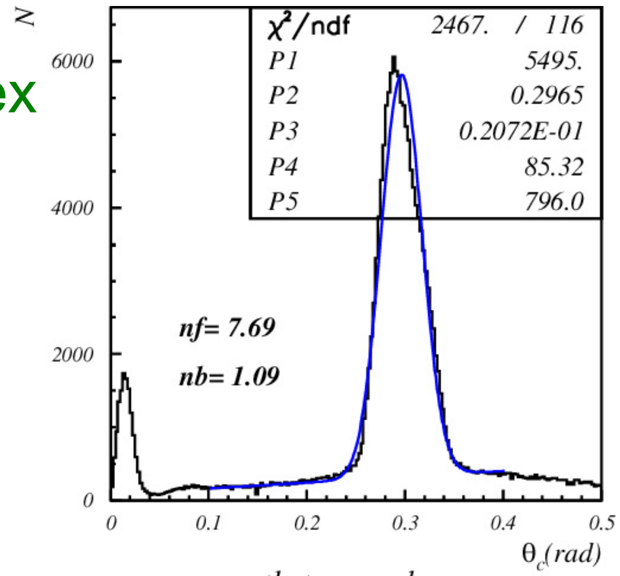
→ focusing

Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

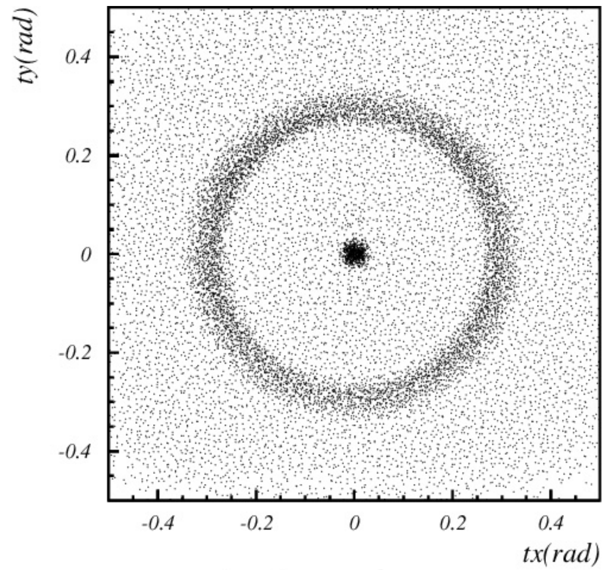
Cherenkov radiator for ARICH: focusing radiator configuration

4cm aerogel single index



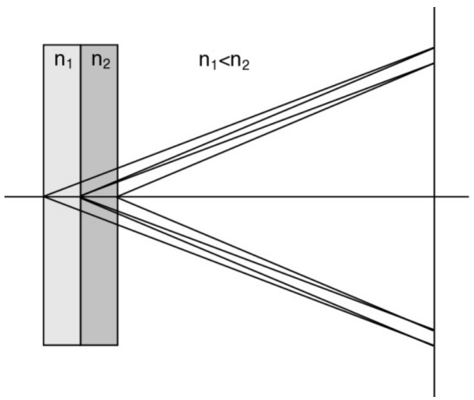


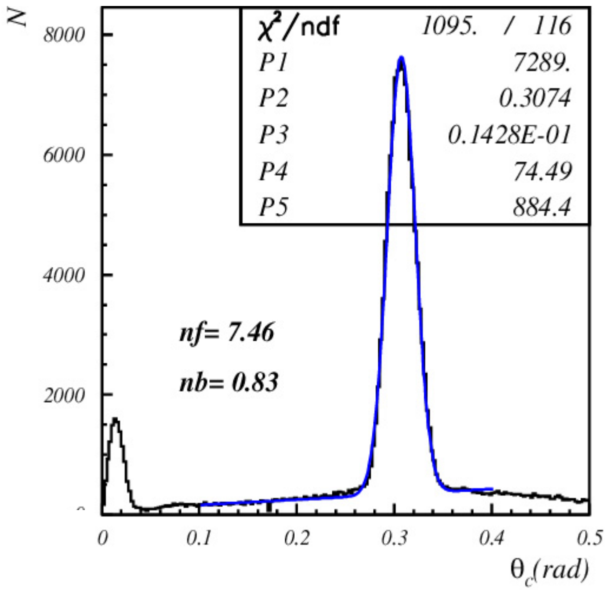
theta cerenkov

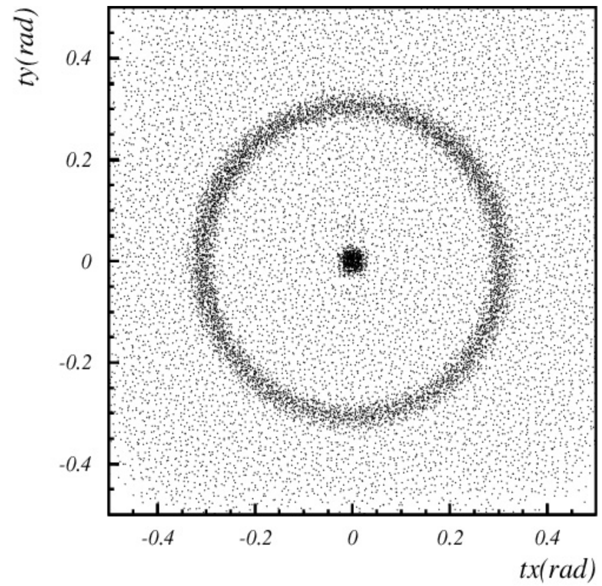


ring in cerenkov space

2+2cm aerogel





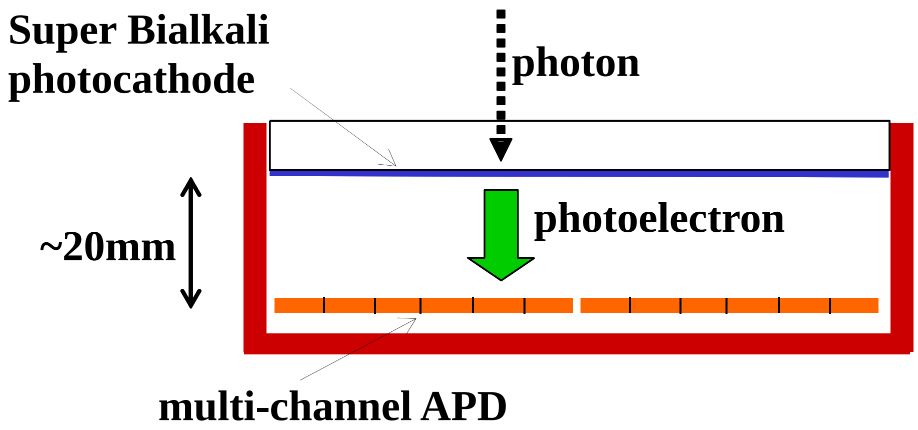


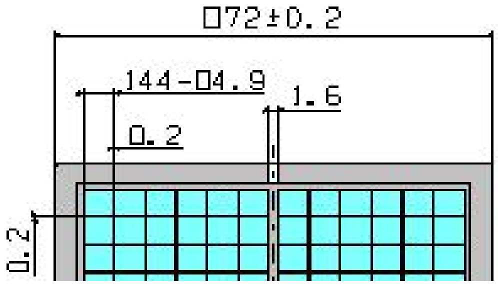
→NIM A548 (2005) 383

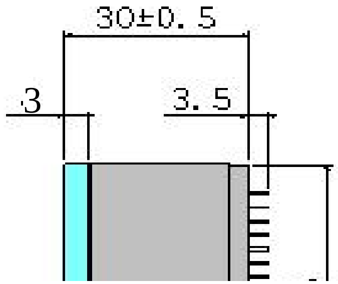
ARICH photon detector: HAPD

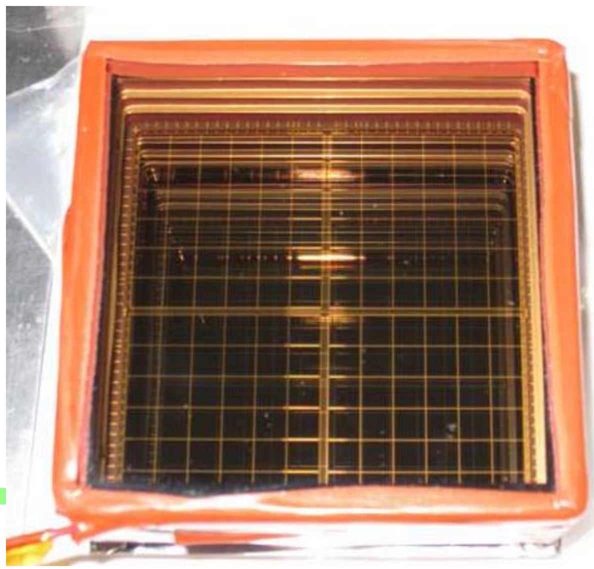
Hybrid avalanche photo-detector developed in cooperation with Hamamatsu Photonics K.K. (proximity focusing configuration):

- 12 x12 channels (~ 5 x 5 mm^2)
- size ~ 72 mm x 72 mm
- ~ 65% effective area
- total gain > 4.5x10^4 (two steps: bombardment > 1500, avalanche > 30)
- detector capacitance ~ 80pF/ch.
- super bialkali photocatode, typical peak QE ~ 28% (> 24%)
- works in mag. field (~ perpendicular to the entrance window)







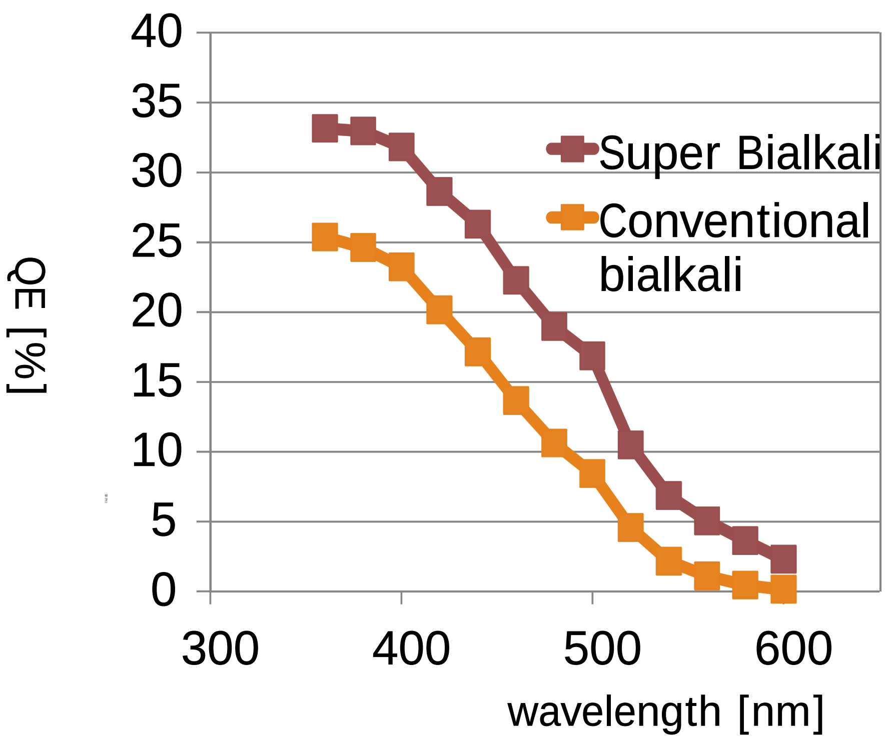


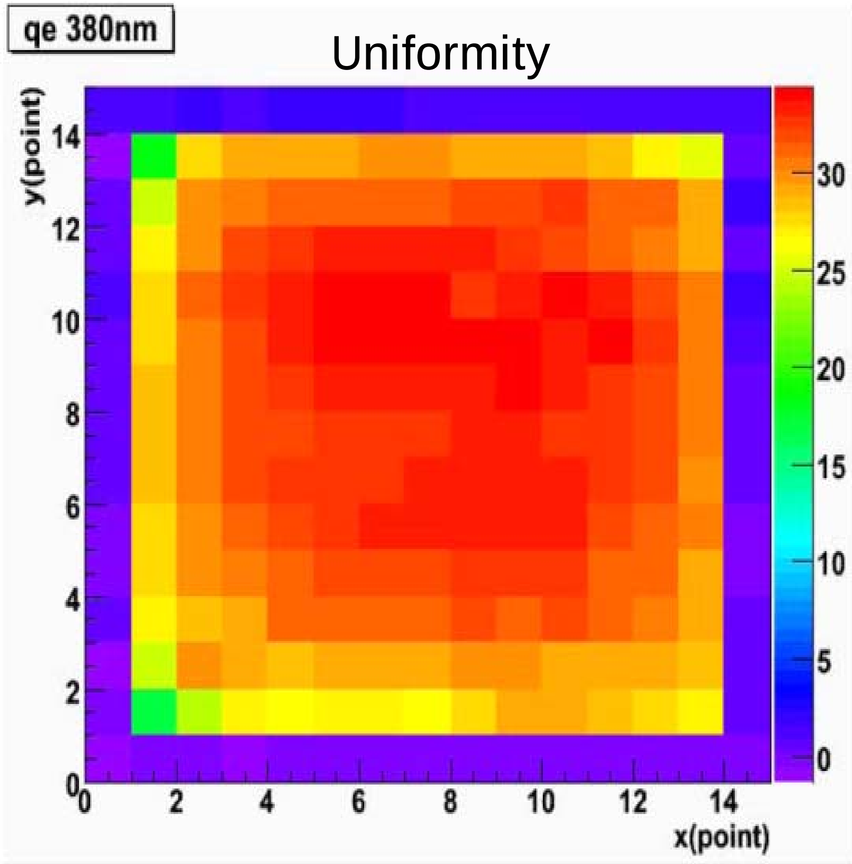
HAPD QE

- peak QE improved by Hamamatsu with super bialkali photocathode:

25% → >30%

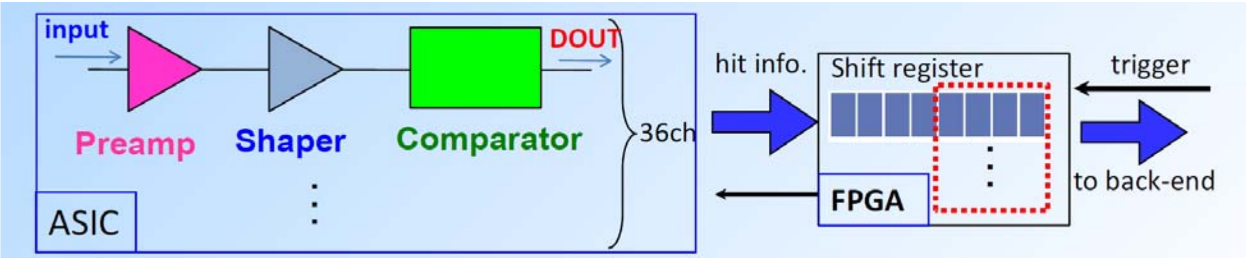
- typically QE is somewhat lower at the edges of the HAPD

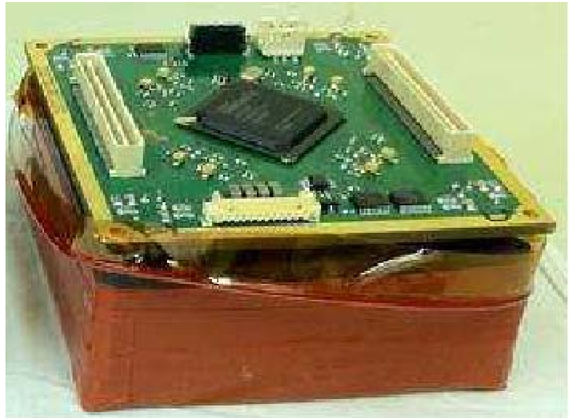


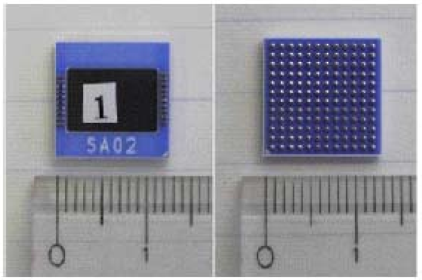


HAPD read-out electronics

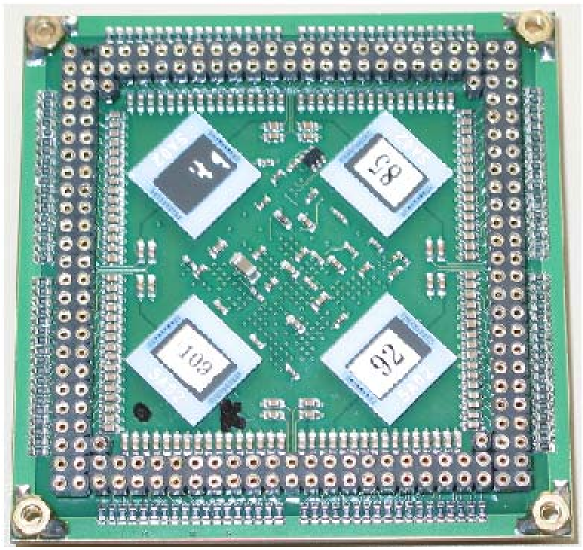
- 36 channel ASIC with preamp., shaper and comparator provides hit information. Settings: 4 step gain, 4 step peaking time, channel offset level. Analog monitor output.
- FPGA (Spartan6) for hit detection, DAQ and monitoring.





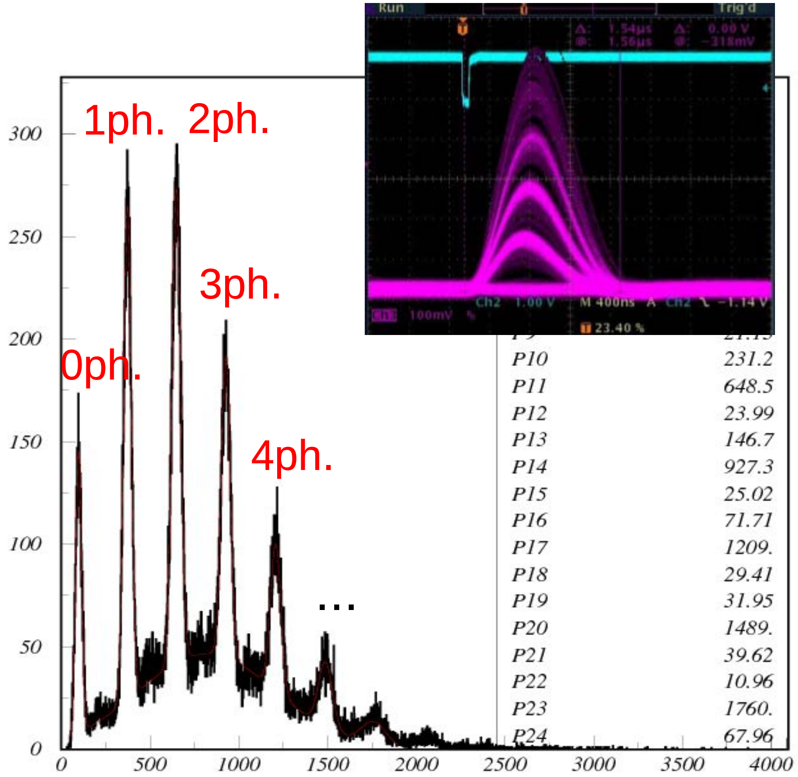


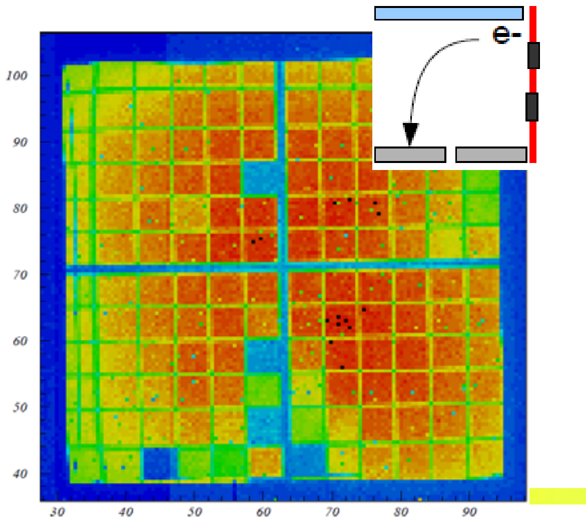
SA02 (36ch)

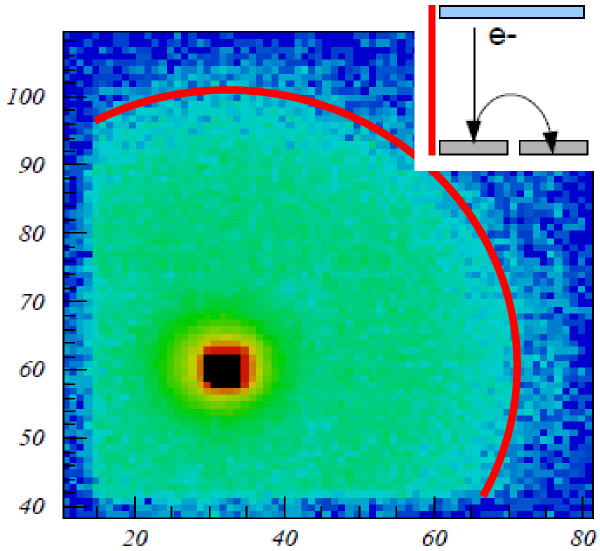


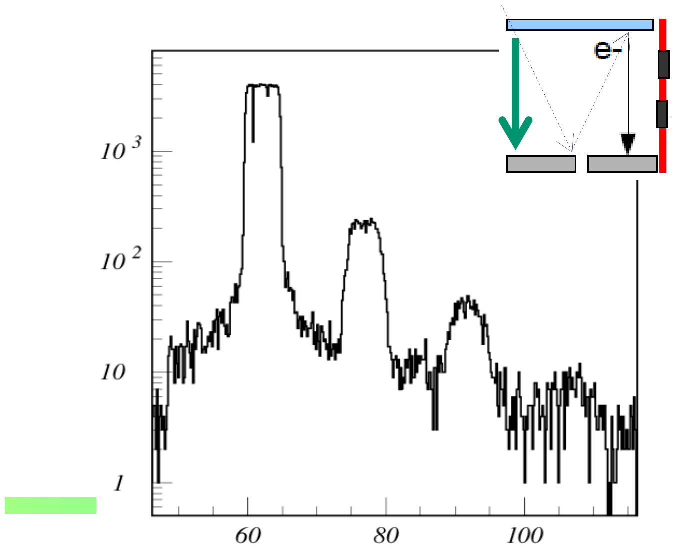
HAPD performance @ B=0T

- excellent photon counting affected only by photo-electron back-scattering → high single photon counting efficiency
- sharp transition between channels
- image distortion due to a non-uniform electric field at the edges
- back-scattering induced cross-talk
- optical cross-talk by reflection from APD surface → weak echo ring



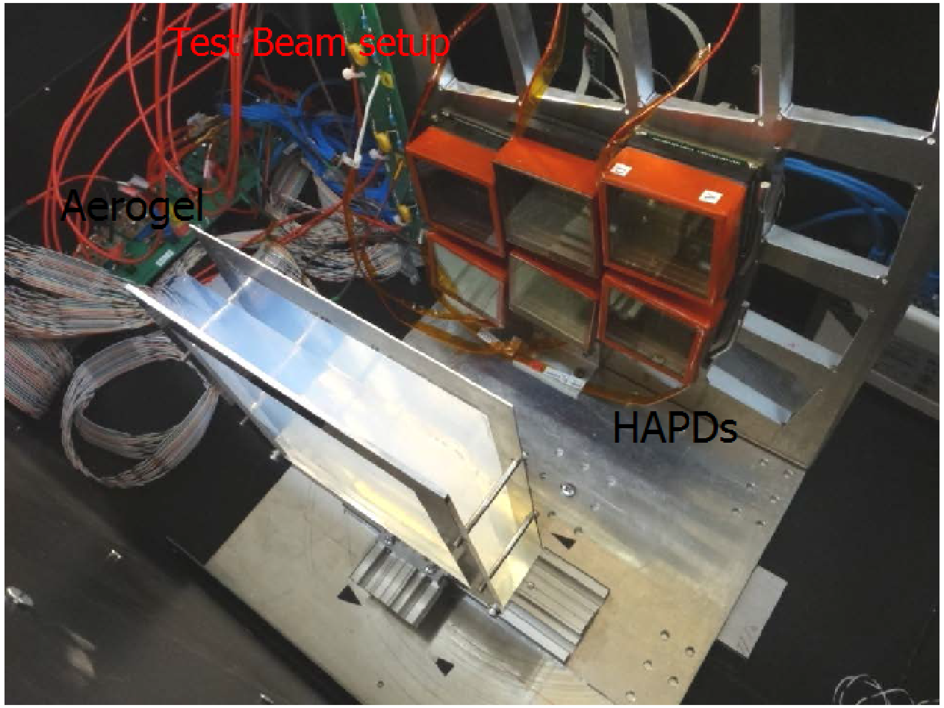


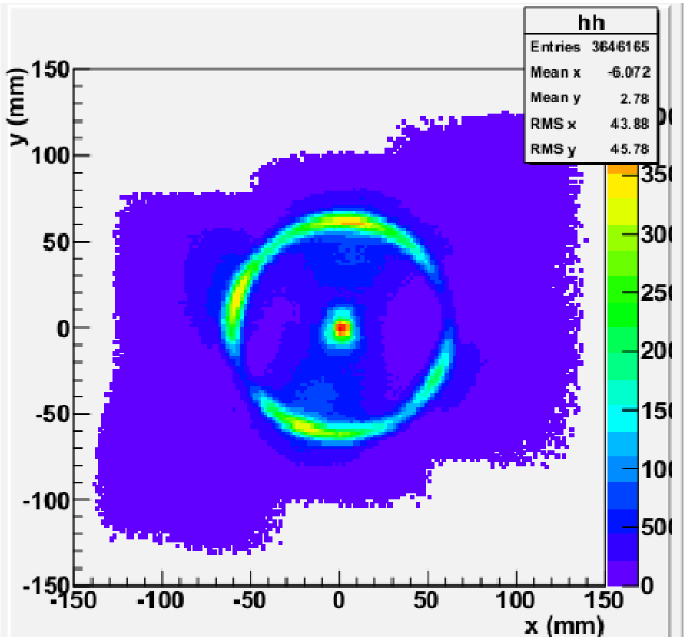


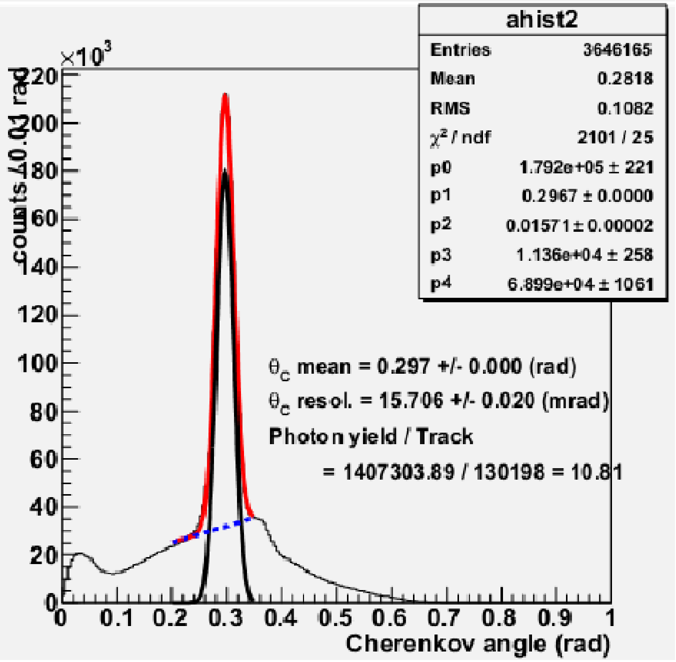


ARICH Prototype performance

- Tests with 120 GeV/c pions @CERN and
- 5 GeV/c electrons @ DESY
- Detected number of photons/ring: ~ 10
- Single ph. Ch. angle resolution: ~ 15 mrad







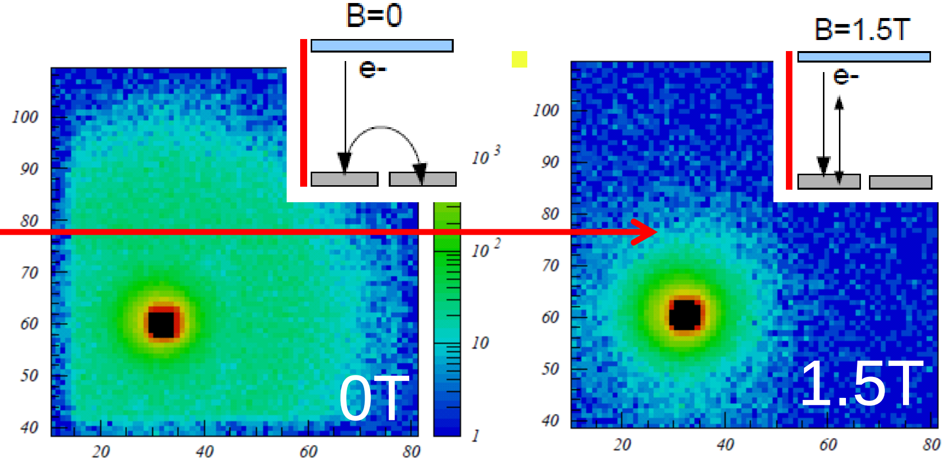
Better than 5σ π/K separation @ 3.5 GeV/c

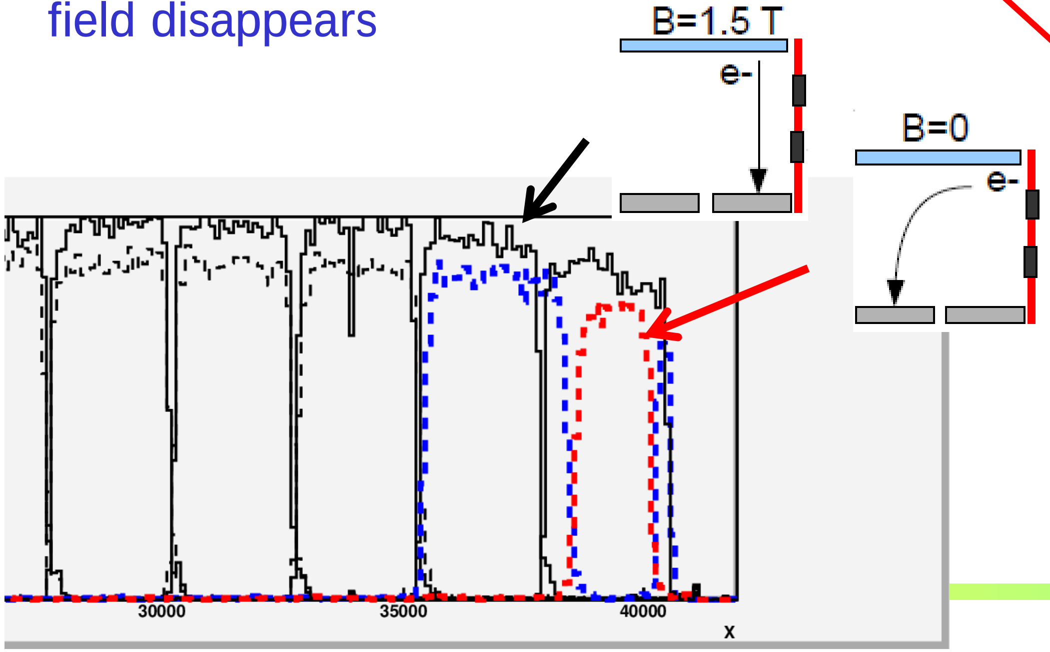
→ NIM A595 (2008) 180

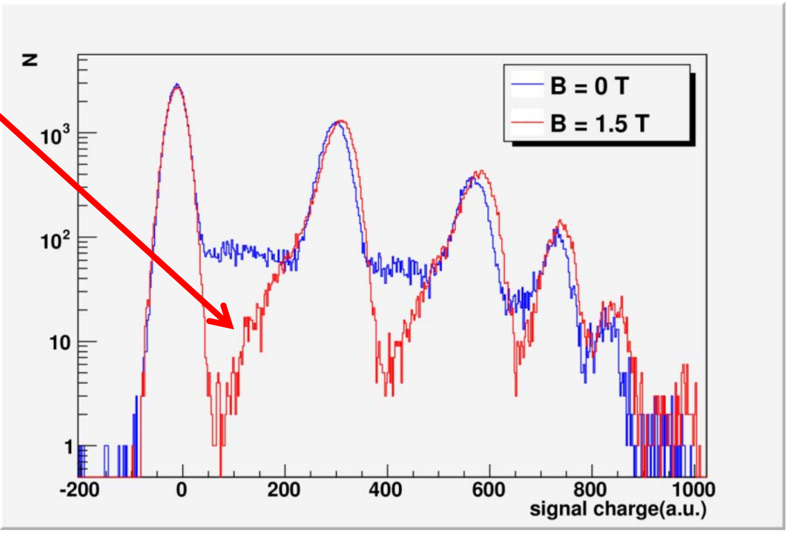
HAPD: operation in 1.5 T

Tests in 1.5 T magnetic field show improved HAPD performance:

- no photoelectron back-scattering cross-talk
- increase of detection efficiency – photoelectron energy deposited at one place
- effect of non-uniformity of electric field disappears

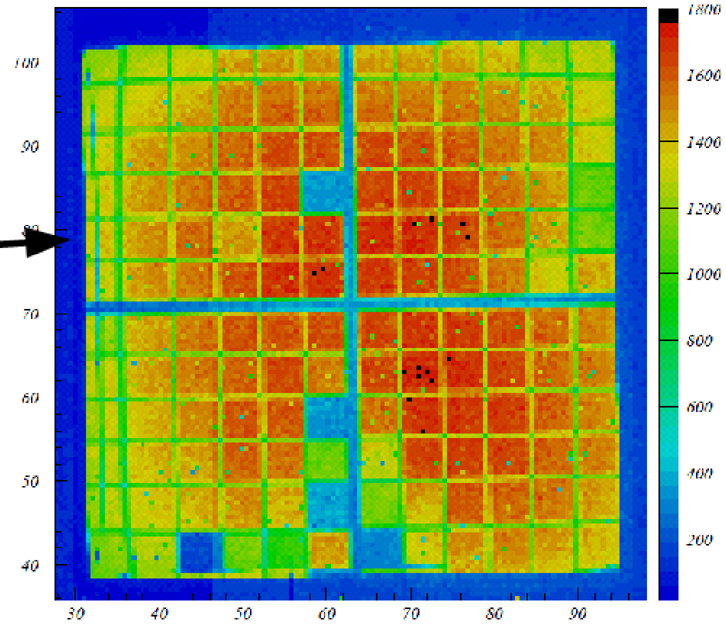




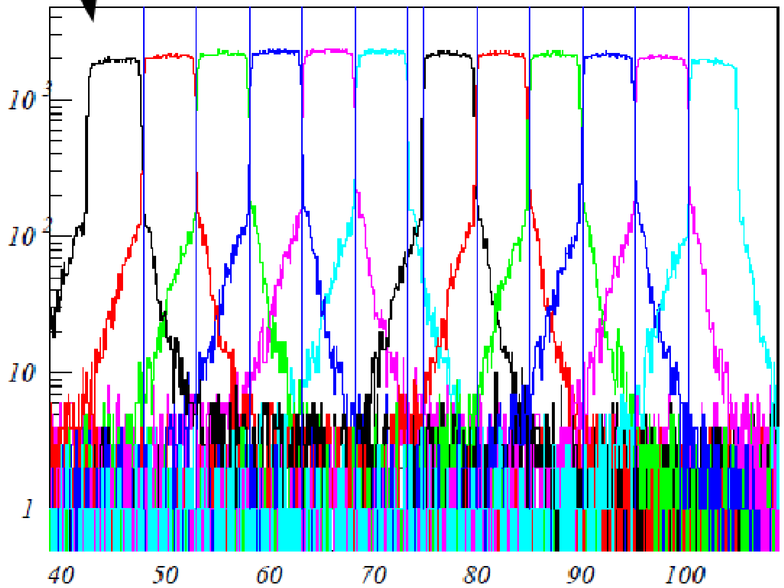


Test in magnetic field 1.5 T

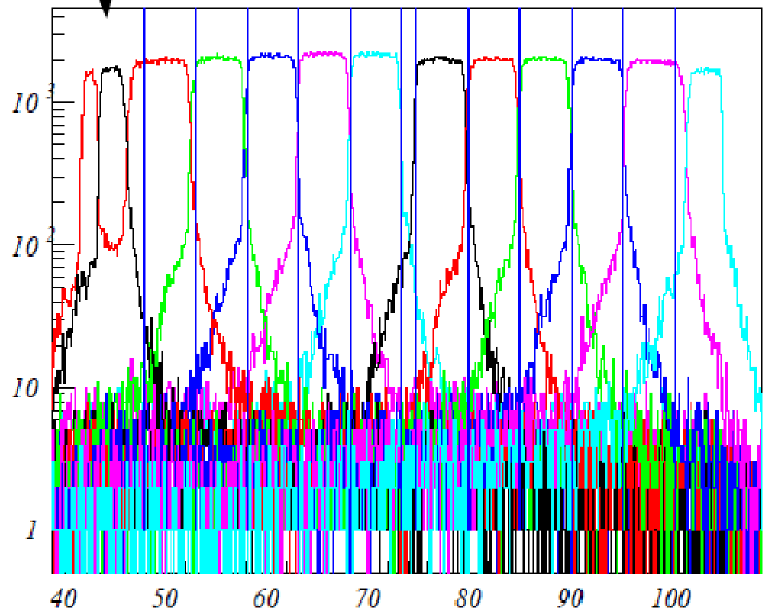
- distortion of electric field lines at HAPD edge produces irregular shapes of areas covered by each channel
- in magnetic field photoelectrons circulate along the magnetic field lines and distortion disappears



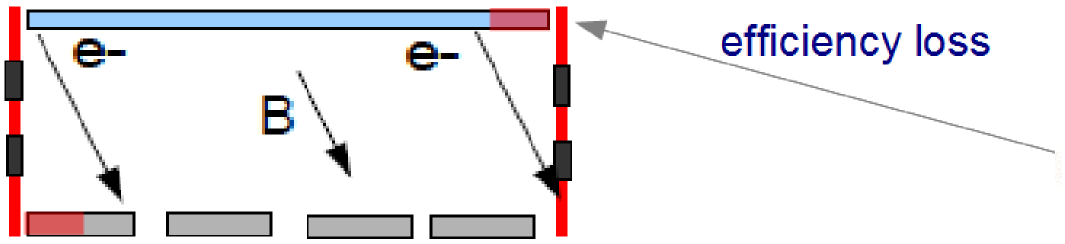
magnetic field 1.5 T

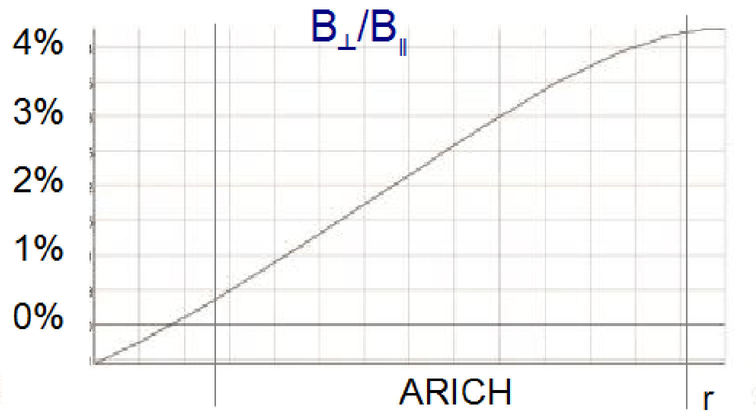


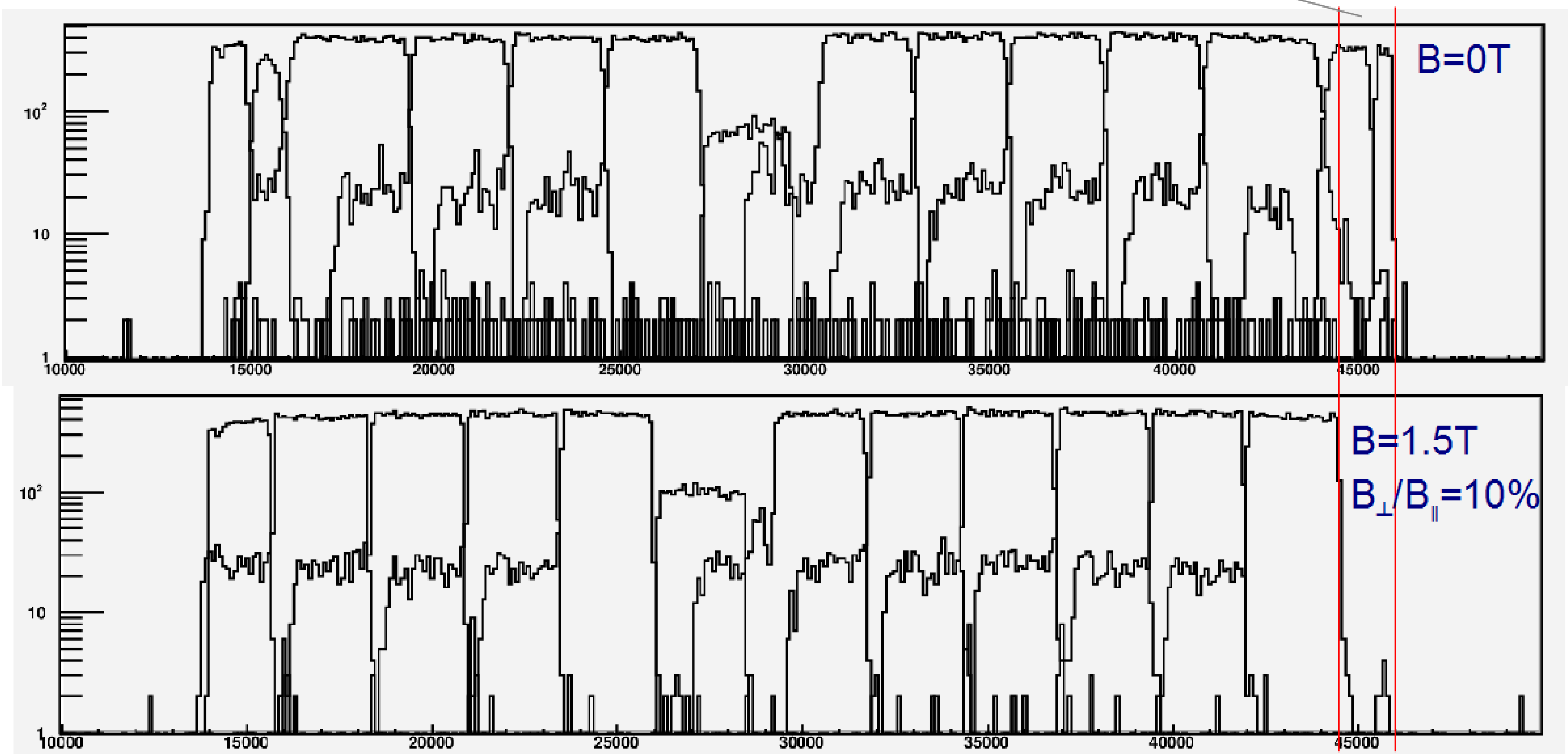
no magnetic field



In non-perpendicular mag. field the image shifts and part of the active area is lost!



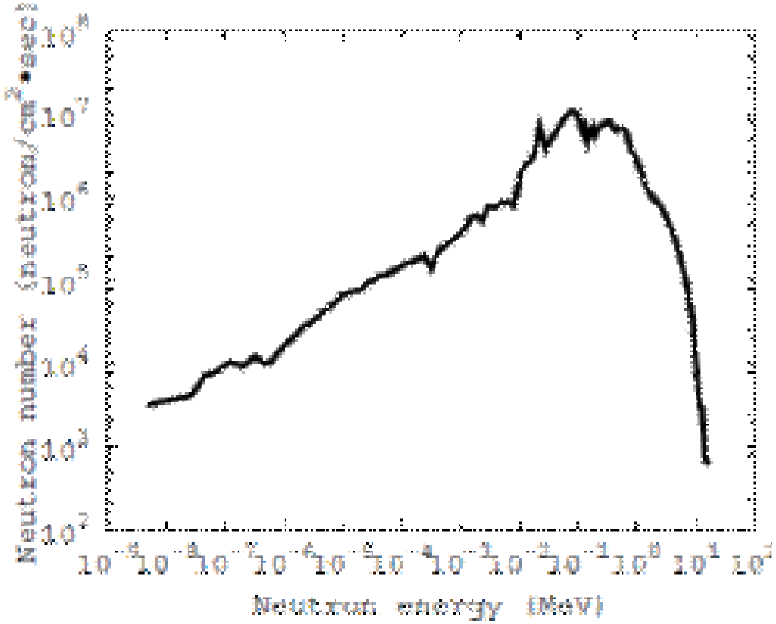


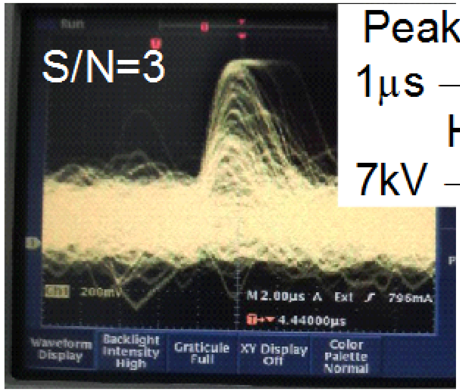


Neutron irradiation

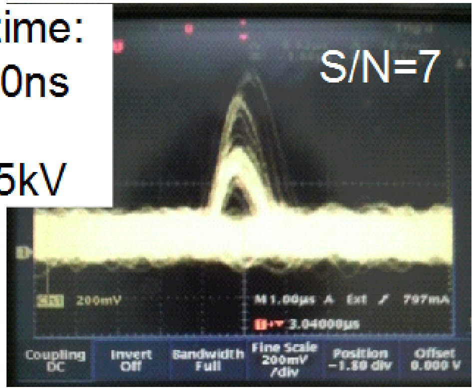
Reactor "Yayoi" @ Tokyo U.

- Expected total fluence 10^{12} n/cm^2
- Tests of original design: S/N drops to 7 @ 5×10^{11}n/cm^2

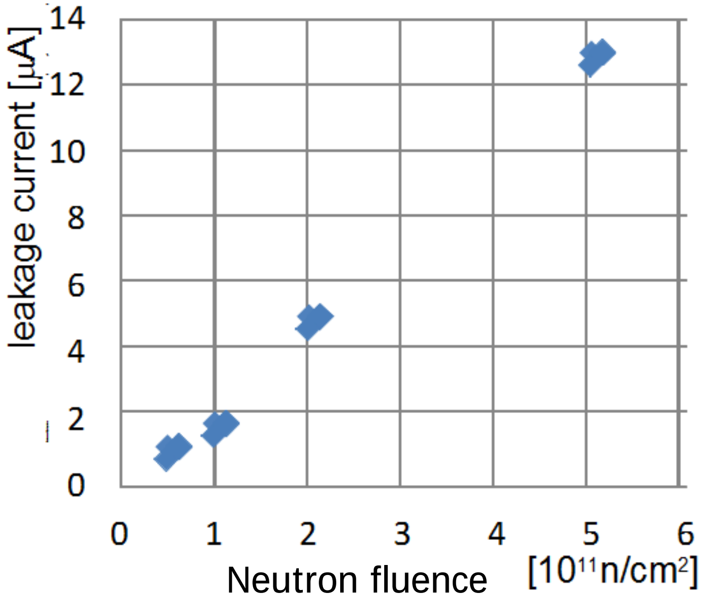




Peaking time:
1μs → 250ns
HV:
7kV → 8.5kV



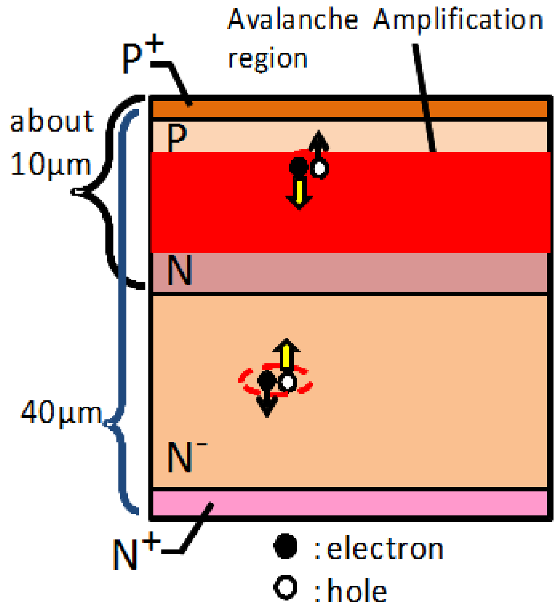
→ Expected S/N~5 @ fluence 10^{12} n/cm^2, marginal operation

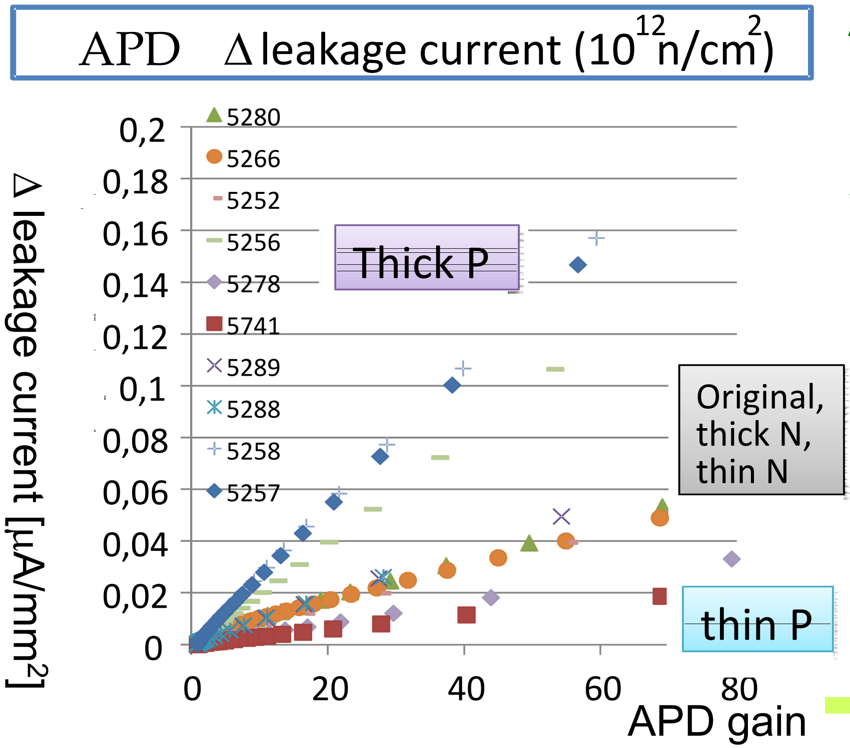


- Re-optimization of peaking time for larger leakage currents → shorter peaking time in final ASIC version
- Optimization of APD structure

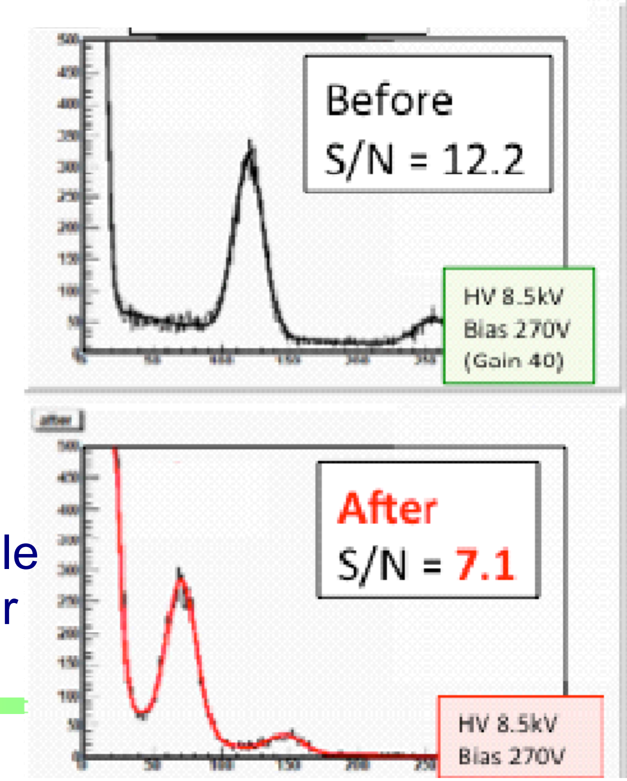
Neutron damage

Modification of APD structure:
- Thinner p layer to reduce increase of the leakage current after irradiation – main source of leakage current are thermally generated electrons in p layer due to the lattice defects produced by neutrons
- Thinner p^+ layer to increase bombardment gain





As expected, the increase of the leakage current is smaller with thin p

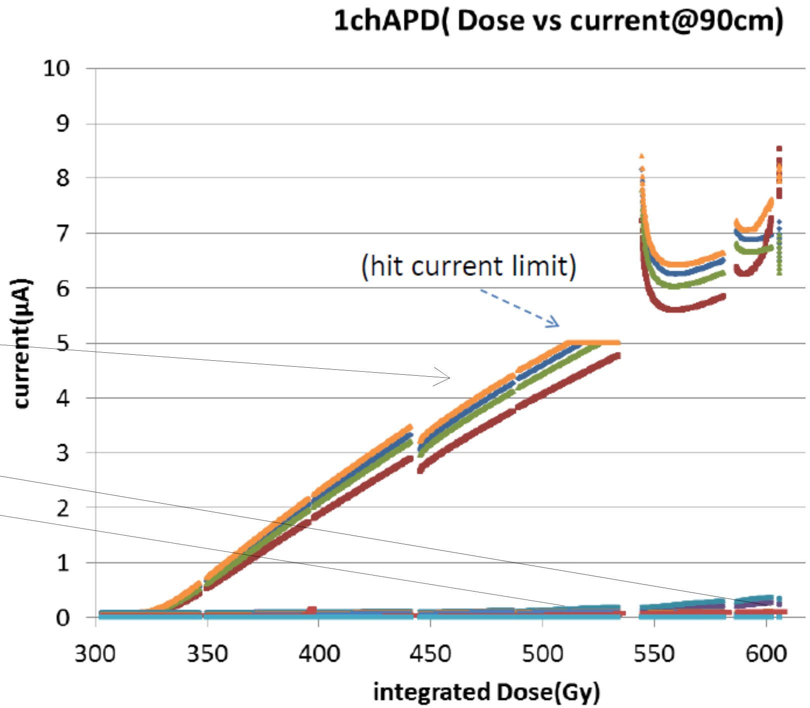


S/N for thin p sample is better than 7 after fluence 10^{12} n/cm^2

Gamma irradiation

^{60}Co irradiation facility @ Nagoya U.

- Expected total dose 100-1000 Gy
- Initial tests indicated fast raise of leakage current and reduction of breakdown voltage – not previously observed with similar APDs
- Possible source: APD for HAPD had additional alkali protection layer to protect APD during photocathode activation process
- To identify the reason extensive tests were done with single channel APDs with different structure prepared by Hamamatsu:
  - "Standard" alkali protection
  - No alkali protection
  - "New" alkali protection



→ APD structure had to be optimized

Optimized APD structure

Neutron irradiation (nonionizing energy loss):

modification of APD internal structure to increase S/N after irradiation:

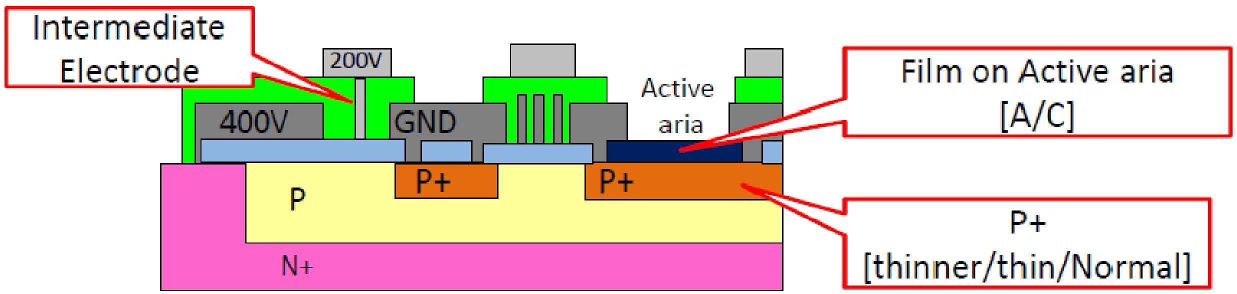
- reduced p layer thickness → reduced leakage current
- reduced p+ layer → increased bombardment gain

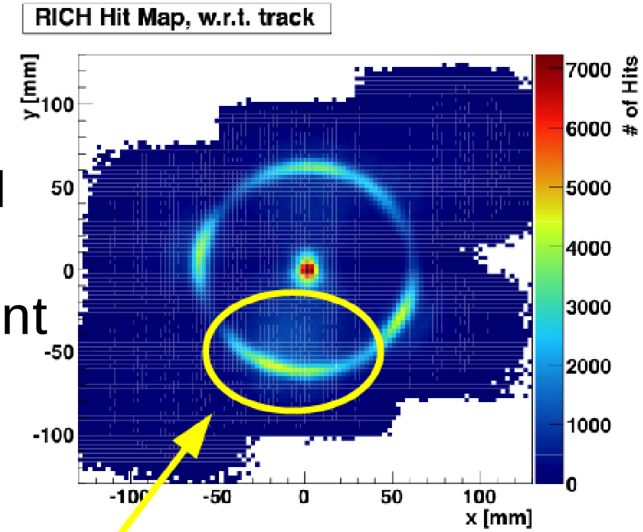
Gamma irradiation (ionizing radiation):

modifications to avoid charge-up efects:

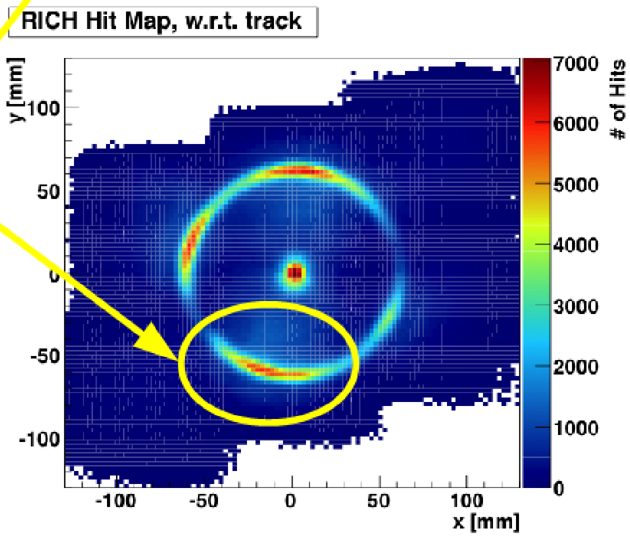
- optimization of protective films
- additional intermediate electrode
- no alkali protection layer

irradiated HAPDs showed comparable results to non-irradiated samples in a beam test





n: 2.1x1012 n/cm2
(QE 21.4%)



n: 0.86x1012 n/cm2
γ: 1 kGy
(QE 31.1%)

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Ageing test - setup

Estimated number of photoelectrons @ Belle II:

- ~ 4×10^{11} ph.e./cm^2/y
  → ~ 10^{11} ph.e./ch./y

Operation parameters:

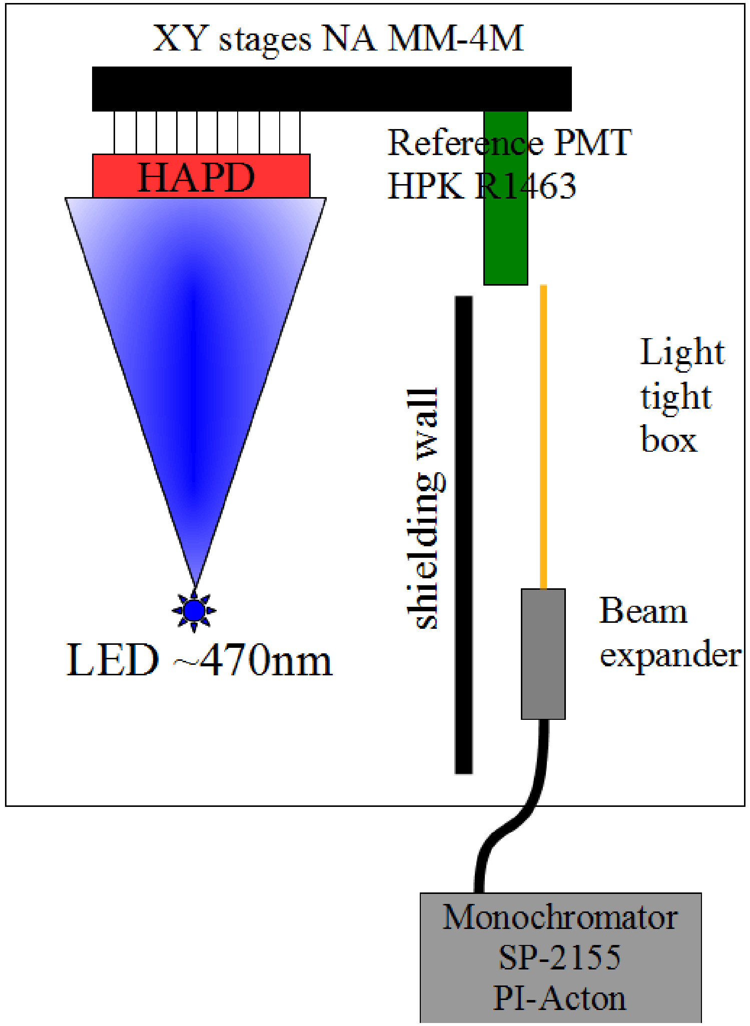
- gain ~ 6×10^4
  (APD ~50, bombardment gain ~1200)
- HV 7 kV

Monitoring:

- anode currents
- signal from 3 channels – ADC and rate
- QE at the beginning and the end

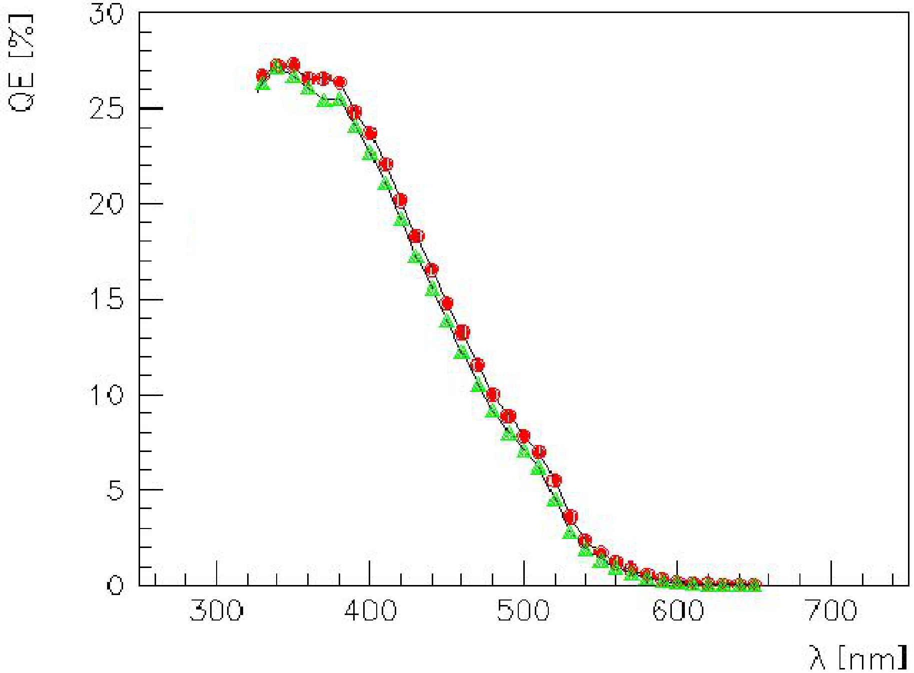
Aging with blue LED:

- ~1 MHz/ch. for 27 days
  → ~20 years of Belle II operation

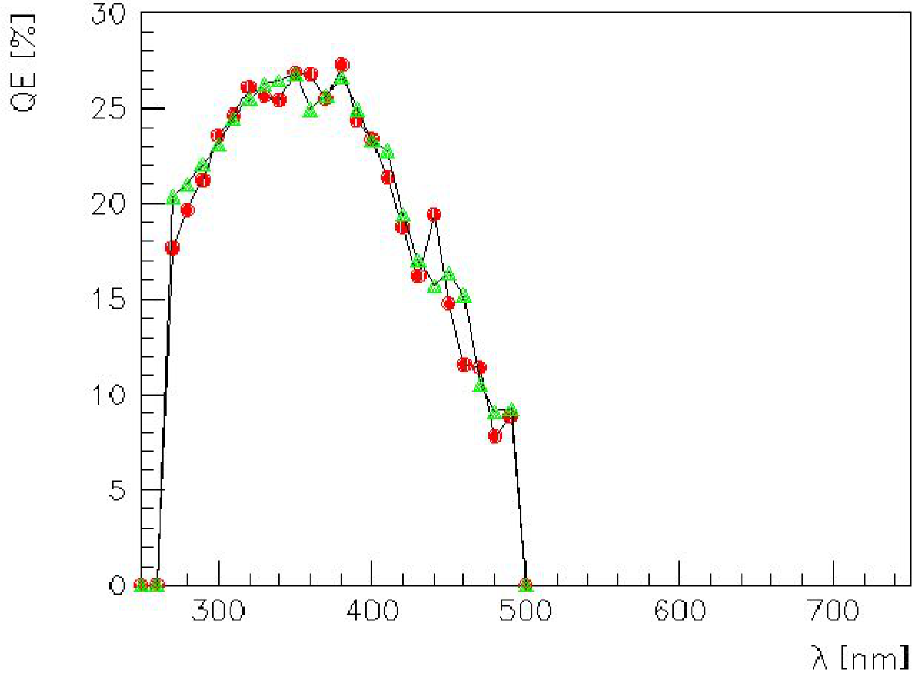


Ageing test - QE measurement

- comparison of initial QE and QE after ~20 years of Belle II show practically no change in performance



- Tungsten lamp



- Deuterium lamp

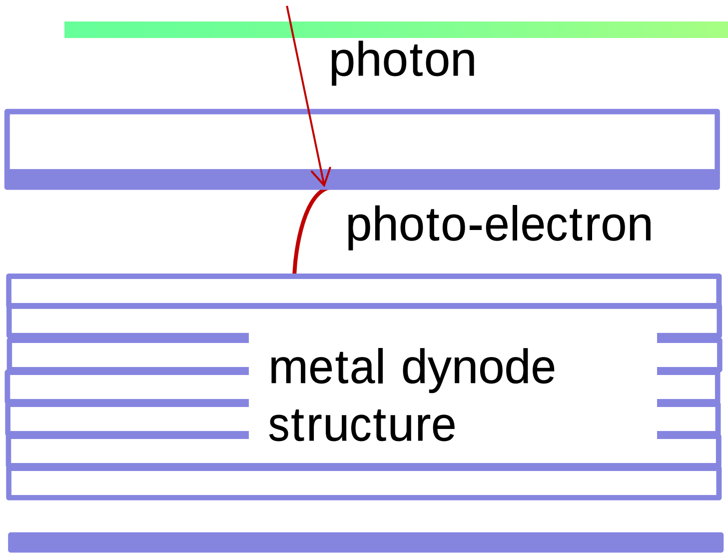
→ no significant change of QE expected during the lifetime of the Belle II

Backscattering, light reflection etc for HAPDs, MCP PMTs and MAPMTs

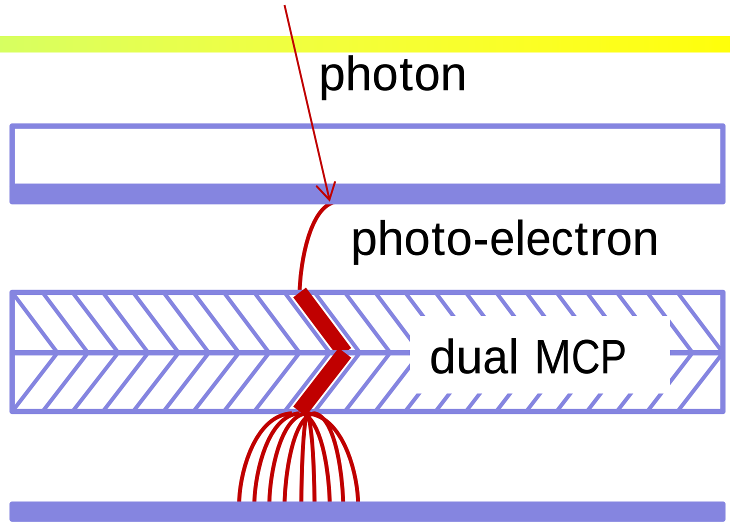
Similarities between different sensor types with a similar (planar) geometry

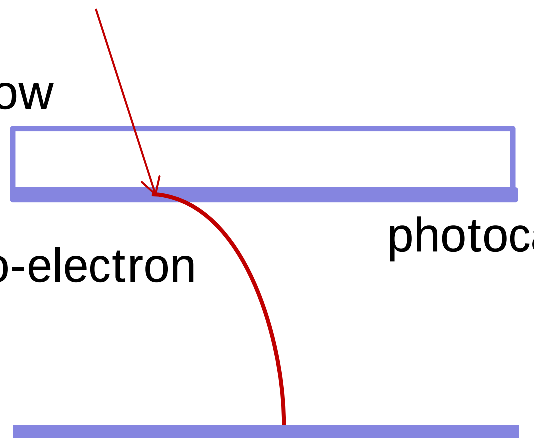
… to add our experince to the nice review talk by Bayarto Lubsandorzhiev

Backscattering, light reflection from the APD etc



photocathode

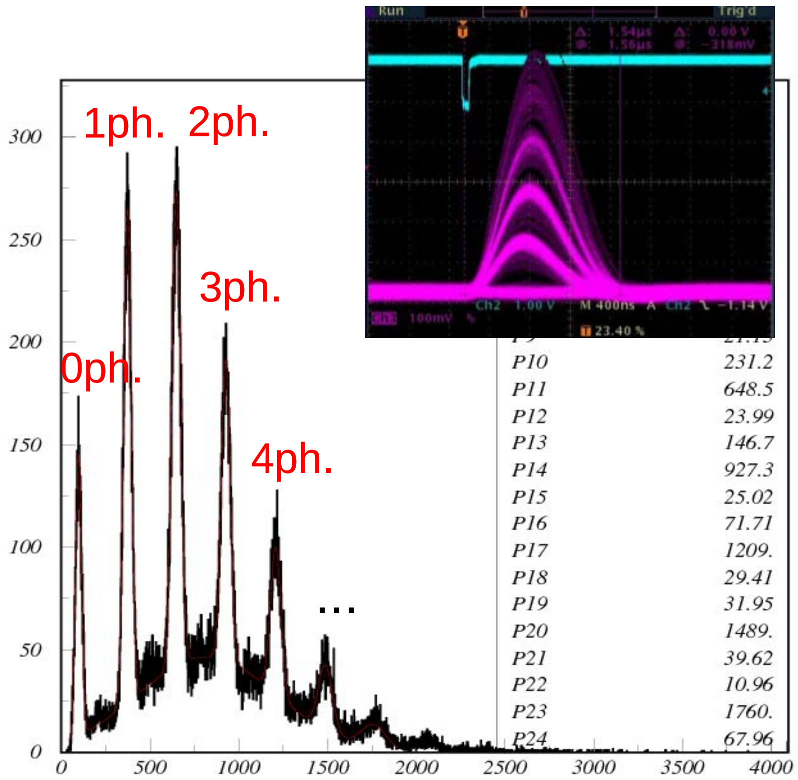


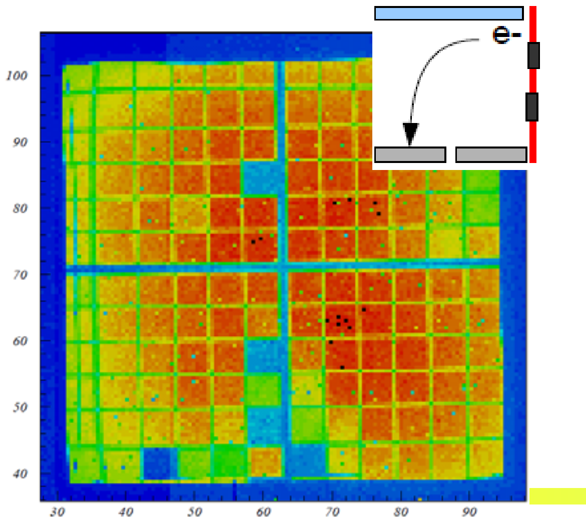


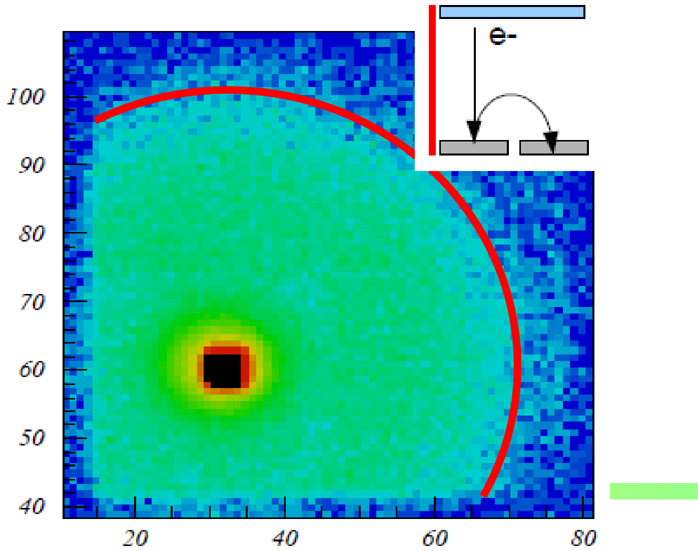
Similar geometries in the photo-electron step
→ A lot of similarities between prox. focusing HAPD, MCP PMTs and MA-PMTs

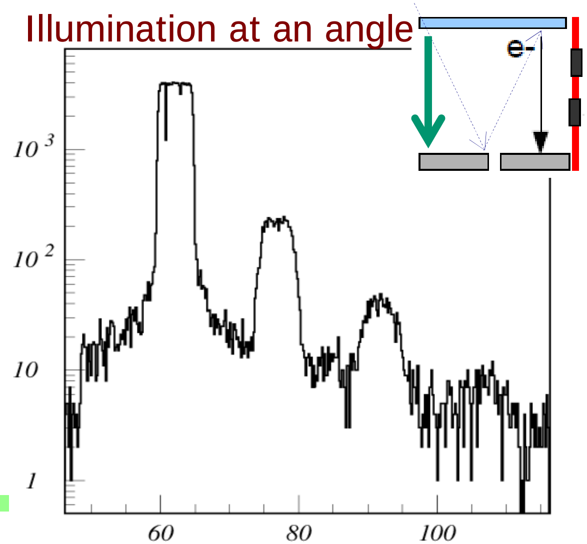
HAPD performance @ B=0T

- excellent photon counting affected only by photo-electron back-scattering → high single photon counting efficiency
- sharp transition between channels
- image distortion due to a non-uniform electric field at the edges
- back-scattering induced cross-talk
- optical cross-talk by reflection from APD surface → weak echo ring

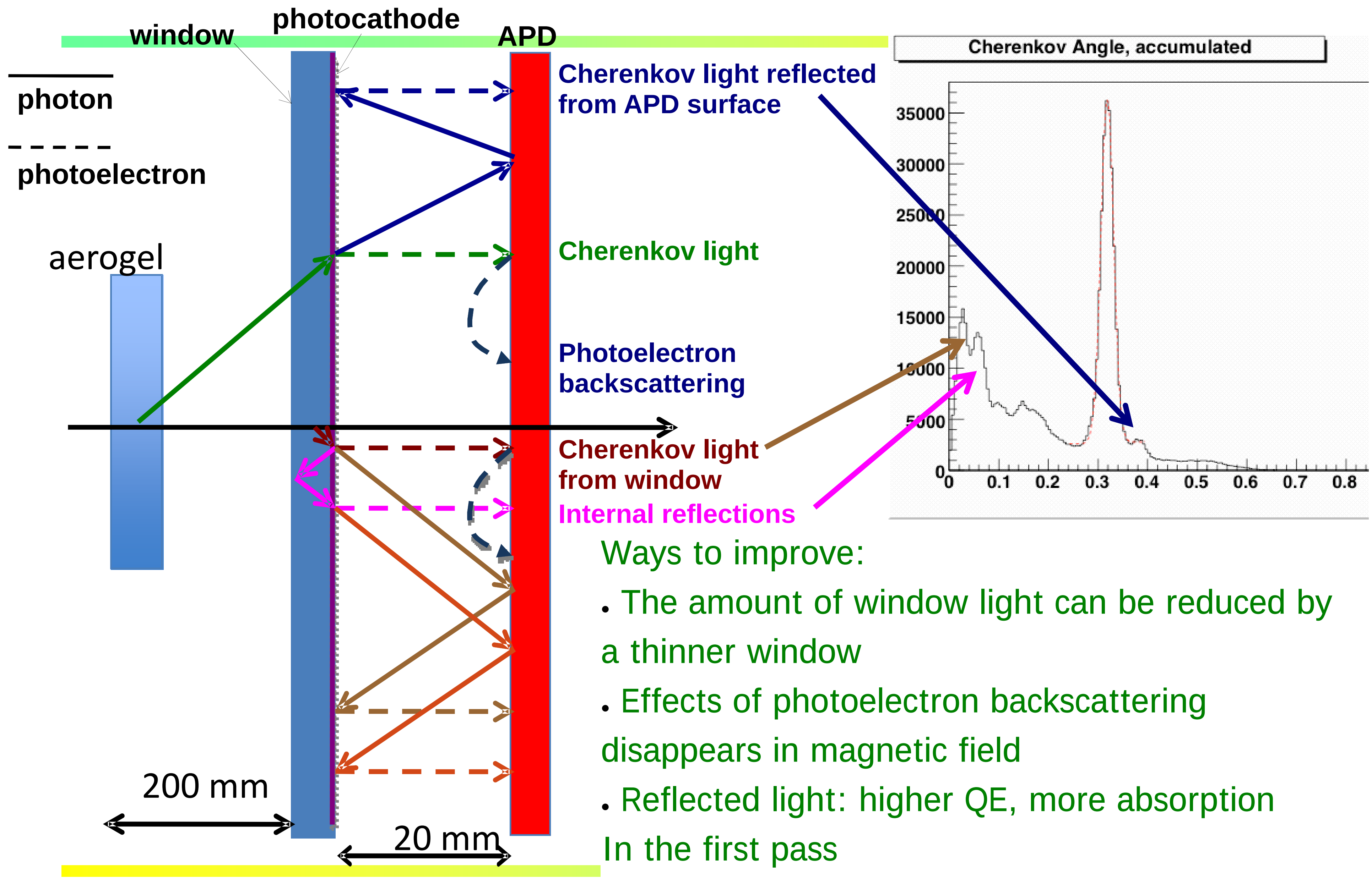








Ring image, background contributions (B=0T)



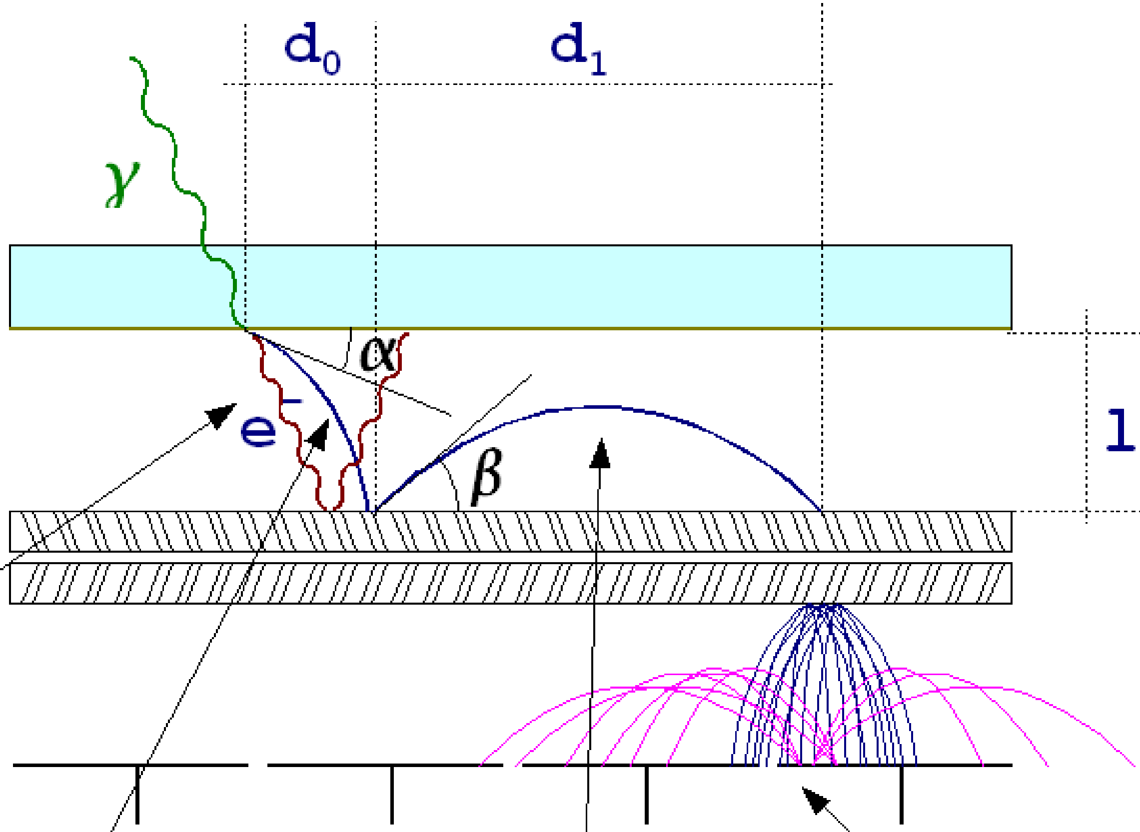
Ways to improve:

- The amount of window light can be reduced by a thinner window
- Effects of photoelectron backscattering disappears in magnetic field
- Reflected light: higher QE, more absorption In the first pass
- Anti-reflective coating?

MCP PMT: processes involved in photon detection

Parameters used:

- $U = 200$ V
- $l = 6$ mm (K-MCP)
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As



Internal-reflection

Photo-electron:

- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

Backscattering:

- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

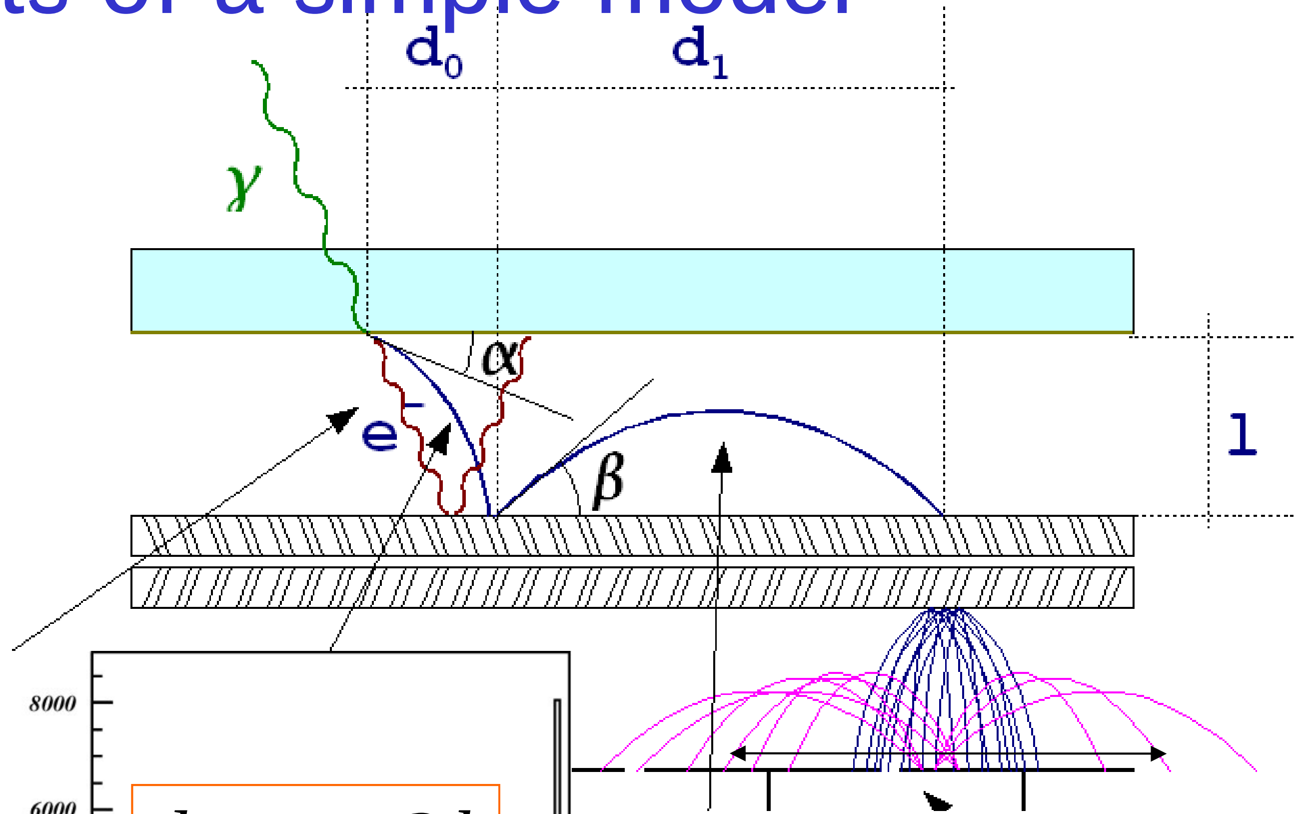
Charge sharing

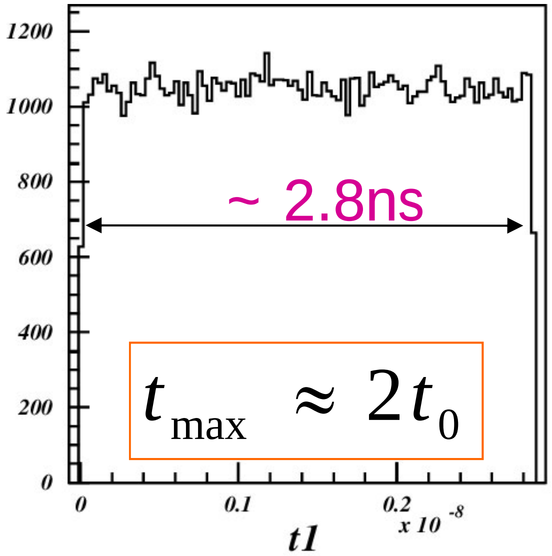
→ JINST 4 (2009) P11017

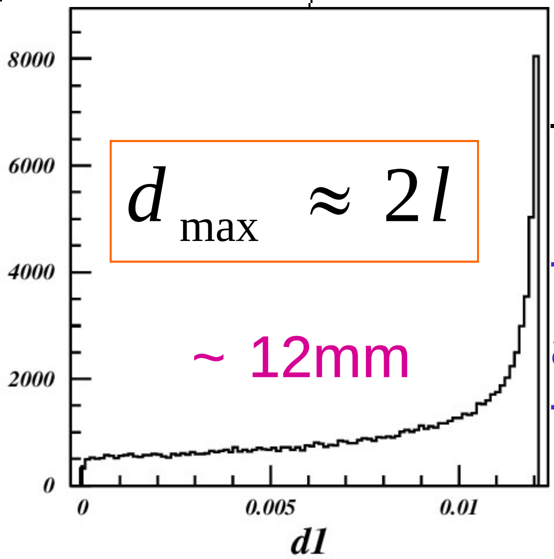
Elastically backscattered photoelectrons, results of a simple model

Parameters used:

- U = 200 V
- l = 6 mm (K-MCP)
- E_0 = 1 eV
- m_e = 511 keV/c²
- e_0 = 1.6 10^{-19} As





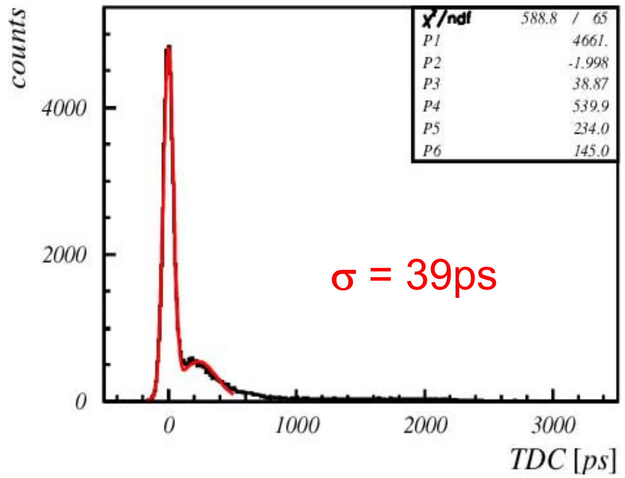


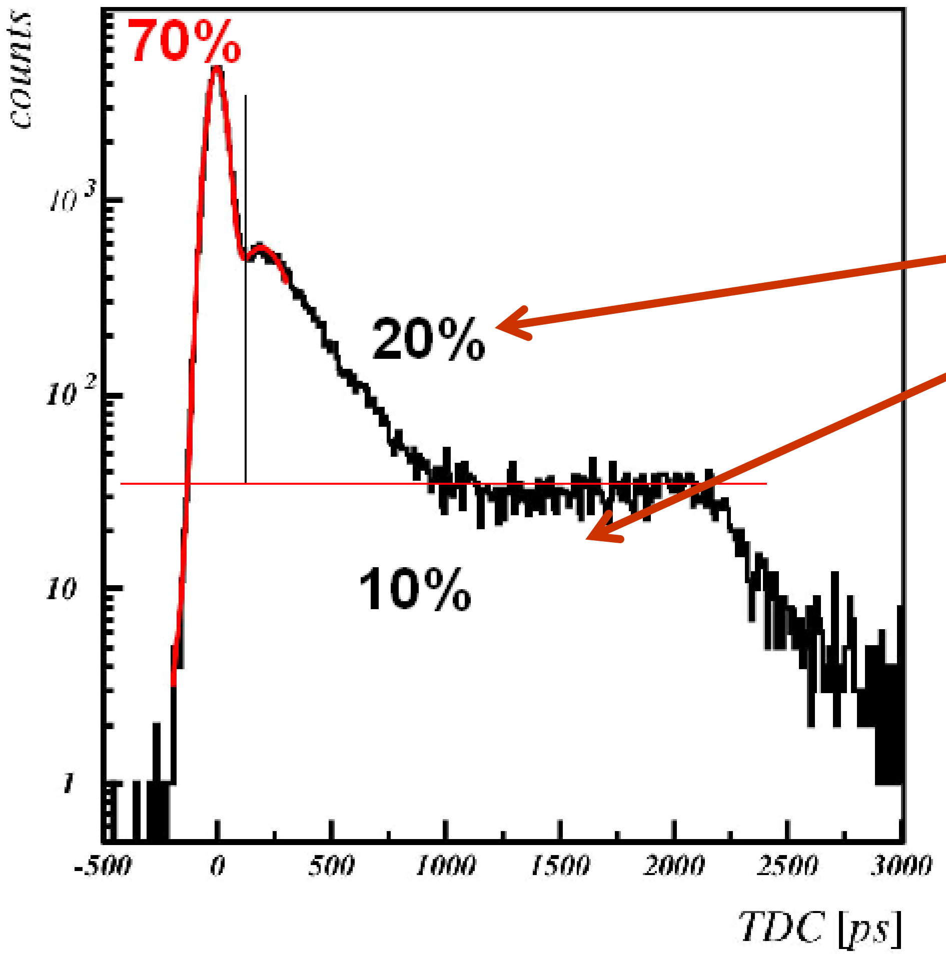
Distributions assuming that back-scattering by angle β is uniform over the solid angle.

→ JINST 4 (2009) P11017

MCP PMT timing

MCP PMTs: main peak with excellent timing accompanied with a tail





Tails understood (scattering of photoelectrons off the MCP)

- Inelastic back-scattering
- Elastic back-scattering

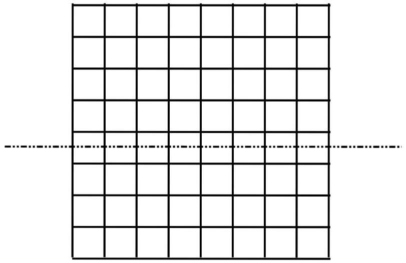
→good agreement with the simple model

Tails can be significantly reduced by:

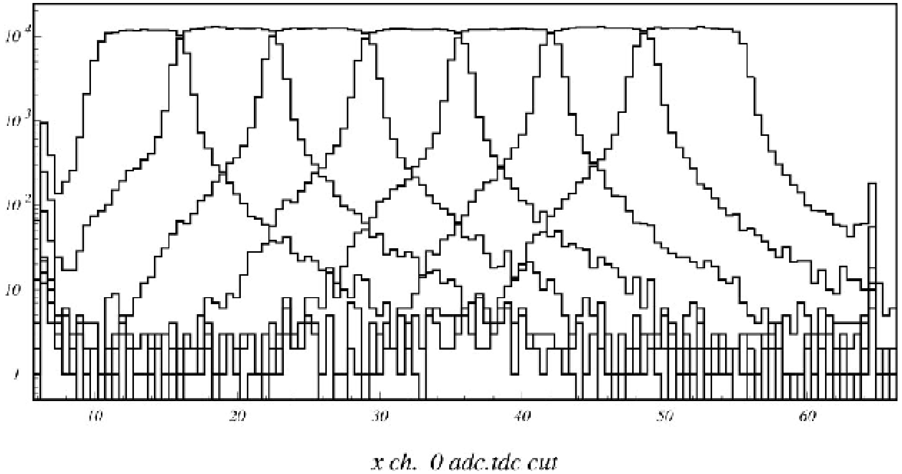
• decreased photocathode-MCP distance and

•increased voltage difference

→ JINST 4 (2009) P110

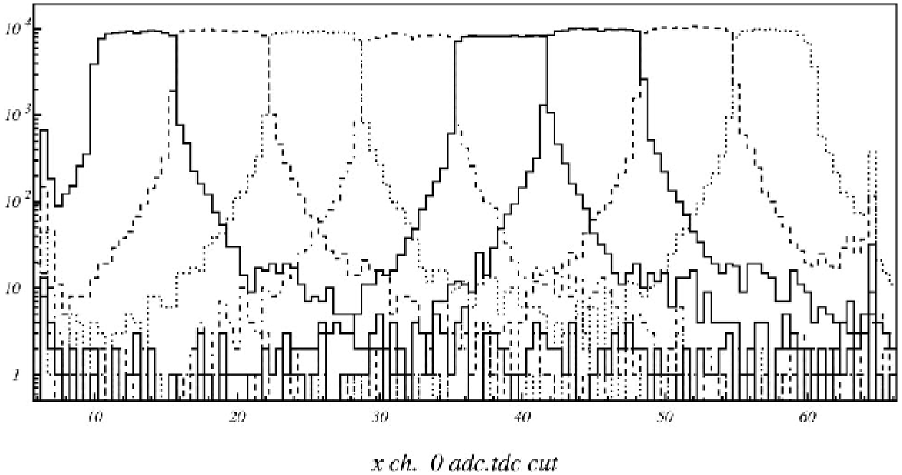


MCP PMT: sensitivity to magnetic field



Number of detected hits on individual channels as a function of light spot position.

B = 0 T,
HV = 2400 V



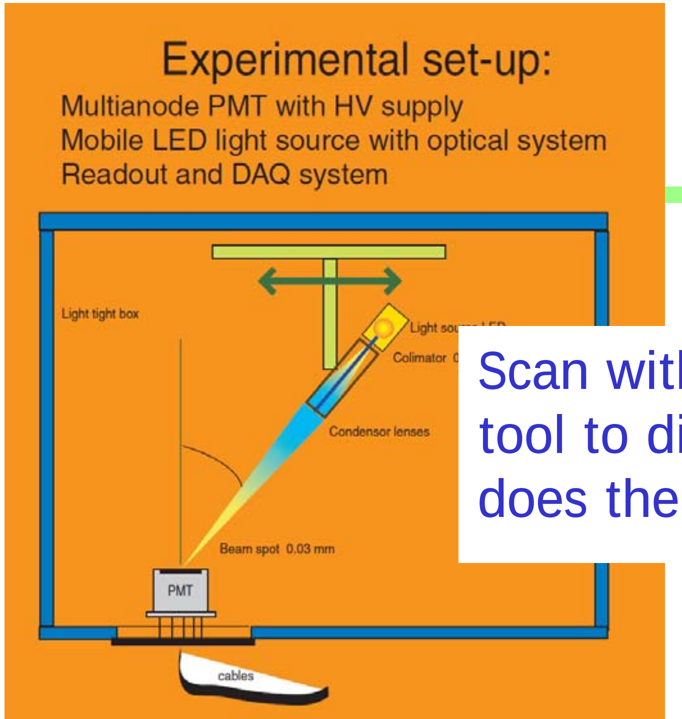
B = 1.5 T,
HV = 2500 V

→ NIMA 595 (2008) 169

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

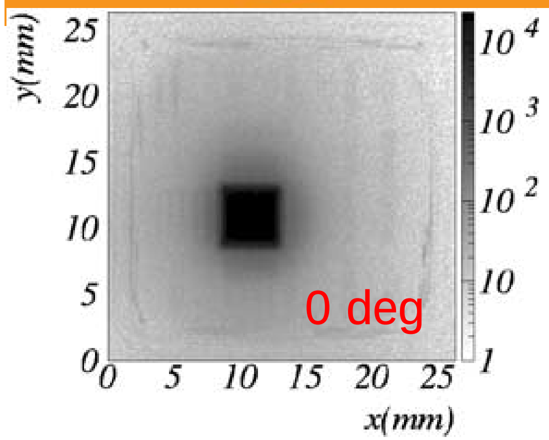
MAPMT: cross talk due to light reflection on the first dynode

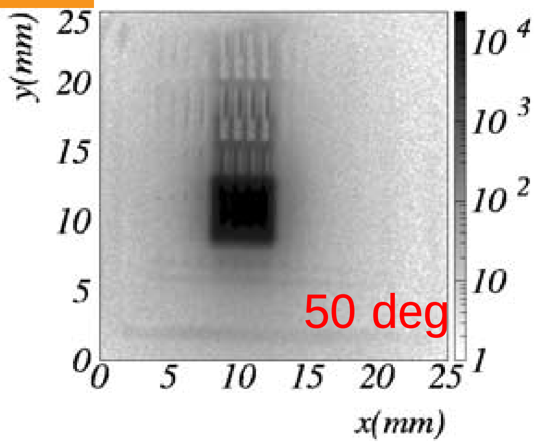
→ NIMA 478 (2002) 391–394

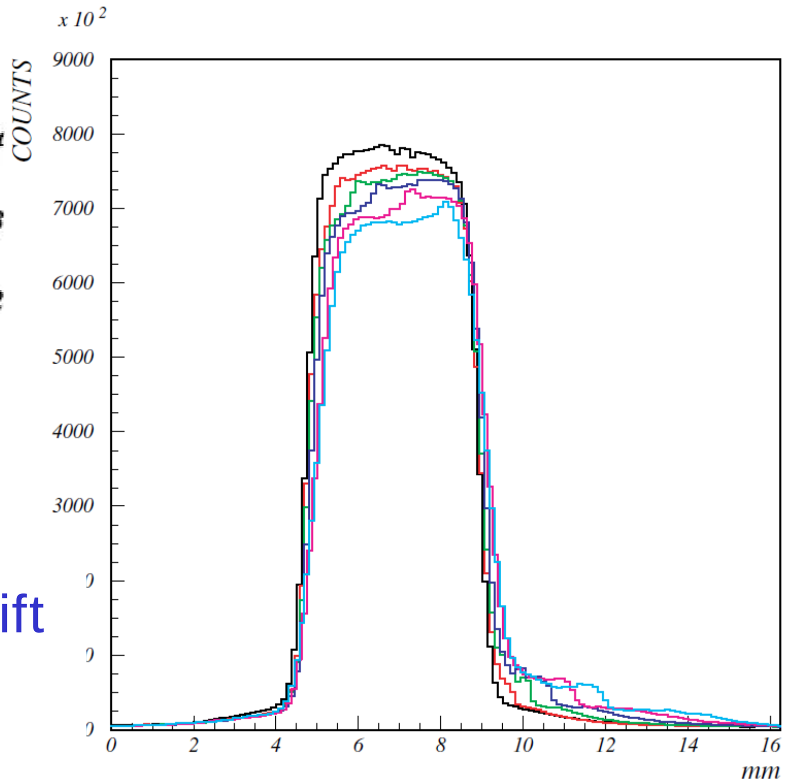


Scan with light beam at an angle – additional tool to disentangle various effects, i.e. where does the photo-effect happen

M16 response:
ferent incident
green 20, dark
blue 50 deg.)
rdinate







Scans across the PMT. In the 50 deg scan shift of the original image can be observed due to photon reflections and photo-effect at the dynode structure.

Summary

- A novel 144 channel HAPD photo-sensor with high single photon detection efficiency was developed in collaboration with Hamamatsu Photonics K.K. for the Belle II ARICH detector
- Results of the beam tests of ARICH prototype show that it is capable of > 4σ pion/kaon separation up to momentum of 4 GeV/c
- HAPD was extensively tested and optimized to ensure that this performance will be maintained throughout the experiment:
- Neutron irradiation tests showed increase of the leakage current but a good S/N can be kept with modified APD structure and readout ASIC
- APD was modified to prevent a rapid increase of the leakage current and lowering of the breakdown voltage after γ irradiation
- Aging test showed that no degradation of photocathode performance is expected due to the normal operation
- HAPDs, MCP PMTs and MAPMTs have some similarities because of similar geometries