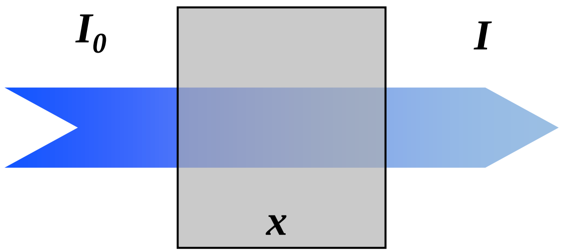
7th International Conference on
New Developments In Photodetection
Tours, France, June 30th to July 4th 2014
NDIP

Photon Detection and Imaging with Gaseous Counters

Fabio Sauli
TERA Foundation and CERN



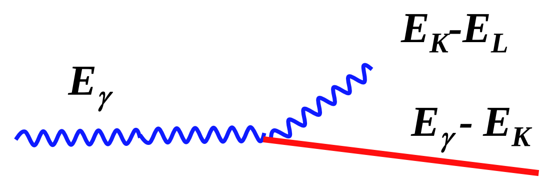
I_0 : incoming flux
I : outgoing flux

$$I = I_0 e^{-\frac{x}{l}} = I_0 e^{-mc}$$

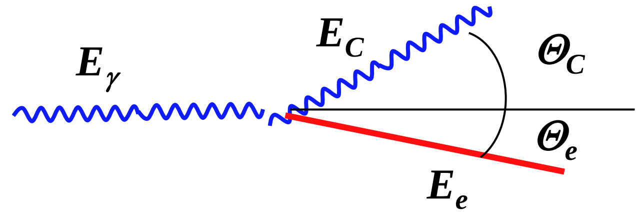
$$l = \frac{1}{Ns} \qquad N = N_0 \frac{r}{A}$$

l: absorption length (cm)
μ: mass absorption coefficient (cm^2g^{-1})
ρ: density (g cm^{-3})
N: atoms (molecules) cm^{-3}
s: absorption cross section (cm^2)
A: Avogadro number

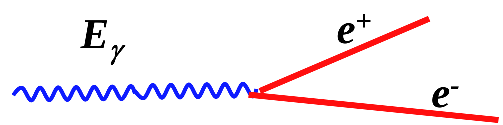
PHOTOELECTRIC:

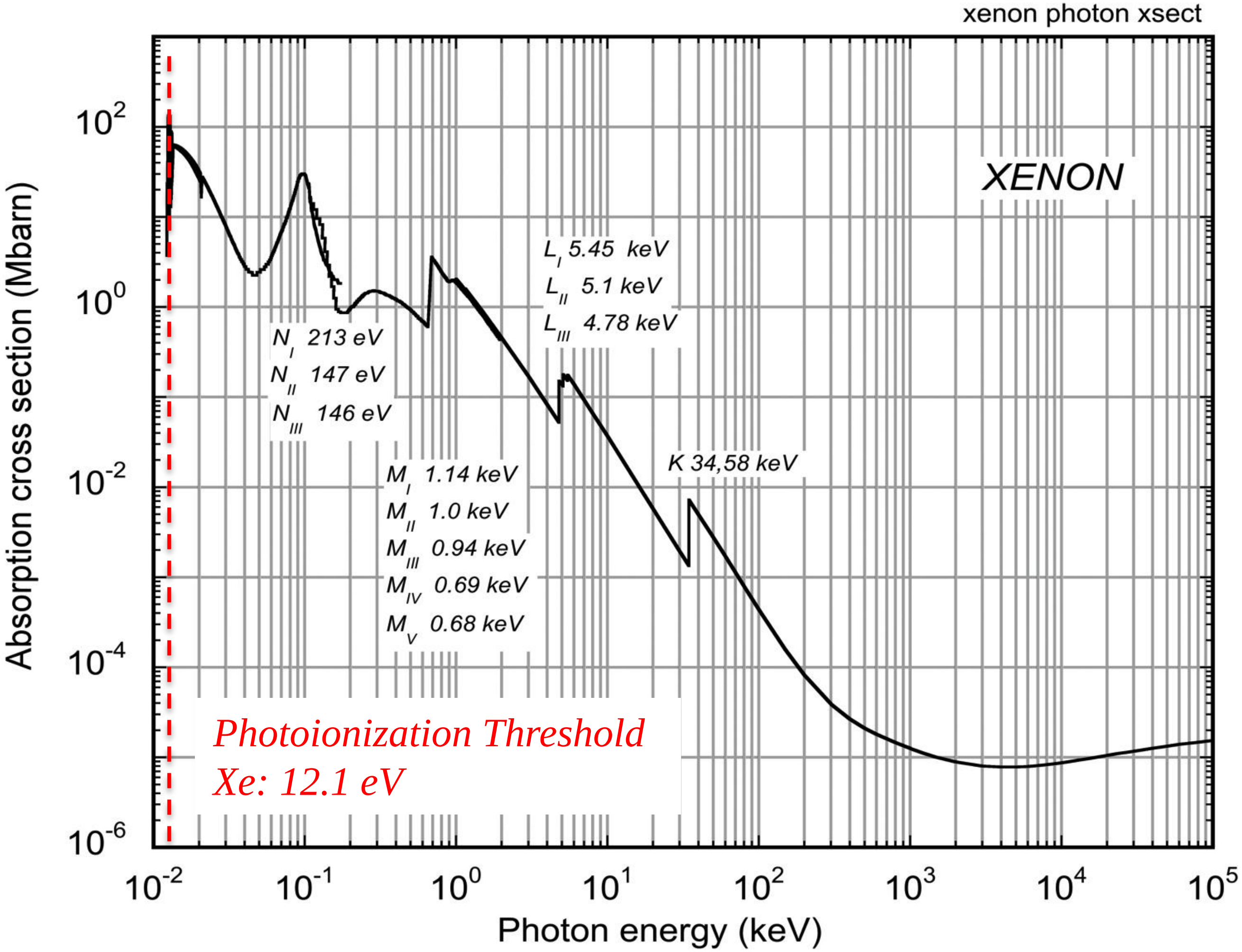


COMPTON SCATTER:



PAIR PRODUCTION

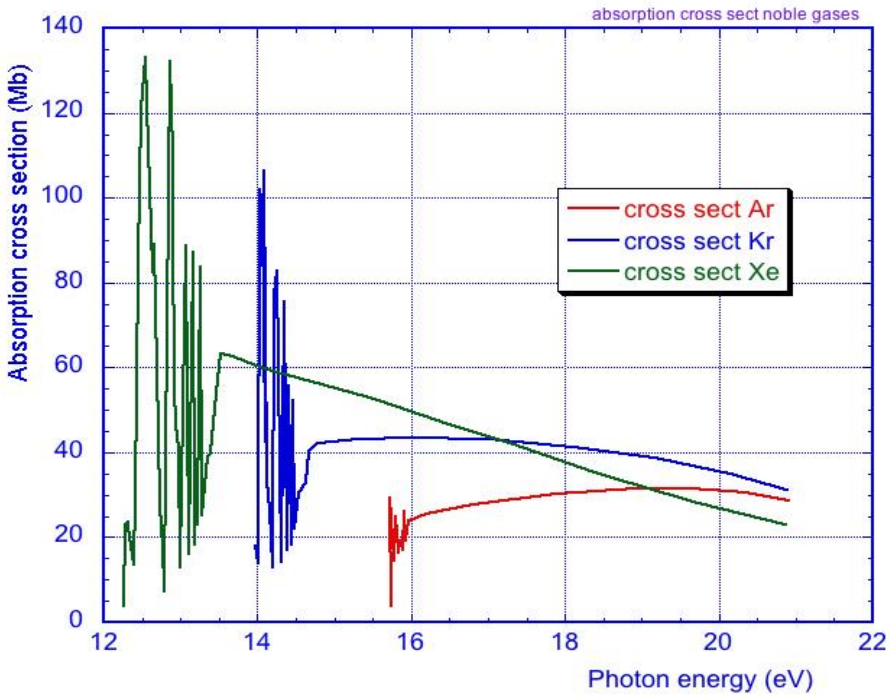




1 Mbarn=10^{-18} cm^2

http://xdb.lbl.gov/
http://henke.lbl.gov/optical_constants/
http://www.nist.gov/pml/data/xraycoef/

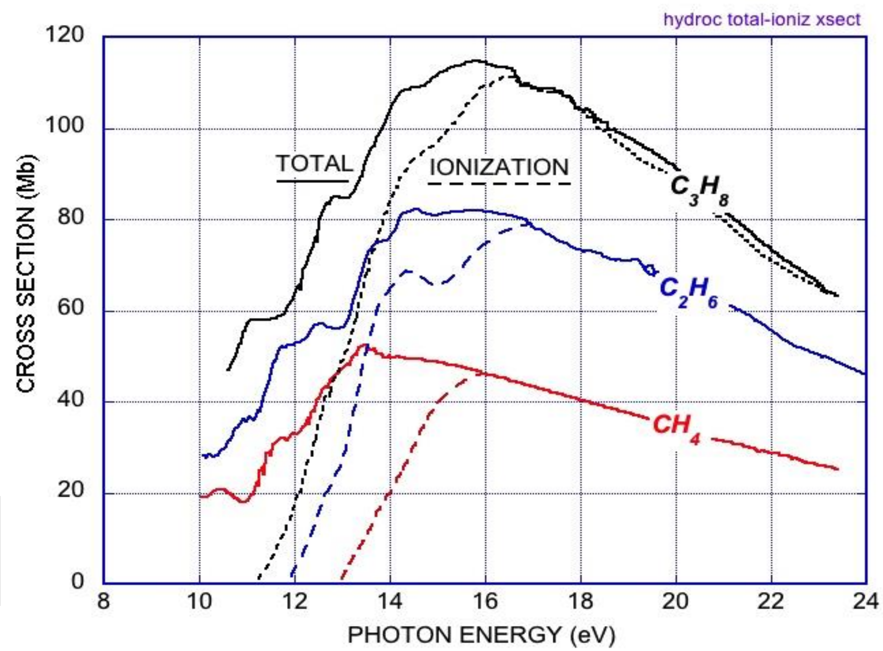
NOBLE GASES: PHOTOIONIZATION THRESHOLD



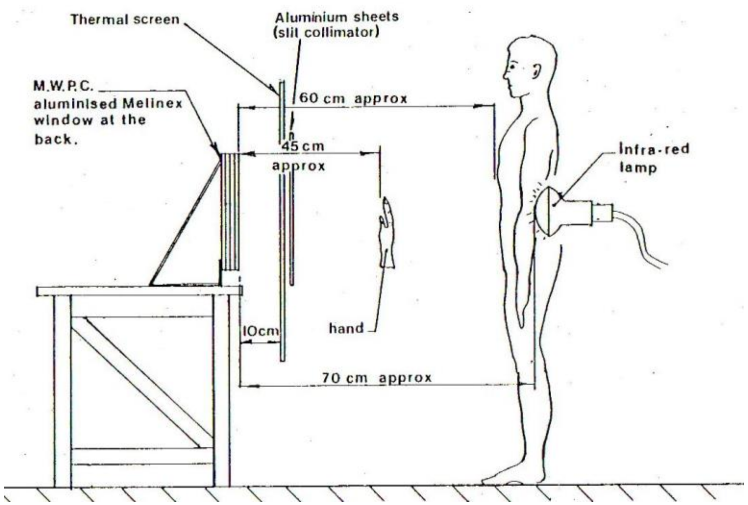
H. S. W. Massey, Electronic and Ionic impact Phenomena (Oxford Press 1969)

G. Marr, Photoionization Processes in Gases (Academic Press NY 1967)

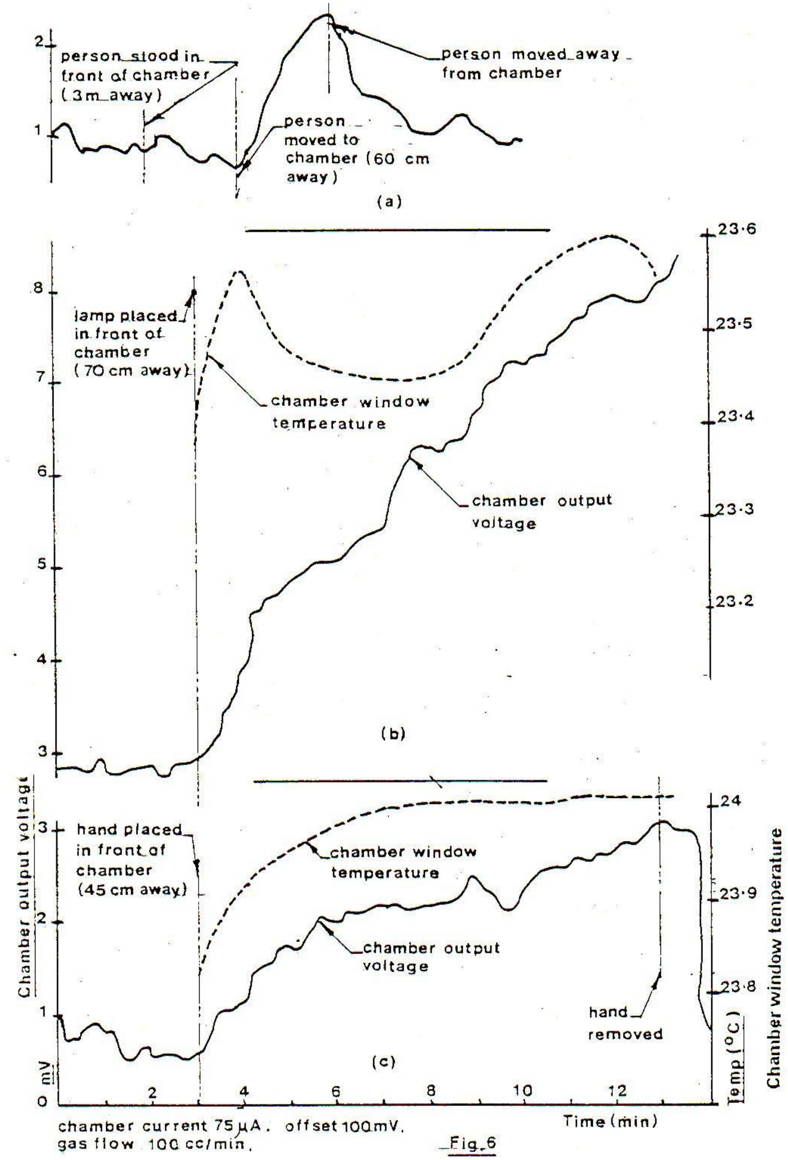
MOLECULAR GASES:
TOTAL AND IONIZATION CROSS SECTIONS



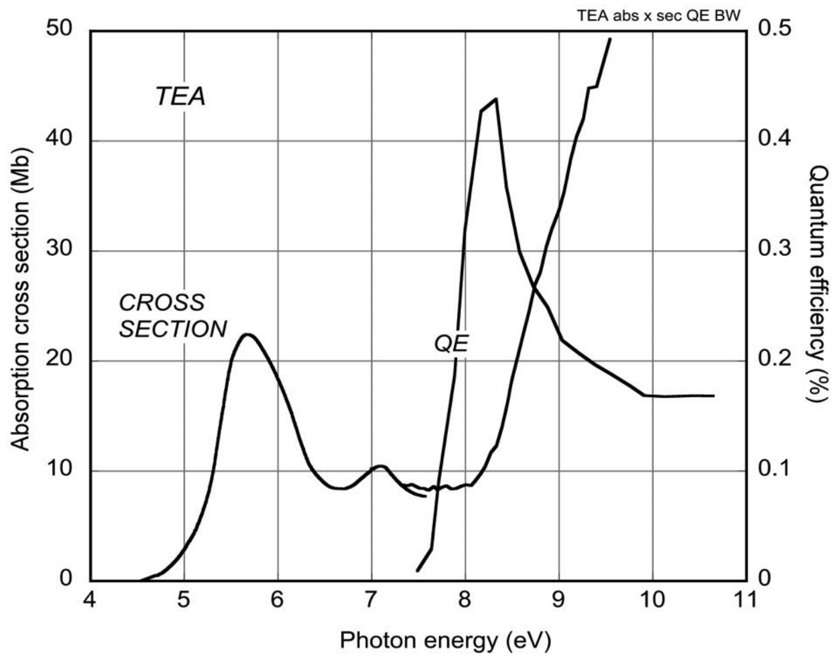
STUDY OF GLOW DISCHARGES IN MWPCs
Rutherford Lab (1979)



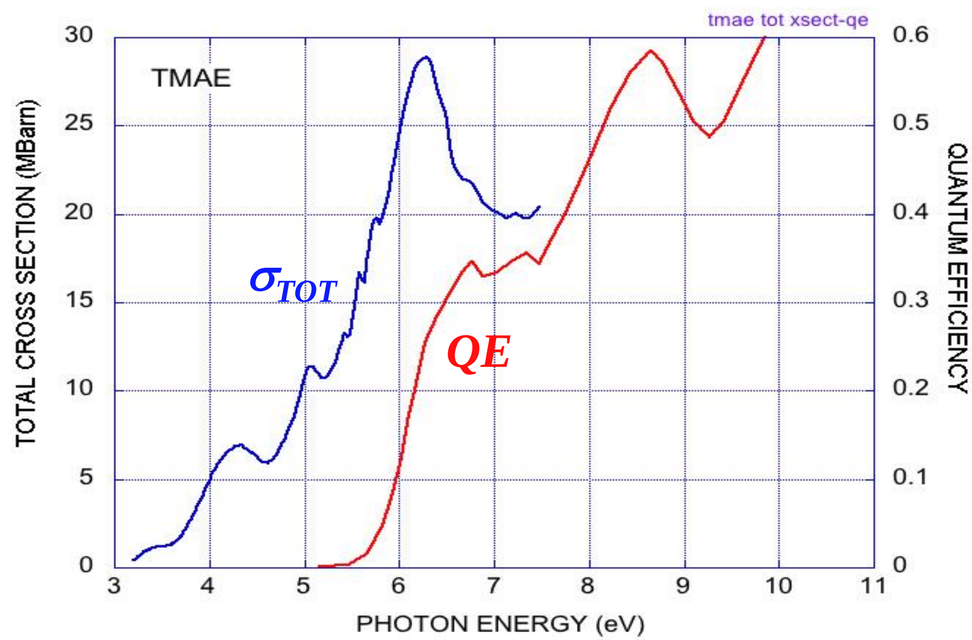
J.B. Marsh, K.H. Souten and B. O'Hagan
RL-79-038 (1979)



Triethylamine (TEA) $(C_2H_5)_3N$
$E_i = 7.5$ eV

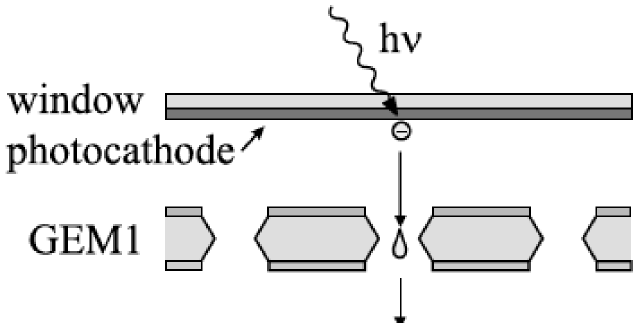


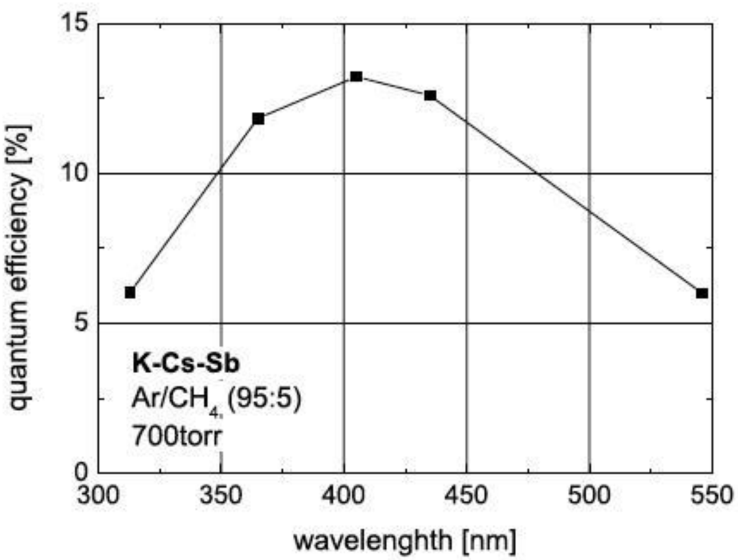
Tetrakis-dimethilamino-ethylene (TMAE)
$C[(CH_3)_2N]_4$
$E_i = 5.3$ eV



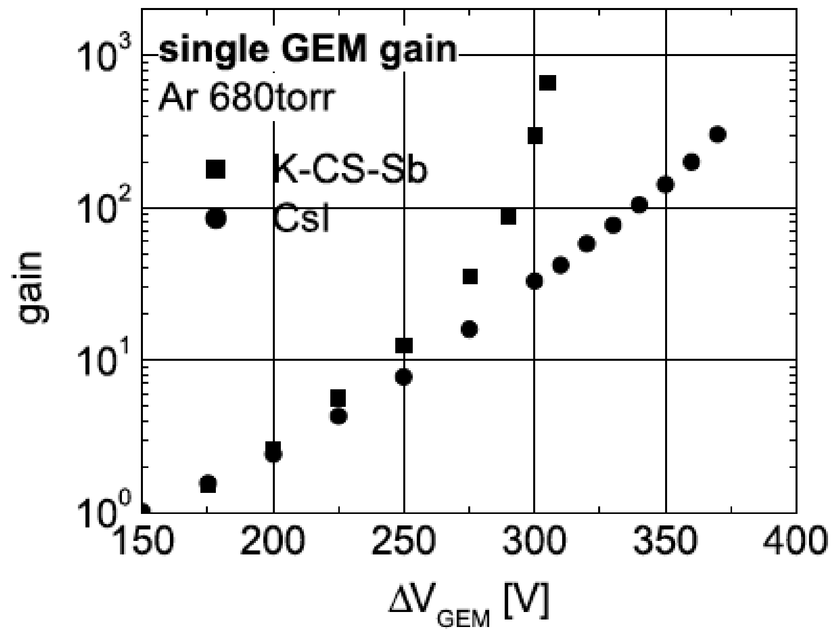
R. Holroyd et al, Nucl. Instr. and Meth.A261(1987)440

GAS ELECTRON MULTIPLIER (GEM) WITH SEMI-TRANSPARENT PHOTOCATHODE





PROBLEMS OF ION BACKFLOW:
- GAIN DIVERGENCY DUE TO PHOTON FEEDBACK
- PHOTOCATHODE DAMAGE DUE TO ION BOMBARDMENT

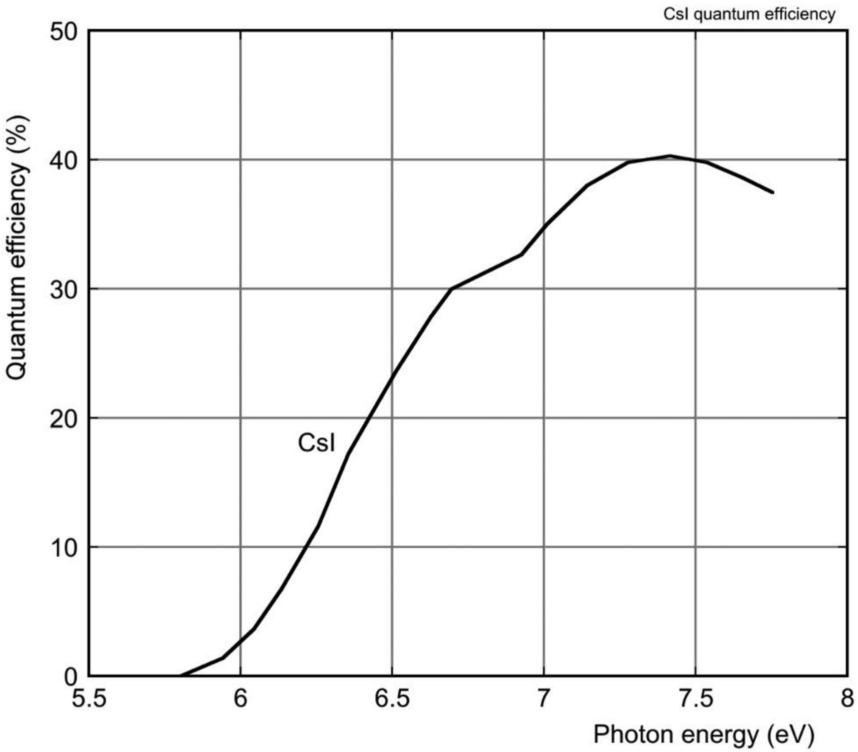


D. Mörmann et al, Nucl. Instr. and Meth. A504(2003)93

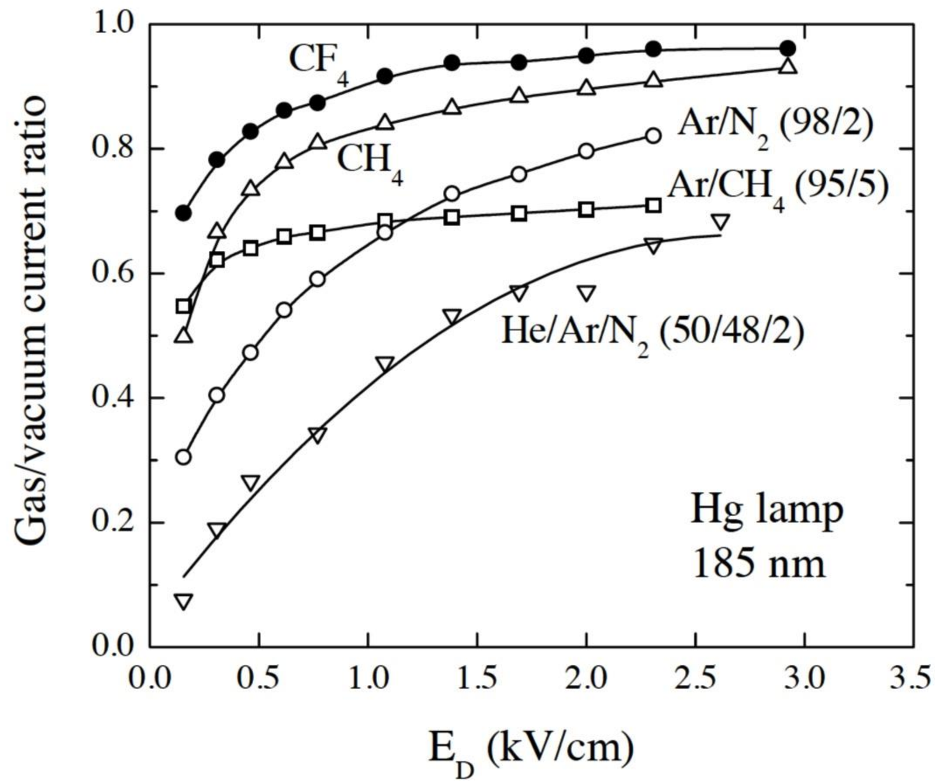
NEW STRUCTURES:
COBRA, MICRO-HOLES AND STRIPS, PACEM….

R. Chechik, A. Breskin, Nucl. Instr. and Meth. A595(2008)116

CsI QUANTUM EFFICIENCY



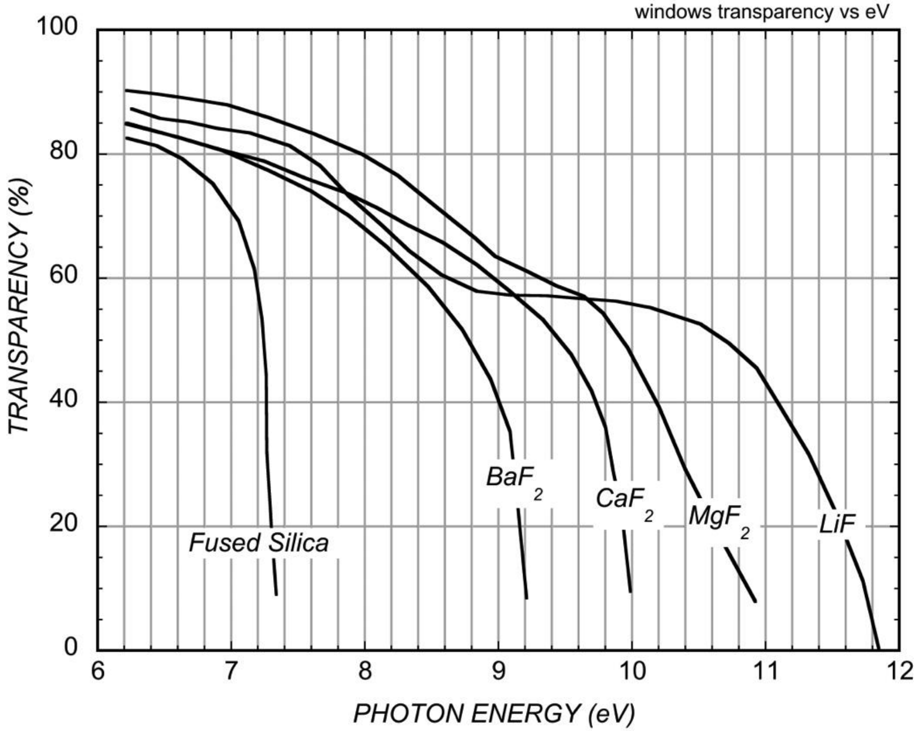
FIELD DEPENDENCE OF THE PHOTOELECTRON EXTRACTION EFFICIENCY



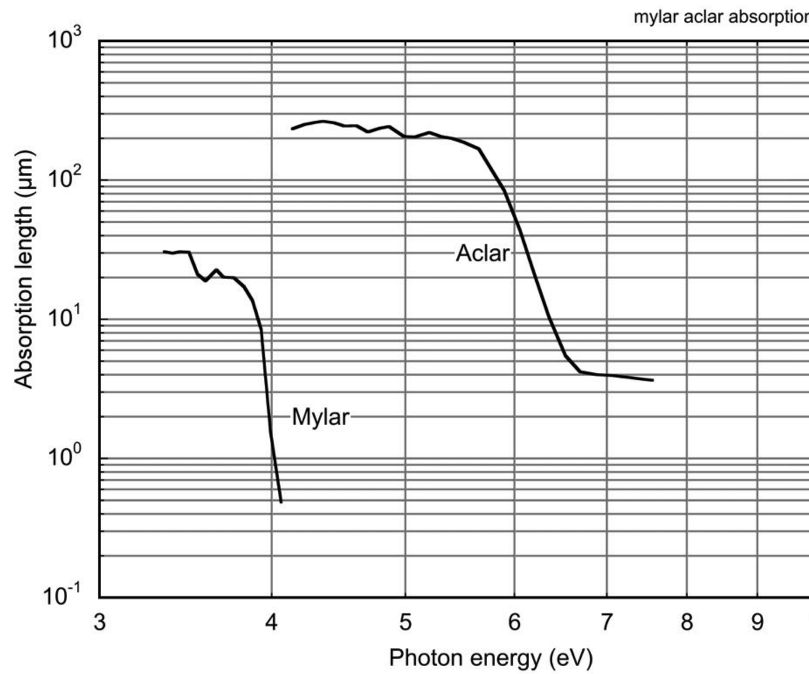
J. Seguinot et al, Nucl. Instr. and Meth. 297(1990)133

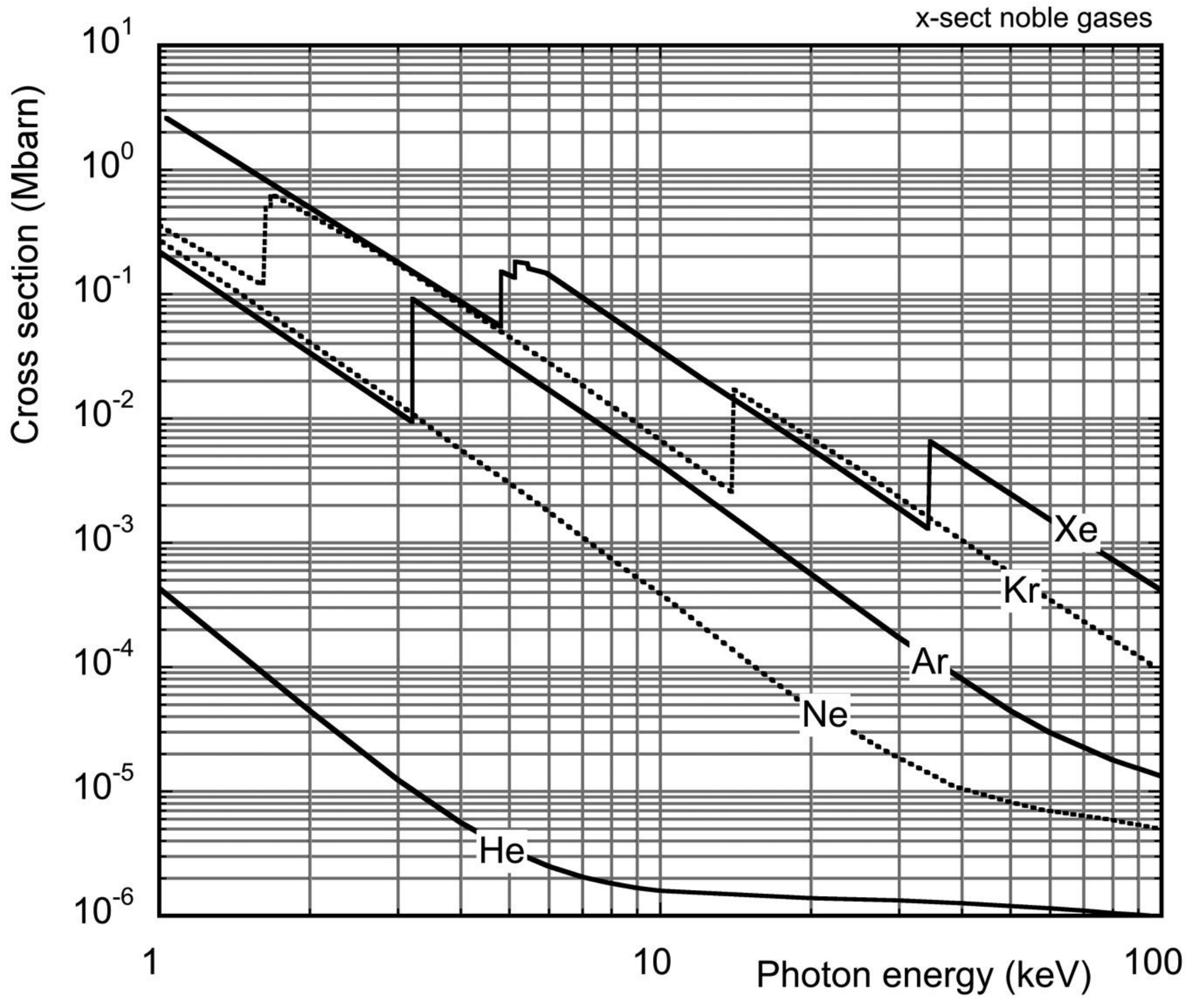
A. Breskin et al, Nucl. Instrum. and Meth. A483(2001)670

UV GLASS AND FLUORIDE CRYSTALS:

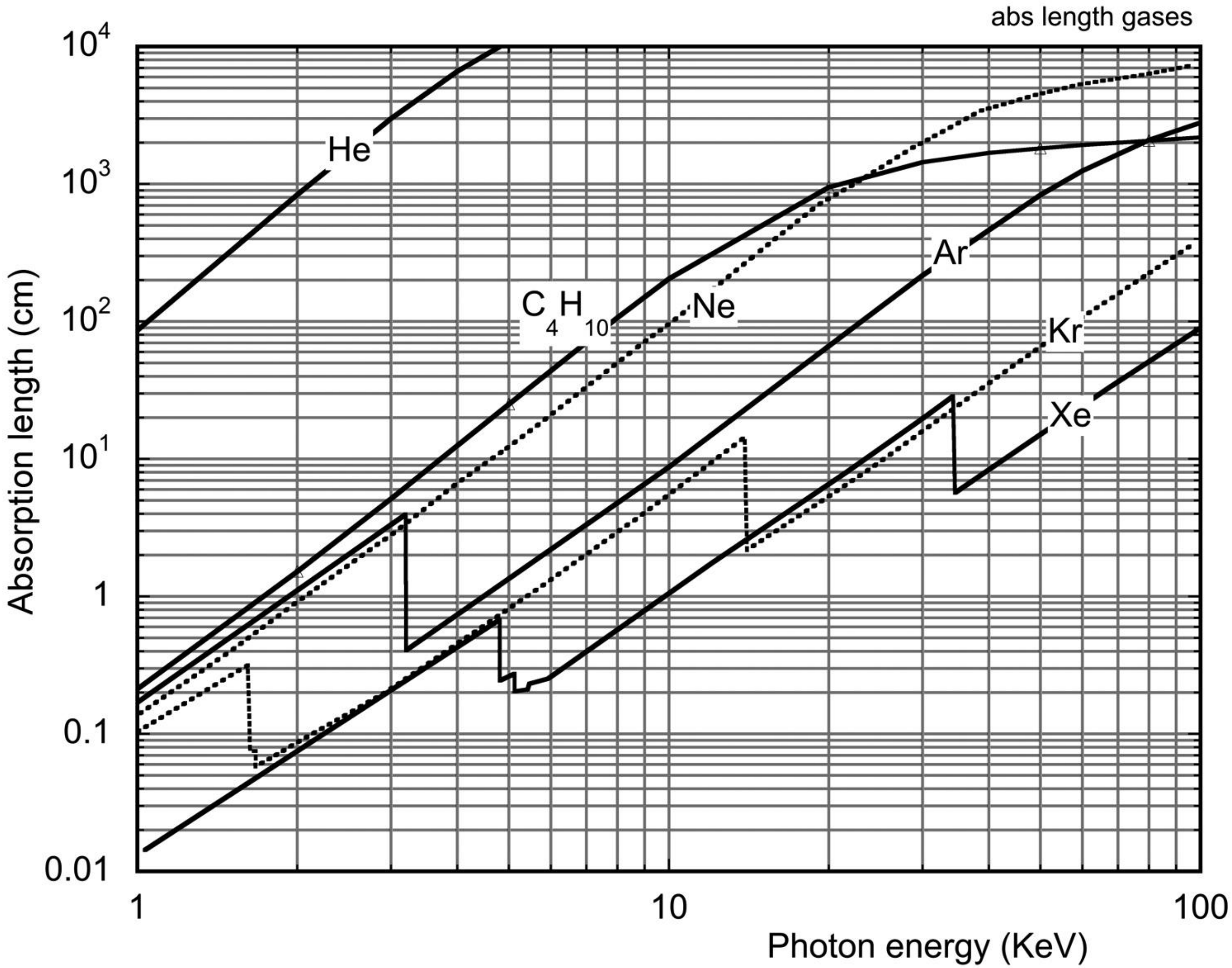


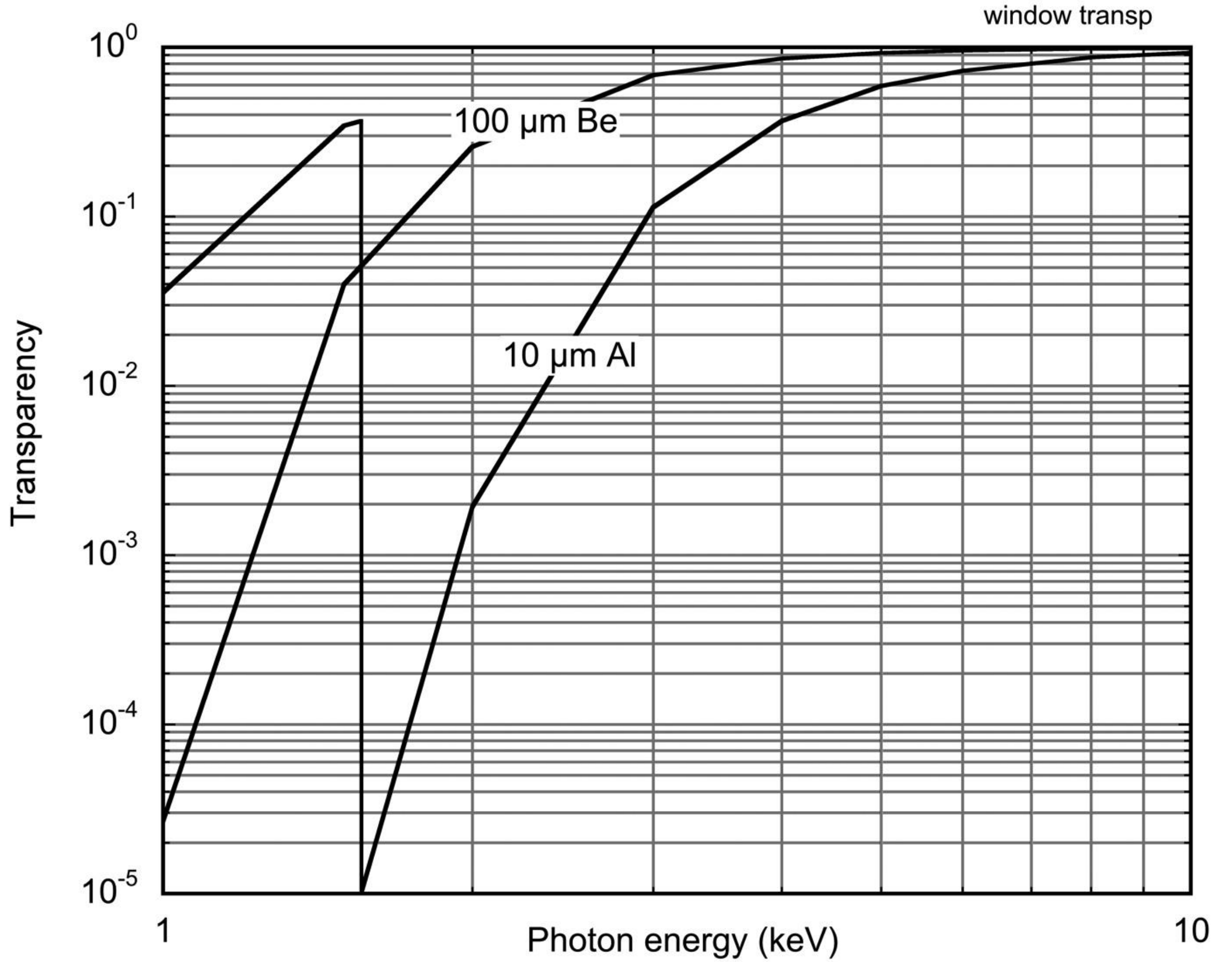
THIN POLYMER FOILS:



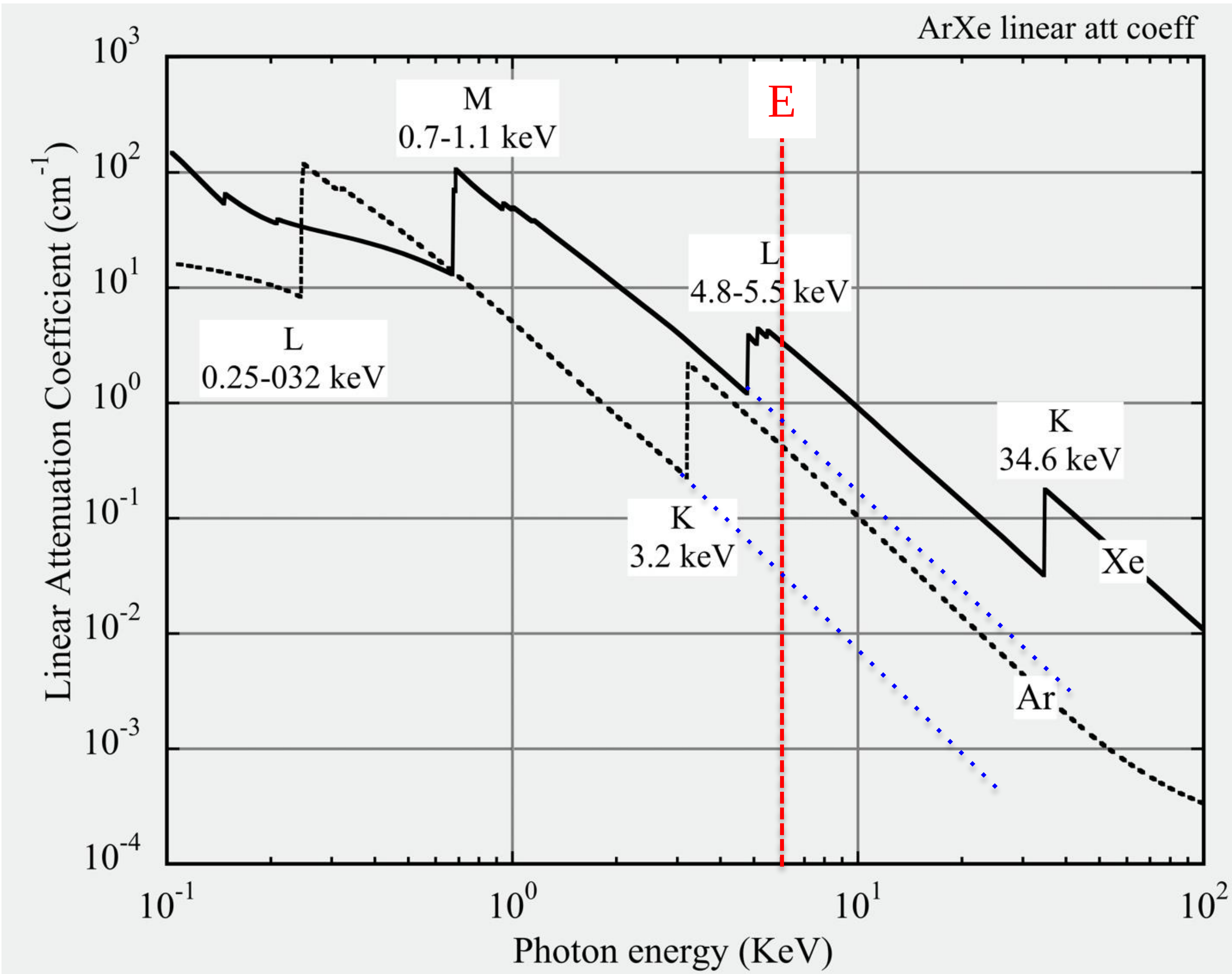

x-sect noble gases
Cross section (Mbarn)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
100
Photon energy (keV)
Xe
Kr
Ar
Ne
He

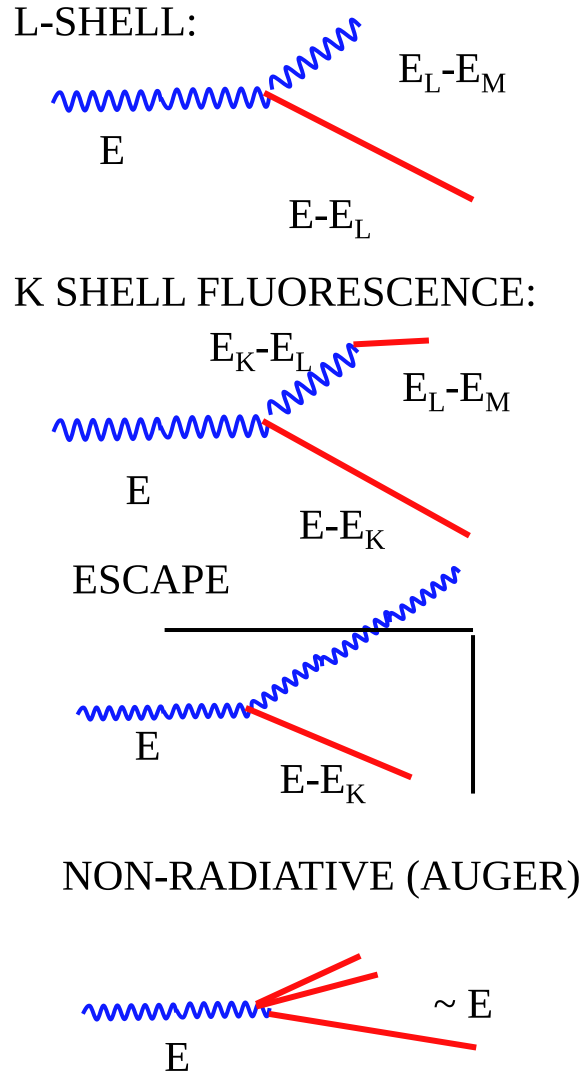
GASES AT STANDARD TEMPERATURE AND PRESSURE (STP: 0^0C, 1 atm):



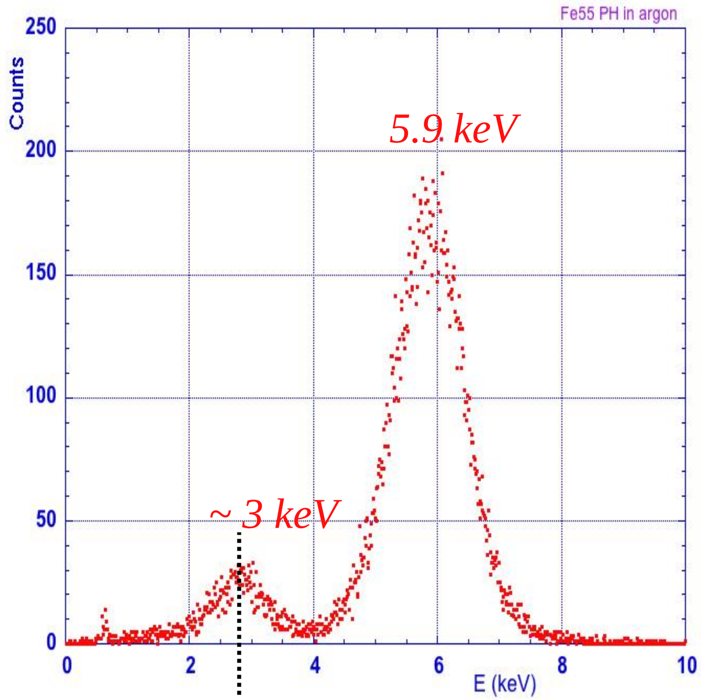

window transsp
100 µm Be
10 µm Al
Transparency
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1
10
Photon energy (keV)

LINEAR ATTENUATION COEFFICIENT (STP):

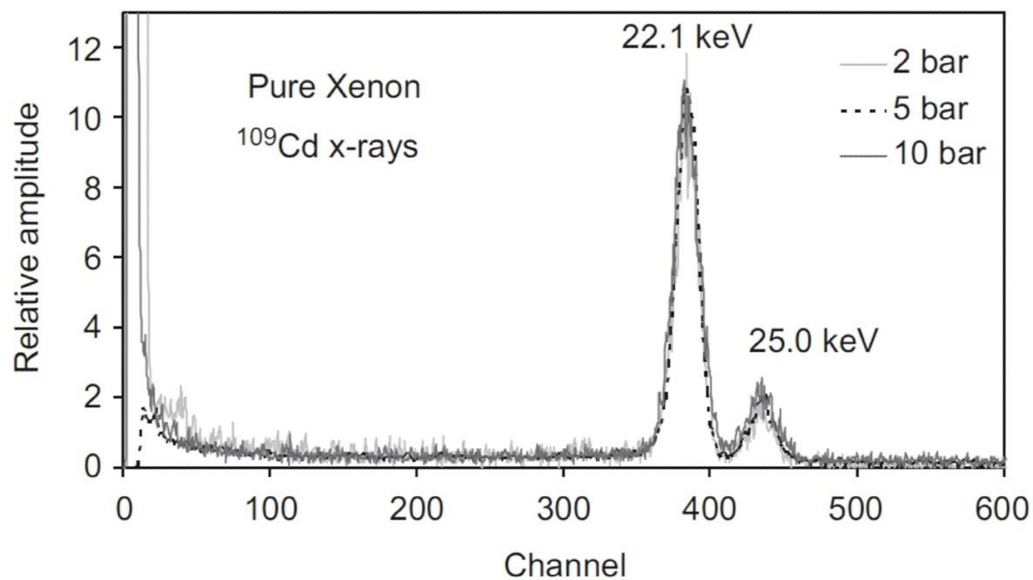




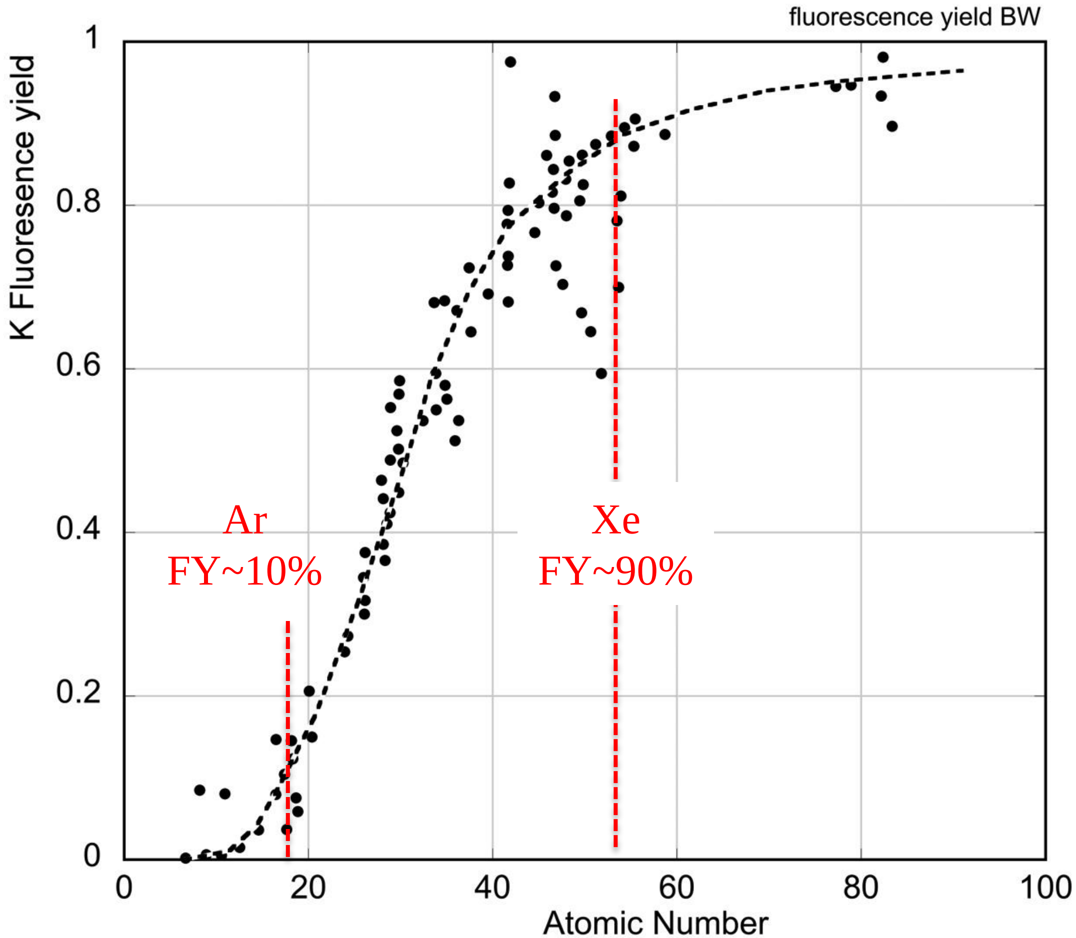
5.9 keV ^{55}Fe SOURCE IN ARGON:



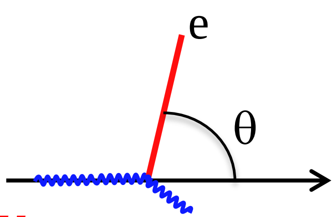
22-25 keV ^{109}Cd SOURCE IN XENON:



FY=FLUORESCENCE/TOTAL



ANGLE:



E_{γ} 5.9 keV

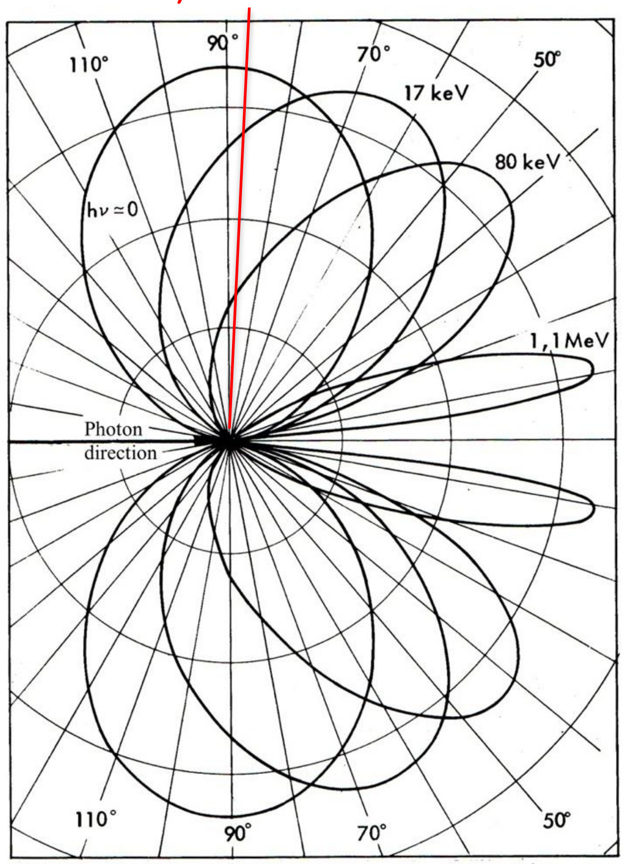
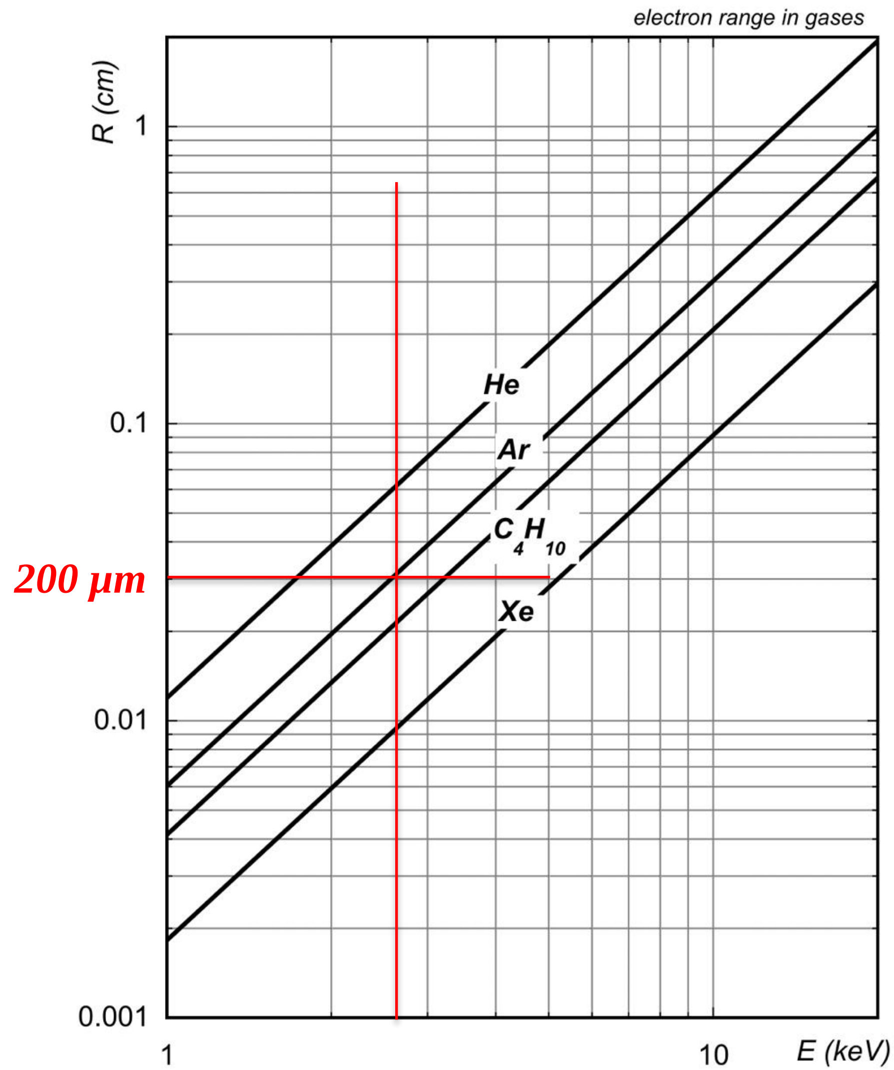
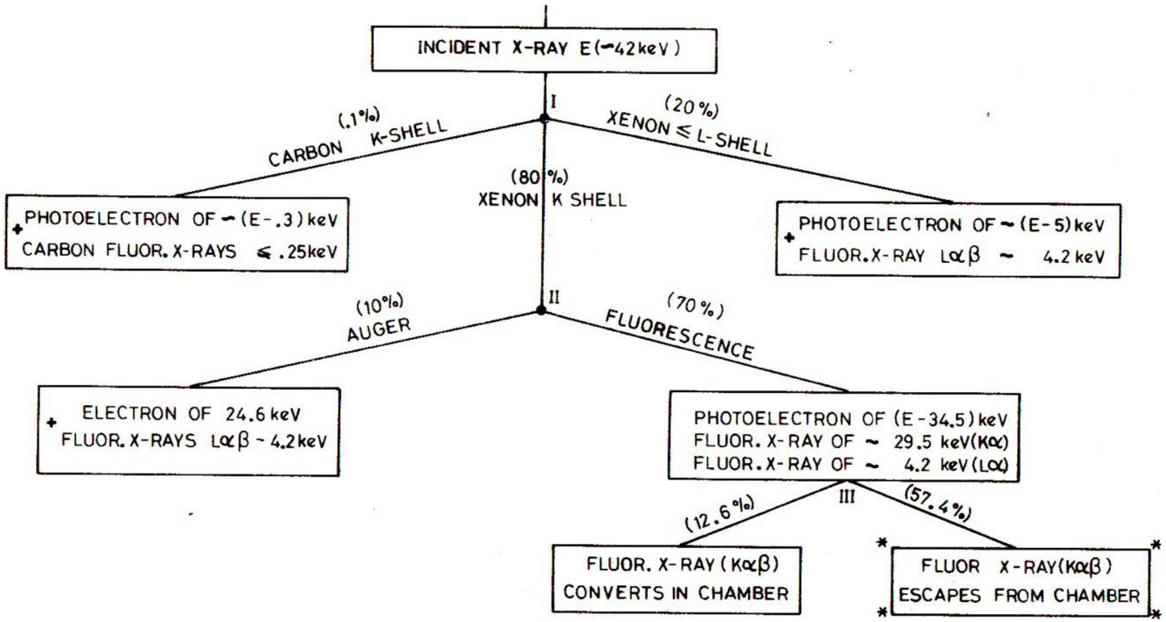


Figura 9.2. Distribuzione angolare dei fotoelettroni; le cur-

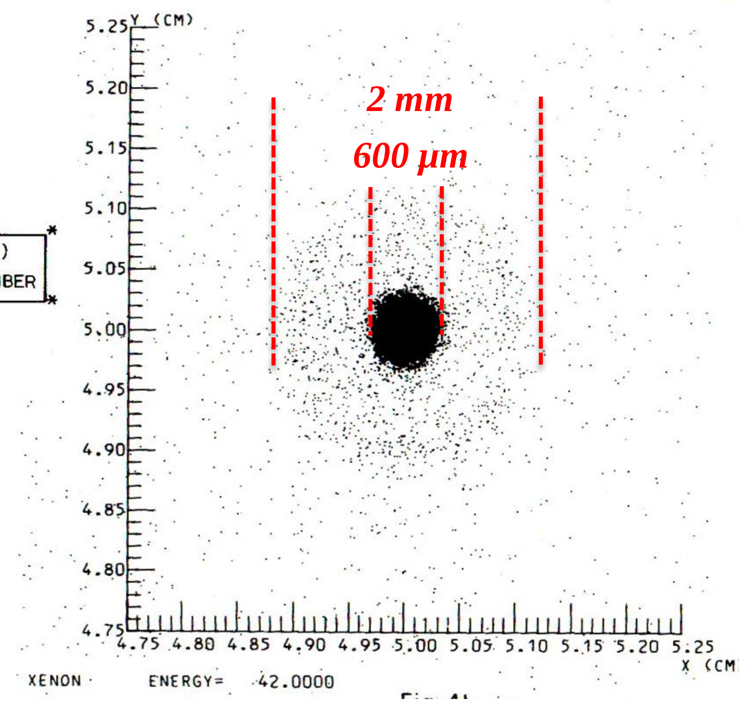
RANGE: $E_e = E_{\gamma} - E_K = 2.7$ keV in Ar



42 keV PHOTONS ON XENON

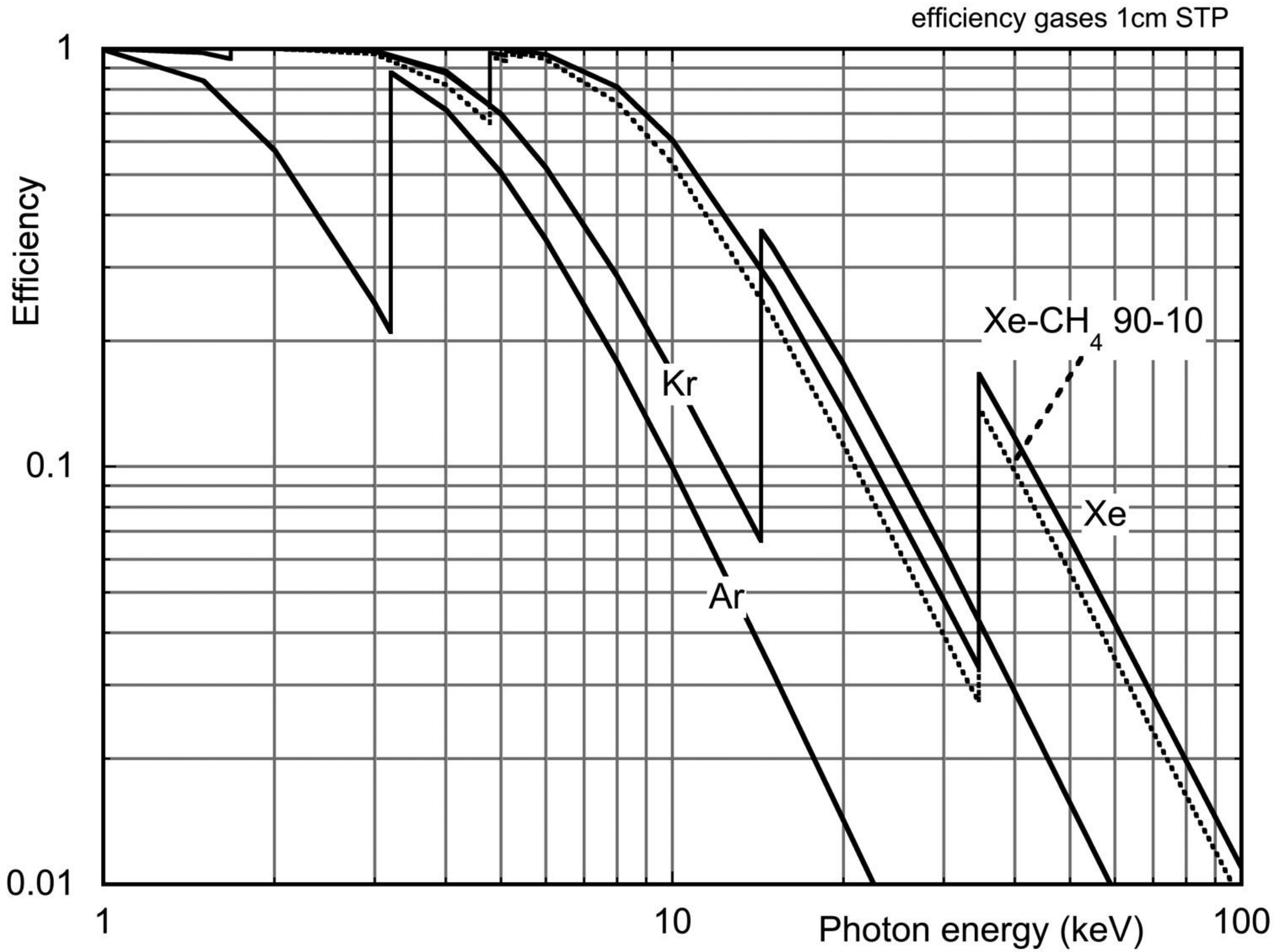


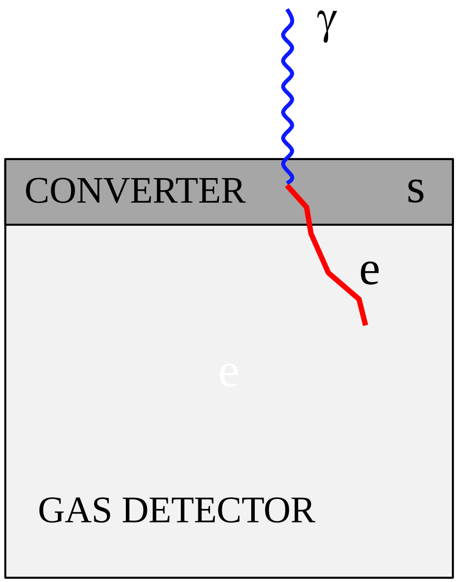
POSITION RESOLUTION FOR A POINT-LIKE COLLIMATED BEAM:



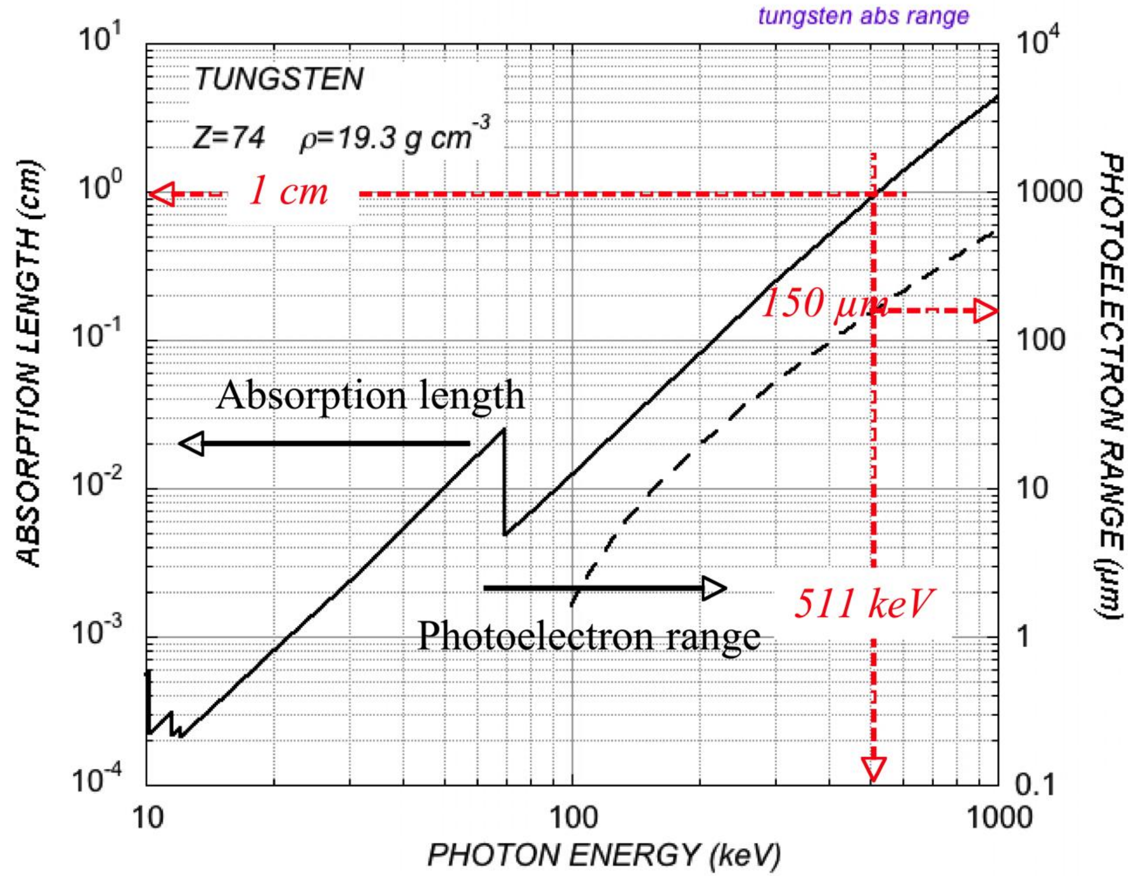
J.E. Bateman et al, RL-75-140

1 cm, STP


efficiency gases 1cm STP
1
0.1
0.01
Efficiency
Kr
Ar
Xe-CH4 90-10
Xe
1
10
100
Photon energy (keV)



USEFUL CONVERTER THICKNESS ~ ELECTRON RANGE



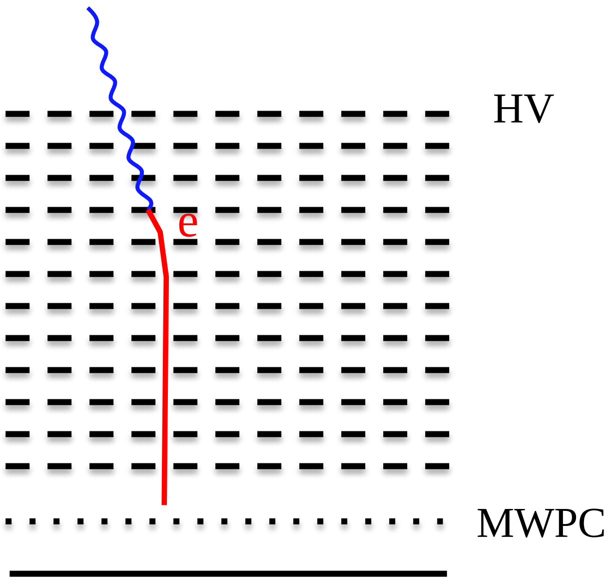
DETECTION EFFICIENCY:

$$e = 1 - e^{-\frac{s}{l}}$$

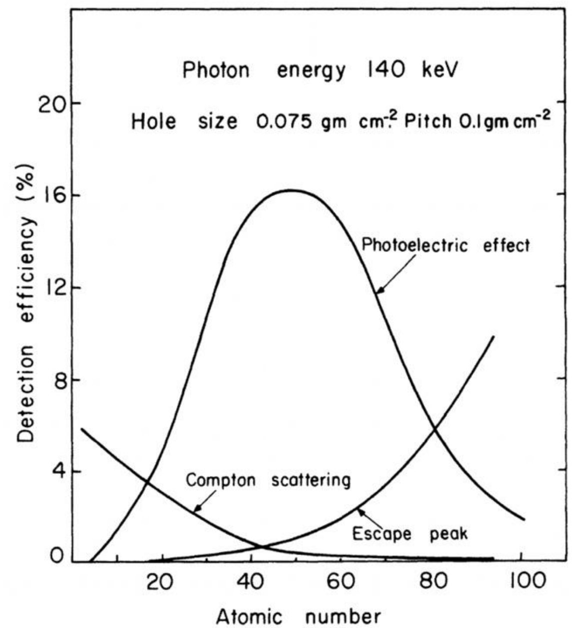
s: converter thickness
λ: absorption length

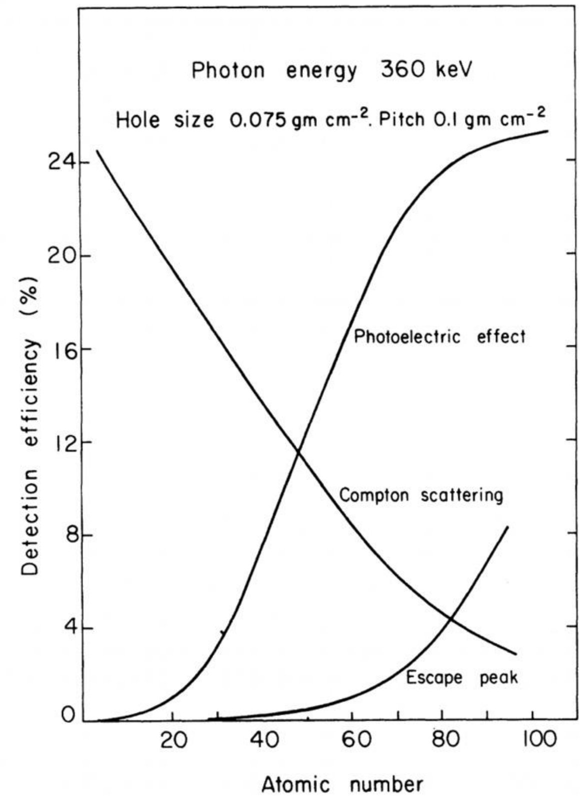
100 μm converter --> ε ~ 1%

HEAVY DRIFT CHAMBER



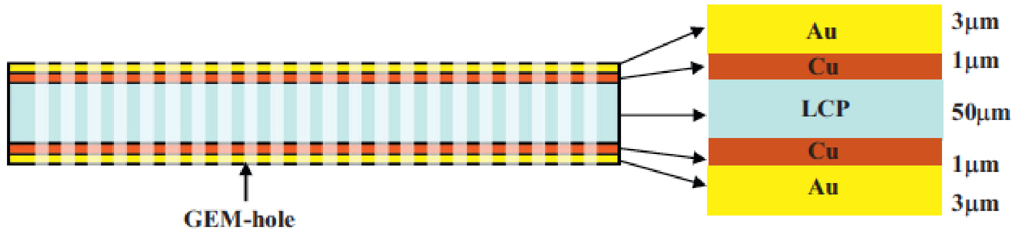
EFFICIENCY VS CONVERTER ATOMIC NUMBER:





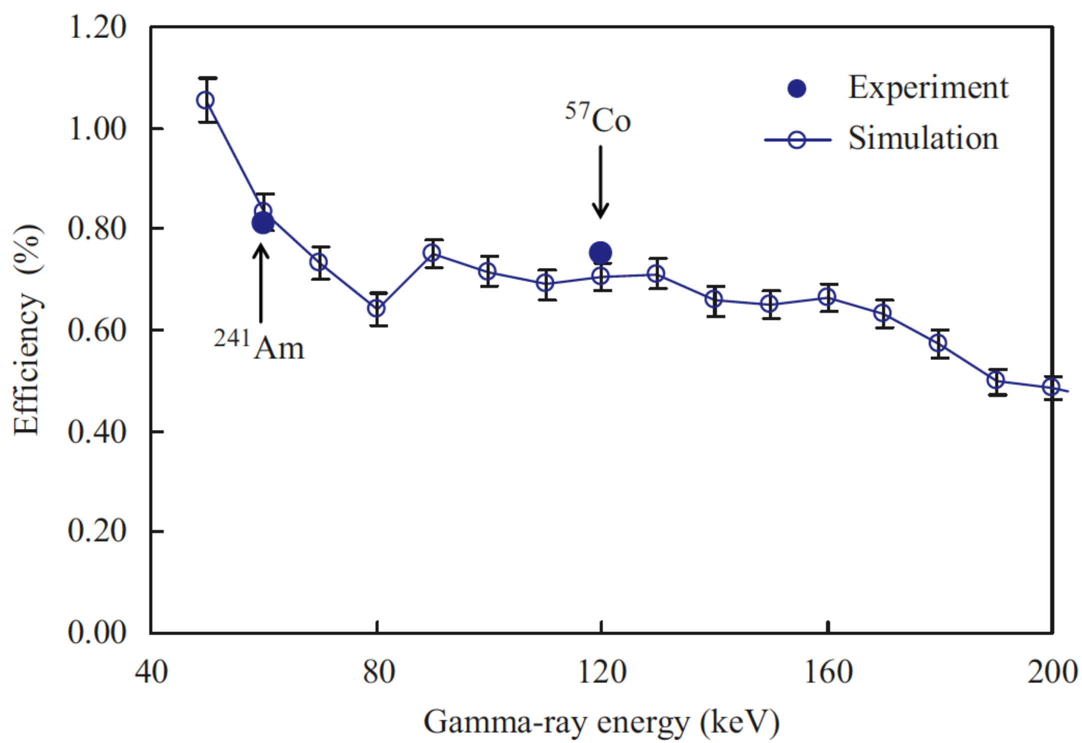
A. Jeavons et al, IEEE Trans. Nucl. Sci. NS-23 (1978)41

GAS ELECTRON MULTIPLIER (GEM) Au-COATED



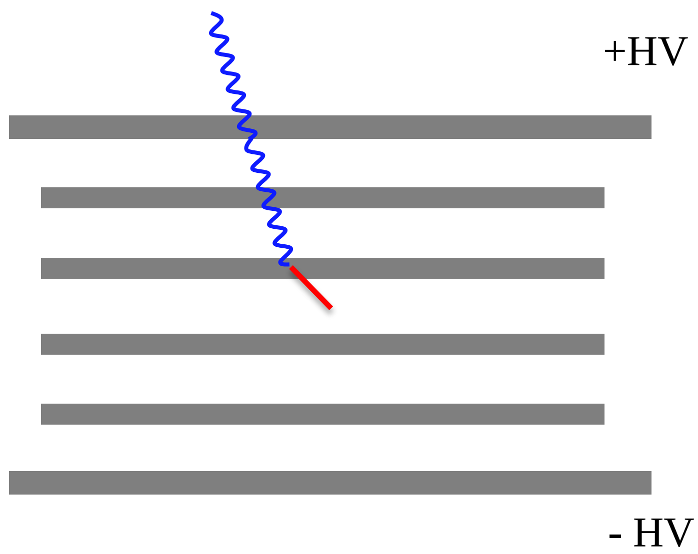
DETECTION EFFICIENCY

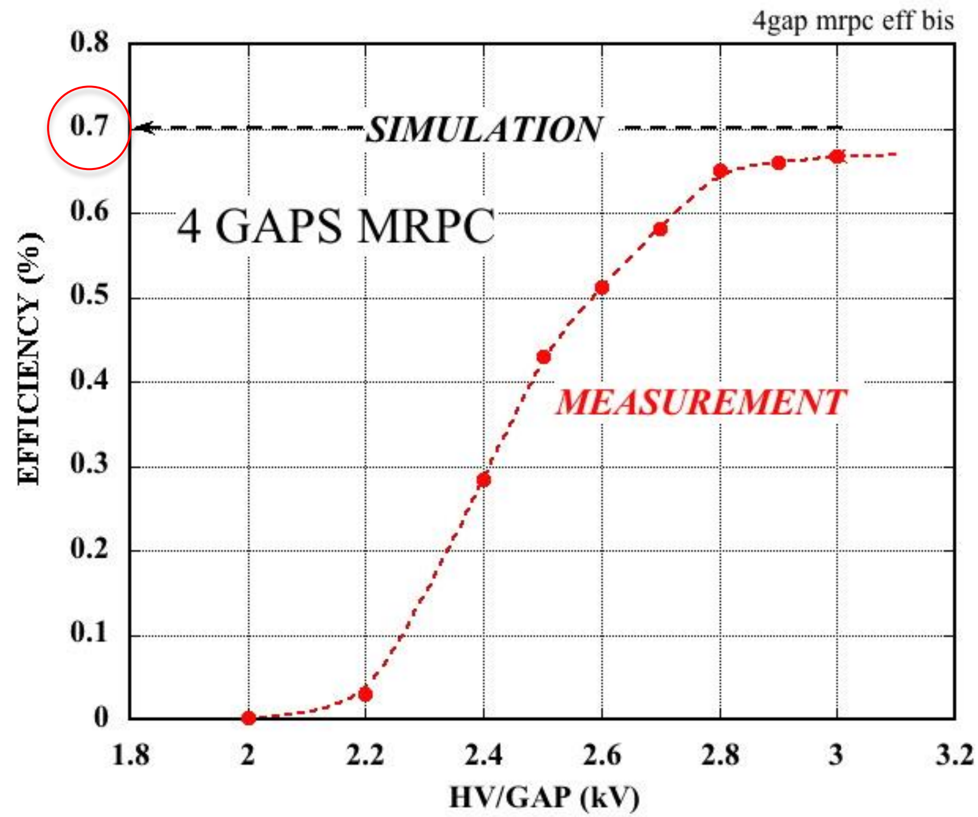
T. Koike et al,
Nucl. Instr. and Meth. A648(2011)180



DETECTION OF 511 keV γ FOR PET
MULTI-GAP RESISTIVE PLATE CHAMBER

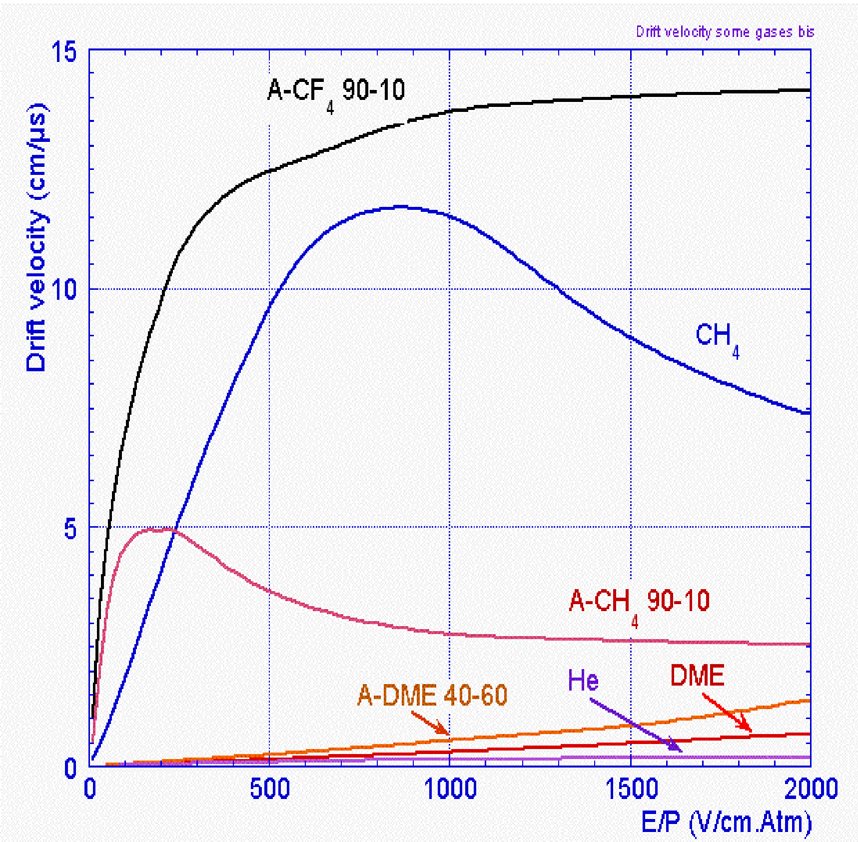
400 µm HIGH RESISTIVITY GLASS PLATES



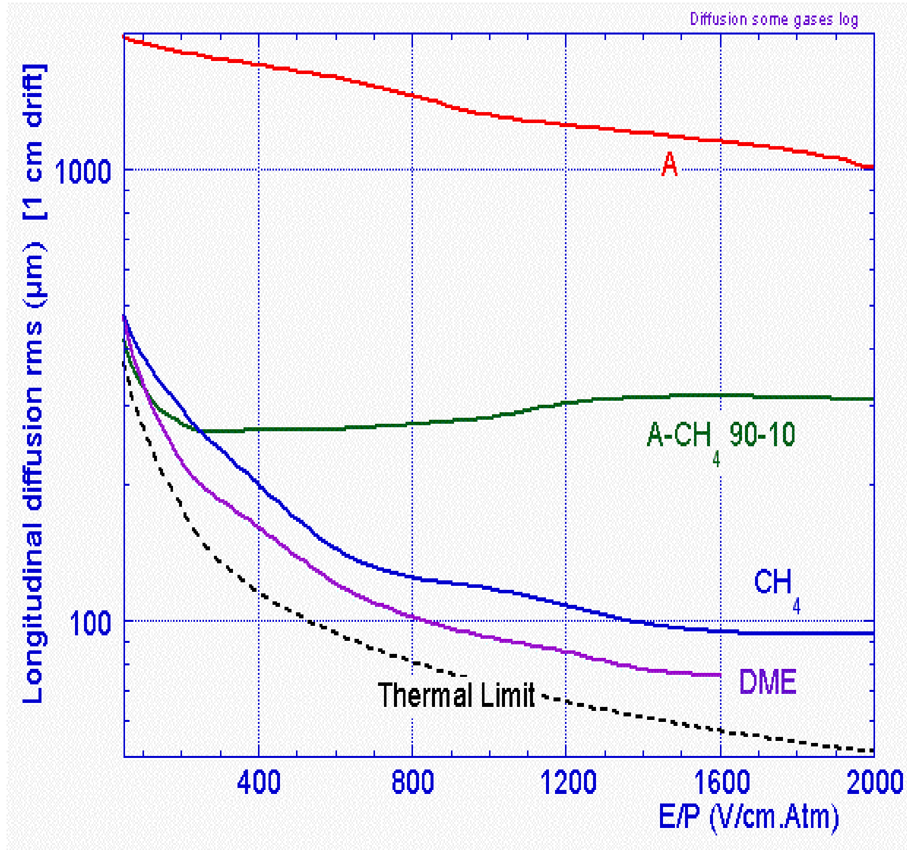


D. Watts et al, J.Rad.Res. 54 (2013)i136

DRIFT VELOCITY



DIFFUSION



COMPUTED WITH MAGBOLTZ:

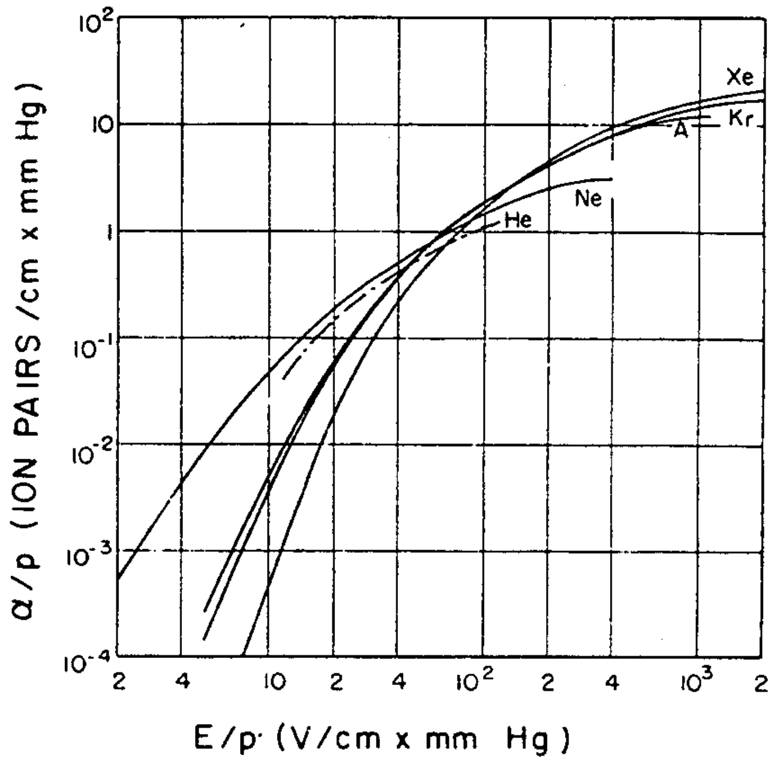
http://rjd.web.cern.ch/rjd/cgi-bin/cross

Mean free path for ionization:

$$l = \frac{1}{Ns} \qquad N\text{: molecules/cm}^3$$

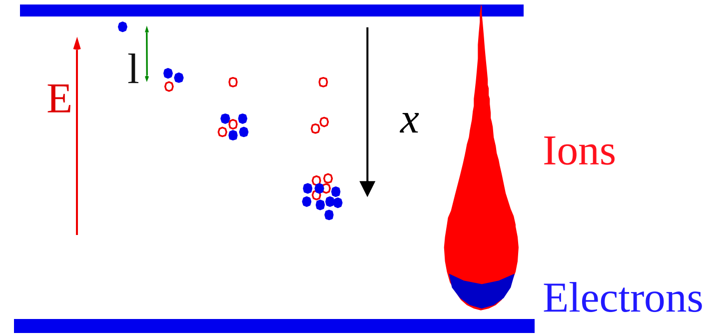
Townsend coefficient:

$$a = \frac{1}{l} \quad \text{Ionizing collisions/cm} \qquad \frac{a}{P} = f\left(\frac{E}{P}\right)$$



S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)

CHARGE MULTIPLICATION IN UNIFORM FIELD



Incremental increase of the number of electrons in the avalanche: $dn = n\,a\,dx$

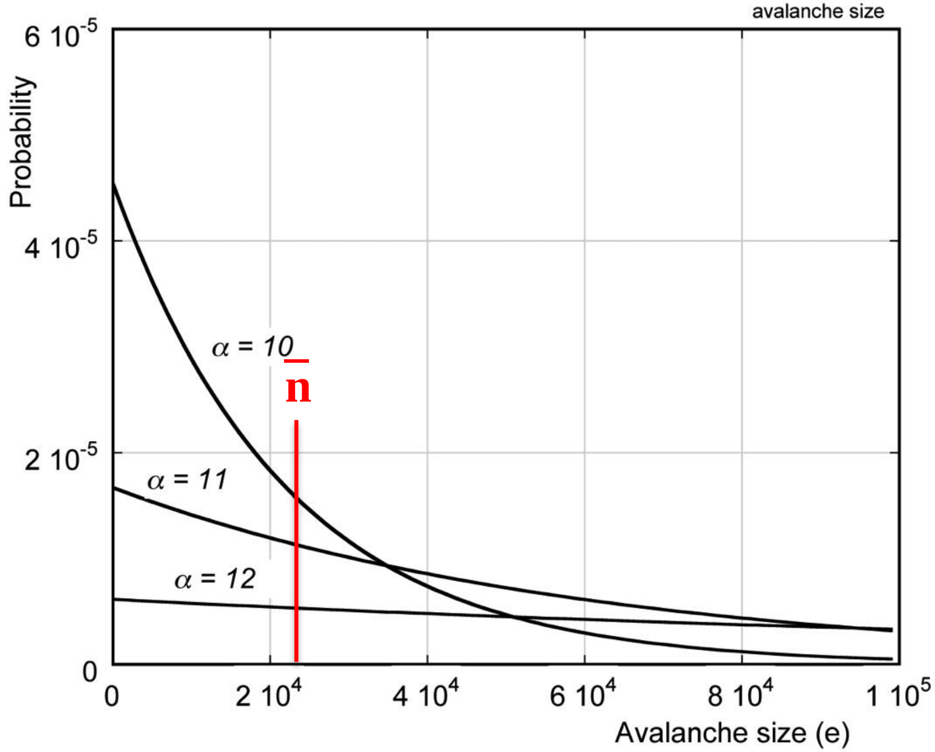
Multiplication factor or Gain: $M(x) = \frac{n}{n_0} = e^{a x}$

Maximum avalanche size before discharge (Raether limit): $Q_{MAX} \approx 10^7$ e

H. Raether, Electron Avalanches and Breakdown in Gases (Butterworth 1964)

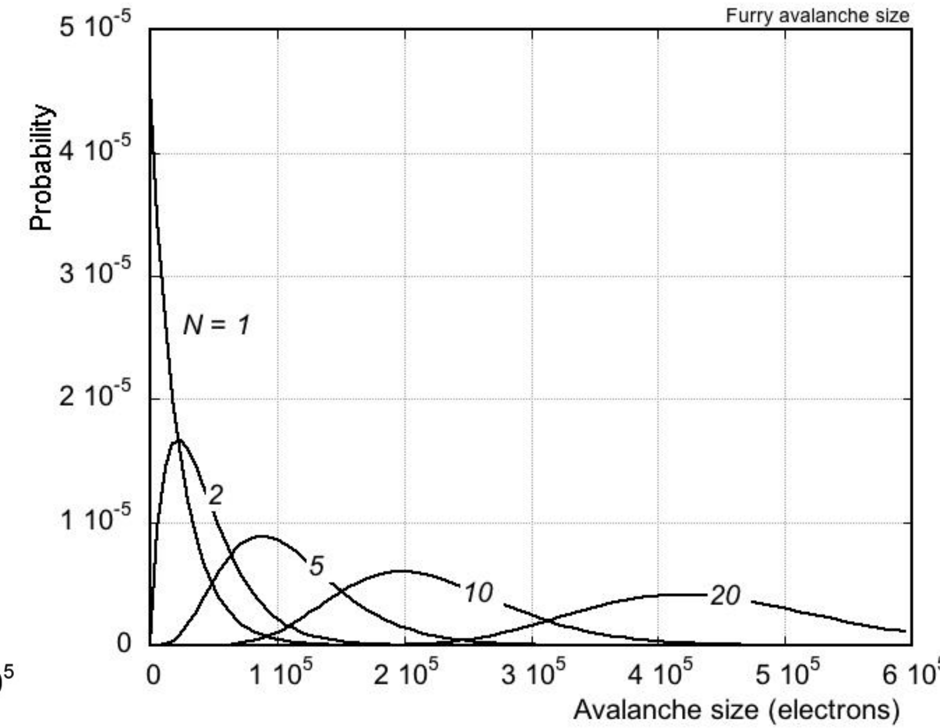
SINGLE ELECTRON
AVALANCHE SIZE DISTRIBUTION

$$P(n) = \frac{e^{-n/\bar{n}}}{\bar{n}} \qquad \bar{n} = e^{\alpha x} \qquad s_{\bar{n}} = \bar{n}$$



N ELECTRONS:

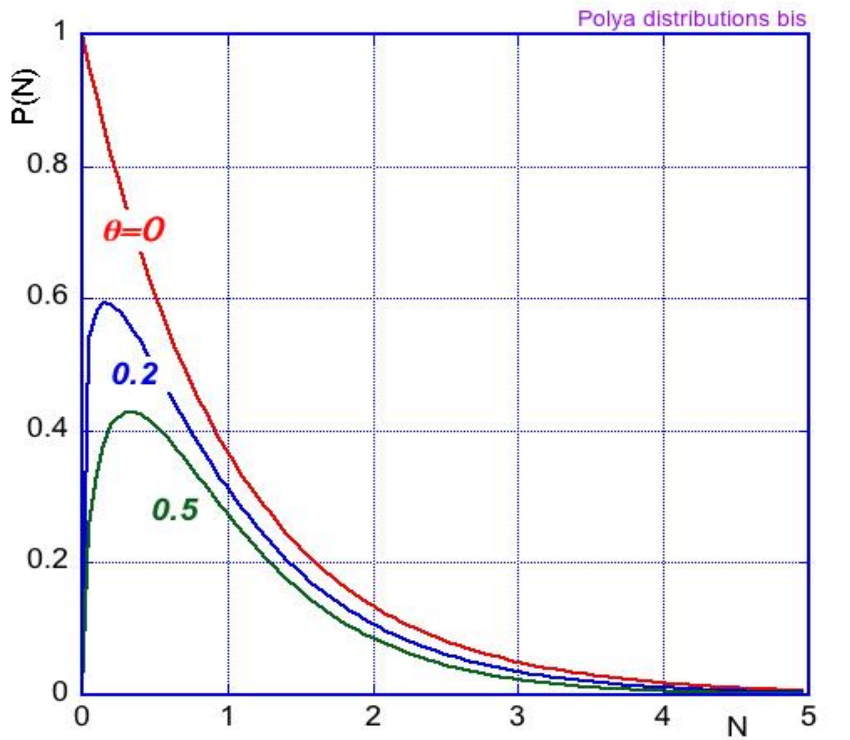
$$P(n,N) = \frac{1}{\bar{n}}\left(\frac{n}{\bar{n}}\right)^{N-1} \frac{e^{-\frac{n}{\bar{n}}}}{(N-1)!}$$



AVALANCHE DISTRIBUTION AT INCREASING GAINS (FIELDS)

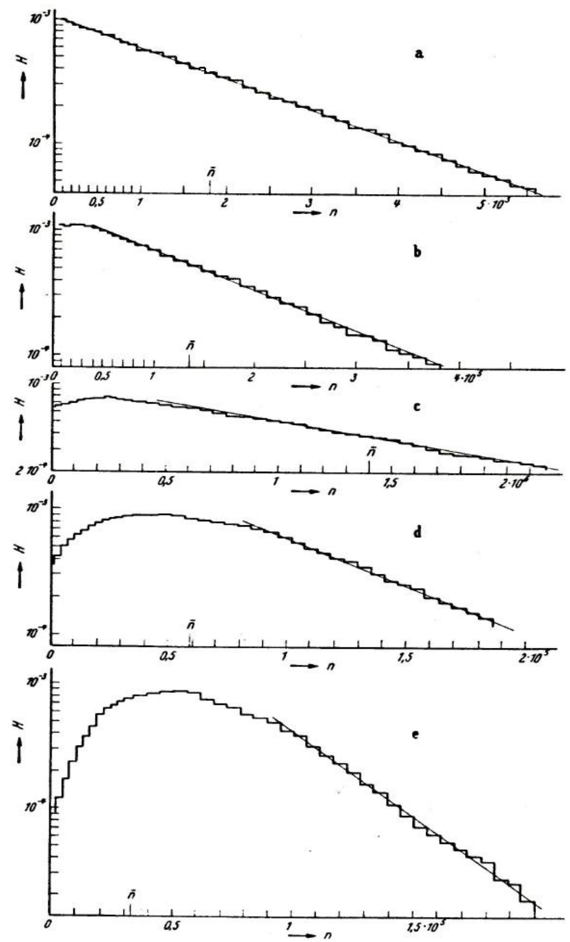
POLYA DISTRIBUTION

$$P(N)=\left[\frac{N(1+\theta)}{\bar{N}}\right]^{\theta} e^{-\frac{N(1+\theta)}{\bar{N}}} \qquad \left(\frac{\sigma_A}{\bar{A}}\right)^2=\frac{1}{\bar{A}}+\frac{1}{1-\theta}\cong\frac{1}{1-\theta}$$



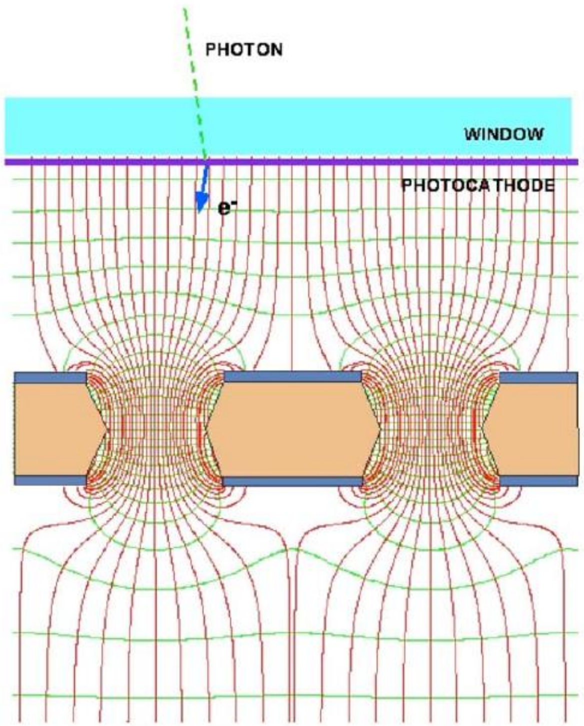
H. Schindler, S.F. Biagi, R. Veenhof,
Calculation of gas gain fluctuations in uniform fields
Nucl. Instr. and Meth. A624(2010)78

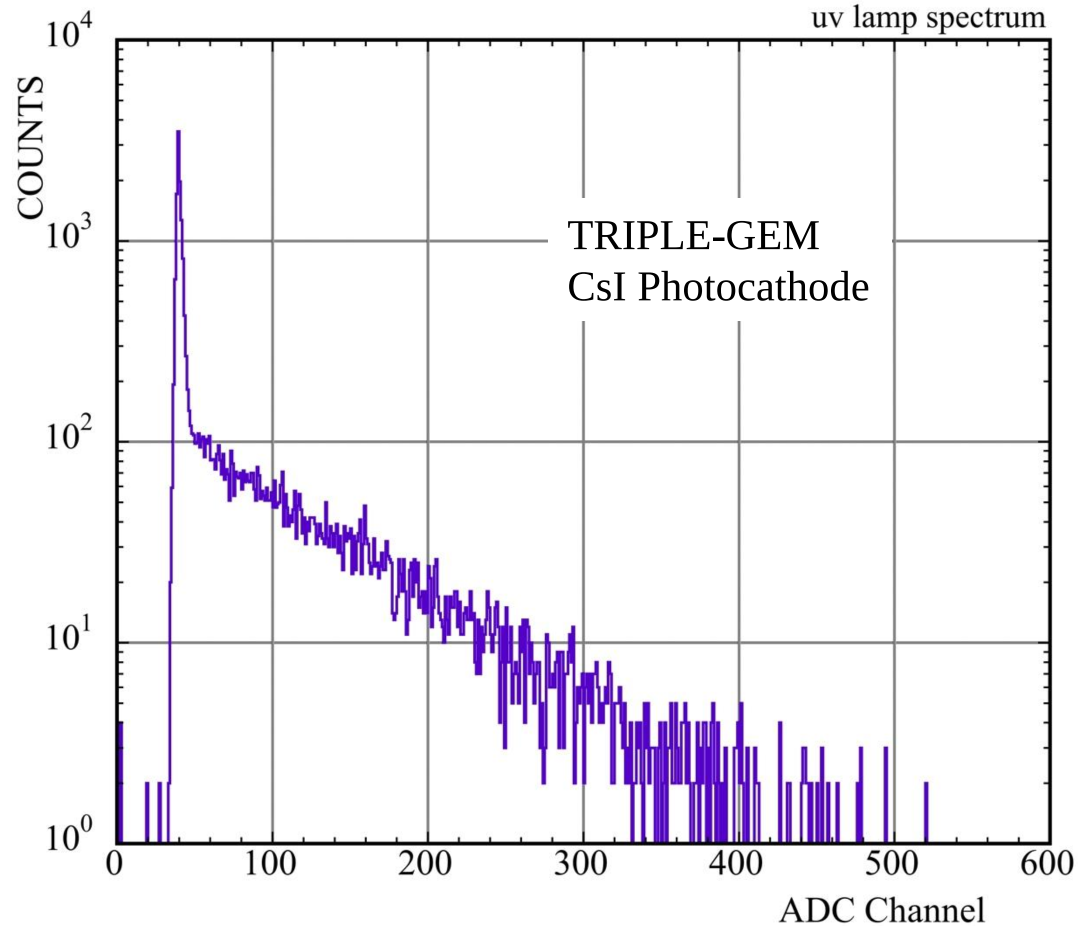
EXPERIMENTAL:



H. Sclumbohm, Zeit. Physik 151(1958)563

GAS ELECTRON MULTIPLIER (GEM)





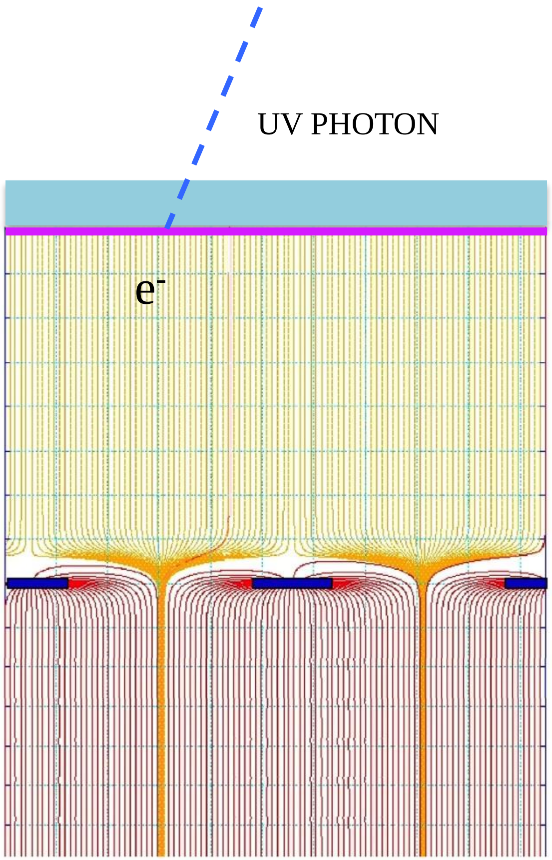
F. Sauli, Nucl. Instr. and Meth. A553(2005)18

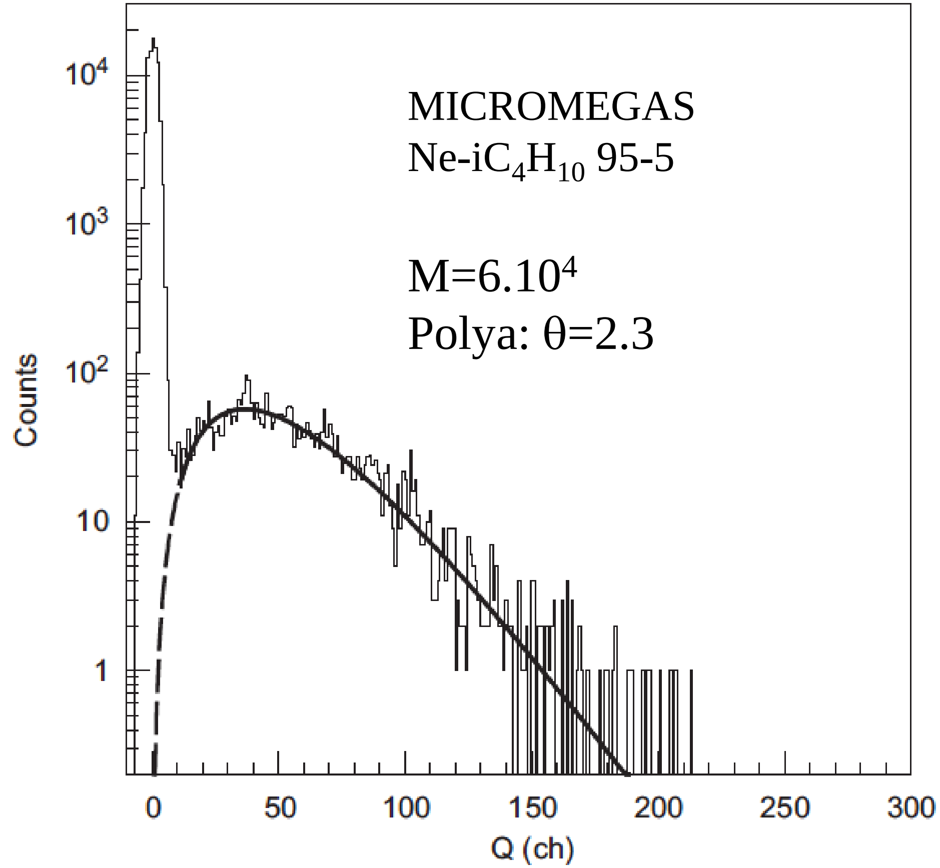
MICROMEGAS

UV PHOTON

WINDOW

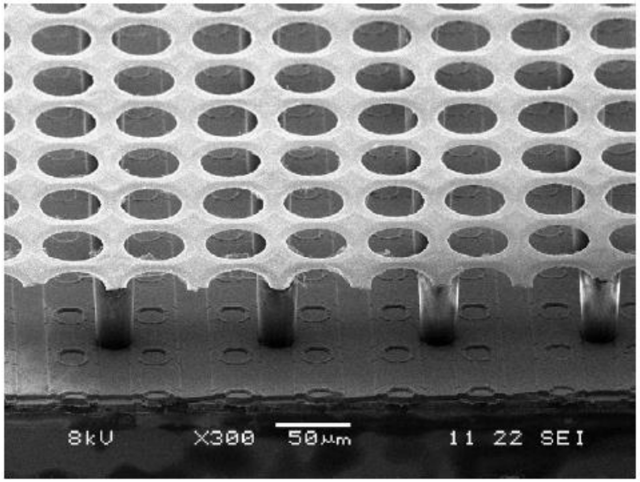
PHOTOCATHODE

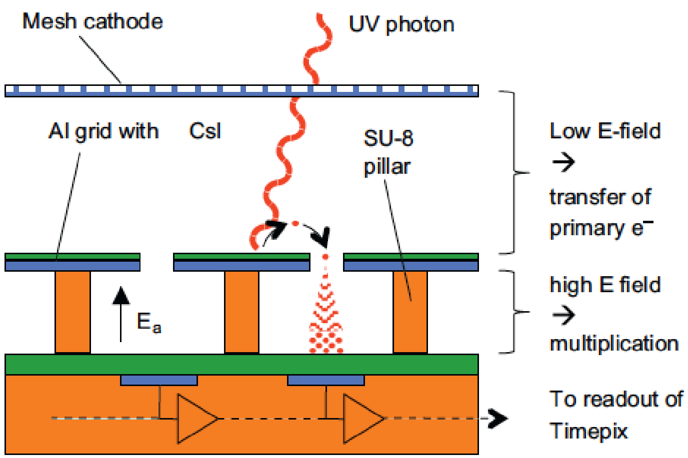


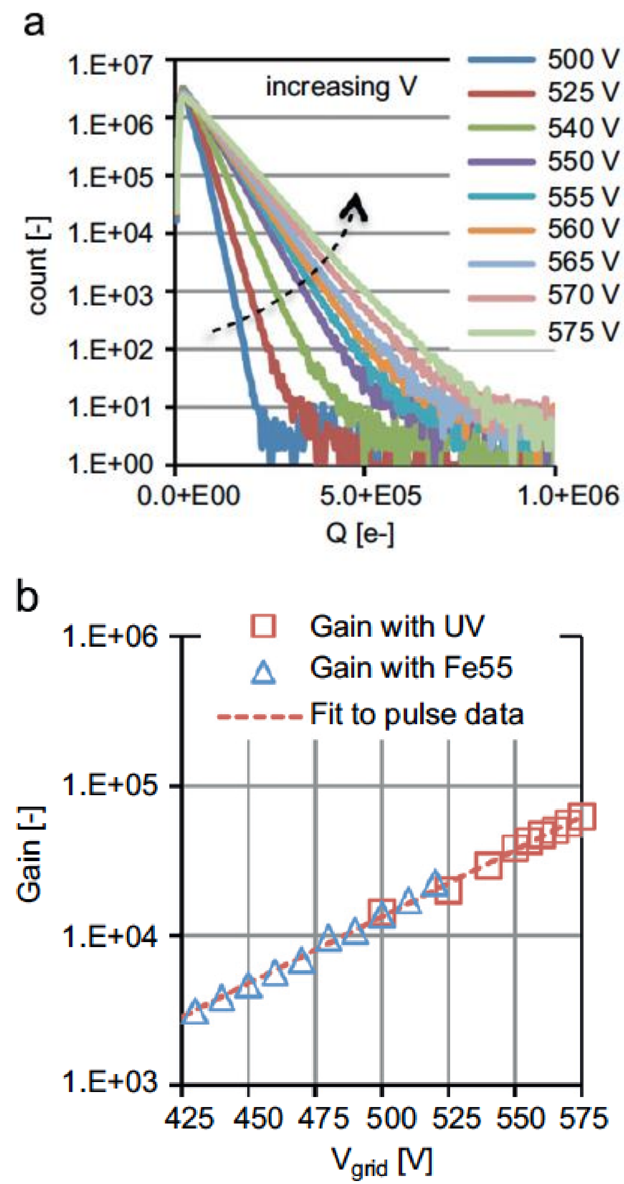


T. Zerguerras et al, Nucl. Instr. and Meth. A608(2009)397

CsI-COATED MICROMEGAS WITH TIMEPIX READOUT







J. Melai et al, Nucl. Instr. and Meth, A628(2011)133

Energy resolution: $$\left(\frac{\sigma_E}{E}\right)^2 = \underbrace{\left(\frac{\sigma_N}{N}\right)^2}_{\text{Ionization}} + \underbrace{\left(\frac{\sigma_M}{M}\right)^2}_{\text{Avalanche statistics}}$$

Average gain: $$M = \frac{1}{N}\sum_{i=1}^{N} A_i = \bar{A}$$ A_i : single electron avalanche size

Gain variance: $$\sigma_M^2 = \left(\frac{1}{N}\right)^2 \sum_{i=1}^{N} \sigma_A^2 \qquad \left(\frac{\sigma_M}{M}\right)^2 = \frac{1}{N}\left(\frac{\sigma_A}{\bar{A}}\right)^2$$

Furry statistics: $$\sigma_A = \bar{A} \qquad \left(\frac{\sigma_A}{\bar{A}}\right)^2 = 1$$

Polya statistics: $$\left(\frac{\sigma_A}{\bar{A}}\right)^2 = \frac{1}{\bar{A}} + b \qquad b = \frac{1}{1+\theta}$$

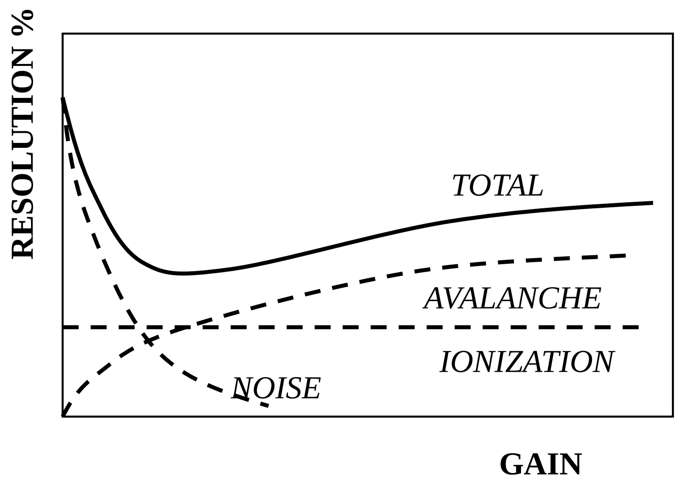
Ionization variance: $$\sigma_N^2 = FN$$ F: Fano factor

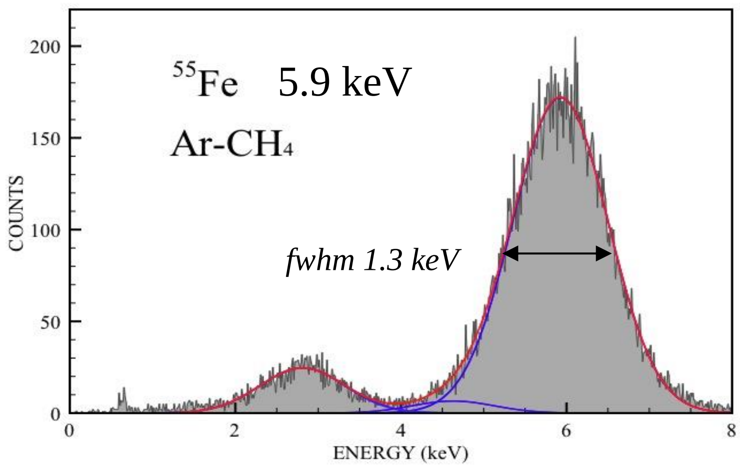
$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{1}{N}(F+b)$$

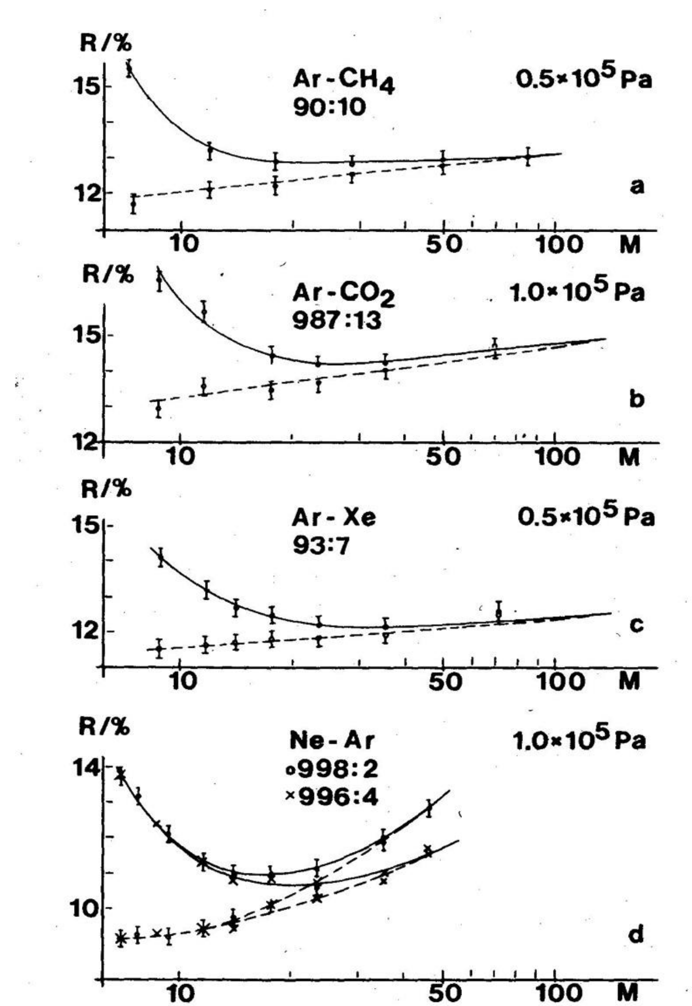
Furry: $b=1$ Polya: $b = 1/(1-\theta)$

FANO FACTORS

GAS	F
Ar	0.19
Ar-CH_4	0.19
Xe	<0.17
Ne+0.5%Ar	0.05

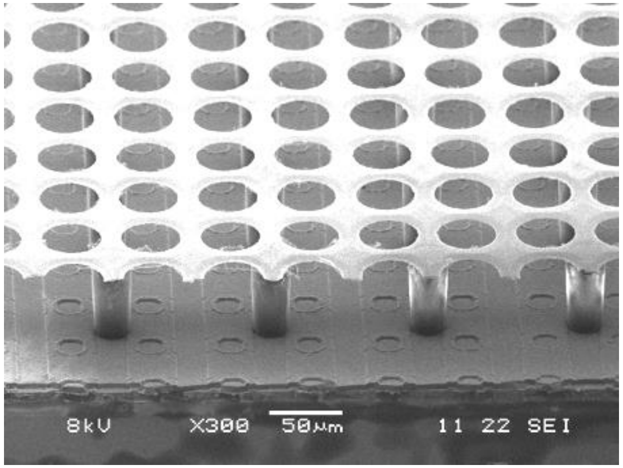




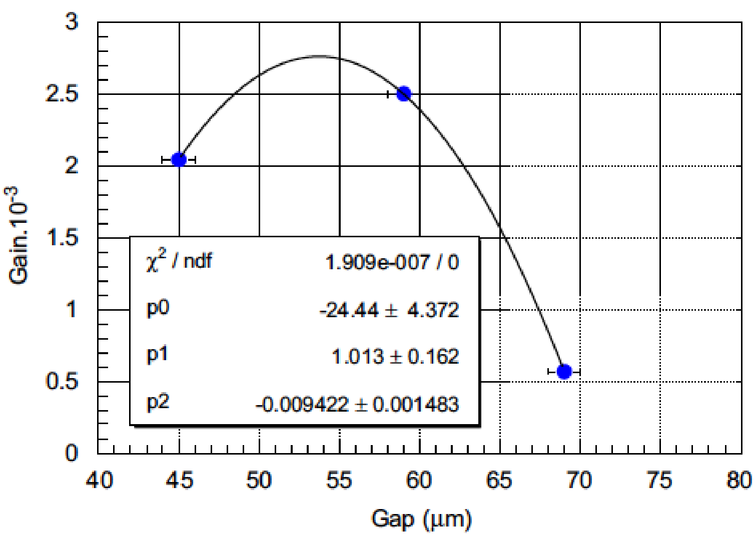


H. Sipilä and E. Kiuru, Adv. X-Ray Analysis 21(1978)

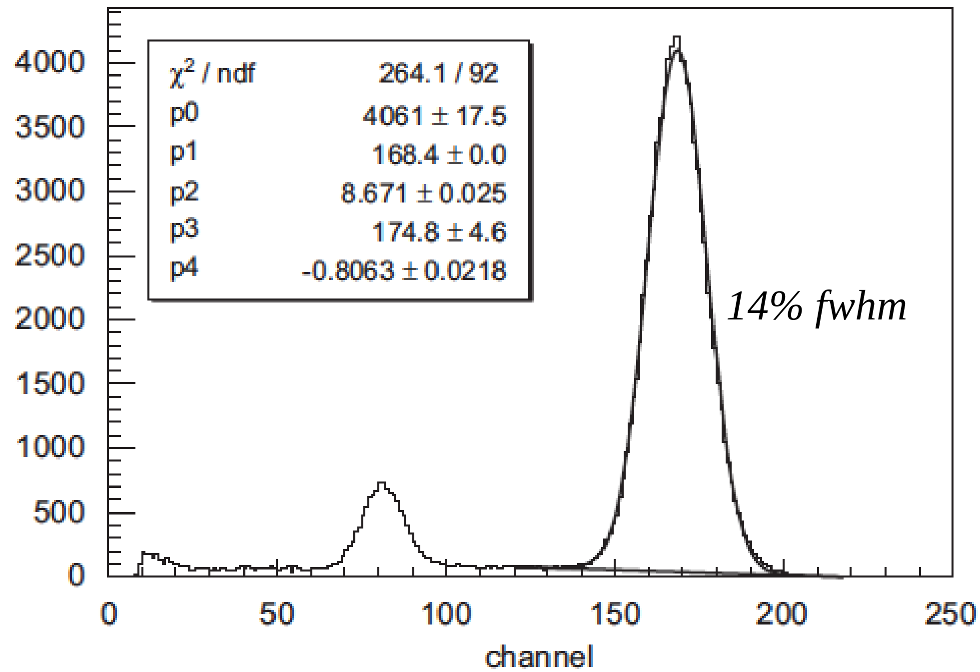
INGRID: MICROMEGAS WITH TIMEPIX READOUT



GAP INDEPENDENCE OF GAIN

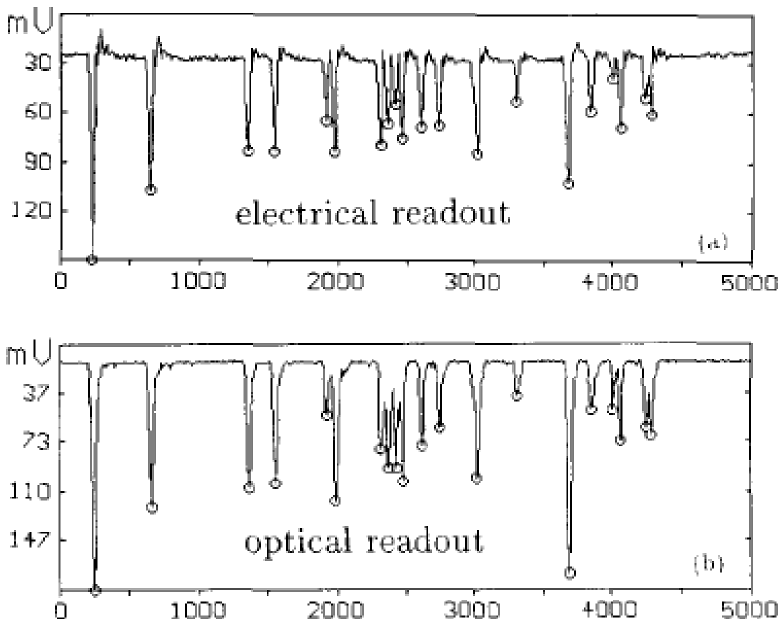


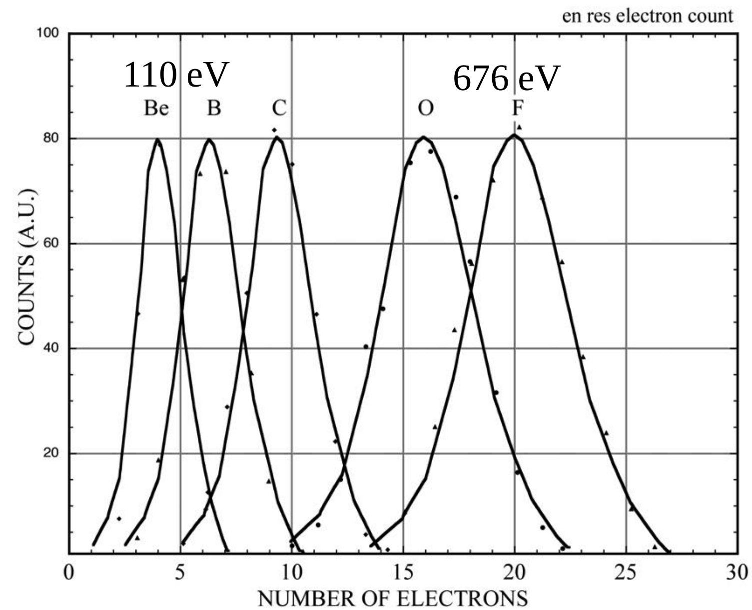
5.9 keV ^{55}Fe in Ar-CH_4 90-10

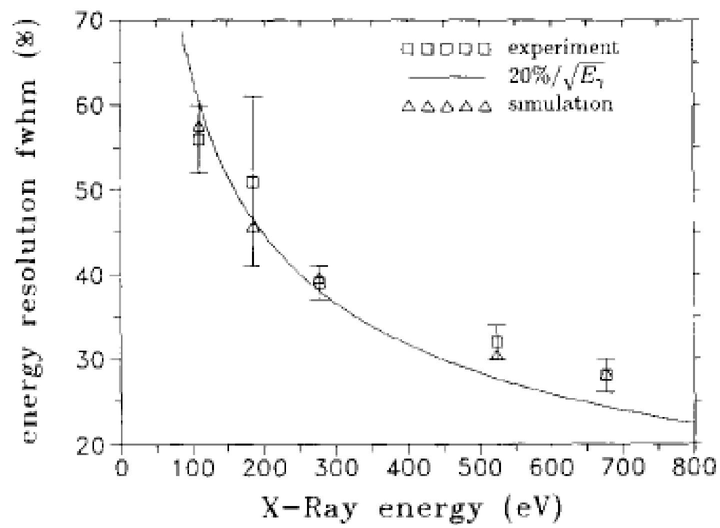


M. Chefdeville et al,
Nucl. Instr. and Meth. A591(2008)147

LOW PRESSURE (10 Torr) PROPORTIONAL COUNTER



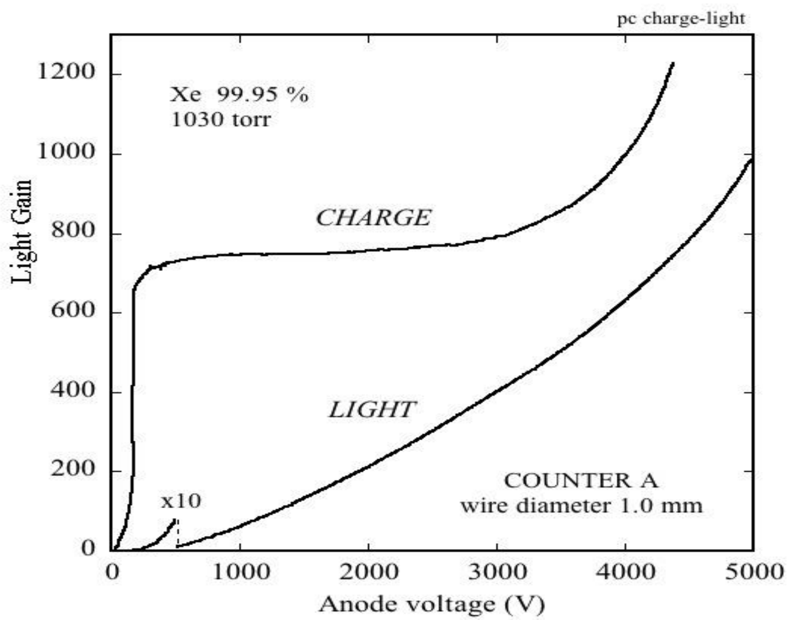


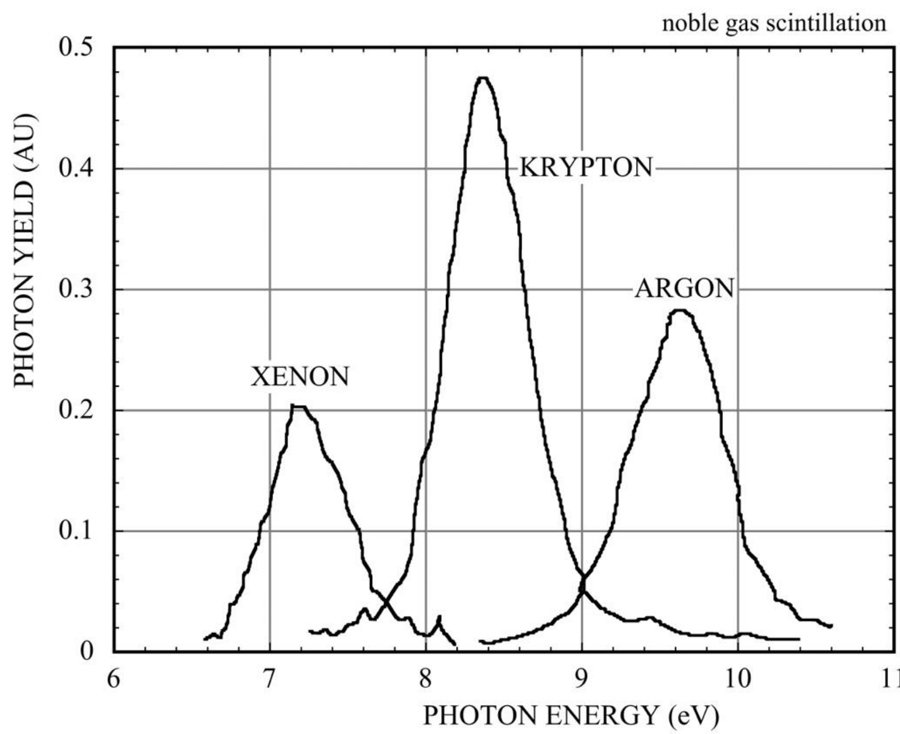


A. Pansky et al, Nucl. Instr. and Meth. A330(1993)150

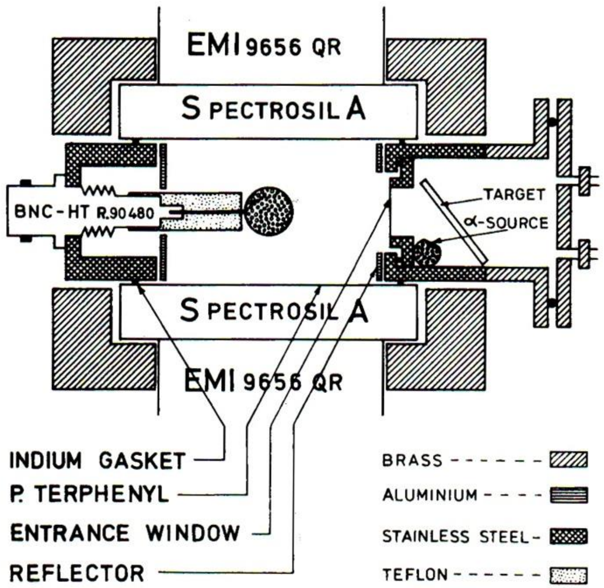
PHOTON EMISSION BEFORE CHARGE MULTIPLICATION:
NO AVALANCHE DISPERSIONS

NOBLE GASES SCINTILLATION SPECTRA ~1bar

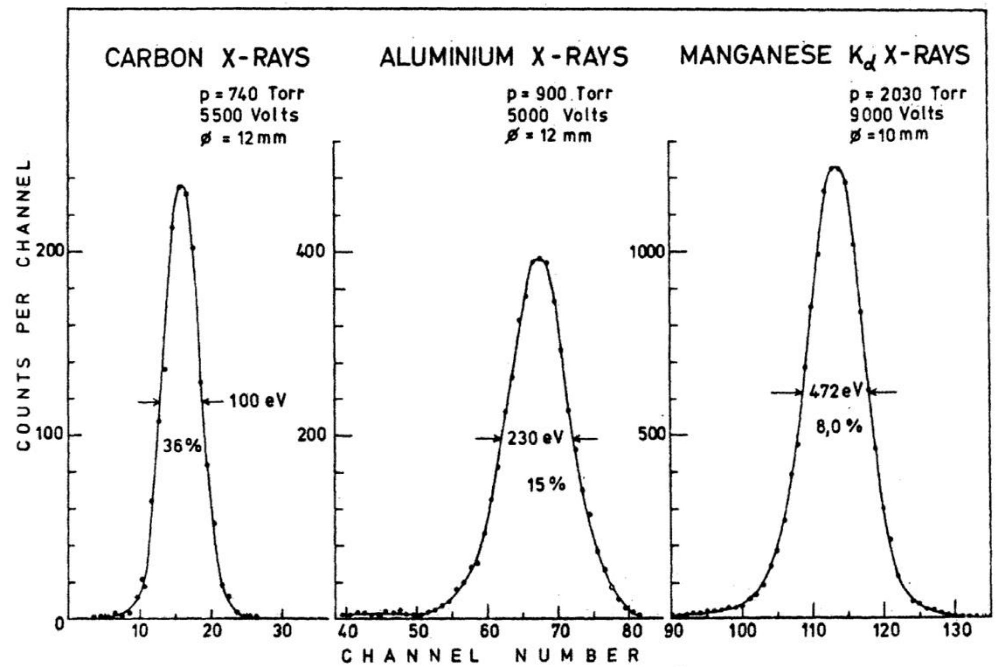




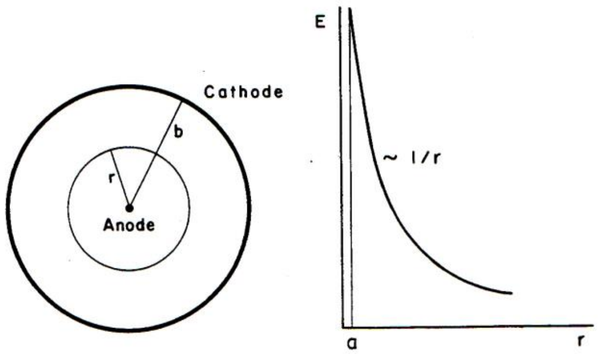
SCINTILLATION COUNTERS



ENERGY RESOLUTION:
CLOSE TO STATISTICAL LIMIT

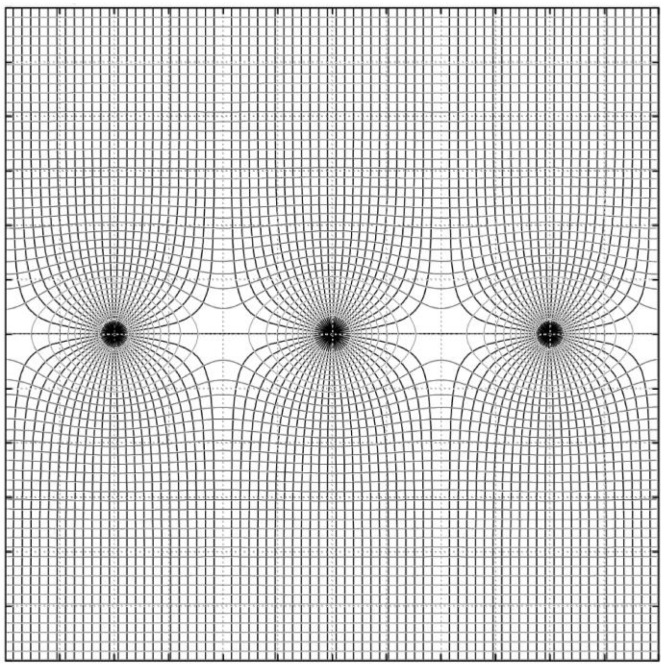


A. Policarpo et al, Nucl. Instr. and Meth. 102(1972)337



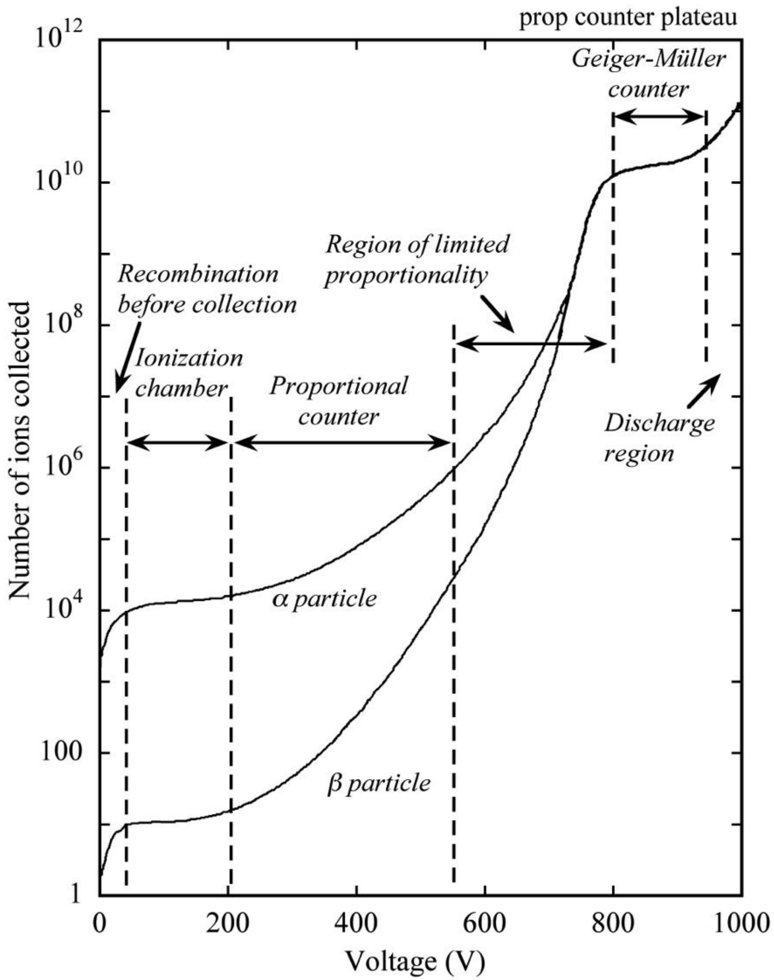
SINGLE WIRE COUNTER

E. Rutherford and H. Geiger, Proc. Royal Soc. A81 (1908)141

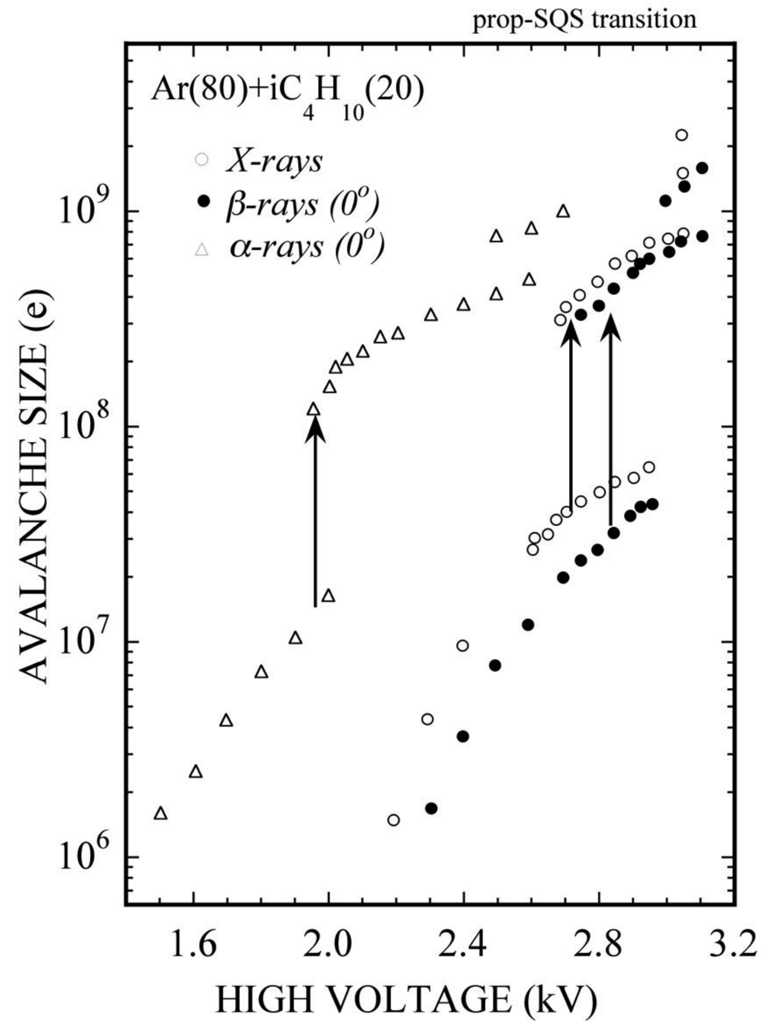


MULTI-WIRE PROPORTIONAL CHAMBER

G. Charpak et al, Nucl. Instr. and Meth. 62(1968)262

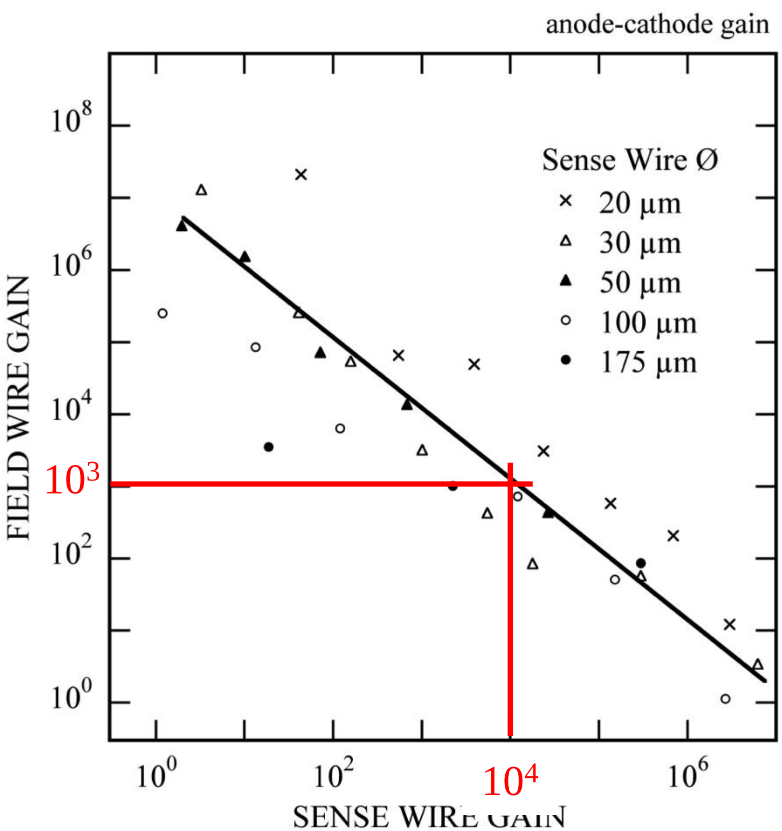


STREAMER TRANSITION



N. Koori et al, Jap. J. Appl. Phys. 25(1986)986

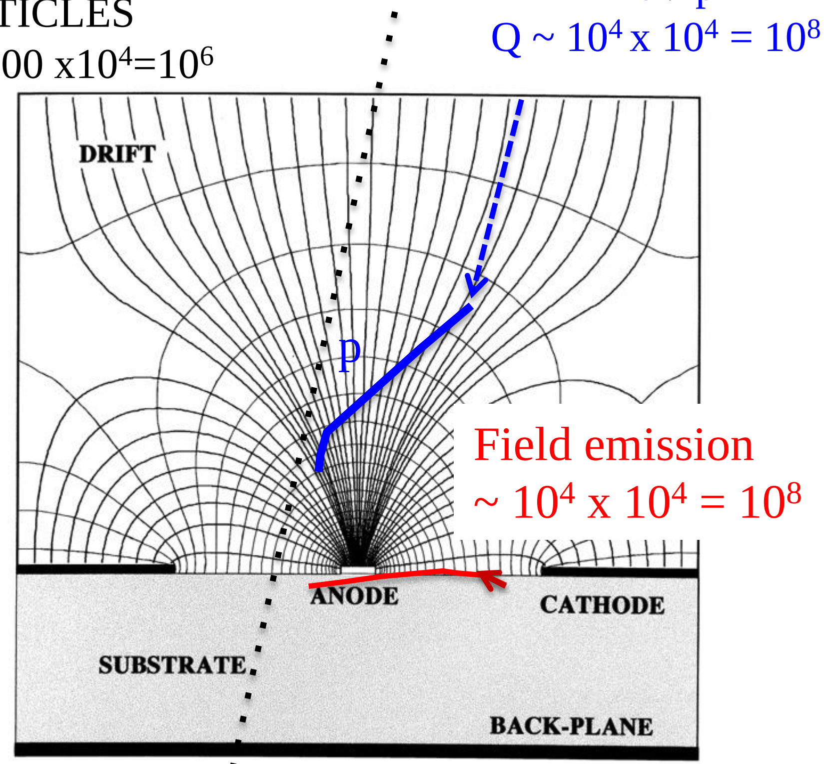
TOTAL CHARGE Q > 10^7----> DISCHARGE



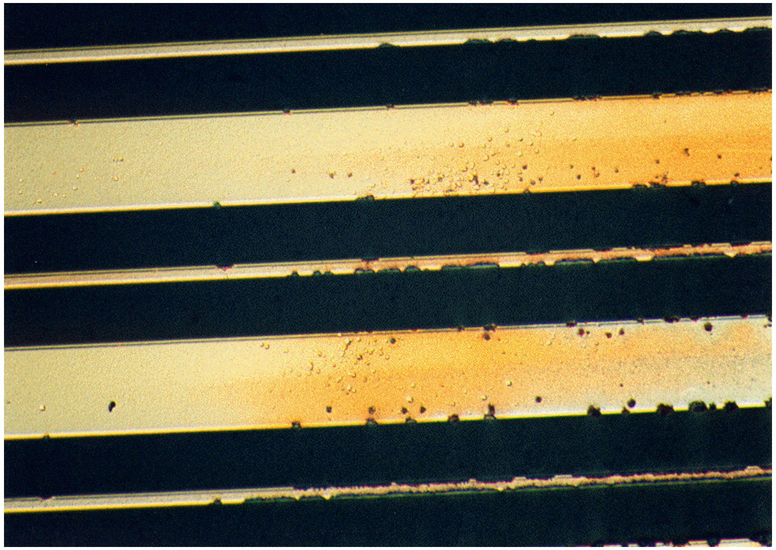
N. Koori et al, Jap. J. Appl. Phys. 25(1986)986

DISCHARGES IN MICROSTRIP CHAMBERS

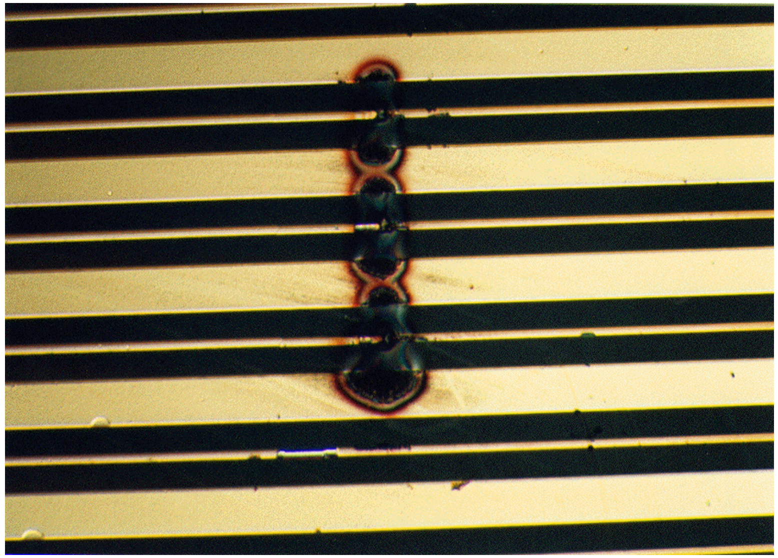
MINIMUM IONIZING PARTICLES
Q= 100 x10^4=10^6



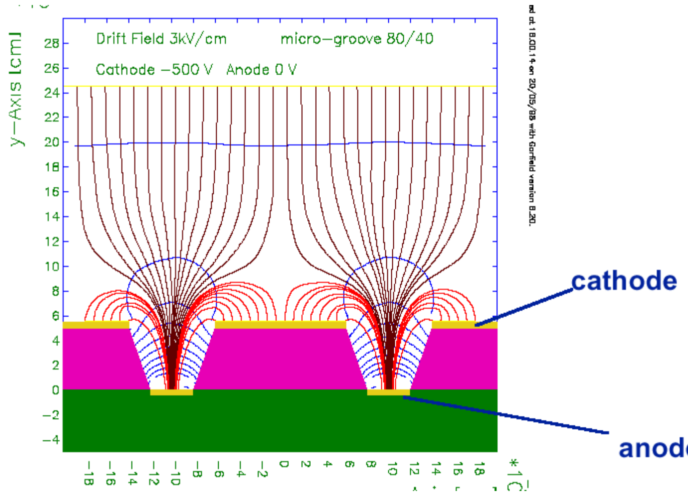
EFFECTS OF DISCHARGES IN MSGCs



Fabio's Museum of Horrors

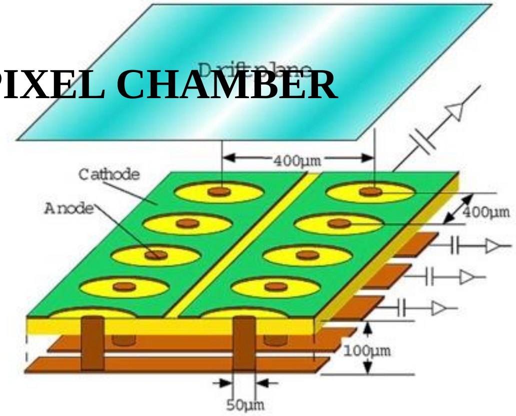


MICRO-GROOVE CHAMBER



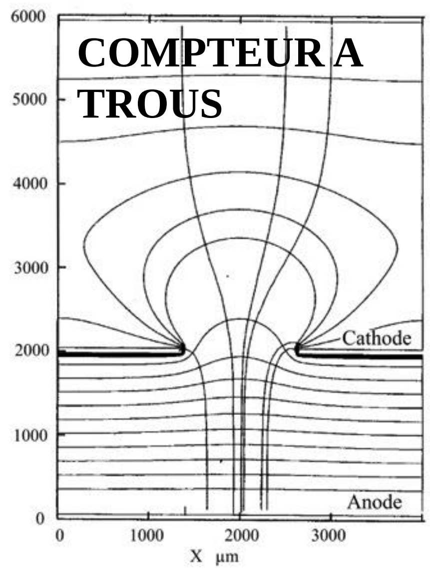
R. Bellazzini et al,
Nucl. Instr. Meth. A424(1998)444

MICRO-PIXEL CHAMBER



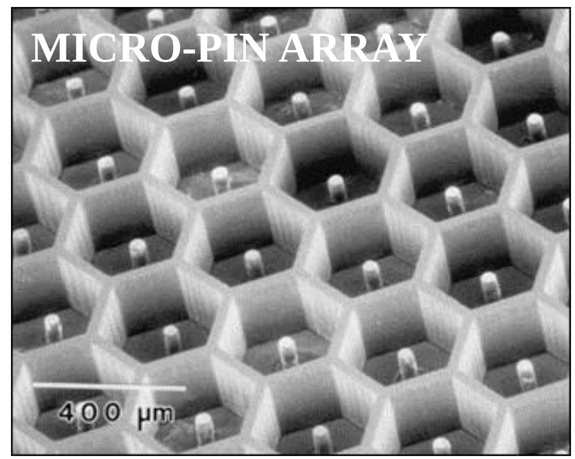
A. Ochi et al,
Nucl. Instr. and Meth. A478(2002)196

COMPTEUR A TROUS



F. Bartol et al
J. Phys.III France 6(1996)337

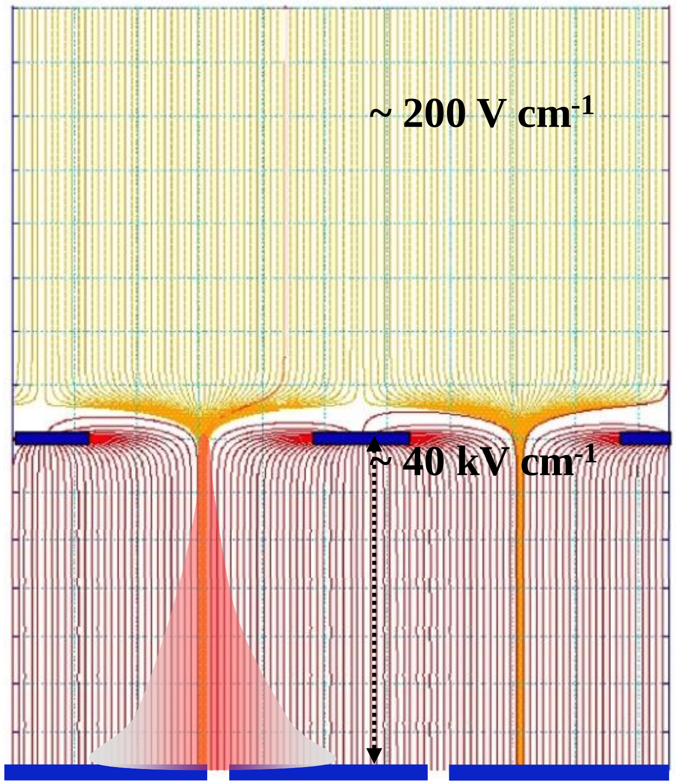
MICRO-PIN ARRAY



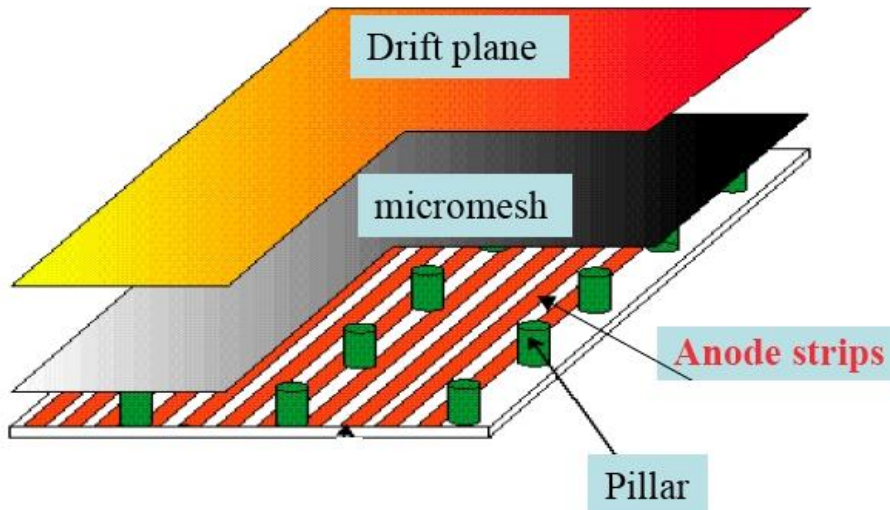
P. Rehak et al
IEEE TNS-47(2000)1426

Ioannis Giomataris (1996)

HIGH/LOW FIELD REGIONS
SEPARATED BY A MESH

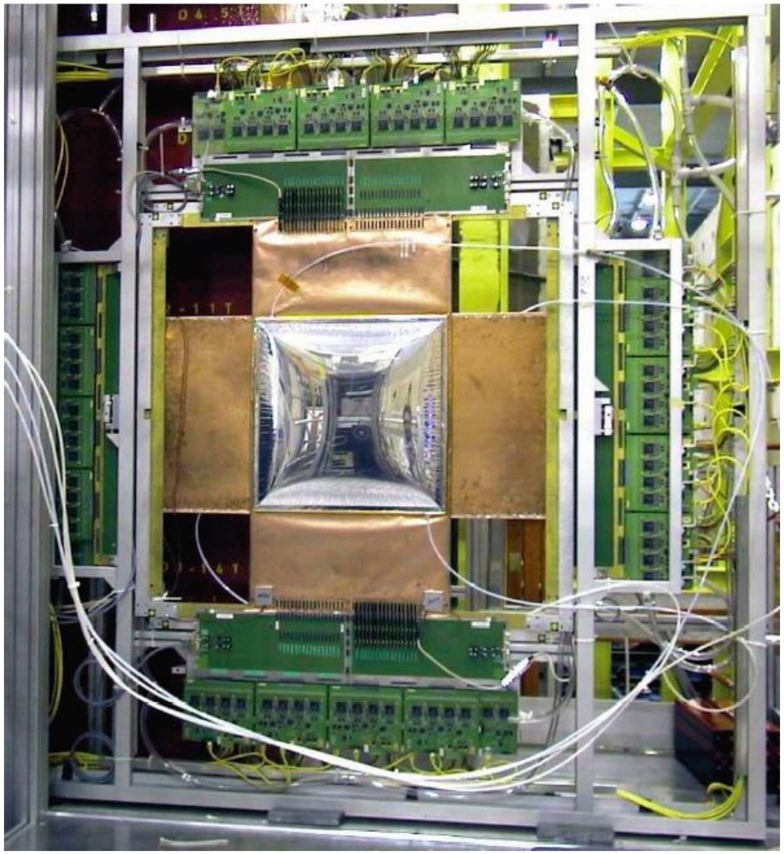


GAP UNIFORMITY:
SPACERS OR PILLARS

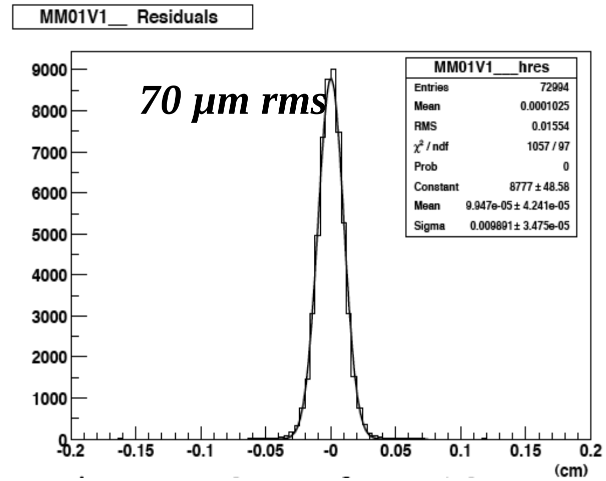


Y. Giomataris et al, Nucl. Instr. and Meth. A 376(1996)29

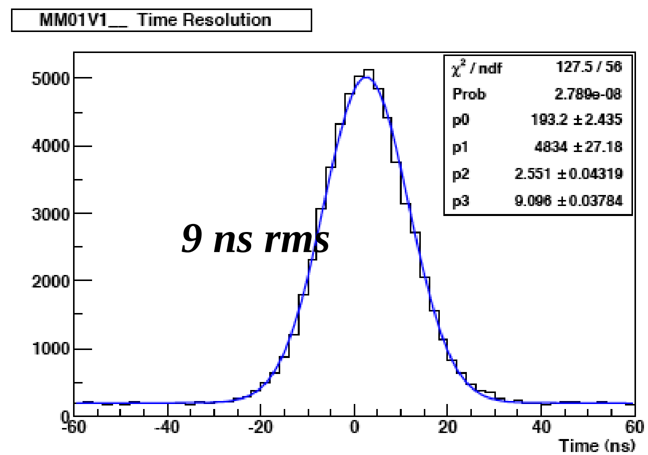
12 planes in 3 stations X,Y, U, V
40x40 cm^2 active
350 µm strips with digital readout



SPACE RESOLUTION:

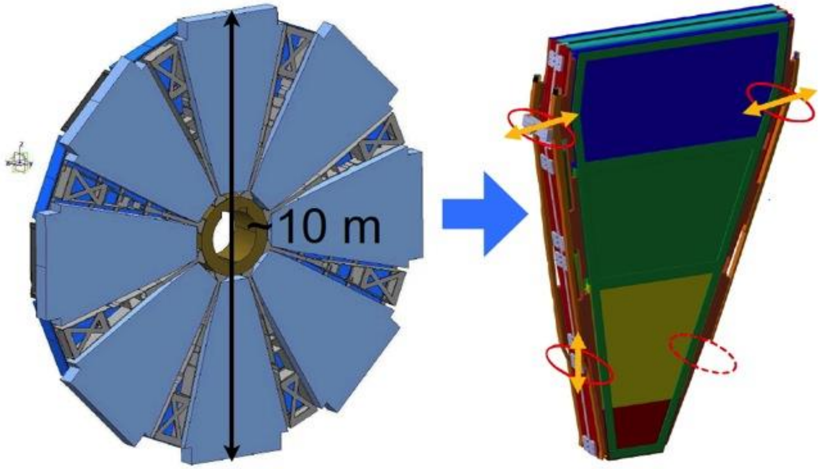


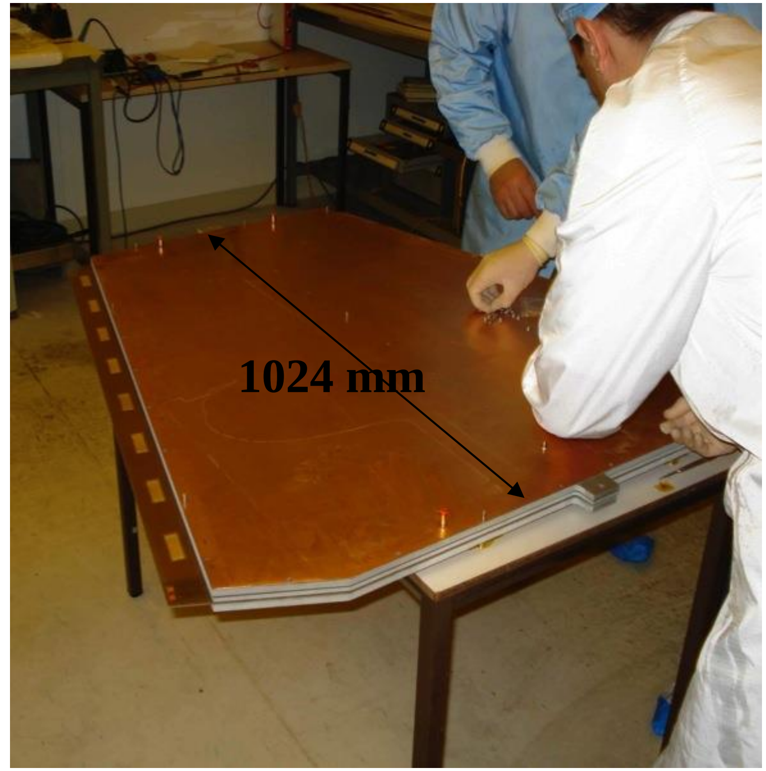
TIME RESOLUTION:

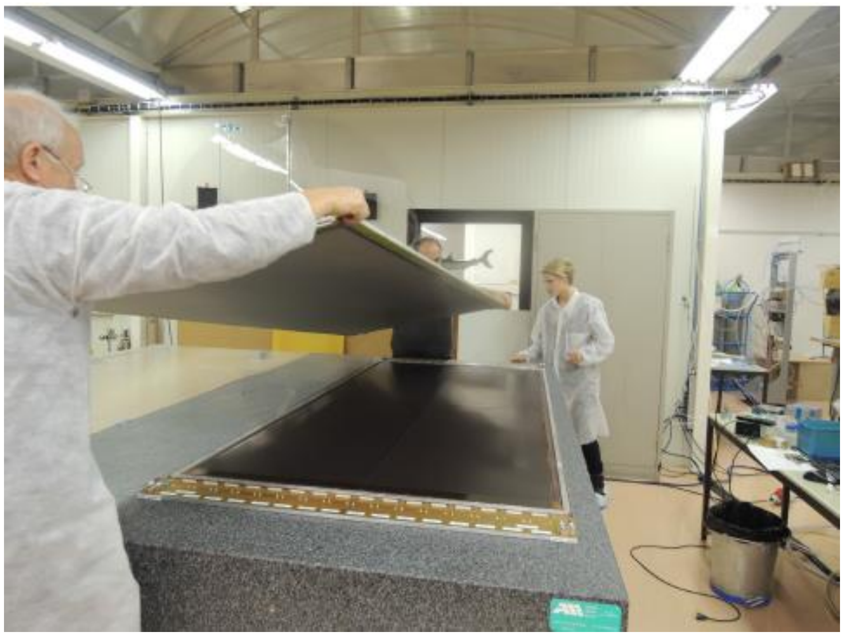


C. Bernet et al, Nucl. Instr. and Meth. A536(2005)61

ATLAS FORWARD MUON UPGRADE:







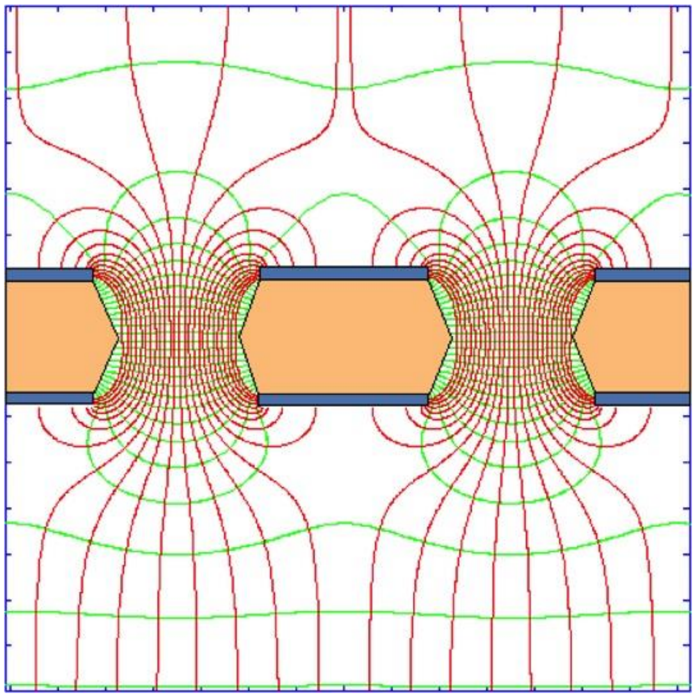
J. Wotschack, RD51 Meeting (CERN 2013)

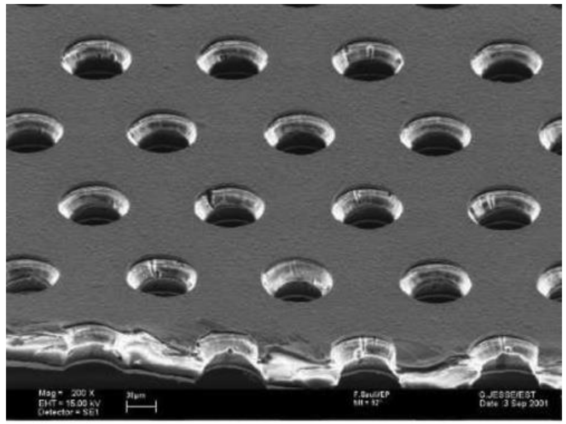
J. Wotschack, JINST 7, C02021 (2012)

Fabio Sauli (1997)

STANDARD GEM:70 µm Ø at 140 µm PITCH

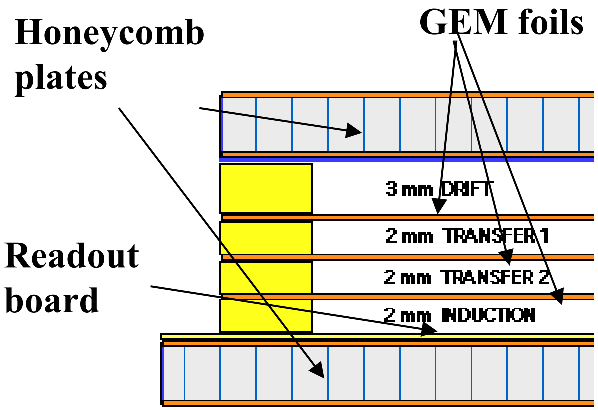
THIN (50 µm) METAL-COATED POLYMER FOIL WITH HIGH DENSITY OF HOLES:





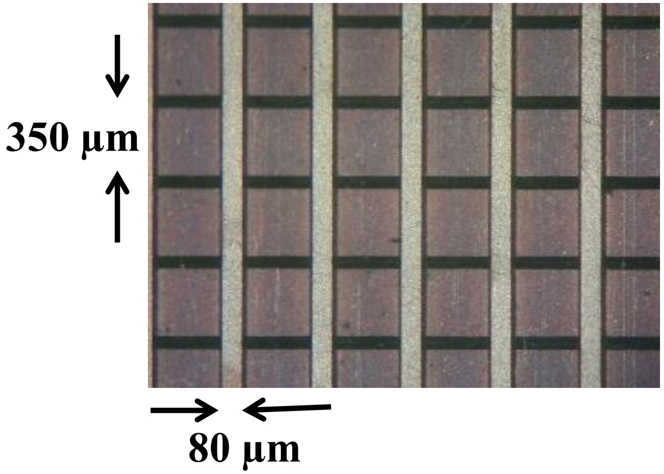
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

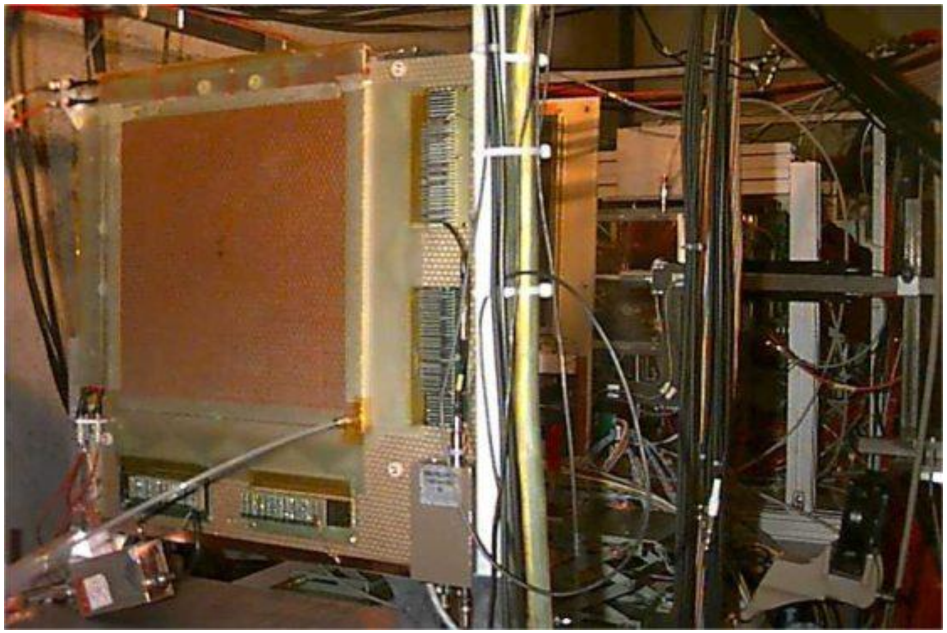
31x31 cm^2 active Total thickness in active area ~ 0.7% X_0



22 DETECTORS, OPERATIONAL 2002-2012

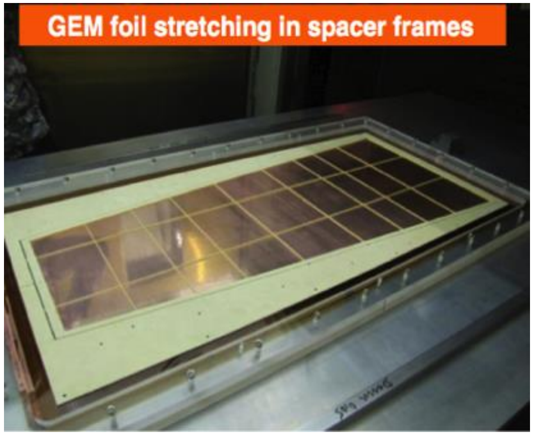
2-D readout board: 400 μm pitch strips

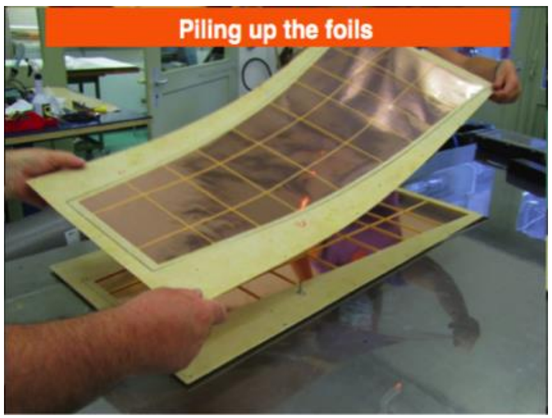




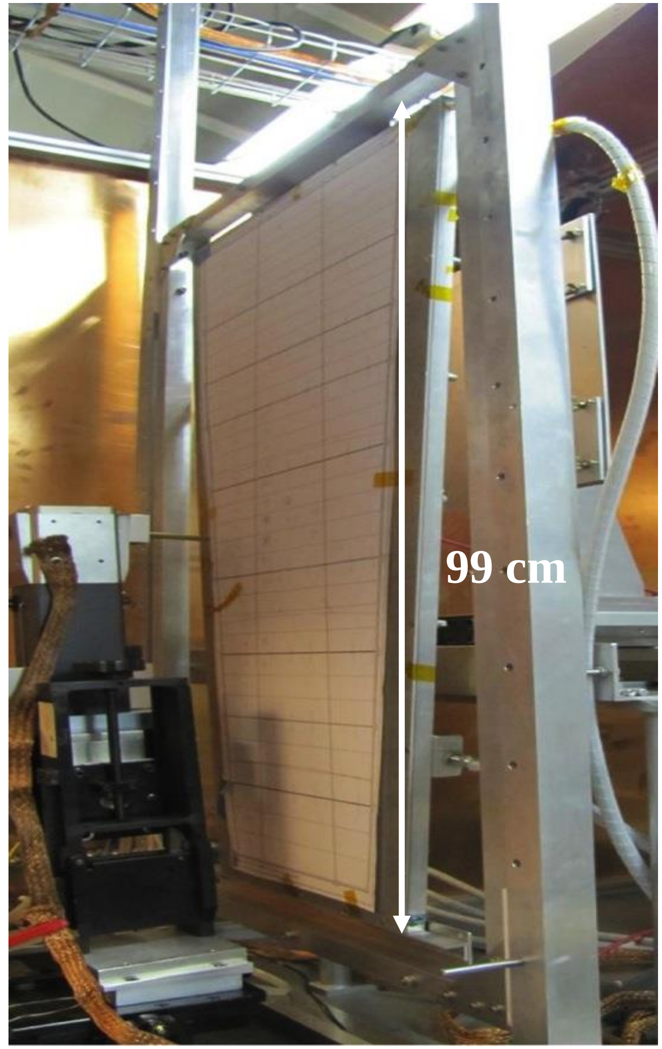
C. Altumbas et al,
Nucl. Instr. and Meth. A490(2002)177

B. Ketzer et al, Nucl. Instr. and Meth. A535(2004)314



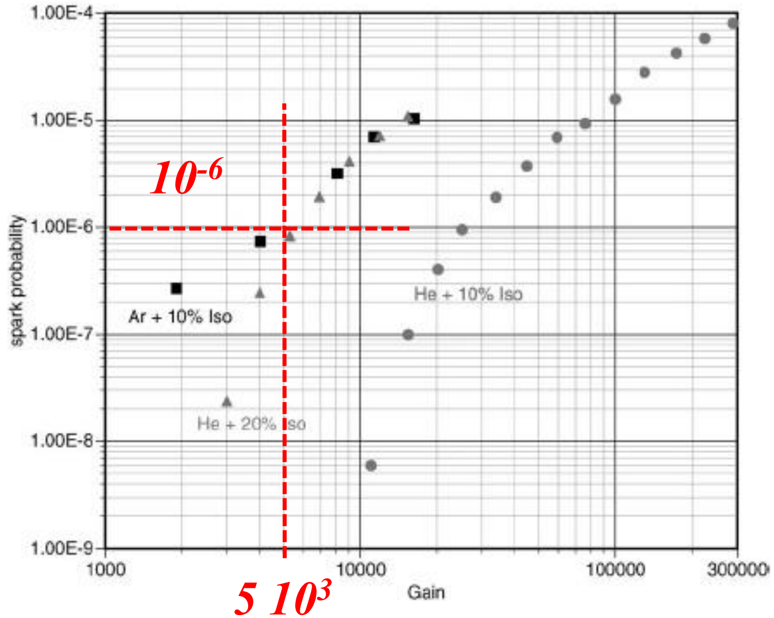


M. Tytgat, MPGD 2013



D. Abbaneo et al, JINST 9(2014)C01053

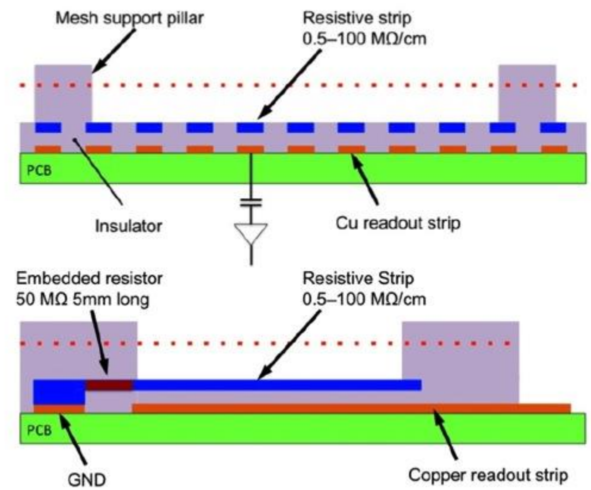
SPARK PROBABILITY IN HADRON BEAM

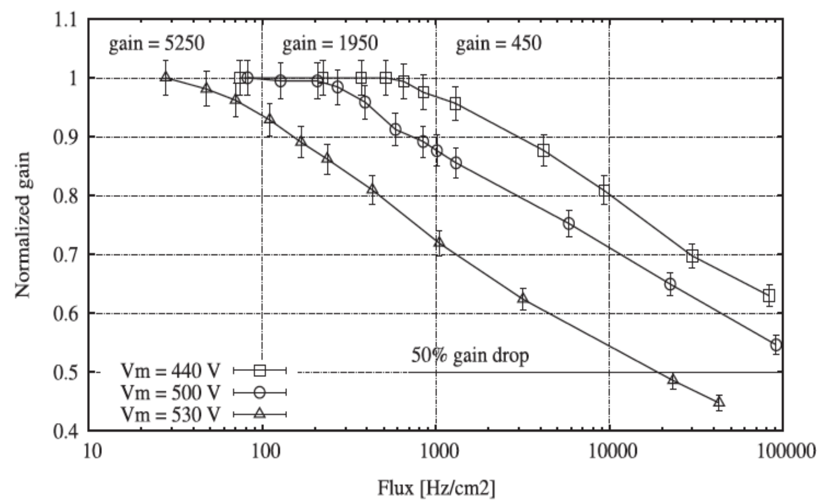


FOR A GAIN OF 5.10^3 , 10^6 PARTICLES s^{-1}:
~ ONE DISCHARGE PER SECOND

A. Delbart et al,
Nucl. Instr. and Meth. A478(2002)205

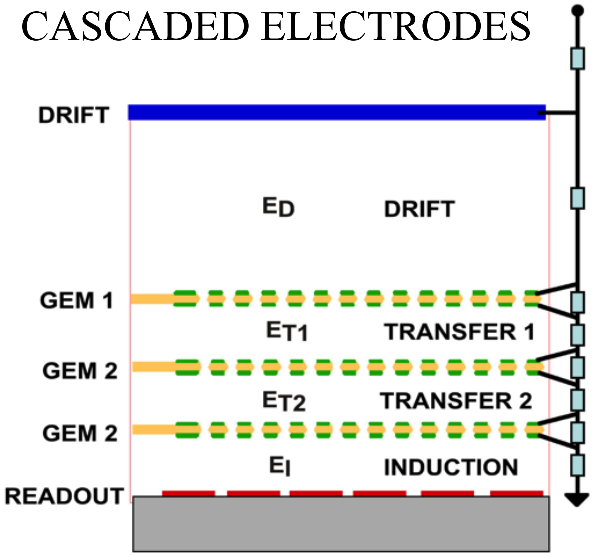
RESISTIVE MICROMEGAS





J. Galán et al, Nucl. Instr. and Meth. A732(2013)229

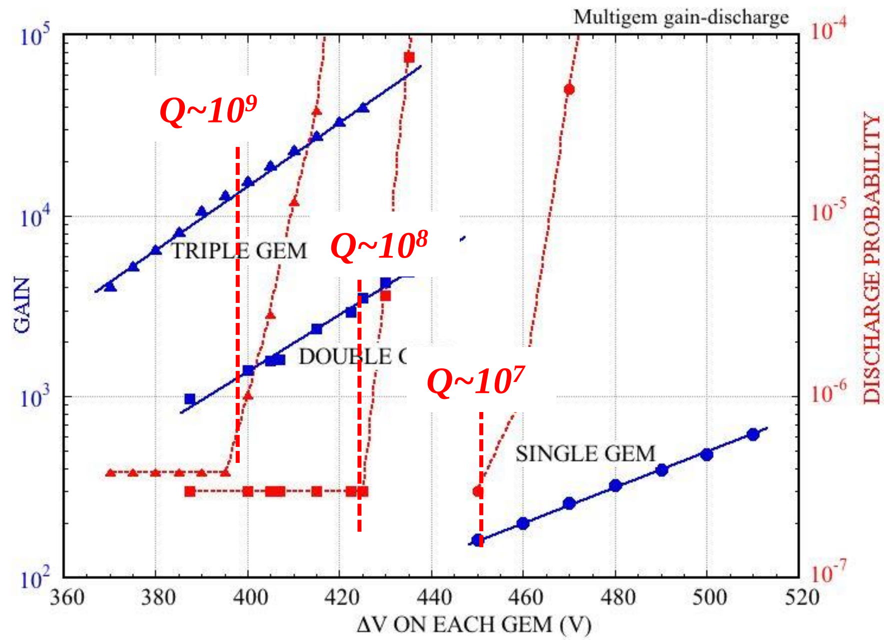
TRIPLE-GEM:
CASCADED ELECTRODES



C. Büttner et al,
Nucl. Instr. and Meth. A409(1998)79

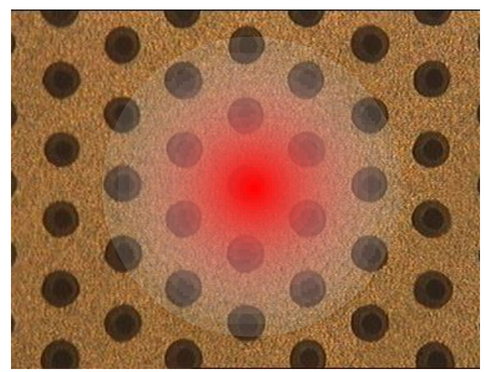
HIGHER GAIN, LOWER VOLTAGE ON EACH GEM

DISCHARGE RATE ON ~ 5 MeV α (10^5 e)

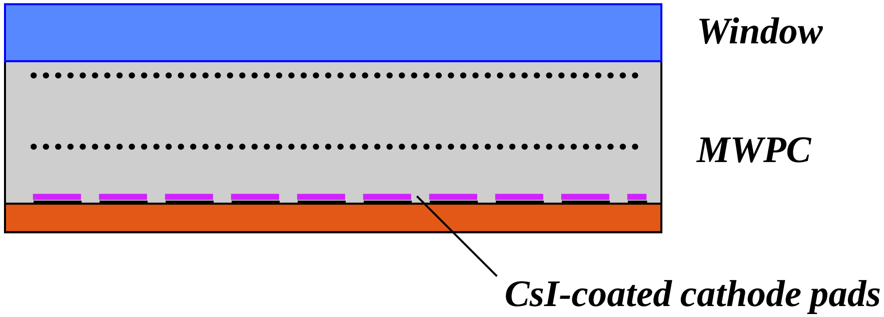


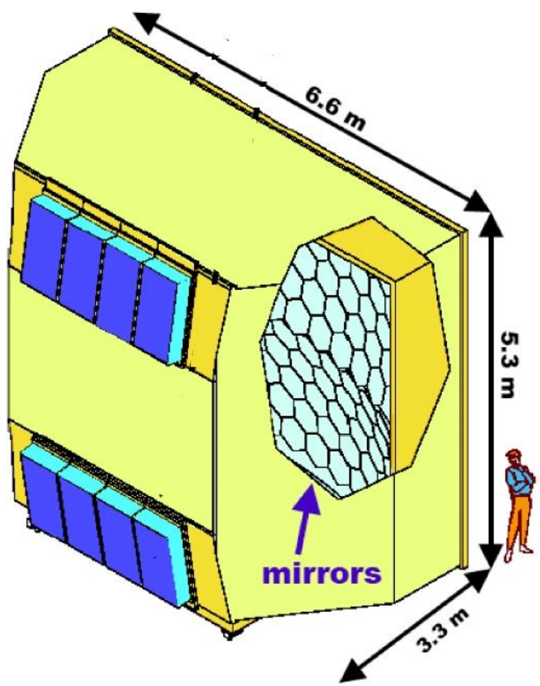
WHAT ABOUT THE RAETHER LIMIT?

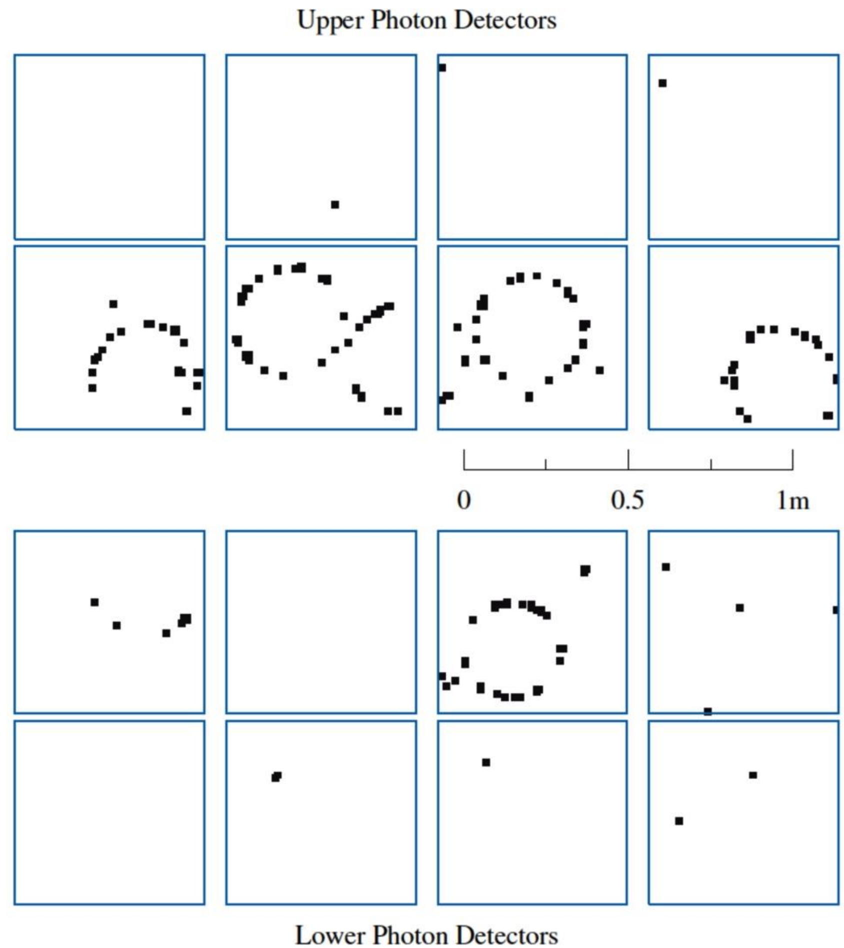
IN MULTI-GEMS, THE CHARGE SPREADS OVER MANY INDEPENDENT HOLES!



COMPASS RING IMAGING CHERENKOV COUNTER (RICH)

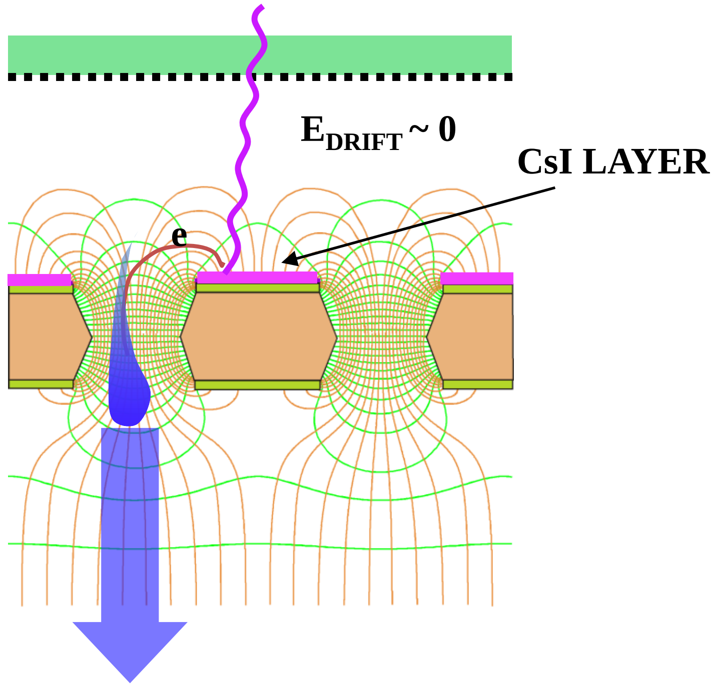






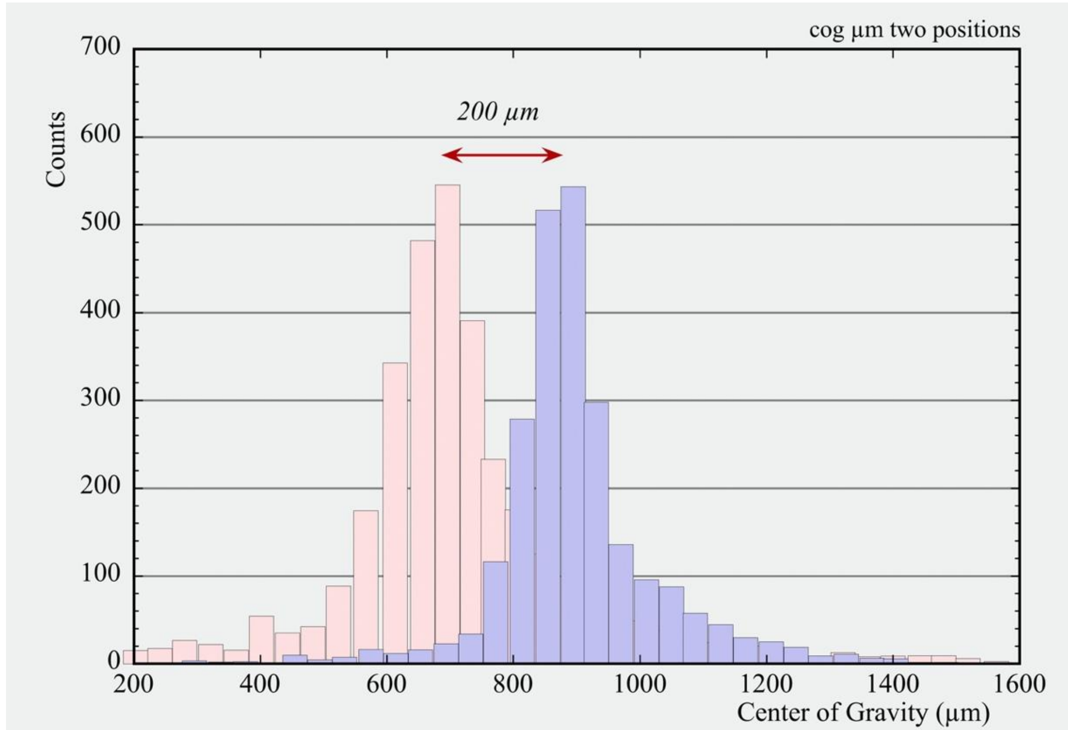
E. Albrecht et al, Nucl. Instr. and Meth. A502(2003)112

GEM WITH REFLECTIVE CsI PHOTOCATHODE COATING



FURTHER AMPLIFICATION

POSITION ACCURACY:
TWO COLLIMATED PHOTON BEAMS AT 200 µm

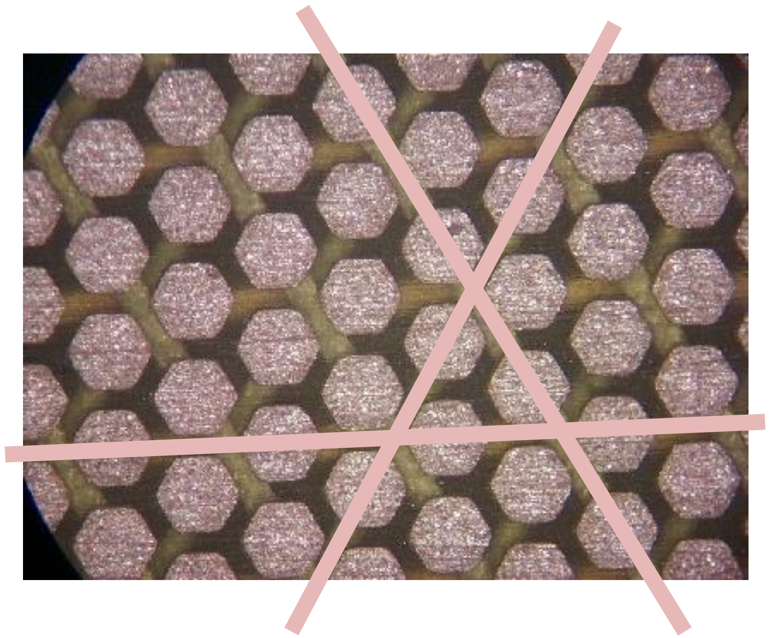


D. Mormann et al,
Nucl. Instr. and Meth. A478(2002)230

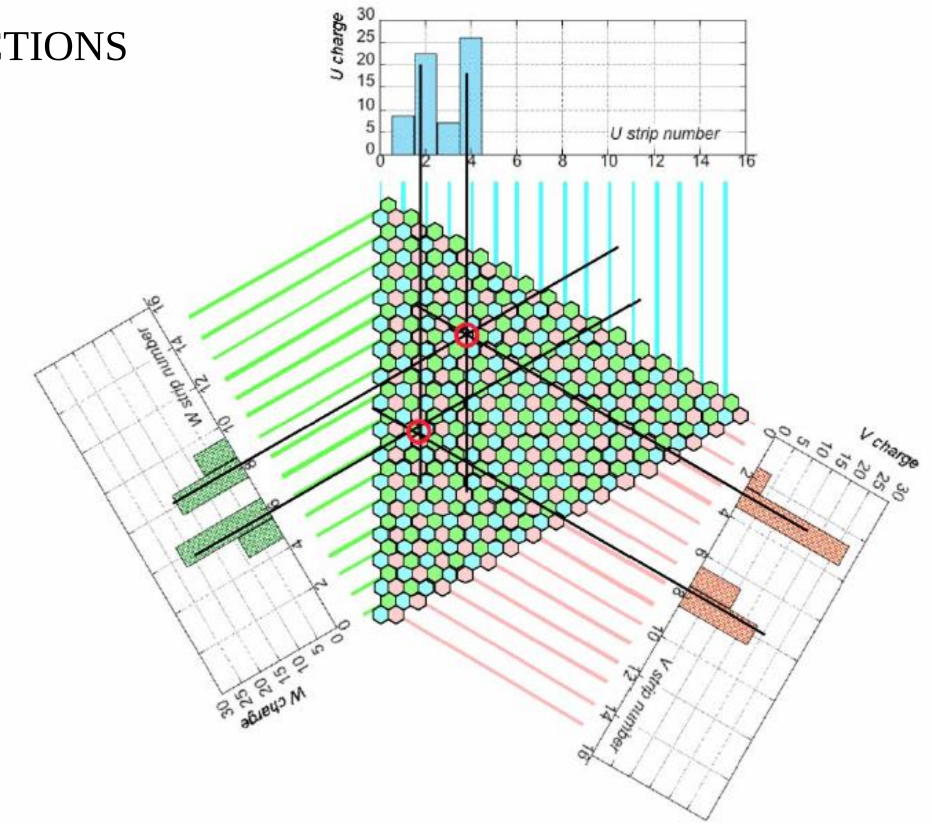
T. Meinshad. L. Ropelewski, F. Sauli
Nucl. Instr. and Meth. A535(2004)324

TRIPLE GEM WITH HEXABOARD READOUT

MATRIX OF HEXAGONAL PADS
INTERCONNECTED ALONG THREE DIRECTIONS

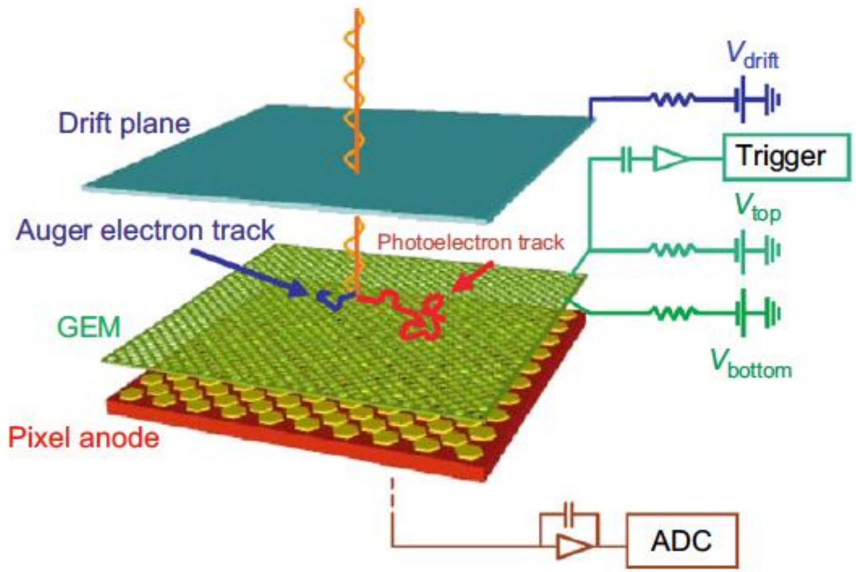


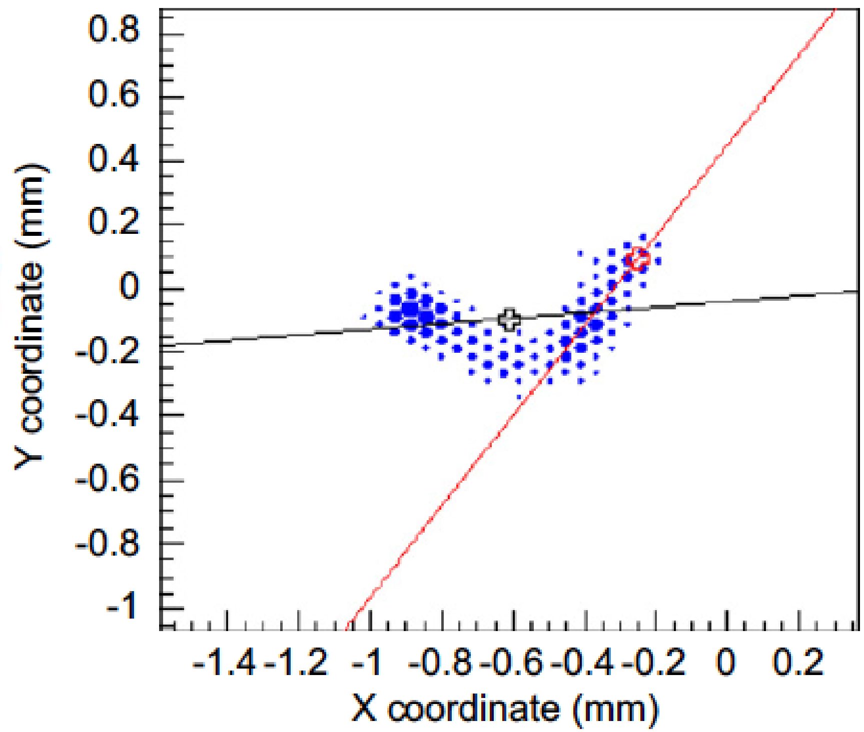
TWO-PHOTONS EVENT:



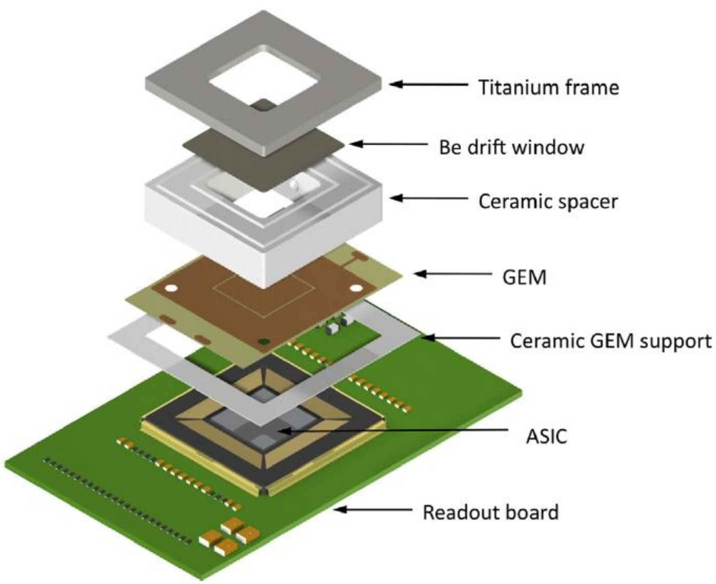
F. Sauli et al, IEEE NSSS 2004 Conf. Rec.Vol. 1, 12

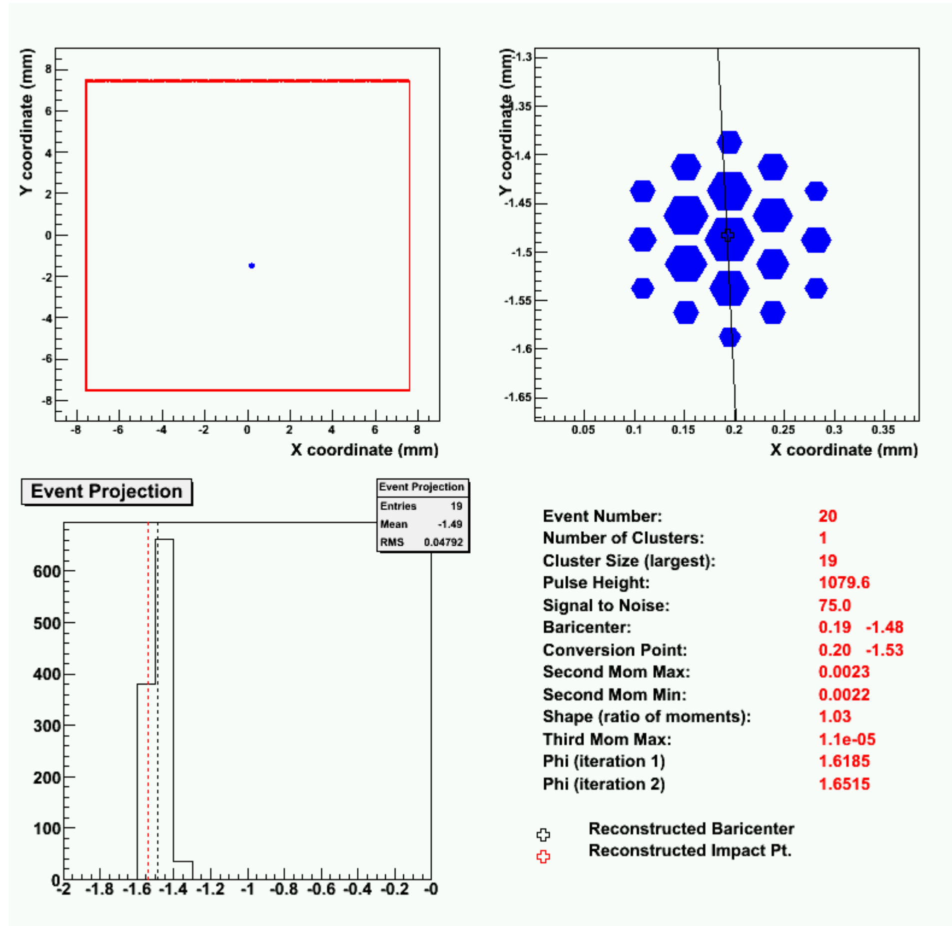
X-RAY POLARIMETER



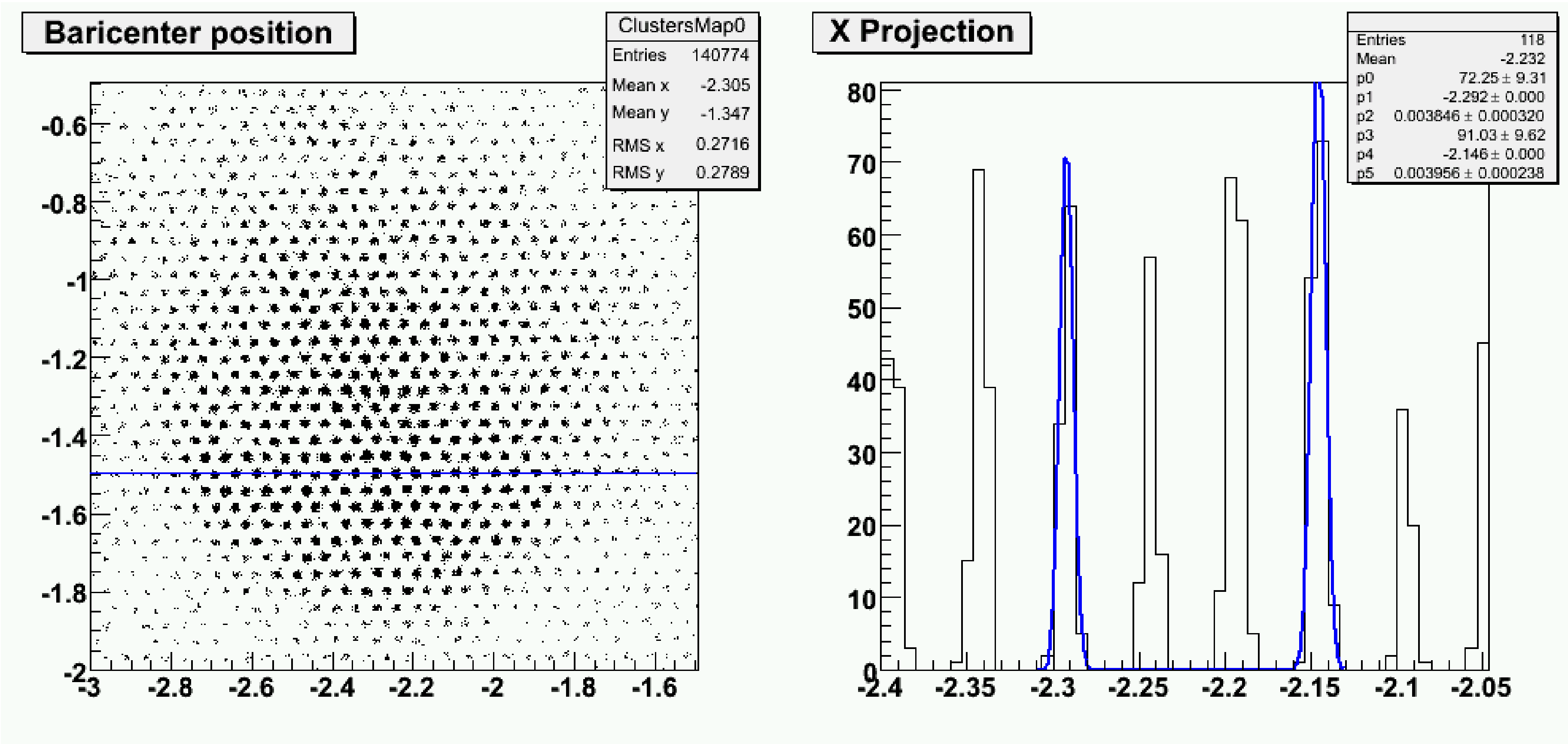


R. Bellazzini et al, Nucl. Instr. and Meth. A623(2010)766





R. Bellazzini et al, Nucl. Instr. and Meth. A581(2007)246

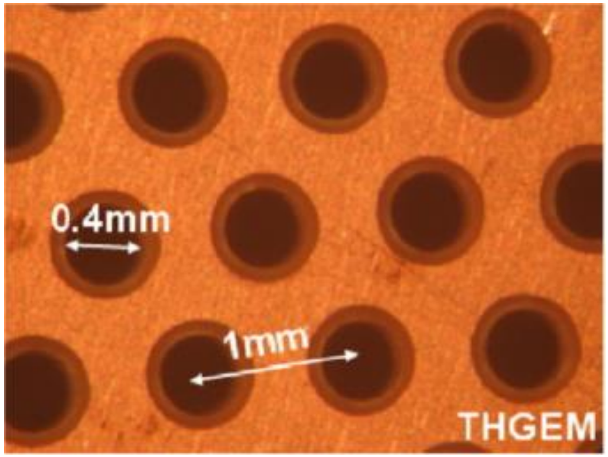


$\sigma \sim 4\ \mu m$

R. Bellazzini et al, Nucl. Instr. and Meth. A581(2007)246

MECHANICAL DRILLING OF METAL-CLAD PC BOARD:

- SELF-SUPPORTING
- HIGH GAIN



R.Chechik et al,
Nucl. Instr. and Meth. A535(2004)303

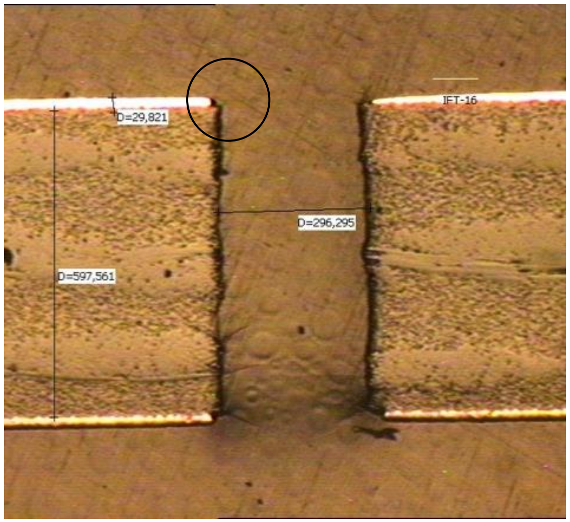
A. Breskin et al,
Nucl. Instr. And Meth. A623(2010)132

ALSO NAMED LARGE ELECTRON MULTIPLIER (LEM)

P. Janneret, Thesis at Neuchatel University (2001)

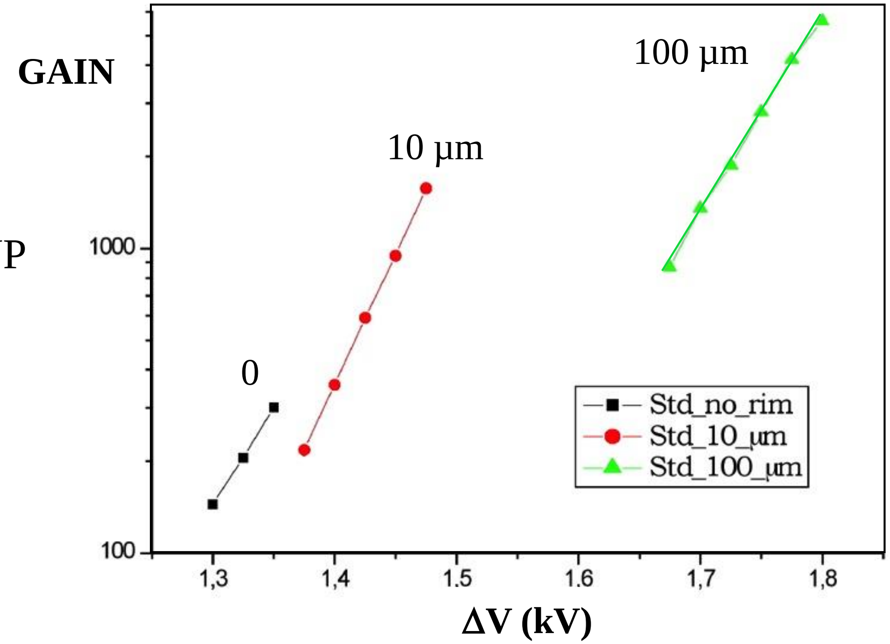
A. Badertscher et al, Nucl. Instr. And Meth. A617(2010)188

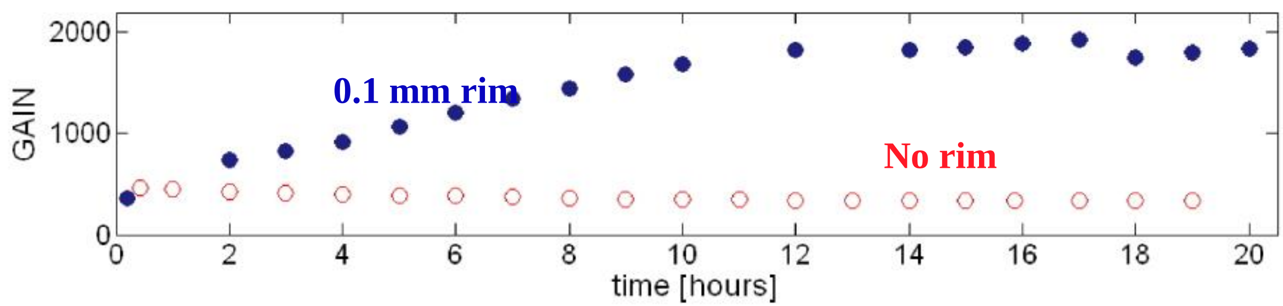
DEVELOPMENT FOR THE COMPASS RICH UPGRADE



LARGE RIM:
- HIGH GAIN
- CHARGING UP

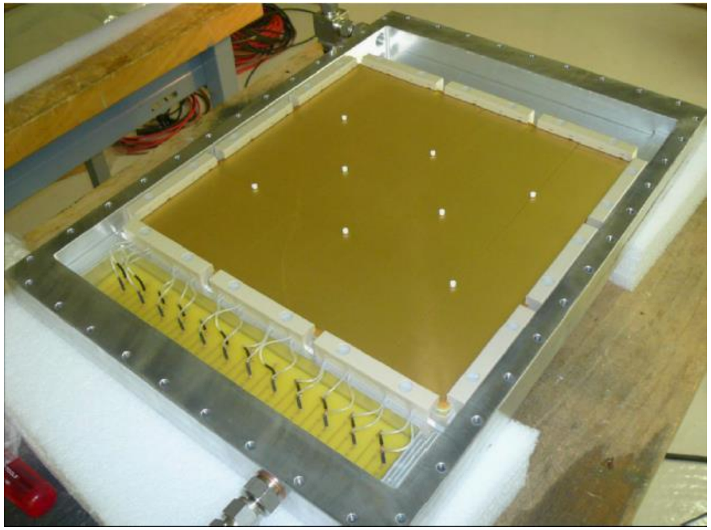
RIMLESS:
- LOW GAIN
- STABLE



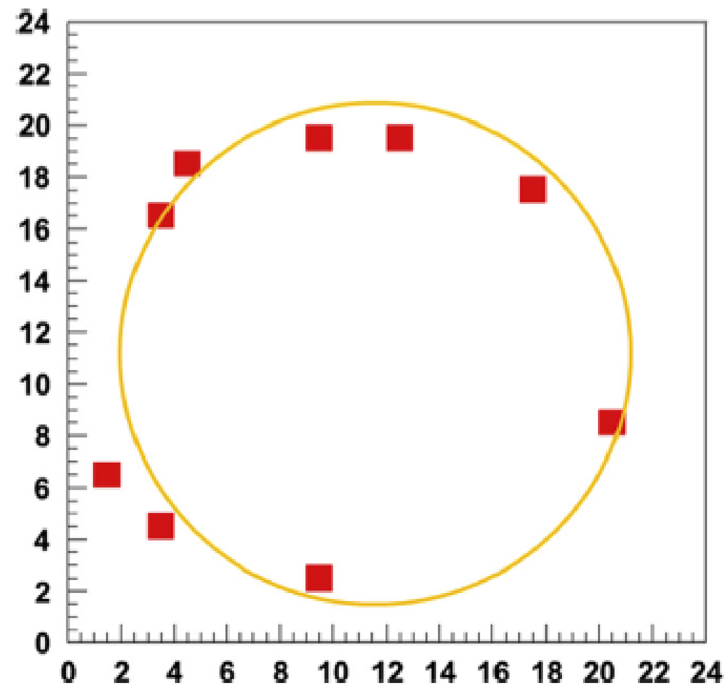


M. Alexeev et al, Nucl. Instr. and Meth. A695(2012)159

COMPASS RICH UPGRADE PROTOTYPE
TRIPLE-THICK GEM CsI-COATED 30x30 cm^2



9-PHOTONS RING



M. Alexeev et al, Nucl. Instr. and Meth. A732(2013)264

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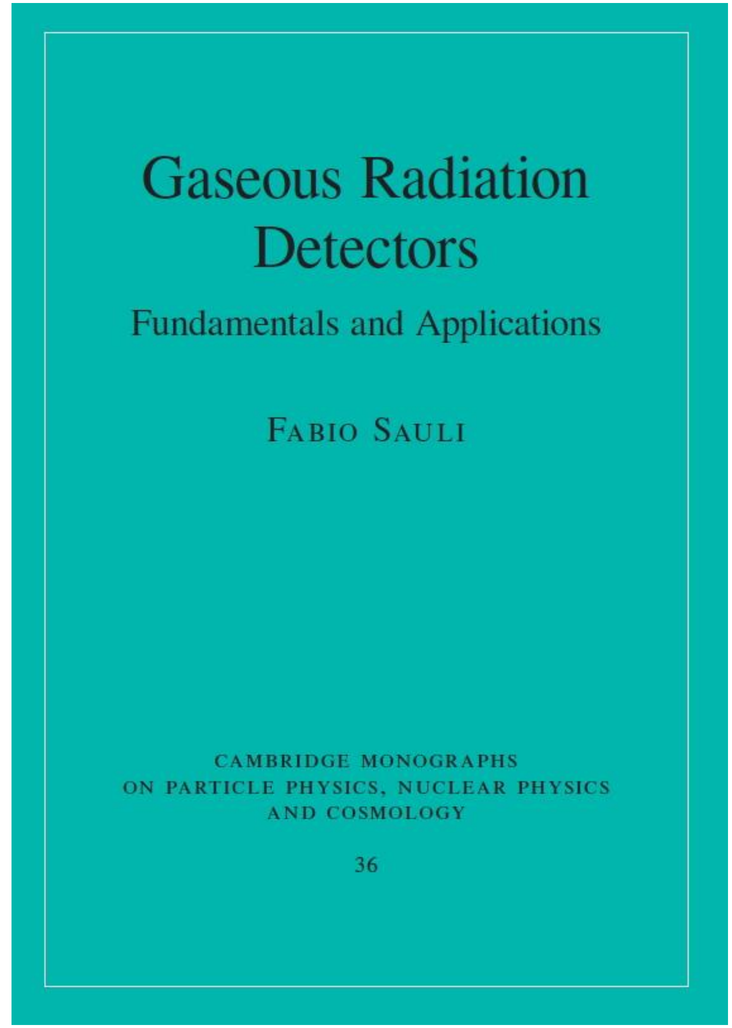

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