Hybrid Photon Detectors (HPD)

&

Multi Anode Photo Multiplier Tubes (MAPMT)

C. Joram, CERN EP

Direct collaborators in HPD development at CERN:

A. Braem, C. Chesi J. Séguinot, P. Weilhammer

Thanks for excellent (PPT) material to

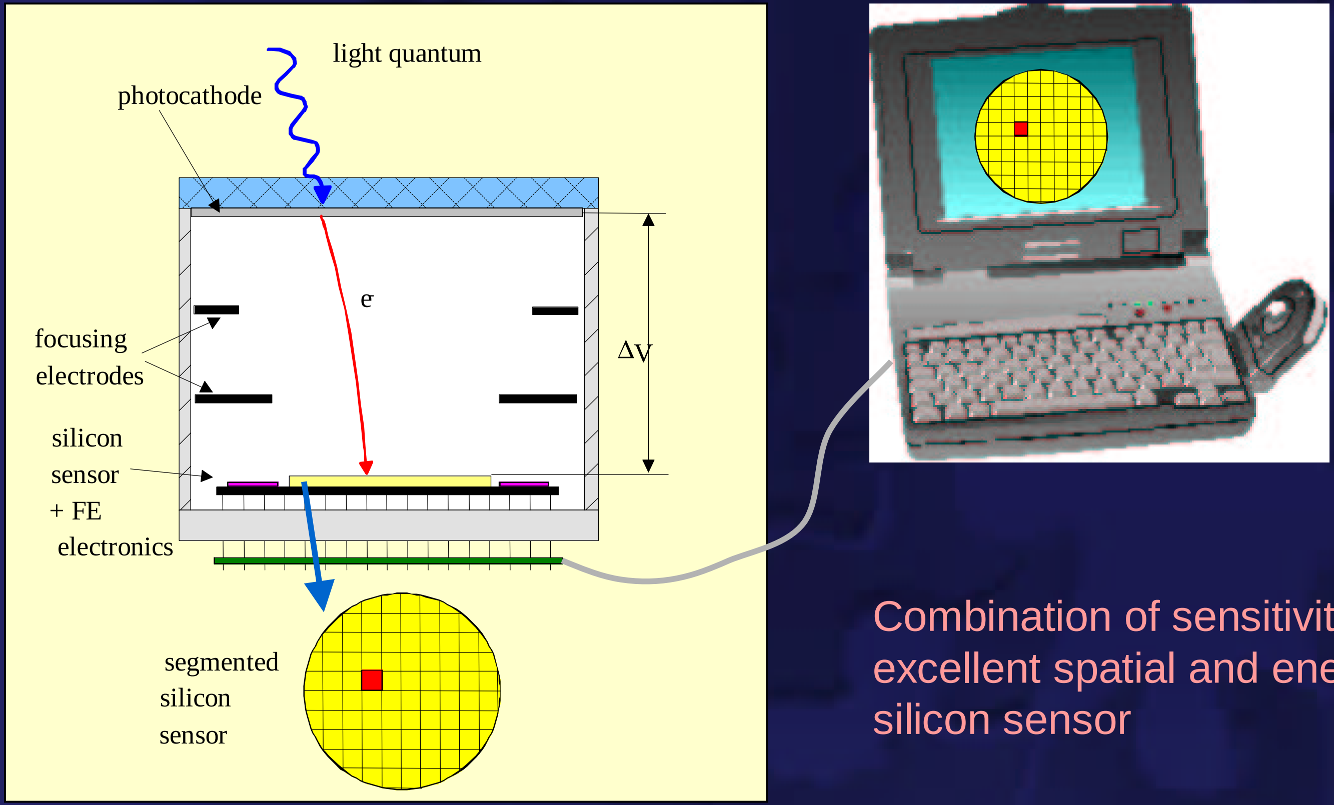
Priscilla Cushman (Minnesota): HPDs for CMS HCAL readout
Thierry Gys (CERN): Pixel HPD for LHCb RICH
Franz Müheim (Glasgow): MAPMT for LHCb RICH
Ray Mountain (Syracuse): BTEV RICH
Roberto Pani (Rome), Flat Panel PMTs

Outline

- HPDs
  - Principle and limitations
  - Recent and ongoing developments in HEP
  - Development of a 10-inch HPD for astrophysics
  - Development of an HPD for medical imaging

- MAPMTs
  - Principle and limitations
  - The LHCb RICH with MAPMT readout
  - Flat Panel PMTs

Hybrid Photon Detectors (HPD)



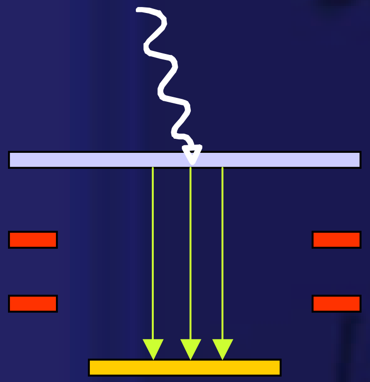
Combination of sensitivity of PMT with excellent spatial and energy resolution of silicon sensor

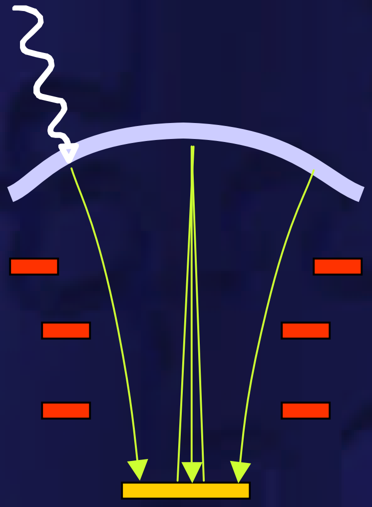
Gain: $G \approx \frac{e \cdot U_C}{3.6\,\mathrm{eV}}$ U_C = 20 kV → G ~ 5000

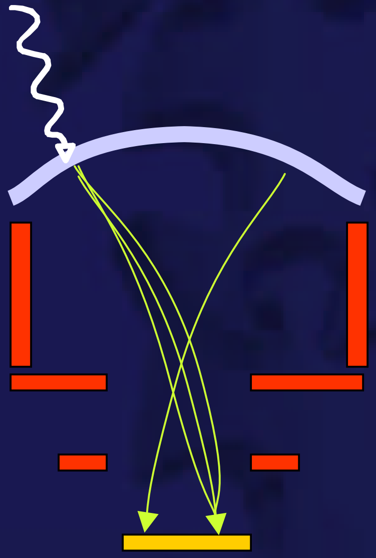
Gain is achieved in a single dissipative step !

$\sigma_G \approx \sqrt{F \cdot G}$ small compared to $\sigma_{\mathrm{electronics}}$

Classical HPD designs







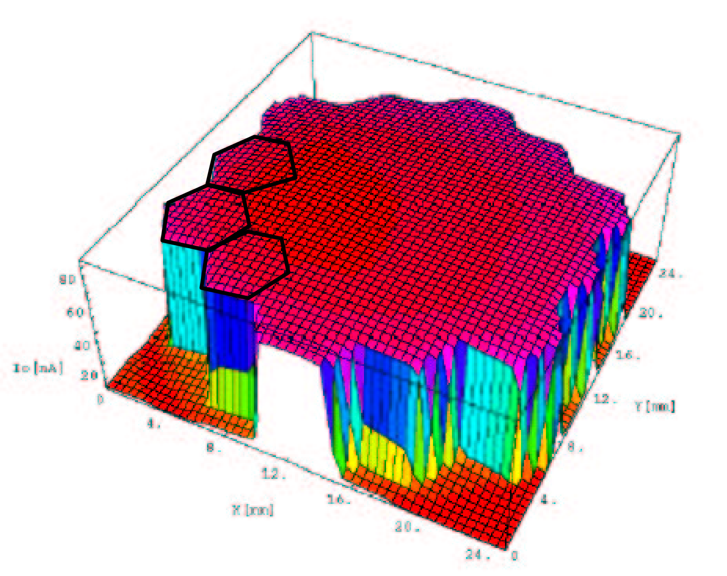
- Proximity focused
- 1:1 imaging
- Operates in axial magnetic fields.

- ‘Fountain’ focused
- Demagnification D
- No real focusing → ballistic point spread
- Intolerant to magnetic fields

- ‘Cross’ focused
- Demagnification D
- Focusing leads to small point spread
- Intolerant to magnetic fields

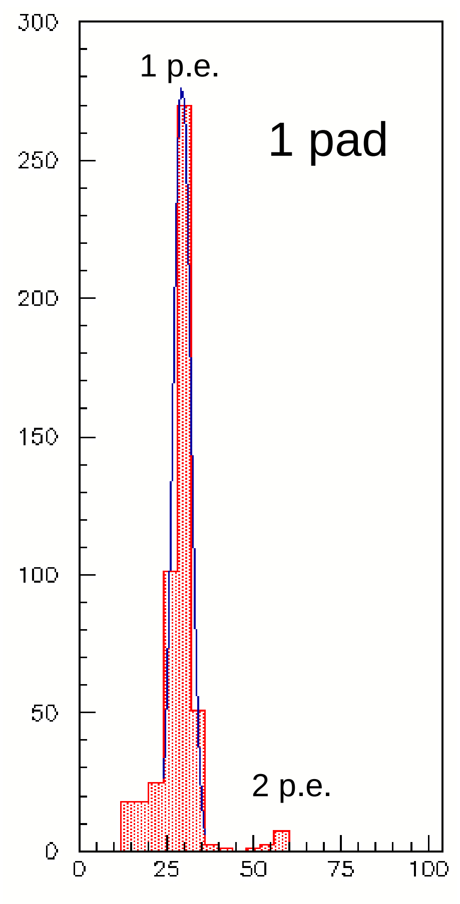
Main advantages of HPD technology

- Excellent signal definition
- Allows for photon counting
- Free choice of segmentation (50 µm - 10 mm)
- Uniform sensitivity and gain
- no dead zones between pixels



CMS HCAL
19-pixel HPD
(DEP, NL)

10-inch TOM HPD (U_C = -25 kV)

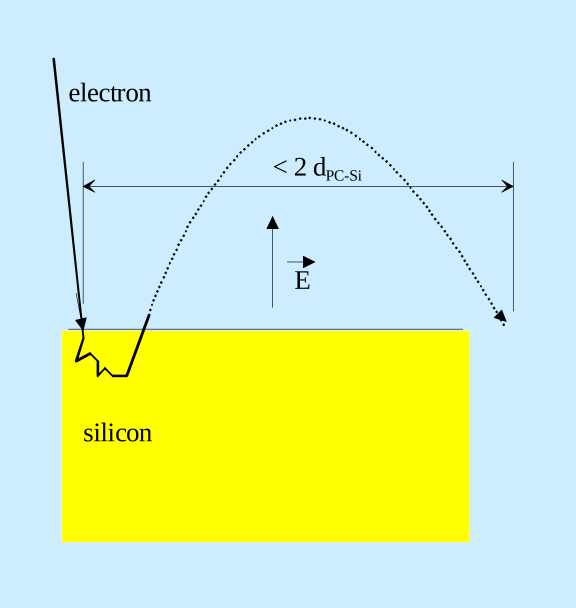


pulse height (ADC counts)

Drawbacks

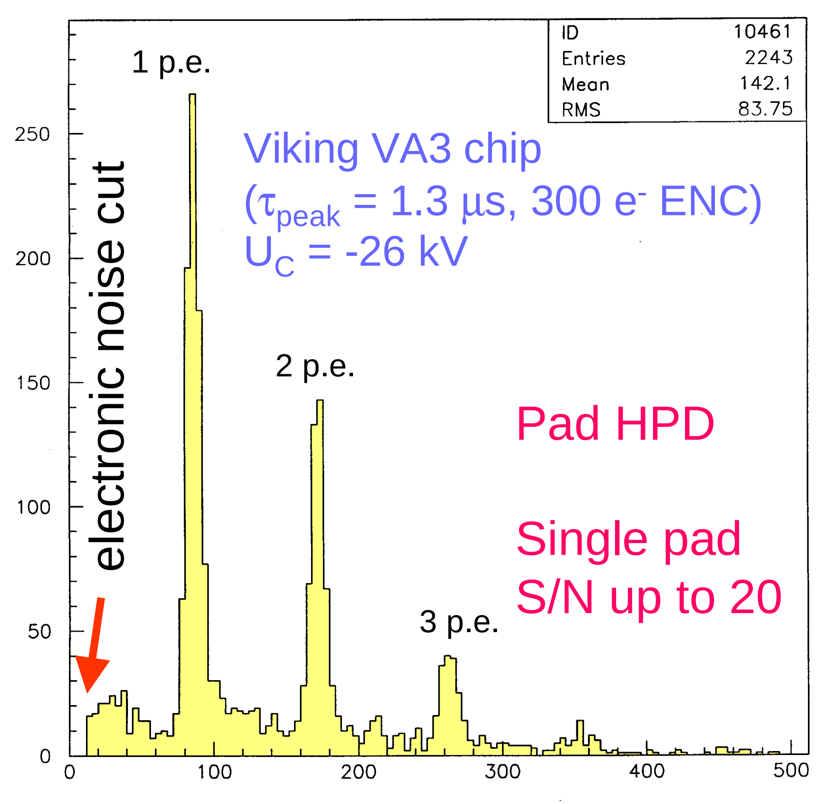
- Rel. low gain (3000 - 8000) → low noise electronics required
- Expressed sensitivity to magnetic fields

- Looking a bit closer: Back scattering of electrons from Si surface



back scattering probability at E ≈ 20 keV: α_{Si} ~ 0.18 - 0.2

~ 20% of the electrons deposit only a fraction 0≤ε<1 of their initial energy in the Si sensor .



Viking VA3 chip
(τ_{peak} = 1.3 µs, 300 e$^-$ ENC)
U$_C$ = -26 kV

Pad HPD

Single pad
S/N up to 20

Consequence 1: Photoelectron charge peaks show low energy shoulder down to Q = 0.
→ p.e. detection efficiency < 1

$$\varepsilon_{det}^{p.e.} = 1 - \frac{n_{\sigma}^{noise}}{(S/N)} \cdot \alpha_{Si}$$

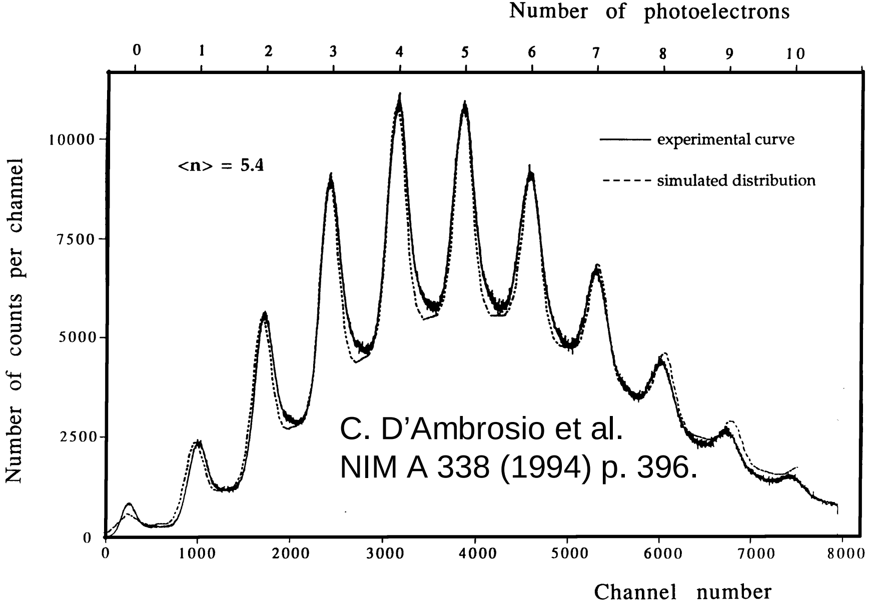
$$\text{example: } n_{\sigma}^{noise} = 4,\ \text{S/N} = 10,\ \varepsilon_{det}^{p.e.} = 0.924$$

Consequence 2

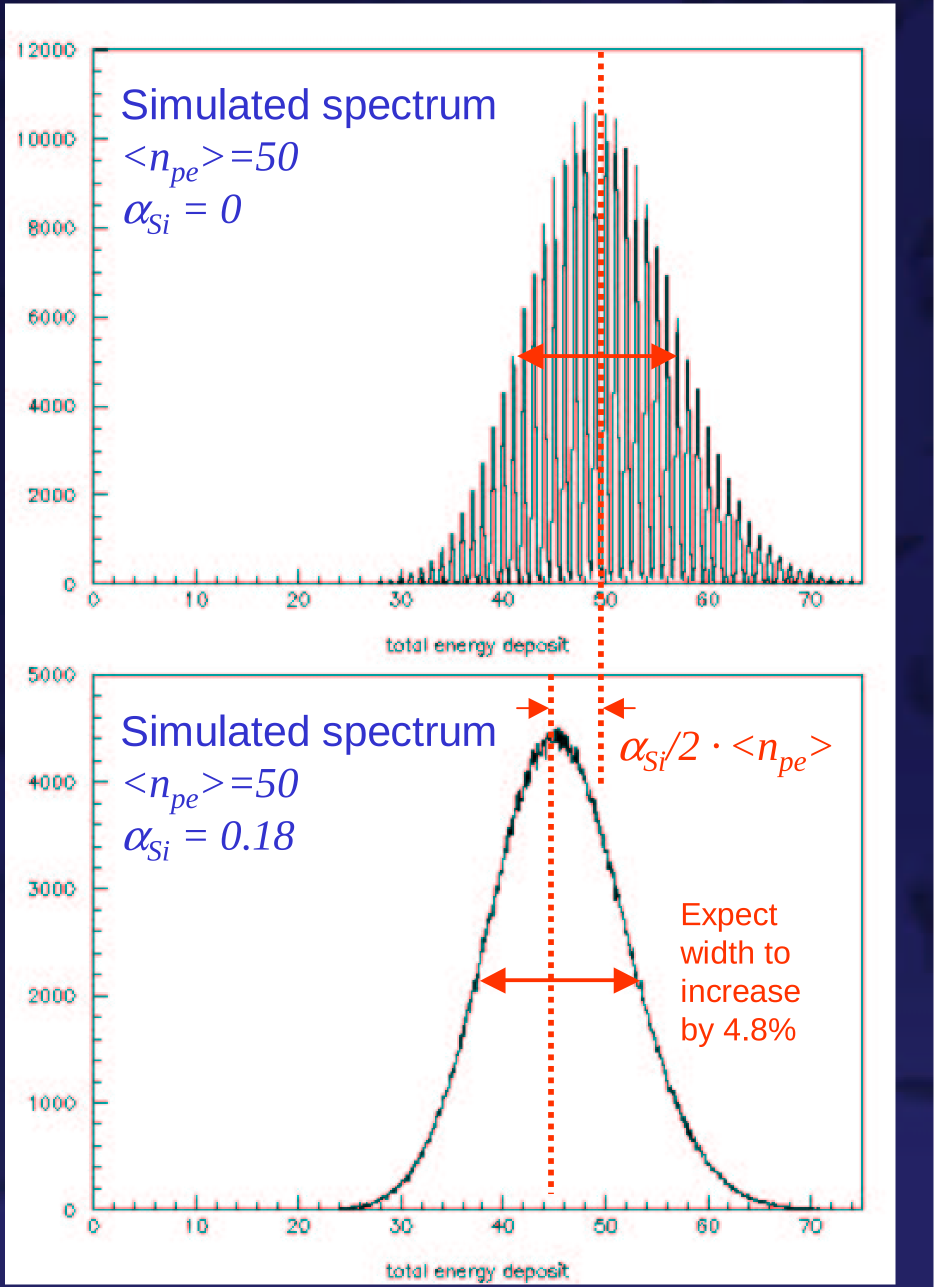
For higher light levels, the back scattering effect leads to “combinatorial continuum” under the peaks.

$\alpha_{Si} \approx 0.2$

Measured spectrum with $<n_{pe}>=5.4$



C. D’Ambrosio et al.
NIM A 338 (1994) p. 396.



Simulated spectrum
$<n_{pe}>=50$
$\alpha_{Si} = 0$

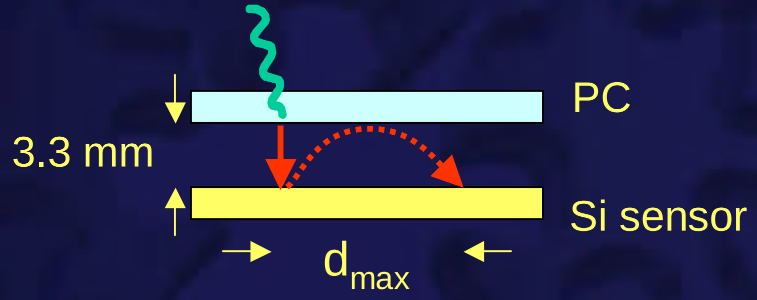
Simulated spectrum
$<n_{pe}>=50$
$\alpha_{Si} = 0.18$

$\alpha_{Si}/2 \cdot <n_{pe}>$

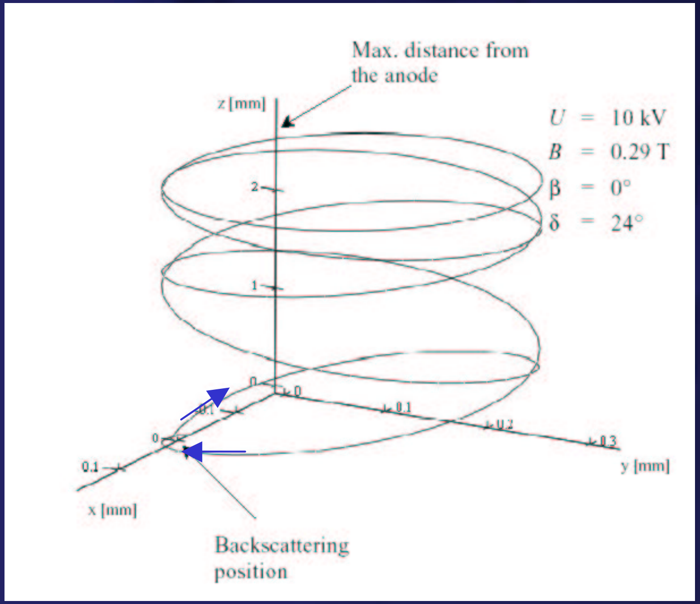
Expect width to increase by 4.8%

Consequence 3: Back scattered electrons can hit another cell of the Si sensor → cross talk

CMS HCAL HPD
Gap: 3.3 mm
→ d_{max} = 6.6 mm (B=0)

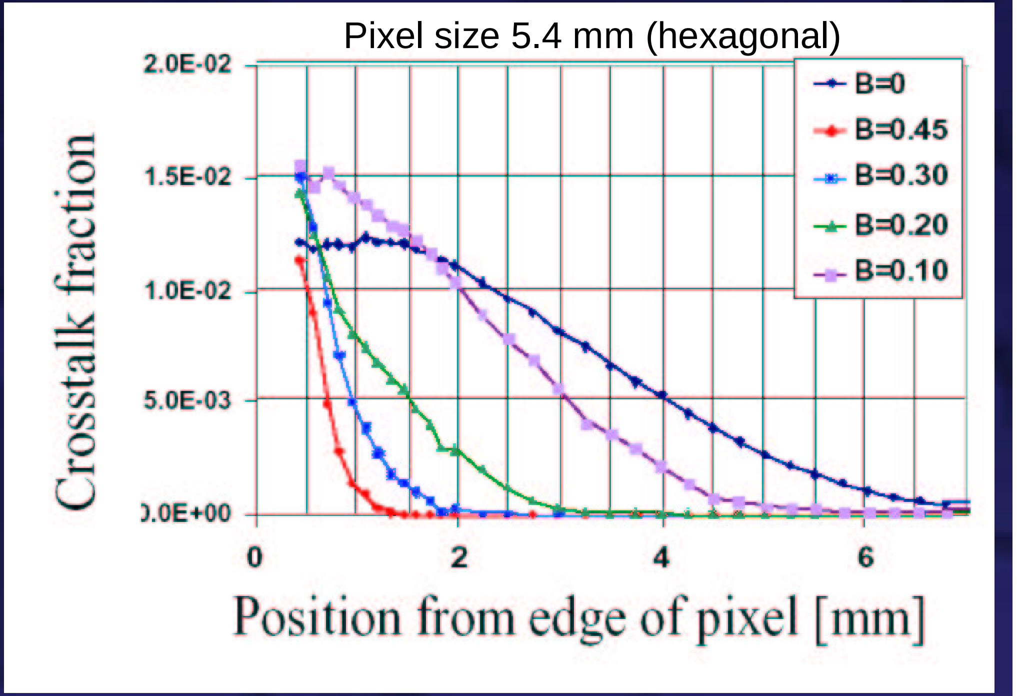


Trajectories can become very complex in presence of magnetic fields.



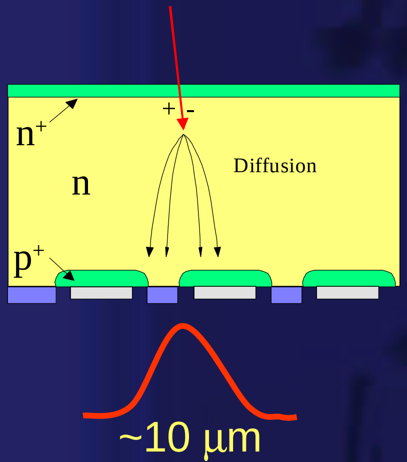
C. D'Ambrosio, H. Leutz, CERN-EP/2002-072

Strong axial magnetic field solves problem completely.

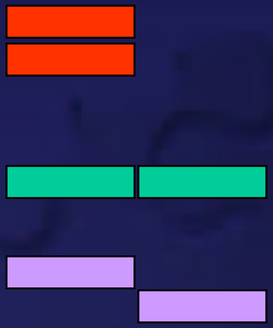


P.B. Cushman and A.H. Heering "CMS HCAL Hybrid Photodiode Design and Quality Assurance Stations". ICFA IB, Vol. 25, 2002

- Looking a bit closer (2): Charge sharing between Si pixels



Only significant for small
(≤ 100 µm) pixels

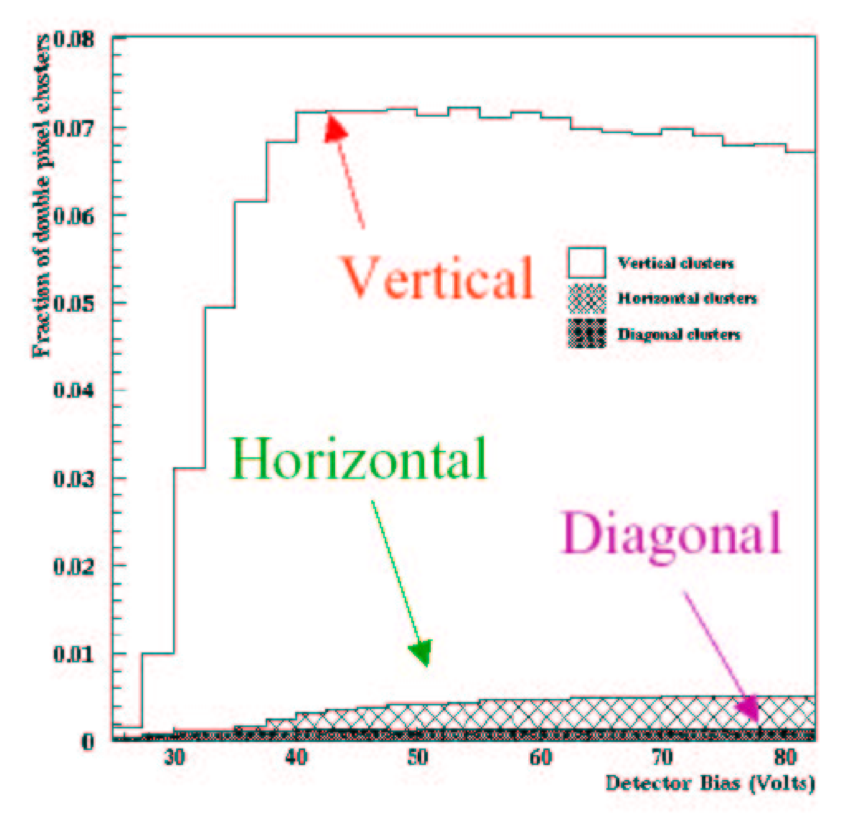


vertical

horizontal

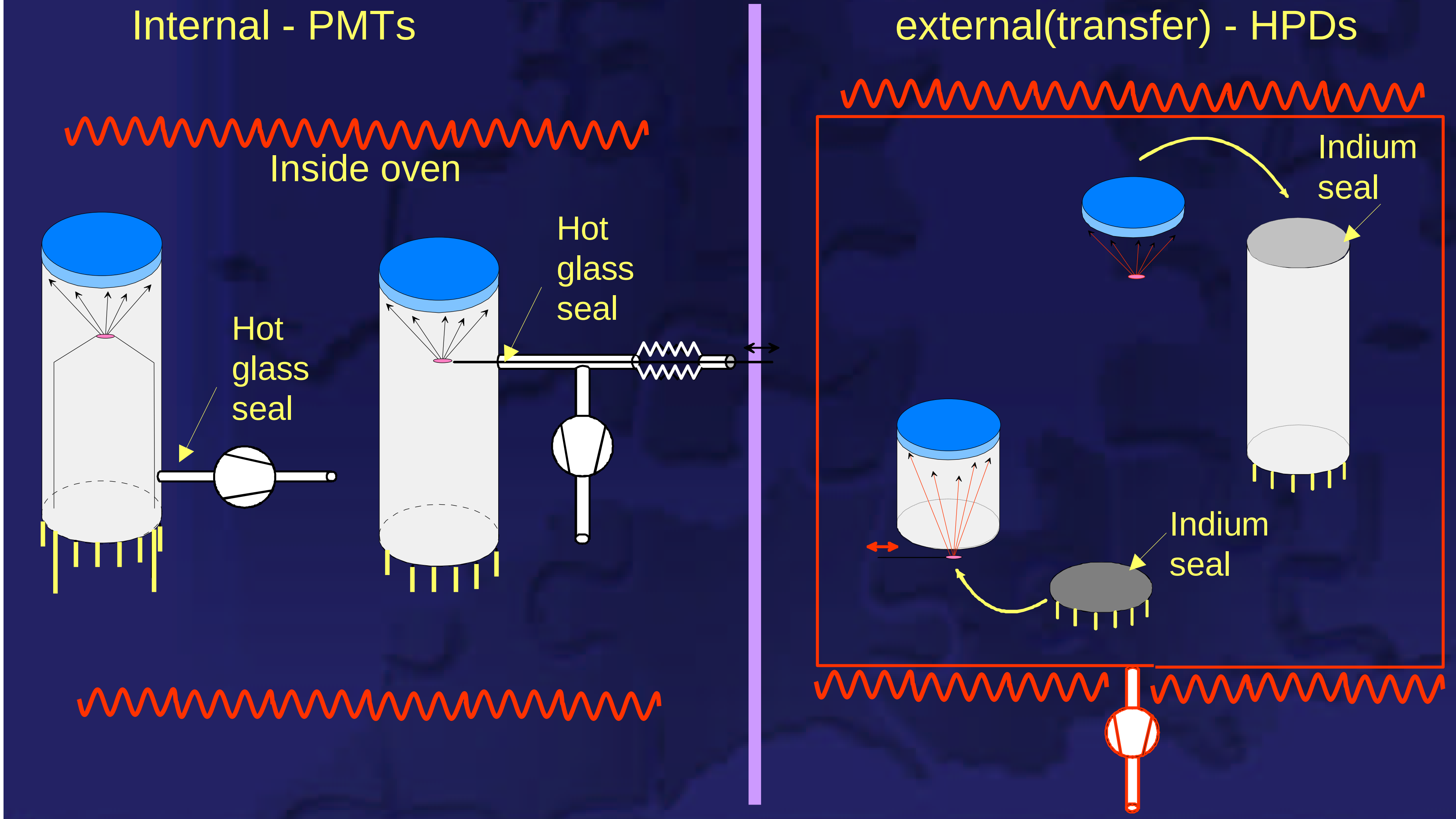
diagonal

Example: LHCb Pixel tube (T. Gys et al.)
Pixel size: 50 x 425 µm



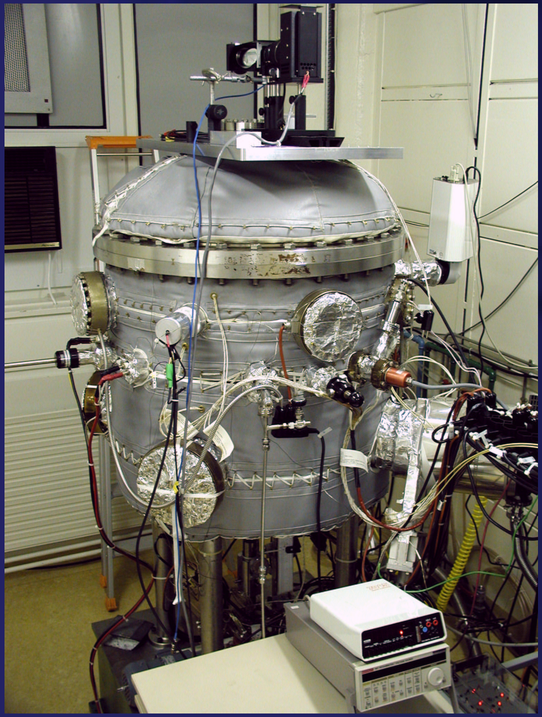
Phototube fabrication

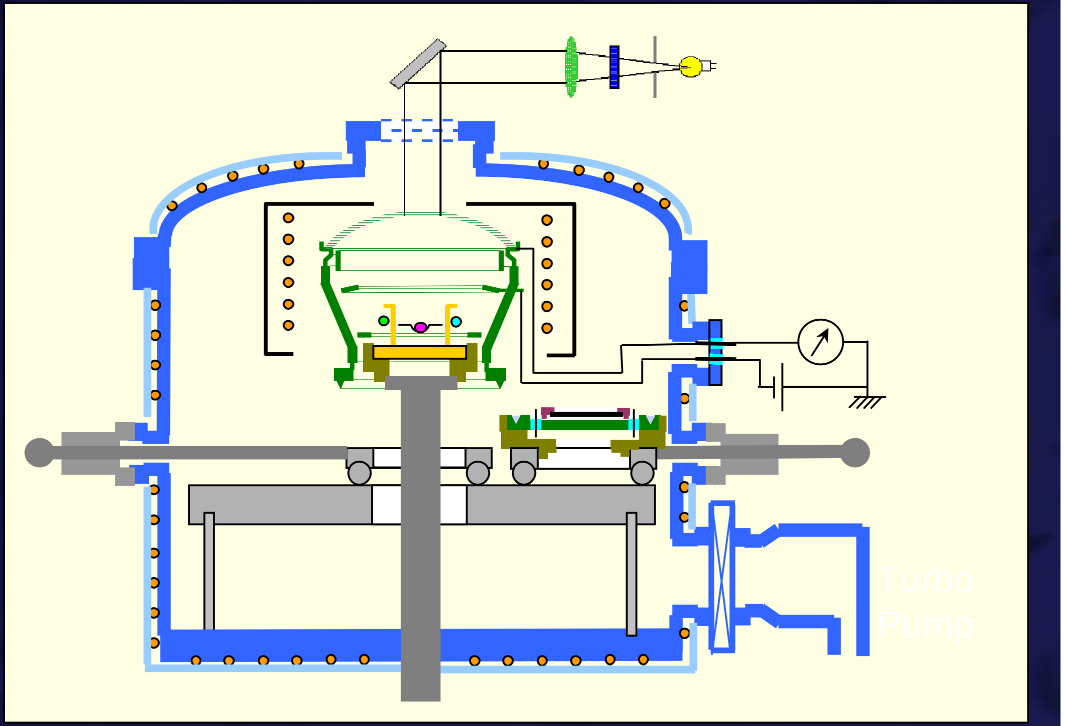
comparison of process types (very schematic)



HPD fabrication @ CERN

Facilities and infrastructure for the fabrication of large HPDs (up to 10”Ø) have been developed at CERN.



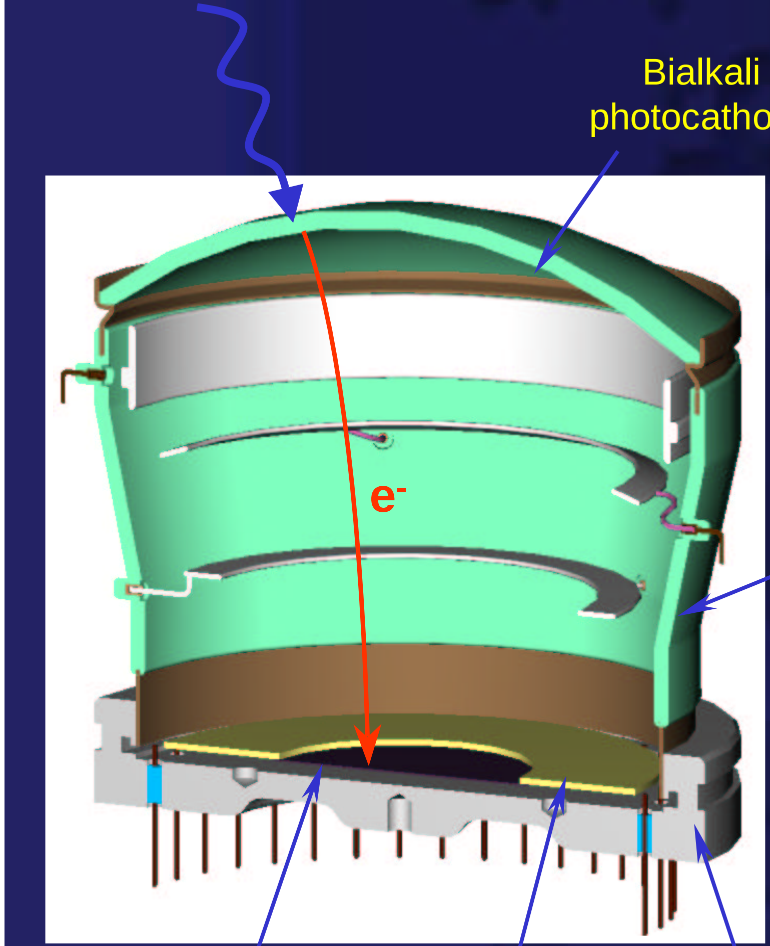


All ingredients for photodetector production are available:

- Design/simulation
- Photocathode processing (bialkali, Rb_2Te, CsI)
- Glass / ceramic tube manufacturing
- Indium sealing technique

The 5-inch Pad HPD

(originally developed for LHCb RICH)



Bialkali photocathode

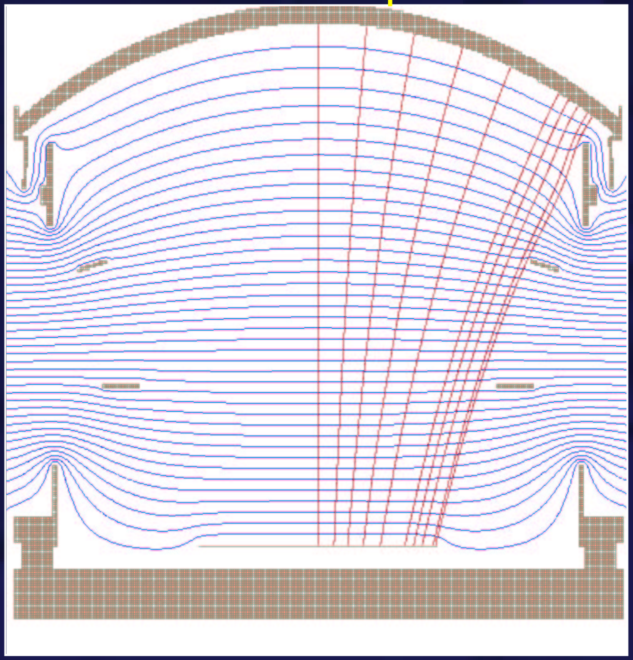
glas body

Si sensor

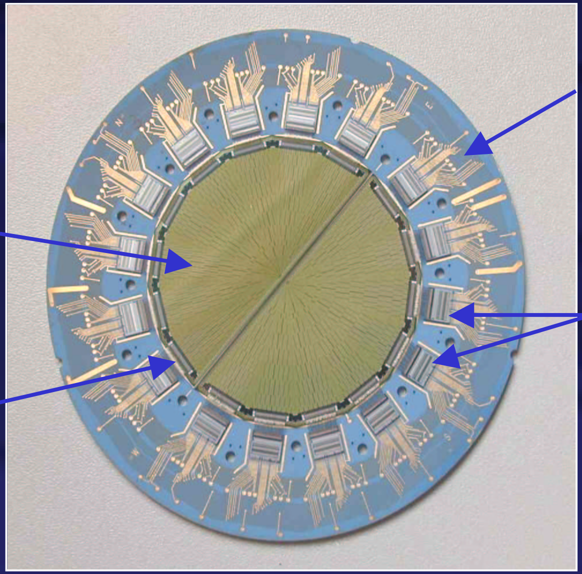
Front end electronics

Indium joint

electron optics



Si sensor and electronics



Ceramic with 2 signal layers

Si Sensor
2048 pads
(1x1 mm^2)

16 VA2/3 chips
(Ideas Norway)

Wire bonds

Performance

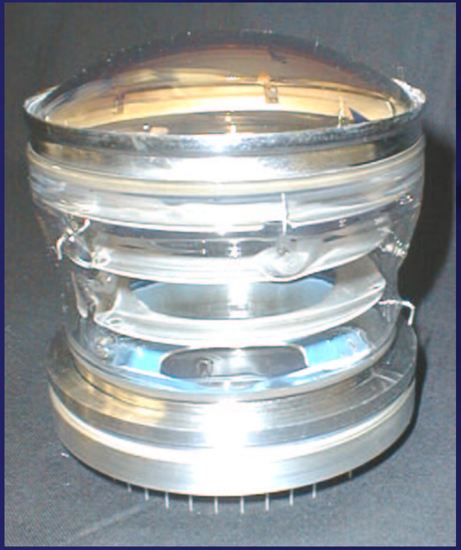
4 Pad HPDs imaging Cherenkov ring from aerogel

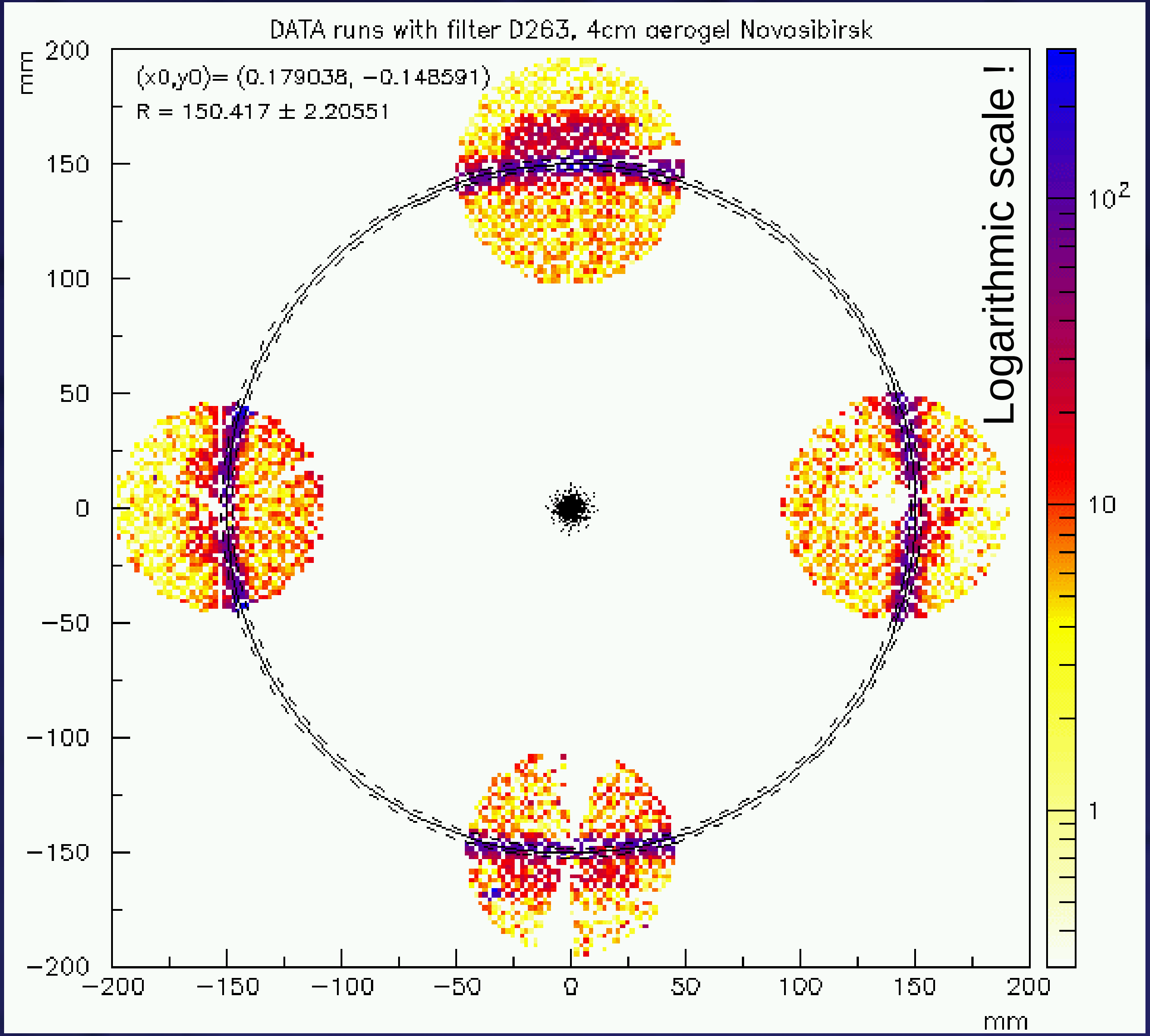
T. Bellunato et al., subm. to NIM A

NIM A 442 (2000) 128-135

NIM A 478 (2002) 400-403

www.cern.ch/ssd/Pad_HPD





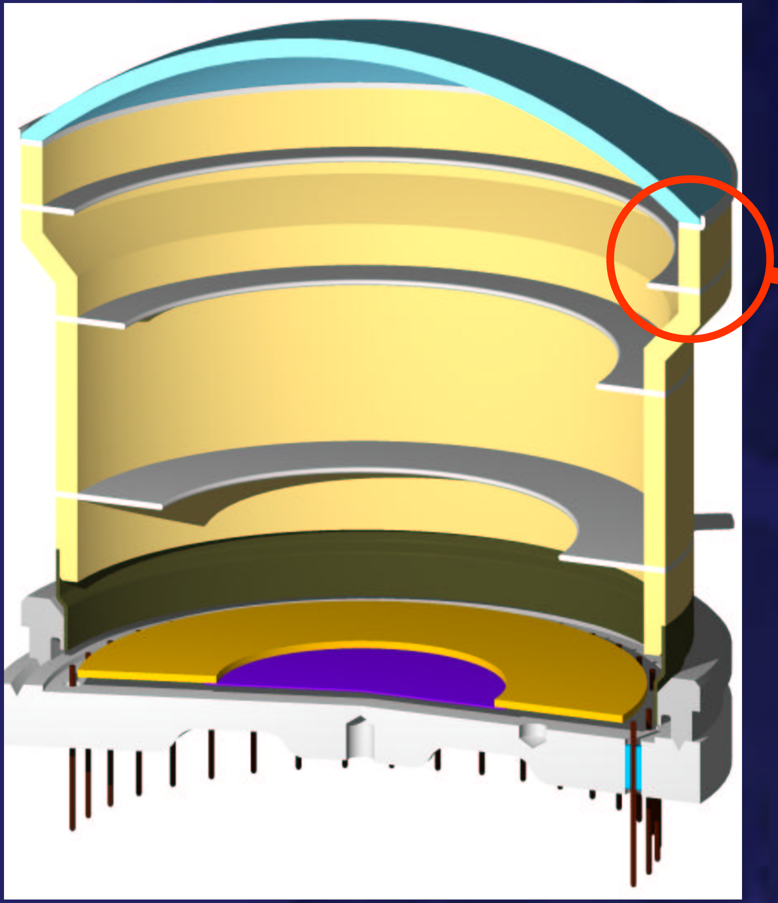
Currently under development: 5-inch Pad HPD with Ceramic Envelope

(Together with INFN Milano, C. Matteuzzi et al, and PHOTEK (UK))

Application: Characterization of aerogel as Cherenkov radiator.

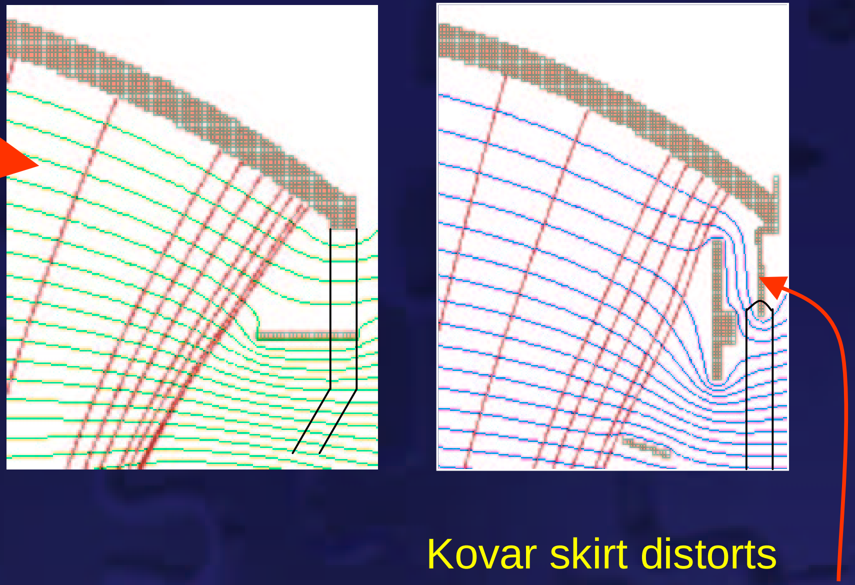
Ceramic body, Indium sealed window

→ better mechanical precision
→ simplified electrostatics



new “ceramic”

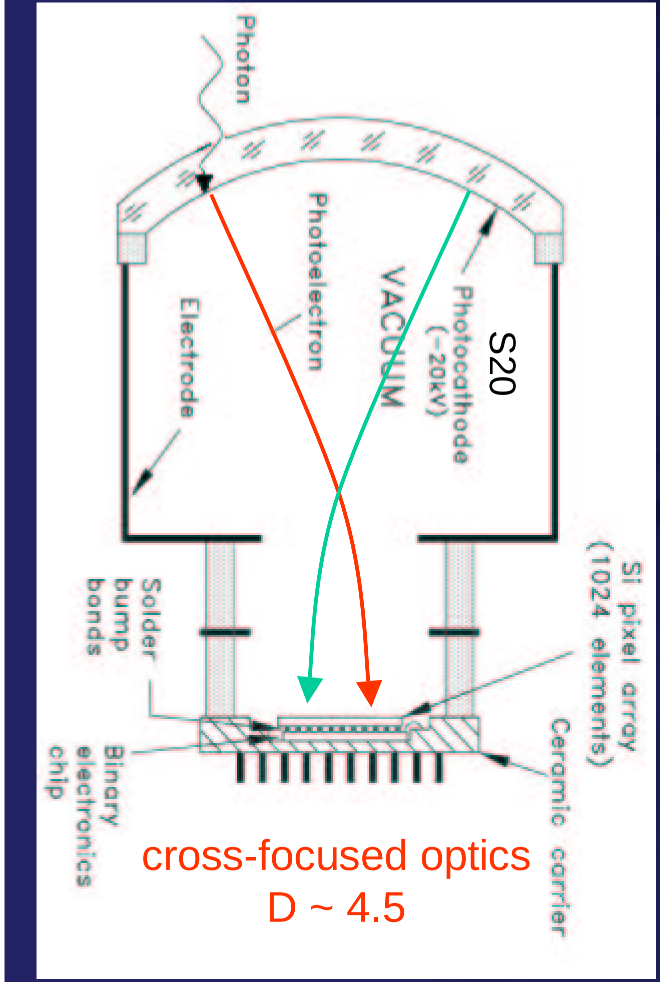
old “glass”



Kovar skirt distorts E-field. Additional ‘bleeder’ electrode required .

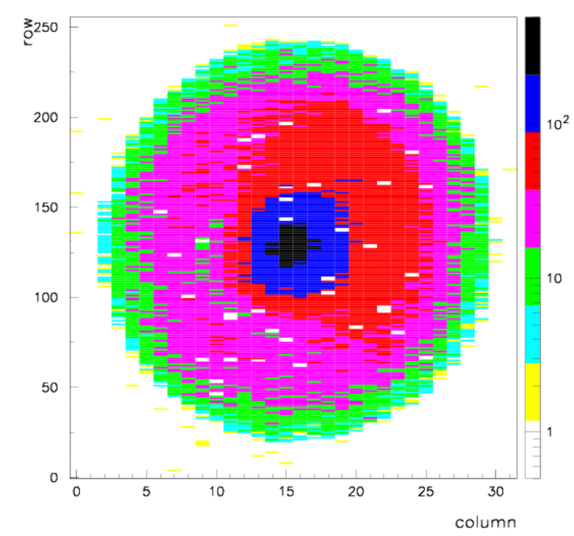
Another HPD for HEP…

Pixel HPD co-developed by CERN/LHCb and DEP (NL)



cross-focused optics
D ~ 4.5

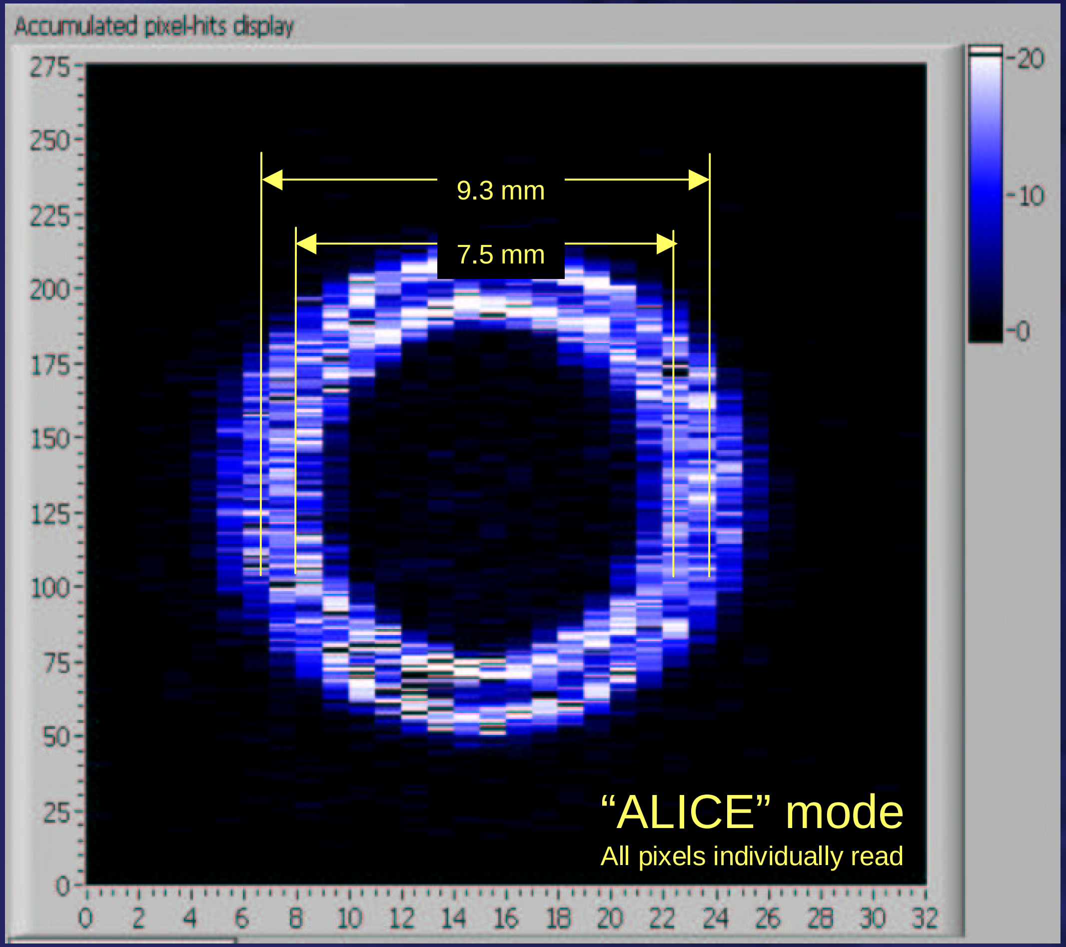
Special feature: fast (25 ns) pixel detector with 8192 channels (62.5 × 500 μm^2), organized in 1024 super-pixels of 500 × 500 μm^2 size.



Imaging of LED spot

www.cern.ch/~gys/LHCb/PixelHPDs.htm M. Campbell et al., LHCb note 2002-0048 RICH

August / September 2003 test beam. First operation at 40 MHz.



Online event display:

PS T9 - air radiator - 10 GeV/c

Double rings of e^- and π^-

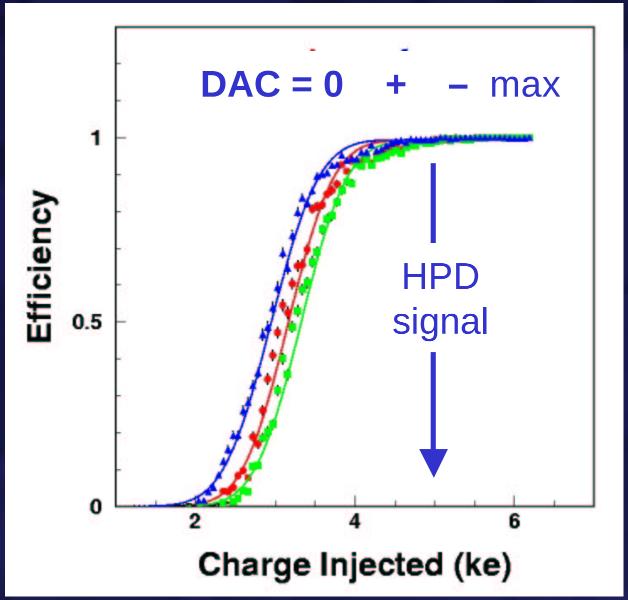
First performance estimates meet all specifications, except det. efficiency $\varepsilon_{det} \sim 0.87$ (prel.)

HPD Development for BTEV RICH

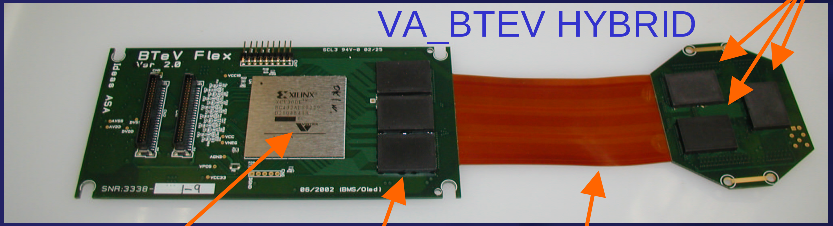
Like LHCb prototype tube, but with a 163 pixel anode (hex close packed) and external electronics.
Effective pixel size on cathode: 5.6 mm

va_btev chip: PA + shaper + discriminator, 64 ch., τ_p = 75 ns,

Discriminator Threshold Scan (Single Channel)



3 *va_btev* ASICs



FPGA for digital interface

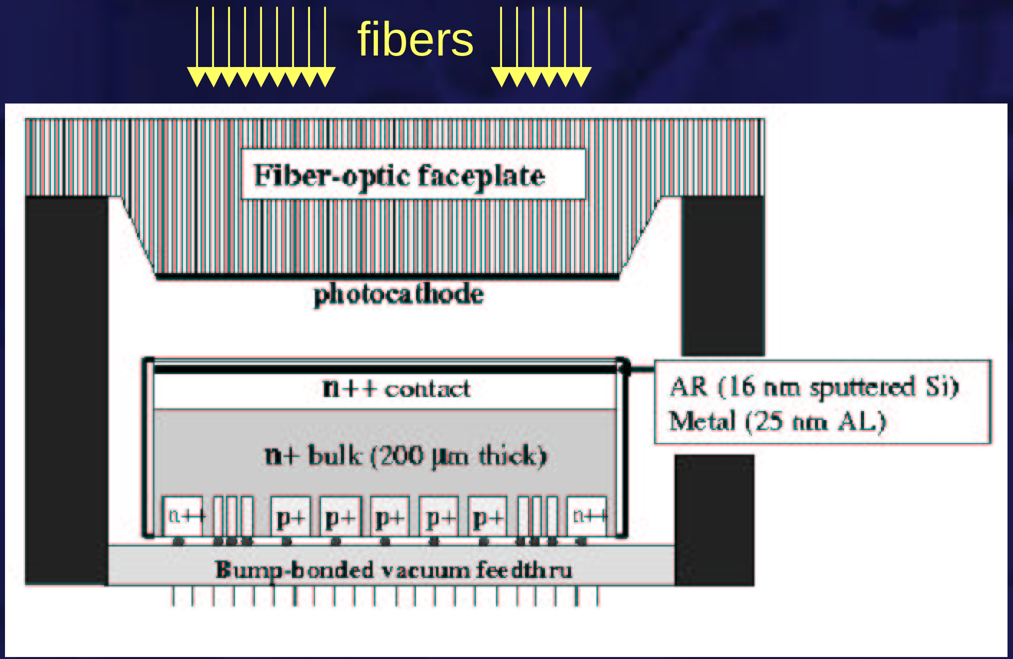
3 level shifters

Flex neck to negotiate tight mechanical constraints

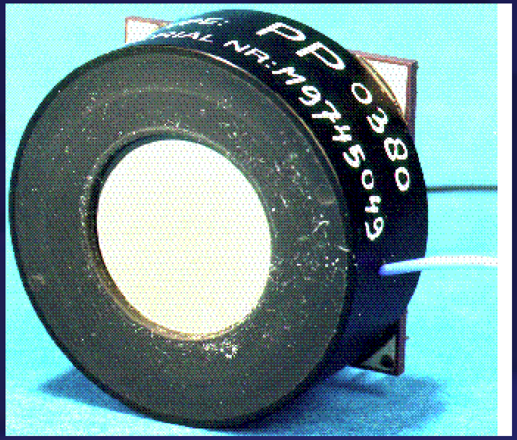
- 15 tubes + readout sets available and successfully lab tested.
- Full RICH system test in beam at FNAL in spring 2004

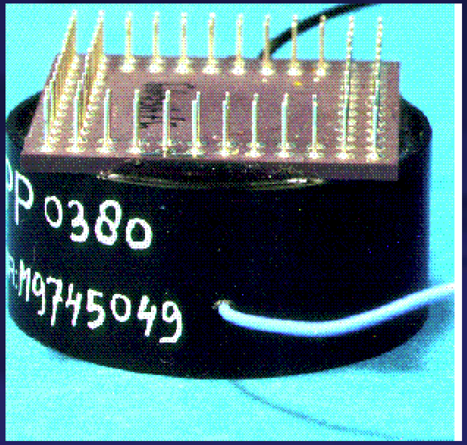
HPD for the CMS HCAL Readout

(co-development CMS – DEP)



- Proximity focused optics.
- 27 mm active diameter
- S20 photocathode
- 19 or 73 hex pixels,
  5.4 or 2.68 mm flat-to-flat
- Very small acceleration gap
  (3.3 mm)
- Gain = 2500 (12 kV)
- External electronics





P.B. Cushman and A.H. Heering "CMS HCAL Hybrid Photodiode Design and Quality Assurance Stations“. ICFA IB, Vol. 25, 2002

The TOM Project

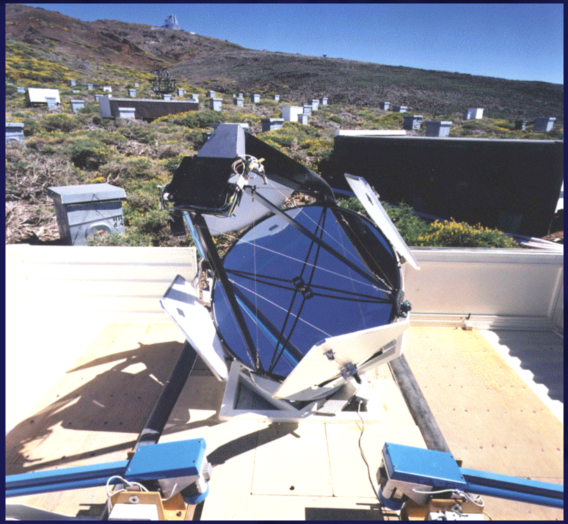
Tom Ypsilantis
1928-2000

Development of 10-inch HPDs with solar blind Rb_2Te cathodes for the CLUE experiment

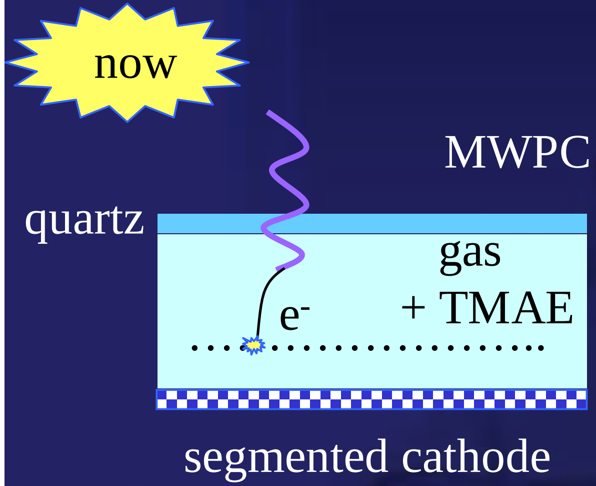
CERN + Pisa (INFN/University)

M. Giunta , N. Malakhov, A. Menzione, A. Picciolo, F. Raffaelli

CLUE =
Cherenkov Light Ultraviolet Experiment

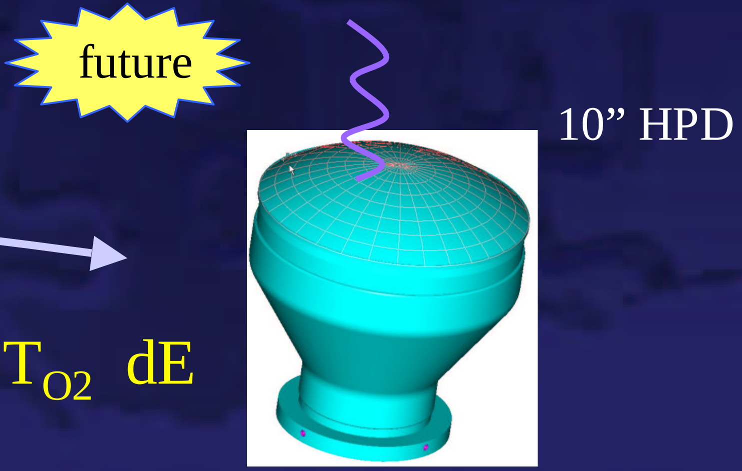


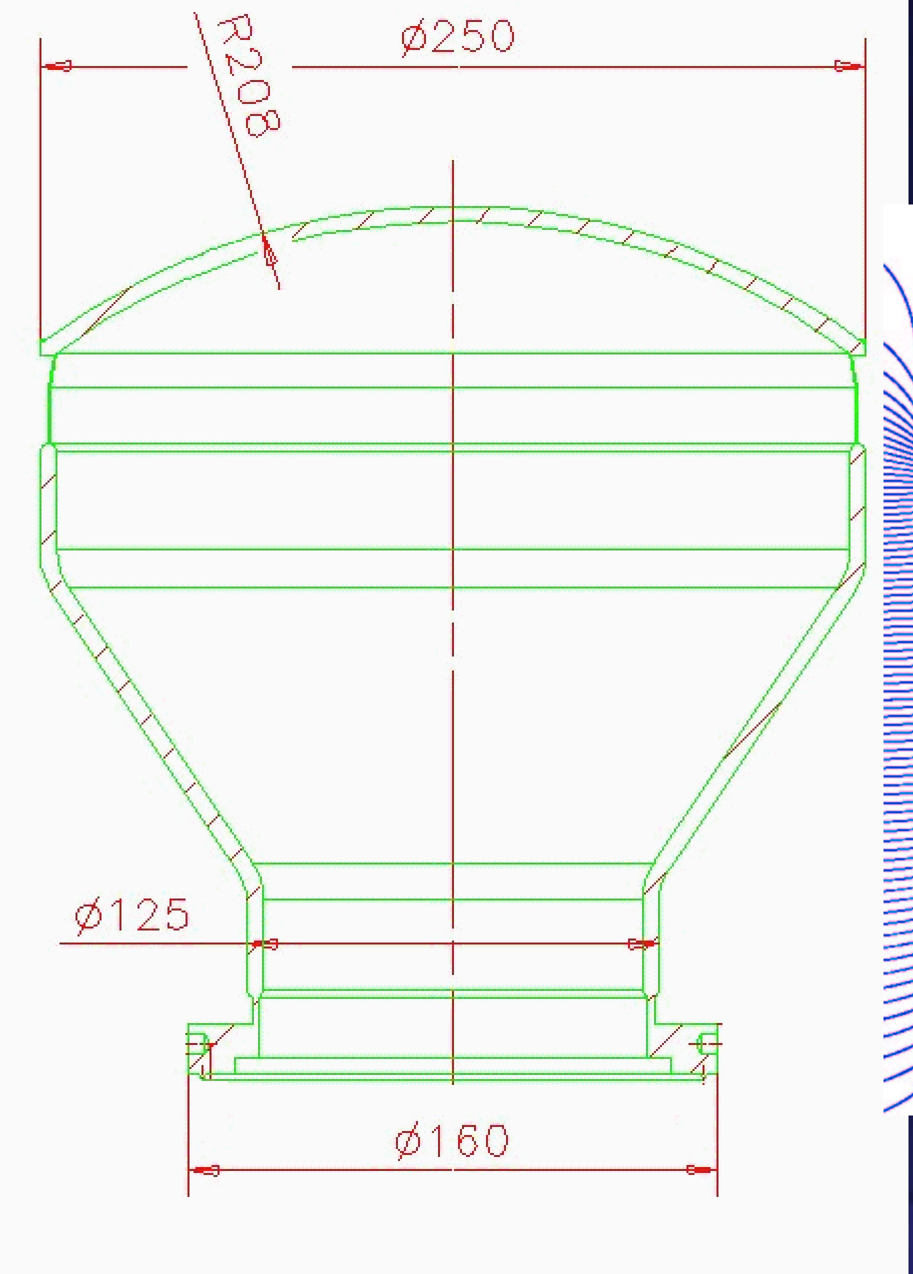
CLUE = 9 air shower Cherenkov telescopes. F/1 parabolic mirror, 1.8 m Ø. UV detector in focal plane



× 20

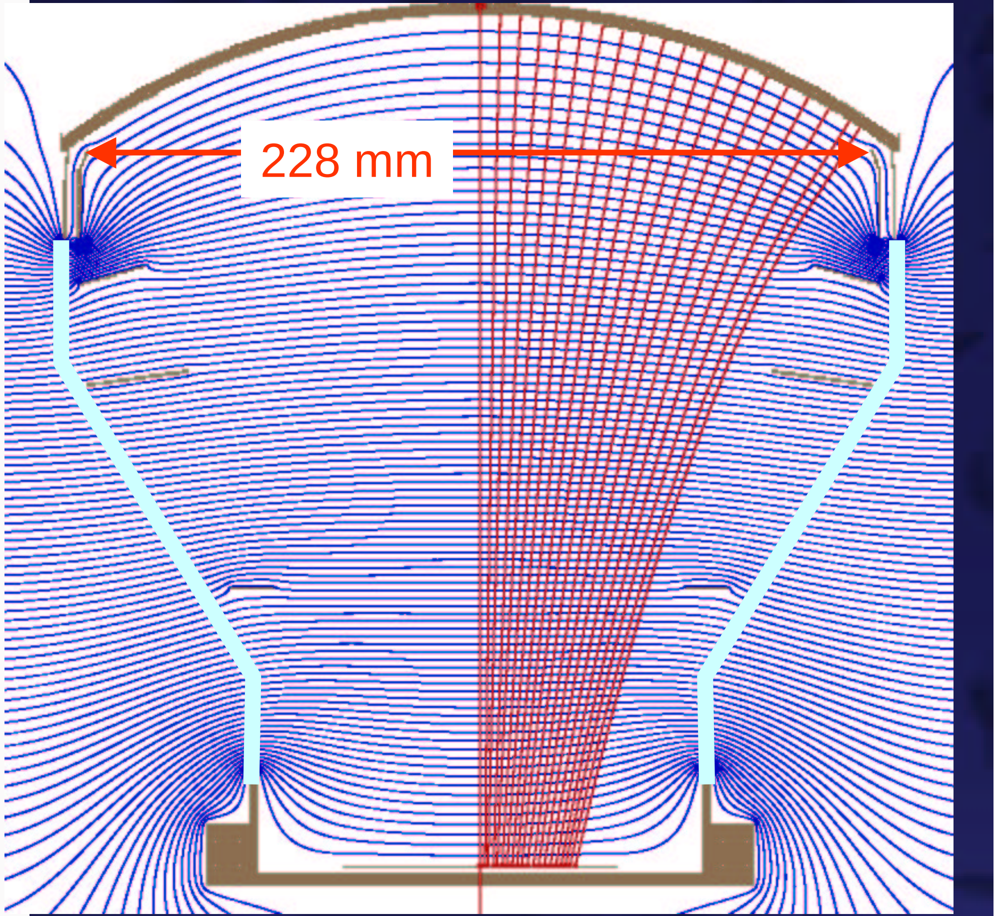
$$N_{pe} \sim \int QE \cdot T_{quartz} \cdot T_{O2}\; dE$$



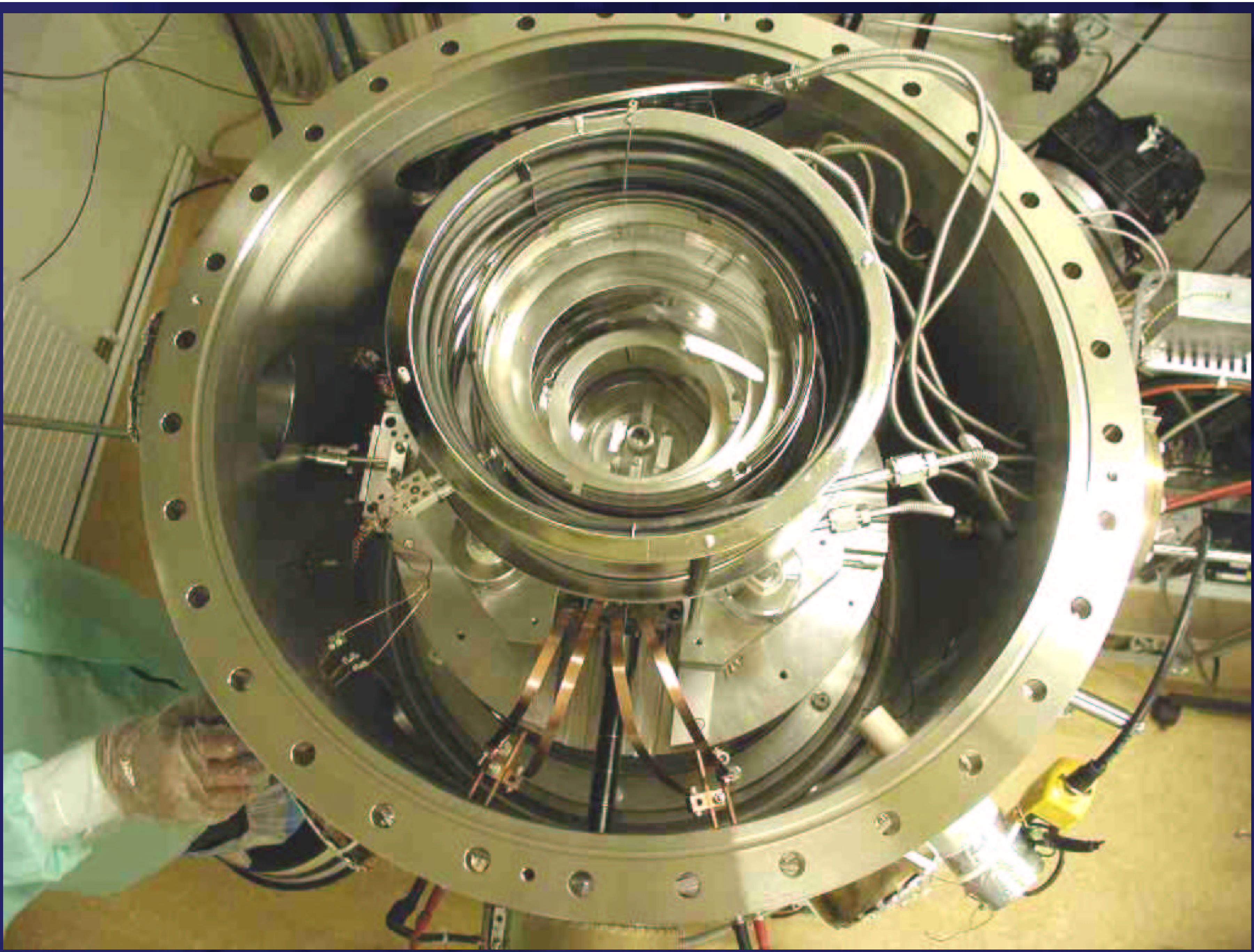


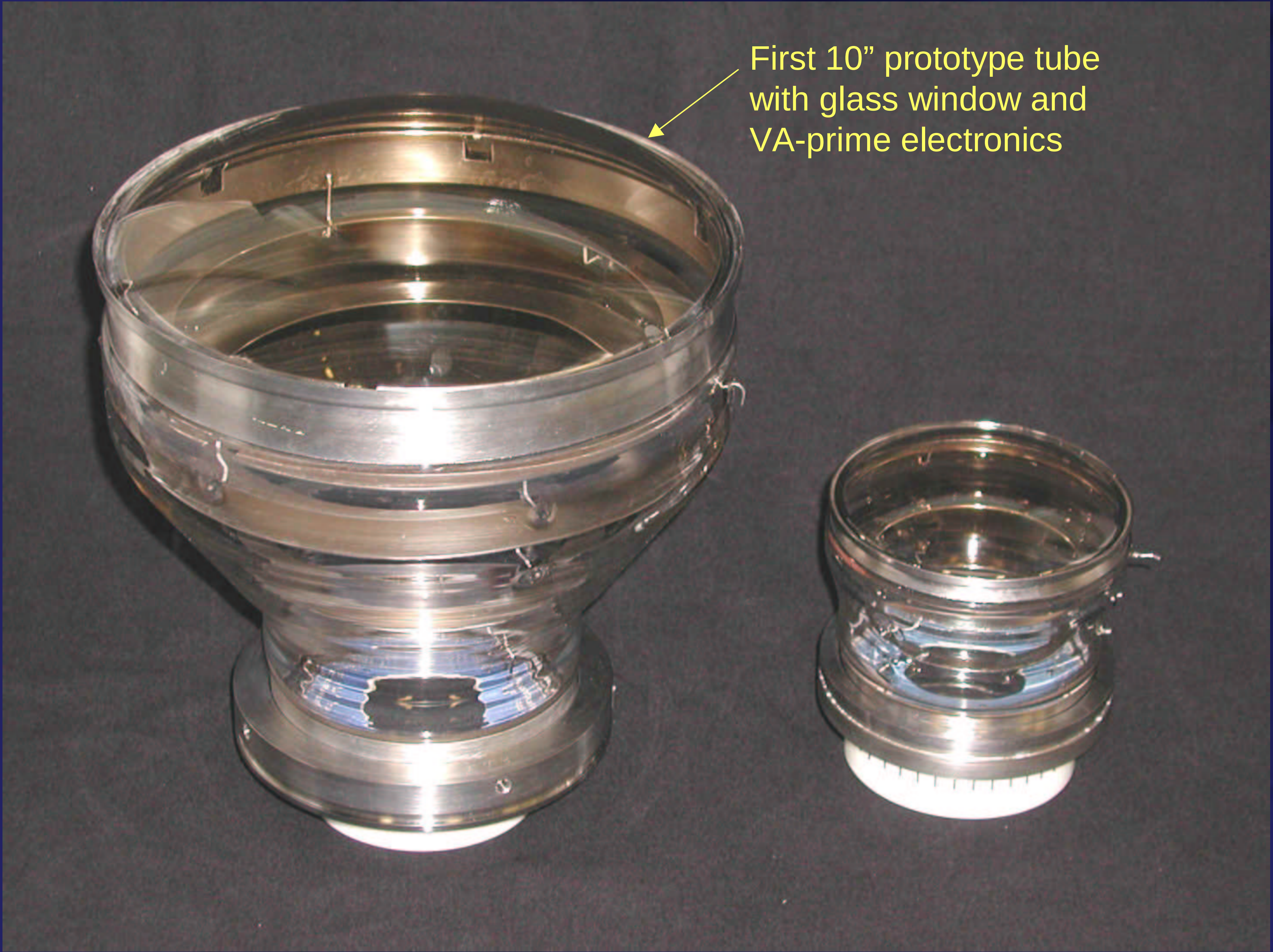
Electron optical simulations

(SIMION 7.0)

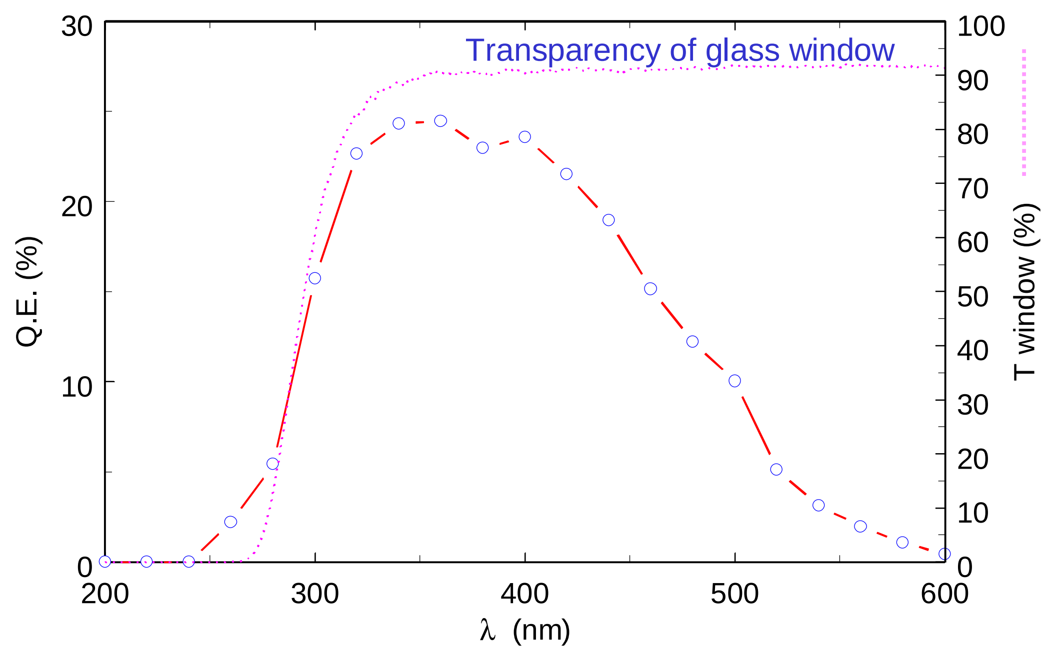


U = -20 / -19.6 / -16. / -13.5 / -7 kV





First 10” prototype tube with glass window and VA-prime electronics

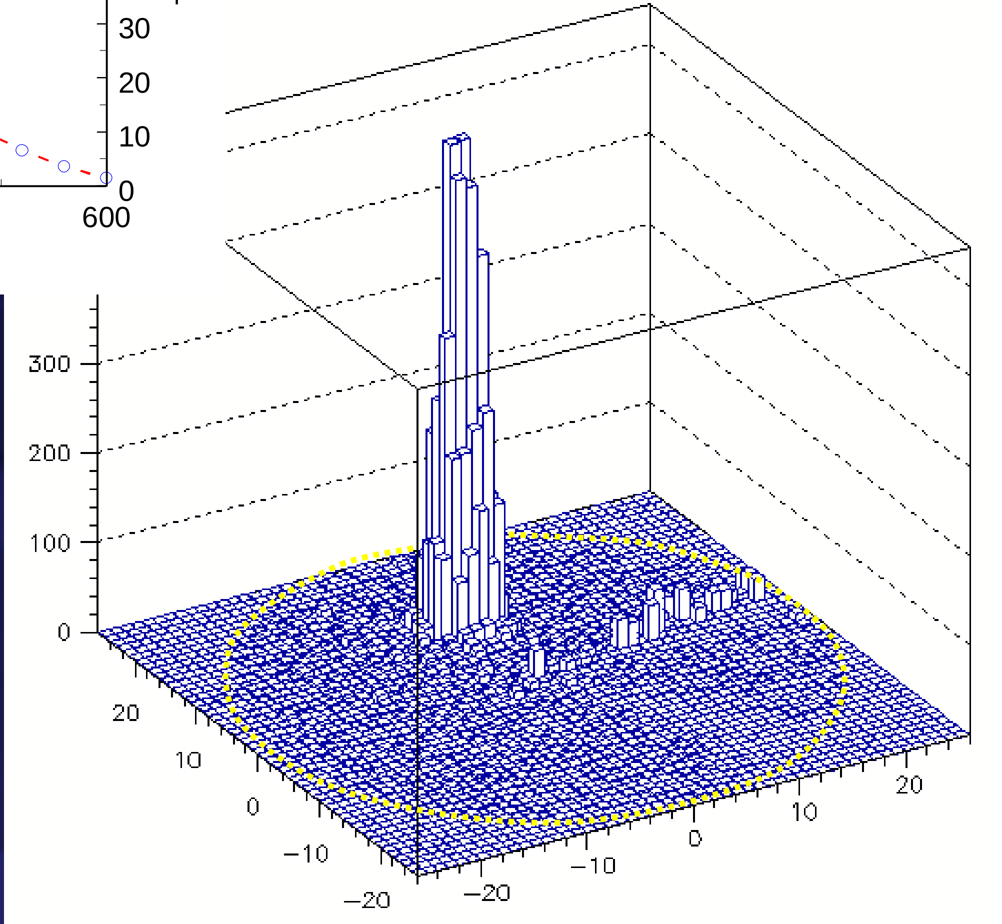


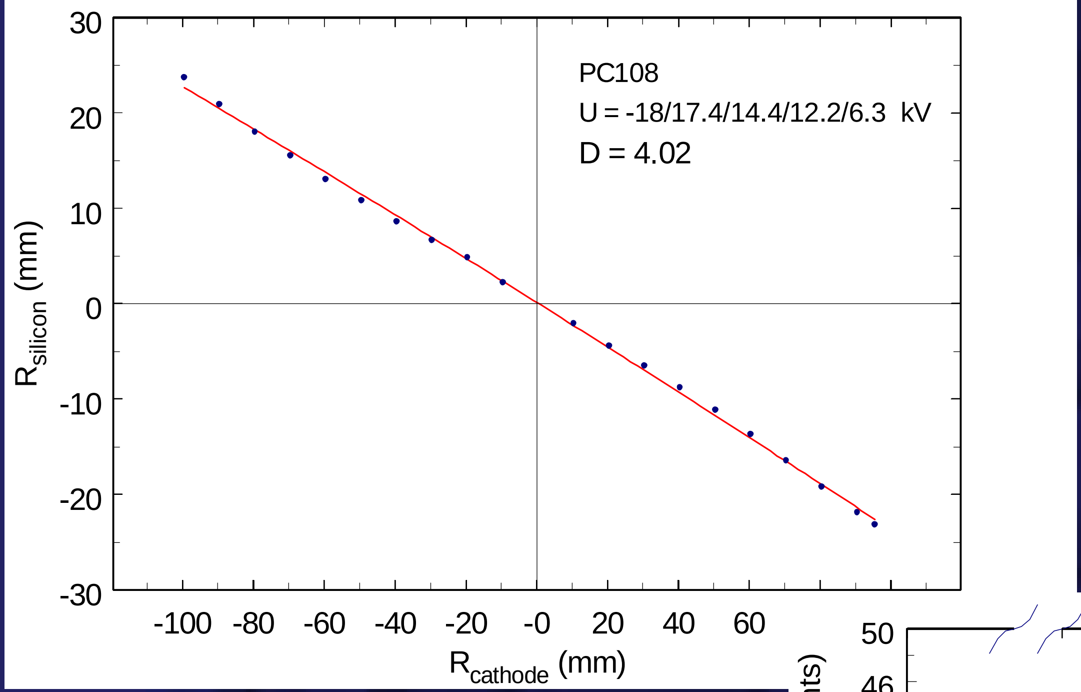
Quantum Efficiency

Sealed 10-inch HPD with bialkali cathode (normal glass window)

Si pad map

Spot from D_2 flash lamp (few noisy pixels)





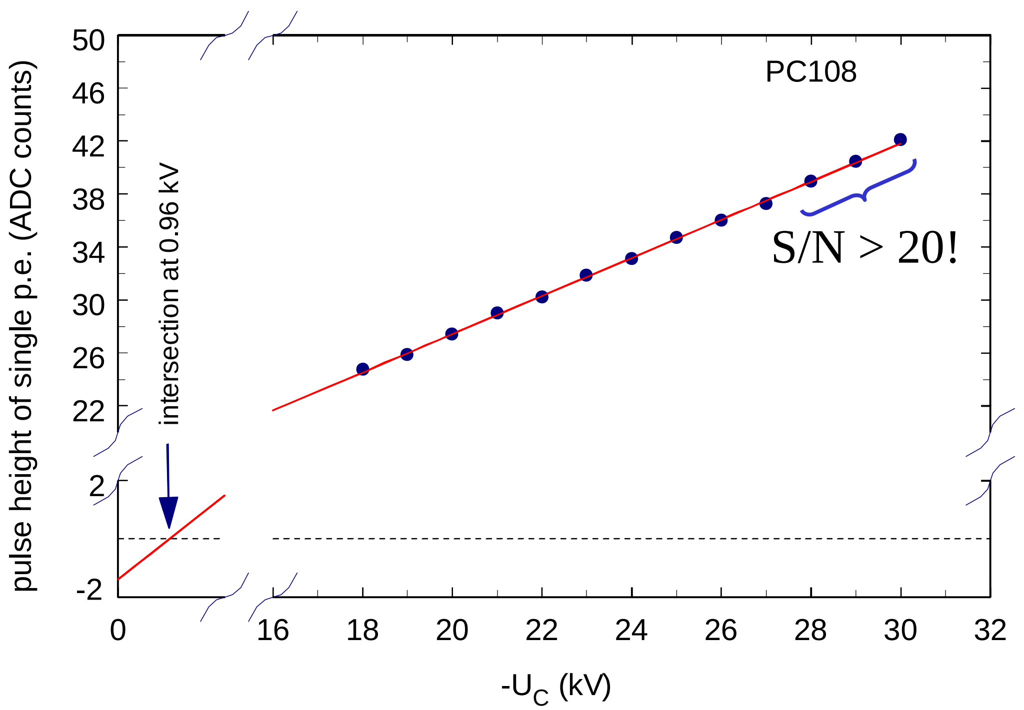
Electron optics

Linear demagnification (D ~ 4) over 200-210 mm diameter.

Si sensor too small to assess larger radii.

Signal amplitude vs High Voltage

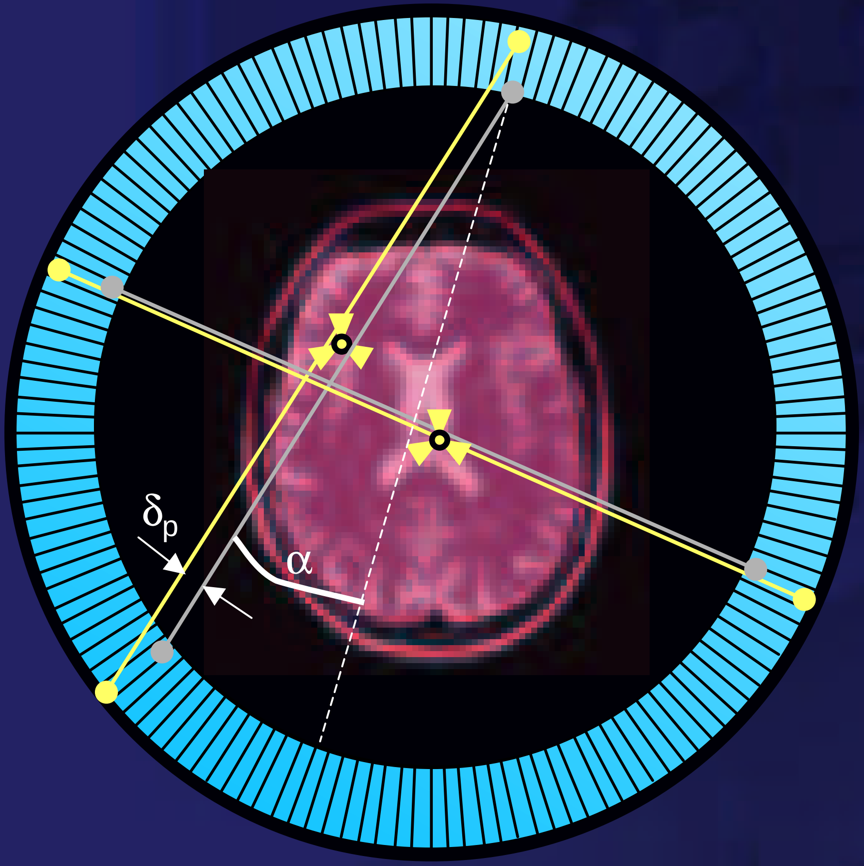
Design HV: 20 kV
Tube can be operated at 30 kV



HPDs for medical imaging: the HPD PET project

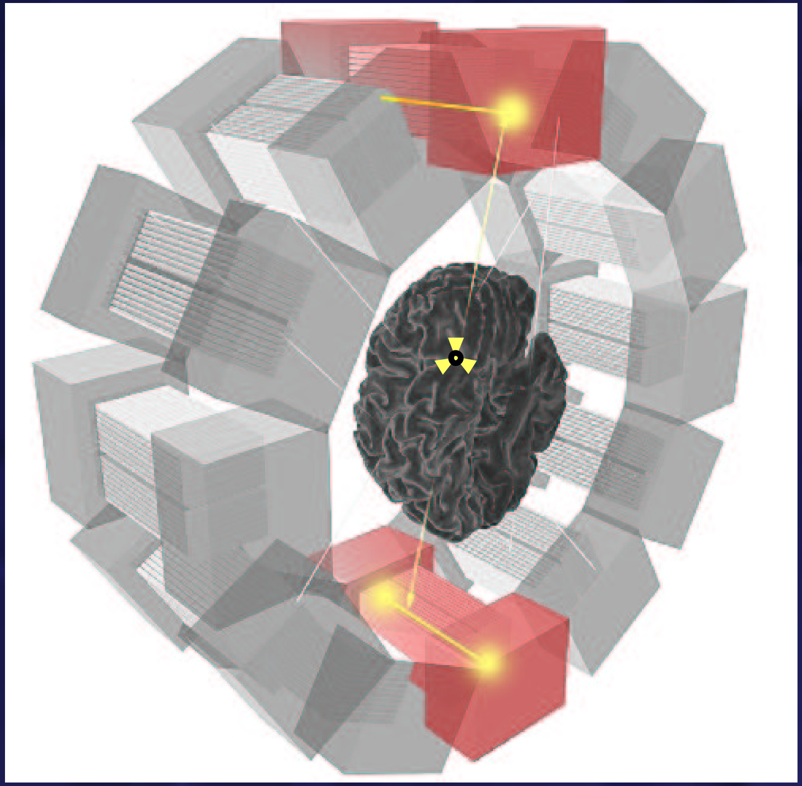
Bari, Rome, HUG Geneva, Univ. Geneva, CERN, and others

The PET parallax dilemma



Standard PET geometry

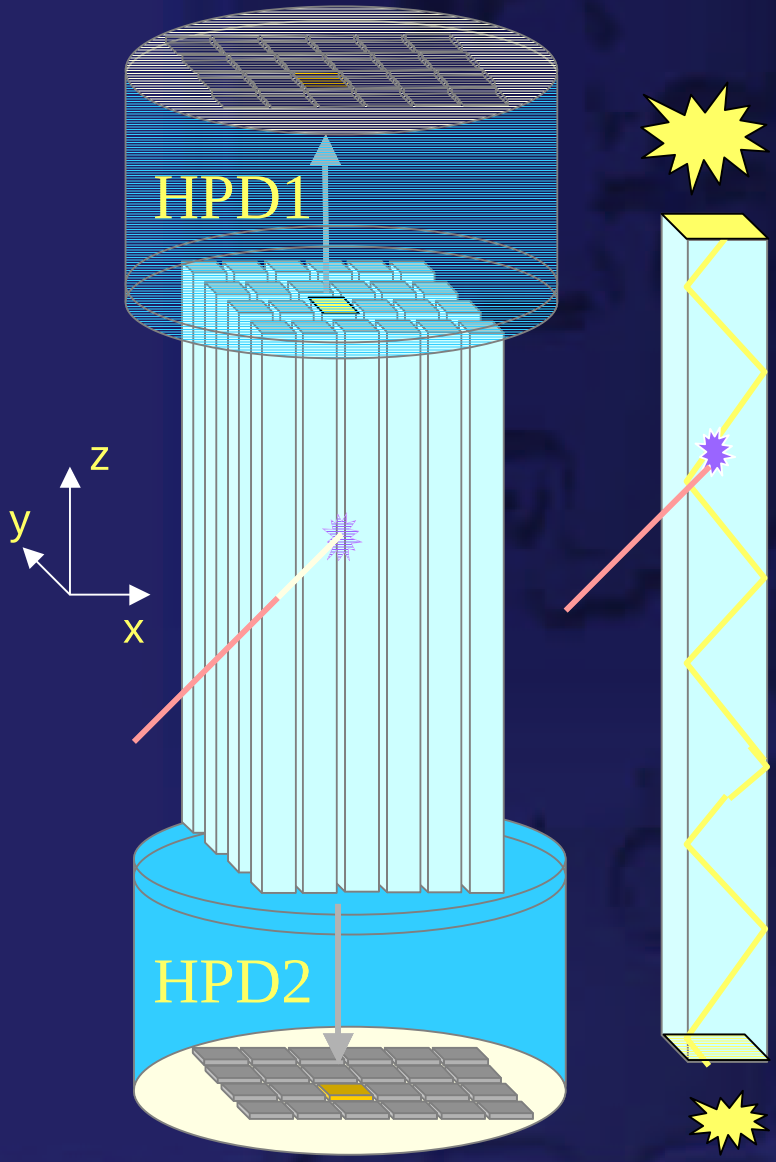
New 3D axial concept



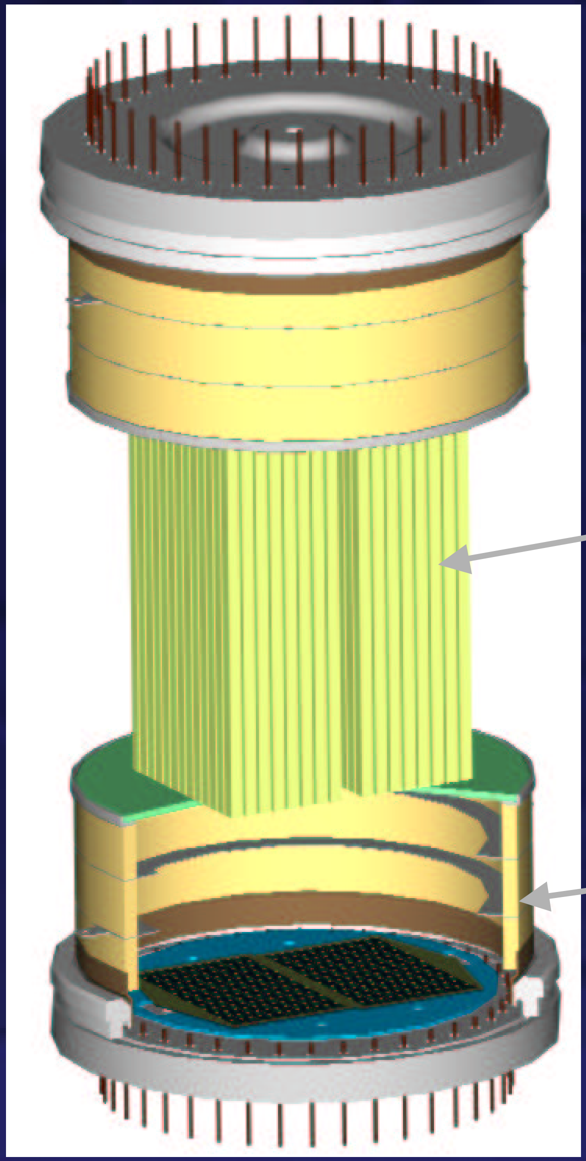
Axial arrangement of camera modules based on matrices of long crystals read out on both sides by HPDs

The HPD PET camera

Principle



Technical realization

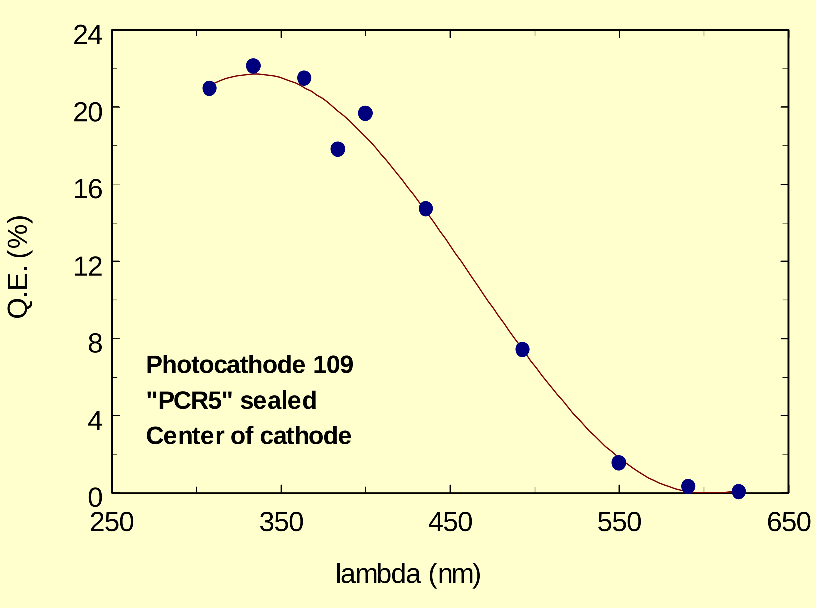


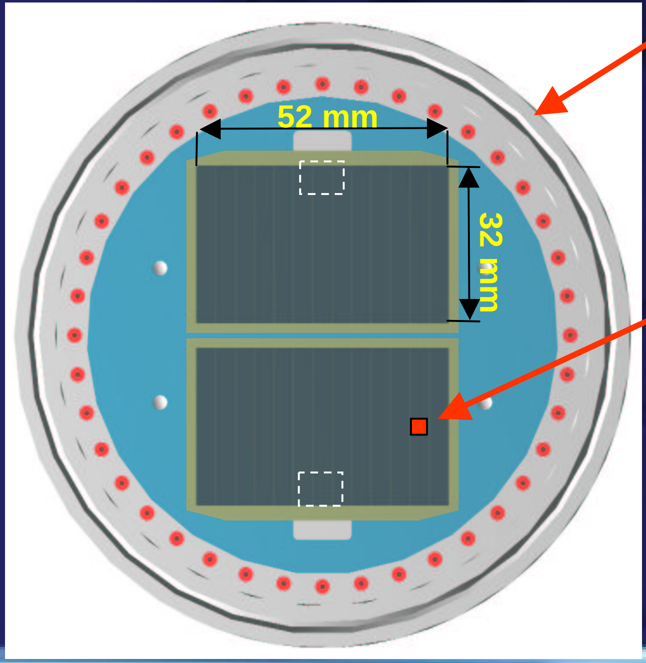
208 crystals (YAP) 3.2 × 3.2 × 100 mm^3

HPD PCR5

First prototype tube with VA-prime electronics

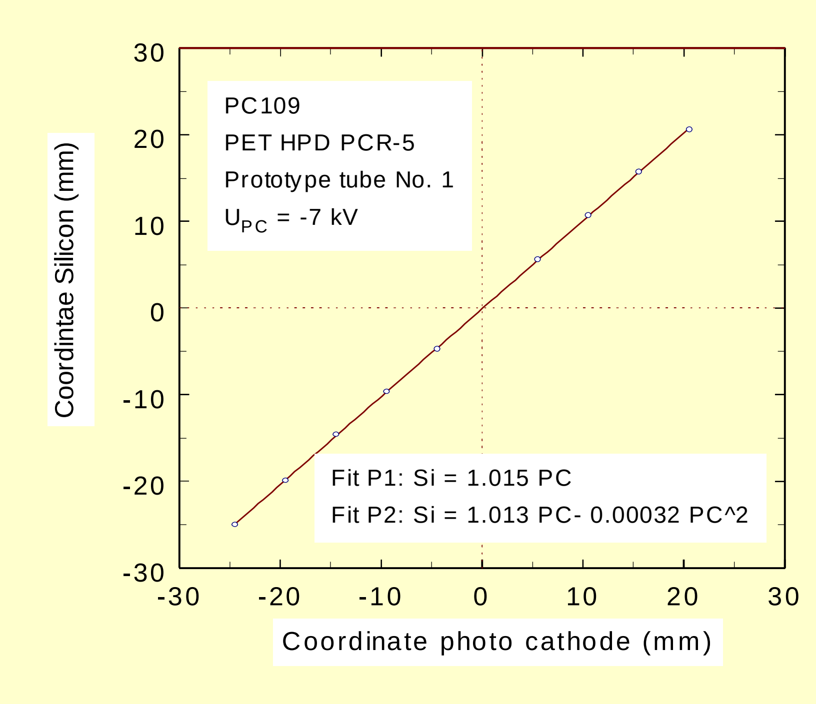
Ceramic envelope with 1.8 mm thick sapphire entrance window
(fully fabricated at CERN)



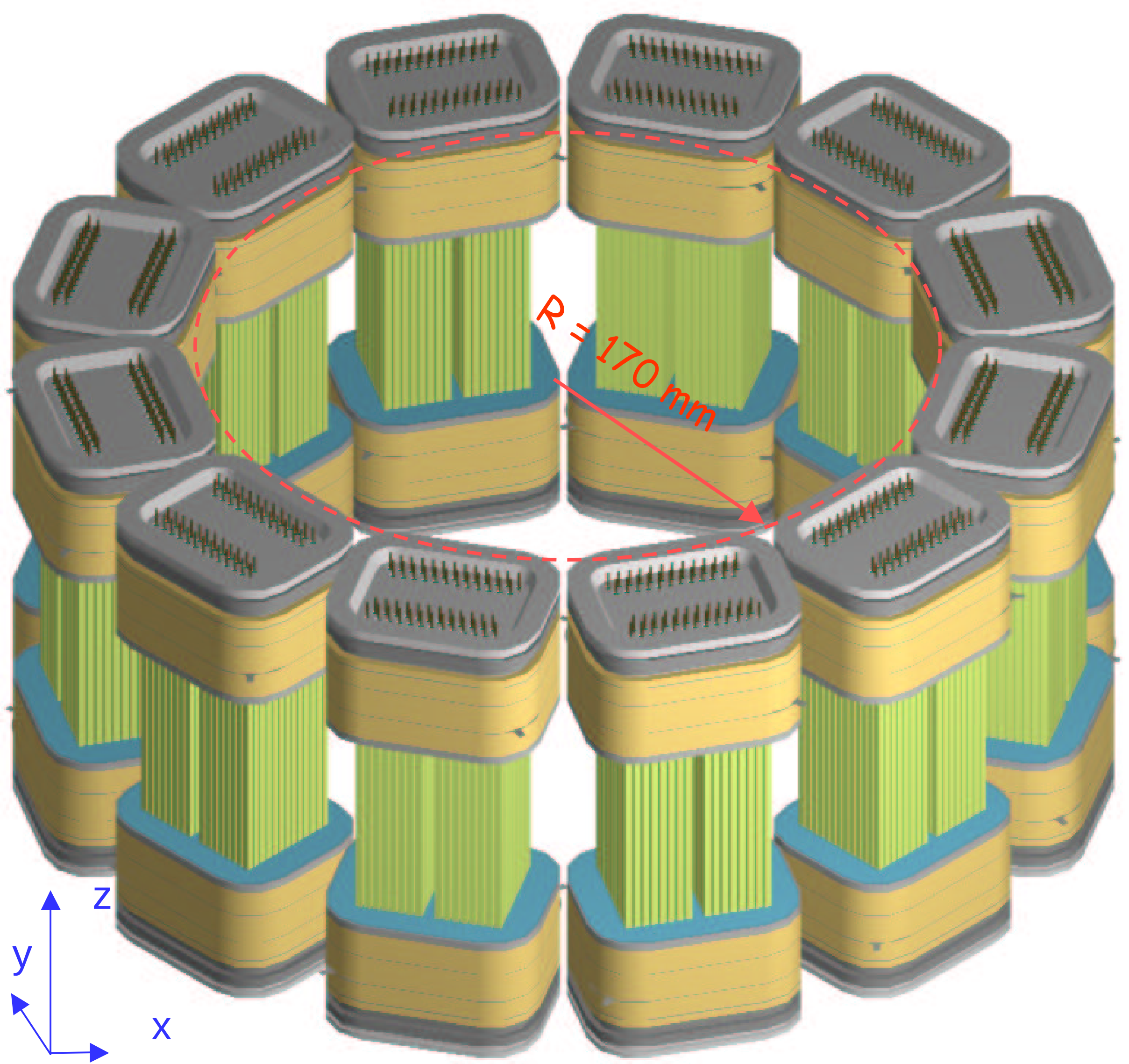


Next step: baseplate with Silicon sensors, matched to crystal geometry and self triggering electronics VA-TA

pad size 4 × 4 mm^2
(recently fabricated)



Far goal: 3D Brain PET scanner with rectangular HPDs



- Energy resolution:

  7 – 7.5 % (FWHM)

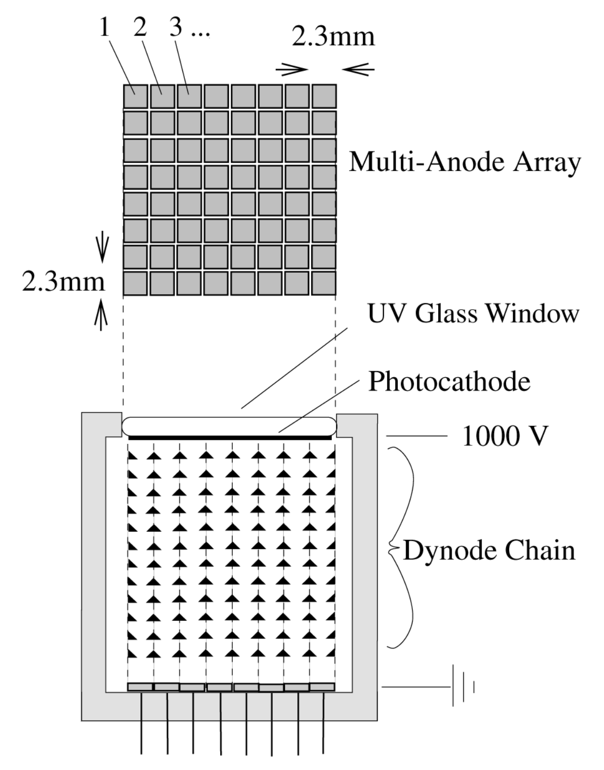
- Spatial resolution (FWHM)

  (x,y) 1.5 - 2.2 mm

  (z)   4.5 mm

Performance is constant over complete field of view !

Multi Anode Photo Multiplier Tubes



64-Channel MaPMT:
Hamamatsu R7600-03-M64

Principle

- Stacks of micro machined perforated metal sheets act as independent dynode channels.
- Independent anodes receive avalanches.

Issues

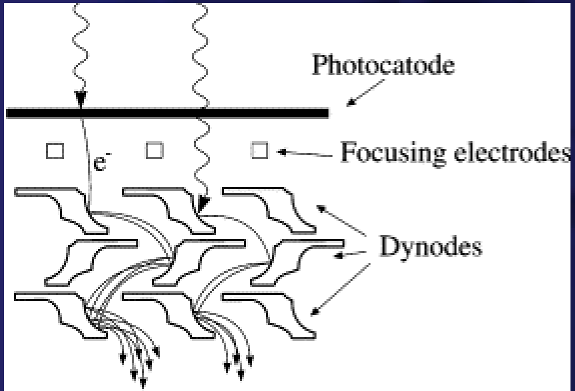
- Active area coverage
- Gain uniformity
- Cross talk
- Sensitivity to magnetic fields

Limitations

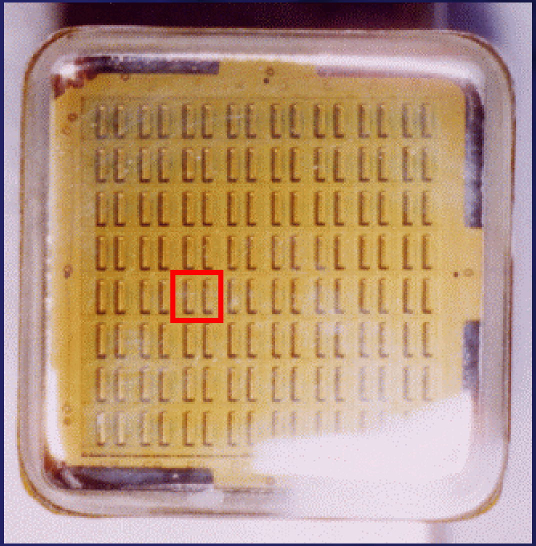
- Number of independent channels (~100)
- Pixel size (~mm)

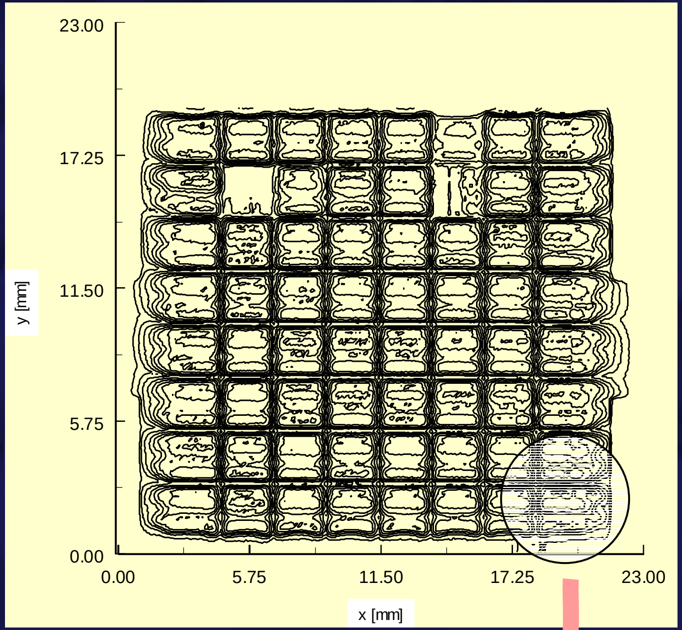
What is the real active area ?

Principle of metal channel dynodes



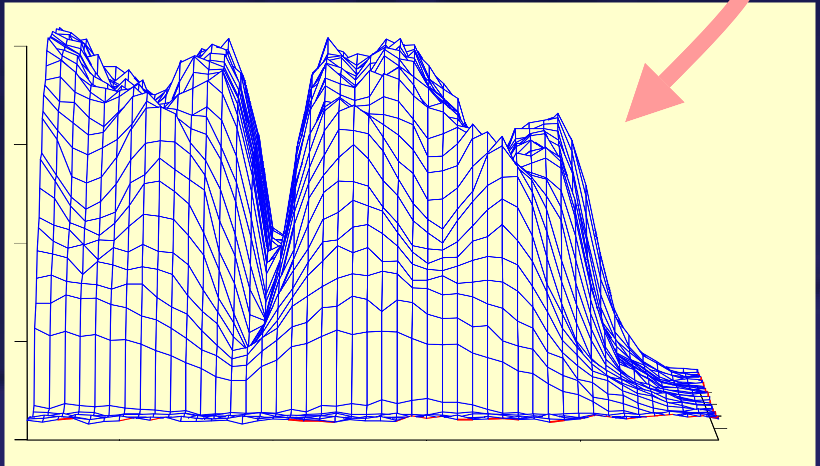
Example: Hamamatsu R7600-M64
64 cells of 2.3 mm □





A. Duane et al. LHCb 98-039

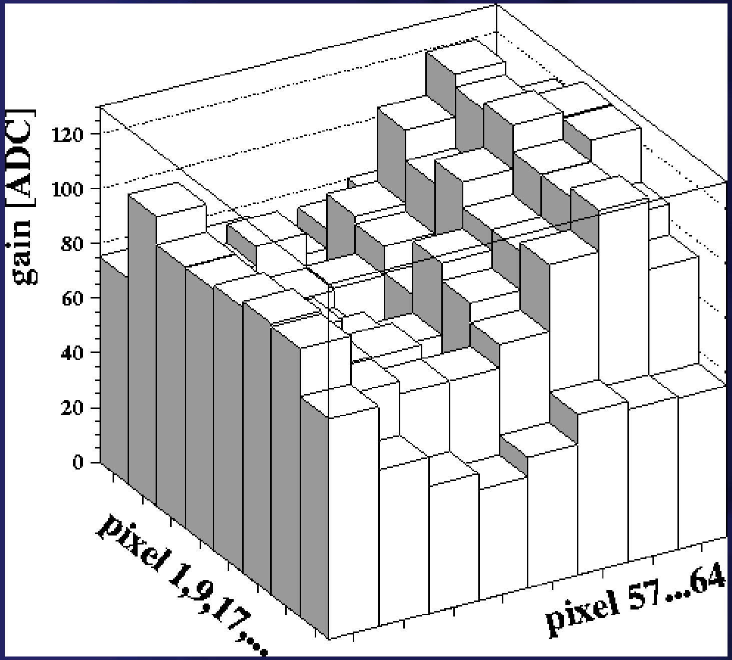
There are gaps between cells !



LHCb results

Gain uniformity

(limited by manufacturing precision of dynodes)



Variation of gain

- within a MaPMT ~ factor 3
- between 2 tubes < 2

Has to be coped with by

- RO electronics
- selection/grouping of tubes

Measurements in magnetic fields

(up to 350 G)

- Loss of gain? → No
- Distortion of pattern? → No
- Loss of photons? → Yes

Loss of photons <10% for unshielded MaPMT:

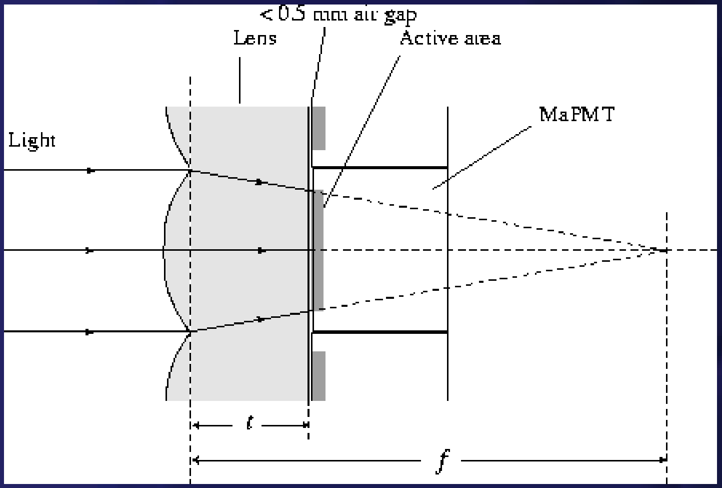
- >20 G B longitudinal
- >200 G B transverse

Loss of photons <10% for single μ-metal shield:

- 0.9 mm thick, 13 mm extension
- >80 G B longitudinal

Active area is very crucial for RICH applications. $N_{pe} \propto A_{active}$

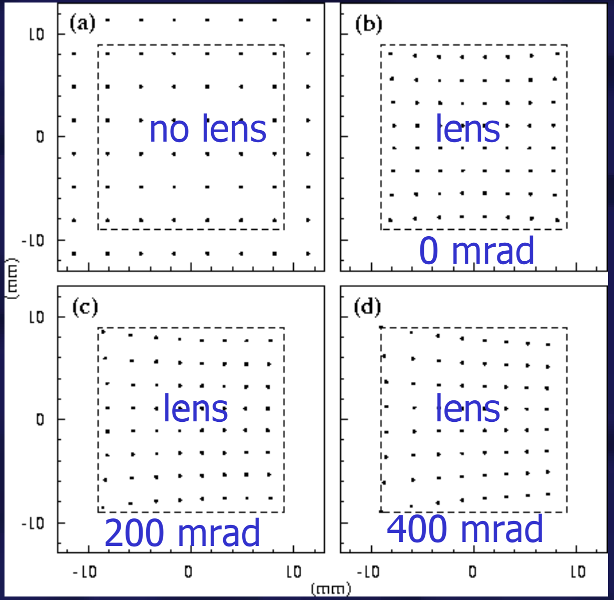
The LHCb solution



Use quartz lenses with one flat and one spherical surface

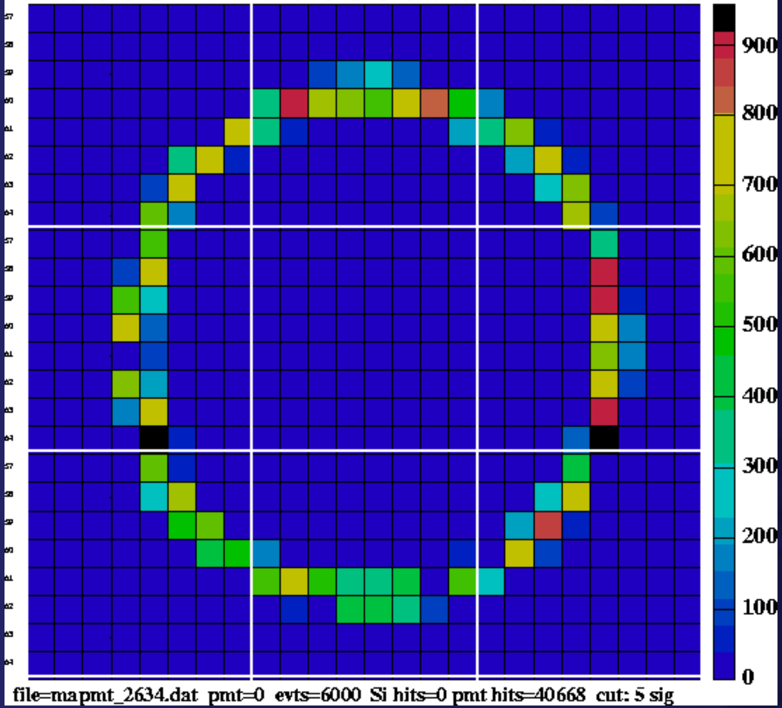
Demagnification (f -d)/f ≈ 2/3

Method is limited to relatively small angles of incidence

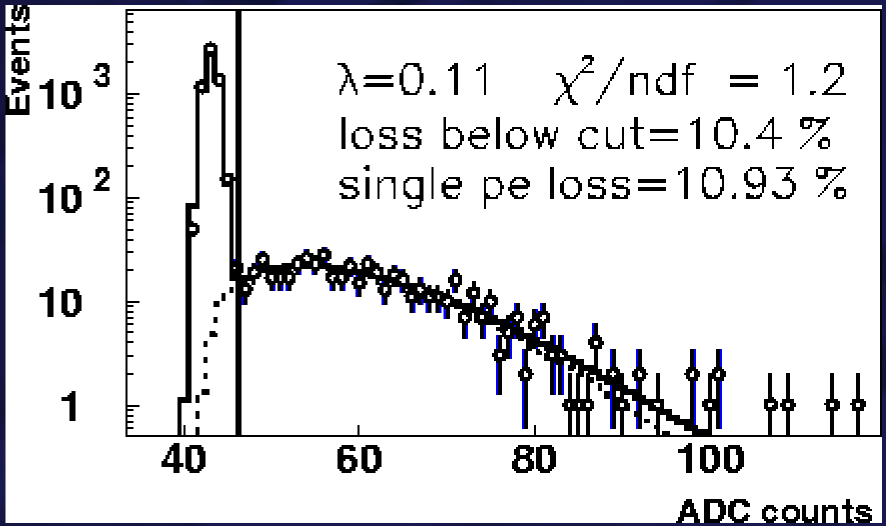


- Without lenses: active area fraction: 38% (includes pixel gap)
- With lenses 85%
- effective pixel size 3.0 mm

LHCb test beam with 3x3 MaPMT array. APV25 readout (40 MHz)



With quartz lenses



Problem:

PMT signals (~100 fC) are very large compared to typical signals foreseen for chips like APV25, Beetle, etc. (5 fC).

Options:

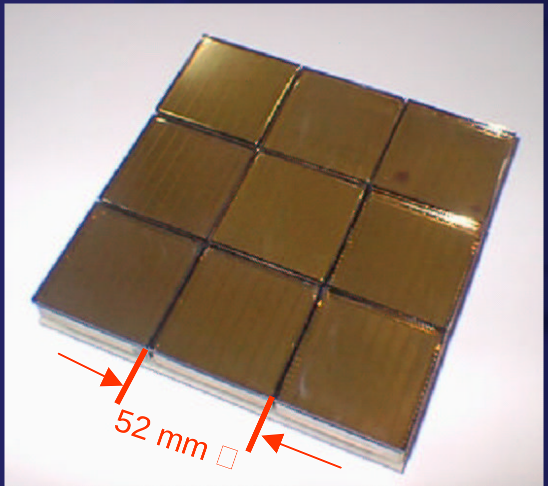
- attenuator network
- special chip
- PMT with fewer dynode stages (12→8)

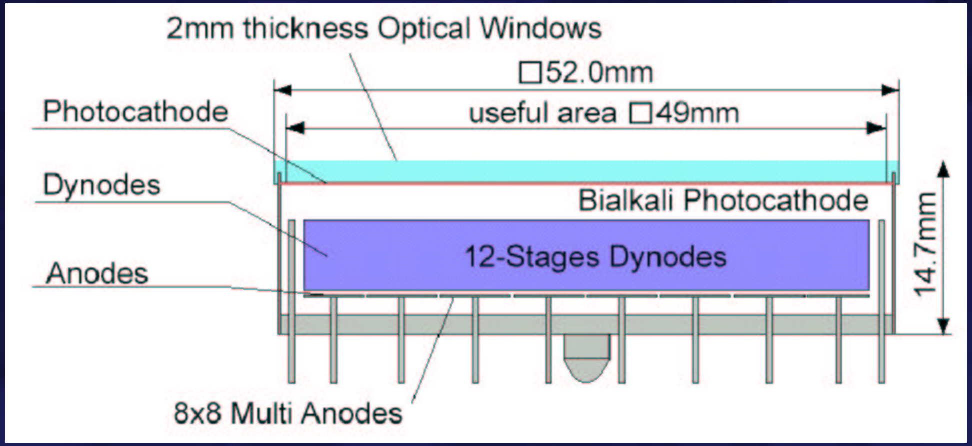
(data by R. Pani)

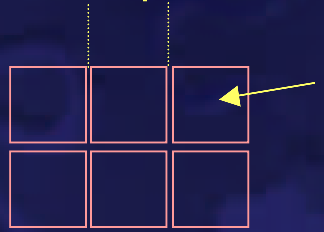
Hamamatsu Flat Panels

(Same technology as Multi Anode Photo Multiplier Tubes)

R8400-M64







6 mm pitch

Pixel size
5.6 mm □

Hamamatsu: $\varepsilon_A = 49^2/52^2 = 89\%$

More conservative: $\varepsilon_A = (64 \times 5.6^2)/52^2 = 74\%$

Gain spread and cross talk like MaPMTs

(data by R. Pani)

Gain spread of 2 different Flat Panels.

27 : 100

53	78	80	77	78	91	100	50
48	81	77	72	72	78	88	47
47	94	82	67	62	69	79	43
42	88	81	59	53	59	65	30
45	91	77	60	54	57	65	29
51	90	79	63	58	57	62	32
49	89	72	63	58	60	62	40
30	51	47	41	41	41	44	27

45 : 100

80	77	69	65	64	63	58	45
89	47	55	62	62	59	58	53
96	79	70	64	59	57	58	54
96	100	81	63	57	64	62	49
92	98	79	61	56	58	63	51
86	89	74	67	63	60	61	55
82	81	72	64	57	56	60	58
73	90	79	71	63	59	63	54

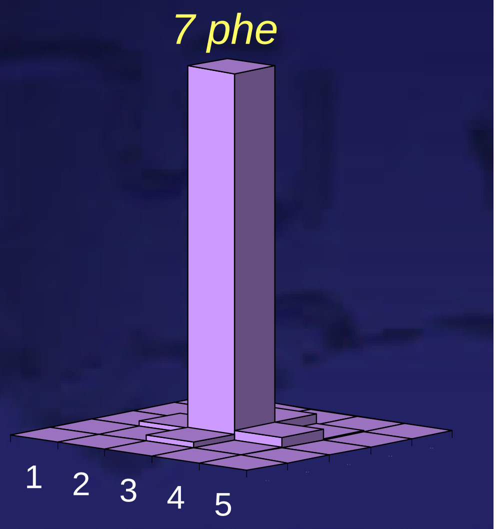
Cross talk of a Flat Panel.

Hamamatsu data

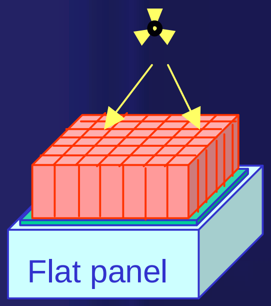
-	-	-	-	-
-	0,2	1,8	0,2	-
-	1,8	100	2,7	-
-	0,2	2,6	0,3	-
-	-	-	-	-

Anode 37 Measured value

-	-	-	-	-
-	<0,1	<0,8	<0,1	-
-	<1,4	100	<2,4	-
-	<0,1	<1,8	<0,1	-
-	-	-	-	-



Application in medical imaging (mammography):
Readout of a CsI(Tl) scintillator array with a Flat Panel



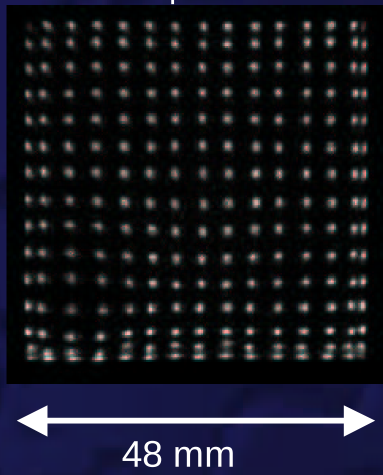
^{57}Co flood field irradiation (122 keV γ)

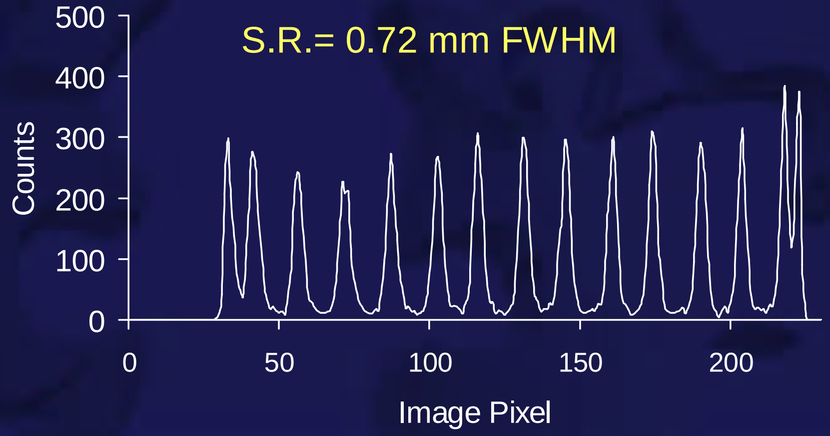
1 crystal produces signal on 5-14 channels.

Calculate centroid (incl. corrections for gain non-uniformity, distortions, etc.) and identify hit pixel.

15x15 array

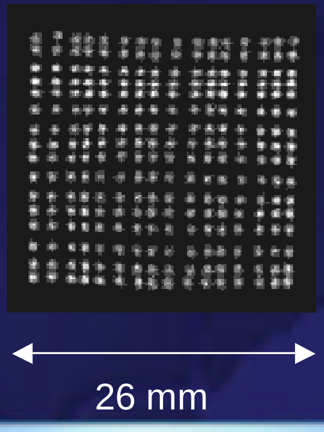
3x3 mm^2 pixel size

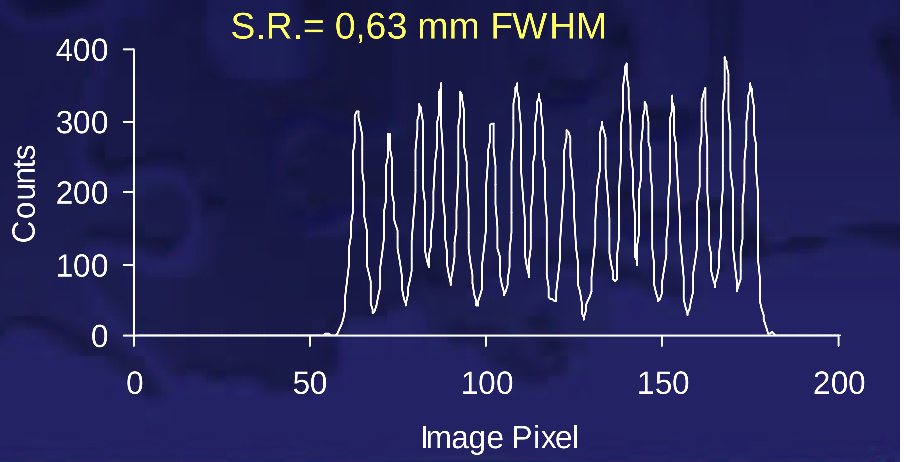




16x16 array

1.4x1.4 mm^2 pixel size





Conclusions

- For many ‘standard’ applications, both HPDs and MAPMTs can do the job
- HPDs beat MAPMTs in signal definition, gain uniformity, flexibility
- The lower gain of HPDs is easily dealt with by state-of-the-art electronics
- Fabrication of HPDs with encapsulated electronics requires numerous advanced technologies (bump/wire bonding, electronics & sensor testing), which a single company does not possess. → ‘Heavy’ development + production.
- The market is dominated by just two companies: Hamamatsu (MAPMT) and DEP (HPD).

→ Both MAPMTs and HPDs are relatively expensive!