RICH 2007
6th International Workshop
on Ring Imaging Cherenkov Counters
15-20 October 2007
Trieste - Italy

Status and perspectives of vacuum-based photon detectors for single photon detection

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CERN – Geneva – Switzerland

Overview disclaimer

- Much more is taking place than what can be covered in 40 minutes!
- The selection criteria were a combination of:
  - the speaker's current activities and interests,
  - those developments coming from relatively 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.

Broad range of requirements

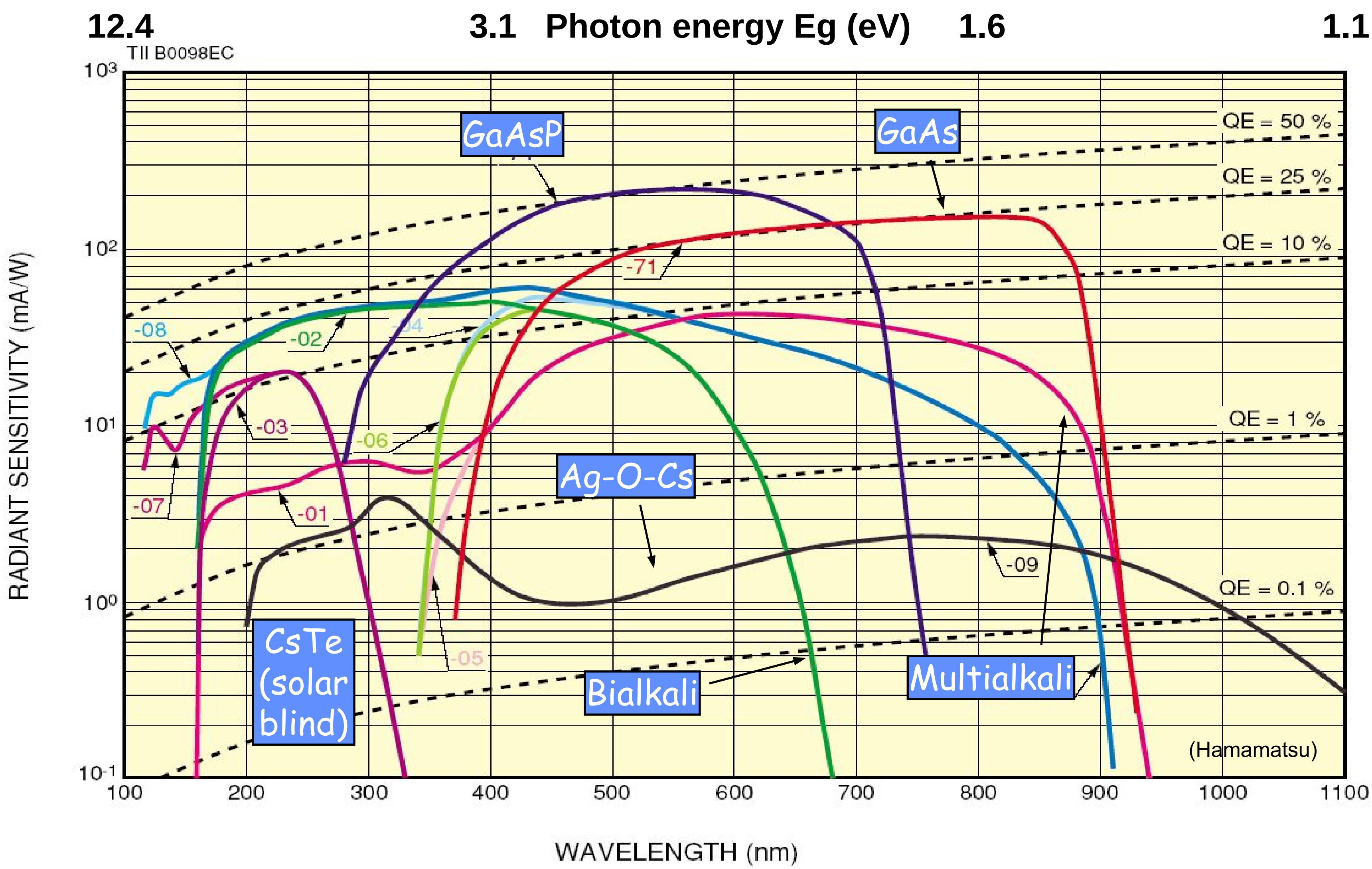
- **Photon detection**
  - Total surface: ~1 mm^2 to ~1 m^2
  - Granularity: ~10 μm to ≥ 10 mm
  - Active area coverage: ≥ 50 %
  - Single-photon sensitivity over a broad spectral range (near UV to infrared)
- **Environment**
  - Magnetic field: 1 mT ≤ B ≤ 4 T
    (axial and/or transverse)
  - Radiation dose: 100 kRad/year (charged particles)
    $5\ 10^{10}$ cm^{-2} (neutrons)
- **Read-out**
  - Maximum occupancy: ≤ 10 %
  - Intrinsic speed: ≤ ns
  - Signal jitter: ~10 ps to ~10 ns
  - Signal rate: ~1 Hz to ~100 Mhz
  - Read-out rate: ~1 Hz to ~1 MHz

Broad range of options

This overview will mainly focus on position-sensitive single-photon detectors:

- Multi-anode Photon Multiplier Tubes
- Micro Channel Plate Photon Multiplier Tubes
- Hybrid Photon Detectors
- Electron-bombarded CCD's or alternatives
- Etc.

QE's of typical vacuum photo-cathodes

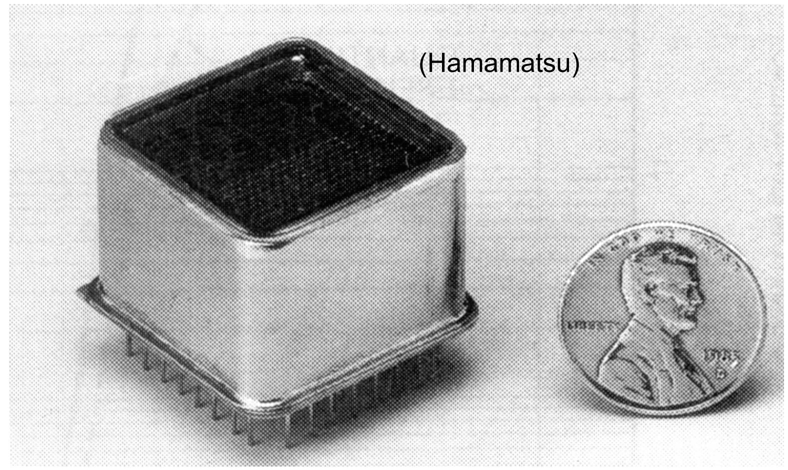


Bialkali: SbKCs, SbRbCs Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

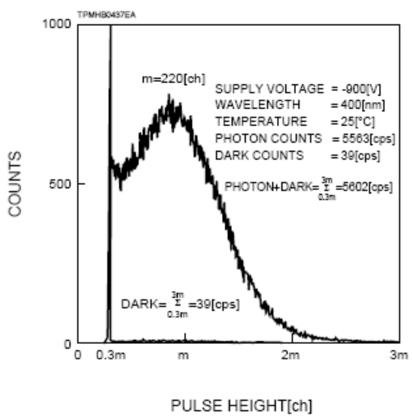
Multi-anode Photon Multiplier Tubes

Main features

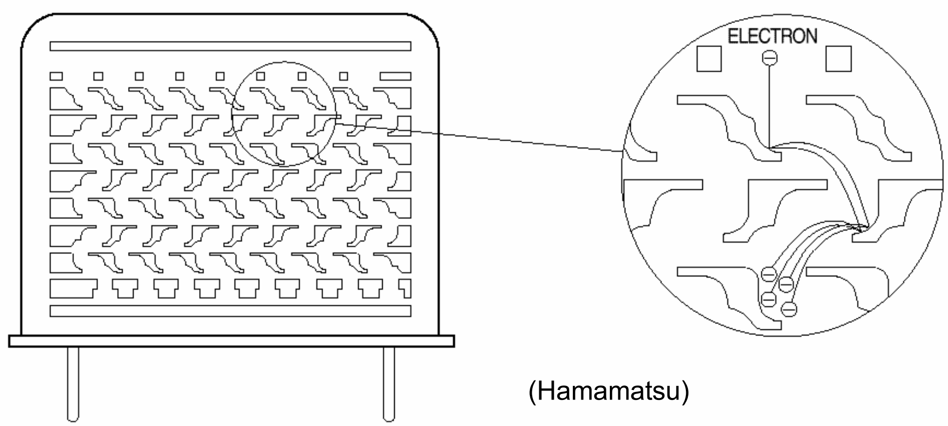
- **Construction**
  - Metal channel dynodes
  - Up to 8×8 channels (2×2 mm^2 each);
  - Size: 28×28 mm^2;
  - Active area 18.1×18.1 mm^2 (41%);
- **Bi-alkali PC:**
  - QE ≅ typ. ≥ 20% @ λ_{max} = 400 nm;
- **Gain ≅ 3 × 10^5**
  - Fluctuation ≅ $\sqrt{g_1} / g_1$ typ. 0.60;
  - Gain uniformity typ. 1 : 2.5;
  - Cross-talk typ. <1-2%



(Hamamatsu)



(Hamamatsu)

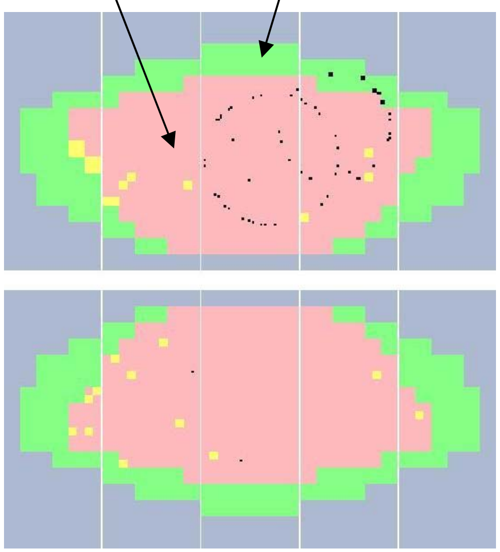


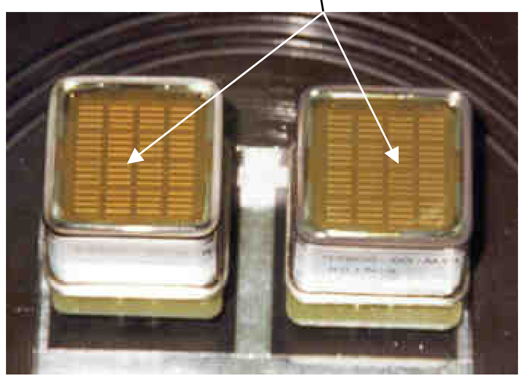
(Hamamatsu)

MaPMT's (2)

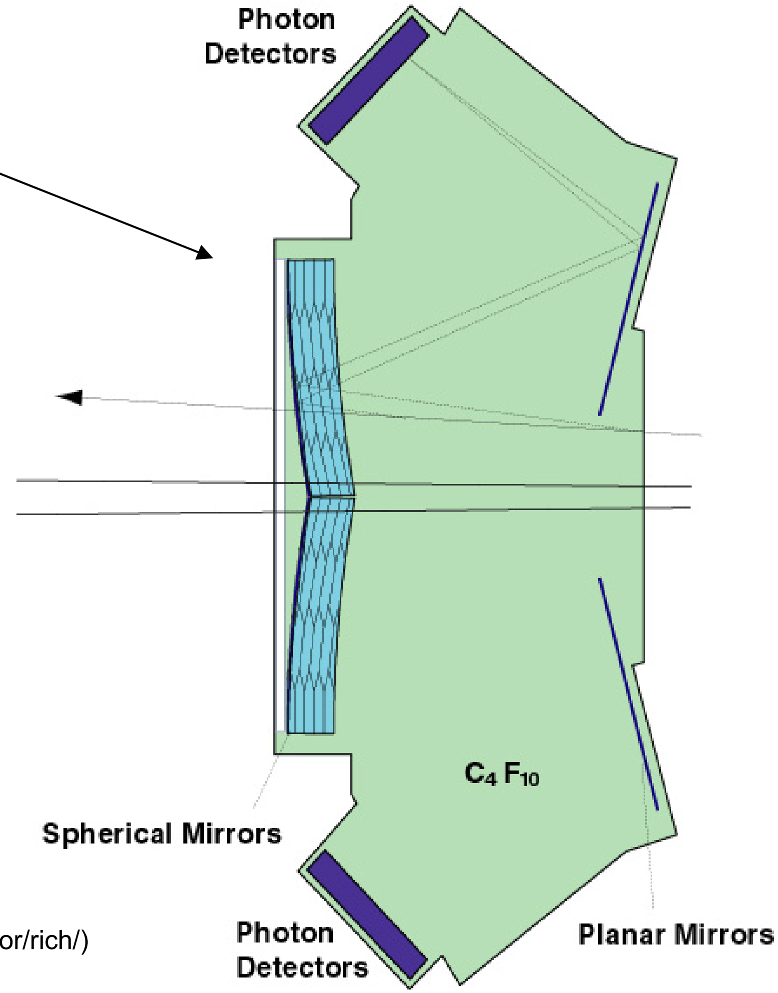
Hera-B RICH detector

- Requirements
  - Rates ~1MHz
  - Long term stability
  - Surface of ~3m²
- 2 types of MaPMT's:
  - 1488 M16 (4.5×4.5mm² pads)
  - 752 M4 (9×9mm² pads)





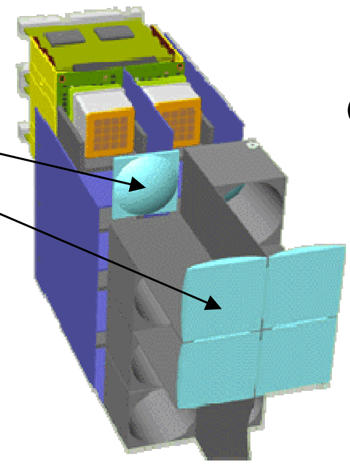
(http://www-hera-b.desy.de/subgroup/detector/rich/)



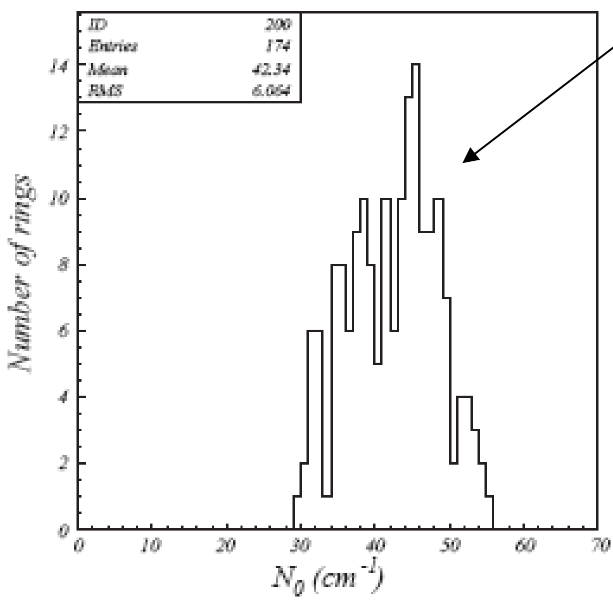
MaPMT's (3)

Hera-B RICH (cont'd)

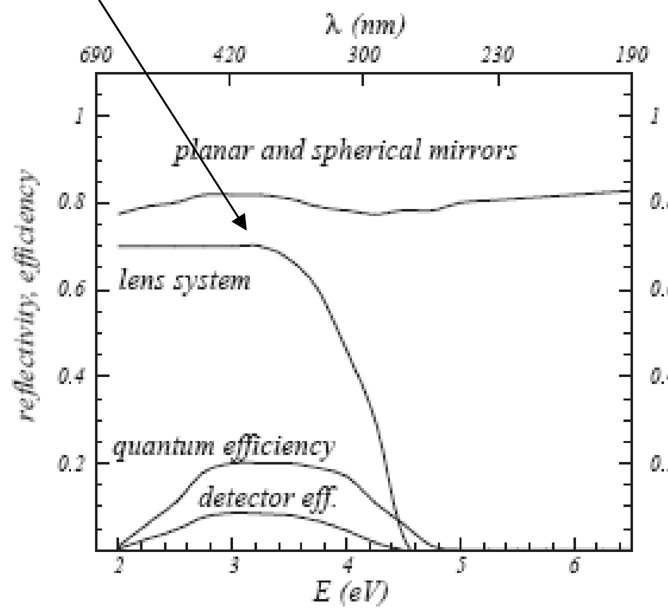
- Use lenses to match active area
  - ~70% transmission
  - drop above 3.5eV photon energy
- Performance:
  - >98% single pe efficiency
  - <0.2% cross-talk
- Quality factor N_0:
  - average value 42 cm^{-1}



(http://www-hera-b.desy.de/ subgroup/detector/rich/)



(I. Ariño et al., NIM A **516** (2004) 445)



MaPMT's (4)

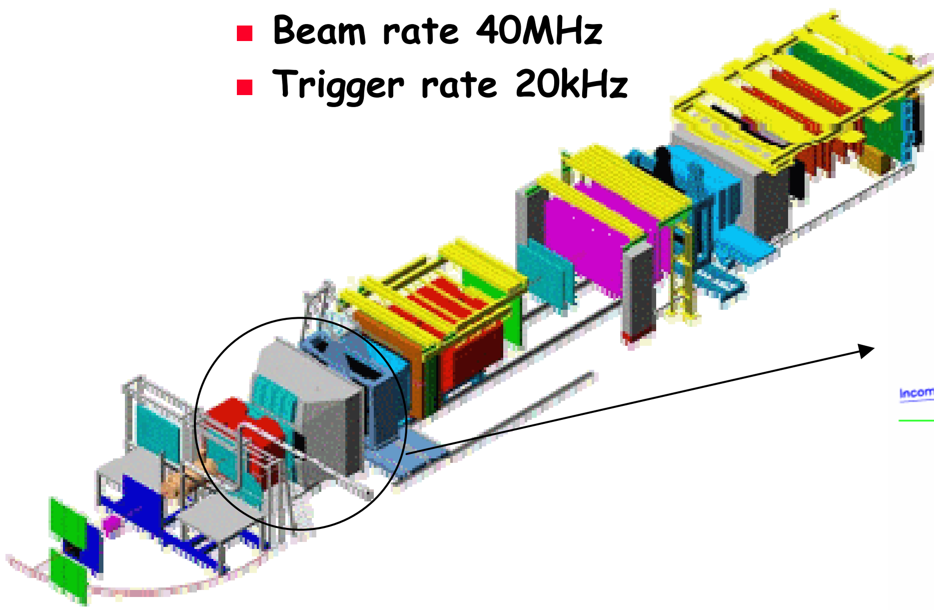
"Old" Compass RICH1 system

- CsI photo-cathodes – MWPC
- 3μsec memory with Gassiplex chip (now reduced to 400ns with APV25-S1 chip)
- Beam rate 40MHz
- Trigger rate 20kHz

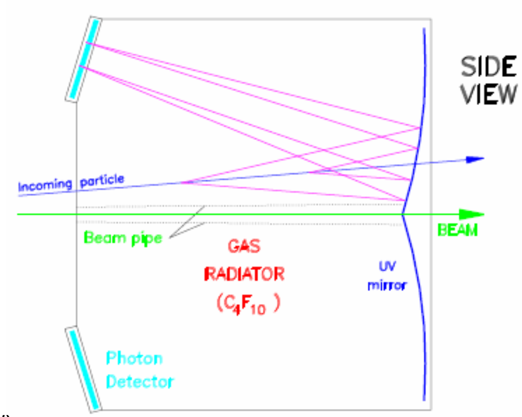
New Compass fast RICH1 (central region)

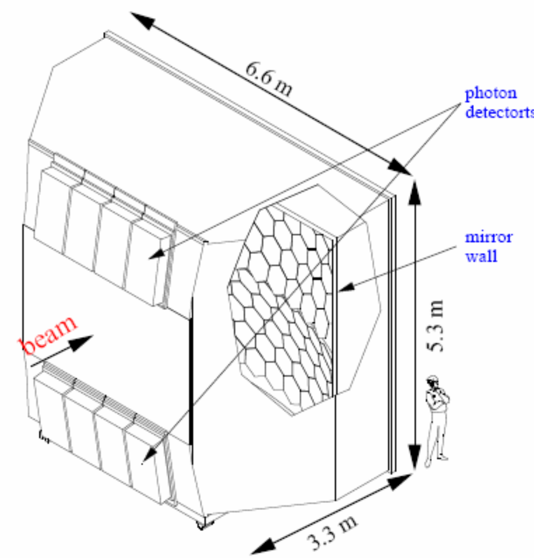
See contribution of F. Tessarotto at this Conference

- 576 M16 MaPMTs (bialkali pc)
- 10nsec time cut
- Beam rate 100MHz
- Trigger rate 100kHz



(http://wwwcompass.cern.ch/compass/)

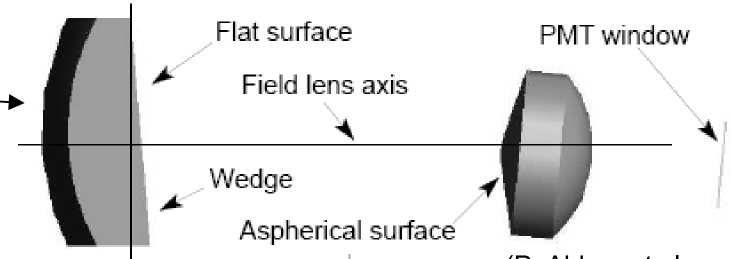


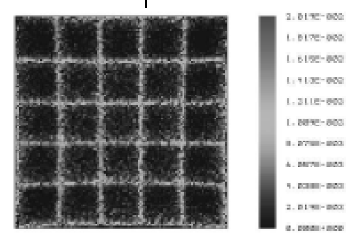


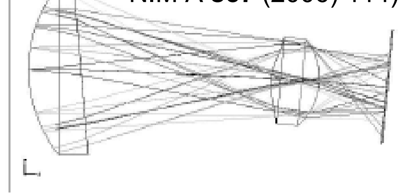
MaPMT's (5)

Compass fast RICH1 (cont'd)

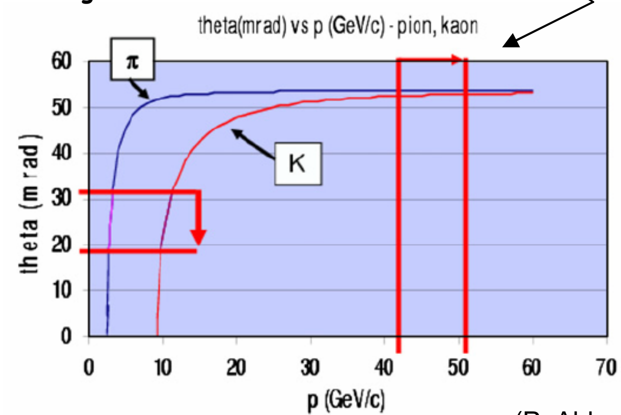
- Lens system "à la" Hera-B
- Extension of the wavelength range
  - $\Rightarrow N_{ph/ring} \approx 40$ (14 w. CsI)
  - $\Rightarrow \sigma_{ring} \approx 0.4$mrad (0.6 w. CsI)



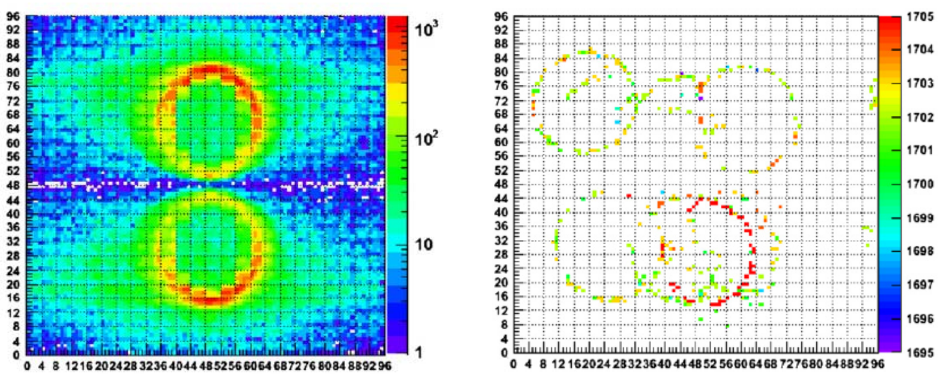


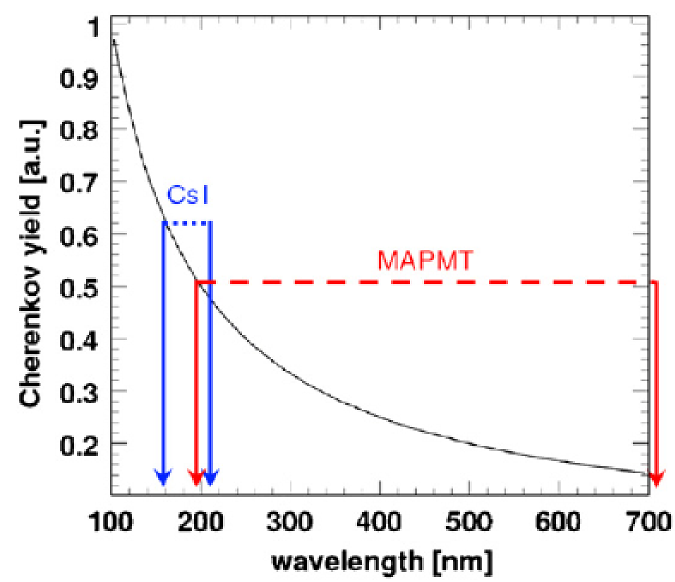


(P. Abbon et al.,
NIM A **567** (2006) 114)



(P. Abbon et al.,
NIM A **580** (2007) 906)



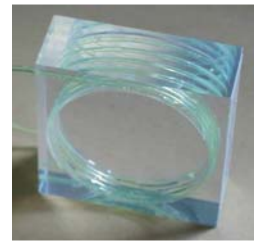


MaPMT's (6)

LHCb pre-shower detector

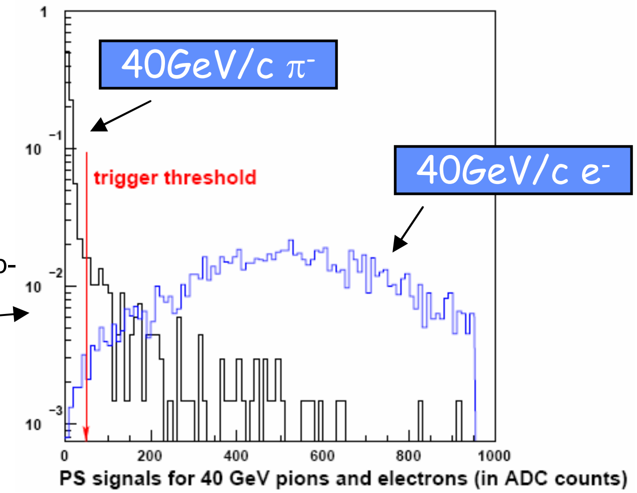
- **Requirements**
  - 2 X_0 Pb sheets inserted between 2 planes of scintillating tiles - ~6000 detector cells
  - Hadronic shower rejection – threshold 5MIP's , accuracy 0.1MIP, range 100MIP's
- **MaPMT readout**
  - typ. 20-30 pe- per MIP
  - wide linearity range

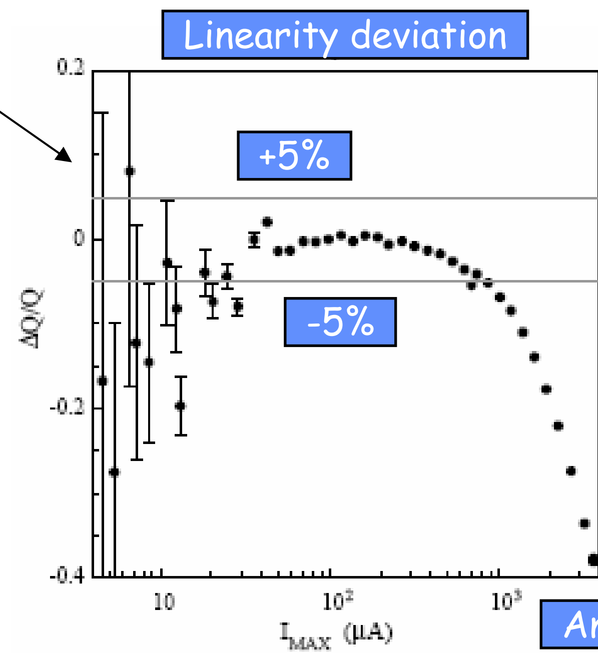
  $\Rightarrow$ low gain $\approx 10^3 - 10^4$
  - low cross talk « 1%
  - ASIC readout chip



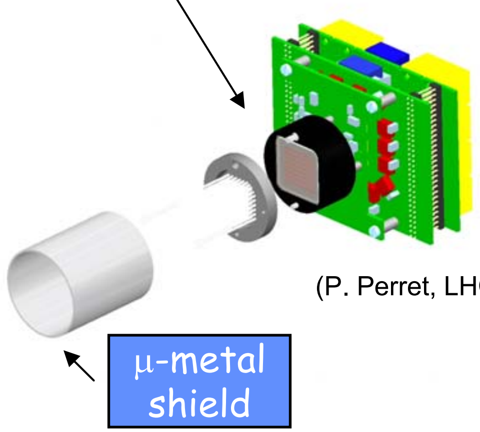
(http://lhcb-calo.web.cern.ch/lhcb-calo/html/photos.htm)

(C. Carloganu, poster presented at Elba Conference 2004, Italy)





(Z. Ajaltouni et al., NIM A **504** (2003) 9)

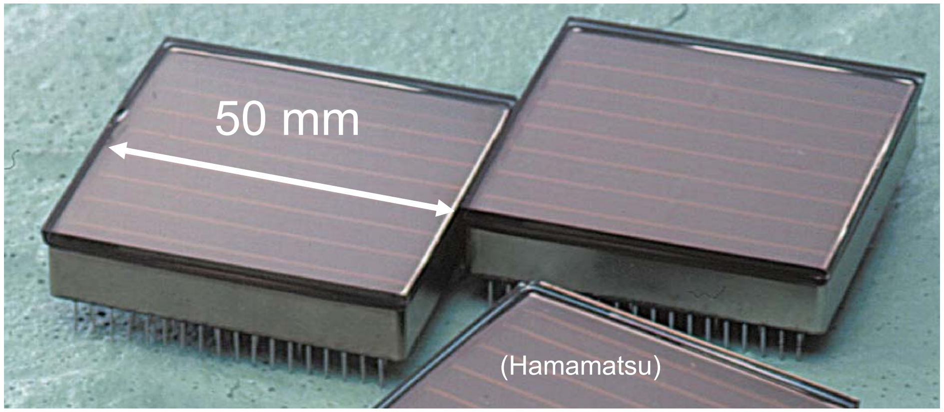


(P. Perret, LHCb-PS EDR)

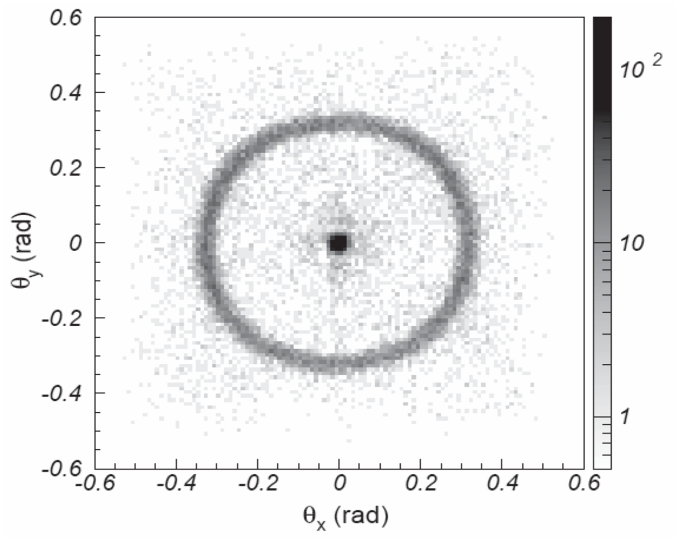
Flat-panel PMT's

- *Main features*
  - 8x8 or 16x16 channels;
  - Compactness;
  - Excellent active area ratio (89%)
- *Belle upgrade*

See contribution of T. Iijima at this Conference

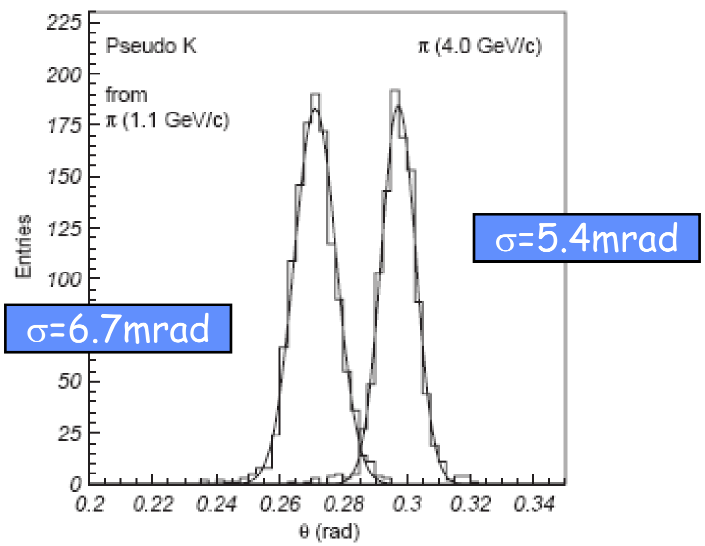


Cherenkov rings from 3 GeV/c π^- through aerogel



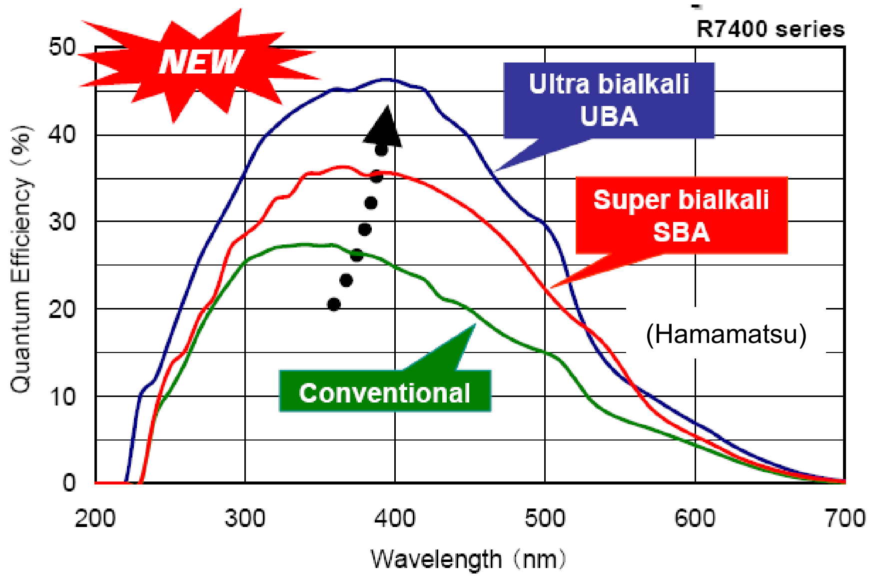
(T. Matsumoto et al., NIM A **521** (2004) 367)

Cherenkov angles from 1.1 and 4 GeV/c π^- through aerogel

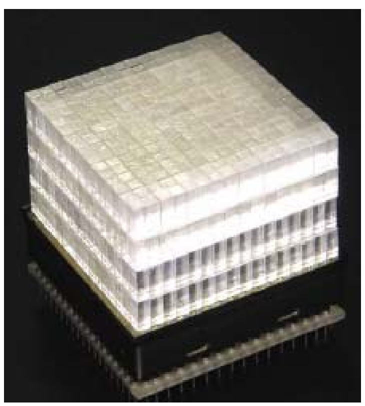


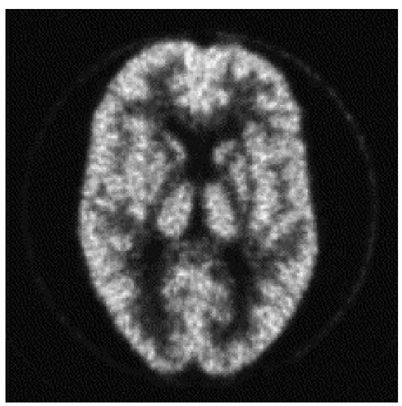
(P. Križan et al., NIM A **553** (2005) 58)

MaPMT's amd flat-panel PMT's: R&D



jPET-D4 brain scanner
GSO crystals





Improved bialkali photo-cathodes

- SBA:
  - Metal package PMTs
  - 1"-3" glass bulb PMTs
- UBA:
  - Metal package PMTs

Improved gain uniformity of flat panel metal package PMTs

- Typ.:
  - 1:3 ⇒ 1:2
- Max.:
  - 1:5 ⇒ 1:4

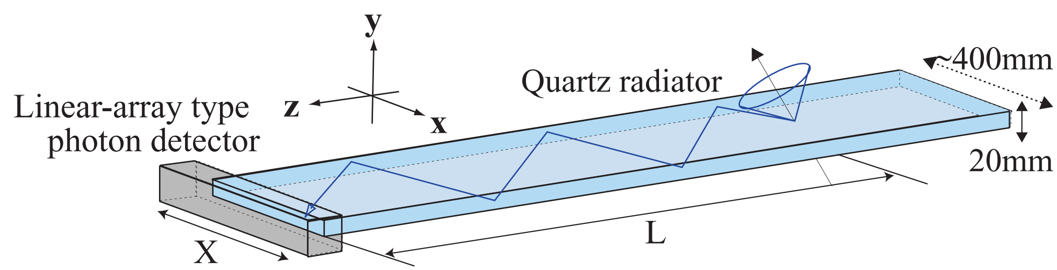
(K. Kitamura et al., NIM A **571** (2007) 231)

Micro Channel Plate PMT's

Barrel PID upgrade for super B factory – TOP Cherenkov counters (Nagoya, KEK)

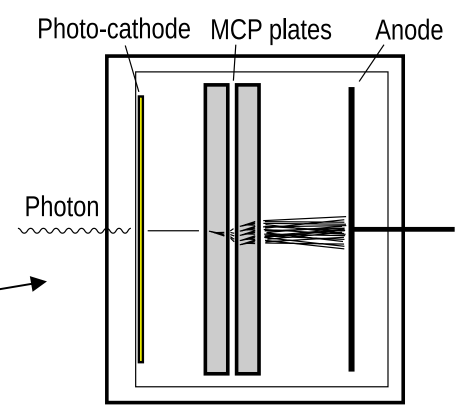
See contributions of K. Inami, P. Križan and A. Lehmann at this Conference

(M Akatsu et al., NIM A **440** (2000) 124)



- **Requirements**
  - Single photon sensitivity
  - Good transit time spread (TTS<50ps)
  - Immunity to high (1.5T) B-field
  - Position-sensitive (~5mm)
  - High detection efficiency

⇒ Best candidate is MCP-PMT

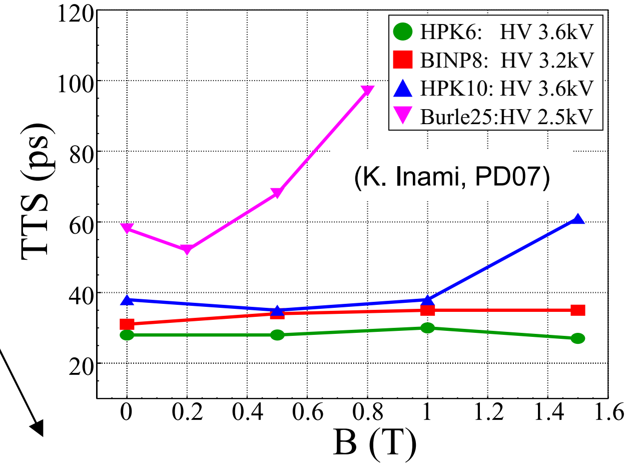


(K. Inami, presented at PD07, Kobe, Japan)

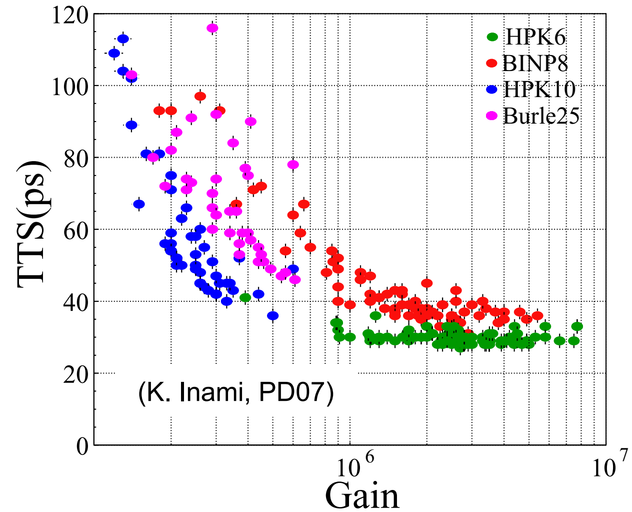
MCP-PMT's (2)

Super B factory upgrade (cont'd)

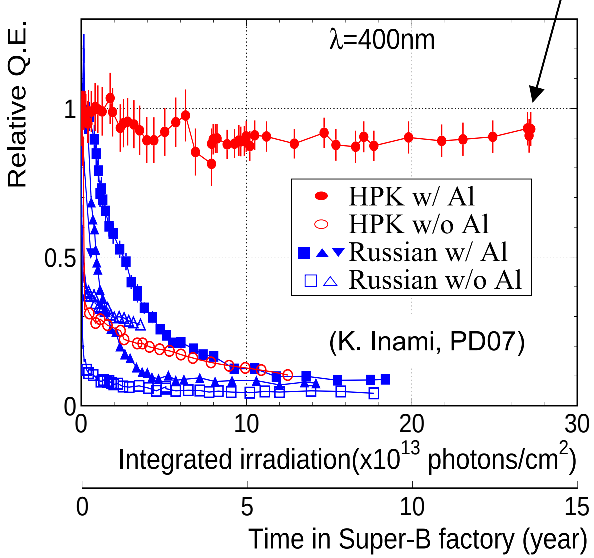
- **MCP-PMT main features**
  - B-field immune due to small (6-25μm) hole diameter – aperture typ. 60%
  - Excellent TTS (30ps for single photons at high gain)
  - Photo-cathode (QE) ageing reduced with Al protective layer but CE drops from typ. 60 to 40%



(M Akatsu et al., NIM A **528** (2004) 763)

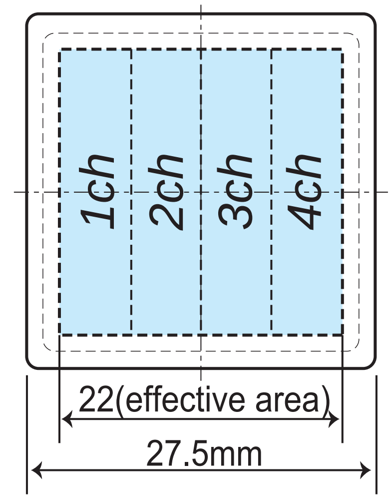


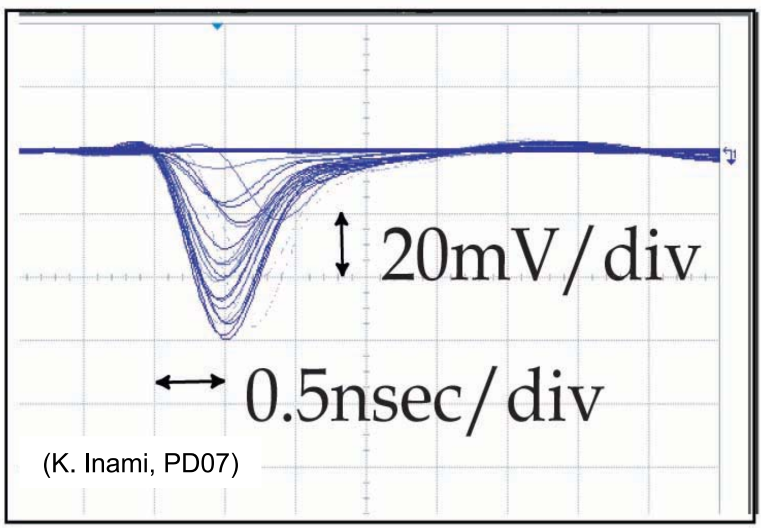
(N. Kishimoto et al., NIM A **564** (2006) 204)



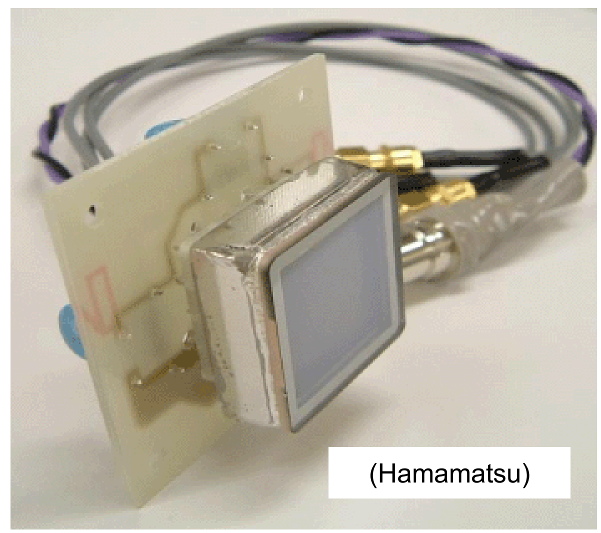
MCP-PMT's: R&D

- **Multi-anode MCP-PMT**
  - Large surface coverage (64%)
  - Linear position information (4×5.3mm×22mm)
  - Fast rise time (400ps)
  - Excellent TTS (30ps for single photons)





(K. Inami, PD07)


(Hamamatsu)

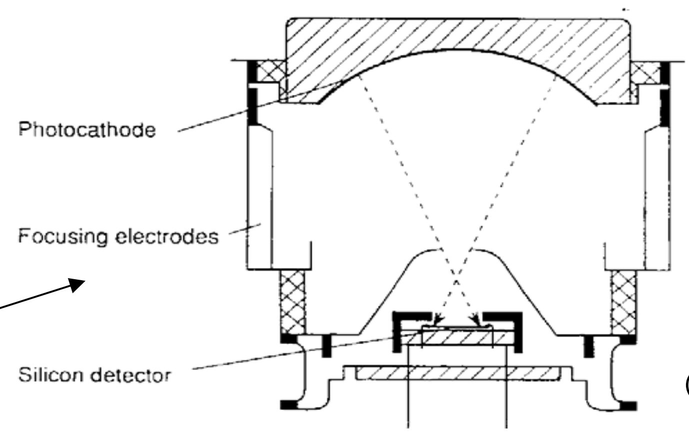
Hybrid Photon Detectors

Main features

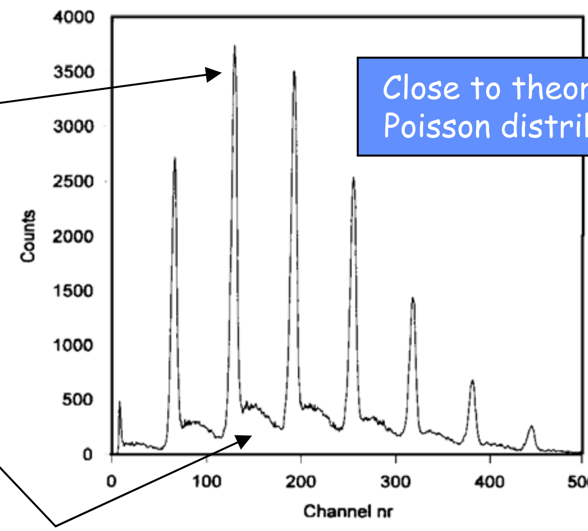
- **Construction**
  - Hybrid technology: vacuum photon detector tube encapsulating a solid-state detector (+ possibly its readout electronics)
  - Segmentation ranges from ~50μm to ~20mm
  - Various possible e-optics designs based on image intensifier technology
- **Gain ≅ 1 to 5 × 10^3**
  - Small intrinsic fluctuations ≅ $\sqrt{F}\times G$ + back-scattering effects

  ⇒ overall noise dominated by electronics noise
  - Gain uniformity typ. 1
  - Cross-talk: see CMS HCAL

(C.A. Johansen et al., NIM A **326** (1993) 295-298)



(Photonis-DEP)



(C.P. Datema et al., NIM A **387** (1997) 100-103)

HPD's (2)

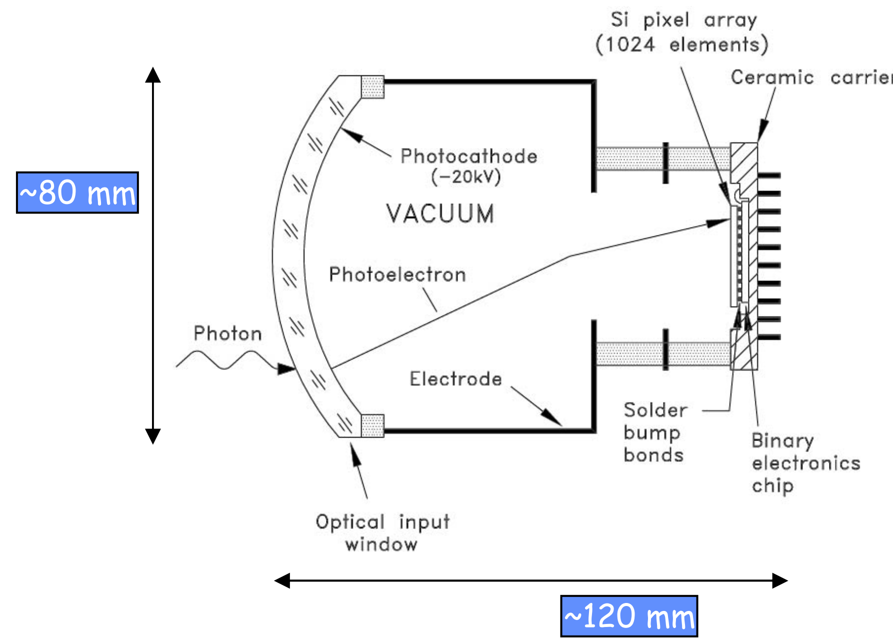
HPDs for LHCb RICH detectors

- **Requirements**

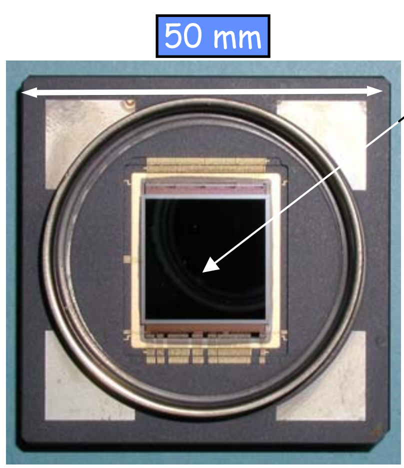
  See contributions of S. Eisenhardt and S. Brisbane at this Conference

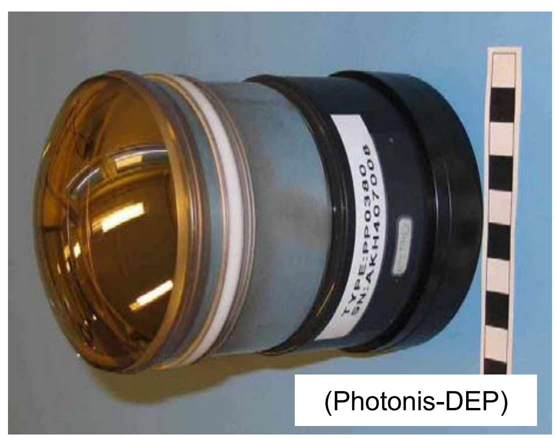
  - **Large area (3.3m²) with high overall active area fraction (~65%)**
  - **Fast compared to the 25 ns bunch crossing time**
  - **Have to operate in a small (1-3mT) magnetic field**
  - **Granularity 2.5x2.5mm²**

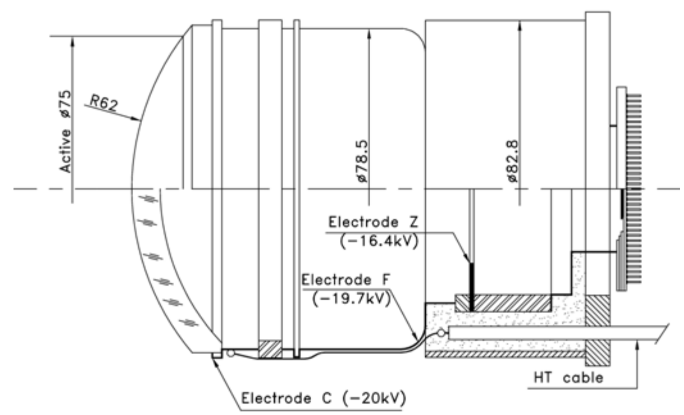
  ⇒ 484 HPDs with 5× de-magnification and custom anode



(Photonis-DEP)



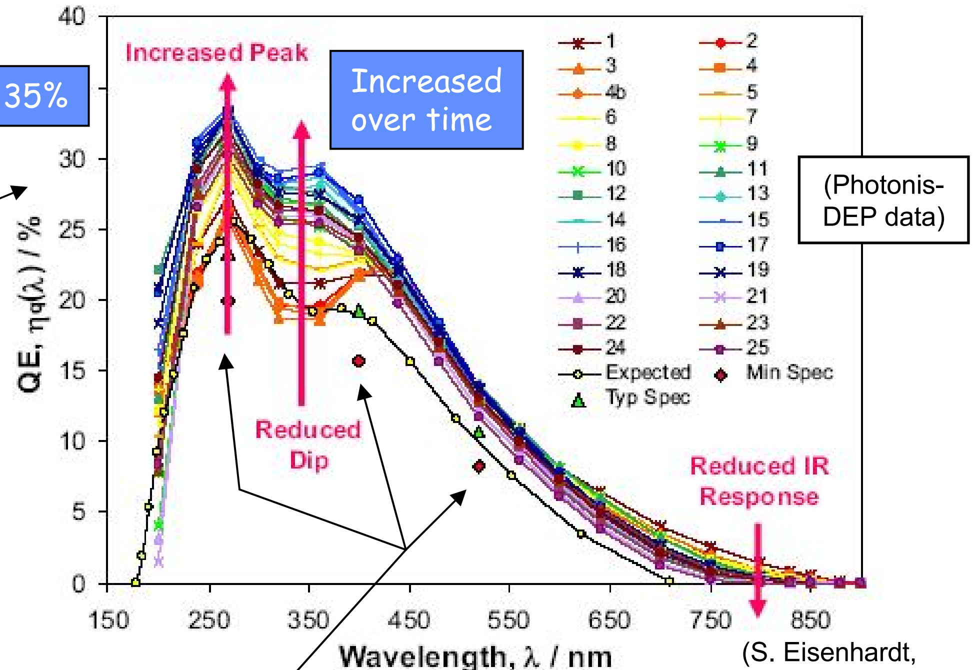

(Photonis-DEP)



HPD's (3)

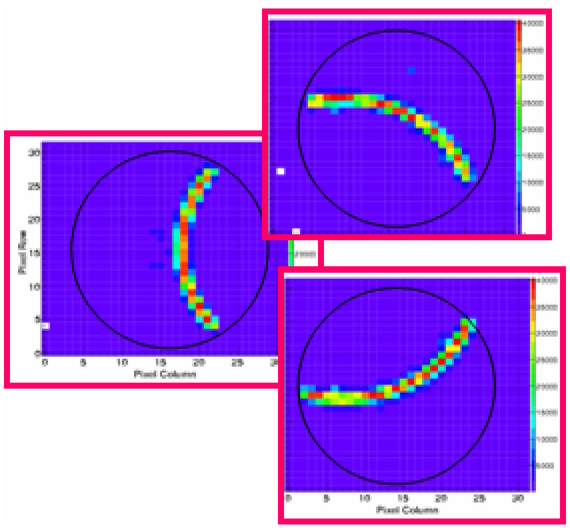
HPDs for LHCb RICHes (cont'd)

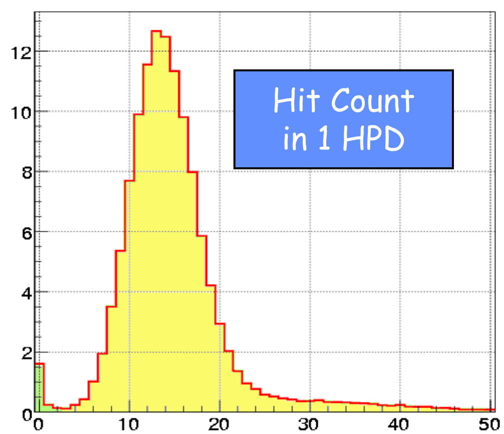
- **HPD photo-cathode**
  - **Must cover 200-600nm wavelength range**
  - **Multi-alkali S20 ($KCsSbNa_2$)**
  - **Improved over production**
  - **Resulted in a ∫QEdE increased by 27% wrt the original specifications**



(S. Eisenhardt, this Conference)

Cherenkov rings from 80 GeV/c π- through C_4F_{10}





Typical and minimum QE specs based on prototypes

(S. Brisbane, this Conference)

RICH 2007

HPD's (4)

HPDs for LHCb RICHes (cont'd)

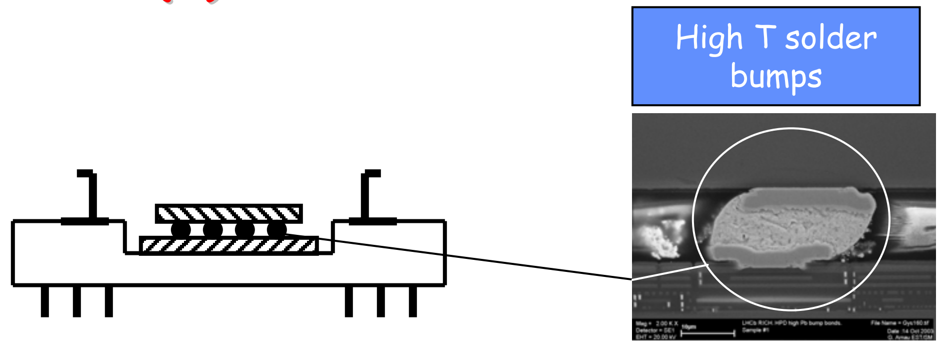
- **Thresholds and noise**
  - The anode is a Si pixel detector with 8192 channels organized in 1024 super-pixels of 500 x 500 μm^2 size, bump-bonded to a custom binary readout chip (lhcbpix1)

    $\Rightarrow$ excellent signal-to-noise ratio achieved by small pixels and optimal sensor-FE coupling

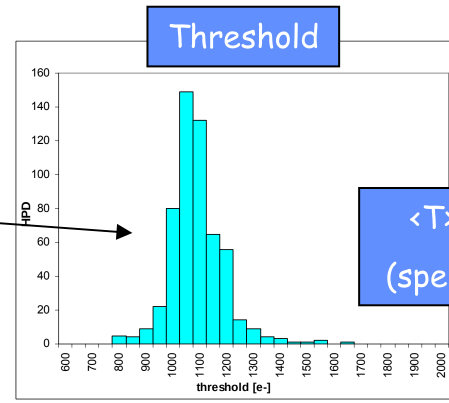
  - Very low average threshold and noise
  - Typical signal is 5000 e- (Si detector dead layer typ. 150nm) with intrinsically low fluctuations (typ. 25 e- rms)

    $\Rightarrow$ ~85% photo-electron detection efficiency for 25ns strobe

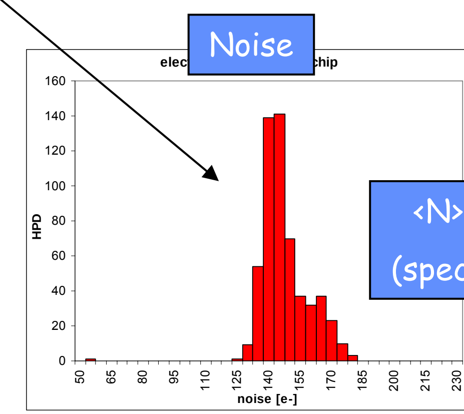
  - Residual inefficiency is dictated by photo-electron back-scattering (18% probability) and charge-sharing effects



(M. Campbell et al., IEEE TNS **53, 4** (2006), 2296)



<T>= 1065 e-
(specs 2000 e-)



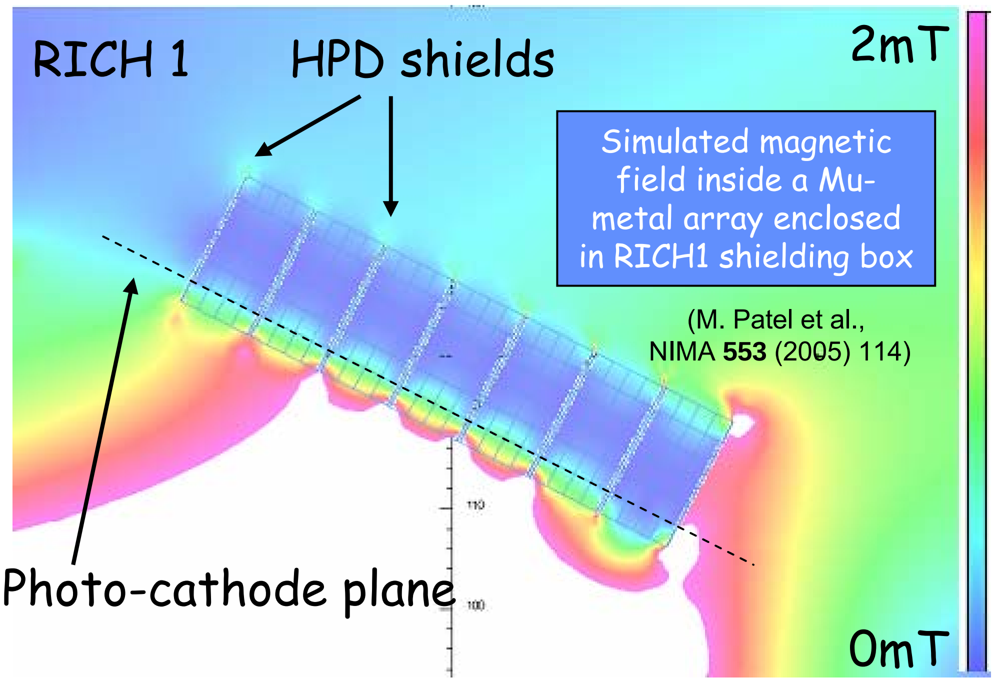
<N>= 145 e-
(specs 250 e-)

(S. Eisenhardt, this Conference)

HPD's (5)

HPDs for LHCb RICHes (cont'd)

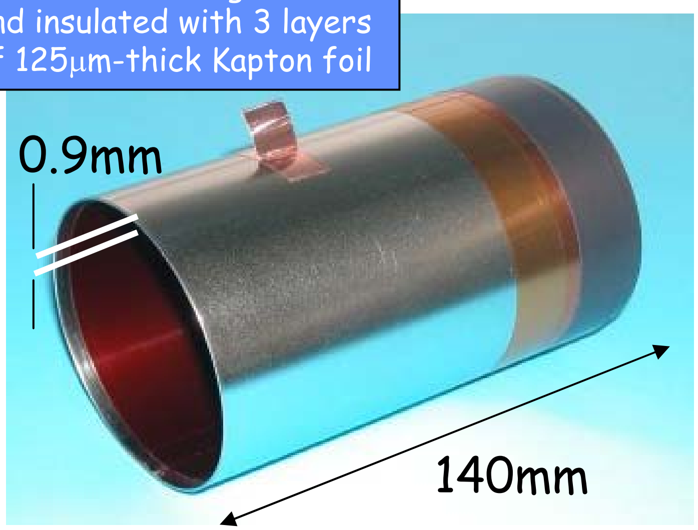
- **Local magnetic shielding**
  - To avoid image loss and minimize distortions, local shielding of HPD's required to reduce B field below 10G (1mT) inside HPD volume
  - With test pattern, reconstruct pixel hit – photon hit position correspondence for each HPD
  - Distortion correction must not degrade pixel size error



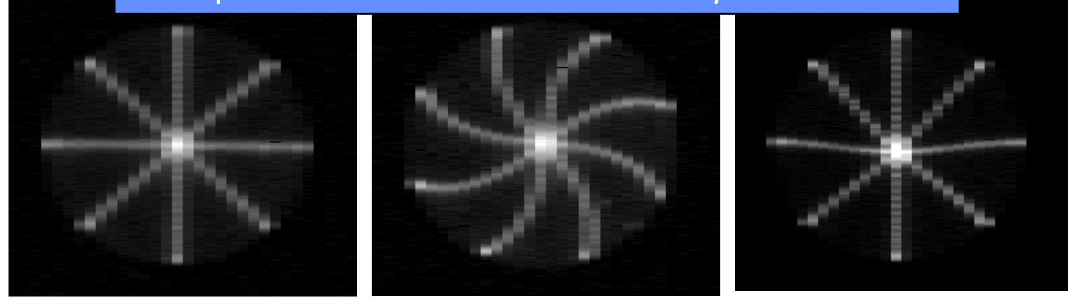
Simulated magnetic field inside a Mu-metal array enclosed in RICH1 shielding box

(M. Patel et al., NIMA **553** (2005) 114)

Mu-metal shield grounded and insulated with 3 layers of 125μm-thick Kapton foil



Test pattern measurements with locally-shielded HPD



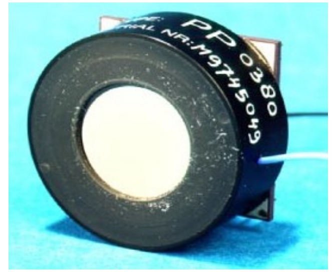
B=0 | $B_{\parallel}$ 30 G (3mT axial) | $B_{\perp}$ 50 G (5mT trans.)

(G. Aglieri Rinella et al., NIMA **553** (2005) 120)

Multi-pixel proximity-focussed HPD

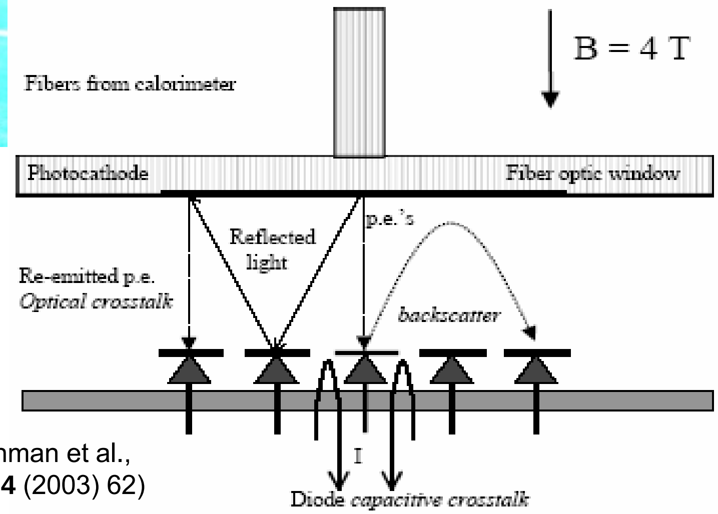
CMS HCAL

- **Requirements**
  - B=4T ⇒ proximity-focussing with 3.35mm gap and HV=10kV;
  - Minimize cross-talks:
    - pe back-scattering: align with B;
    - capacitive: Al layer coating;
    - internal light reflections: a-Si:H AR coating optimized @ λ = 520nm (WLS fibres);

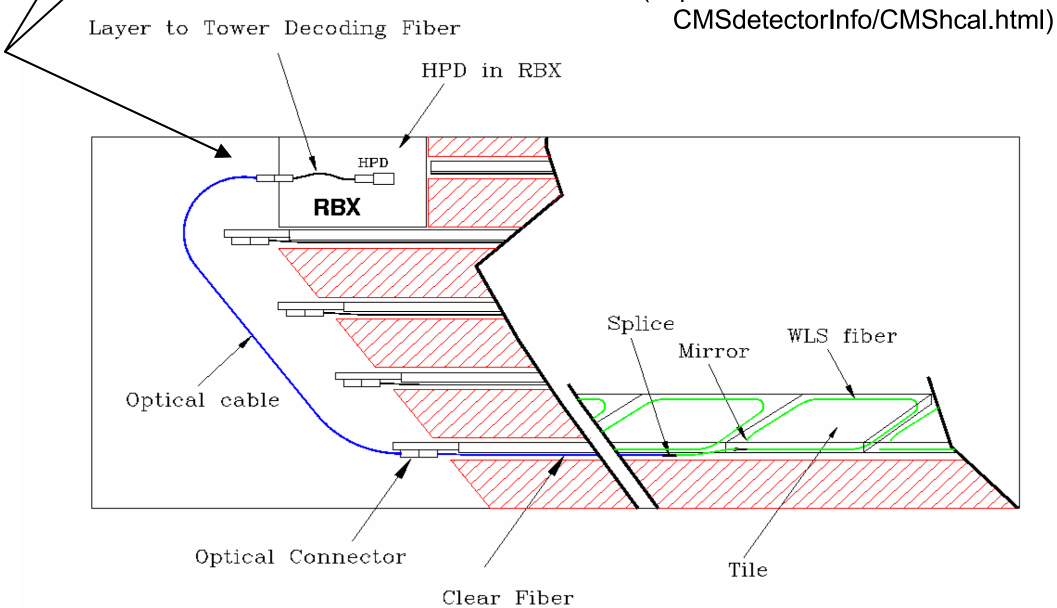


(Photonis-DEP)

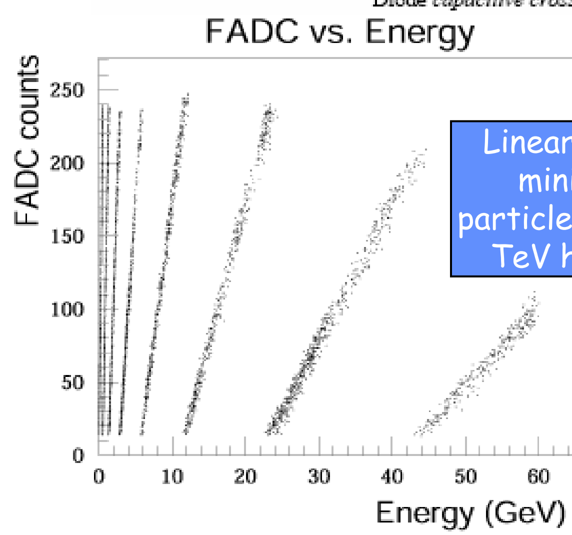
Possible cross-talks



(P. Cushman et al., NIMA **504** (2003) 62)



(http://cmsinfo.cern.ch/Welcome.html/CMSdetectorInfo/CMShcal.html)

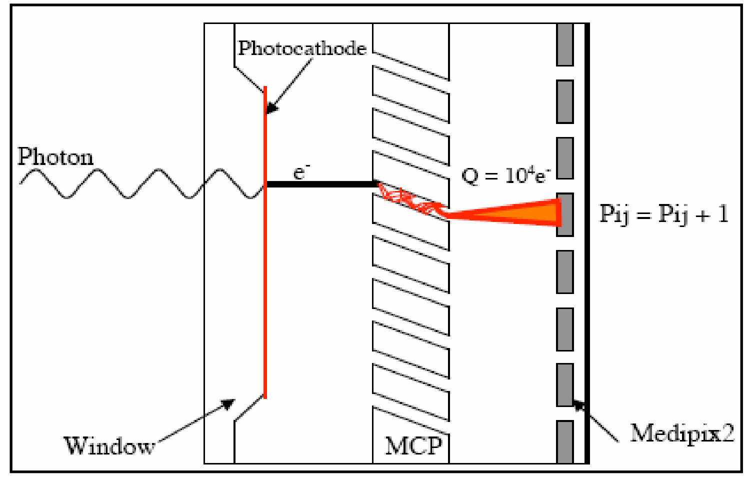


Linear response from minimum ionizing particles (muons) up to 3 TeV hadron showers

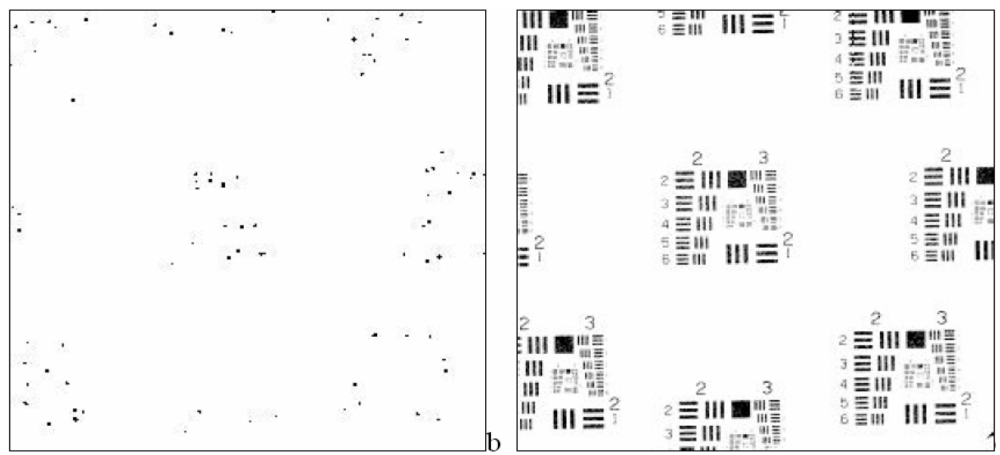
Hybrid MCP for adaptive optics (AO)

Development of next-generation astronomical AO:

- Alternative to replace more conventional high-speed CCD's;
- Aim for IR response, ultra-low noise and several kHz frame-rates;
- GaAs photo-cathode;
- Proximity-focussing electron optics;
- High-gain wide dynamic range MCP;
- Anode: Medipix2 photon-counting chip used both as direct electron detector (55μm pixels) and FE readout electronics;
- Tube development underway

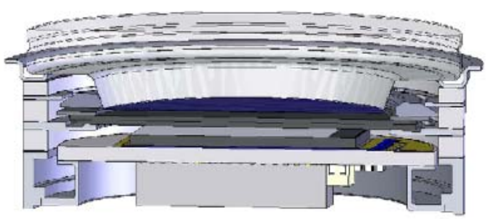


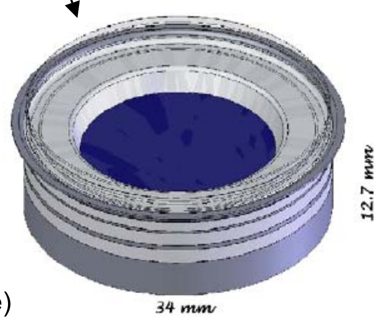
(J. Vallerga et al., NIM A **546** (2005) 263)



Images of USAF test pattern, 100μs (left) and 100s (right) exposures, 50k MCP gain, rear-field voltage 1500V

(B. Mikulec et al., NIM A **567** (2006) 110)





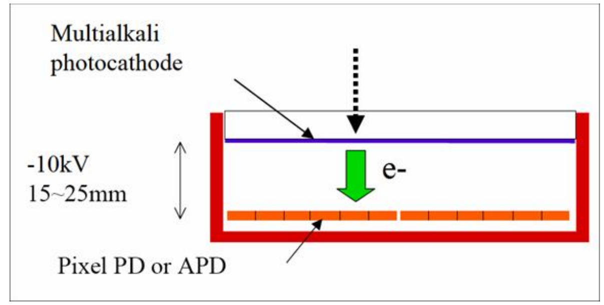
(Burle)

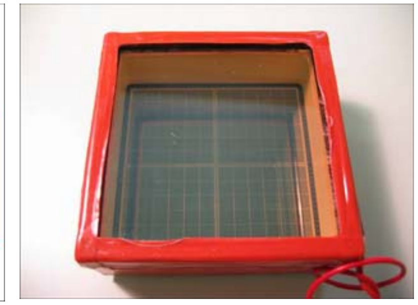
Hybrid Avalanche Photodiode Array: R&D

Aerogel RICH belle Upgrade

See contribution of S. Nishida at this Conference

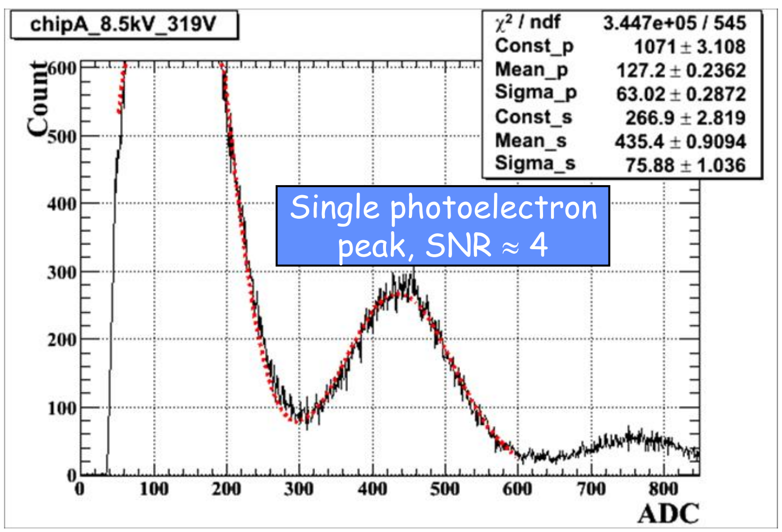
- **Construction**
  - 4 chips of 6×6 APD each 5×5mm^2
  - Immune to B-fields up to 1.5T
  - Active area ratio 64%
  - HV typ. 10kV, V typ. 300V
  - Gain typ. 1000 × 10

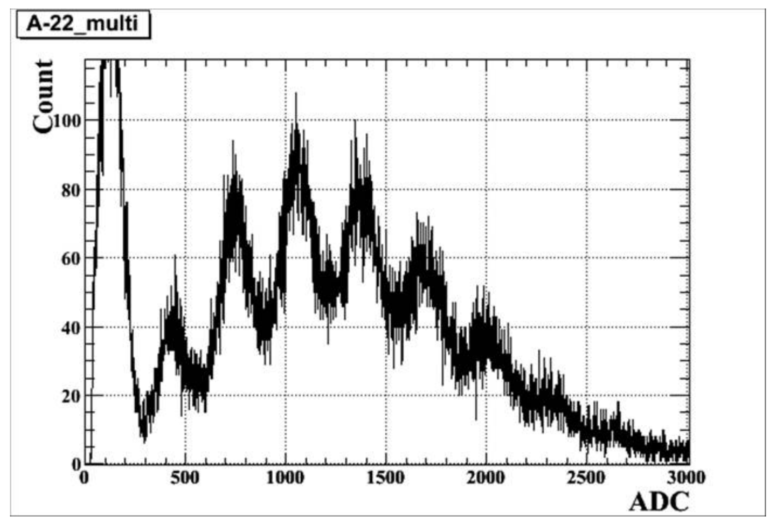




(Hamamatsu)

(I. Adachi, presented at PD07, Kobe, Japan)





GaAs Hybrid Single Avalanche Photodiode: R&D

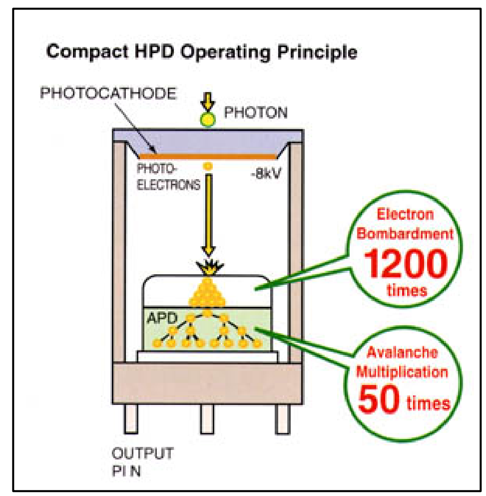
MAGIC telescope upgrade

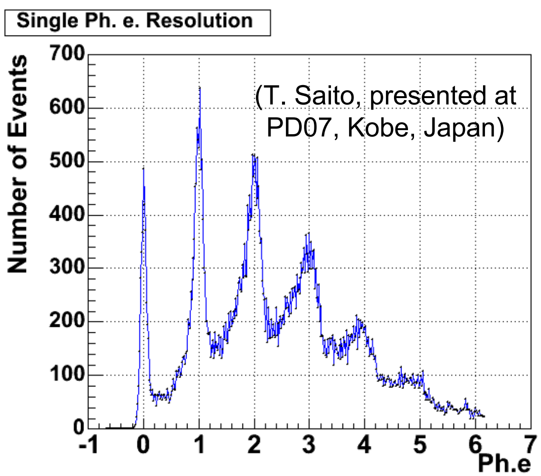
- **Construction**
  - 1 hexagonal APD 28mm in size
  - HV typ. 8kV, V typ. 450V
  - Gain typ. 1500 × 50
  - Avalanche gain T dependence 2%/°C ⇒ T compensation
  - GaAs photo-cathode
  - QE typ. >50% @ λ=500nm
  - QE improved in near UV with WLS coating;20% degradation after 10^4h and 300MHz photon rate

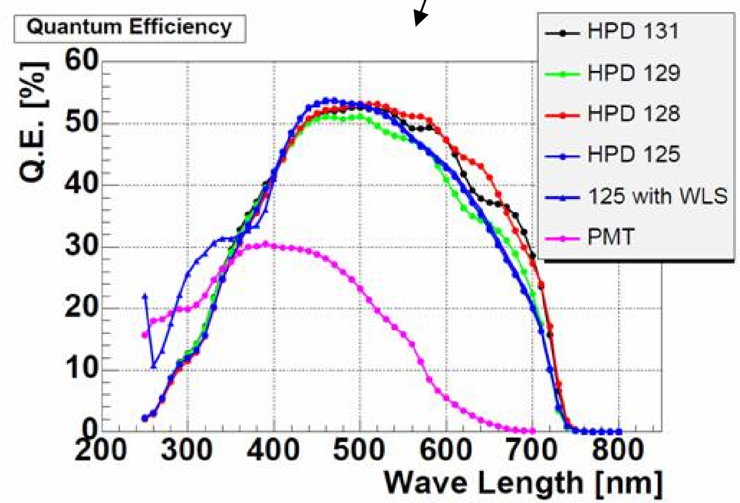
(http://wwwmagic.mppmu.mpg.de/)

(Hamamatsu)

Single avalanche diode HPD





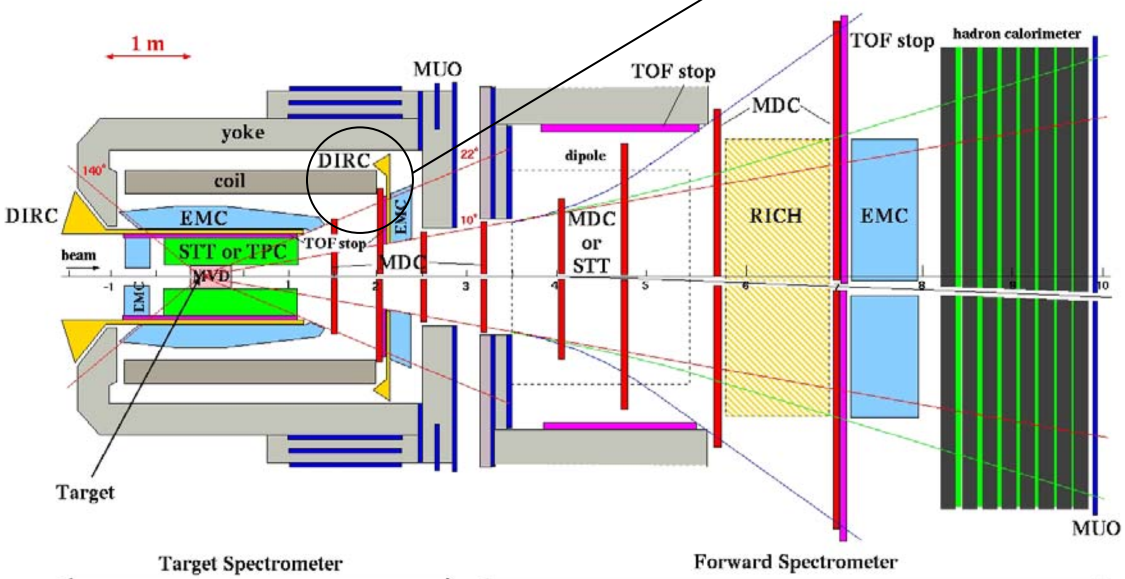


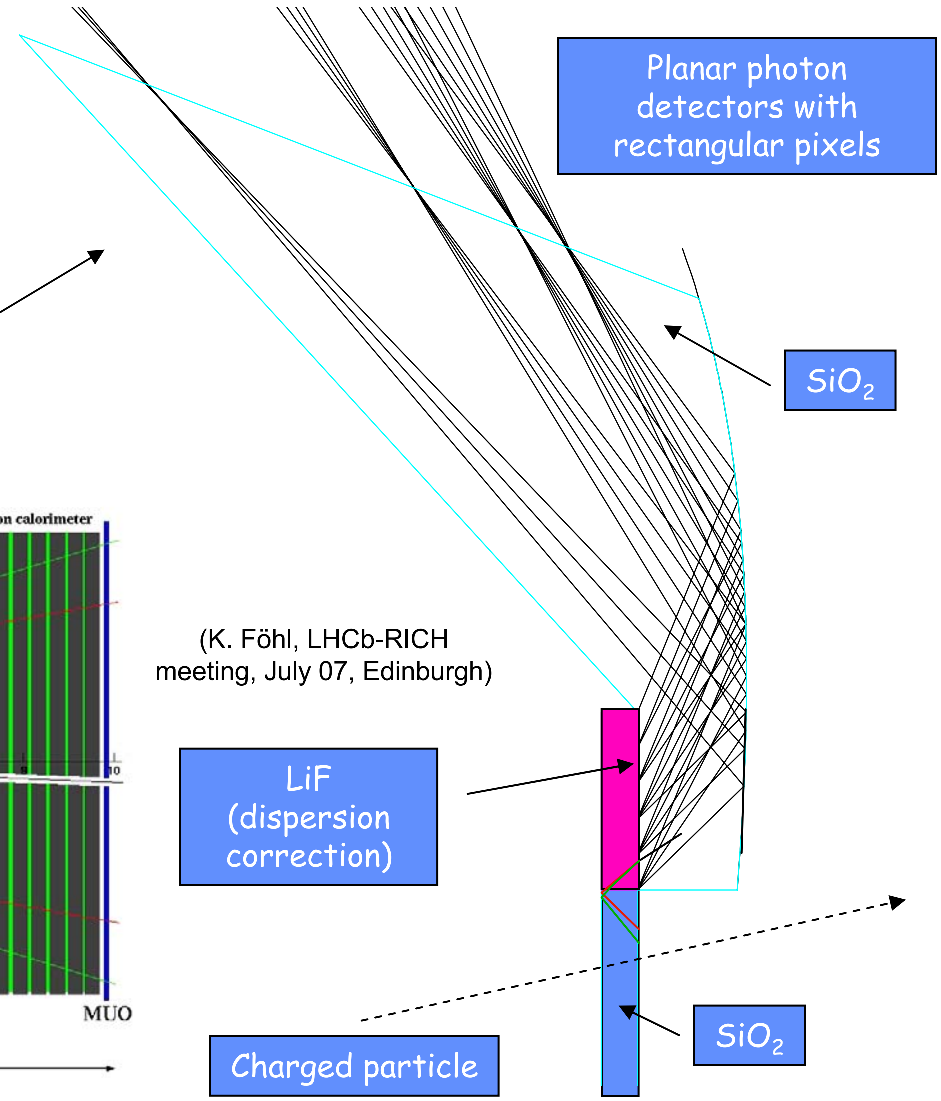
A specific example of photon detector choice

Disc DIRC detector for PANDA

See contribution of K. Föhl at this Conference

- **Requirements**
  - constraints in detector geometry
  - high magnetic field (~1T)
  - high photon rate (MHz/pixel)
  - light cumulative dose
  - radiation dose



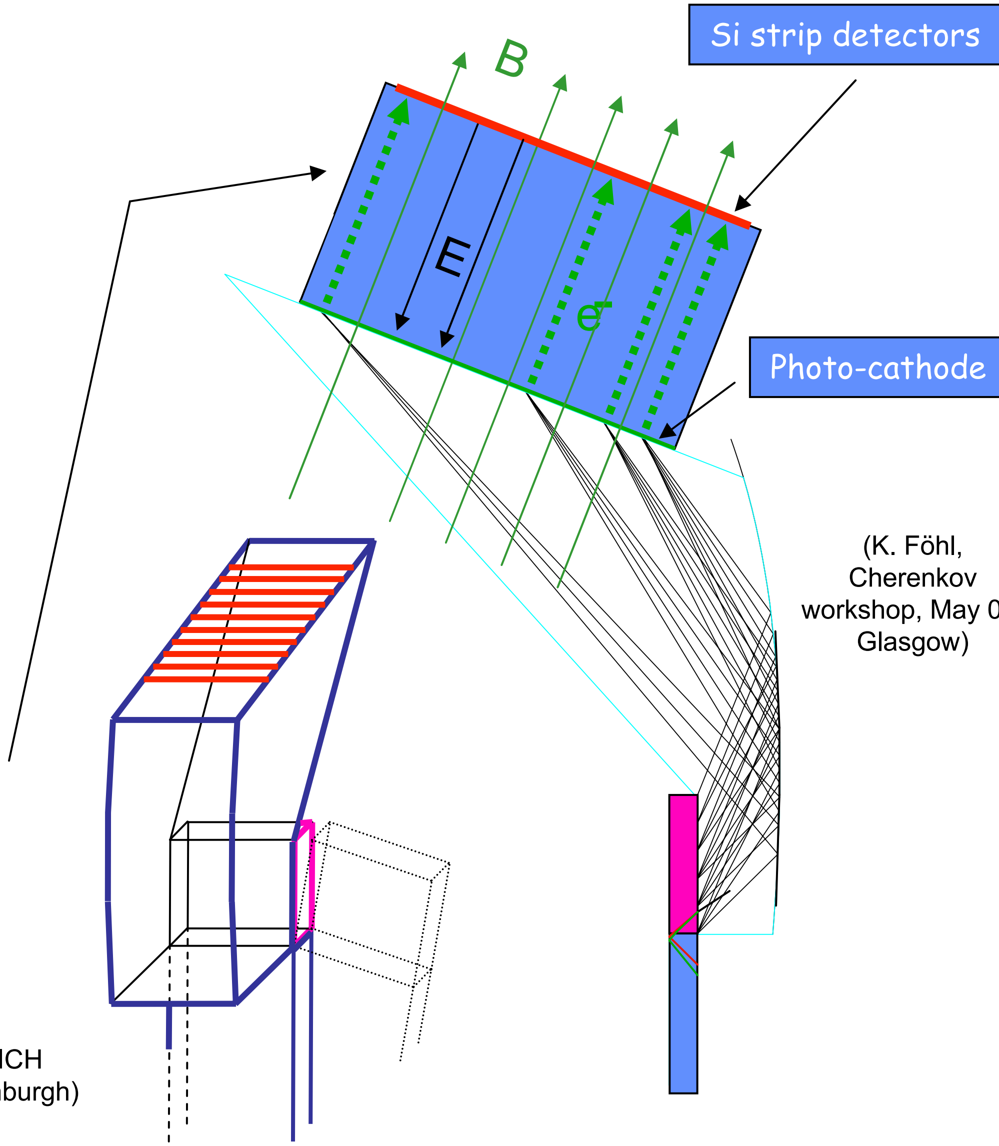


(K. Föhl, LHCb-RICH meeting, July 07, Edinburgh)

A specific example of photon detector choice (2)

Disc DIRC detector for PANDA (cont'd)

- **Photon detector options:**
  - position-sensitive PMT's
    - B-field immunity
    - gain uniformity
  - APDs or similar (MPPC, SiPM, etc.)
    - dark noise vs high signal rate
    - radiation hardness
  - channel plate phototubes
    - overall single pe- efficiency
  - optical fibres and external phototubes
    - fibre connections and related losses
  - HPDs with electro-magnetic imaging
    - alignment with B field
    - radiation hardness
  - Readout electronics?



(K. Föhl, Cherenkov workshop, May 06, Glasgow)

(K. Foehl, LHCb-RICH meeting, July 07, Edinburgh)

Conclusions

- **A lot of innovative techniques are being used or developed!**
  - There is room for improvement on many aspects, including supposedly routine aspects like quantum efficiency of photo-cathodes.
- **Design aspects**
  - Dictated by very specific application requirements
  - Trade-off between:
    - granularity
    - speed
    - active surface
    - ...
    - *cost!*

$\Rightarrow$ no fully optimal solution

- **Design guidelines**
  - Survey of existing technologies
  - Collaboration with industry $\Rightarrow$ 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