Single photon detectors for Cherenkov Imaging Counters

largely based on the outcomes of the recent
6th International Workshop on Ring Imaging Cherenkov Counters - RICH2007 (http://rich2007.ts.infn.it/)
Trieste, Italy, 15 - 20 October 2007

OUTLINE

- INTRODUCTION
  - UBIQUITY OF RICH COUNTERS
  - THE SPECIFICITY OF DETECTING SINGLE PHOTONS
- STATUS AND PERSPECTIVES IN SINGLE PHOTON DETECTORS
  - ISSUES IN THE FILED OF SINGLE PHOTON DETECTORS
  - VACCUM-BASED PHOTON DETECTORS
    - NEW PERSPECTIVES WITH HIGH TIME RESOLUTION PHOTON DETECTORS
  - GASEOUS PHOTON DETECTORS
  - Si-PMs
- CONCLUSION

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PHYSICS & Cherenkov Imaging Detectors

particle and **nuclear** physics with RICHes
(concluded experiments **NOT** included)

field of Physics	experiment	where	status
heavy and light quark spectroscopy	BABAR	SLAC	active
	superBELLE	KEK	proposal
	CLEO III	CORNELL	active
	COMPASS	CERN	active
	COMPASS2	CERN	proposal
	future superB		
	PANDA	GSI	preparation
	MIPP	FERMILAB	active
	GlueX	Jlab	preparation
K physics	P326	CERN	proposal
B physics	BABAR	SLAC	active
	superBELLE	KEK	proposal
	future superB		
	LHCb	CERN	starting
Longitudinal and transverse spin structure of the nucleon, generalized parton distribution function	COMPASS	CERN	active
	COMPASS2	CERN	proposal
	HERMES	DESY	just concluded
	PANDA	GSI	preparation
	PHENIX	BNL	active
	Hall A	JLAB	active
quark-gluon fusion	ALICE	CERN	starting
	ALICE upgrade	CERN	proposal
heavy ion physics	BRAMHMS	RHIC	active
	PHENIX	RHIC	active
	ALICE	CERN	starting
hadron properties in normal and heigh density nuclear matter	CBM	GSI	preparation
	HADES	GSI	active
hypernuclei	PANDA	GSI	preparation

PHYSICS & Cherenkov Imaging Detectors

- the future of a large variety of particle and nuclear physics fields strongly depends on the progress in Cherenkov Imaging Detectors
  (Ubiquity, a part: Tevatron, LHC General Purpose Detectors: more related to lack of space then to lack of interest)
- the high rate capability and the high resolution demands are central
  - Required by future projects:
    - ALICE upgrade
    - CBM
    - PANDA
    - superBELLE / future superB
    - COMPASS2
    - NA62
- **Cherenkov detector role in astroparticle**
  - Flying spectrometers to study CR composition
    - Caprice, AMS, CREAM
  - (Solar and) cosmic ν telescopes
    - Tunka, Amanda, Antares, Nemo, KM3Net
  - High energy gamma-ray astonomy
    - Auger, HESS, MAGIC

These experiments are totally based on the detection of the Cherenkov radiation!

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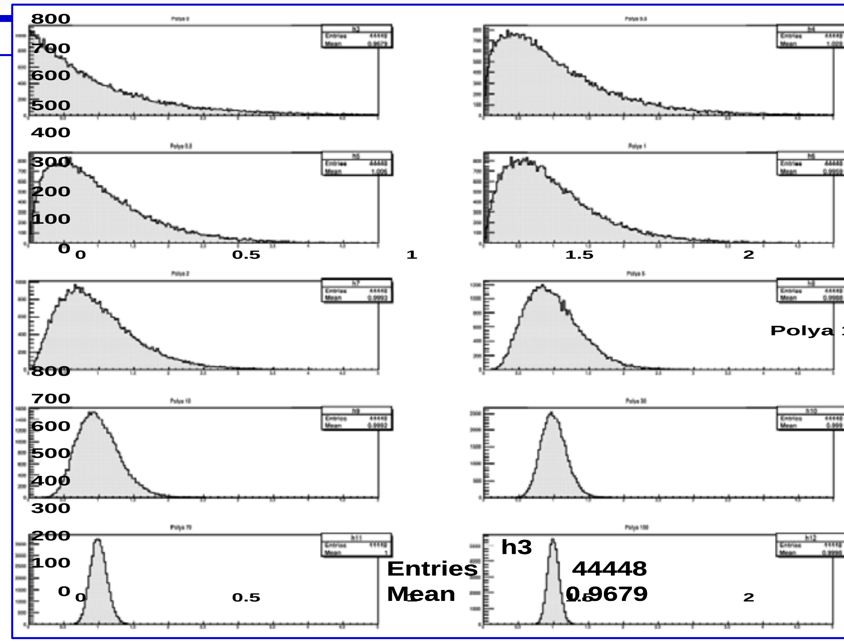
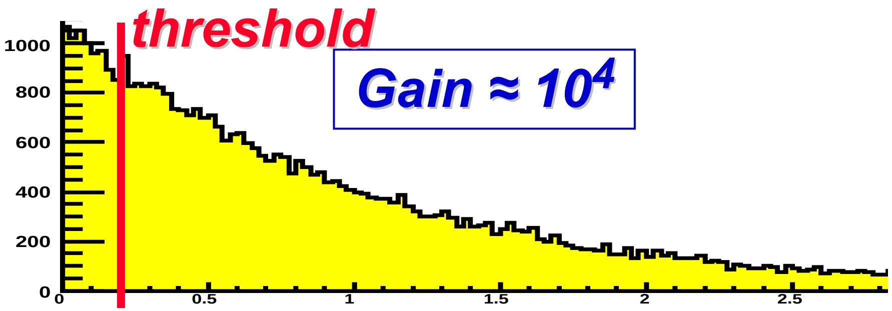
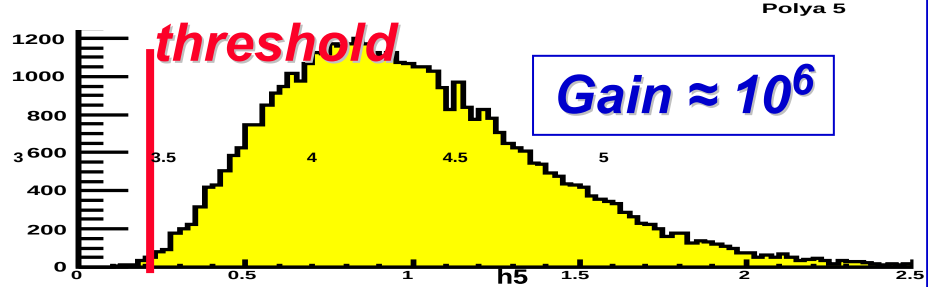
THE SPECIFICITY OF SINGLE PHOTON DETECTION 1/2

STRUGGLING WITH POLYA FUNCTIONS





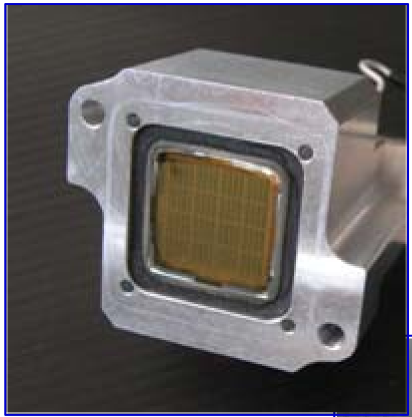
Threshold always critical !
limited pe detection efficiency,
performance instabilities



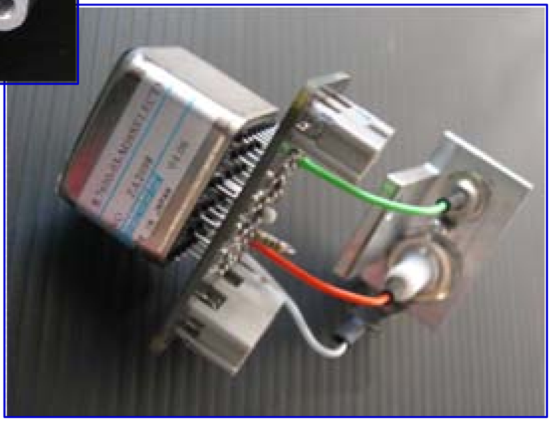
Threshold no longer critical,
good pe detection efficiency
stable behaviour

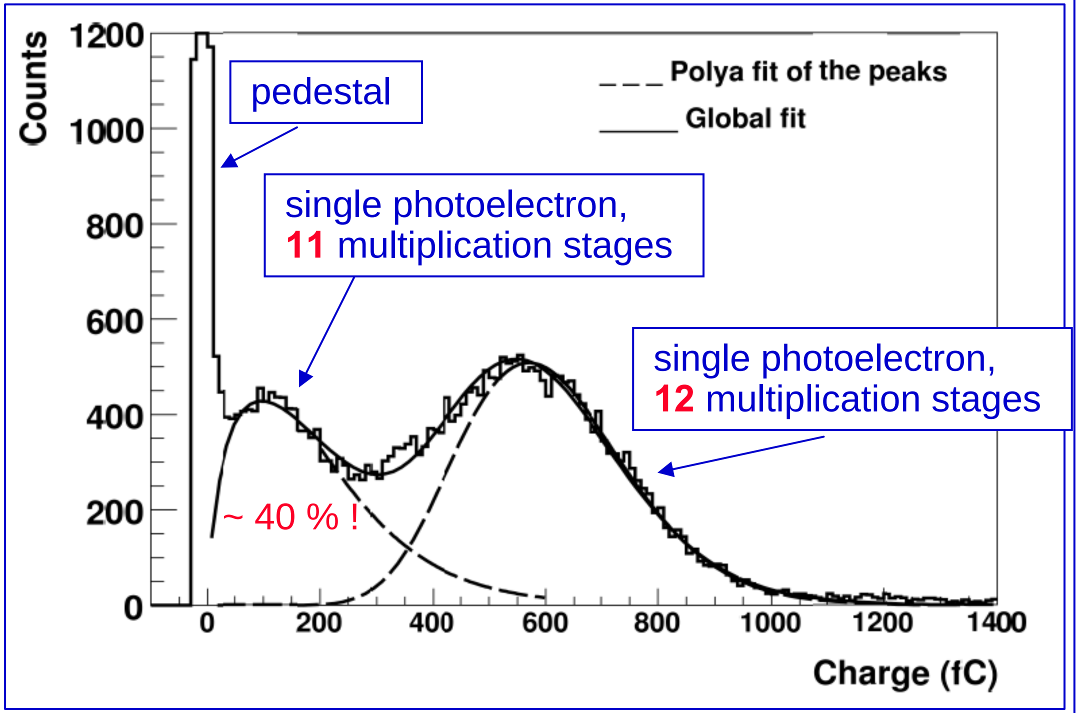
well established detectors can offer surprises
when single photons are detected

an example:



MAPMT
HAMAMATSU
R7600-03-M16





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SINGLE PHOTON DETECTORS 1/2

single photon detectors :

the CENTRAL QUESTION since the beginning of the RICH era

3 groups (with examples, not exhaustive lists)

Vacuum based PDs

- **PMTS (SELEX, Hermes, BaBar DIRC)**
- **MAPMTs (HeraB, COMPASS RICH-1 upgrade)**
  - **Flat pannels (various test beams, proposed for CBM)**
- **Hybride PMTs (LHCb)**
- **MCP-PMT (all the studies for the high time resolution applications)**

Gaseous PDs

- **Organic vapours - in practice only TMAE and TEA (Delphi, OMEGA, SLD CRID, CLEO III)**
- **Solid photocathodes and open geometry (HADES, COMPASS, ALICE, JLAB-HALL A)**
- **Solid photocathodes and closed geometries (FENIX HBD, even if w/o imaging)**

Si PDs

- **Silicon PMs (first tests only recently)**

SINGLE PHOTON DETECTORS 2/2

R&D

the requests:

- QE: high QE (above standard PMT photocathodes having peak-values of 20-25 %)
- r: rate capabilities (> 100 kHz/ mm^2)
- t: time resolution below 100 ps
- B: insensitivity to high magnetic fields (B=1T and more)
- $: reasonable costs to make large systems affordable
- L: Large area and wide angular acceptance of each single sensor

the approaches:

- Poly- and nano-crystalline diamond-based photocathodes (QE)
- Photocathodes based on C nanotubes (QE)

} promising for a far future

- Hybrid avalanche photodiodes HAPD (B)
- Si photomultipliers (QE,r,t,B)
- Microchannel plate (MCP) PMTs (B,t)
- MPGDs + CsI (r, B, $)
- ARCALUX ($)
- Large, wide aperture (hybride) PMTs (L)

} astroparticle experiments

About QE

Comparison criteria

- PDE (Photon Detection Efficiency)
  better than QE
- PDE = $E_{GEOM} \times QE \times E_{pe}$
- also folding with effective Cherenkov spectrum essential !

nevertheless increased QE remains a central goal

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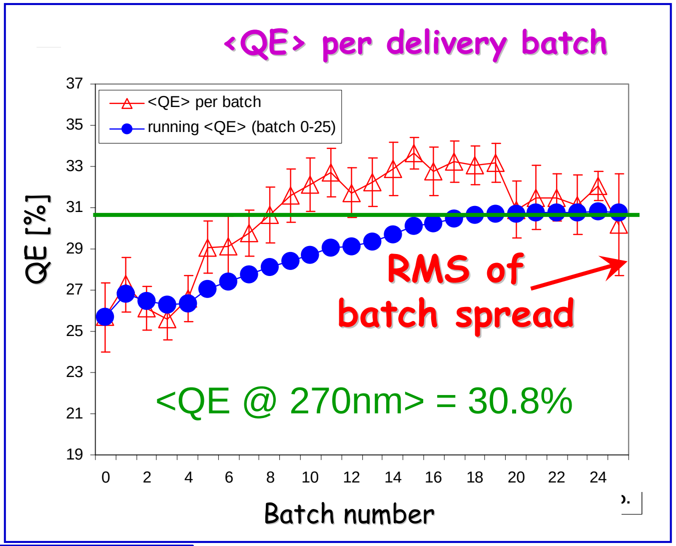
VACUUM BASED PDs - PHOTOCATHODES

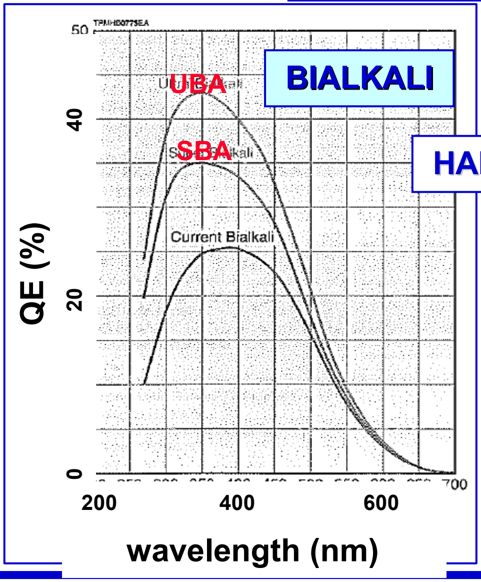
- **STANDARD:**
  peak QE ~ 25%

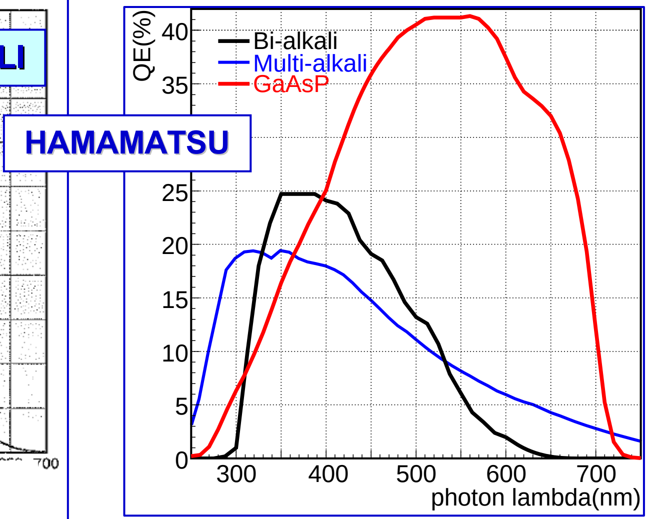
- **The LHCb-production example:**
  - **The necessity of deeper contacts and positive feedback loops with industry**

- **New HAMAMATSU photocathodes with peak-values above 40% !**

LHCb HPD production by DEP

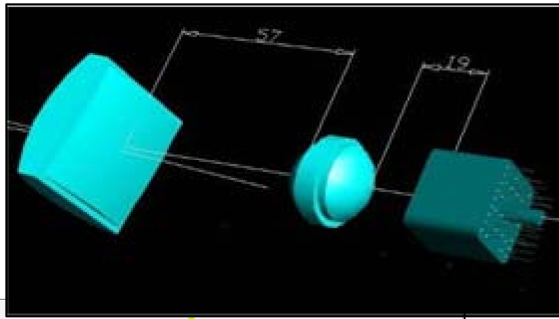


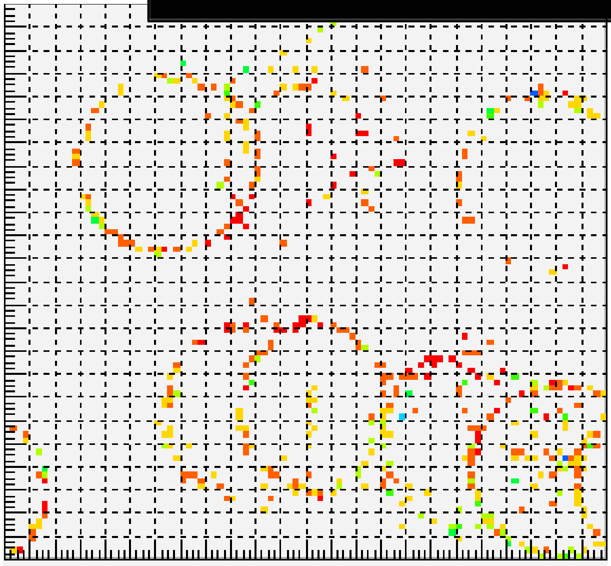




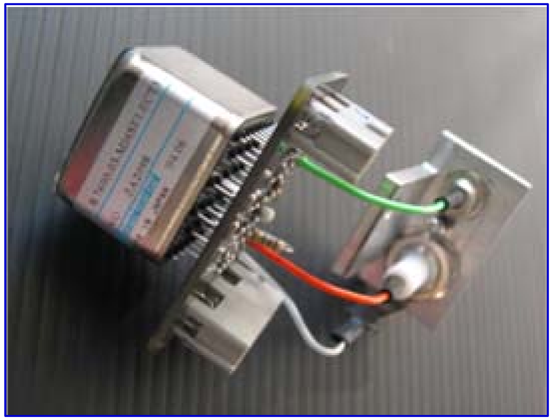
AN UP-TO-DATE EXAMPLE: COMPASS-RICH1

- COMPASS RICH-1 upgrade
  - Hamamatsu 16 anode PMTs (R7600)
  - NEW:UV extended glass coupled to quartz optics
  - NEW: Ratio 1:7 = photocathode s. / telescope entrance s. ($!)
  - wide angular acc. (± 9.5 degrees)
  - NEW: high sensitivity pre-amplifier and fast electronics
  - NEW : dead zone: 2% even with 46 mm pitch
    - ≈ 56 ph.s / ring at saturation
    - time resolution better than 1 ns
    - Cost: 1 M€ / m^2
  - in spite of the large angular acceptance, not adequate for large transverse size detectors which would require higher angular acceptance



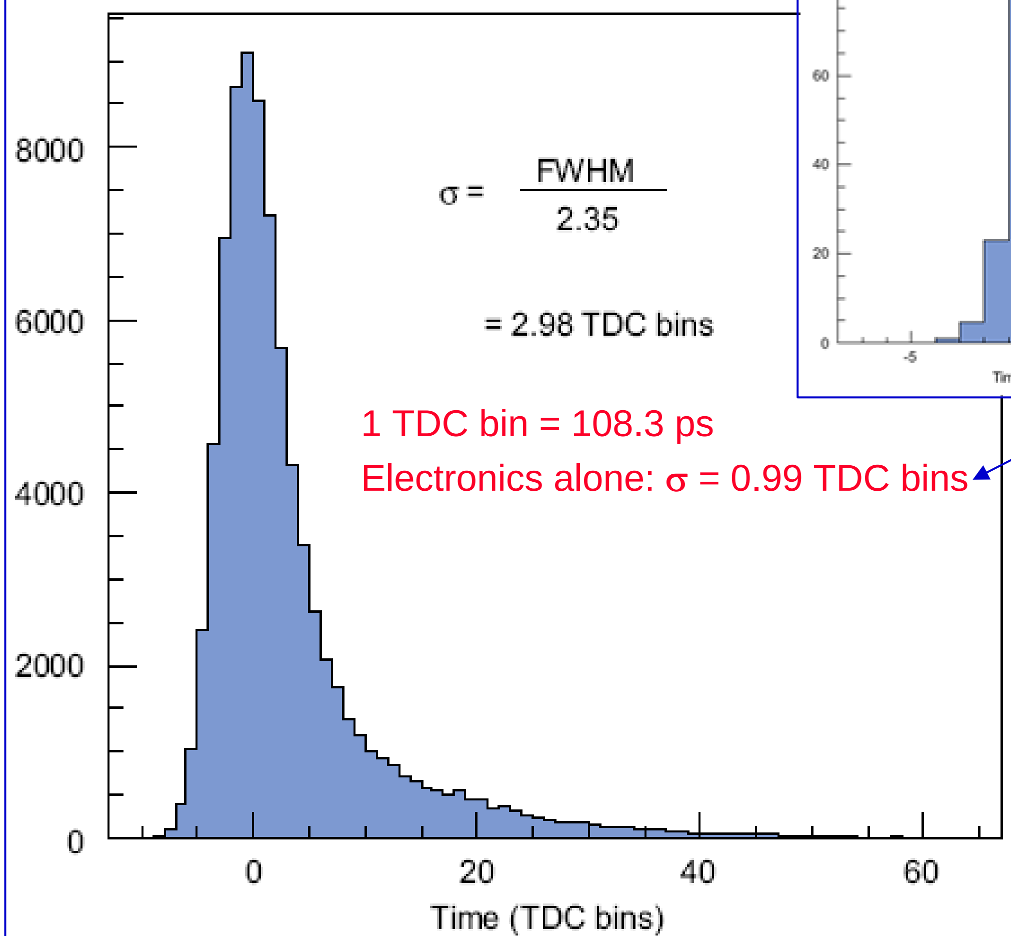


TIME RESOLUTION WITH MAPMTs



MAPMT
HAMAMATSU R7600-03-M16

resolution ~300 ps

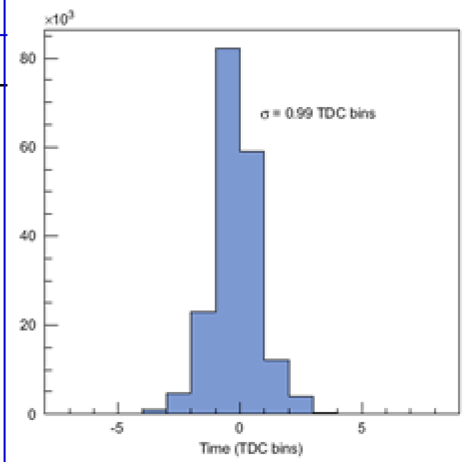


$$\sigma = \frac{\text{FWHM}}{2.35}$$

= 2.98 TDC bins

1 TDC bin = 108.3 ps

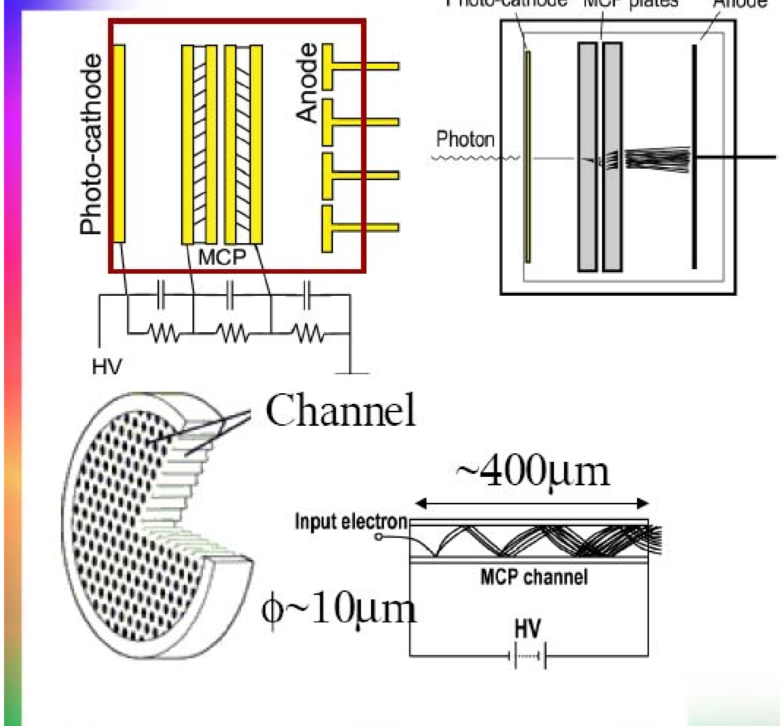
Electronics alone: σ = 0.99 TDC bins



MCP-PMTs

Microchannel Plate PMT

electron multiplication in glass capillaries (∅ ≈ 10 μm)



- very fast time response:
  - signal rise time = 0.5 – 1.5 ns
  - TTS < 50 ps
- high gain:
  - >10^6 with 2 MCP stages
  - single photon sensitivity
- usable in high magnetic fields
- low dark count rate
- quantum efficiency comparable to that of standard vacuum PMTs
- multi-anode PMTs possible
- caveats:
  - life time
  - price

Albert Lehmann RICH 2007 --- Trieste --- October 15-20, 2007

rate issue?

MCP-PMTs – 2 remarkable examples

BINP #73

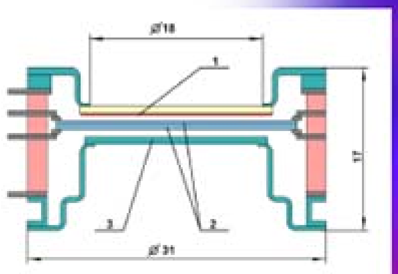


Fig. 1. The MCP PMT layout. 1 – photocathode, 2 – MCPs, 3 – anode. Sizes are in millimeters.

MCP channel diameter (µm)	6
Peak wavelength (nm)	500
Active area (mm x mm)	∅ 18
Number of pixels	1
Pixel size (mm x mm)	∅ 18

Single photon gain

- BINP #73 MCP-PMT well usable for single photon detection at 2 Tesla and at 45° tilt angle

- Single photon time resolution
  - best resolution of ~20 ps obtained for BINP #73

MCP-PMT, 4 ch.s

- Gain = 0.64×10^6
- TTS = 35ps for pe
- High Q.E. (>40% at 500nm) - GaAsP

the DIRC family

- the upgrade of the DIRC concept is via <u>time measurements with unprecedented resolution</u>

TRENDS

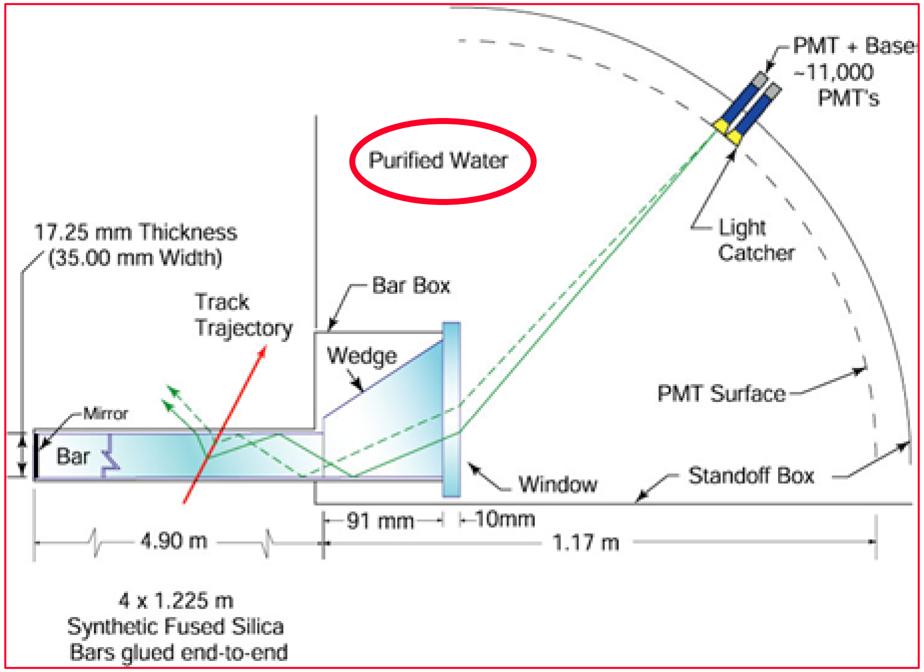
- TOP concept: save on the number of photon detector channels
  - Next step: Focalised TOP: include chromatic correction
- Focusing DIRC: push resolution via chromatic corrections – PROVEN!

RELATED TECHNICAL ASPECTS

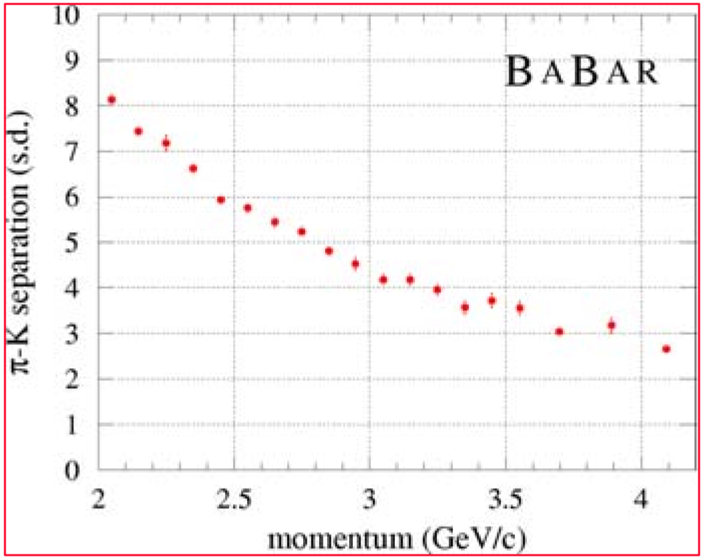
- Photon detectors allowing t resolution ≈ 50 ps → see later
- the t_0 quest
- development of adequate high rate electronics to preserve the t resolution figures in extended systems (≈ 10^5 ch.s)

BABAR DIRC

- **The only DIRC ever built and operated !**



π/K separation power:



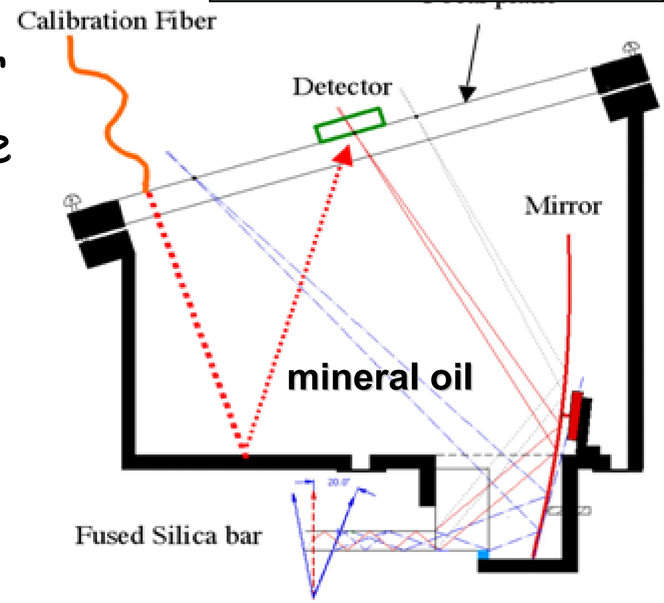
FOCUSING DIRC

J. Schwiening @ RICH2007

A general upgrade of the DIRC concept:

Future DIRC needs to be smaller and faster

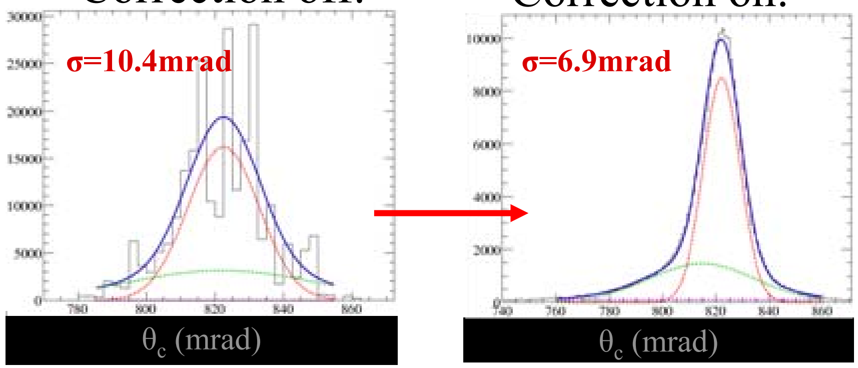
- Focusing (to remove the bar thickness depende and smaller pixels can reduce the expansion volume by a factor of 7-10
- Faster PMTs to remove chramatic dependance and reduce sensitivity to background.



Photon detectors

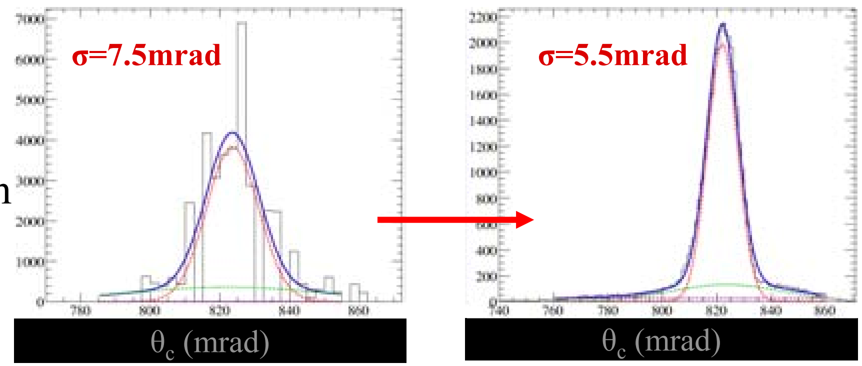
- Hamamatsu H-9500 MaPMTs
- Burle-Photonis MCP-PMT

Correction off: Correction on:



Position 1
Lpath≈10m

Correction off: Correction on:



NEW POSSIBILITIES FOR PID WITH TOF

Key points:

- fast Cherenkov light rather than a scintillation
- new detectors with small transit time spread σ_{TTS} < 30ps
  + statistics to get σ ~/< 10 ps
- Fast electronics

for low momenta:

1) For n ~ 1.03, the required σ_{TOF} ~ 5-10 psec & Lpath ~ 2m
2) For n ~ 1.47, the required σ_{TOF} ~ 15-20 psec & Lpath ~ 2m

No competition possible at high momenta (gaseous radiators) !!!

TOF: NEW OPPORTUNITIES

Conclusions

- **Our present best laser diode results:**
  - $\sigma_{\text{single MCP}} \sim$ 7.2 ps for Npe ~ 50, expected from a 1cm thick radiator.
  - $\sigma_{\text{TTS}} \sim$ 27 ps for Npe ~ 1.
  - Electronics contribution (Amp, CFD, TAC, ADC): $\sigma_{\text{Total\_electronics}} \sim$ 3.4 ps.
  - Upper limit on the MCP-PMT resolution: $\sigma_{\text{MCP-PMT}} \sim$ 4.5 ps, obtained for a modified resistor chain and Npe ~120.
- **Our present best test beam results:**
  - $\sigma_{\text{single MCP}} \sim$ 22.5 ps (believed to be due to a poor radiator Al-coating, and due to not having a fast ADC to correct PH variation).

10/18/07 J. Va'vra, TOF vs. RICH, Trieste, RICH 2007 34

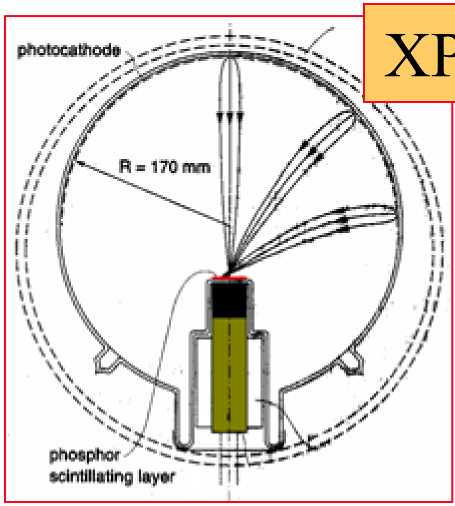
PHOTON DETECTORS FOR ν TELESCOPES

Specific features required

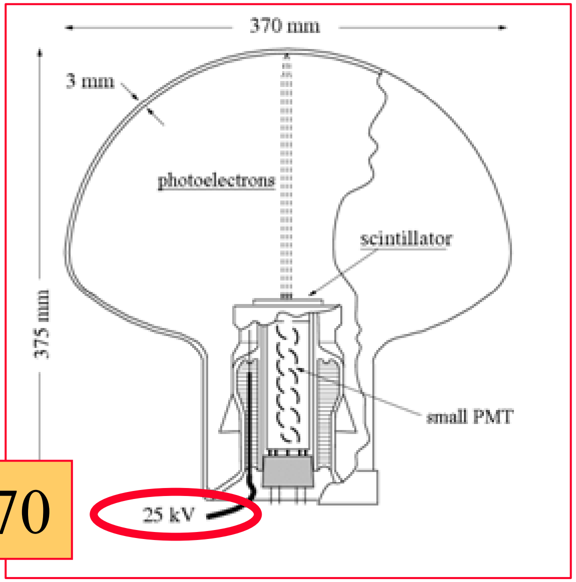
→ Hybrid phototubes with luminescent screen:
Light amplifier + small conventional type PMT

- High sensitivity to Cherenkov light
  → bialakali photocathode (next slide)
- Large sensitive area and 2π acceptance
  → hemispherical photocathode
- High time resolution → hemispherical photocathode
- Good SER (as good as possible) to suppress background
- Low dark current → bialkali photocathode
- Immunity to terrestrial magnetic field
- no prepulses, no late pulses, limited afterpulses
- Fast response (a few ns is enough)
  Light dispersion in water smears
  photons arrival times
  e.g. 100 m - Δt(fwhm) ~ 5ns
  for Mediterranean

XP2600

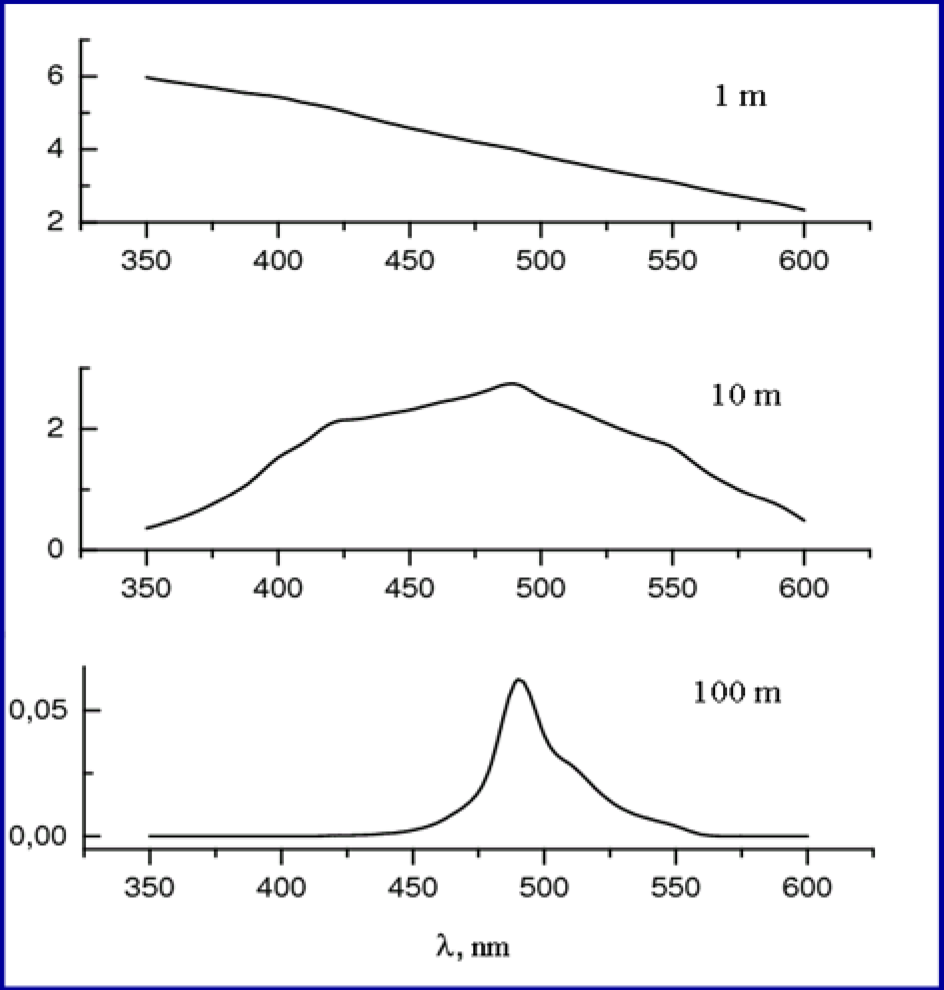


QUASAR-370

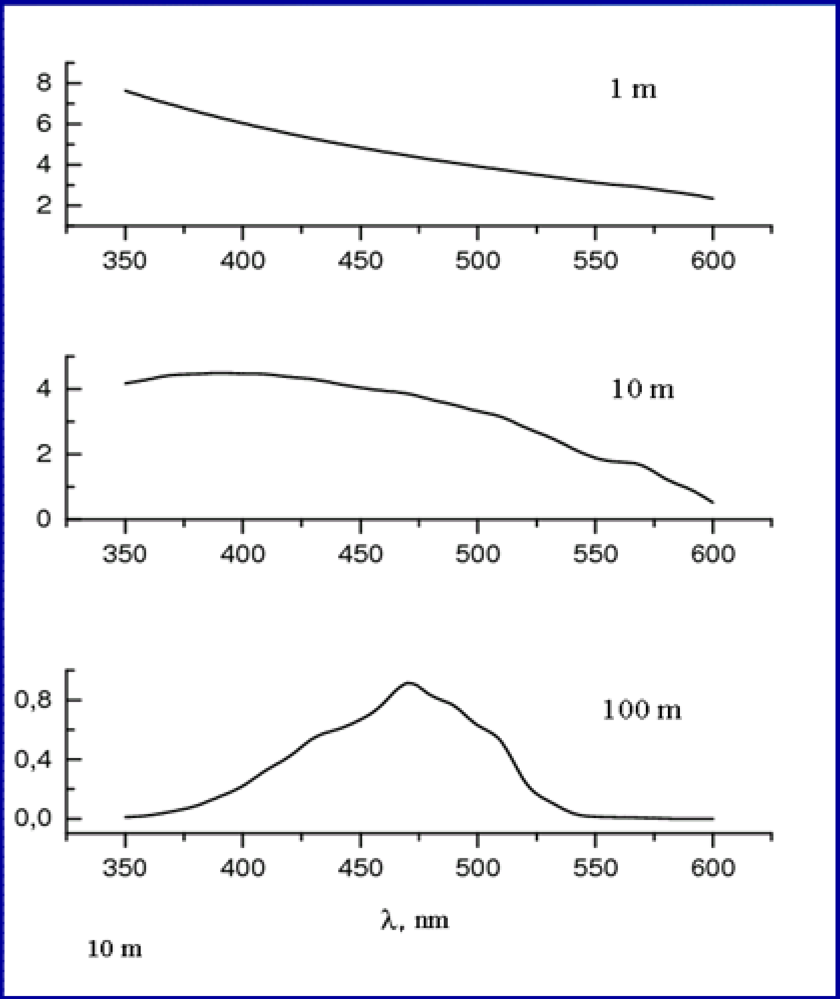


Transformation of Cherenkov light spectrum in water

Baikal



Mediterranean



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LARGE SENSITIVE AREAS ↔ GASEOUS PDs

- photoconverting vapours are no longer in use, a part CLEO III (rates ! time resolution !)

PAST

- the present is represented by MWPC (open geometry!) with CsI
  - the first prove (in experiments !) that coupling solid photocathodes and gaseous detectors works
  - Severe recovery time (~ 1 d) after detector trips
  - Aging
  - Moderate gain: < 10^5 (effective gain: <1/2)

  } ion feedback → CsI ion bombardment

PRESENT

- The way to the future: ion blocking geometries
  - GEM/THGEM allow for multistage detectors
    - With THGEMs: High overall gain ↔ pe det. efficiency!
    - Good ion blocking (up to IFB at a few % level)
    - MHSP: IFB at 10^{-4} level
      - opening the way to the physicists' dream (Philosopher's Stone):
      - Gaseous detectors with solid photocathodes for visible light

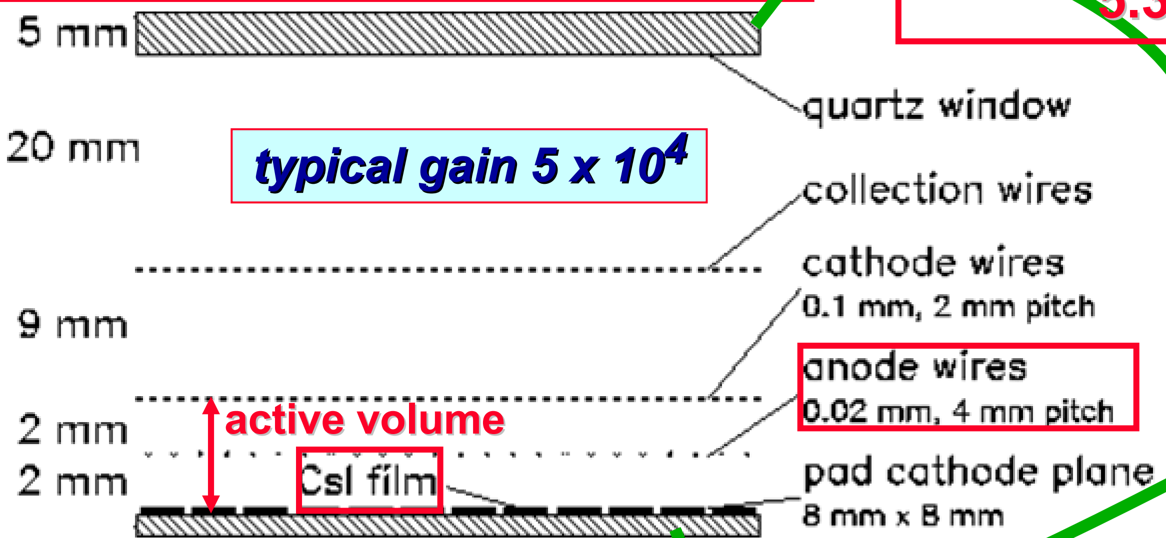
        (this is for far future)

FUTURE

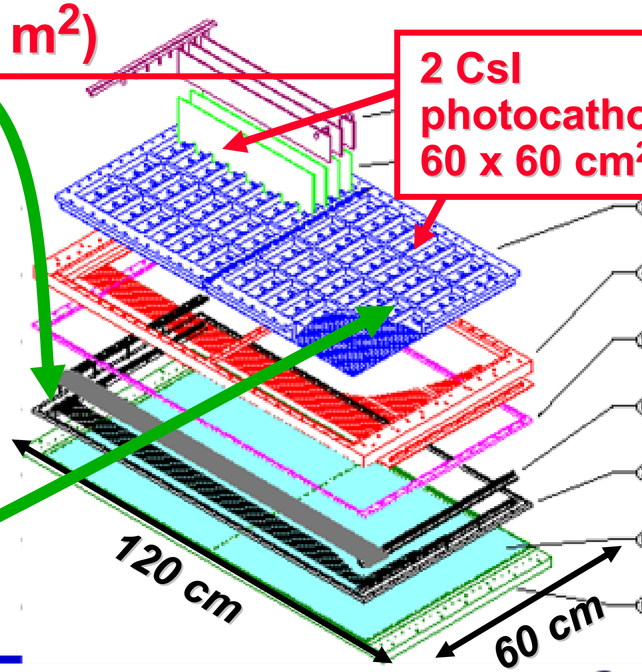
MWPCs with CsI PHOTOCATHODES

gaseous photon detectors developed by RD26
large surface photocathodes in gaseous detectors:
effective QE >20% @ 170 nm routinely obtained
in the following: COMPASS RICH-1 experience

MWPCs with CsI photocathodes, geometry



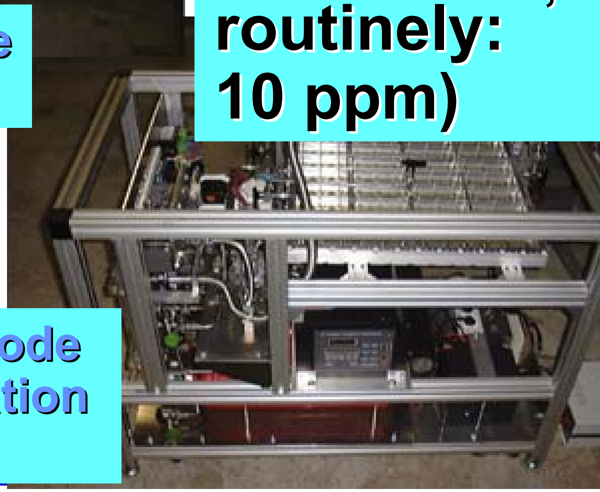
MWPCs with CsI photocathodes, detector components (8 chambers, 5.3 m^2)



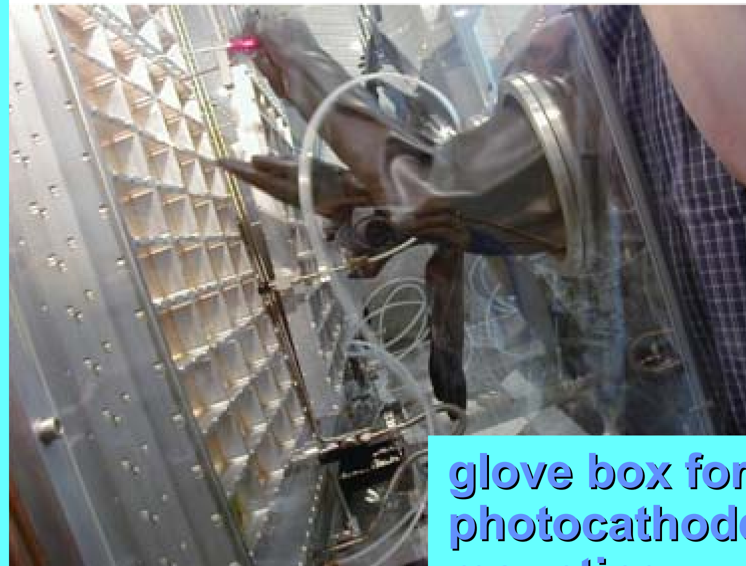
LARGE SIZE PHOTOCATHODES, COMPASS EXPERIENCE

CsI: hygroscopic, water degrades QE → **never exposed to air (max 50 ppm O_2, routinely: 10 ppm)**

photocathode storing



photocathode transportation system



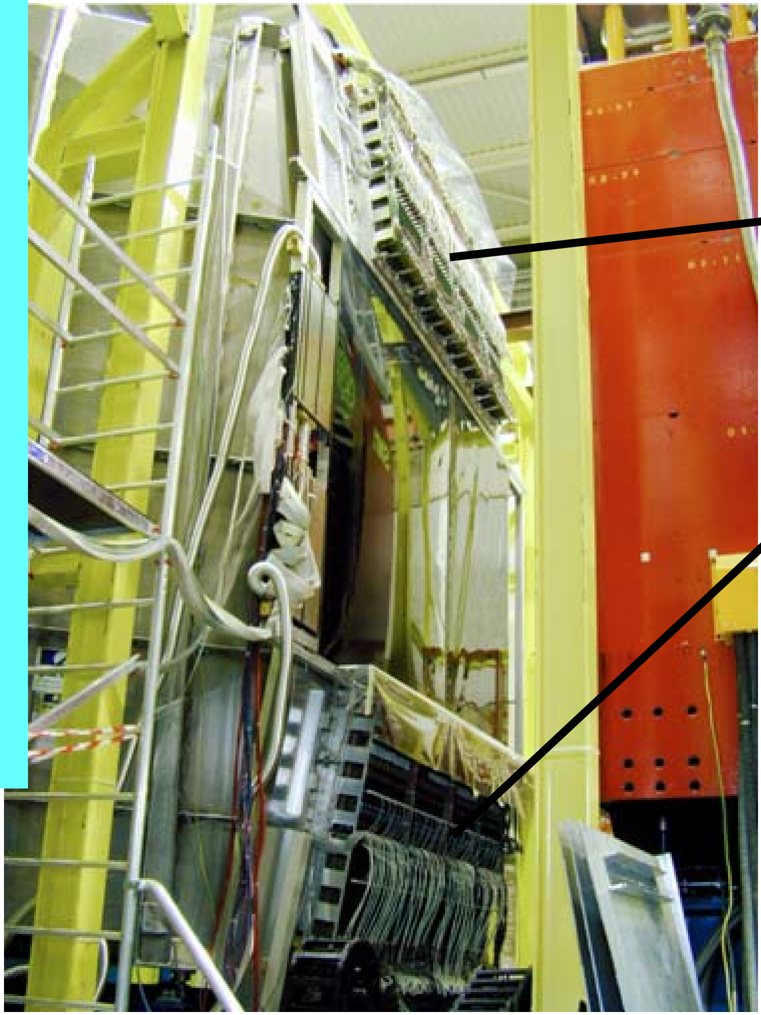
glove box for photocathode mounting

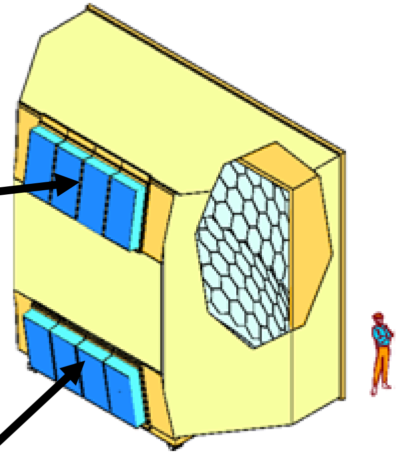
PDs CH4 gas system, semiclosed loop with O_2 and H_2O filters

COMPASS RICH-1 PHOTON DETECTION

photon detectors (PD) :
5.3 m^2 MWPCs with CsI photocathode

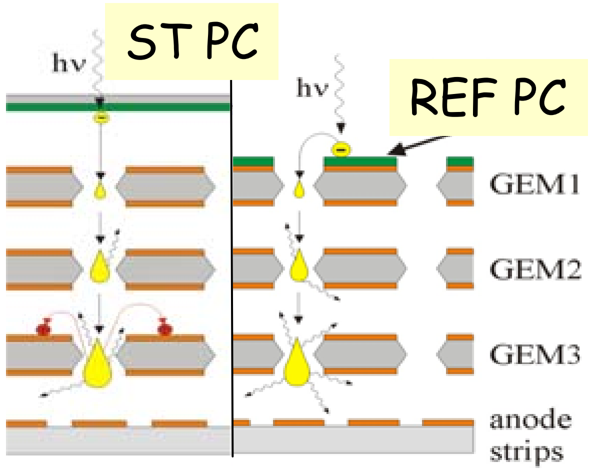
read-out:
84,000 analog read-out ch.s with extended local intelligence

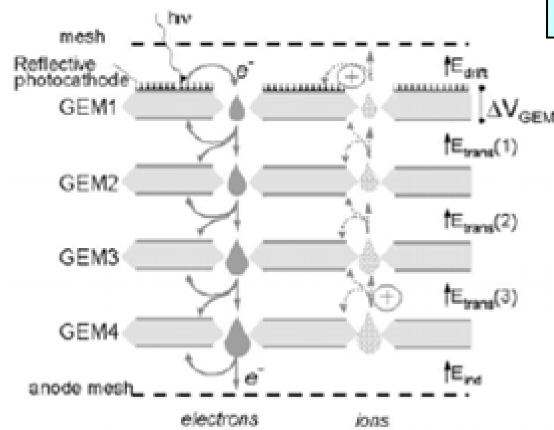


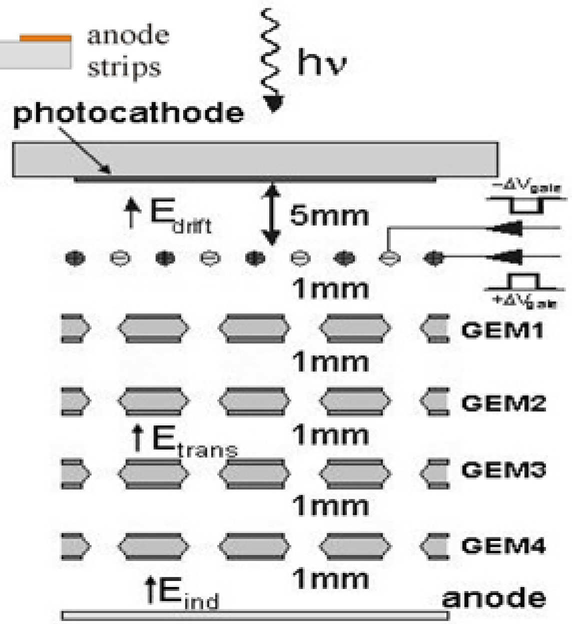


ION BLOCKING GEOMETRIES

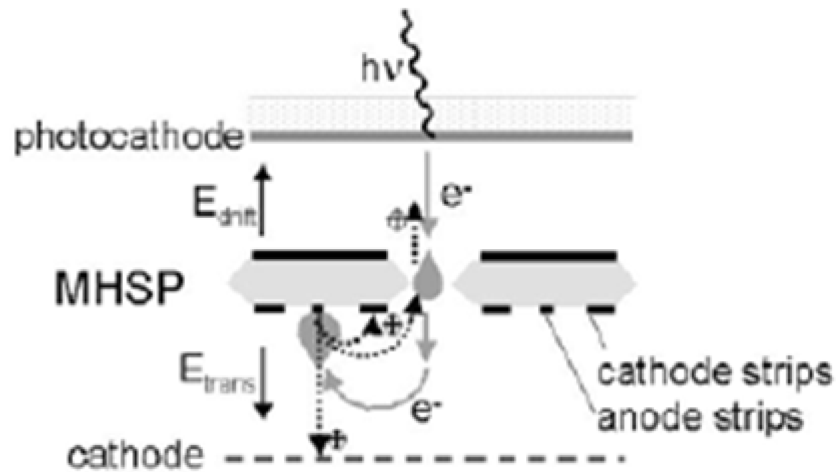
R. Chechwik @ RICH2007







GATED MULTI-GEM



The future starting with HBD

- NOT AN IMAGING COUNTER →
  NO SINGLE PHOTOELECTRON ISSUE
  no specific high gain request

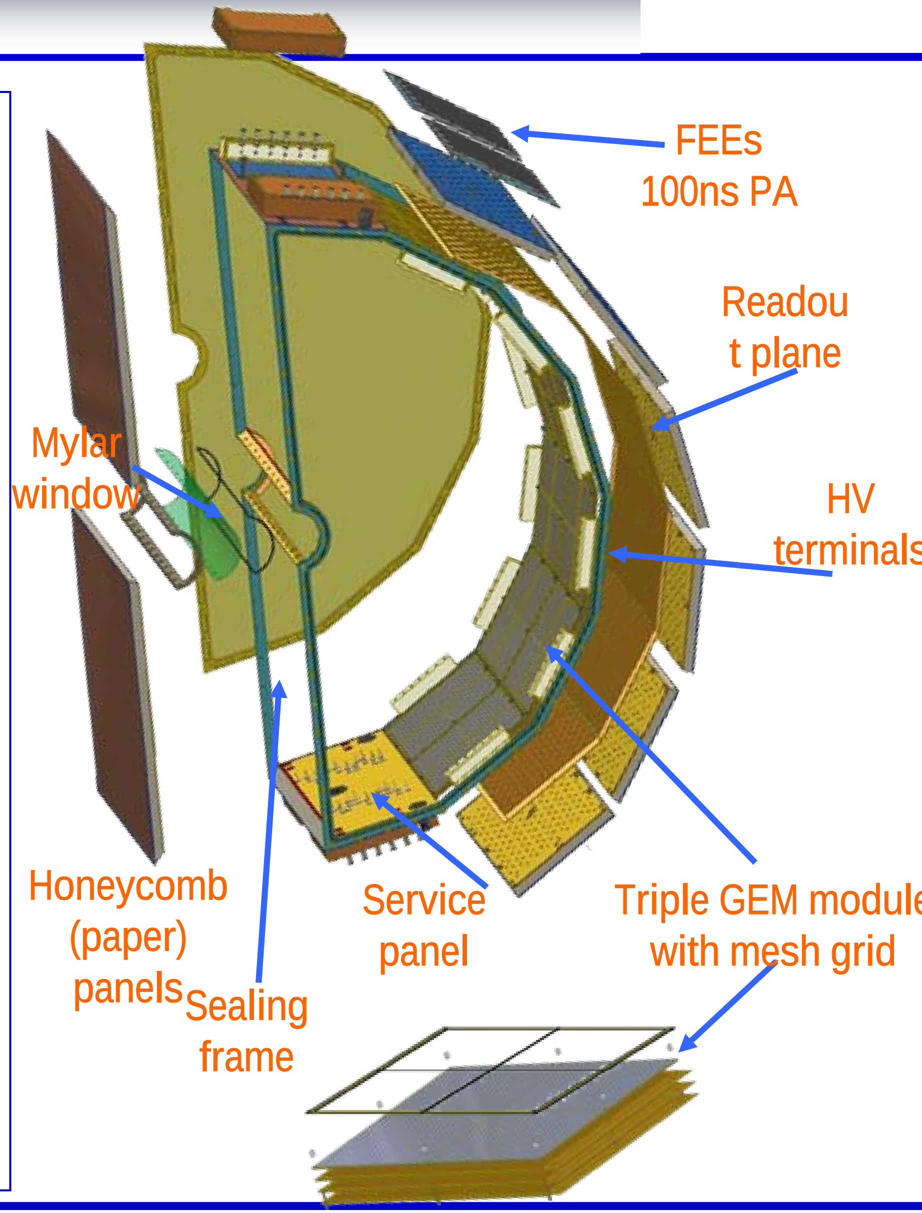
- GEM-based photon detectors
- scheme invented and proved at Weizmann
- Operation in CF_4 also proven in lab→
  windowless detector →
  substantial increase in λ range:
  down to 120 nm (10 eV)

HBD – first application

noise performance: pedestal rms 0.15 fC or 0.2 p.e. at a gain of 5000, but several pe/channel

Photon detector – 1 m^2

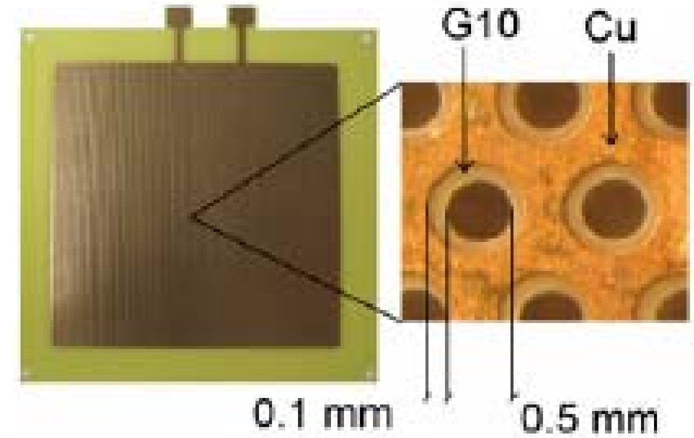
looking forward to learning about the details of the performance !

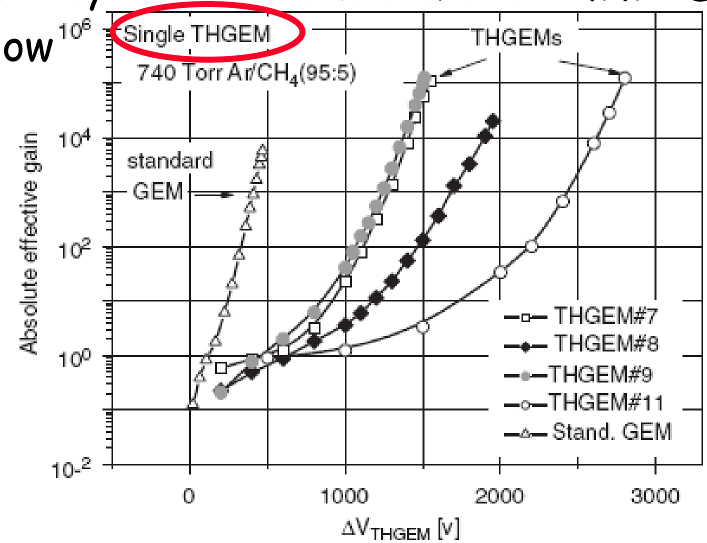


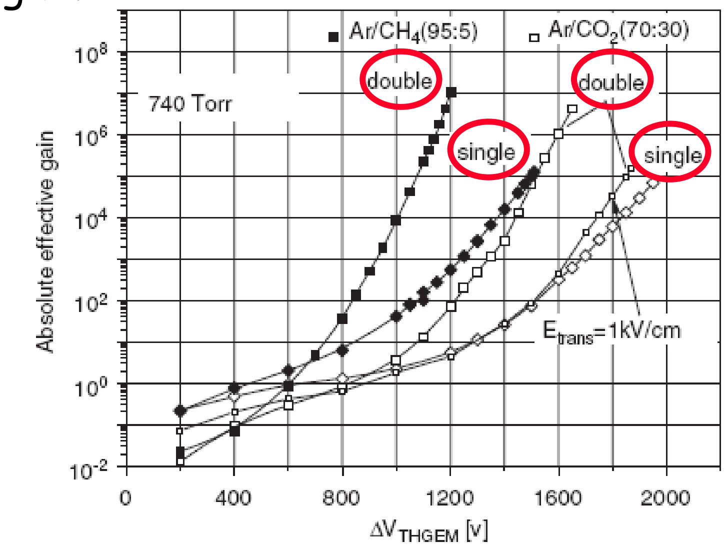
THickGEMs looh promising

THGEMS – Thick GEM-like e-multipliers

- manufactured by standard PCB
- techniques of precise **drilling**
- in G-10 (+ other materials) and **Cu etching**
- Gains for single pe:
  - 10^5 with a single TGEM;
  - 10^7 with cascaded double TGEM
- Fast signals: r.t. <10 ns.
- Counting rate capability: ~ 10^6 avalnches/sec x mm2 @ gain 4x104
- Limited Ion backflow
- TGEM studied with transparent and reflective photocathode







Weizmann group,
NIMA A 558 (2006) 475

WHY ARE WE TRYING WITH THGEMs? WHY COUPLED TO REFLECTIVE PHOTOCATHODES?

- No need of high space resolution (> 1 mm)

- Large area coverage (5.5 m^2 for COMPASS RICH)
  - industrial production
  - stiffness
  - robust against discharge damages
  - easier to build
  - possibilities of high gain

- For reflective photocathodes,
  - no need to keep the window at a fixed potential (2nm Cr → -20%)
  - possibility of windowless geometry
  - higher effective QE (larger pe extraction probability)

→ small photoconversion dead zones (<20%; GEM ~ 40%)

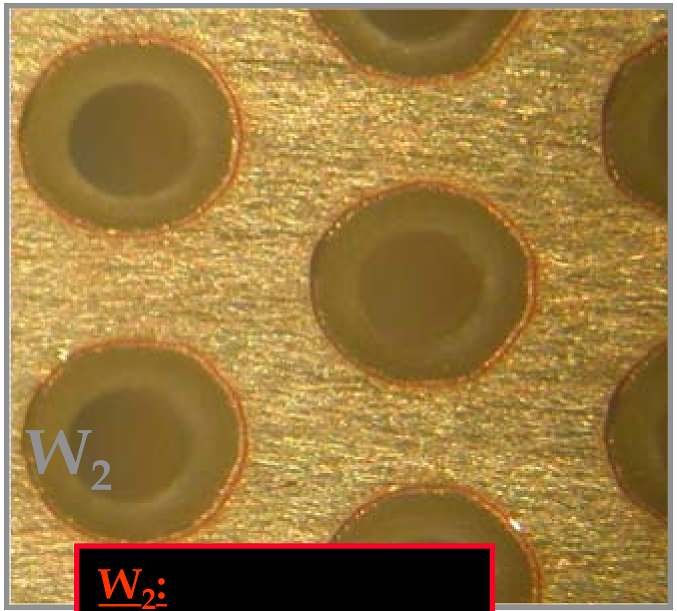
We started and R & D study

EXAMPLES OF THGEMS

A MULTIPARAMETER SPACE TO EXPLORE !

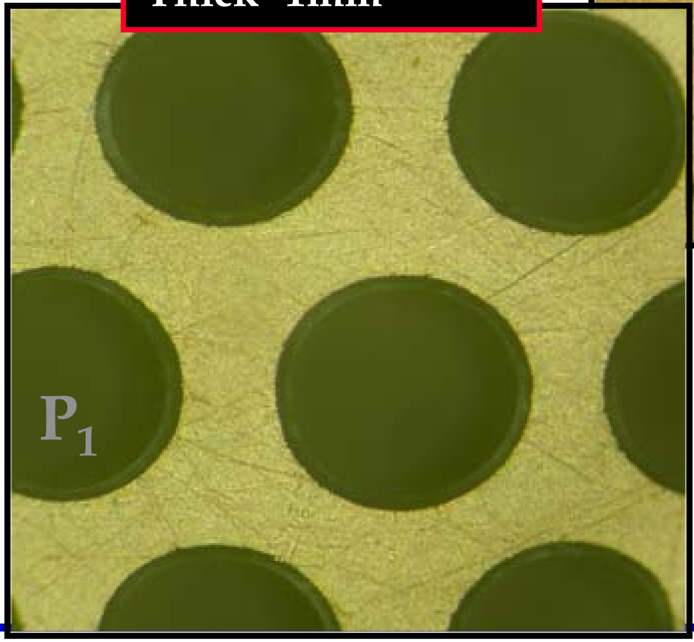
4 geometrical parameters: diameter pitch rim thickness

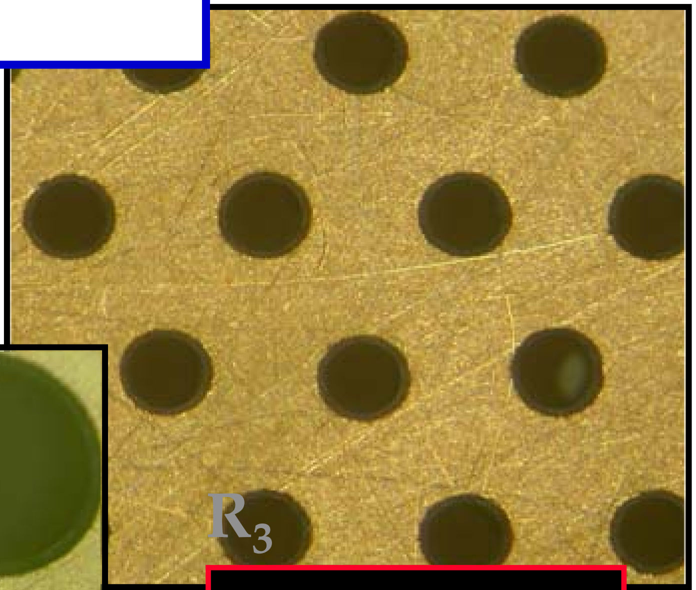
\+ material + production procedure



W_2:
D=0.3 mm
Pitch=0.7 mm
Rim=0.1 mm
Thick=0.4mm

P_1:
D=0.8 mm
Pitch=2 mm
Rim=0.04 mm
Thick=1mm



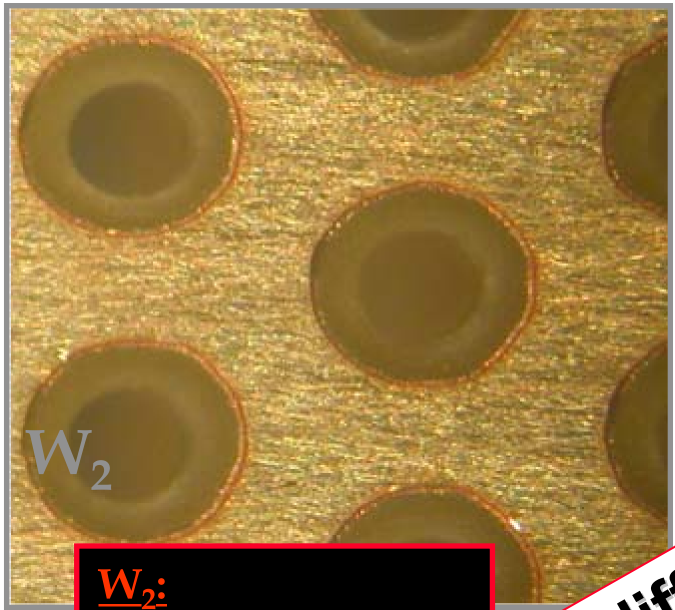


R_3:
D=0.2 mm
Pitch=0.5 mm
Rim=0.01 mm
Thick=0.2mm

A MULTIPARAMETER SPACE TO EXPLORE !

4 geometrical parameters: diameter pitch rim thickness

\+ material + production procedure



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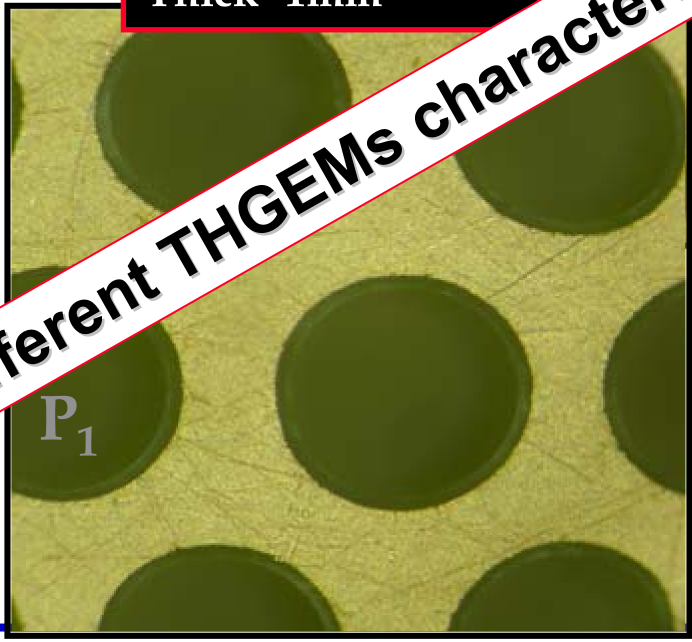
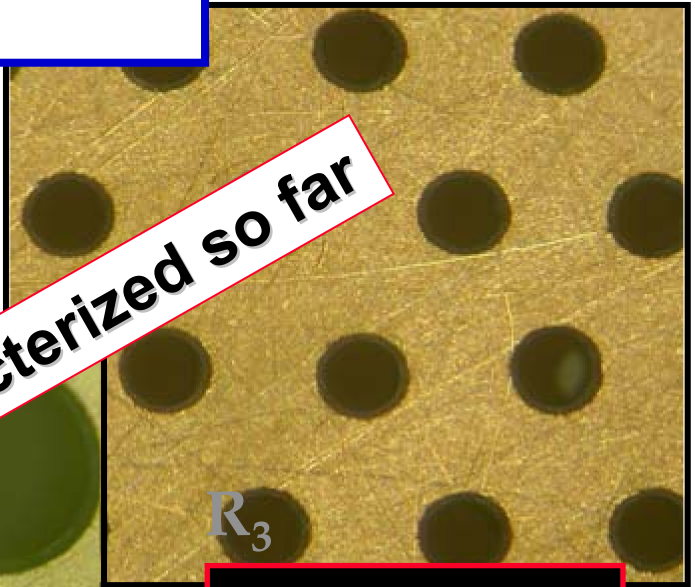


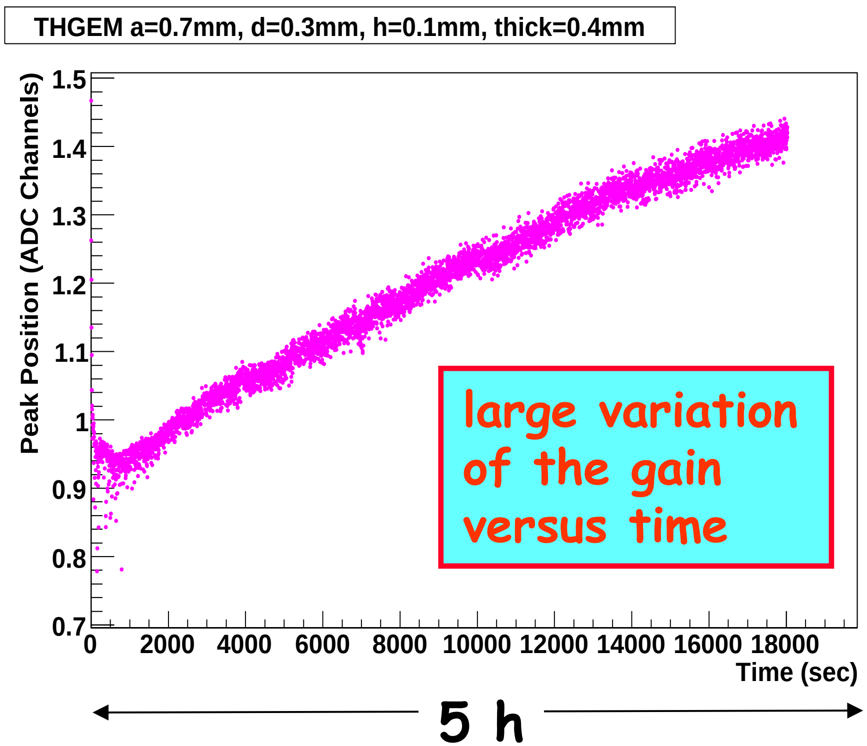
22 different THGEMs characterized so far

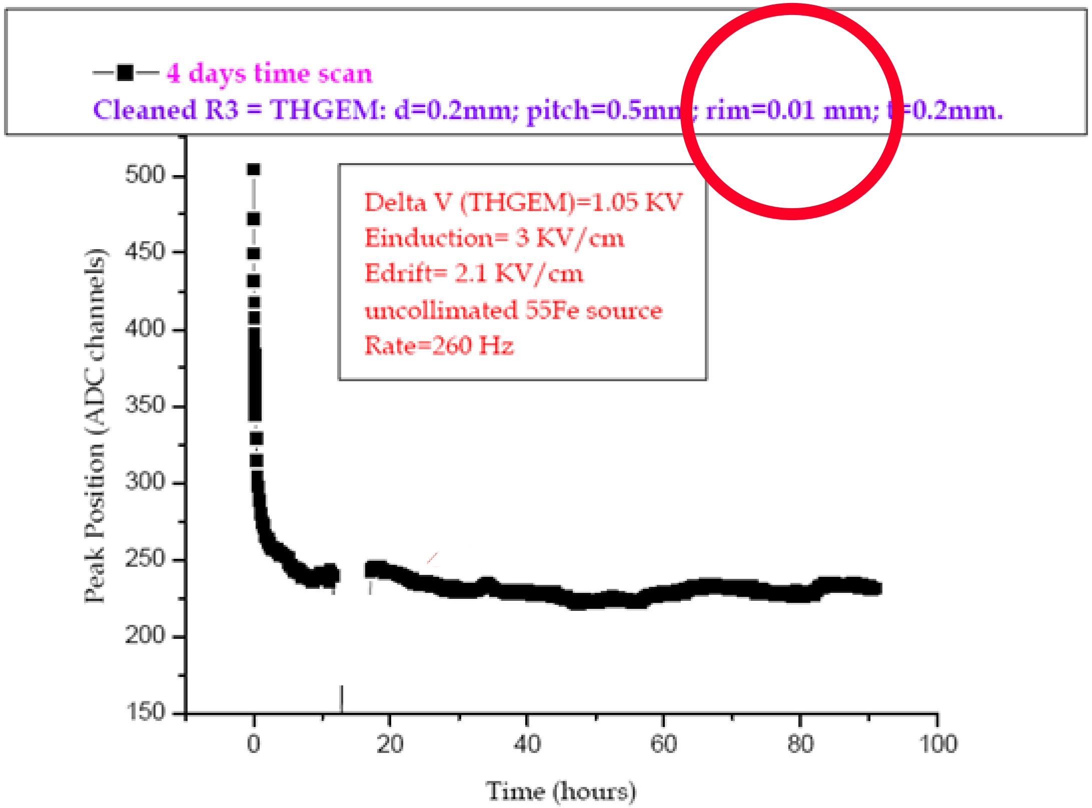


R_3:
D=0.2 mm
Pitch=0.5 mm
Rim=0.01 mm
Thick=0.2mm

GAIN STABILITY

THGEM	Diameter (mm)	Pitch (mm)	Rim (mm)	Thick (mm)
W_2	0.3	0.7	0.1	0.4





2007 IEEE Nuclear Science Symposium Conference Record MP5-3

Understanding the gain characteristics of GEMs inside the Hadron Blind Detector in PHENIX.

W. Anderson, B. Azmoun, C.-Y. Chi, Z. Citron, A. Dubey, J. M. Durham, Z. Fraenkel, T.Hemmick, J. Kamin, A. Kozlov, A.Milov, M. Naglis, R. Pisani, I. Ravinovich, T. Sakaguchi , D. Sharma, A. Sickles, I. Tserruya, C. Woody

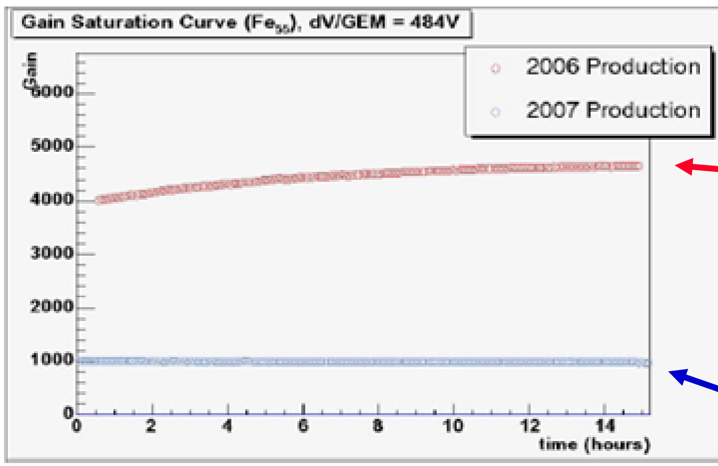


Fig. 11. Gain as a function of time after HV was on for 3 days. Red points are for a GEM stack comprised of GEMs produced in 2006; blue points are for a stack of 2007 GEMs.

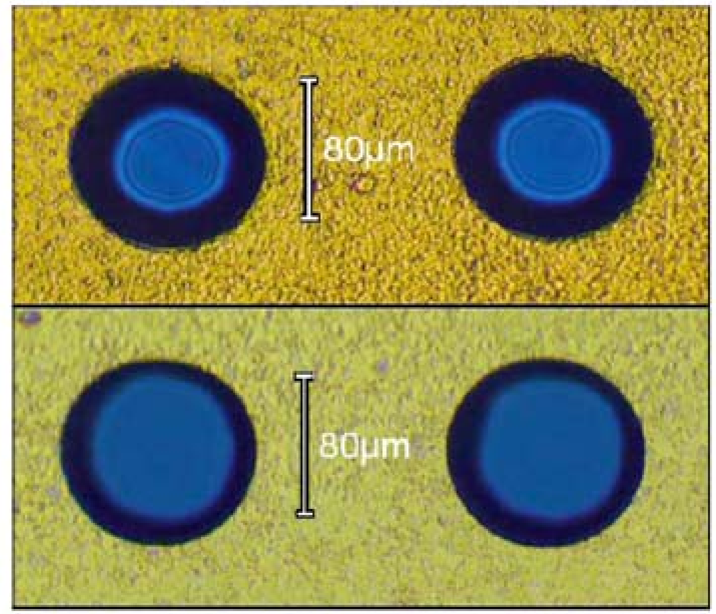
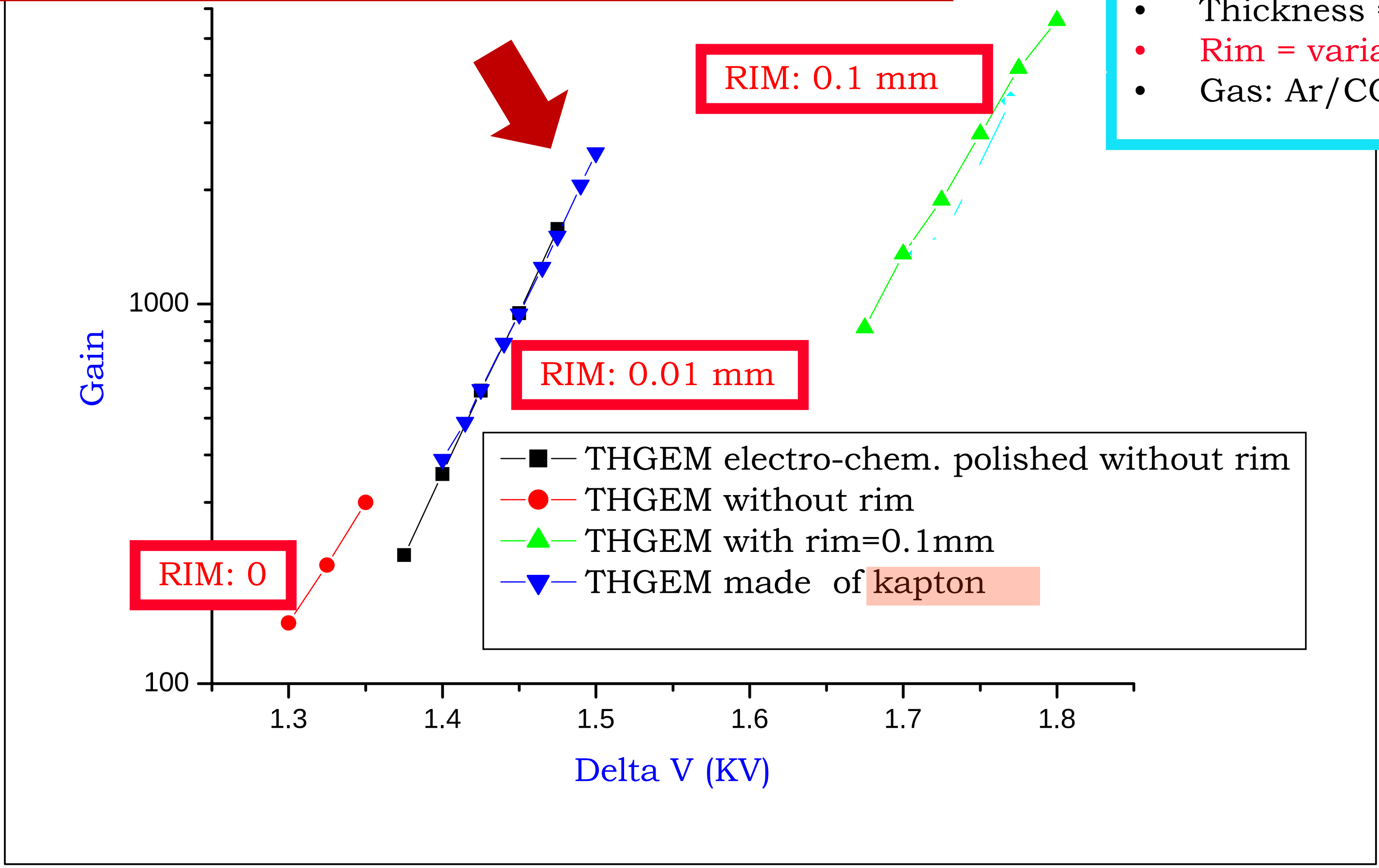


Fig. 12. GEM holes viewed under a microscope. 2006 production GEMs are shown above; 2007 production GEMs are below.

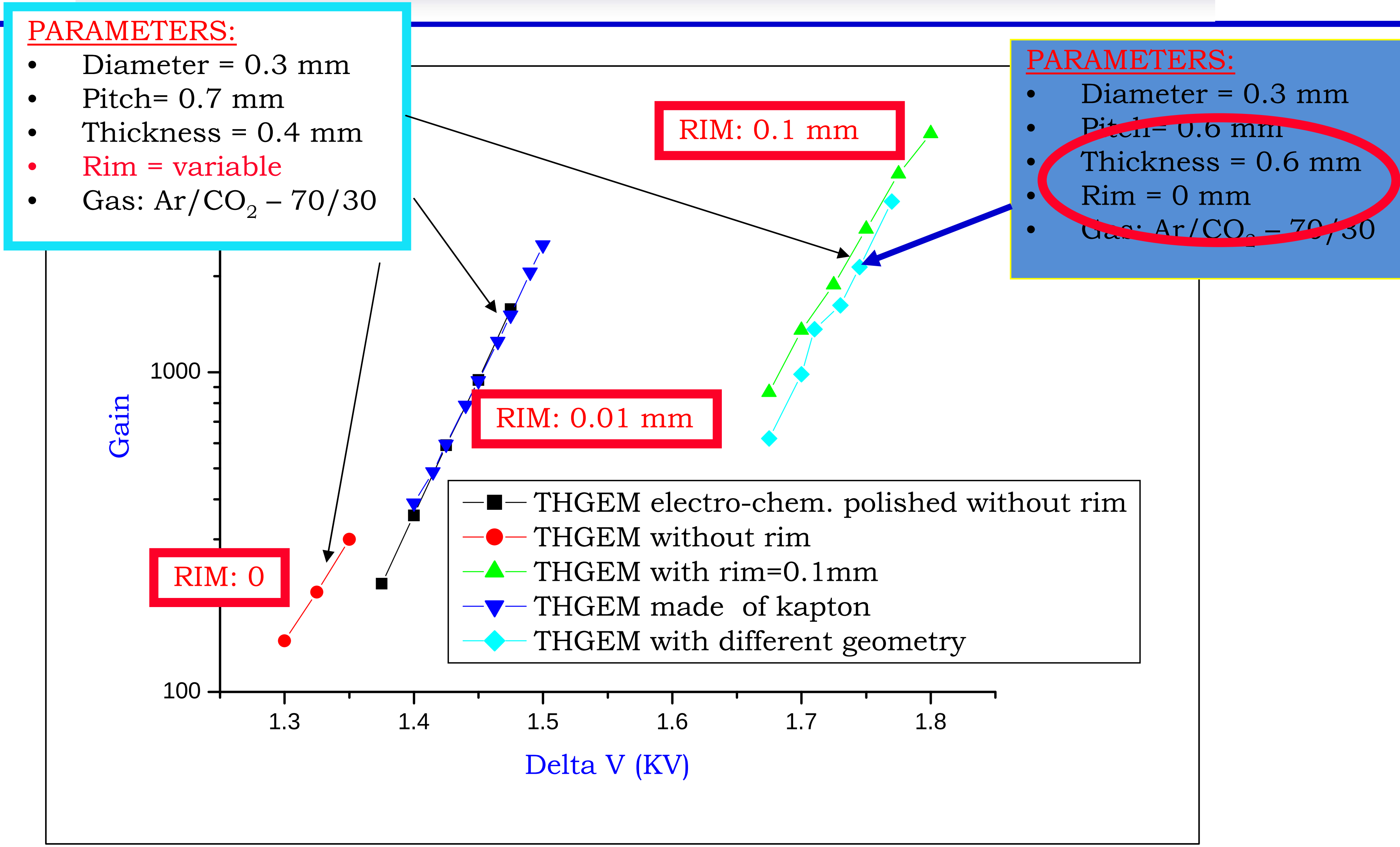
MORE ABOUT GAIN

The gain of the electro-chem. polished THGEM is overlapped by the gain of the kapton THGEM

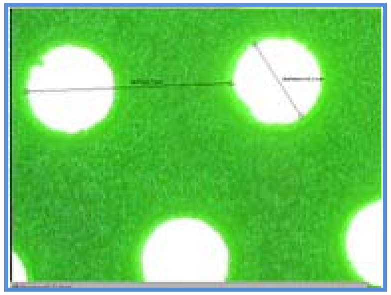
PARAMETERS:
- Diameter = 0.3 mm
- Pitch= 0.7 mm
- Thickness = 0.4 mm
- Rim = variable
- Gas: Ar/CO_2 – 70/30



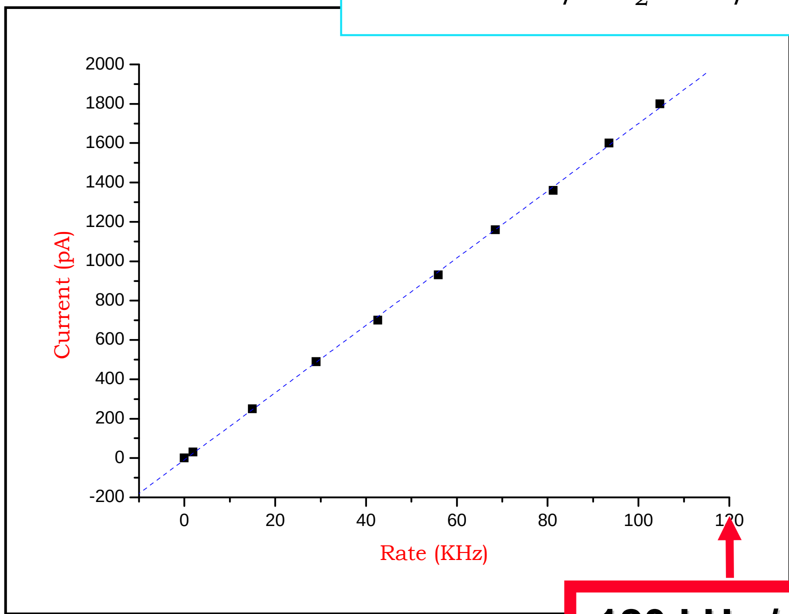
MORE ABOUT GAIN



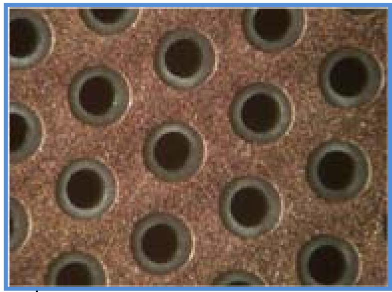
ARE THGEM DEVICES FOR HIGH RATERS ?



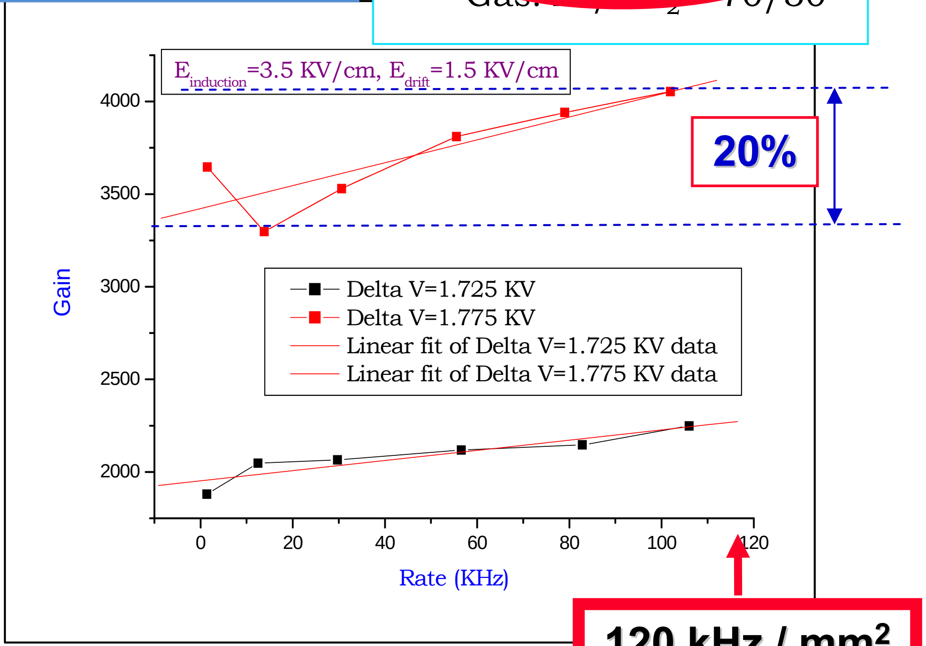
PARAMETERS:
- Diameter = 0.3 mm
- Pitch= 0.7 mm
- Thickness = 0.4 mm
- Rim = 0 mm
- Gas: Ar/CO_2 – 70/30



120 kHz / mm^2



PARAMETERS:
- Diameter = 0.3 mm
- Pitch= 0.7 mm
- Thickness = 0.4 mm
- Rim = 0.1 mm
- Gas: Ar/CO_2 – 70/30



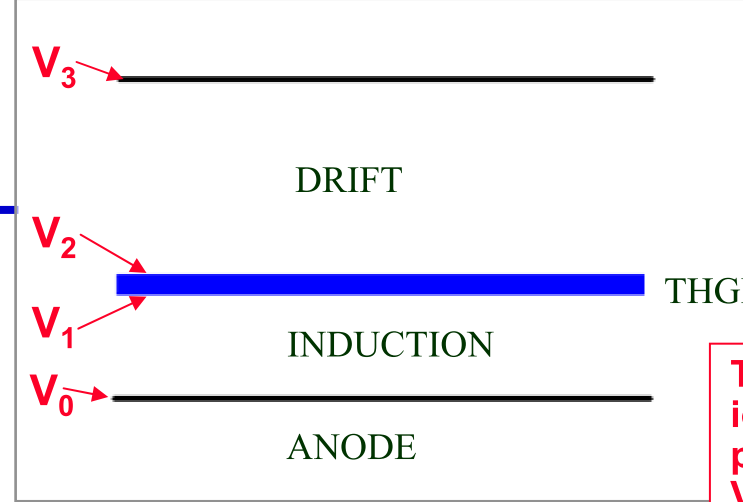
120 kHz / mm^2

RECALL:
120 kHz/ mm^2, 300 e- → single photoelectron rates of ~35 MHz/ mm^2

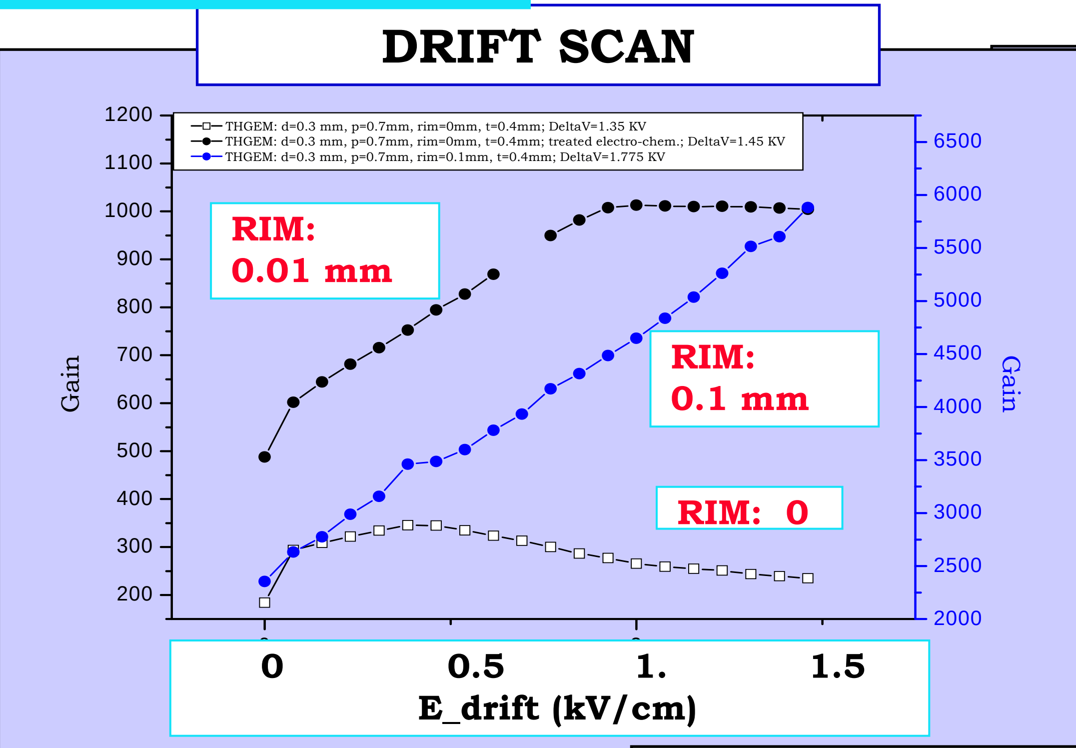
TUNING CHAMBER PARAMETERS

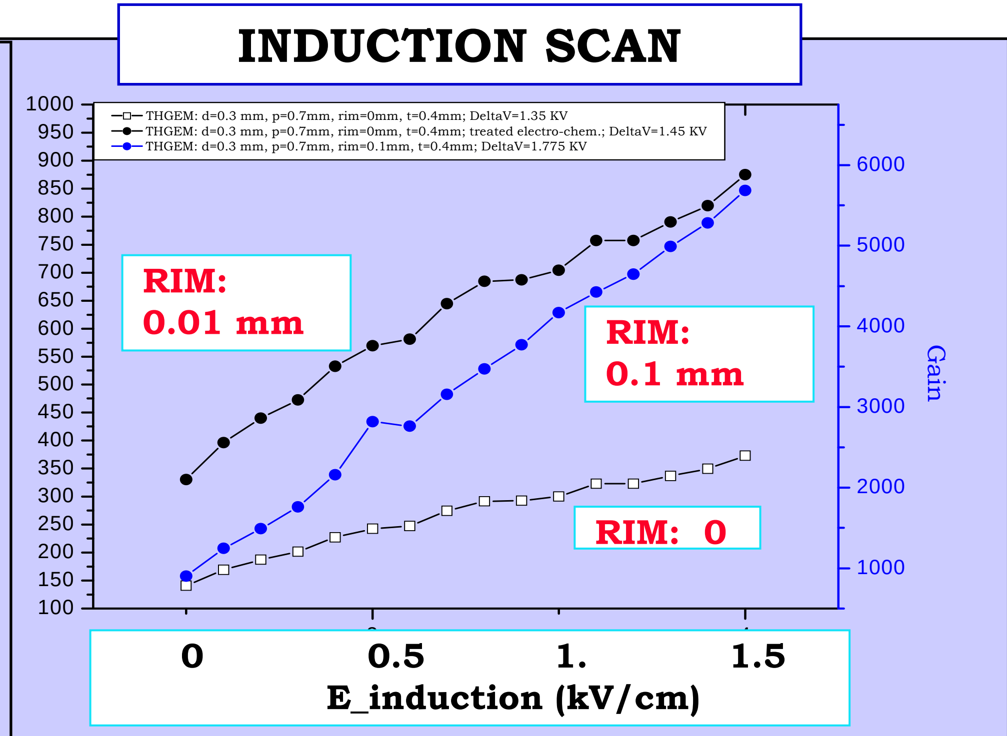
PARAMETERS:

- Diameter = 0.3 mm
- Pitch= 0.7 mm
- Thickness = 0.4 mm
- Rim = variable
- Gas: Ar/CO_2 – 70/30



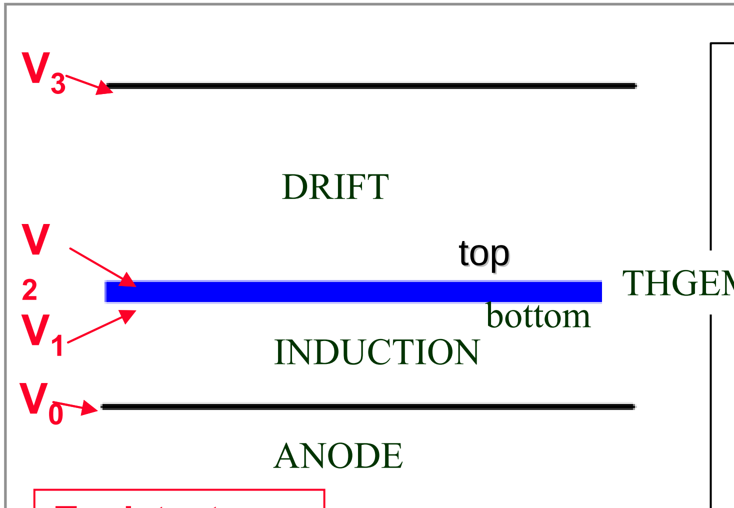
To detect ionizing particle : $V_3 > V_2 > V_1 > V_0$



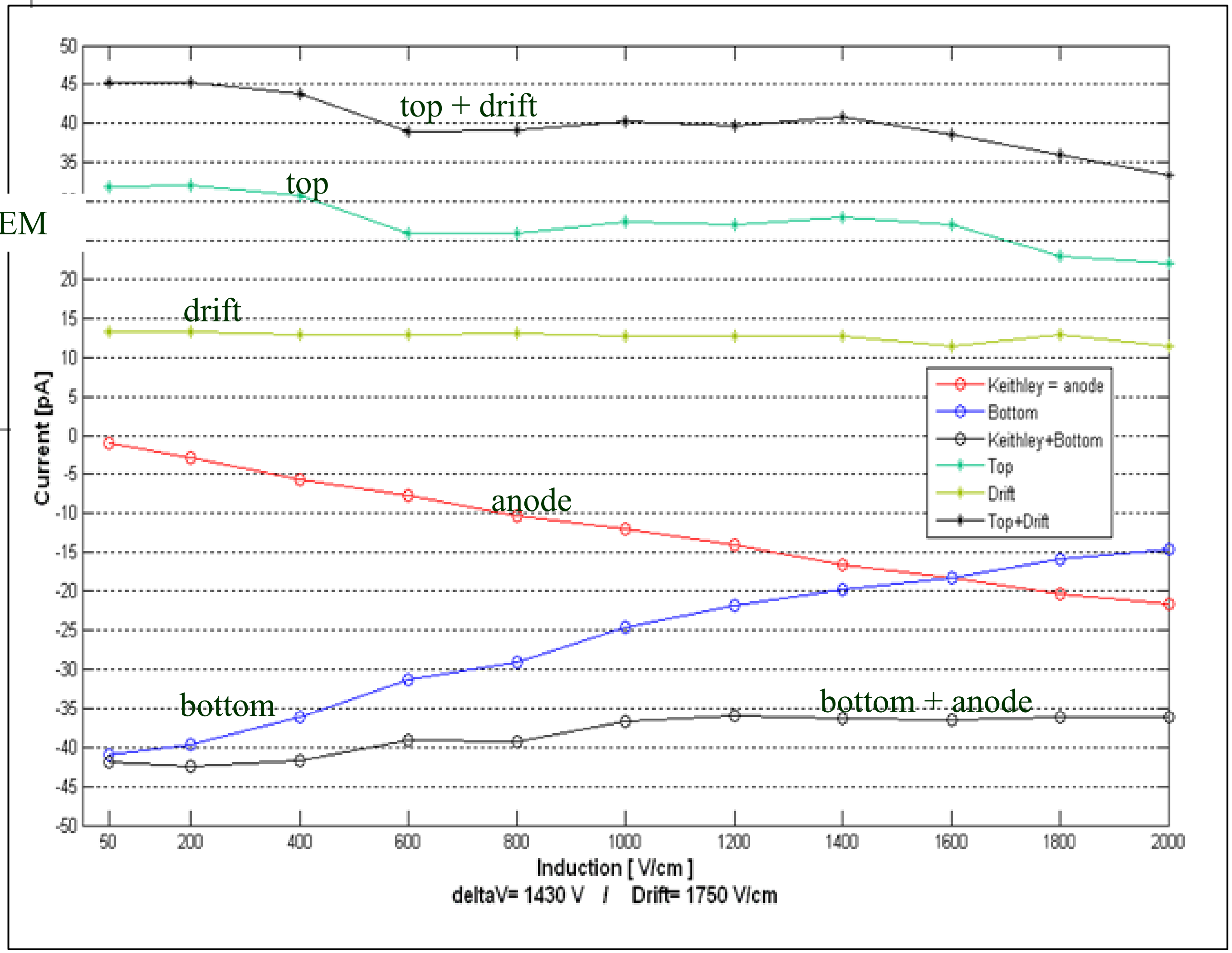


X-Ray Source: ~1 mm^2, rate ~1.7KHz.

UNDERSTANDING THE CURRENT FLOW



To detect ionizing particle :
$V_3 > V_2 > V_1 > V_0$



R & D on going

stay tuned !

OUTLINE

- INTRODUCTION
  - UBIQUITY OF RICH COUNTERS
  - THE SPECIFICITY OF DETECTING SINGLE PHOTONS
- **STATUS AND PERSPECTIVES IN <u>SINGLE</u> PHOTON DETECTORS**
  - ISSUES IN THE FILED OF SINGLE PHOTON DETECTORS
  - VACCUM-BASED PHOTON DETECTORS
    - NEW PERSPECTIVES WITH HIGH TIME RESOLUTION PHOTON DETECTORS
  - GASEOUS PHOTON DETECTORS
  - **Si PMs**
- CONCLUSION

Si PMTs For Cherenkov Imaging applications

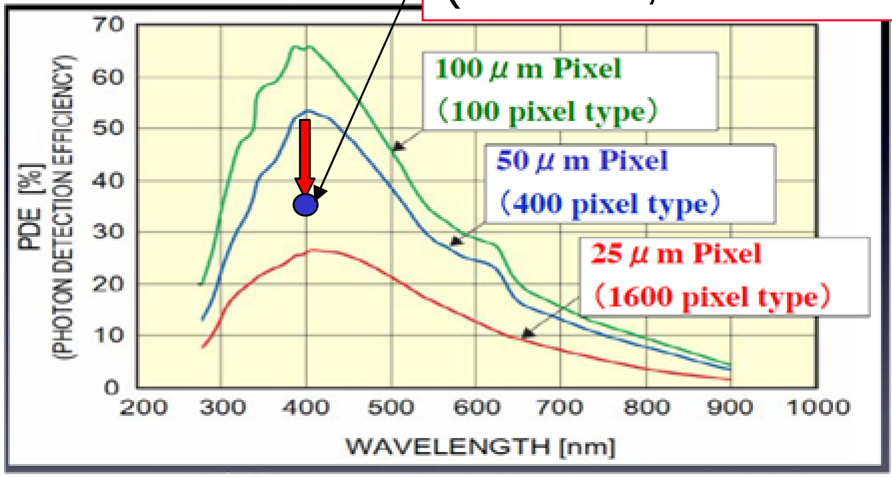
- High QE, small size
- High noise rate (noise pulse = pe pulse)
- Noise rates varying with environmental conditions (T) and aging

Issues towards the use for Cherenkov Imaging detectors:

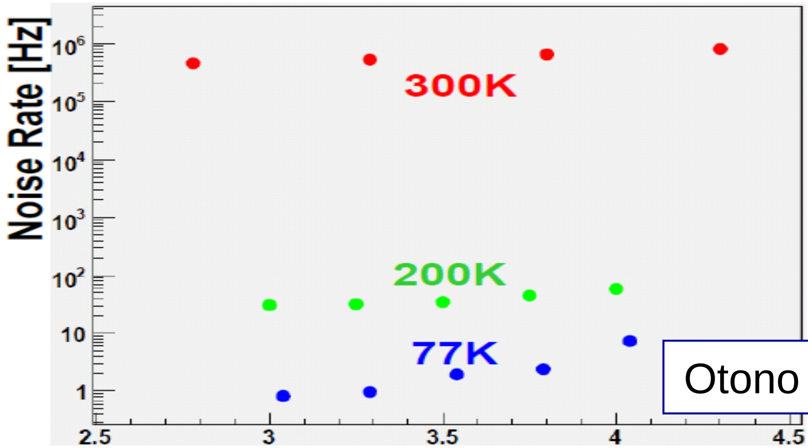
- Larger area
- Lower noise rates
- Stability of noise rates (T, aging)
- Less cross-talk

not ready for applications

Afterpulsing and cross talk should be taken into account. (J. Haba, RICH2007)



Measured with photocurrent. From HPK catalogue:
HC100
HC050
HC025



Otono @PD07

Si-PM studies for BELLE PID upgrade

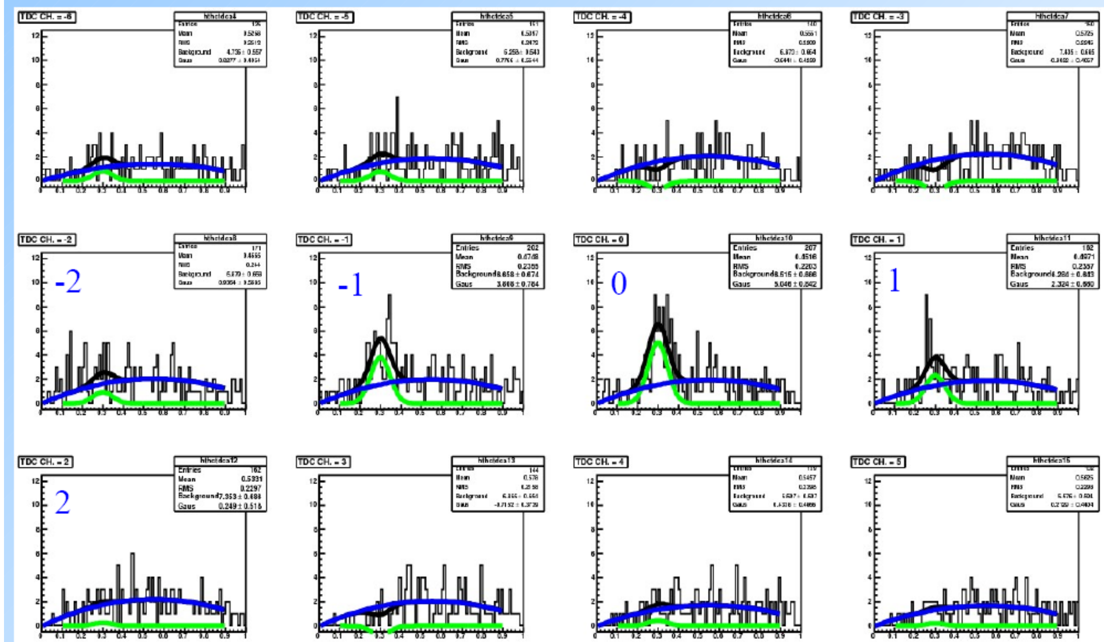
S. Korpar @ RICH2007

- 6 Hamamatsu SiPMs used:
  - 2x HC100; background ~400kHz
  - 2x HC050; background ~200kHz
  - 2x HC025; background ~100kHz

$N_{SiPM}/N_{PMT} \times S_{PMT}/S_{SiPM} \sim 4.2$

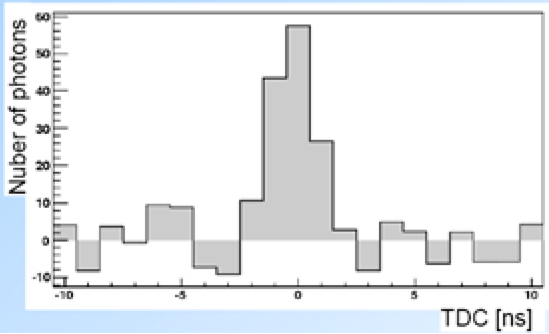
→ Per photon detector area SiPMs give 4 x more photons.

Cherenkov angle distributions for 1ns time windows



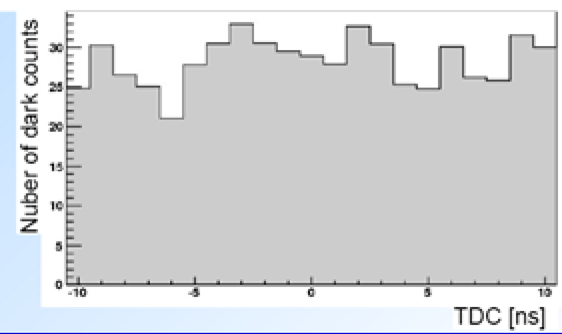
Signal and noise

Number of Cherenkov photons for 1ns time windows.



Number of background hits in ring area (±2σ) for each 1ns time window.

Handles:
Light guides
Smaller t window



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CONCLUSION

Single photon detectors represent
a field of great vitality and enthusiasm

These detectors are challenging, but established and novel techniques and technologies offer handles to overcome the challenge

The progress in single photon detection offers encouraging perspectives for the future of <u>Cherenkov Imaging Counters</u>