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Performance of Hybrid Photon Detectors with 80% active area for the RICH counters of LHCb

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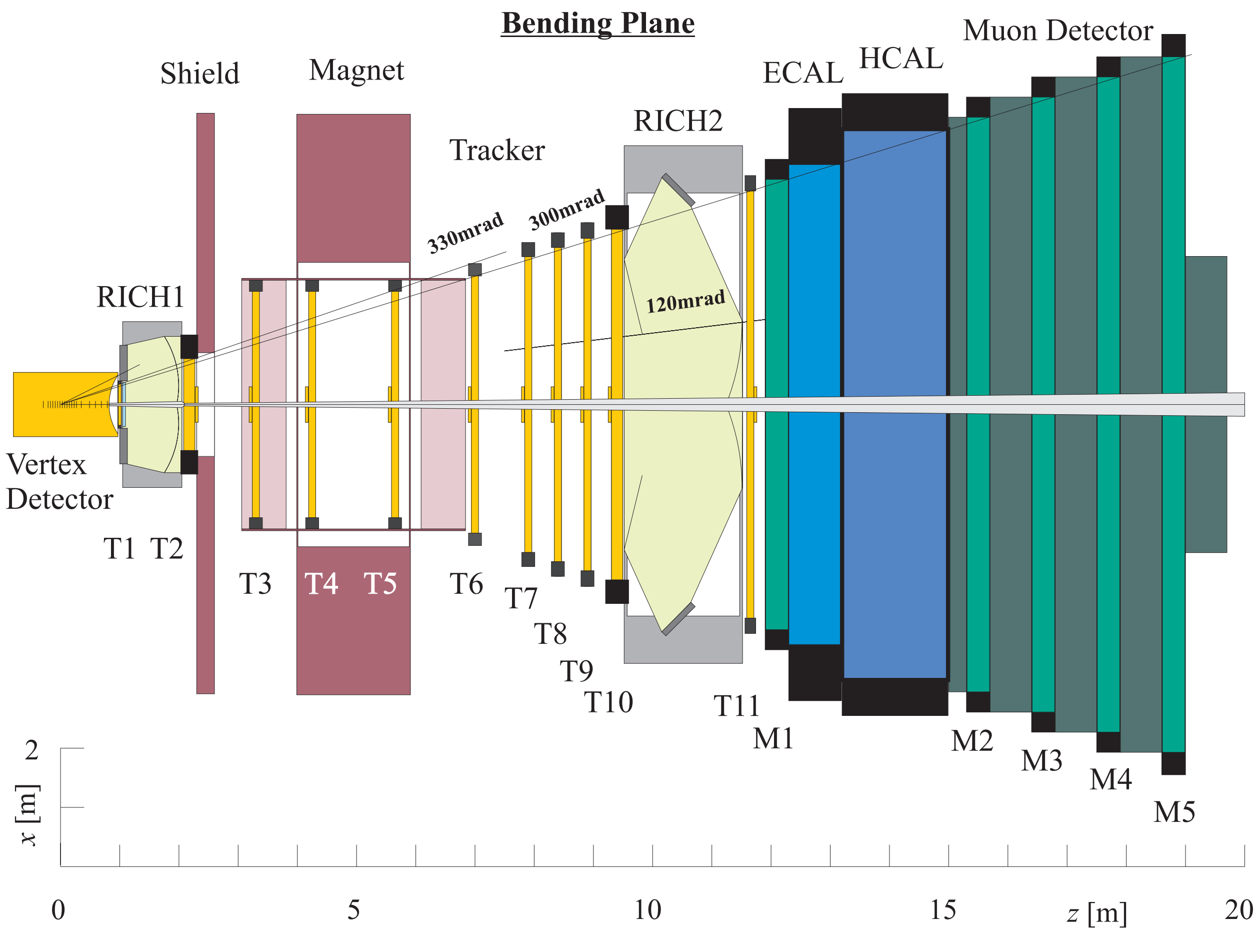
Outline of the talk

- **Introduction**
  - The LHCb detector
  - Overall RICH system requirements
- **The pixel-HPD**
  - Basic principle
  - Half-scale prototype
- **Full-scale tube developments**
  - Baseline dimensions
  - Phosphor screen version
  - 61-pixel HPD version
- **HPD cluster test in RICH1 prototype**
  - Experimental setup
  - C_4F_{10} Cherenkov ring detection
- **Front-end and readout electronics**
  - Pixel architecture
  - Current status
- **Conclusions**

The LHCb detector

LHCb is a single-arm spectrometer with a forward angular coverage from 10 to 300 mrad, dedicated to precision studies of CP asymmetries and of rare decays in the B-meson system

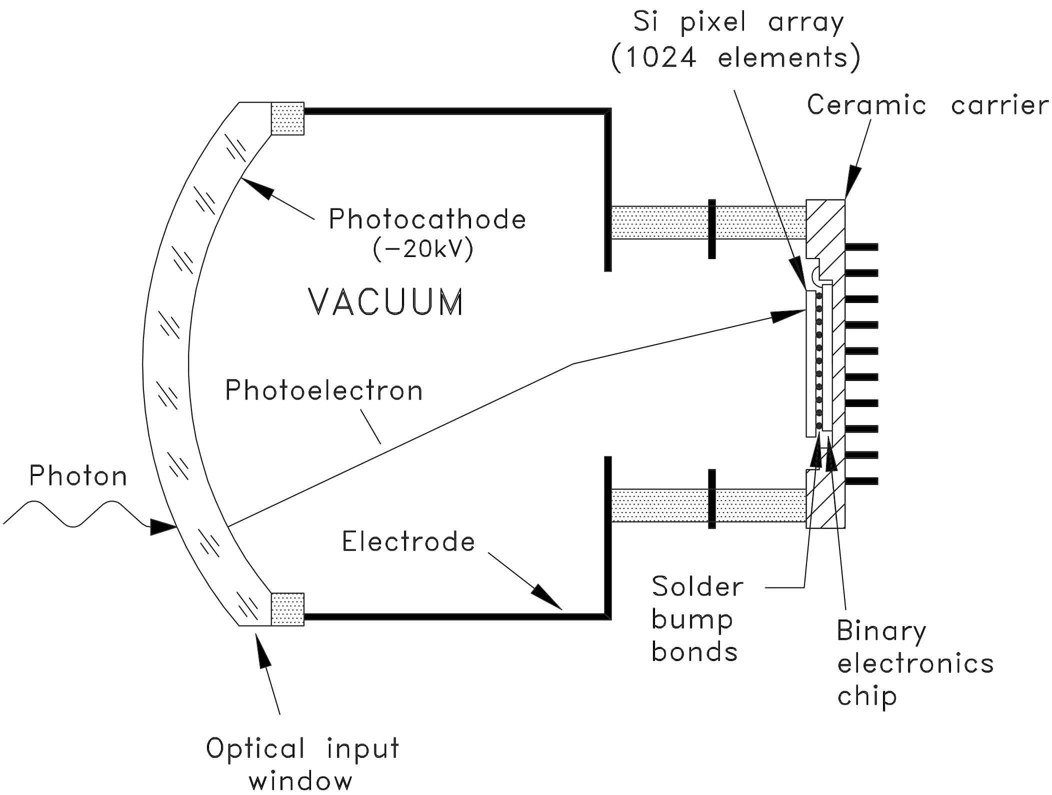


Particle identification over the momentum range 1-150 GeV/c will be achieved by two Ring Imaging CHerenkov (RICH) counters

Overall RICH system requirements

- **Photon detection**
  - ~2.9 m^2 total surface
  - Granularity: 2.5×2.5 mm^2
  - Active area coverage $\geq$ 70 % (~340'000 channels)
  - Single-photon sensitivity (λ = 200-600 nm)
- **Environment**
  - Magnetic stray field: $\leq$ 100 gauss (without shielding)
  - Radiation dose: $\leq$ 3 kRad/year
- **Read-out**
  - Maximum occupancy: $\leq$ 10 %
  - BCO identification ($\tau_s \approx$ 25 ns)
  - High L0-trigger rate (1 MHz)
- **Photo-detector options**
  - Pixel-HPD: cross-focussing geometry, enclosed binary pixel readout (this talk)
  - Pad-HPD: "fountain" tube geometry, enclosed analogue pad readout (see talk E2 by F. Filthaut)
  - Multi-anode PMT: metal channel dynodes external analogue readout

The pixel-HPD
(basic principle)



<u>Main features:</u>

- Cross-focussed electron optics
  - good spatial resolution
  - allow tube close packing and magnetic shielding

- Enclosed binary front-end electronics
  - high signal-to-noise ratio
  - limited number of feed-throughs
  - simpler readout electronics

<u>Prototype tube development:</u>

Close collaboration with industry

Half-scale prototype tube (fully tested in 1998)

- **Baseline design:**
  - Tube features
    - 40:11 mm cross-focussed electron optics
    - 30 μm RMS point spread function
    - S20 (multi-alkali) photo-cathode
    - 20 kV nominal potential (5000 e^-- h pairs)
  - LHC1 binary front-end electronics chip
    - 100 ns peaking time
    - comparator threshold:

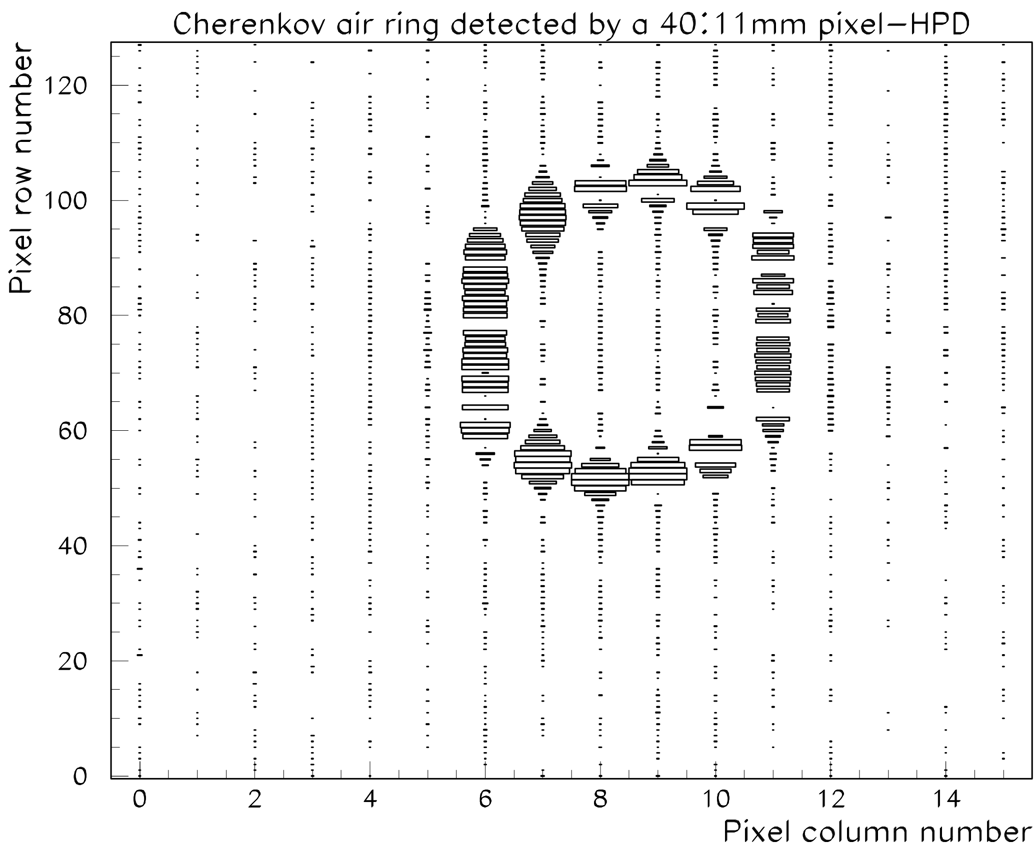
      3000 e^- average minimum
      500 e^- RMS spread

- **Electron optics performance:**
  - Design confirmed

- **Single photoelectron detection efficiency:**
  - ε = 81 %

    (for pixels sensitive at 20 kV)

Half-scale prototype tube
(1998 beam test results)



<u>Figure of merit for Cherenkov light detection:</u>

$90\ \text{cm}^{-1} \leq N_0 \leq 120\ \text{cm}^{-1}$

$N_0 = N_{pe}/(L \times \sin^2\theta_c)$

(air radiator, 1/4 scale prototype of RICH1)

Full-scale prototype tube

- **Baseline design**
  - Improved electron optics (tetrode structure)

    ⇒ ~ 80 % active area

  - 72:18 mm cross-focussed electron optics
  - 40 μm RMS point spread function
  - S20 (multi-alkali) photo-cathode
  - 20 kV nominal potential (5000 e^-- h pairs)

    ⇒ ~ 500 tubes for the entire RICH system

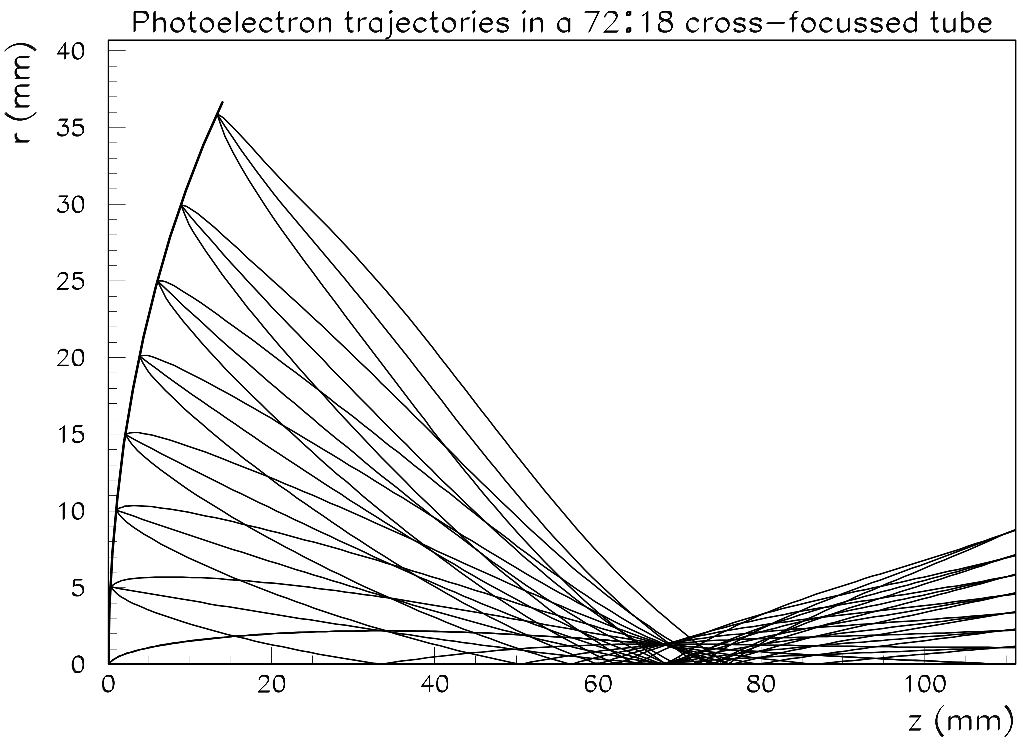
- **First prototype**
  - Phosphor screen anode
  - CCD readout

    ⇒ check of active area, electron-optics, photo-cathode uniformity, magnetic field sensitivity and shielding options.

- **Second prototype**
  - 61-pixels anode
  - external VA2 front-end (1.2 μs peaking time)

    ⇒ check of response to Cherenkov light, installation of a 3-HPD cluster in the LHCb-RICH prototype.

Cross-focussed optics (simulated)



Radial (vertical) dimension stretched for clarity
Only one tube half shown

Photoelectrons emitted with 1 eV energy,
0° and ±45° angle wrt normal to the pK

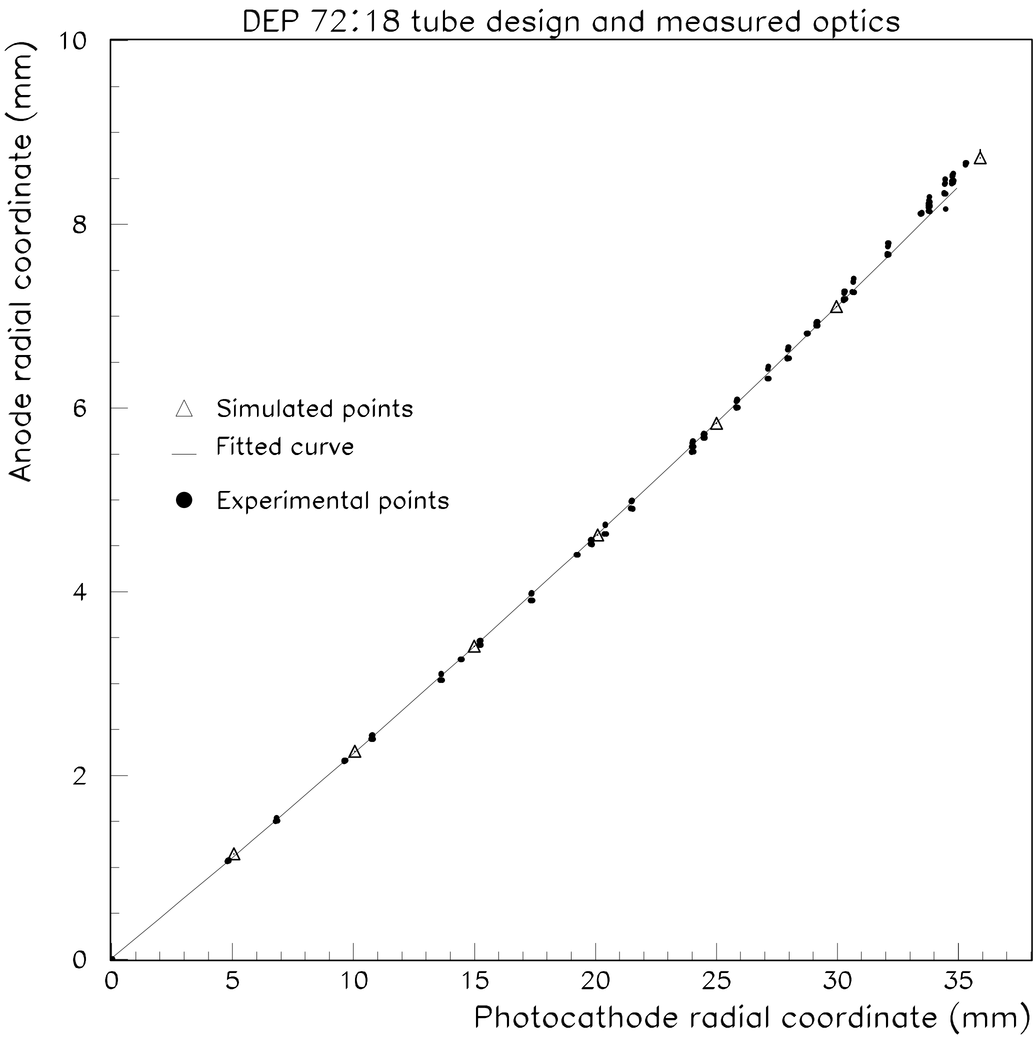
Demagnification ≈ 4:1
Edge distortion ≈ 11 %
Point spread function ≈ 40 µm RMS

Phosphor screen prototype (photograph)

Preliminary tests at the factory:

20 kV high voltage operation
19 % QE @ λ = 400 nm
Point spread function: 35 μm RMS (on-axis)
47 μm RMS (edge)

Phosphor screen prototype (electron optics performance)

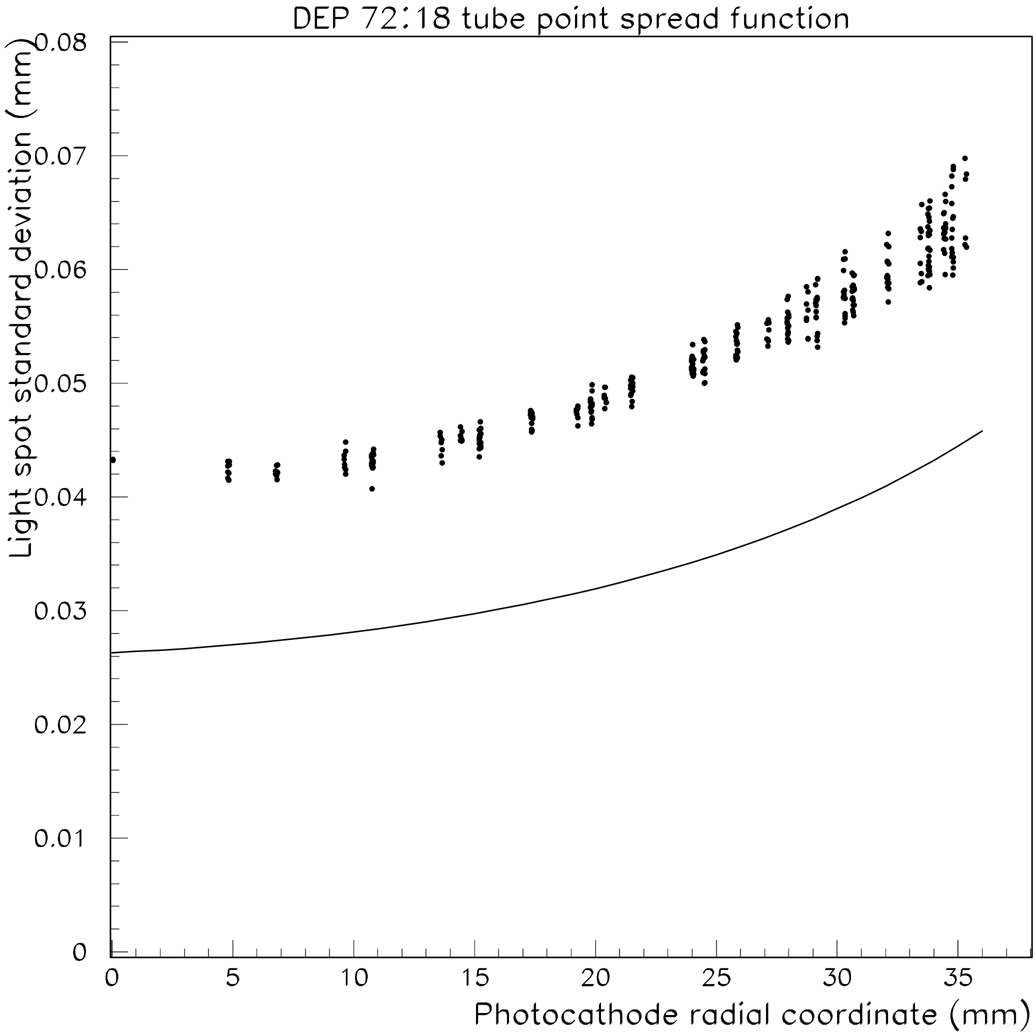


LED spot scan (~200 measurement points):

Active area: $(75/83)^2 = 81.7$ %
(including window lens effect)

Demagnification: 0.216 (on-axis)
0.245 (edge)

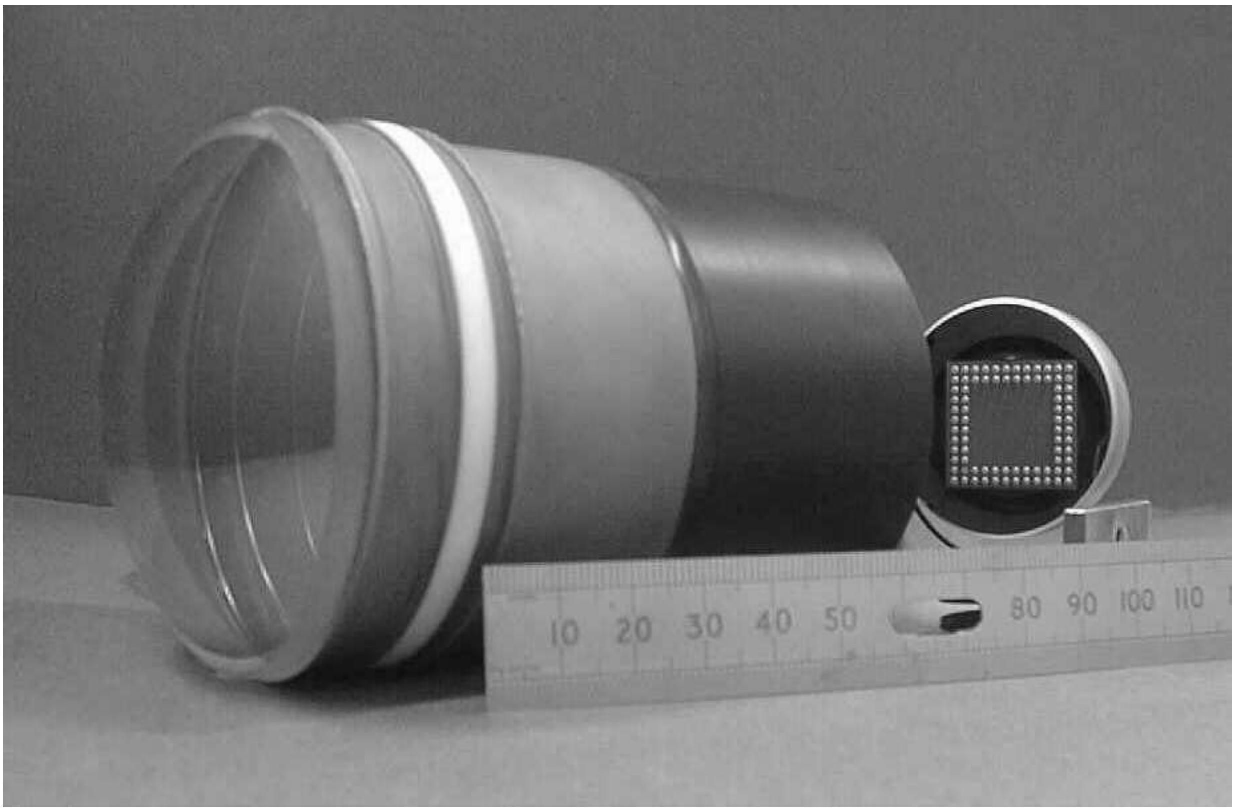
Phosphor screen prototype (point spread function)



<u>LED spot scan (~200 measurement points):</u>

Point spread function: 33 µm RMS (on-axis)
54 µm RMS (edge)
CCD pixel size: 11 µm RMS
LED spot size: 25 µm RMS (on-axis)

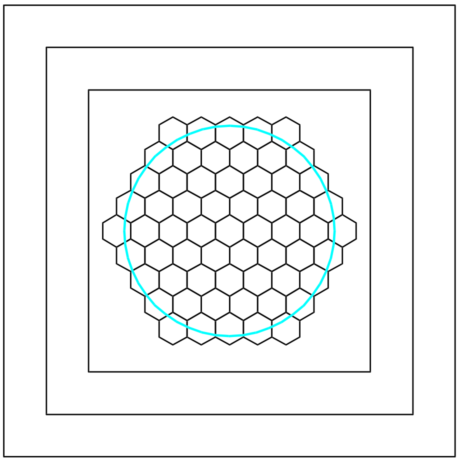
61-pixel HPD prototype (photograph)



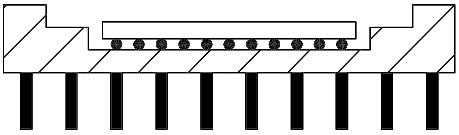
<u>Preliminary tests at the factory:</u>

20 kV high voltage operation
16 % ≤ QE ≤ 20 % @ λ = 400 nm
(can be optimized for Cherenkov light detection)
Leakage current per pixel: ~ 0.2 nA typical

61-pixel HPD prototype
(anode configuration)



TOP
VIEW



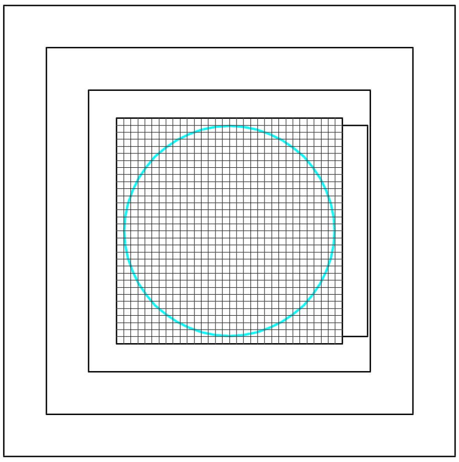
SIDE
VIEW

Present configuration:

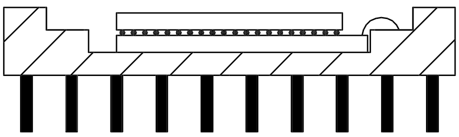
Silicon detector:
- 61 hexagonal pixels
- each ~ 2 mm in size

$\Rightarrow$ ~ 10 mm granularity

Front-end electronics:
- External
- Analogue (VA2)
- 1.2 µs peaking time



TOP
VIEW



SIDE
VIEW

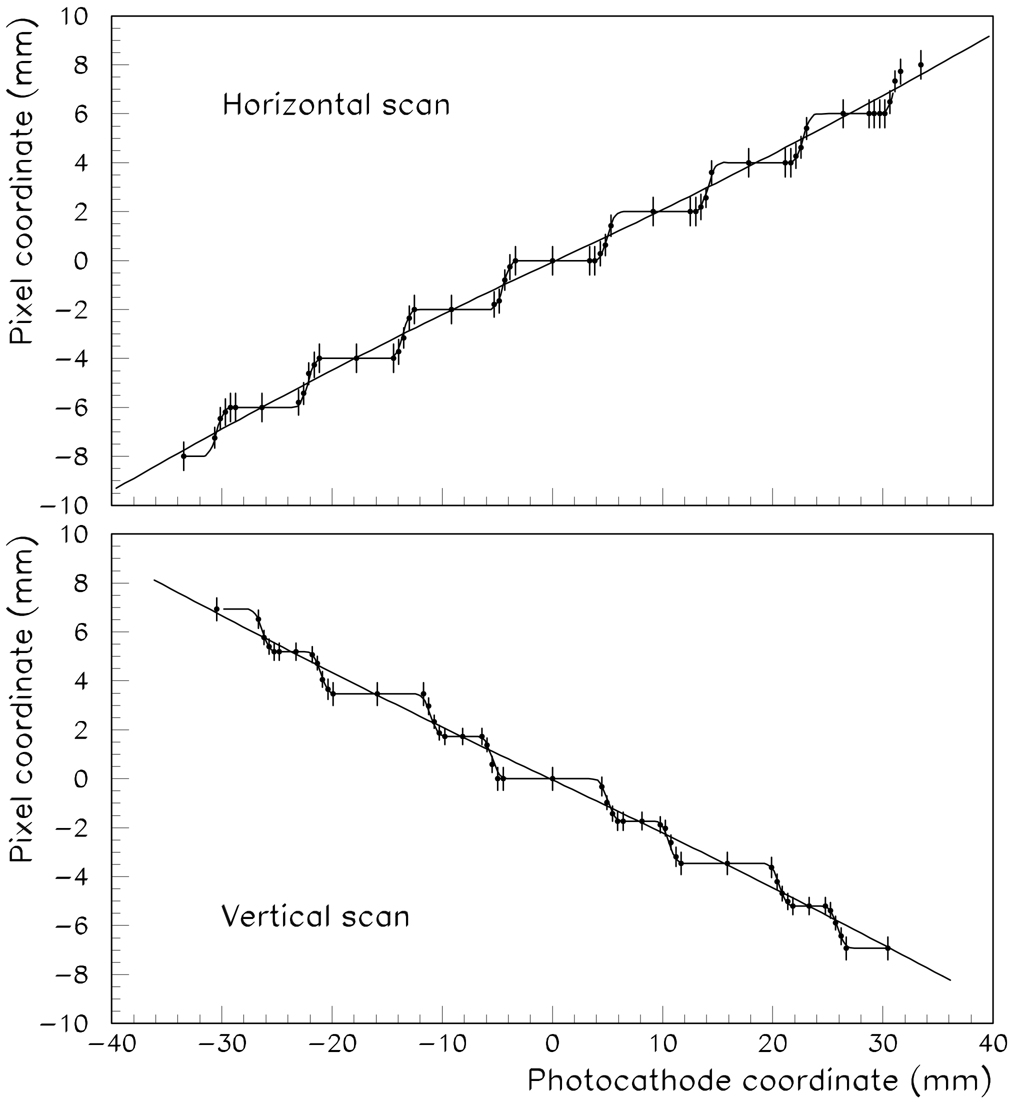
Final configuration:

Silicon detector:
- 1024 square pixels
- each 500 µm in size

$\Rightarrow$ ~ 2.5 mm granularity

Front-end electronics:
- Enclosed
- Binary (Alice-LHCb chip)
- 25 ns peaking time

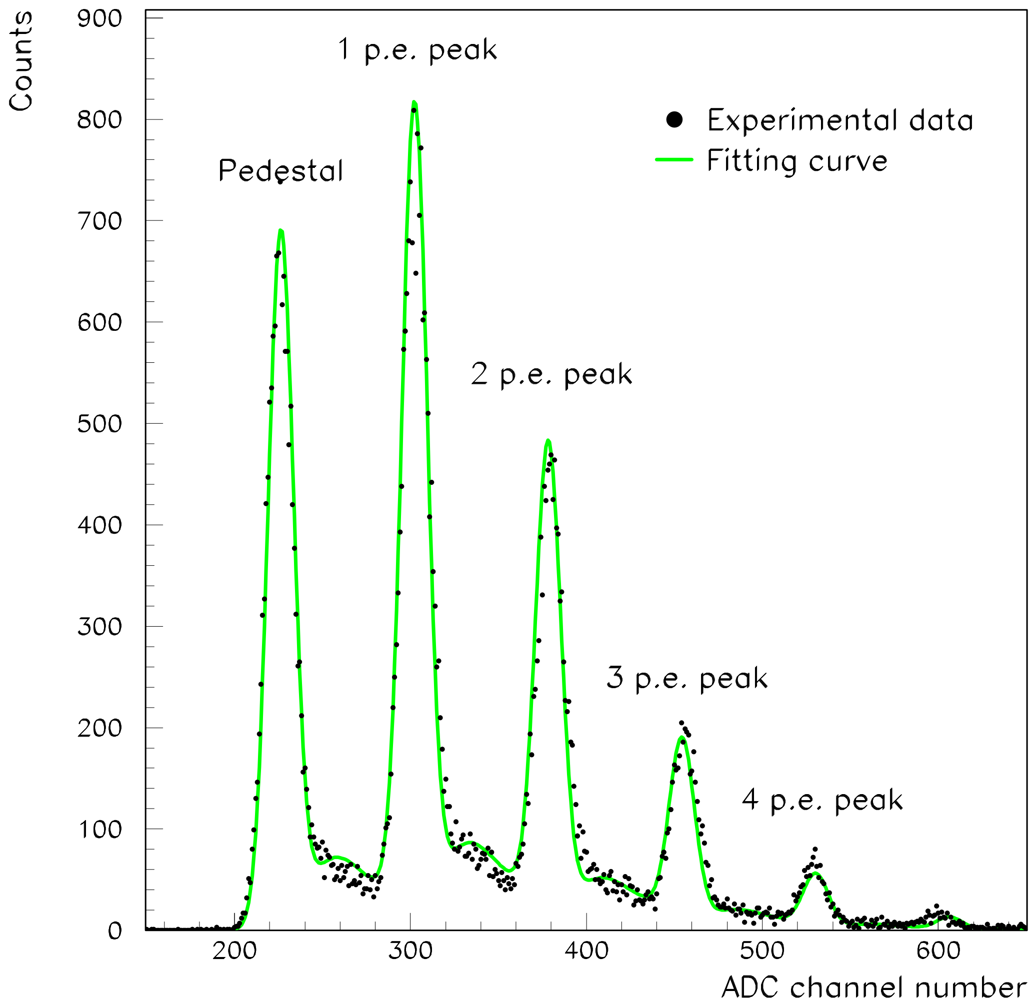
61-pixel HPD prototype (electron optics performance)



LED spot scan (~2 × 50 measurement points):

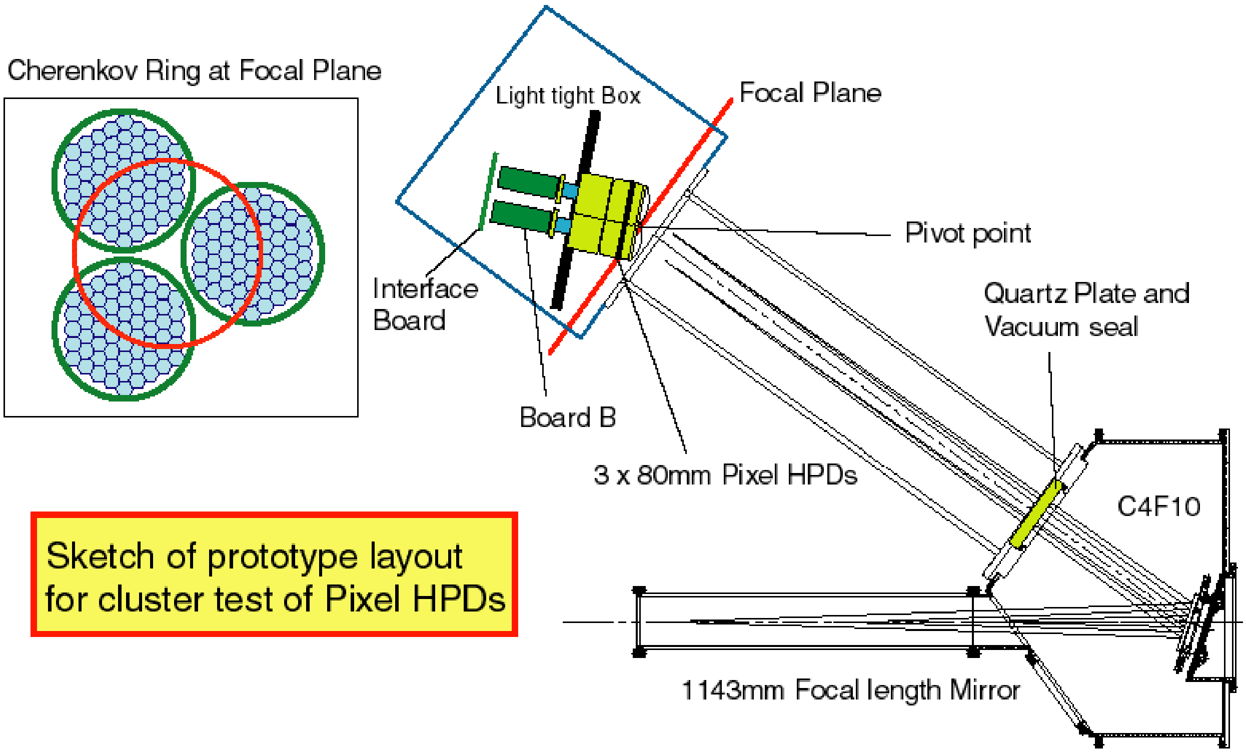
Design values confirmed

61-pixel HPD prototype (single photoelectron response)



Typical signal-to-noise ratio ≈ 11
(External VA2 front-end electronics,
1.2 µs peaking time)

HPD cluster test in RICH1 (experimental setup)



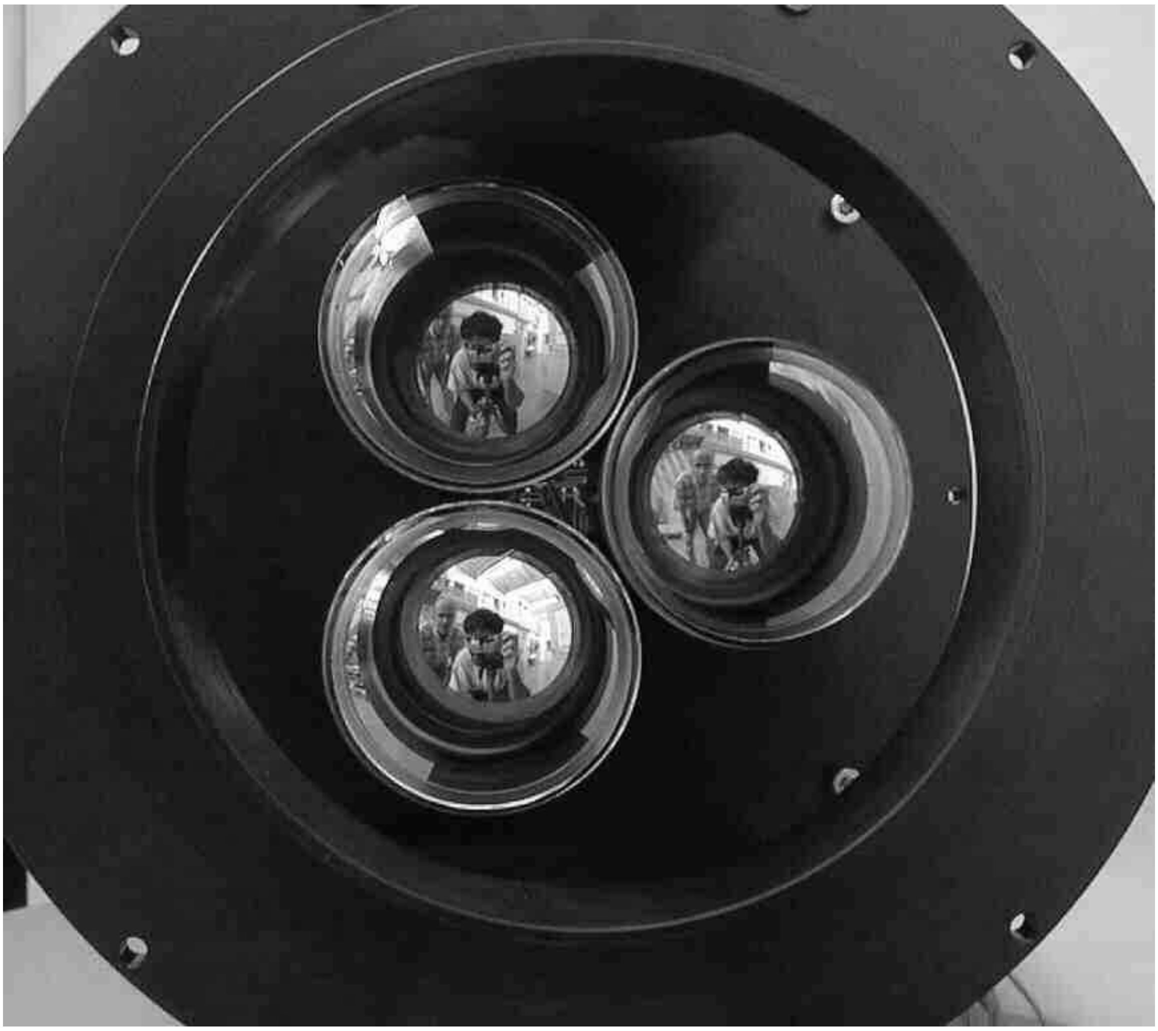
Cherenkov angle is 53 mrad with C4F10 radiator at 1000mbar

n.b This sketch is NOT an engineering drawing

Particle beam: 120 GeV/c π^-

Gas radiator: C_4F_{10} , 100 cm length

HPD cluster test in RICH1 (photograph)



Total sensitive surface ≥ 135 cm^2

Tube separation: 2 mm

Nominal operating voltage: 20 kV

HPD cluster test in RICH1 (C_4F_{10} Cherenkov rings)

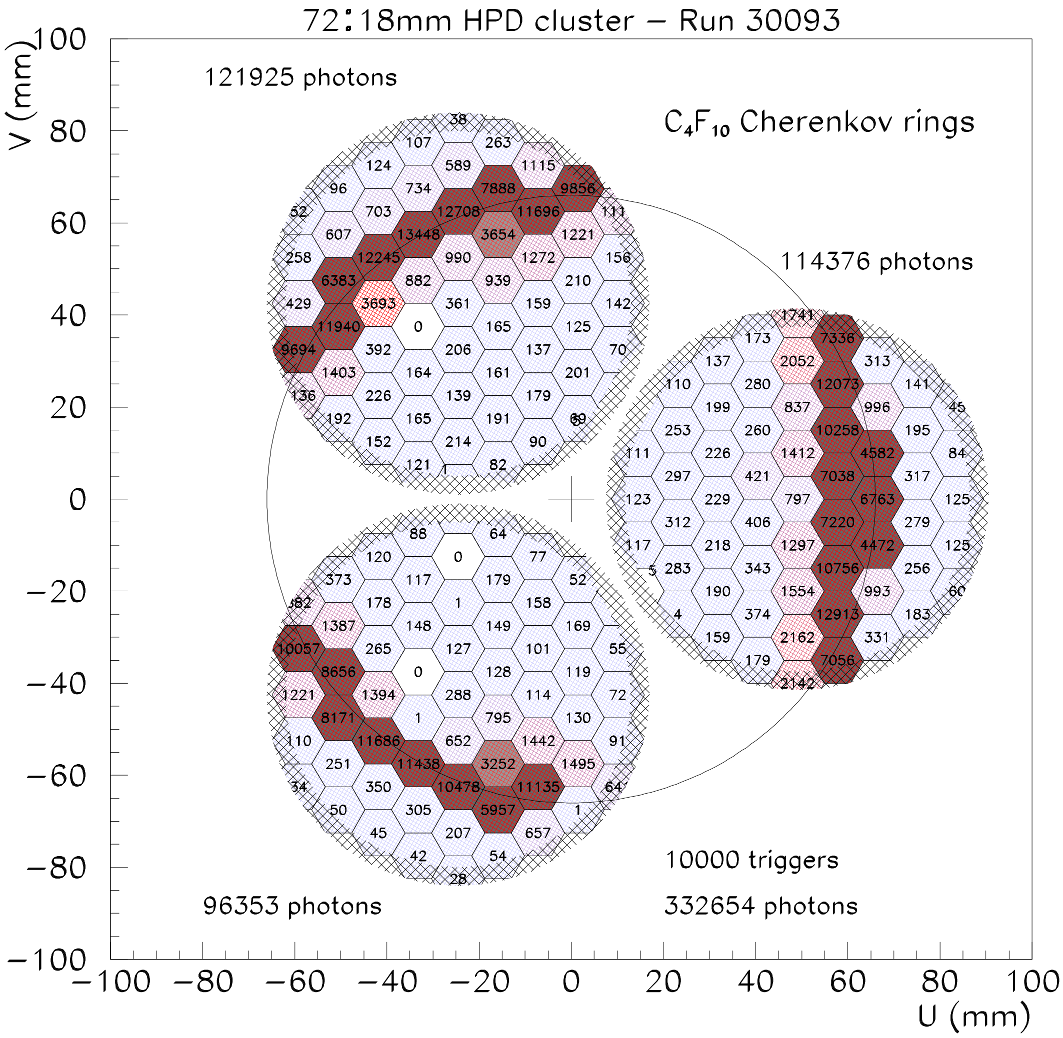
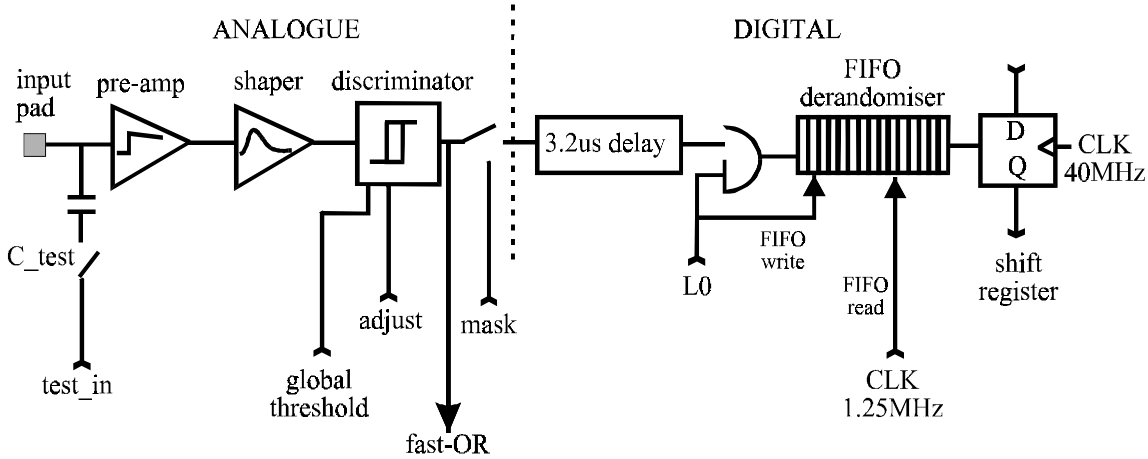


Figure of merit for Cherenkov light detection:

$N_0 \approx 190\ \mathrm{cm}^{-1}$ (very preliminary estimate)

Pixel cell



◆ Specifications

- **Analogue**
  - **25 ns peaking time**
  - **Low (2000 e-) and uniform (200 e- RMS) discriminator threshold**
- **Digital**
  - **3.2 µs delay with 25 ns precision**
  - **16-event de-randomizing buffer**
  - **Column shift register clocked at 40 MHz**

- **Radiation tolerant to 30 krad**

- **Low power consumption < 80 µW per channel (i.e. ~ 600 µW per pixel)**

Current status for electronics

- **Reliability of pixel chips inside vacuum**
  - Bake-out cycles
  - Outgassing
  - Bump- and wire-bonding
  - Power consumption

  $\Rightarrow$ results are encouraging

- **Analogue + digital developments**
  - 25 ns peaking time achieved on 0.5 µm Alice test chip
  - 1500 e^- threshold, 160 e^- RMS (25 e^- with 3-bit adjustment) measured on 0.25 µm Alice test chip
  - 0.25 µm test chip radiation tolerant up to 30 Mrad
  - Digital delay functional

Conclusions

- **Full-scale prototype tube**
  - Improved electron optics provide:
    - large sensitive area (~45 cm^2)
    - high active-to-total area ratio (~80%)
  - Both phosphor screen and 61-pixel versions perform as expected
  - Single-photoelectron response:
    - typical signal-to-noise ratio ≈ 11 (with 61-pixel anode and external VA2 front-end electronics)

- **HPD cluster test in RICH1 prototype**
  - Successful operation in real environment
  - C_4F_{10} Cherenkov rings detected
  - Figure of merit $N_0 \approx 190\ cm^{-1}$ (preliminary)

- **Pixel front-end and readout electronics**
  - 1998 pixel developments meet LHCb requirements
  - Chip currently under design compatible with LHCb and Alice operation