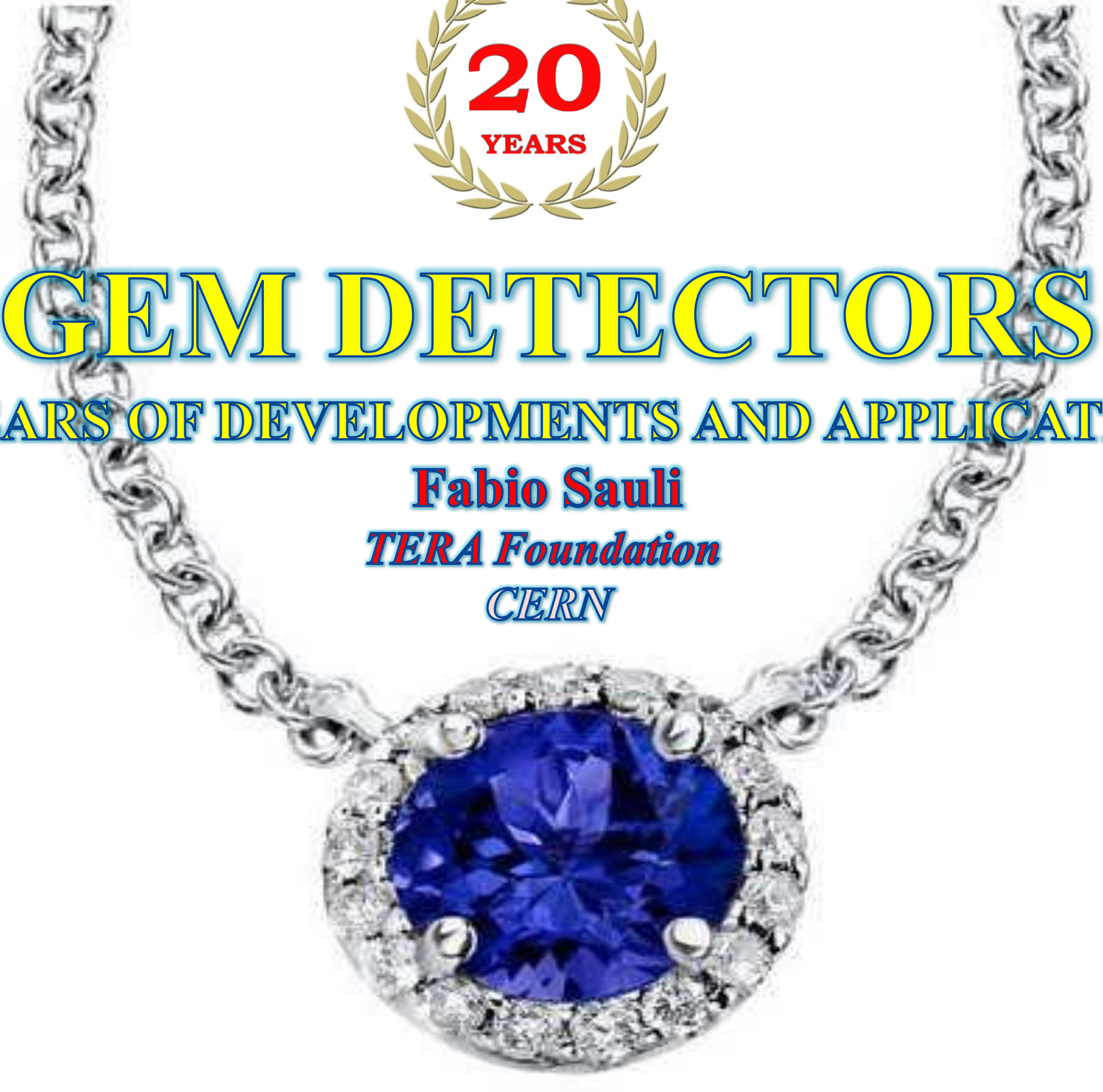


20 YEARS

# GEM DETECTORS

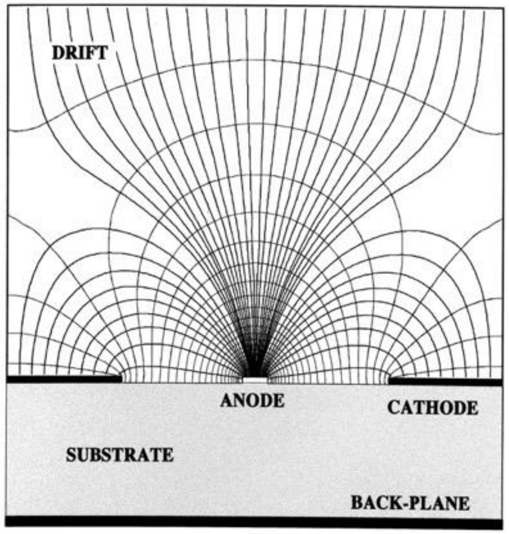
## 20 YEARS OF DEVELOPMENTS AND APPLICATIONS

**Fabio Sauli**

***TERA Foundation***

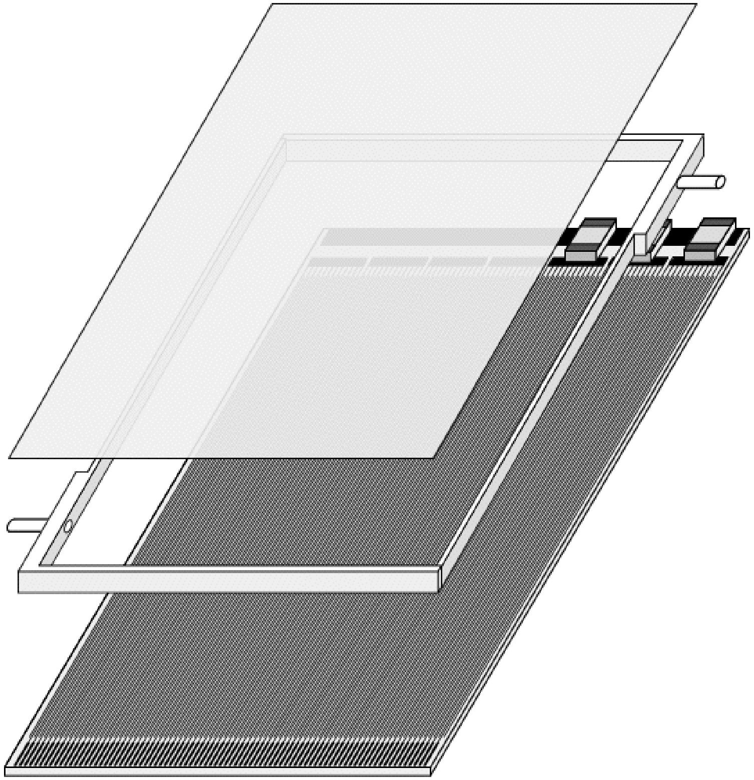
***CERN***

THIN METAL STRIPS ON GLASS SUBSTRATE




*A. Oed,*
*Nucl. Instr. and Meth. A263(1988)351*

LIGHT AND COMPACT DETECTOR CONSTRUCTION



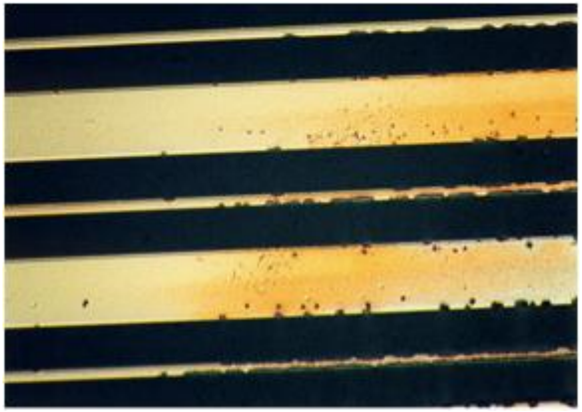
*J. Bohm et al, Nucl. Instr. and Meth. A360(1995)34*

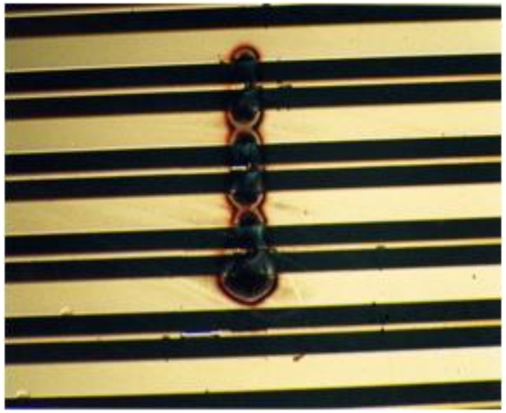
RATE CAPABILITY ~ 1 MHz/mm$^2$
POSITION ACCURACY ~ 40 µm
2-TRACK RESOLUTION ~ 500 µm

**HERA-B MSGC INNER TRACKER ~ 200 MSGC 20x20 mm$^2$**
**CMS CENTRAL TRACKER ~ 5500 MSGC**

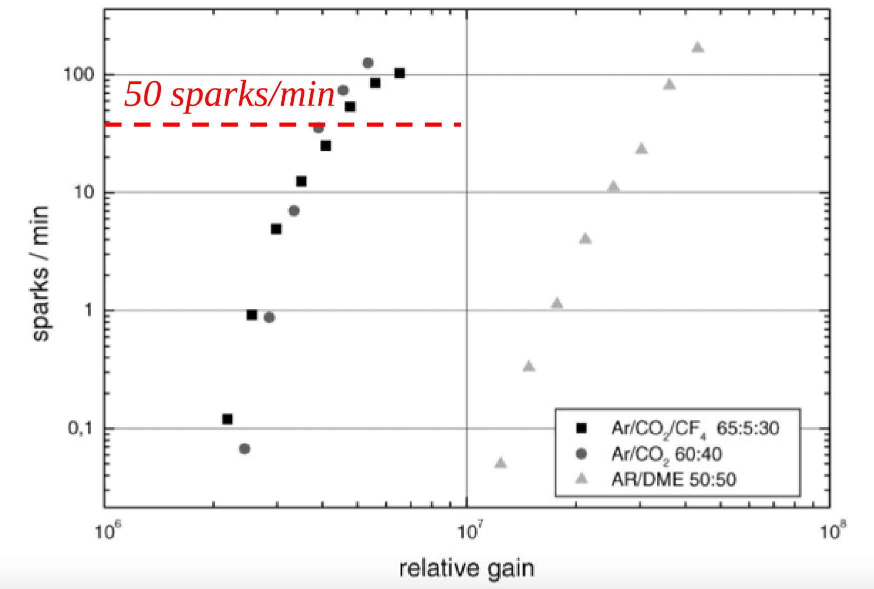
# MSGC: DISCHARGE PROBLEMS

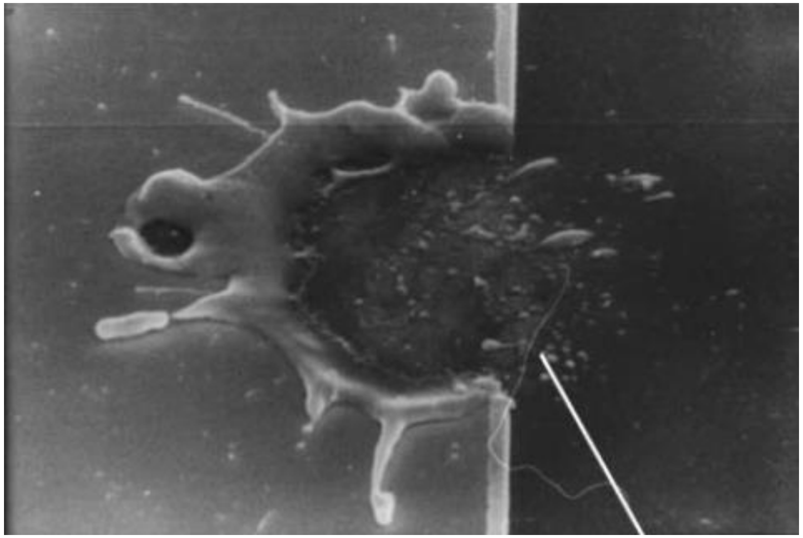
MILD OR SERIOUS DISCHARGE PROBLEMS!



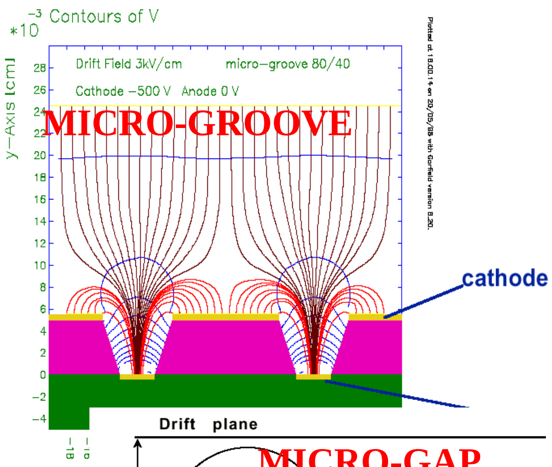


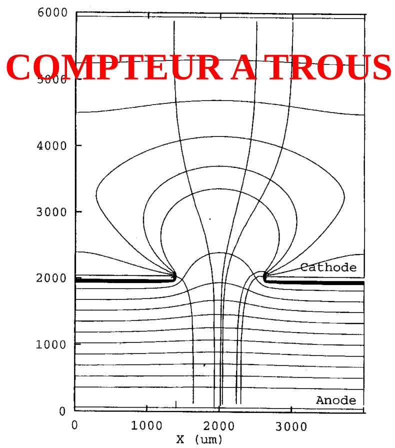
HERA-B MSGC INNER TRACKER

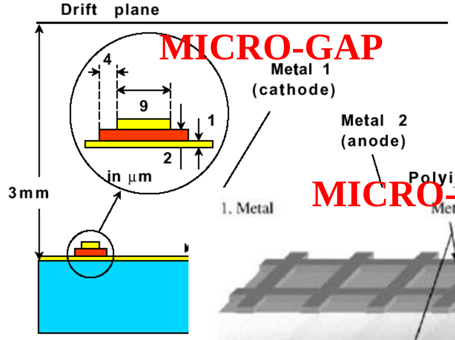


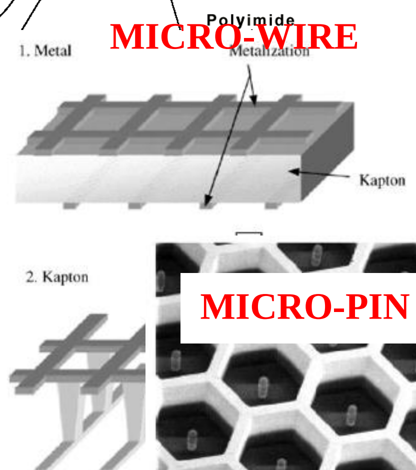



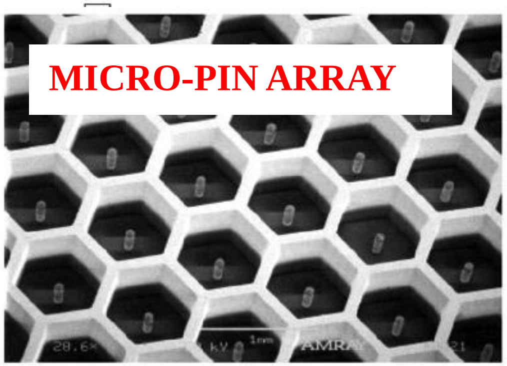
S. Keller et al, Nucl. Instr. and Meth. A419(1998)382

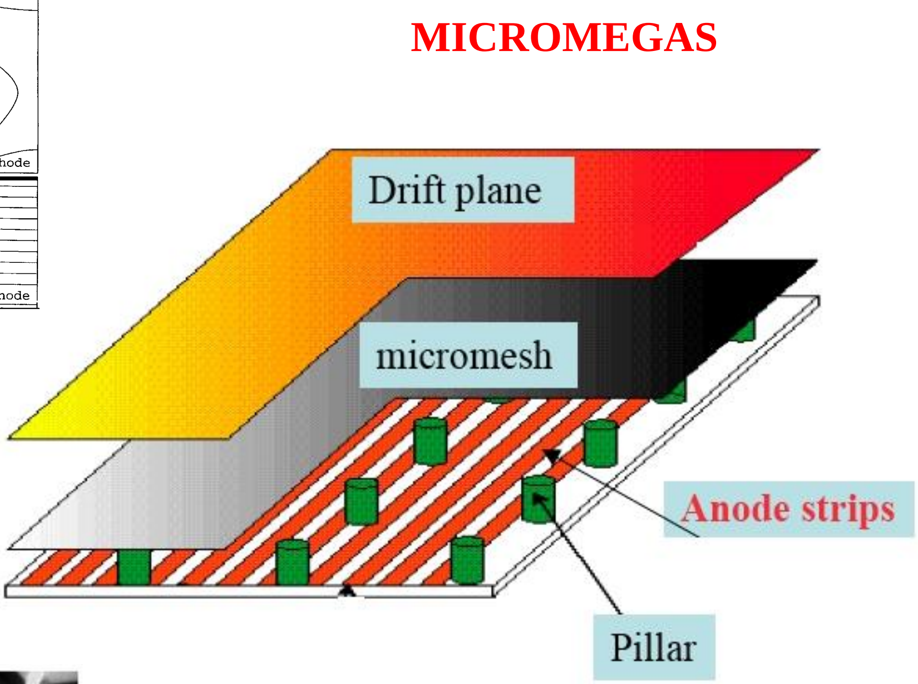


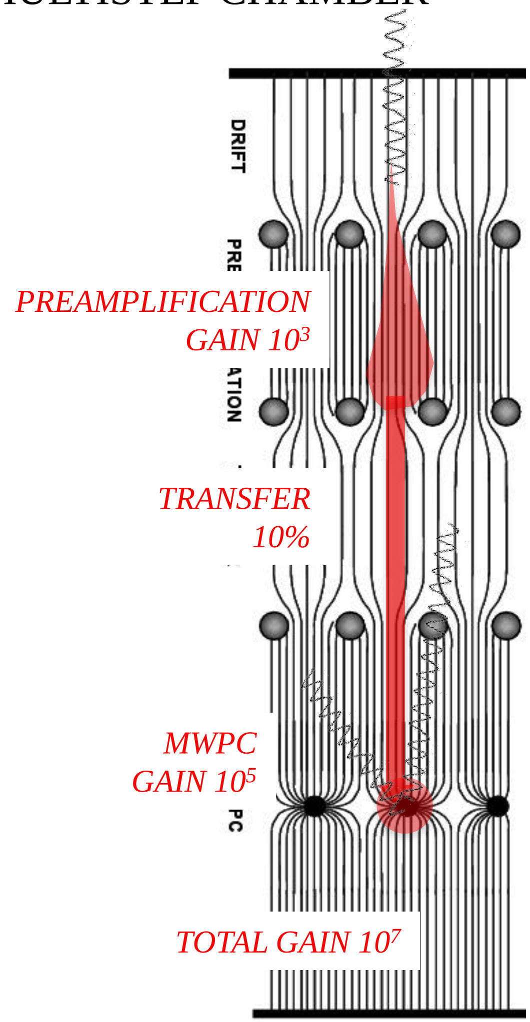




*Y. Giomataris,*
*Nucl. Instr. and Meth. A419(1998)239*

# 1978: THE MULTISTEP CHAMBER (MSC)

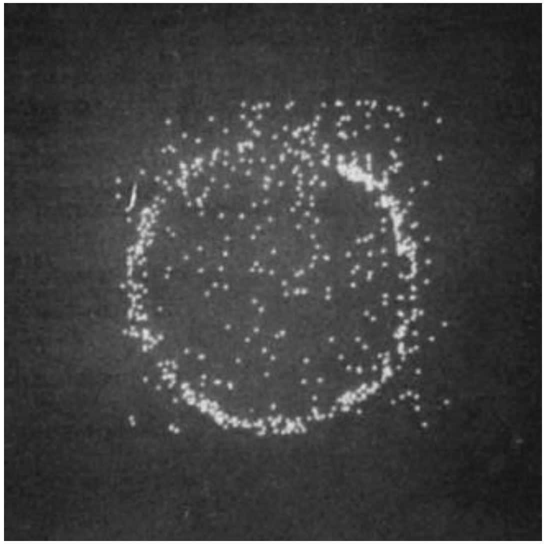
UV PHOTONS DETECTION (RICH): MWPC WITH PHOTOSENSITIVE GAS (TEA)

MULTISTEP CHAMBER



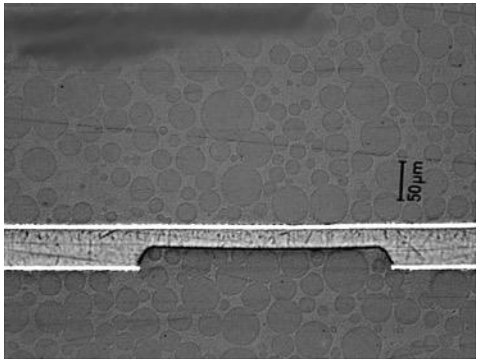

SINGLE ELECTRON DETECTION
SIMULATED CHERENKOV RING
(COLLIMATED UV SOURCE)

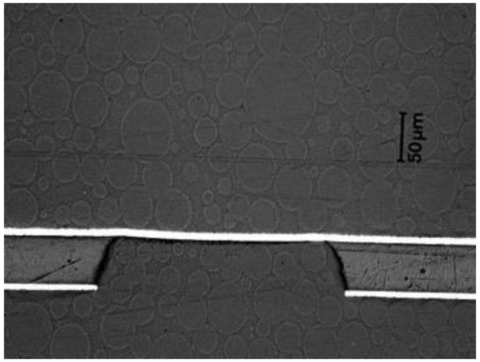
**E605 RICH**

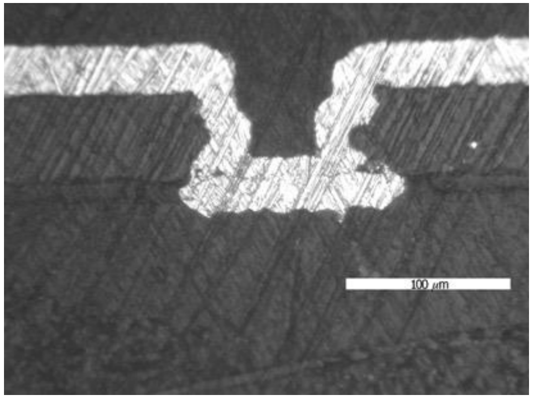


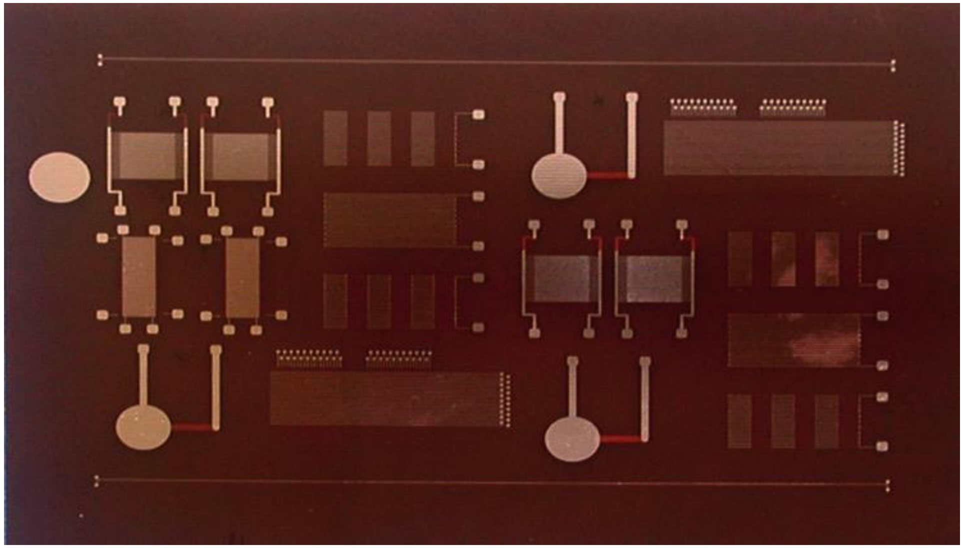
*G. Charpak and F. Sauli, Phys. Lett. 78B(1978)723*

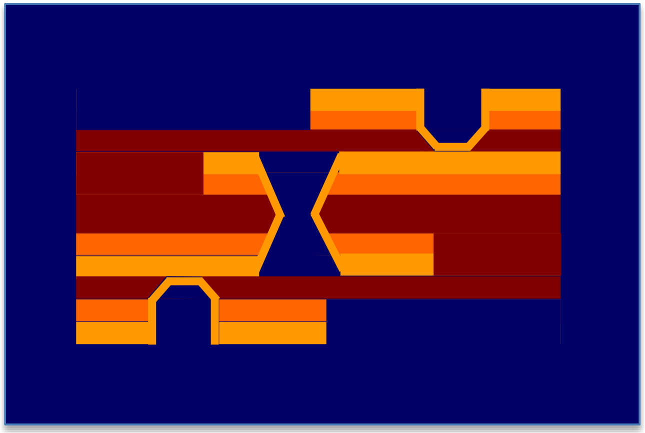
POLYIMIDE ETCHING:
CONTACTS THROUGH FLEXIBLE PRINTED CIRCUITS
Angelo Gandi and Rui De Oliveira
CERN's Printed Circuit Workshop (EST-DEM)



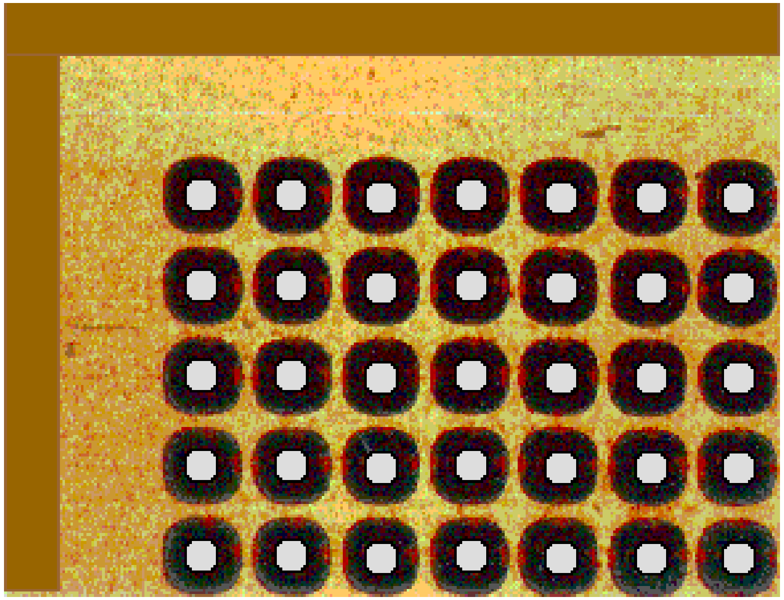



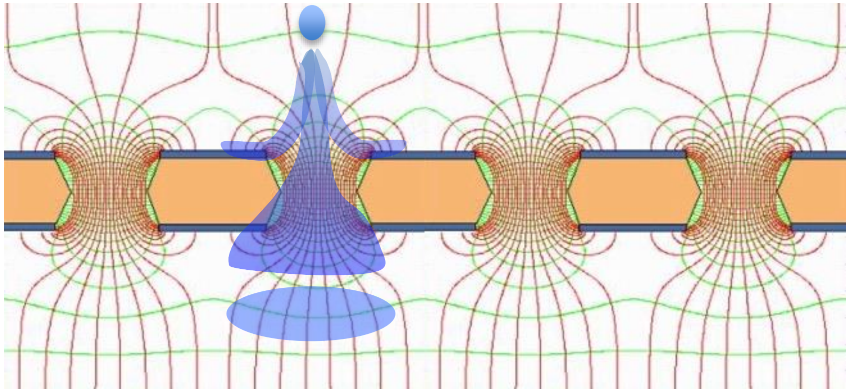





THE GAS ELECTRON MULTIPLIER (GEM):
100 μm PITCH HOLES ON COPPER-CLAD POLYIMIDE FOIL

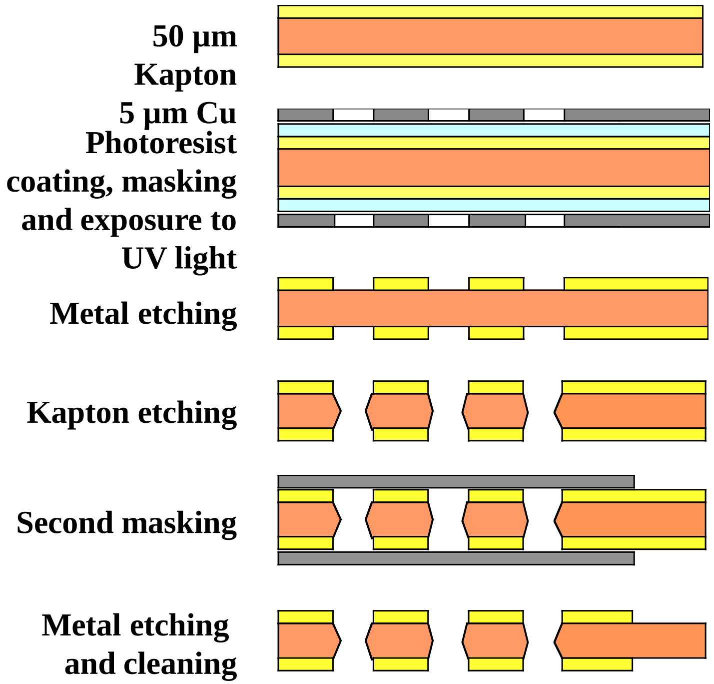




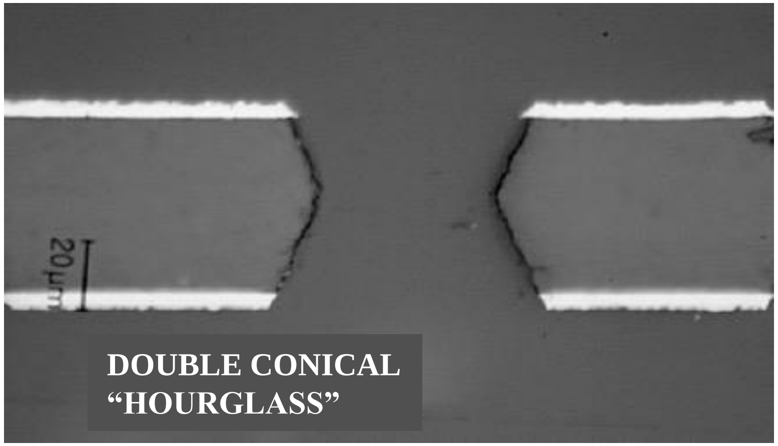
PRESENTED AT:
IEEE Nuclear Science Symposium & Medical Imaging Conference
Anaheim, CA November 3-9, 1996

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

## DOUBLE MASK PHOTOLITHOGRAPHY

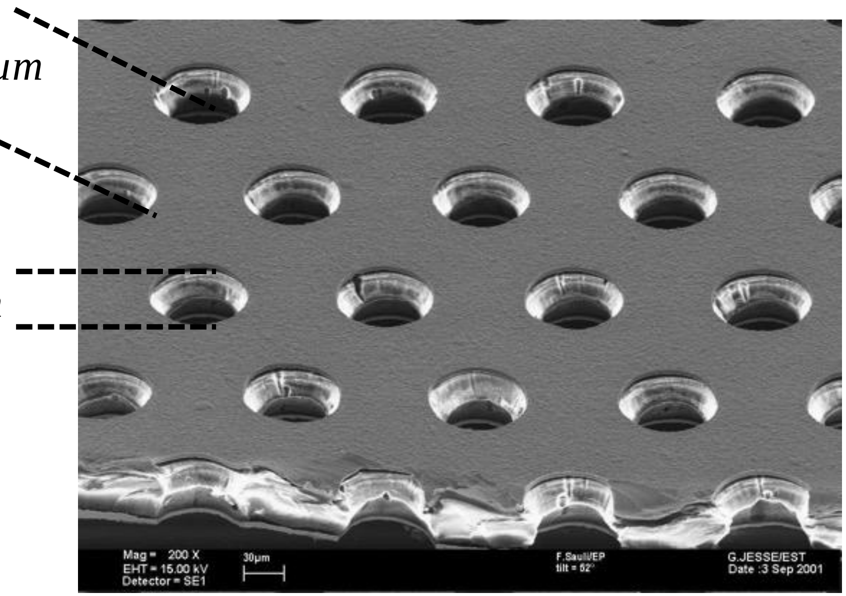



## “STANDARD” GEM

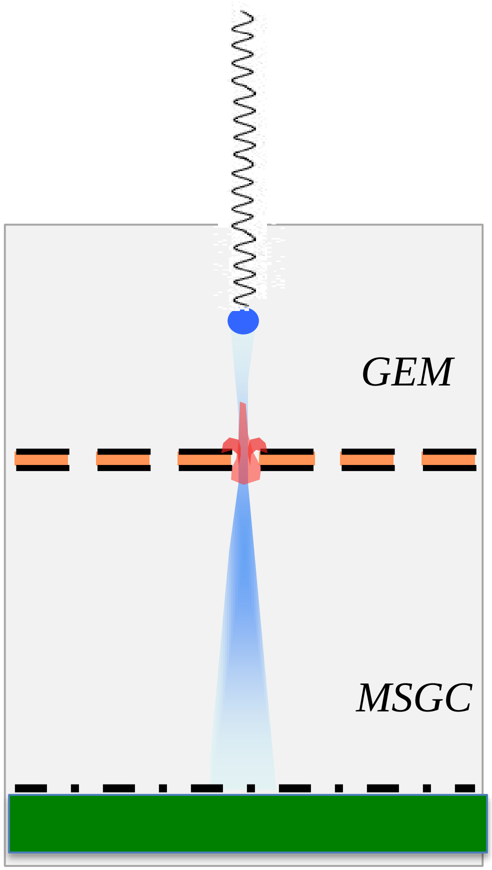



*140 µm*

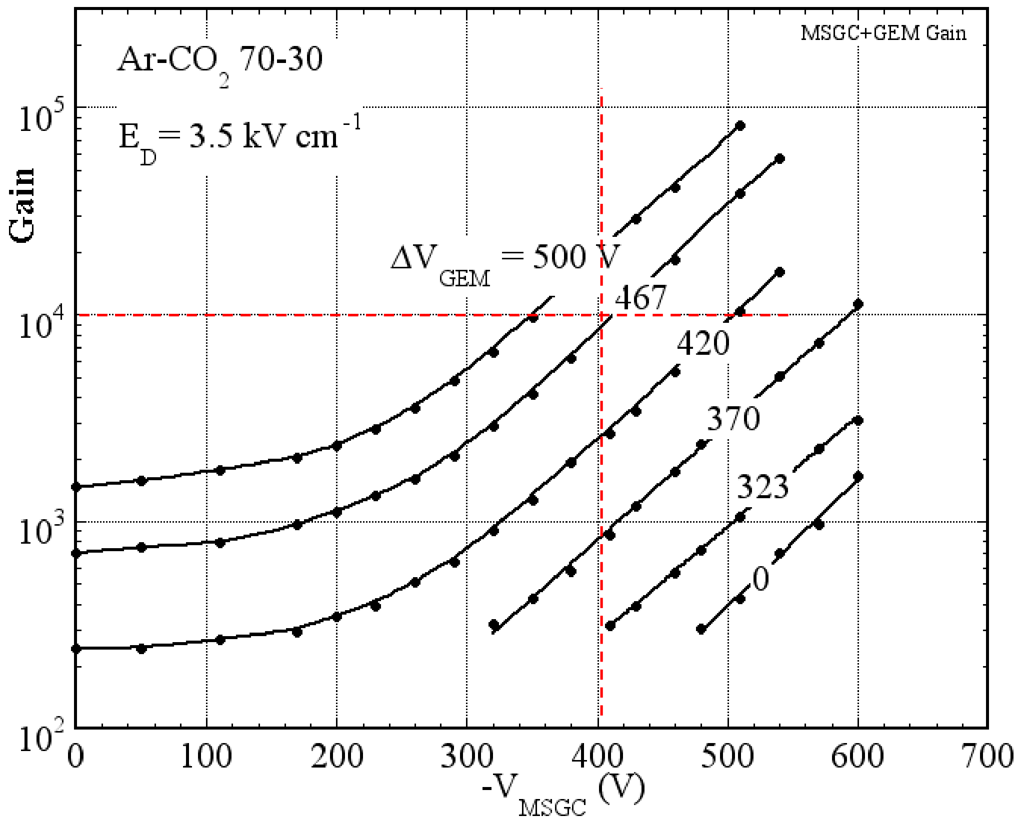
*70 µm*



MSGC WITH GEM PREAMPLIFIER

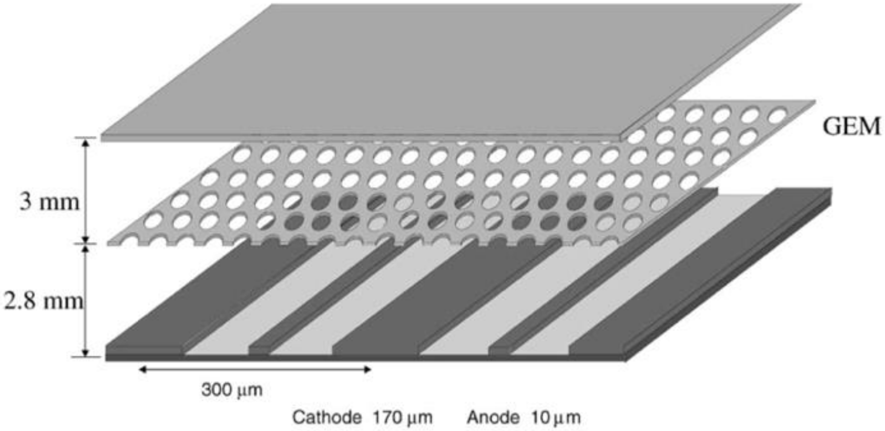


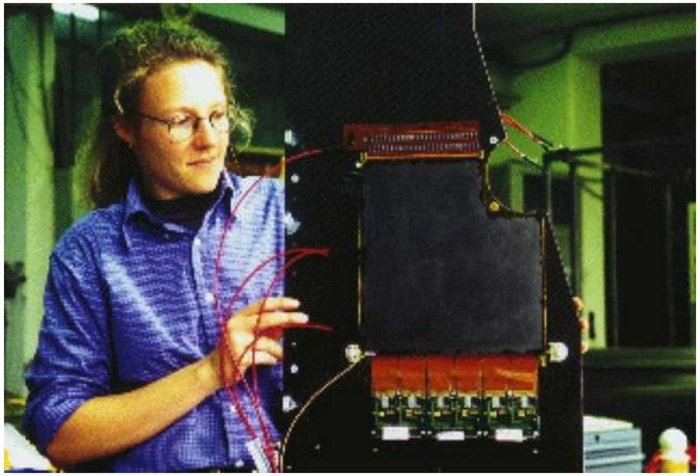

COMBINED GAIN CURVES



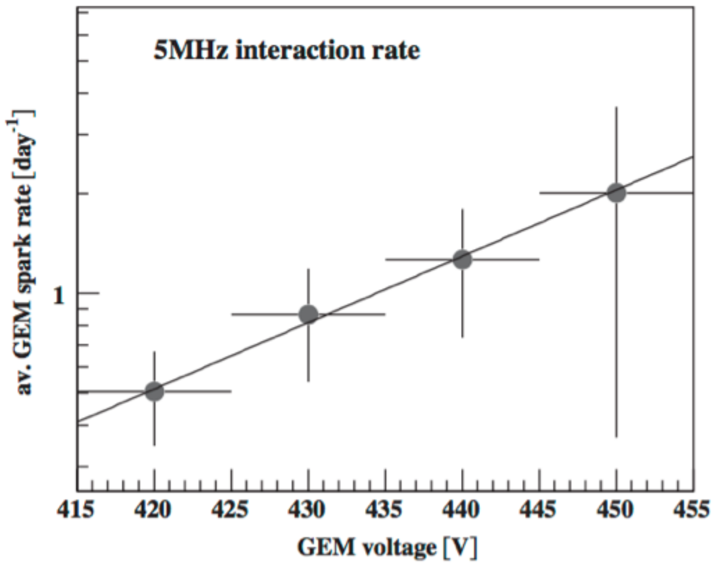

*R. Bouclier et al, Nucl. Instr. and Meth. A396(1997)50*

# HERA-B MSGC+GEM



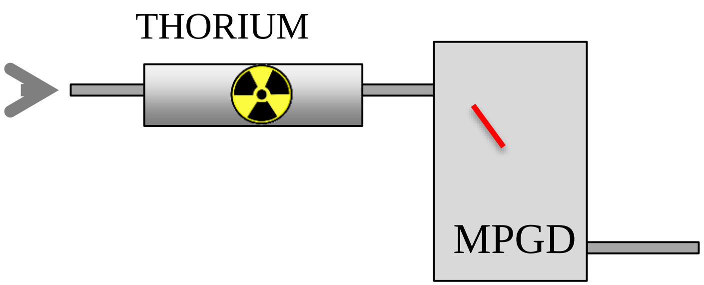
CERN's Printed Circuit Workshop (EST-DEM)

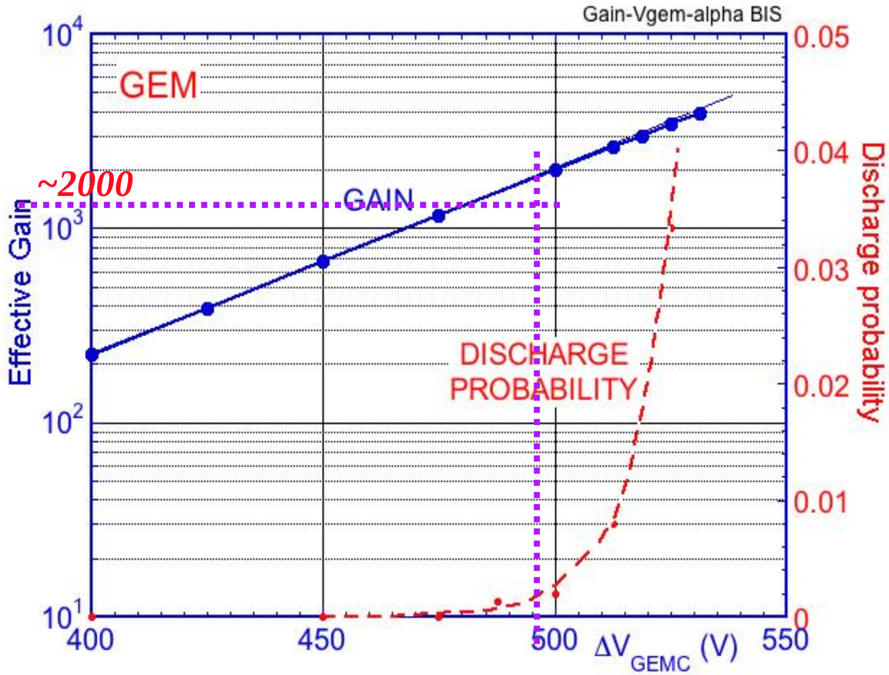

*Bagaturia et al,*
*Nucl. Instr. and Meth. A490(2002)223*

# *MPGD DISCHARGE STUDIES*

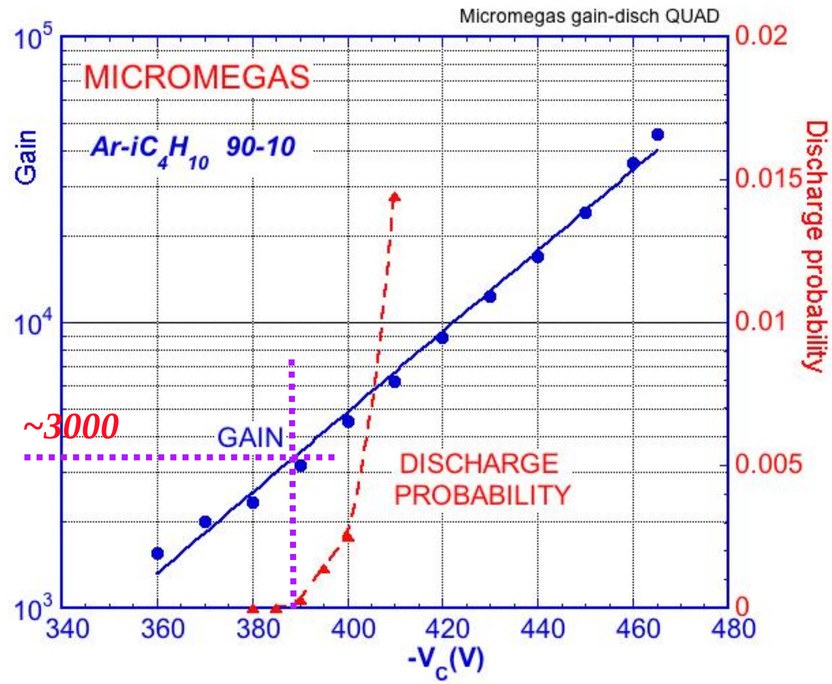
GASEOUS α SOURCE: $^{232}$Th -> $^{232}$Rn+α (6.4 MeV) ΔE ~ 500 keV ~ $10^4$ e I$^+$




GEM:




MICROMEGAS:

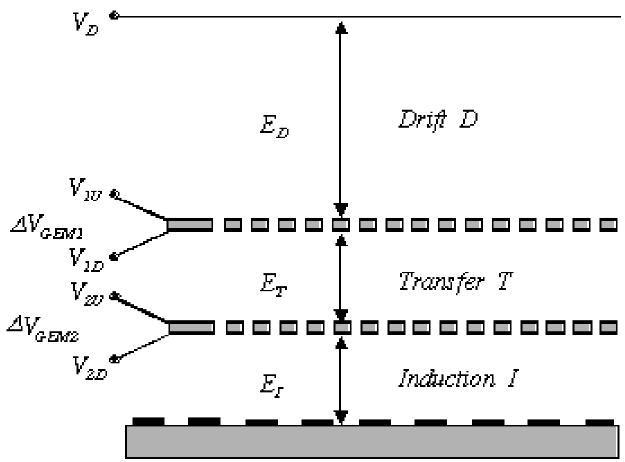



Q ~ $10^4 . 10^3 = 10^7$ e I$^+$

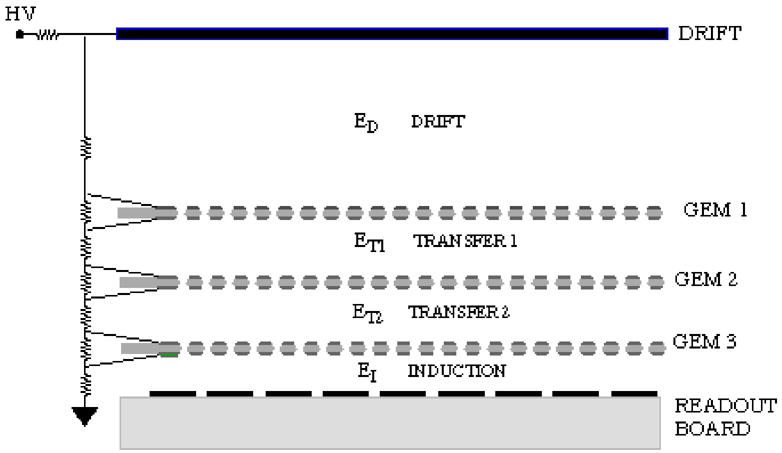
**RAETHER LIMIT**

*A. Bressan et al.Nucl. Instr. and Meth. A424(1999)321*

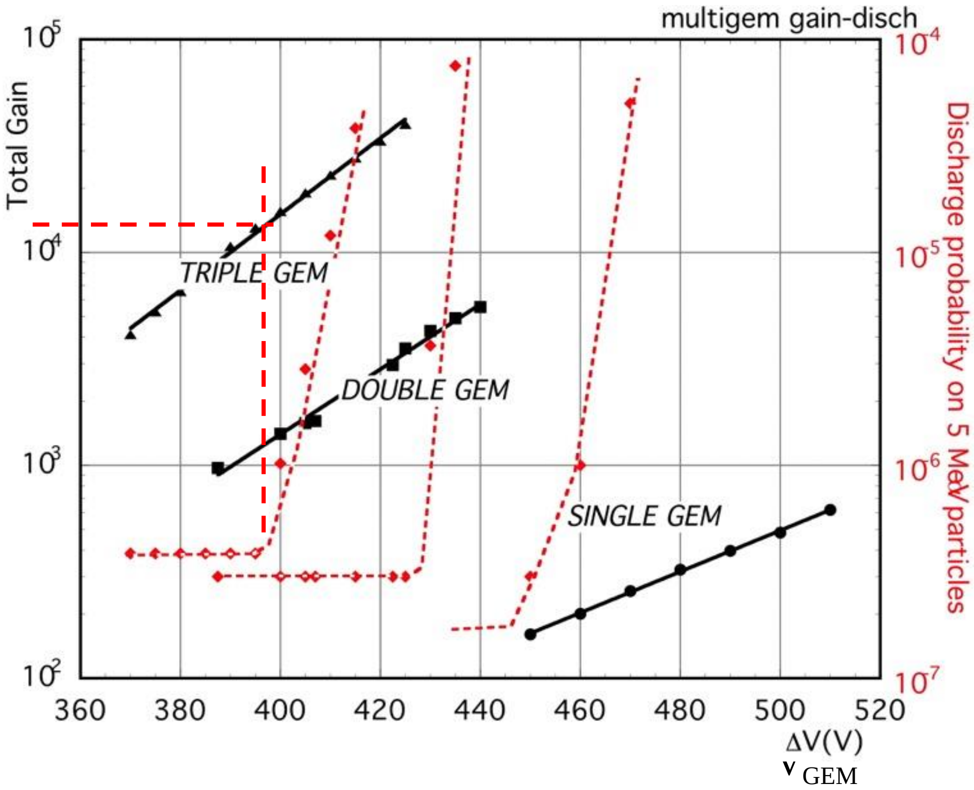
DOUBLE GEM




TRIPLE GEM

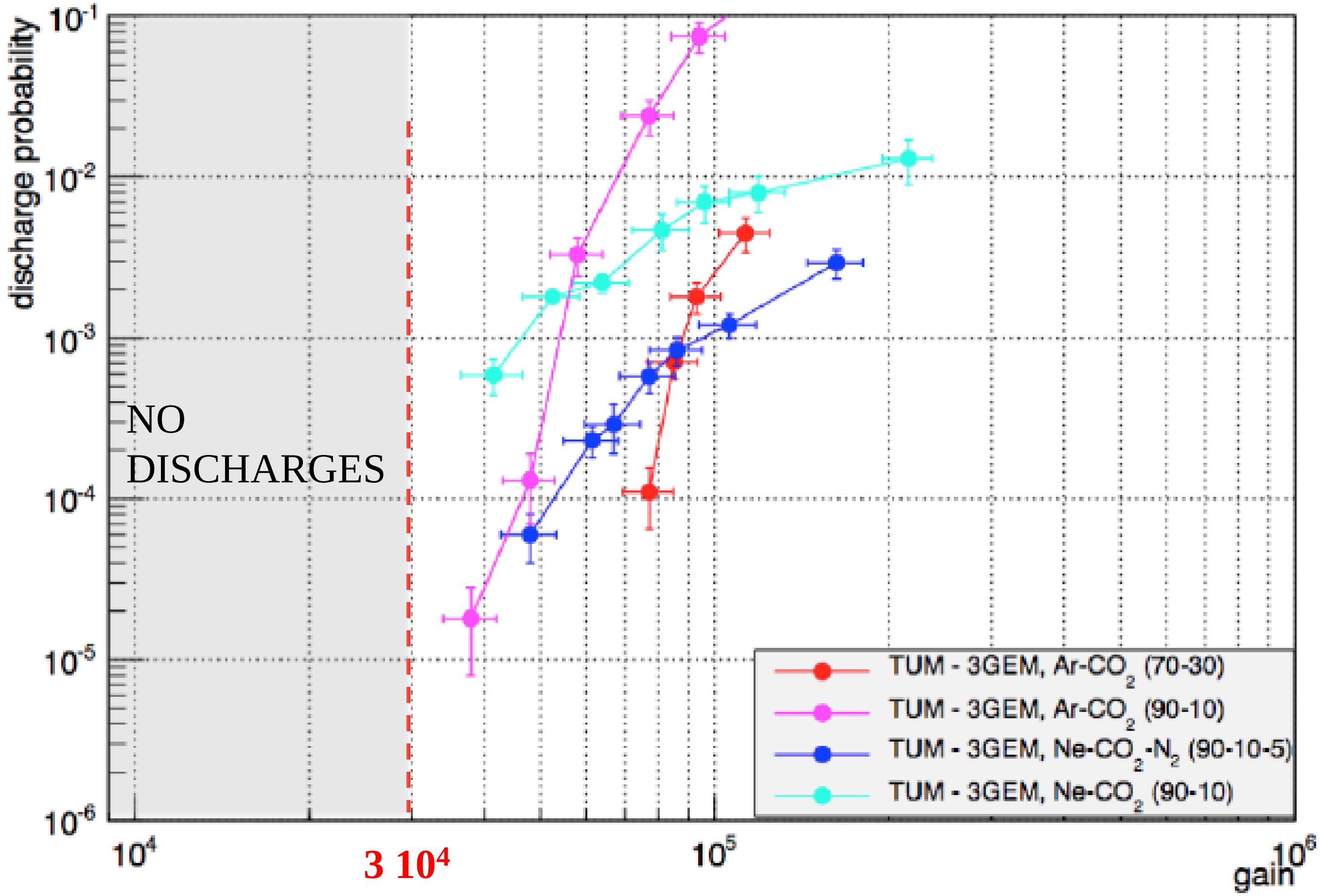



- HIGHER GAINS
- REDUCED ION BACKFLOW
- LOWER DISCHARGE PROBABILITY



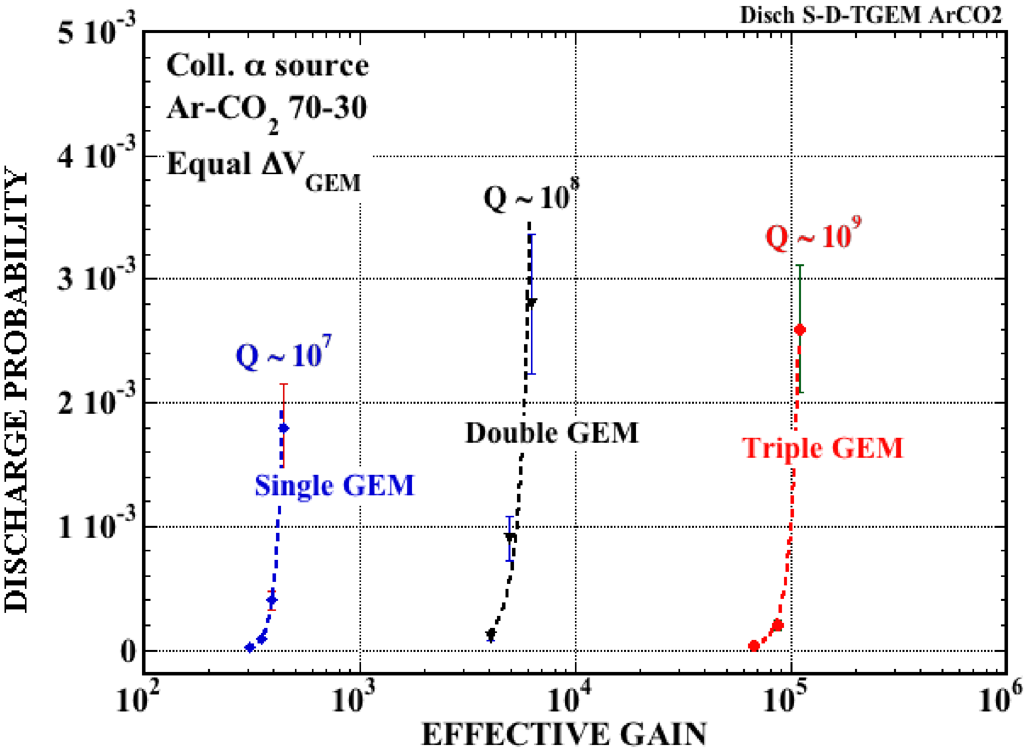

S. Bachmann et al, Nucl. Instr. and Meth. A 443(1999)464

$^{220}$Rn INTERNAL α SOURCE TRIPLE GEM

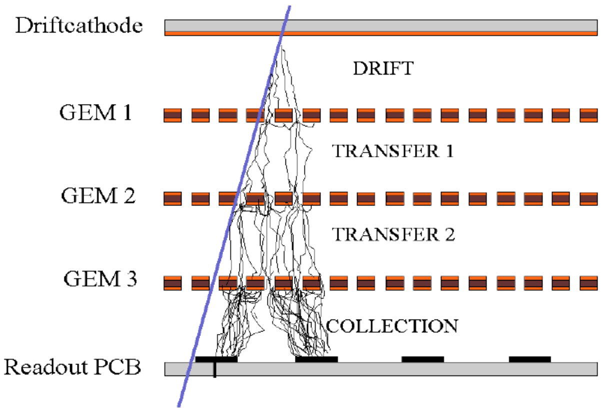



*P. Gasik RD51Coll. Meeting (CERN 2016)*

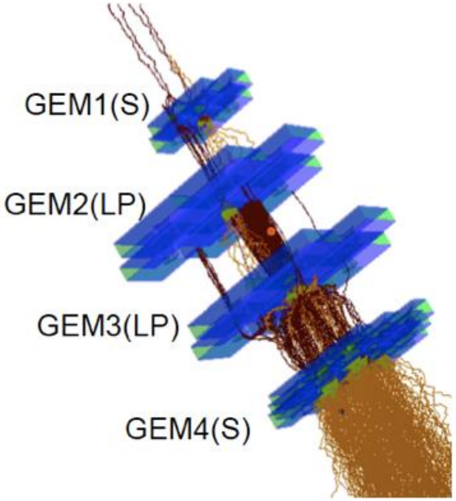
DISCHARGE PROBABILITY ON ~ MeV α




IN MULTI-GEMs, THE CHARGE SPREADS BY DIFFUSION OVER MANY HOLES!




4-GEM SIMULATION (ALICE TPC)



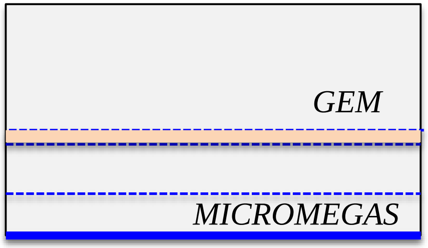

**WHAT ABOUT THE RAETHER LIMIT?**

VERY LARGE GAINS OBSERVED IN PURE NOBLE GASES
CHARGE CONFINEMENT: HOLES ARE (QUASI) INDEPENDENT

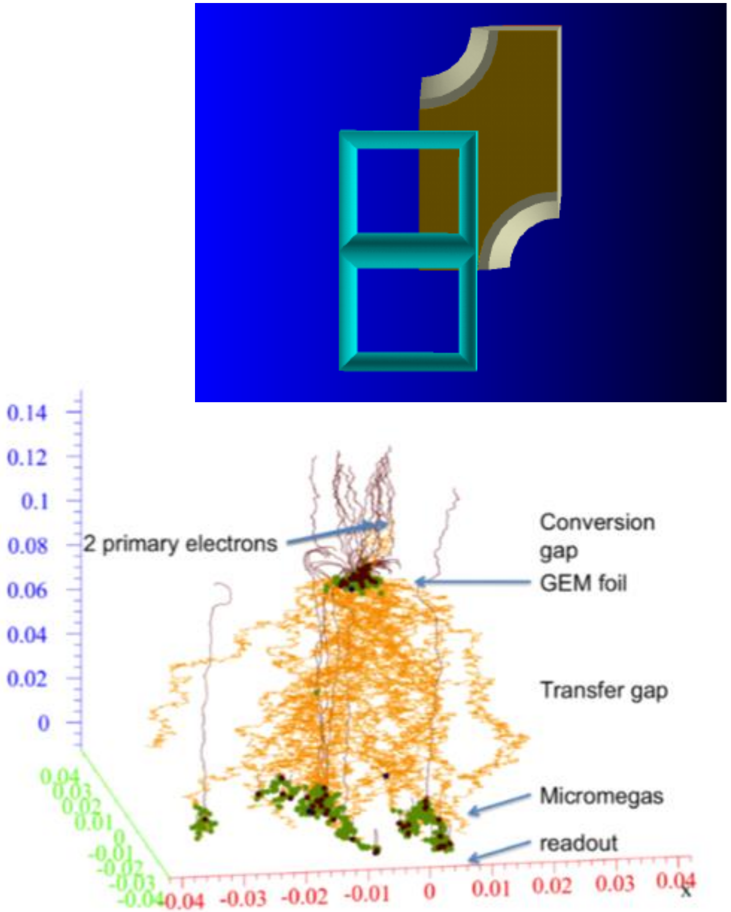
*A. Buzulutskov et al, Nucl. Instr. and Meth. A433(1999)471*

*P. Bhattacharya, MPGD Workshop (Trieste 2015)*

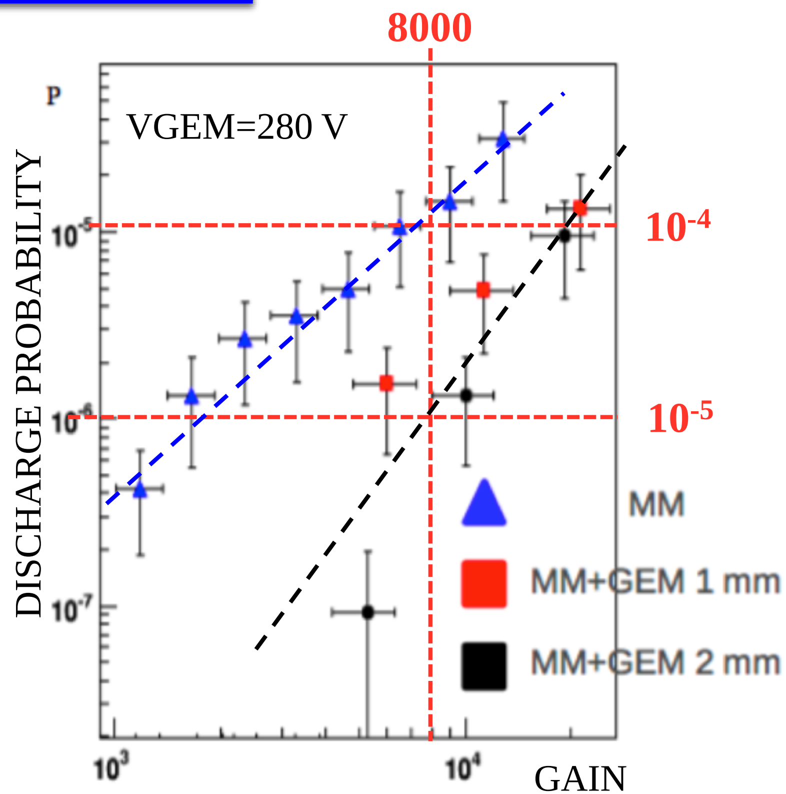
GEM + MICROMEGAS




AVALANCHES SIMULATION
GEM+MICROMEGAS




1 GeV π BEAM

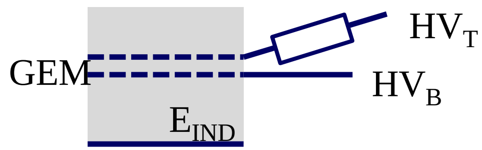



*S. Procureur et al, Nucl. Instr. and Meth. A659(2011)91*

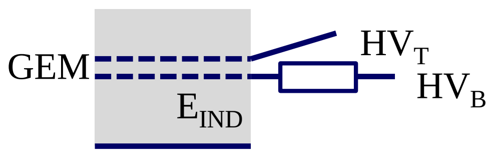
*M. Vandenbroucke, JINST 7(2012)C05014*

DISCHARGE PROPAGATION: LAST GEM TO ANODE

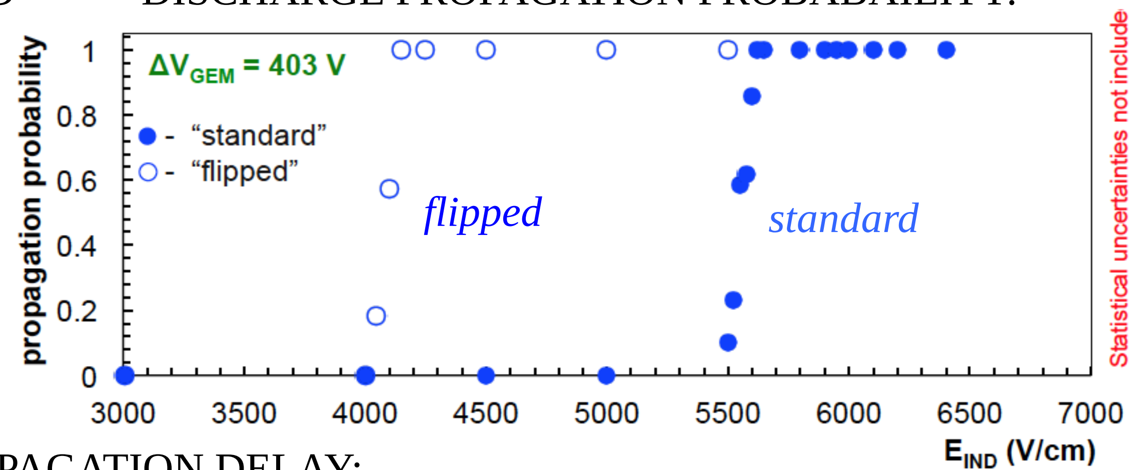
SECTORS POWERING: STANDARD



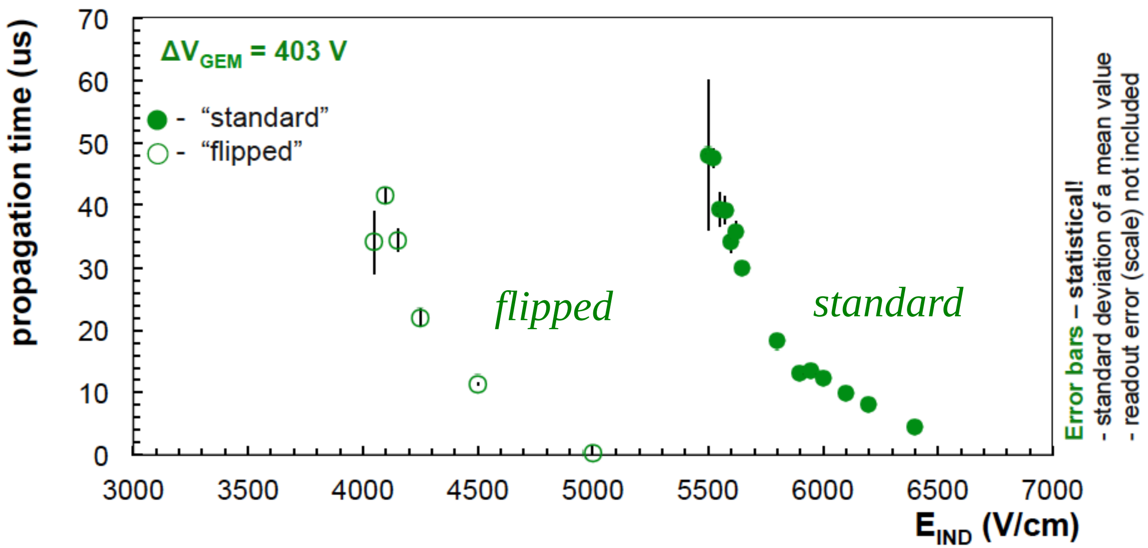

FLIPPED:




DISCHARGE PROPAGATION PROBABAILITY:




DISCHARGE PROPAGATION DELAY:

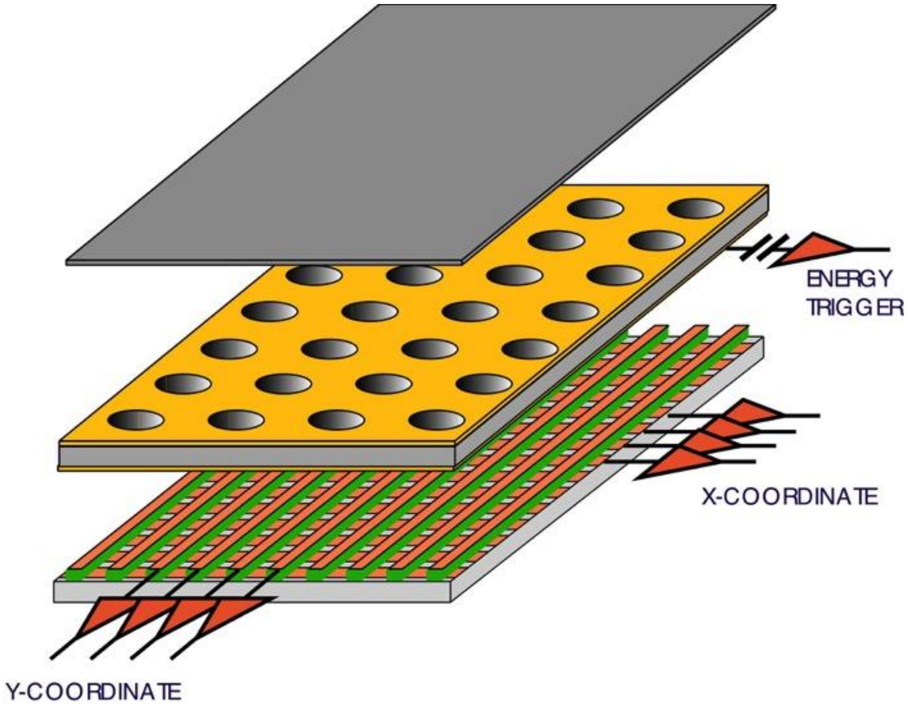



ALICE

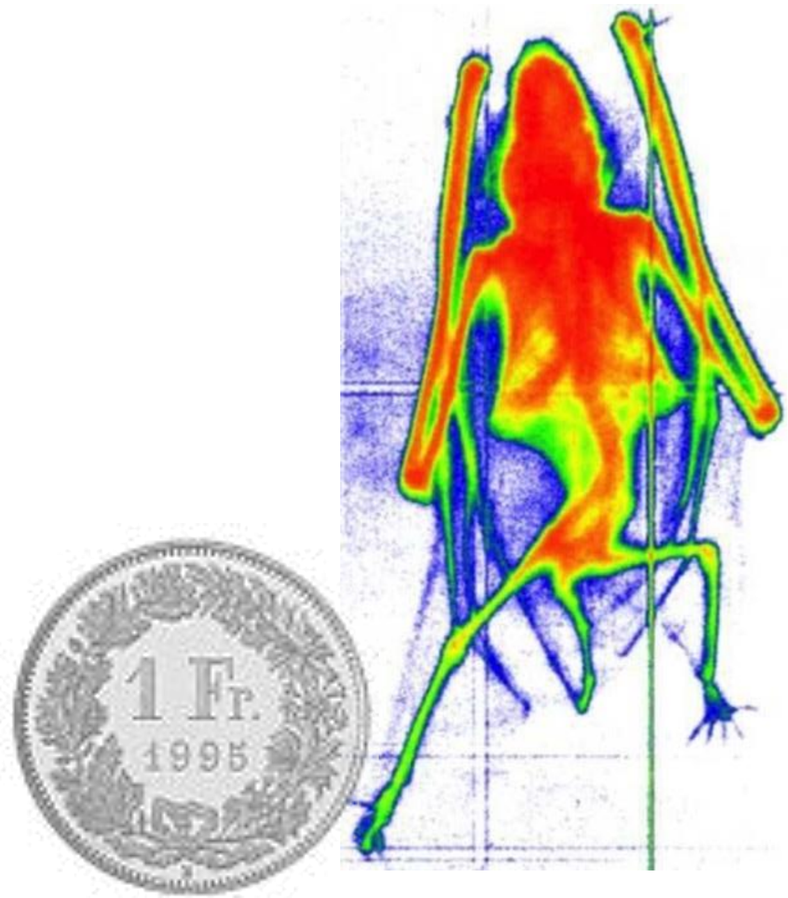
*P. Gasik RD51Coll. Meeting (CERN 2016)*

# SINGLE GEM X-RAY DETECTOR

2-DIMENSIONAL CARTESIAN STRIPS READOUT




6 keV RADIOGRAPHY

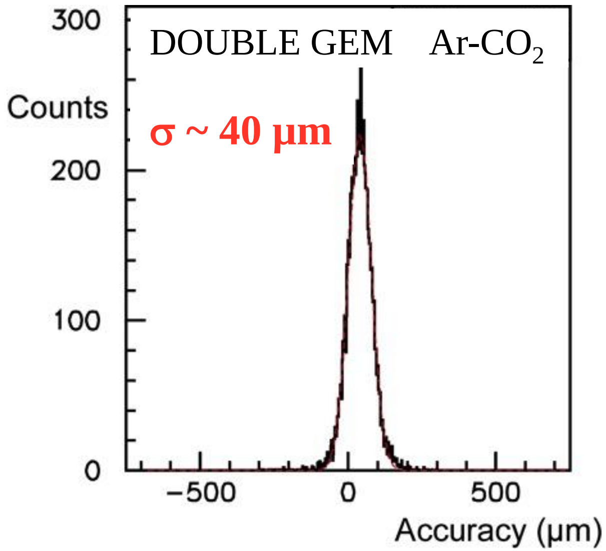



- HIGH PROPORTIONAL GAINS
- FAST ELECTRON SIGNAL
- READOUT PLANE AT GROUND POTENTIAL
- PATTERNED AT WILL

*A. Bressan et al,*
*Nucl. Instr. and Meth. A425(1999)254*

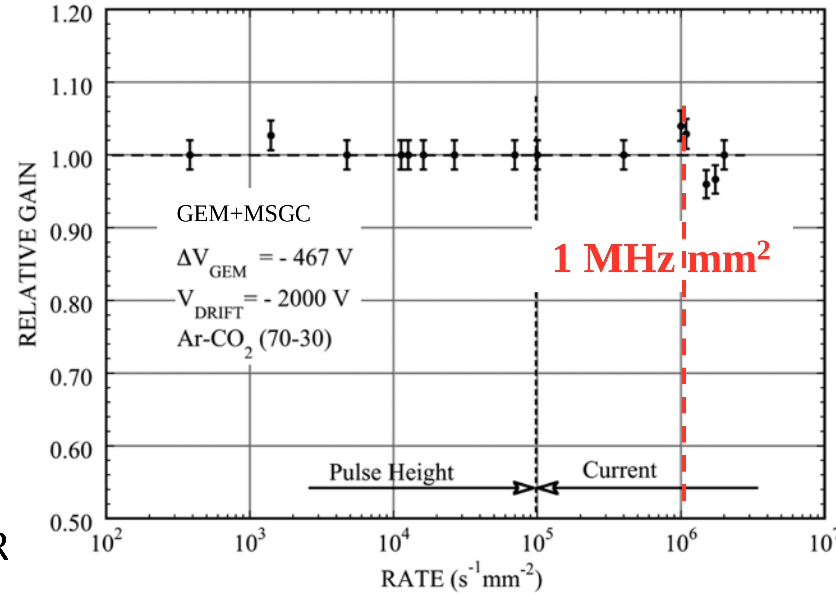
# MAIN GEM PERFORMANCES: MIPS

## LOCALIZATION ACCURACY



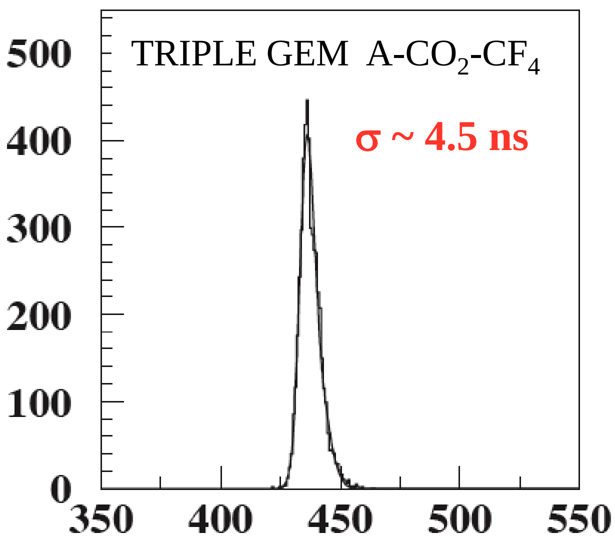

*A. Bressan et al, Nucl. Instr. and Meth. A425(199)262*

## SINGLE GEM RATE CAPABILITY



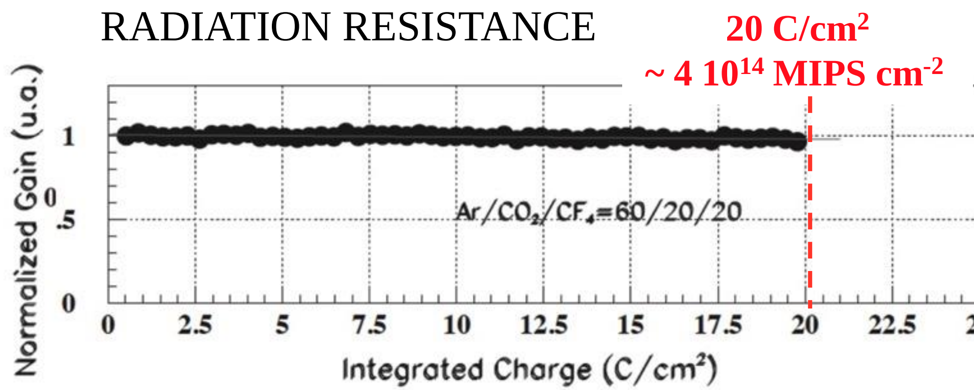

*J. Benlloch et al, IEEENS-45(1998)234*

## TIME RESOLUTION: LHCB MUON TRIGGER



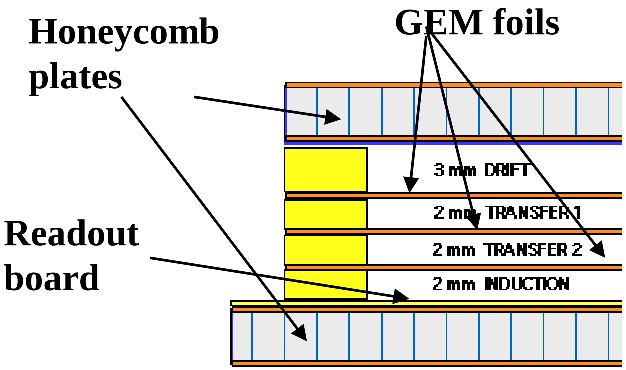

*M. Alfonsi et al, Nucl. Instr. and Meth. A535(2004)319*

## RADIATION RESISTANCE

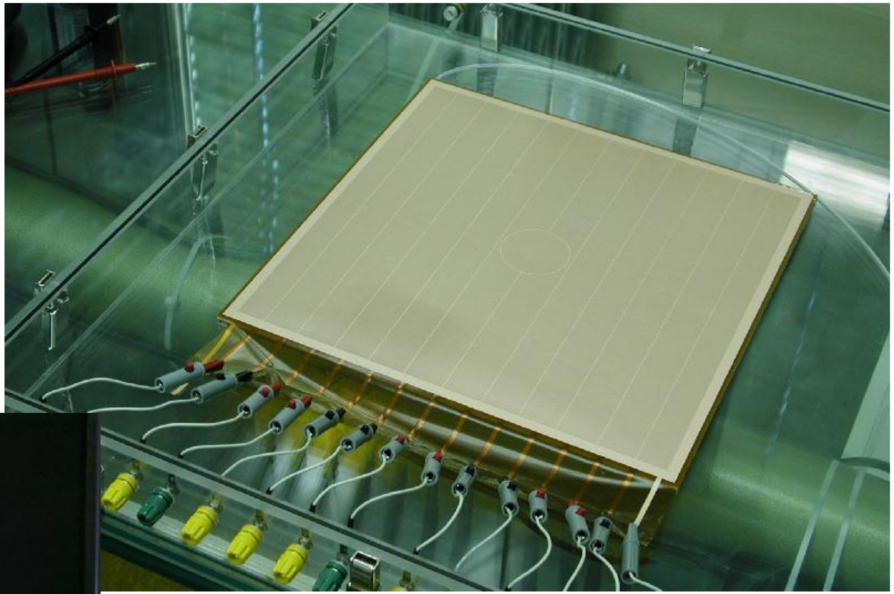



*M. Alfonsi et al, Nucl. Instr. and Meth. A518(2004)106*

~30 TRIPLE GEM 30x30 cm$^2$ - 2D CARTESIAN READOUT




HV TESTING DURING ASSEMBLY

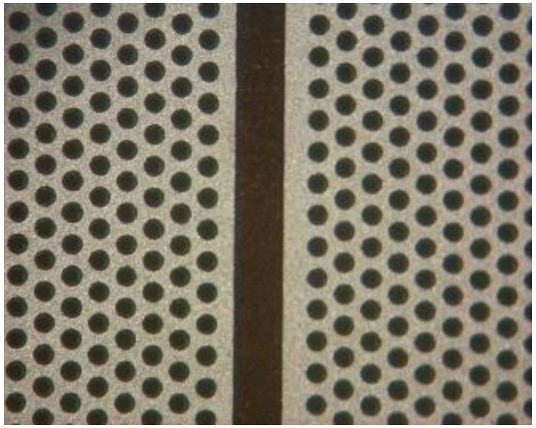


*L. Ropelewski*

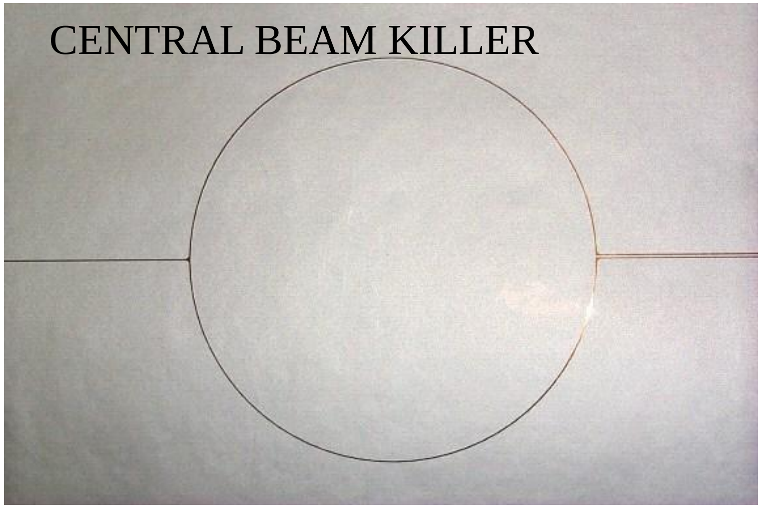
*C. Altumbas et al,*
*Nucl. Instr. and Meth. A490(2002)177*

# GEM SECTORS AND READOUT PATTERNS

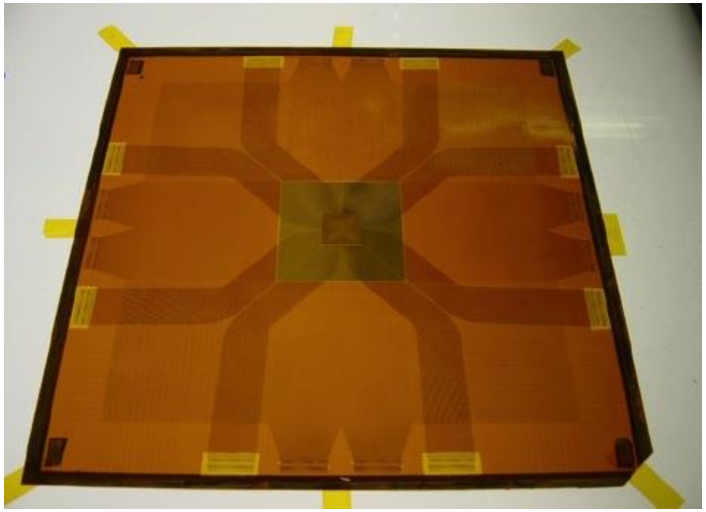
GEM SECTORS SEPARATION (200 µm)



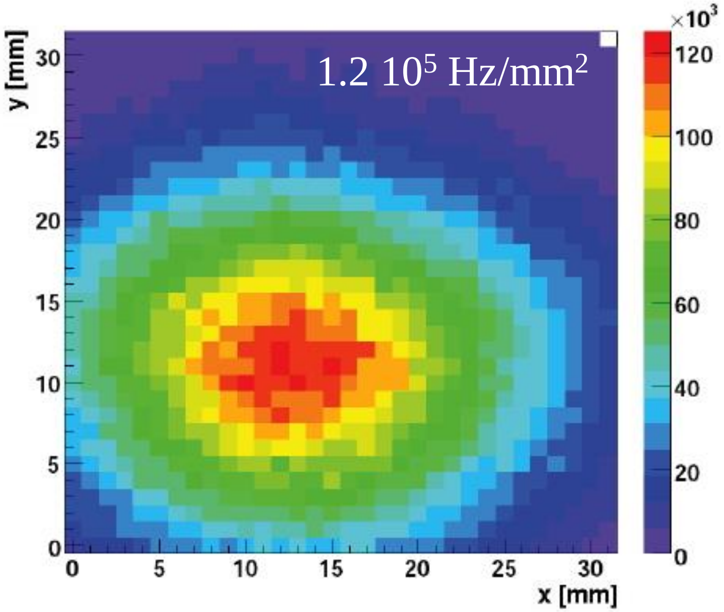
CENTRAL BEAM KILLER



1x1 mm$^2$ PIXELS AND STRIPS



MEASURED FLUX IN HADRON BEAM:

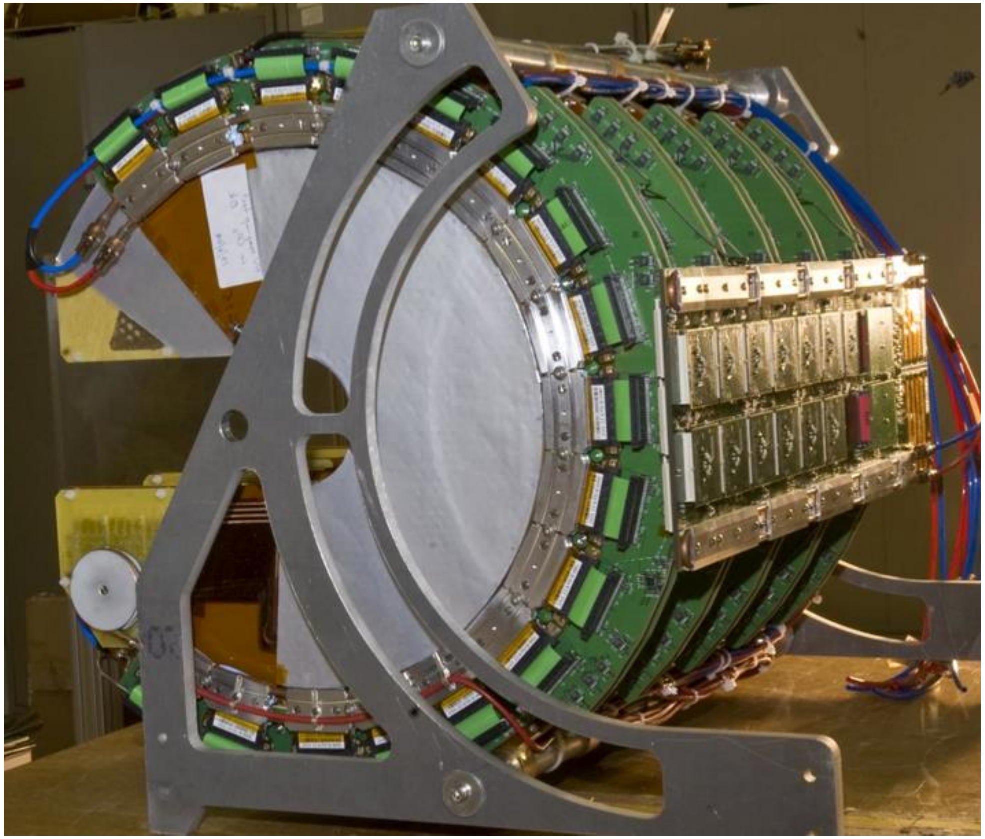



*M. Krämer et al, 2008 IEEE Nucl. Sci. Symp. Conf. Rec.*

# TOTEM TRIPLE GEM FORWARD CMS TRACKER

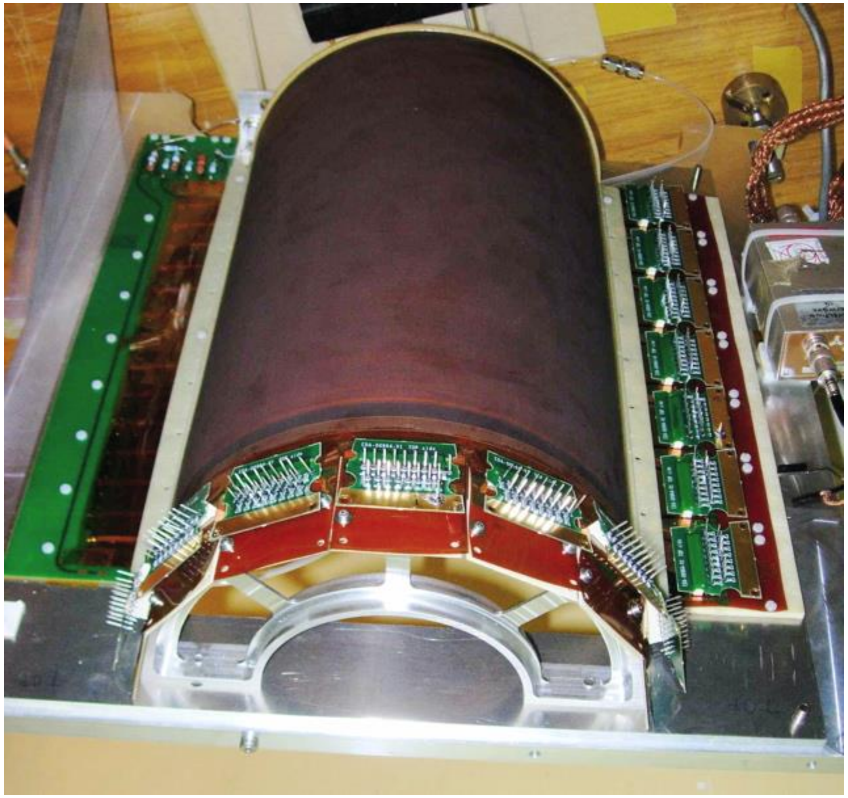
SEMI-CIRCULAR MODULES

TEN-GEM TOTEM FORWARD SECTOR



*M.G. Bagliesi et al, Nucl. Instr. and Meth. A617(2010)134*

TRIPLE-GEM PROTOTYPE



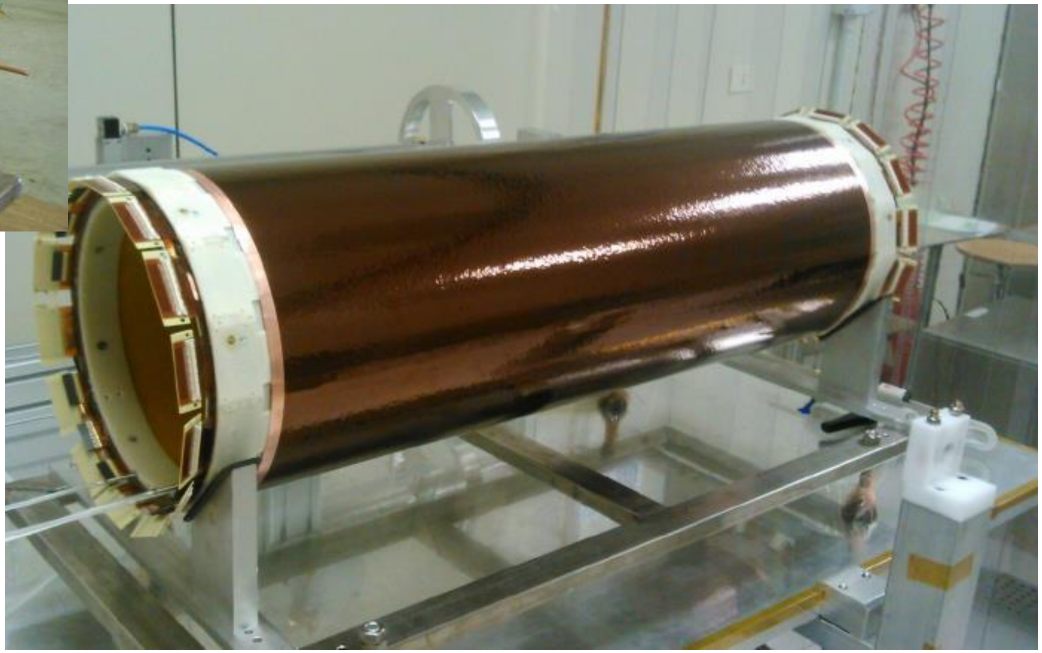
*GAS DETECTORS DEVELOPMENT*
*CERN*
*L. Ropelewski….M. Van Stenis…..*

# CYLINDRICAL GEM DETECTORS

KLOE-2 INNER TRACKER

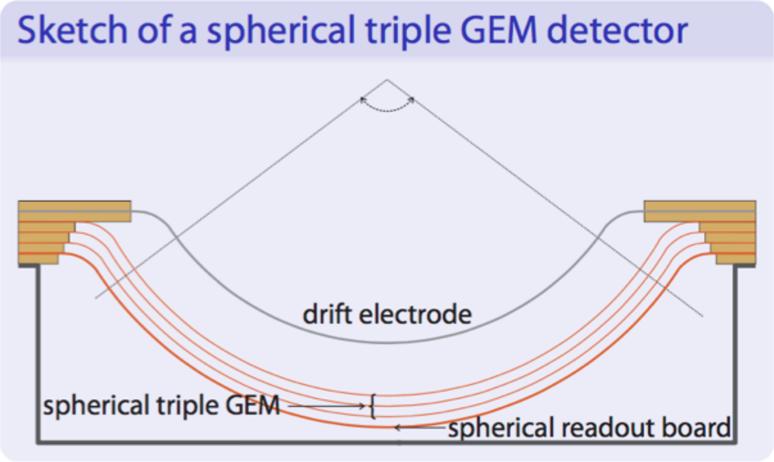
*A. Balla et al,*
*Nucl. Instr. and Meth. A732(2013)221*

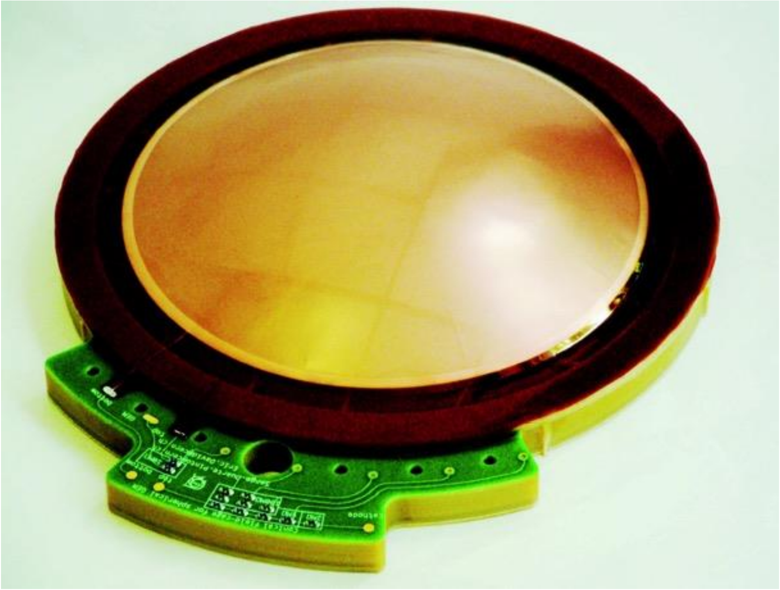
BES III DETECTOR at IHEP (Beijing)

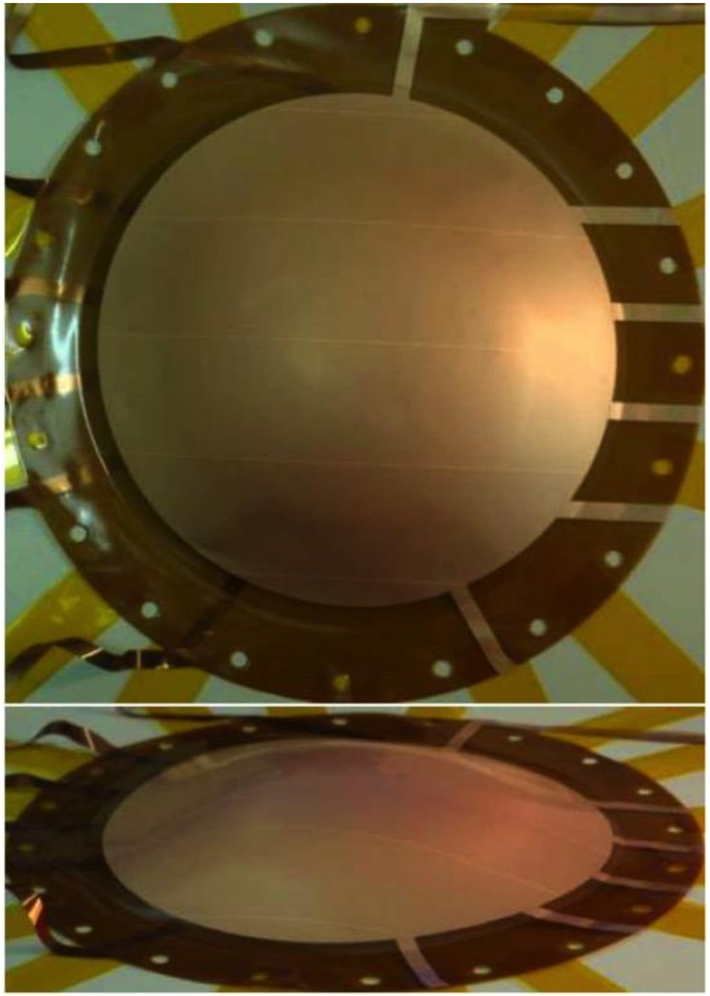


*R. Farinelli, RD51 Coll. Meeting (Aveiro 2016)*

# "SPHERICAL" MULTIGEM AND READOUT BOARD





*S. Duarte Pinto arXiv:1011.5528v1*
*IEEE 2011 Nucl. Sci. Symp. Conf. Rec.*

SINGLE MASK PHOTOLITOGRAPHY
R. De Oliveira, CERN EP-DT-EF

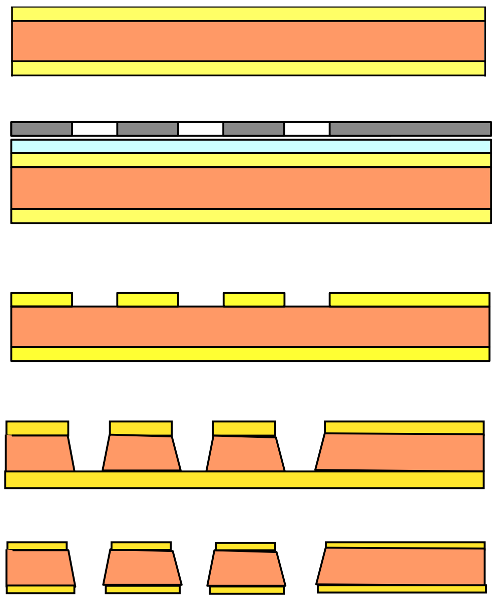
Cu-clad Kapton

Single mask Photoresist

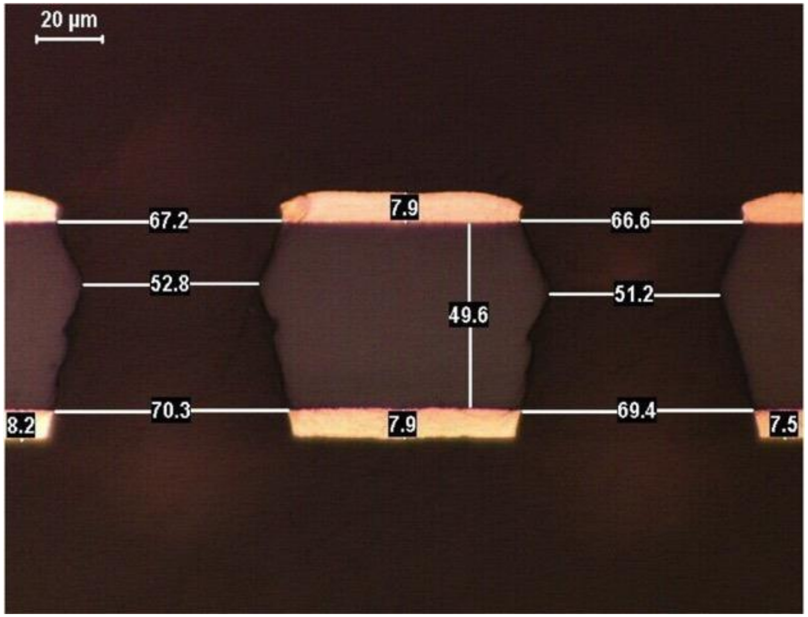
Cu etching

Kapton etching

Second Cu etching



"CYLINDRICAL" HOLES




*M. Alfonsi et al, Nucl. Instr. and Meth. A617(2010)151*

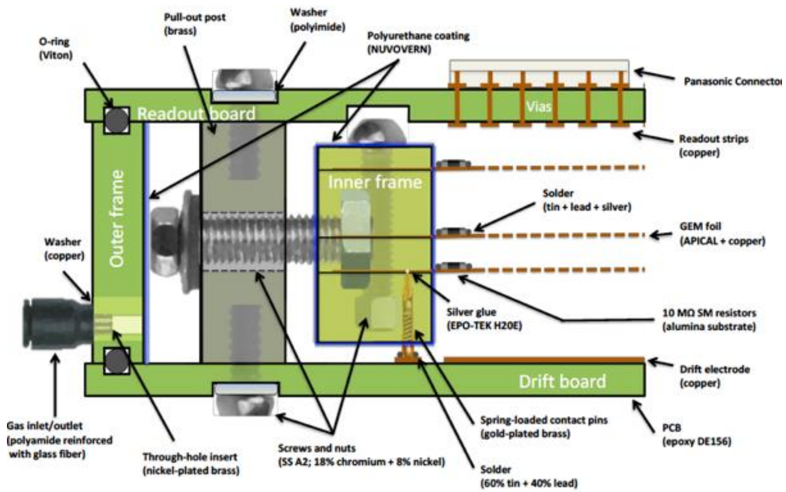
# CMS HIGH-$\eta$ MUON DETECTOR UPGRADE

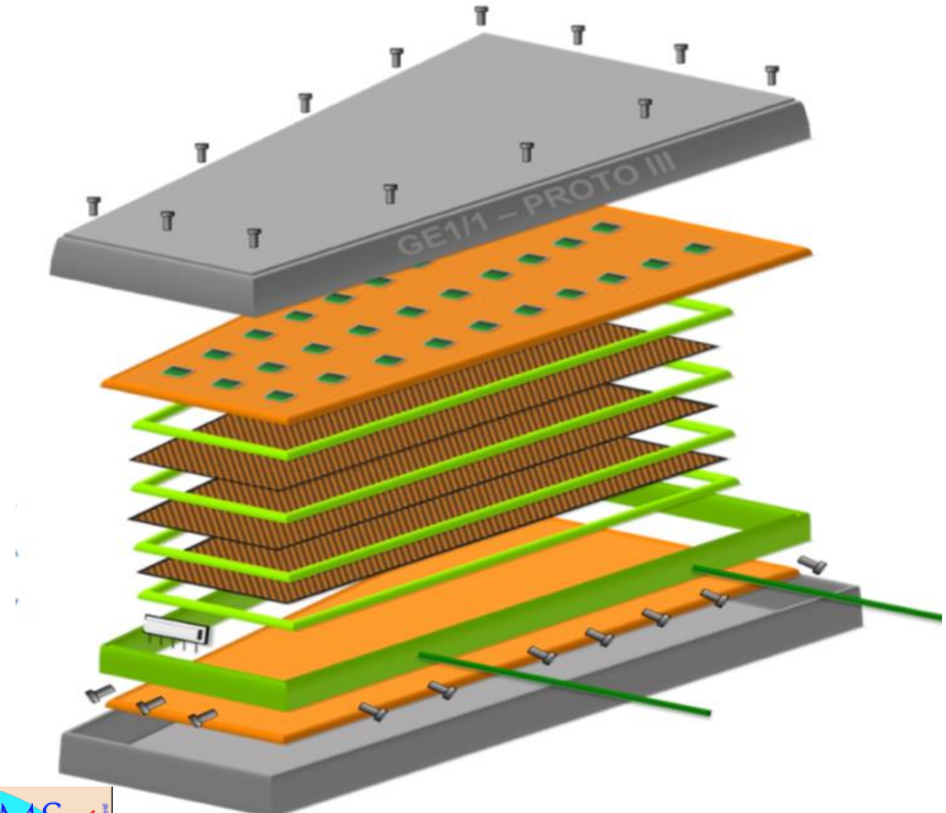
Archana Sharma, CMS GEM Upgrade Project Manager

DISMOUNTABLE MECHANICAL ASSEMBLY
EDGE STRETCHED GEM FOILS
CERN-INFN-BONN

GEM MODULES: 100-120 cm x 22-45 cm
36 SUPERCHAMBERS IN EACH ENDCAP

*M. Alfonsi et al, Nucl. Instr. and Meth. A617(2010)151*

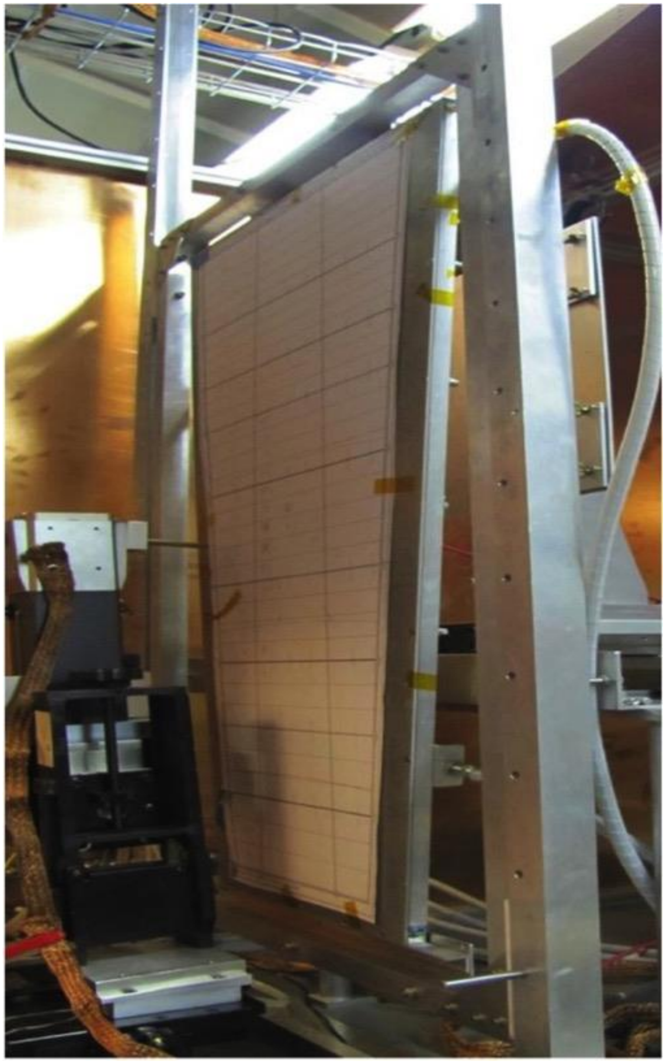


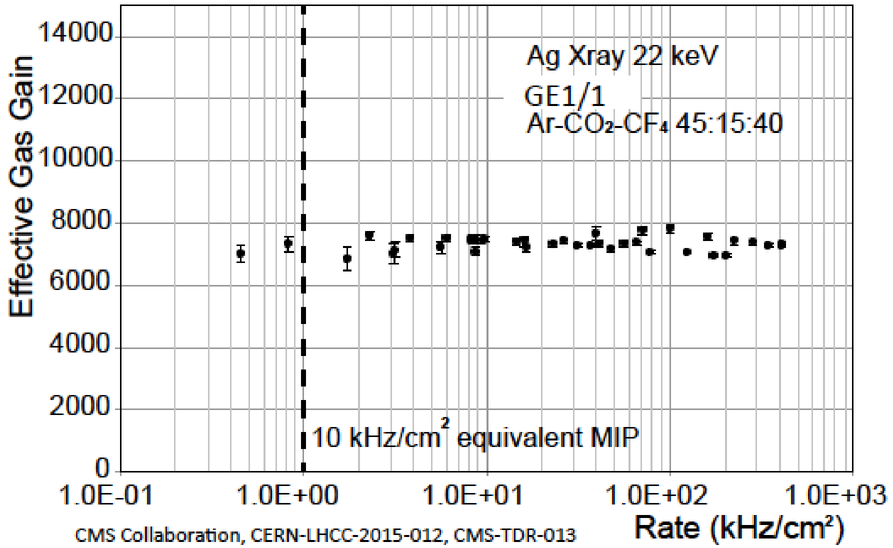



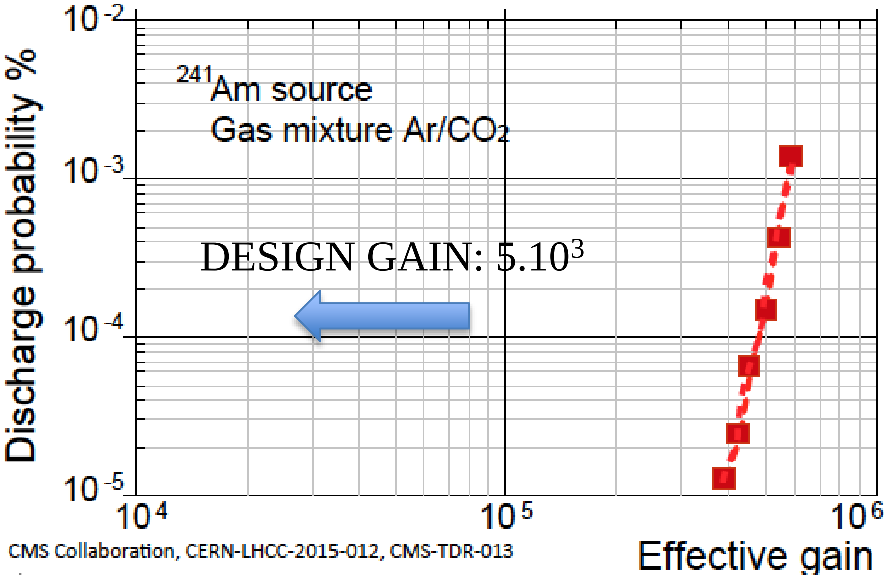

*D. Abbaneo et al,*
*Nucl. Instr. and Meth. A732 (2013) 203*

*B. Dorney, MPGD WORKSHOP (Trieste 2015)*

LARGE PROTOTYPE IN TET BEAM



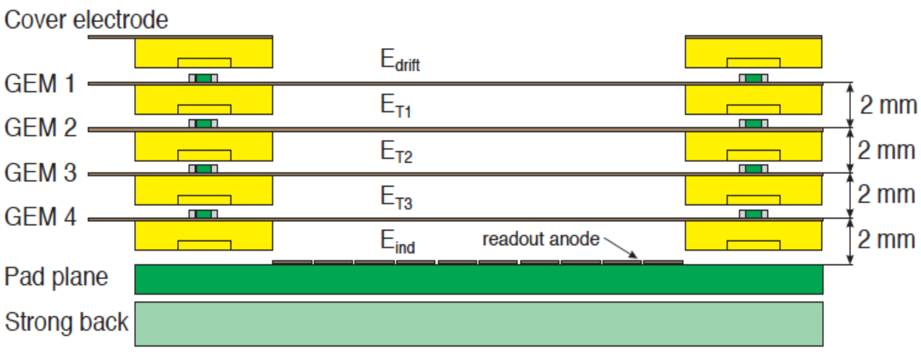


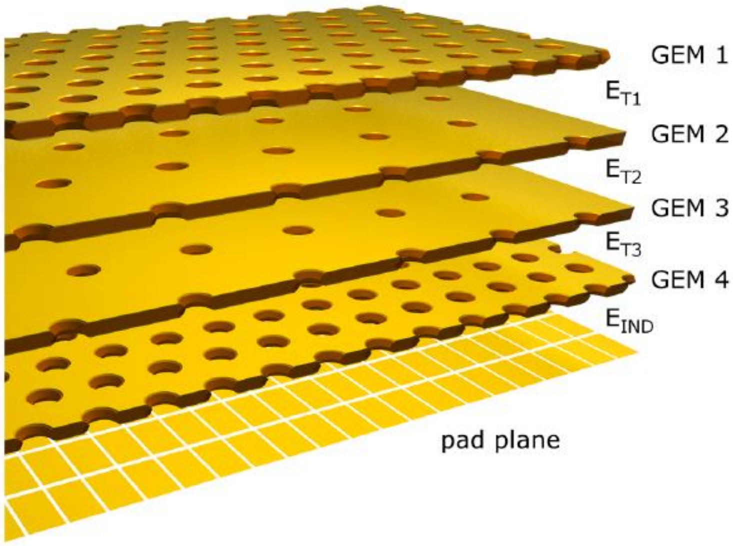



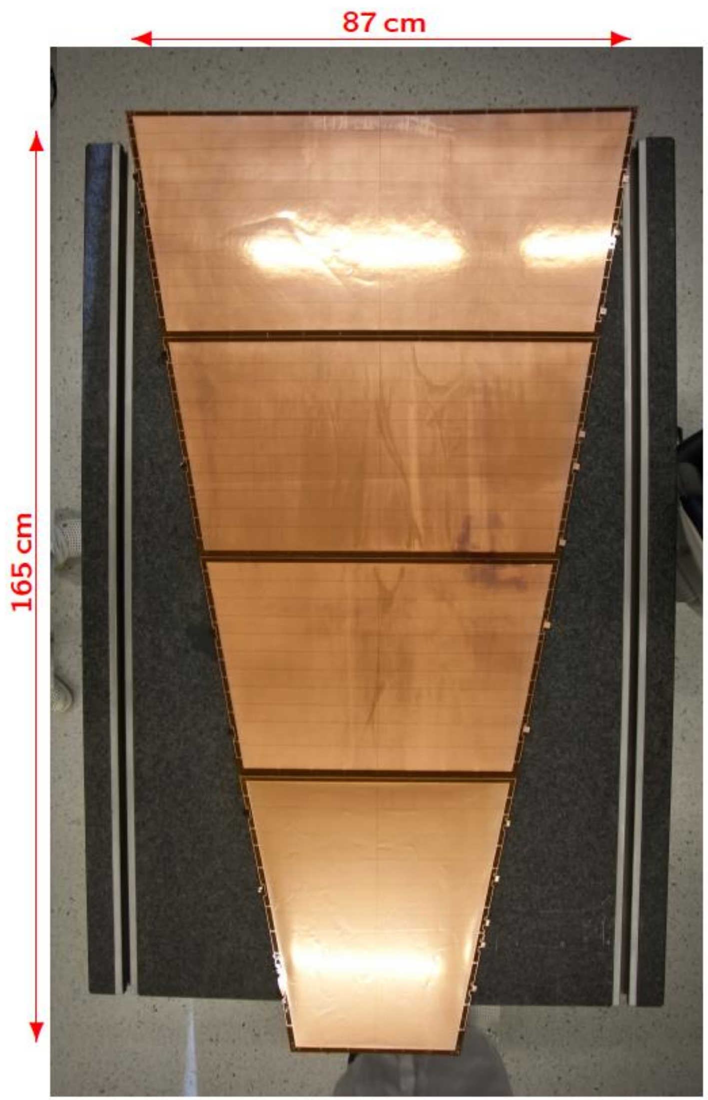

B. Dorney, MPGD Workshop (Trieste 2015)

Chilo Garabatos, Deputy Project Leader

QUAD-GEM WITH STAGGERED HOLES

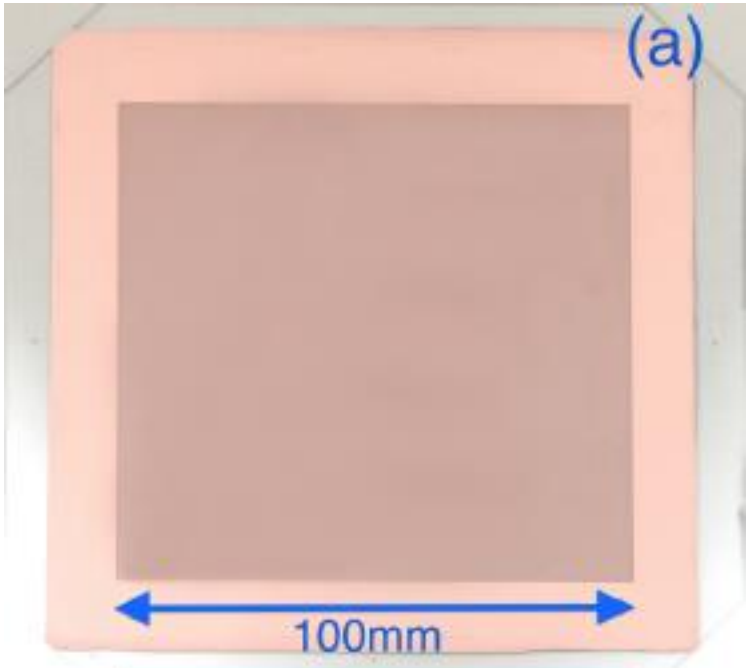


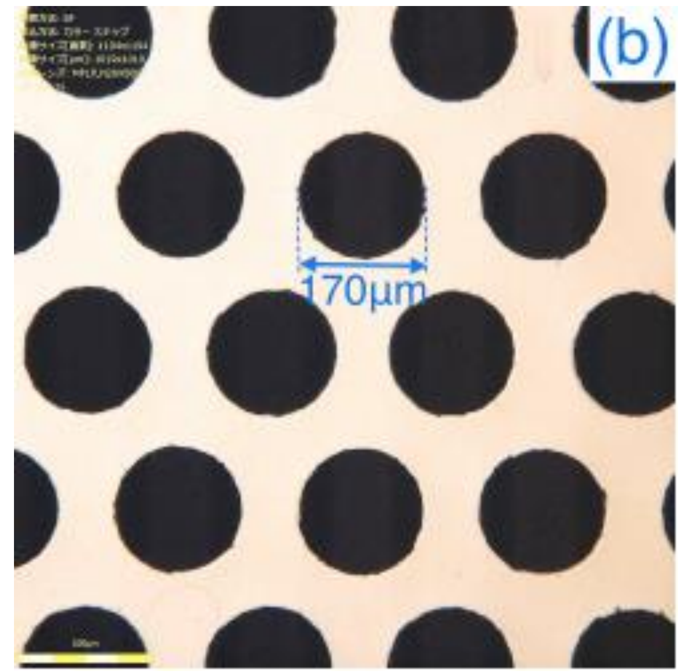



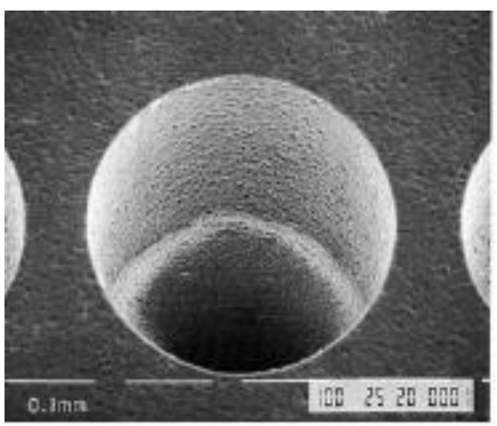

*A. Deisting, MPGD Workshop (Trieste 2015)*

GLASS GEM




- GOOD GAIN UNIFORMITY
- GOOD ENERGY RESOLUTION
- NON-OUTGASSING MATERIALS

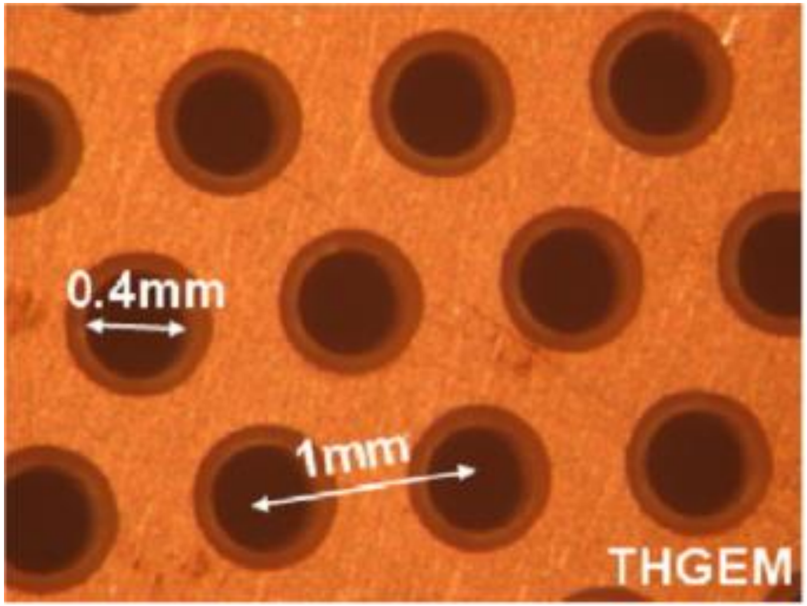



*H, Takahashi et al, Nucl. Instr. and Meth. A724(2013)1*

ALSO CALLED LARGE ELECTRON MULTIPLIER (LEM)

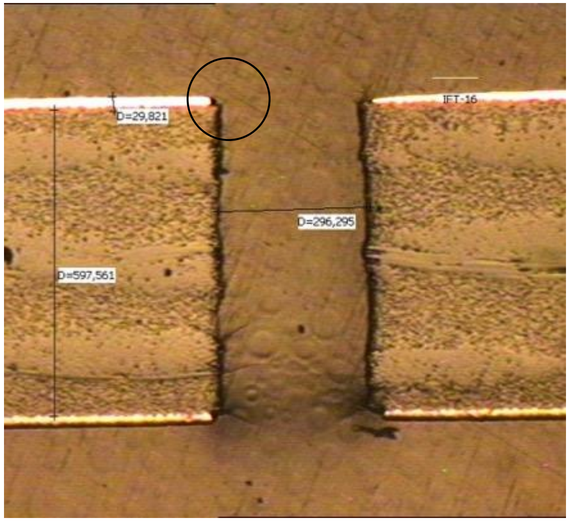
MECHANICAL DRILLING OF METAL-CLAD PC BOARD
- SELF-SUPPORTING
- HIGH GAIN (?)





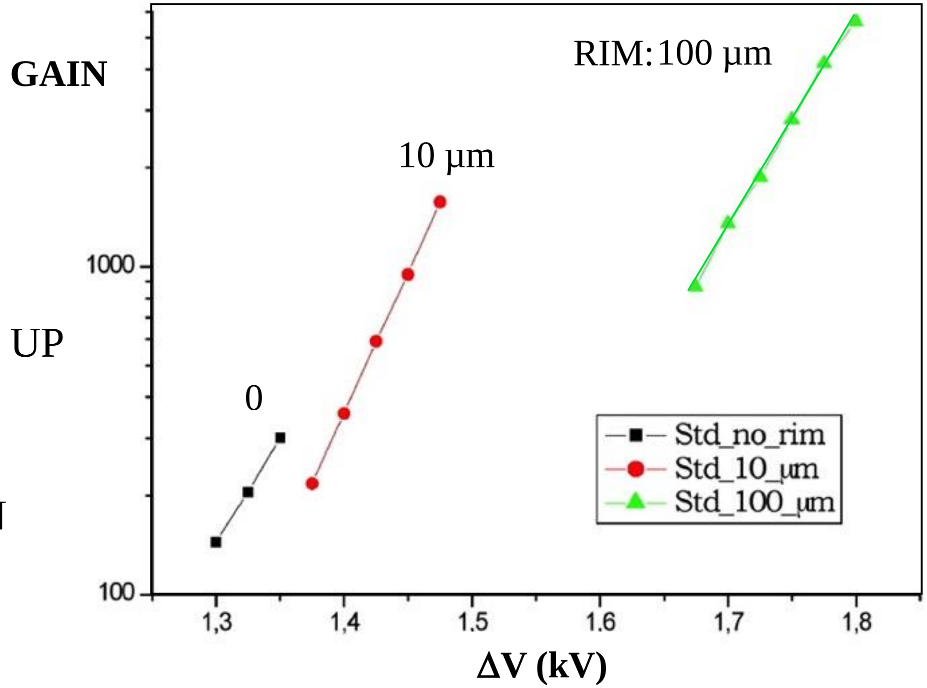
*R.Chechik et al, Nucl. Instr. and Meth. A535(2004)303*

DEVELOPMENTS FOR THE COMPASS RICH-1 UPGRADE

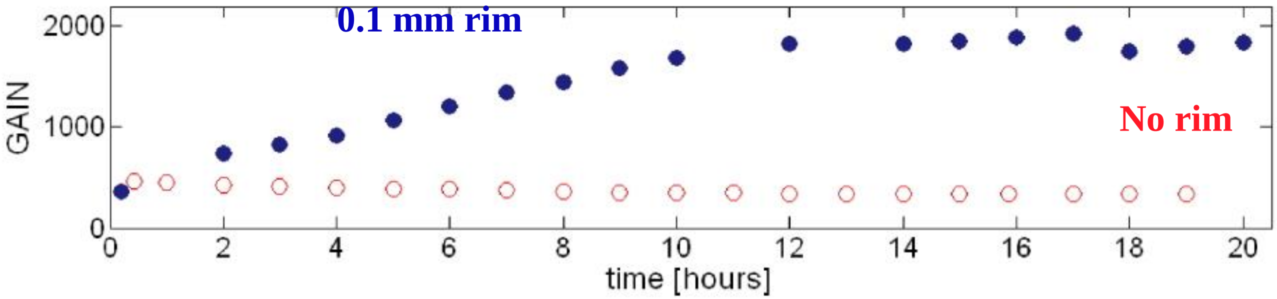



LARGE RIM:
- HIGH GAIN
- CHARGING UP

RIMLESS:
- LOW GAIN
- STABLE




GAIN VS TIME (CHARGING UP EFFECT):

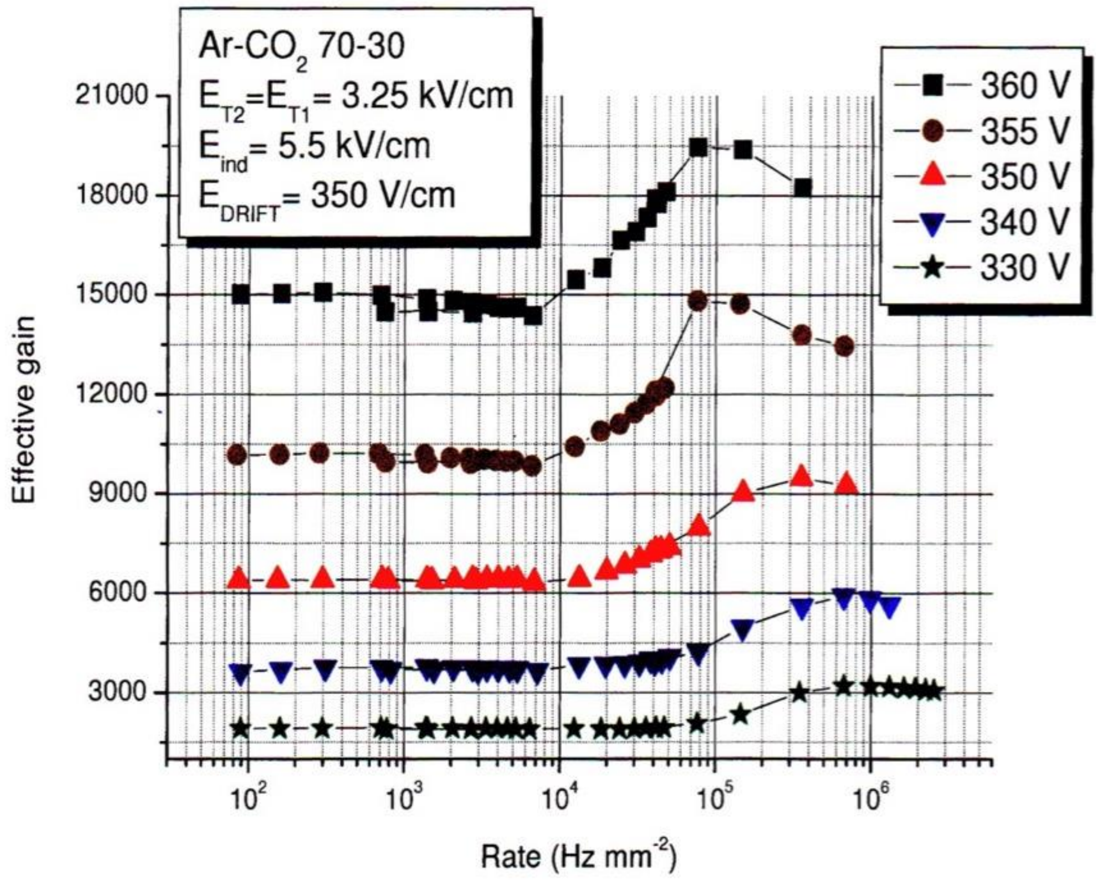



*M. Alexeev et al, Nucl. Instr. and Meth. A695(2012)159*

MULTIPLE STRUCTURES

# MULTIGEM GAIN AT VERY HIGH RATES

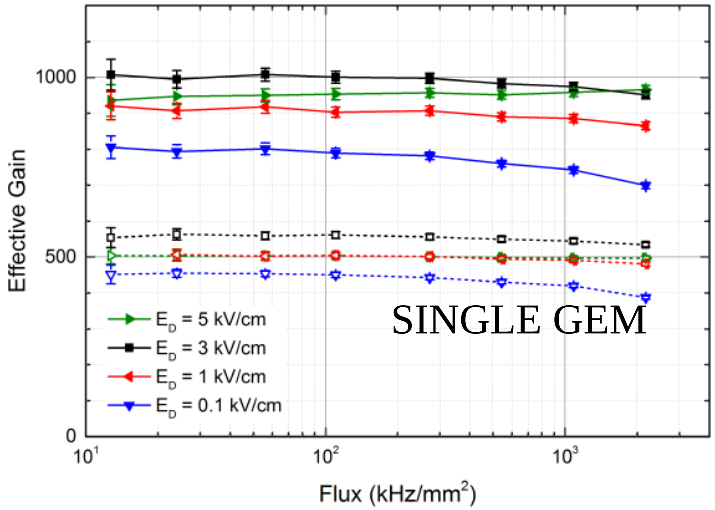
GAIN VS X-RAY RATE: TRIPLE GEM (2006)



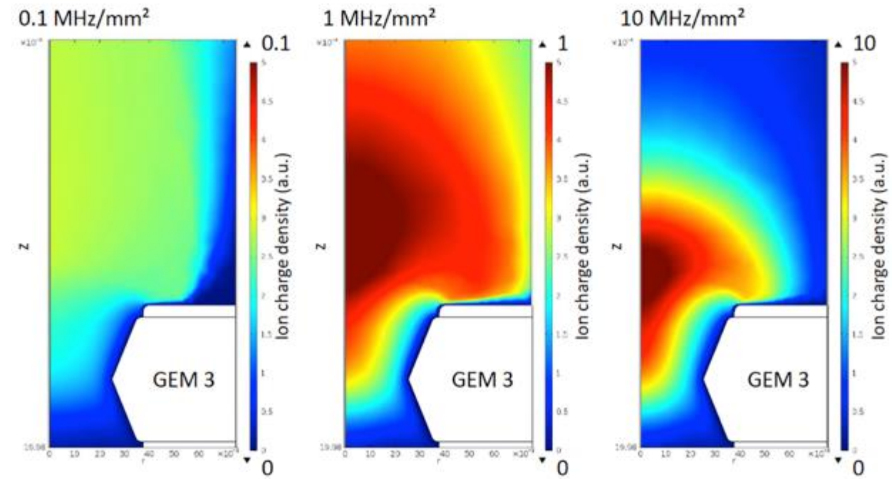

*P. Everaerts, PhD Thesis Gent University (2006)*

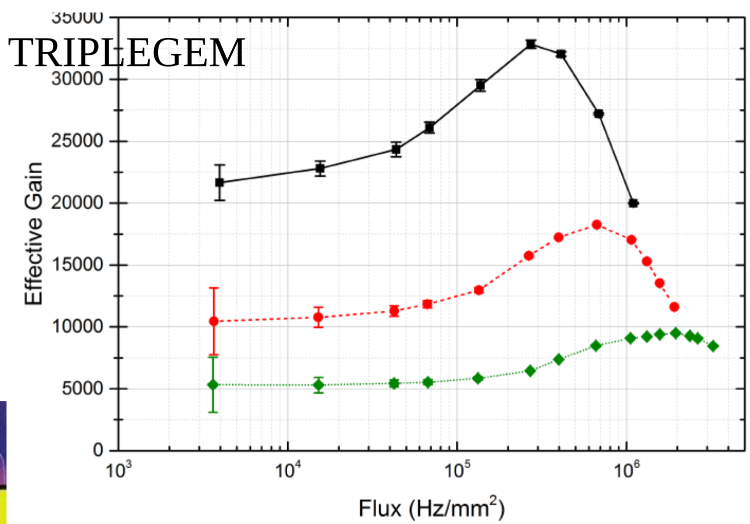
# MULTIGEM GAIN AT VERY HIGH RATES

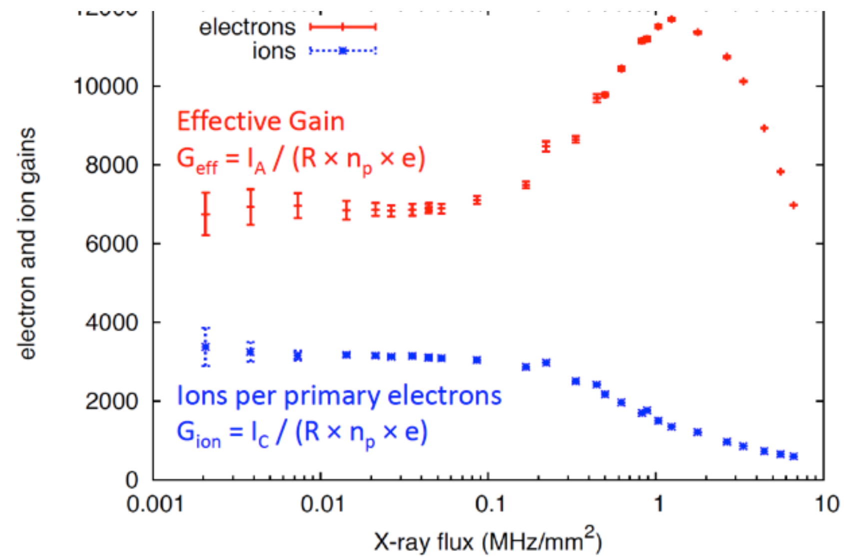
NEW MEASUREMENTS (2015)




SIMULATION: CHARGE DENSITIES VS RATE




*P. Thuiner, PhD TU Vienna (2016)*

*S. Franchino et al, IEEE 2015 Nucl. Sci. Symp. Conf. Rec.*

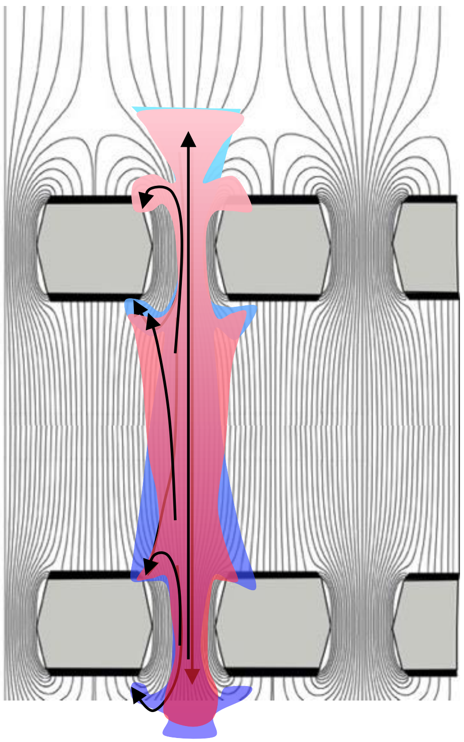
POSITIVE IONS BACKFLOW (OR FEEDBACK):

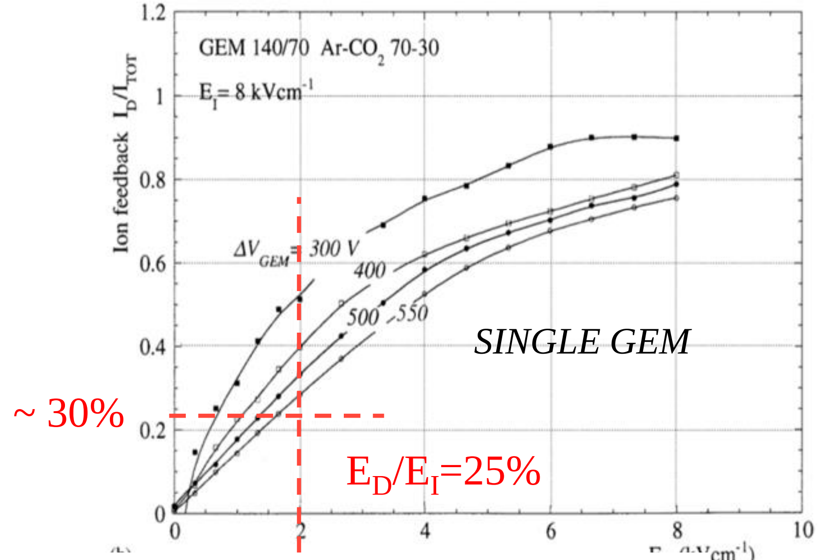
$$IBF = \frac{I_{DRIFT}}{I_{ANODE}}$$

THE WISH:
ONE IBF ION PER PRIMARY

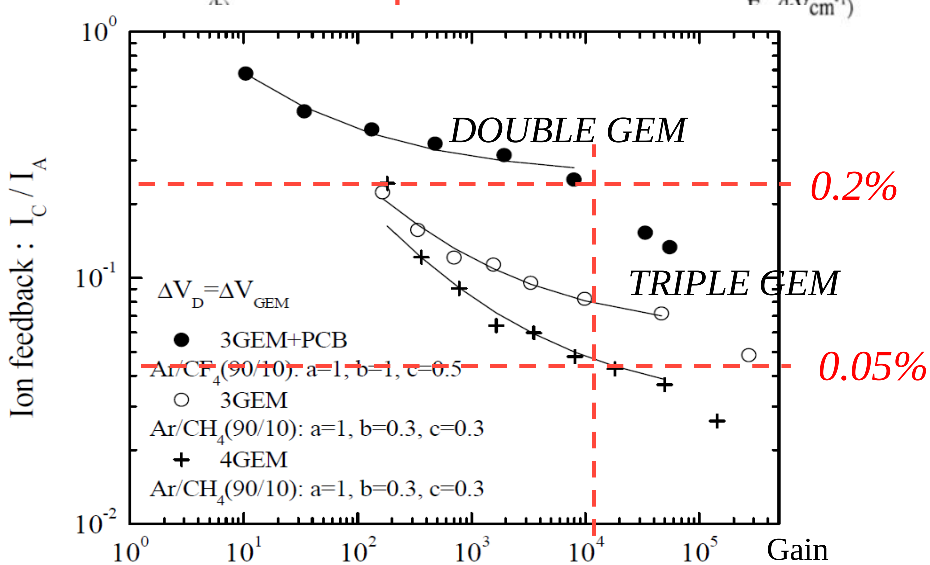
$$IBF \leq \frac{1}{GAIN} \approx 10^{-4}$$

MULTIGEMS:THE IBF VALUE DEPENDS ON GEOMETRY, FIELDS AND DIFFUSION:





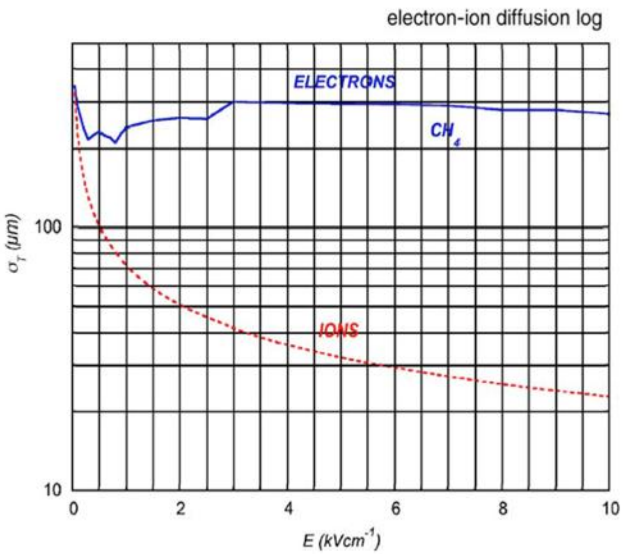

S. Backmann et a, l
Nucl. Instr. Meth. A438(1999)376



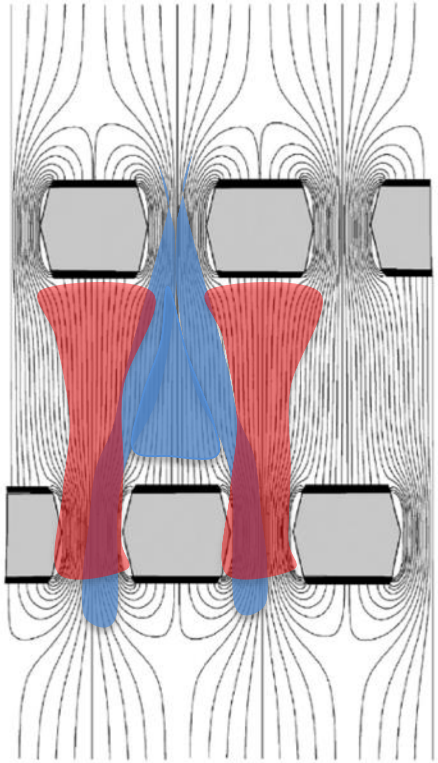

A. Bondar et al, Nucl. Instr. and Meth. A496(2003)325

# ION BACKFLOW REDUCTION: OFFSET HOLES

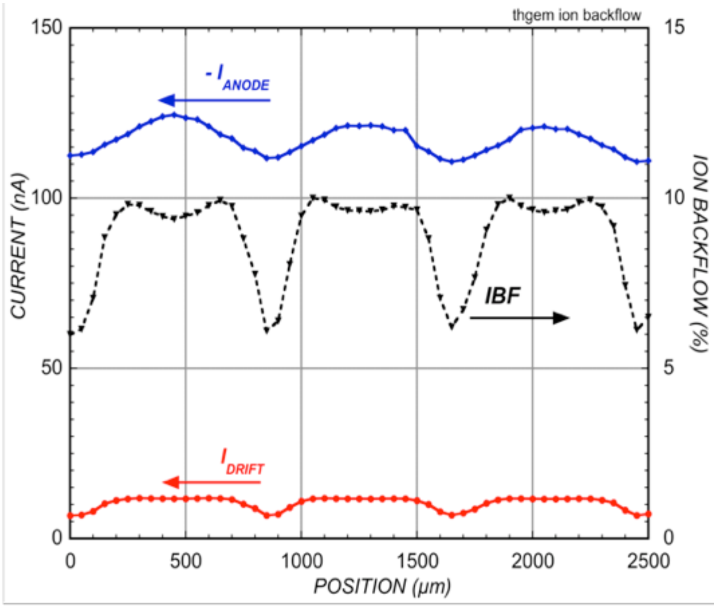
$e^-$ $I^+$ TRANSVERSE DIFFUSION:




EXPLOIT THE DIFFERENCE BETWEEN IONS' AND ELECTRONS' DIFFUSION IN AN OFFSET DOUBLE GEM

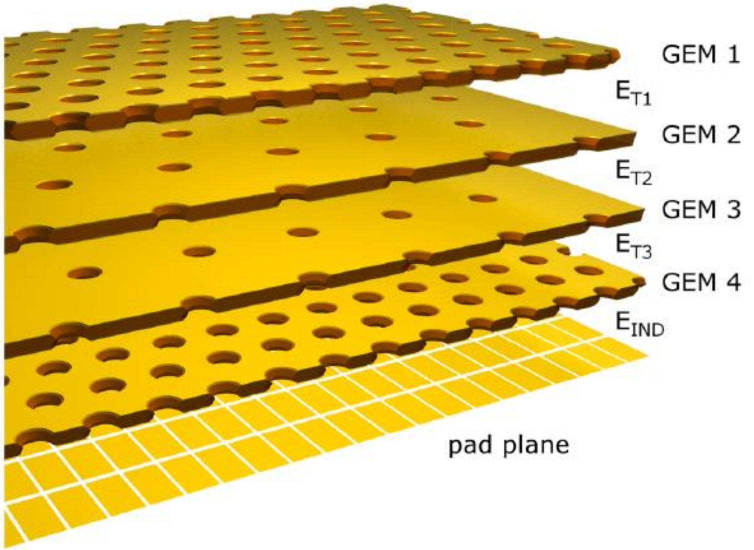


OFFSET SCAN:

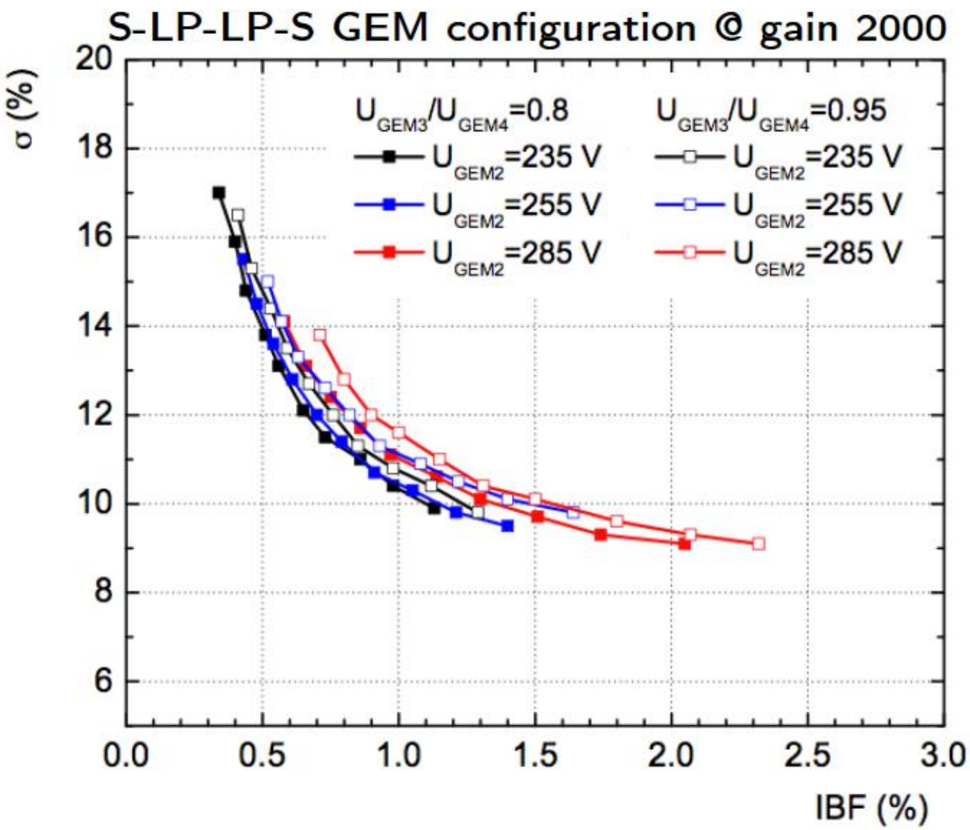



*F. Sauli et al, Nucl. Instr. and Meth. A560(2006)269*

FOUR GEMS WITH STAGGERED HOLES




ENERGY RESOLUTION VS IBF:



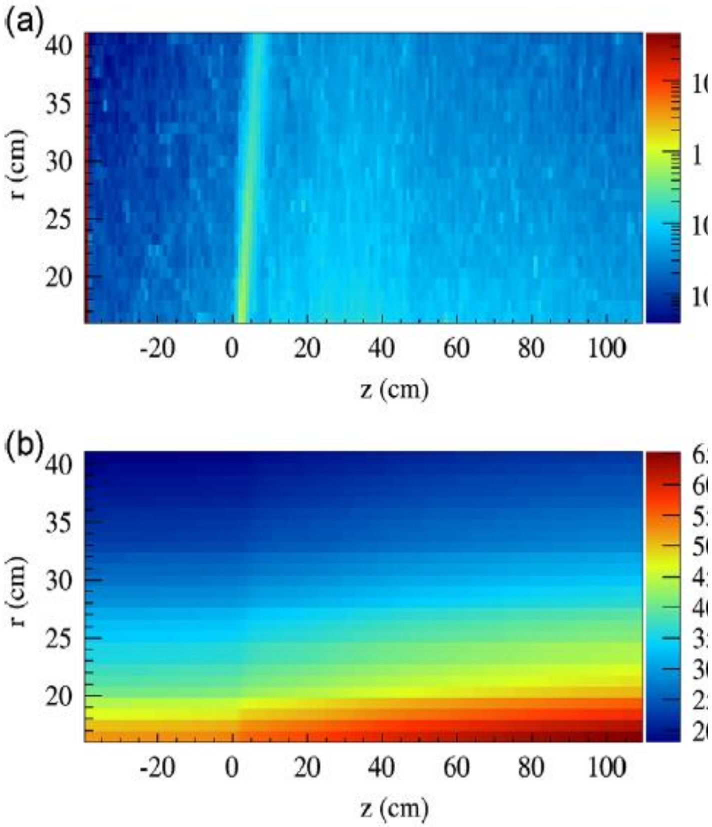

GEM 1 & 4: STANDARD PITCH 140 µm
GEM 2 & 3: LARGE PITCH 280 µm

*A.Deisting, MPGD Workshop (Trieste 20125)*

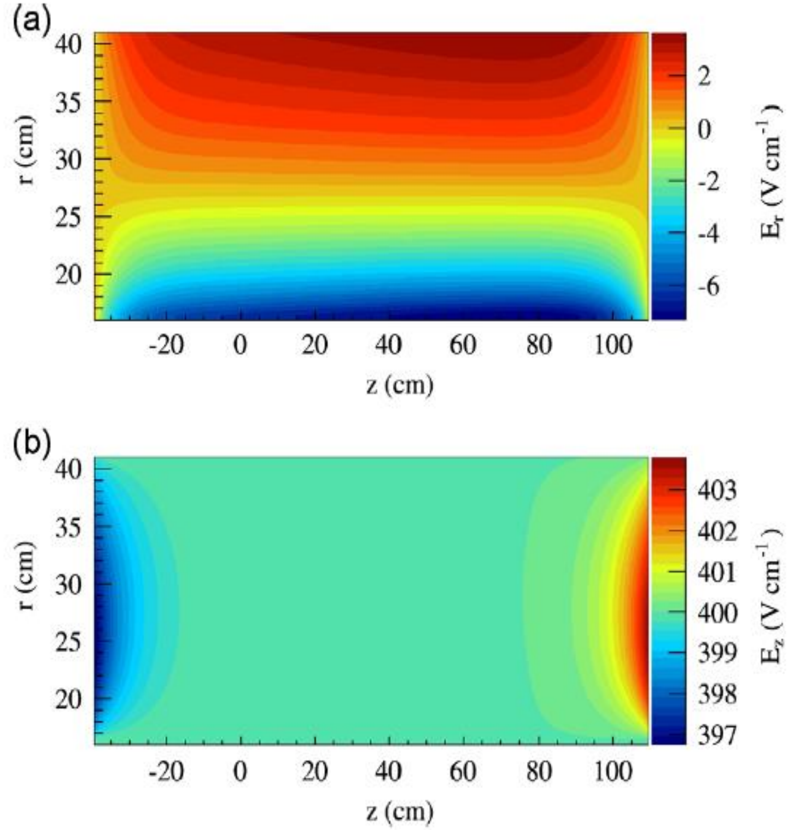
TRIPLE GEM OPERATED IN Ne-$CO_2$ 90-10

2 $10^7$ p-p ANNIHILATIONS GAIN M=2000 IBF 2.5 $10^{-3}$

SPACE CHARGE DENSITY:

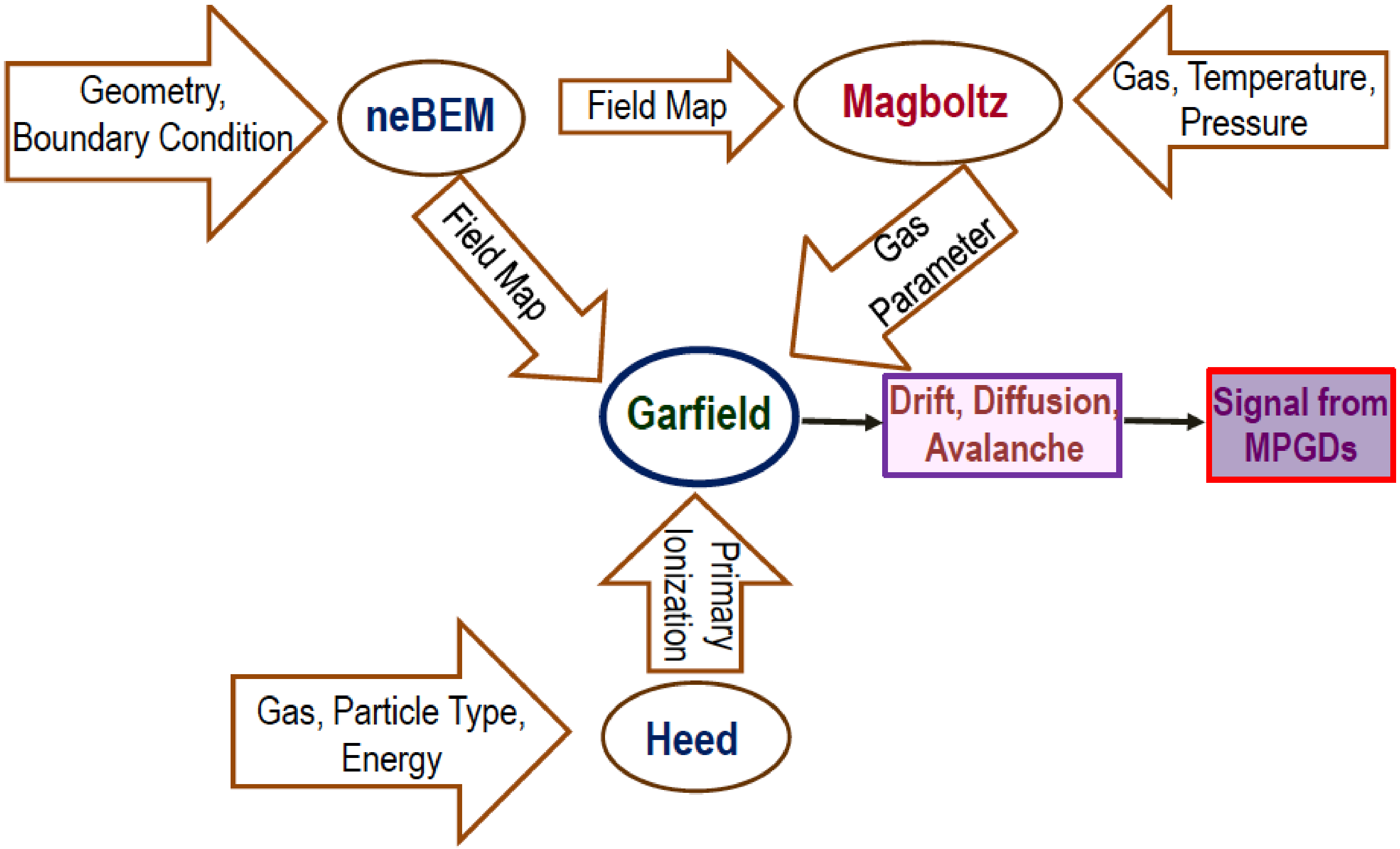



ELECTRIC FIELD DISTORTIONS:



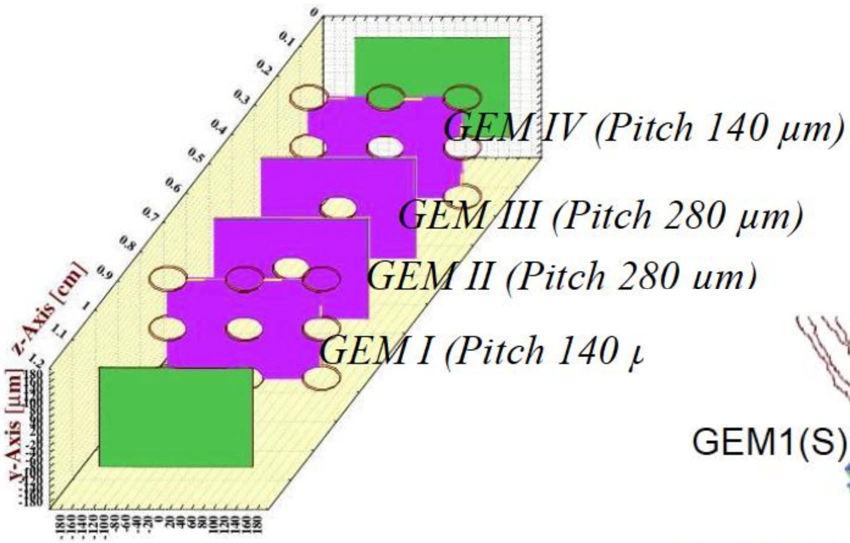

*F.W. Bohmer et al,Nucl. Instr. and Meth. A719(2013)101*

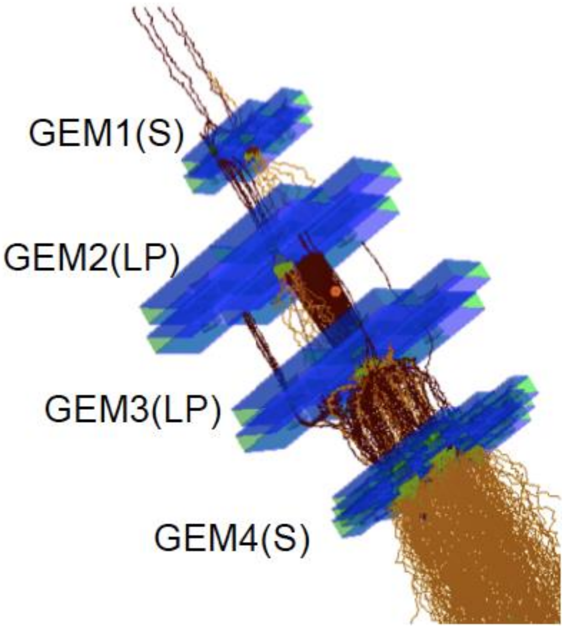
MAGBOLTZ (Steve Biagi)
GARFIELD (Rob Veenhof)
+ ELECTRIC FIELD, ENERGY LOSS,...

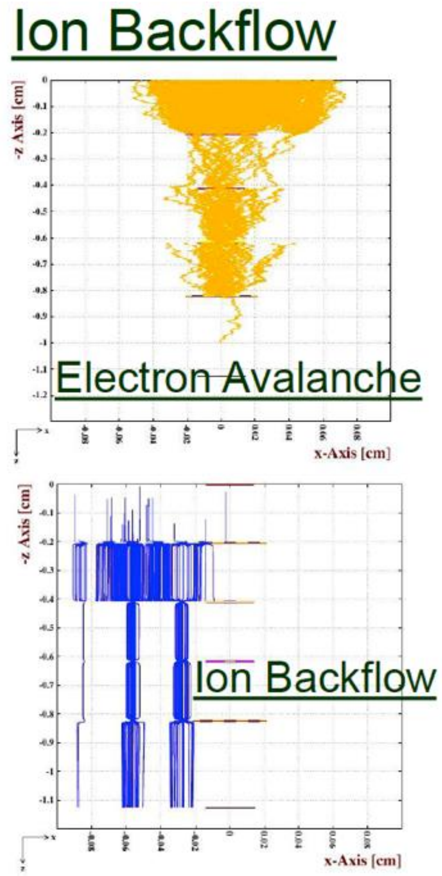



*P. Bhattacharya, RD51 Collaboration*

ALICE GEM TPC SIMULATION

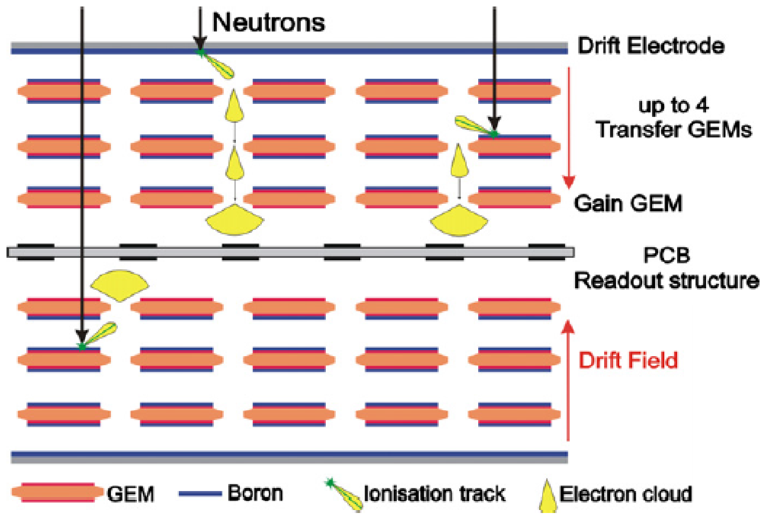


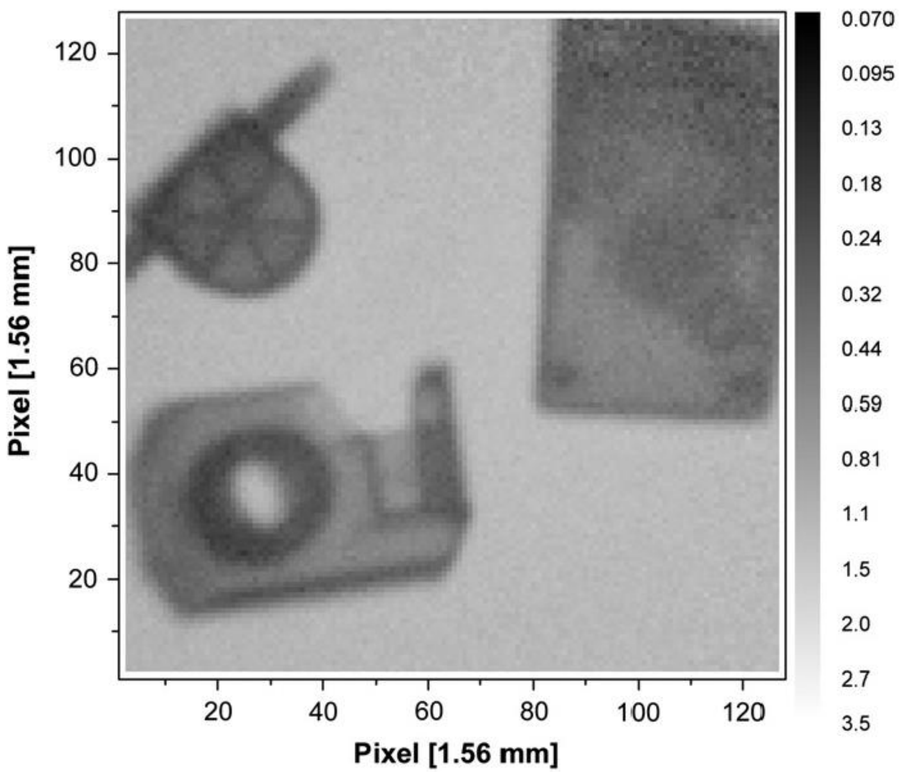




P. Bhattacharya, MPGD Workshop (Trieste 2015)

CASCADE: $^{10}$B-COATED GEM ELECTRODES




THERMAL NEUTRON RADIOGRAPHY



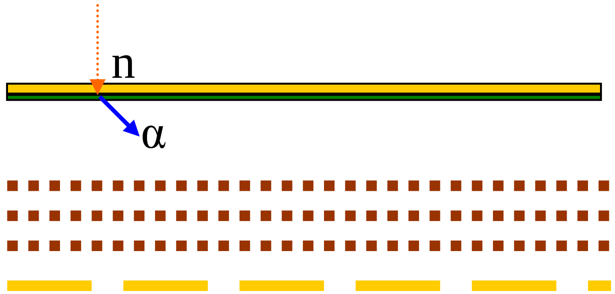

*M. Klein and Ch. Schmidt, Nucl. Instr. and Meth. A628(2011)9*

# NEUTRON DETECTORS

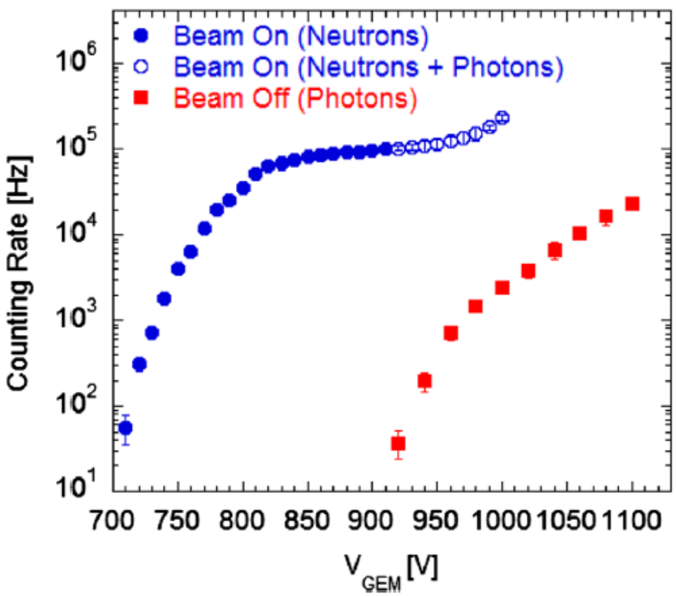
b-GEM:

TRIPLE GEM WITH ALUMINUM FOIL CATHODE COATED WITH 1 μm OF BORON CARBIDE

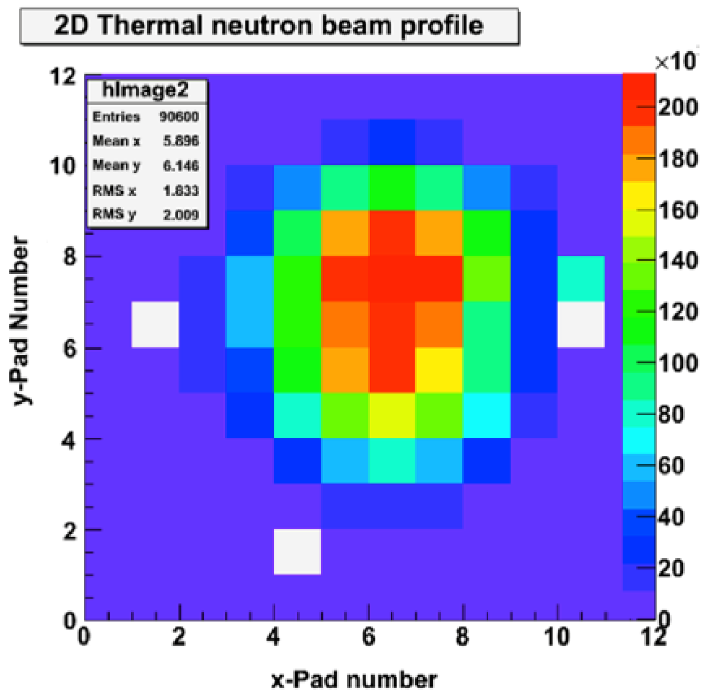
READOUT: 144 PADS, 8x8 mm$^2$




SENSITIVITY TO GAMMA BACKGROUND:



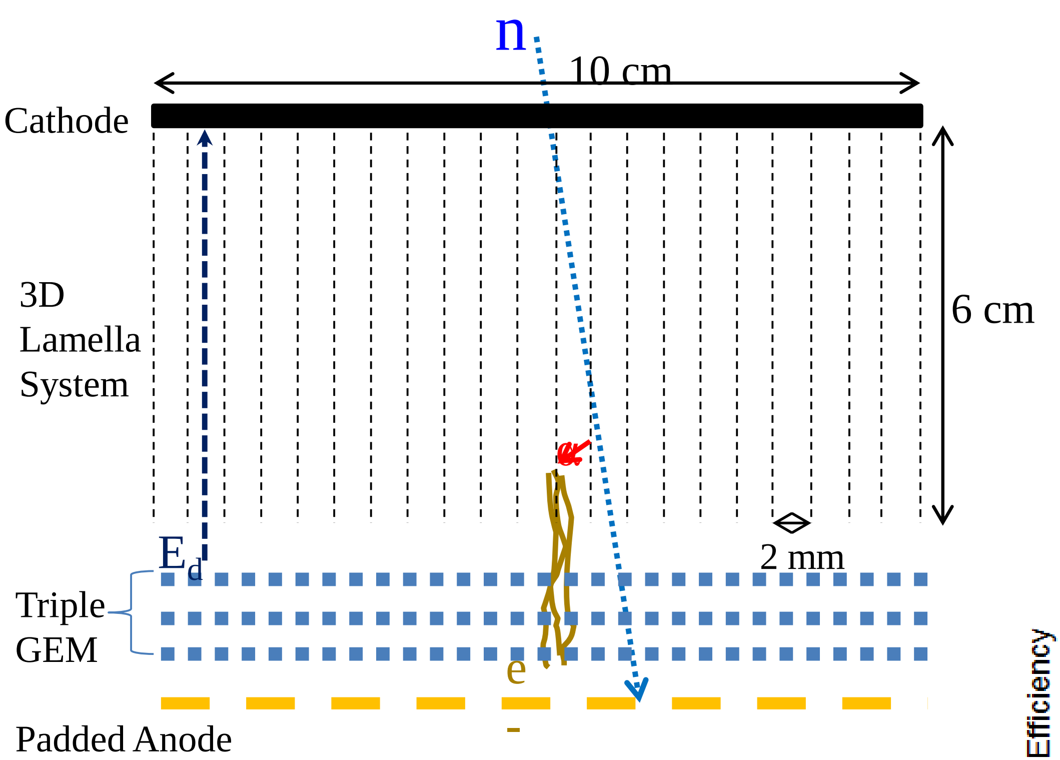

2-D THERMAL NEUTRON BEAM PROFILE




*G. Croci et al, Nucl. Instr. and Meth. A732(2013)217*

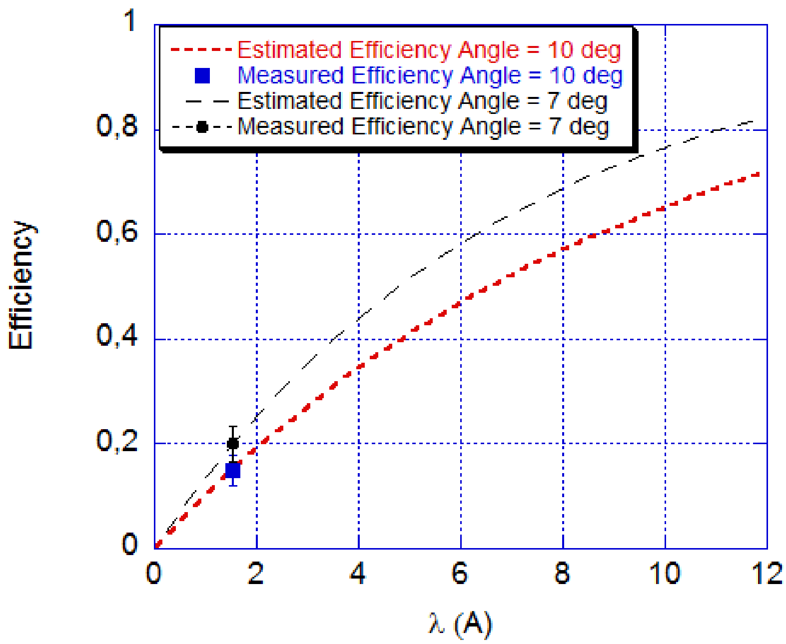
## BORON ARRAY NEUTRON DETECTOR (BAND-GEM)

Alumina Lamellas coated on both sides with $^{10}B_4C$




G. Croci et al, MPGD Workshop (Trieste 2015)

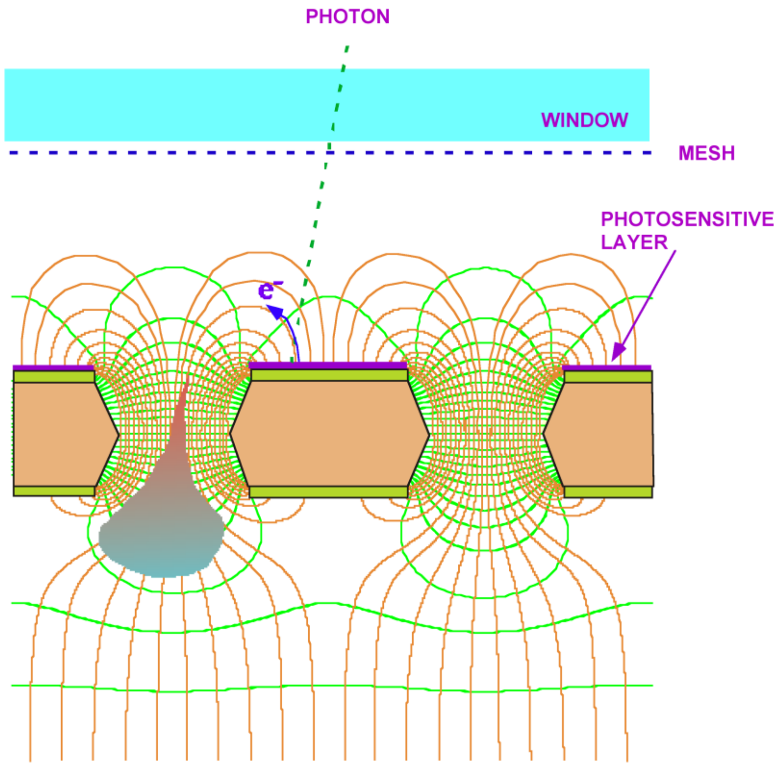
## 48 LAMELLAS PROTOTYPE



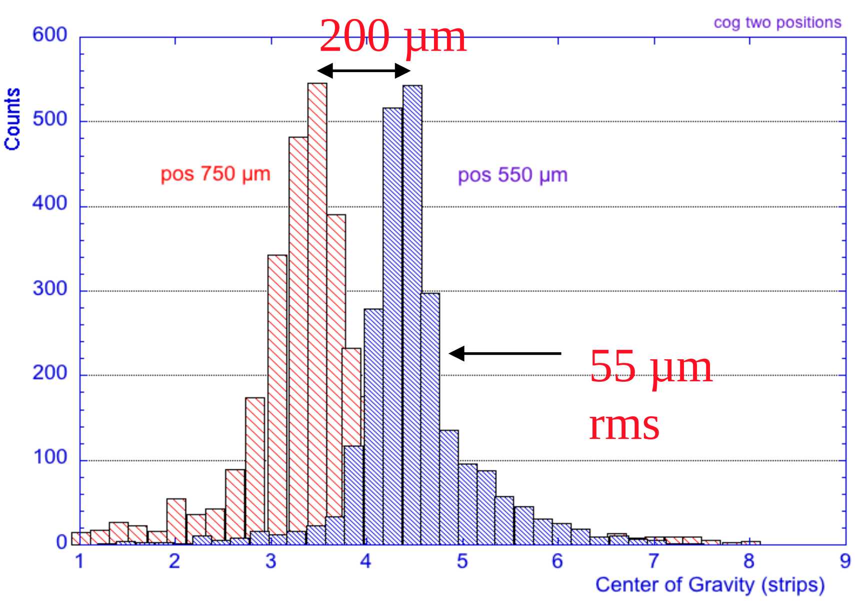
# UV PHOTON DETECTION: CsI PHOTOCATHODES

REFLECTIVE CsI PHOTOCATHODE ON UPPER GEM ELECTRODE

- NO PHOTON FEEDBACK
- INSENSITIVE TO DIRECT IONIZATION

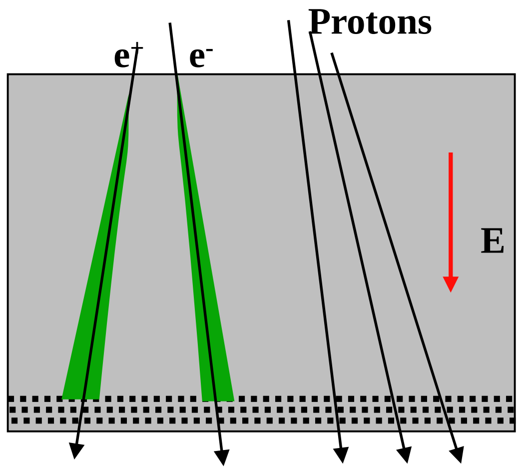


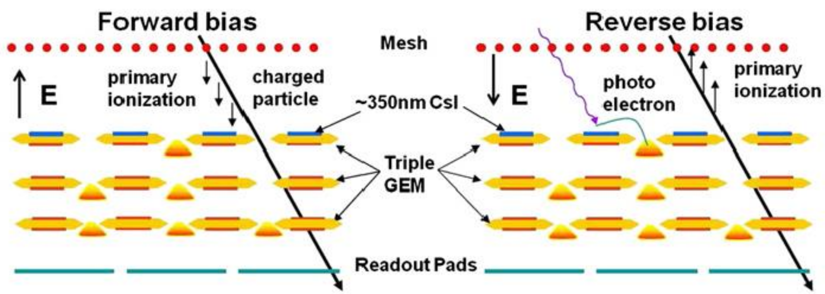

TRIPLE GEM
COLLIMATED SINGLE UV PHOTON SOURCE
POSITION ACCURACY

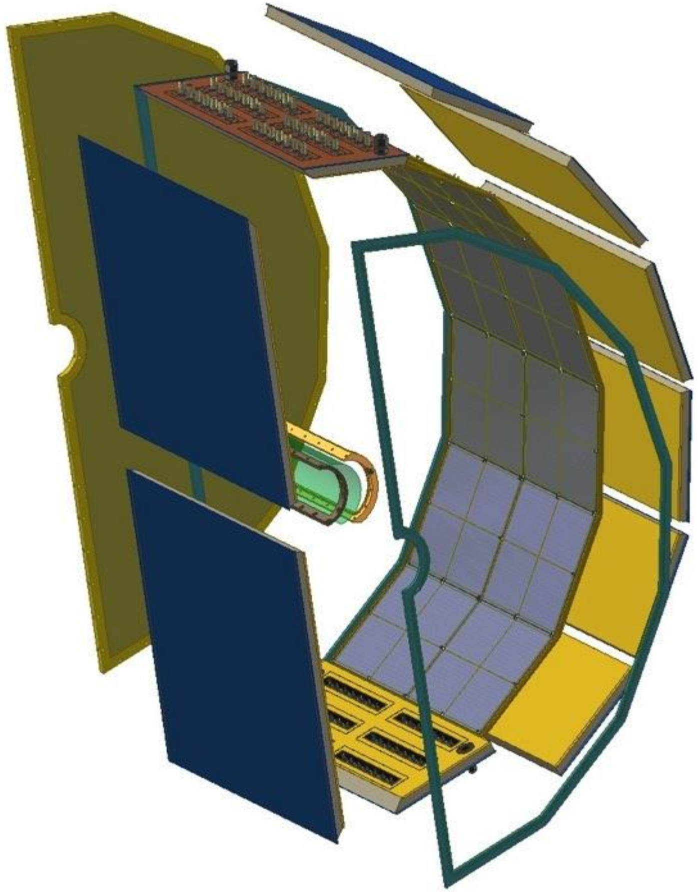



*T. Meinschad, L. Ropelewski and F. Sauli, NIMA 535(2004)324*

"INVERSE FIELD" TPC



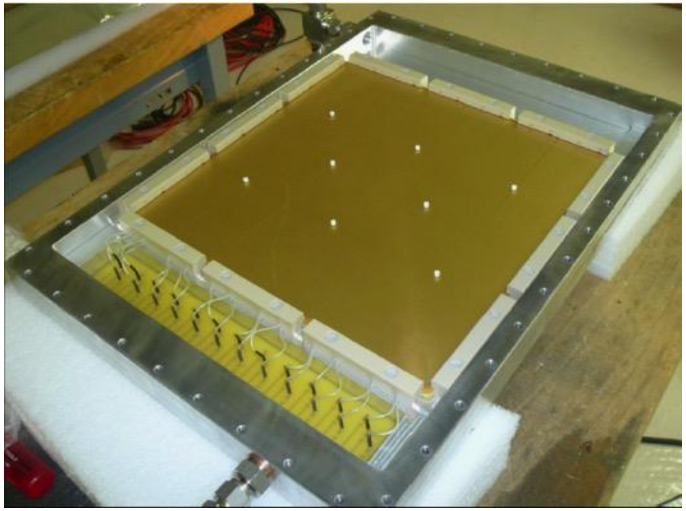



*C. Aidala et al, Nucl. Instr. and Methods A502(2003)200*

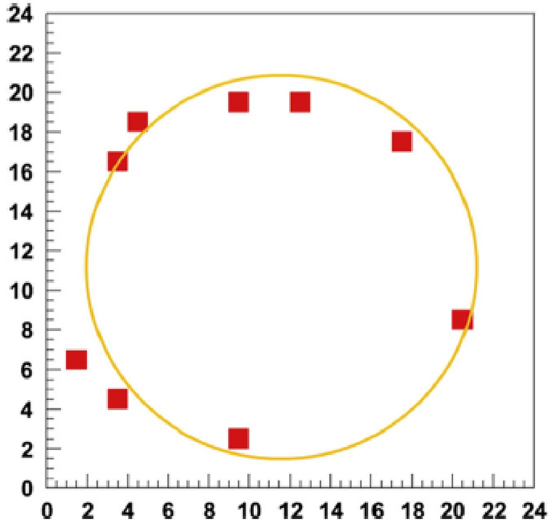
*Z. Fraenkel et al, Nucl. Instr. and Methods A546(2005) 466*

THICK GEM CsI-COATED 30x30 $cm^2$

TRIPLE THGEM PROTOTYPE



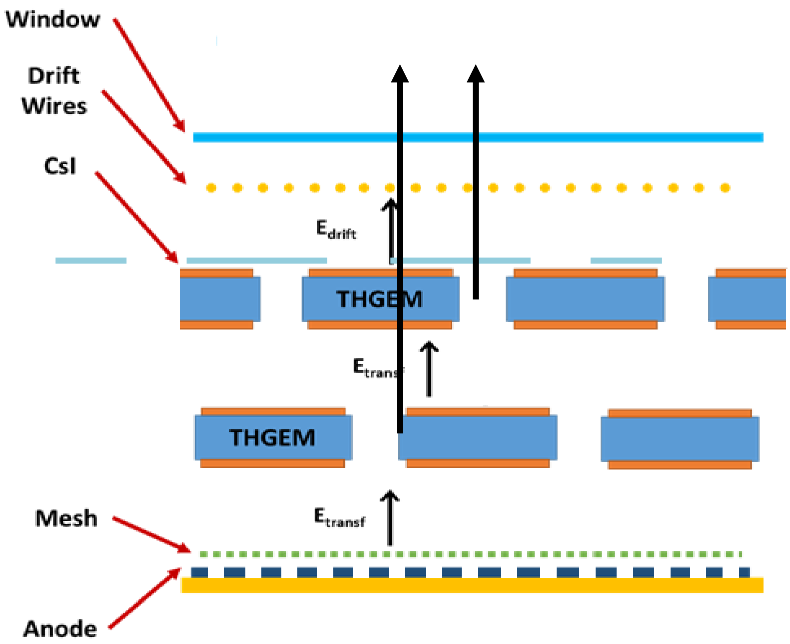
SINGLE EVENT (6 GeV $\pi^-$ BEAM)

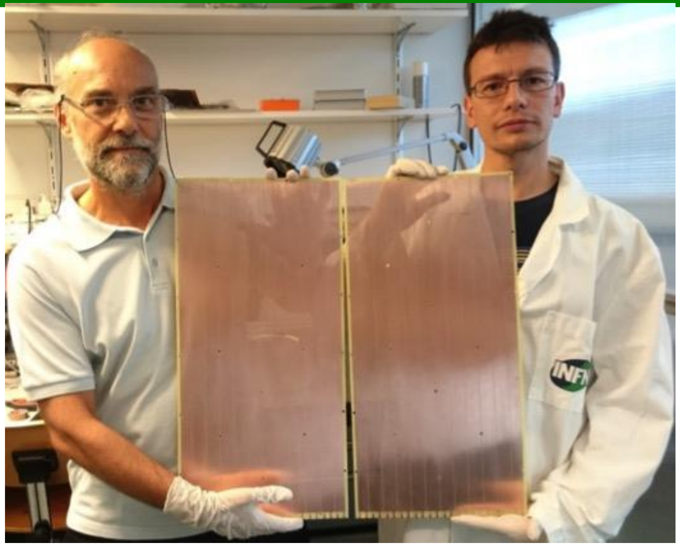



*M. Alexeev et al, Nucl. Instr. and Meth. A732(2013)264*

COMPASS RICH-1 MPGD UPGRADE

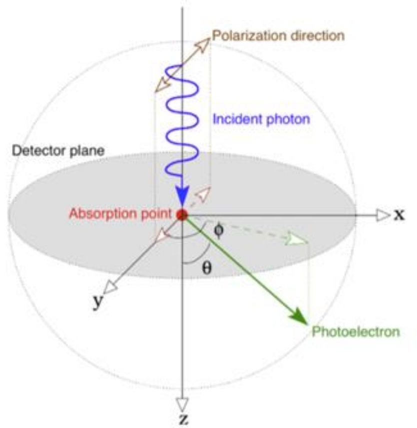
DOUBLE STAGGERED THGEMS+MICROMEGAS

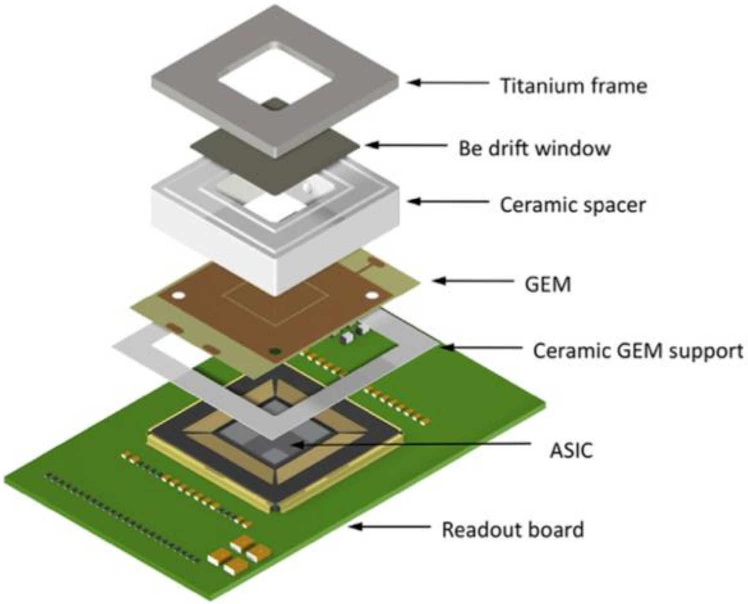


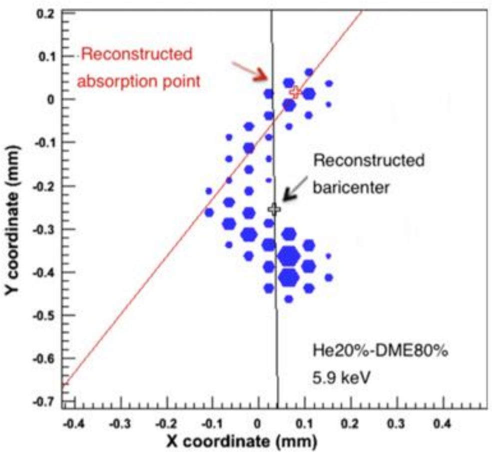

*M. Alexeev et al, MPGD Workshop (Trieste 2015)*

SOFT X-RAY POLARIMETRY

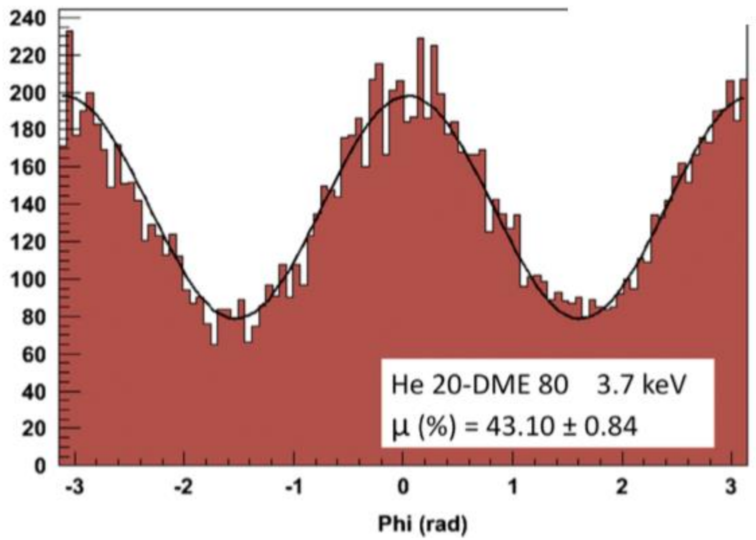



5.9 keV PHOTOELECTRON (80 µm pixels pitch):




MEASURED ANGULAR MODULATION:



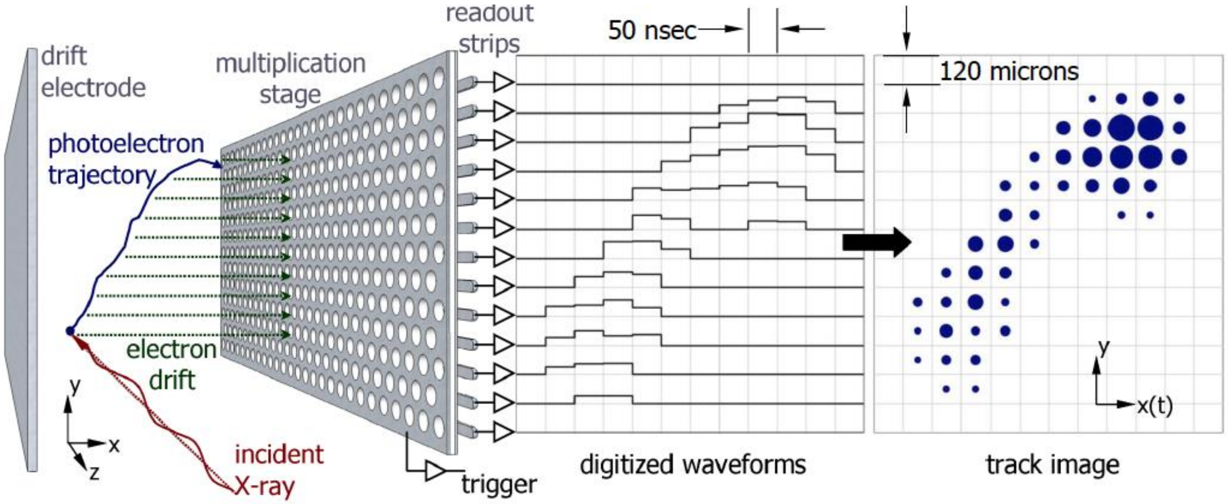

*R. Bellazzini et al, Nucl. Instr. and Meth. A720(2013)173*

# GEM POLARIMETER IN SPACE


GEMS MISSION CANCELLED BY NASA (2012)

NEW MISSION (2017):
POLARIMETRY FOR RELATIVISTIC ASTROPHYSICAL X-RAY SOURCES (PRAXyS)

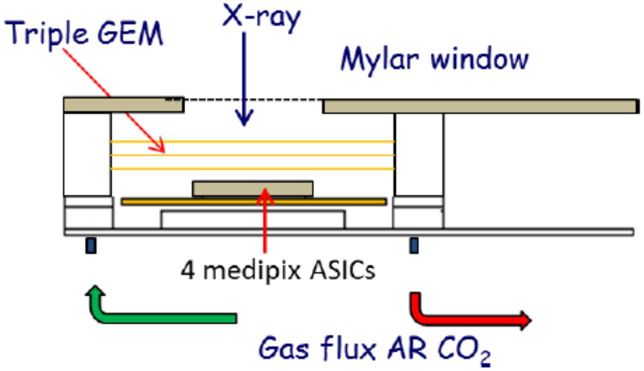
*W.B. Iwakiri et al, Nucl. Instr. and Meth. In press (2016)*



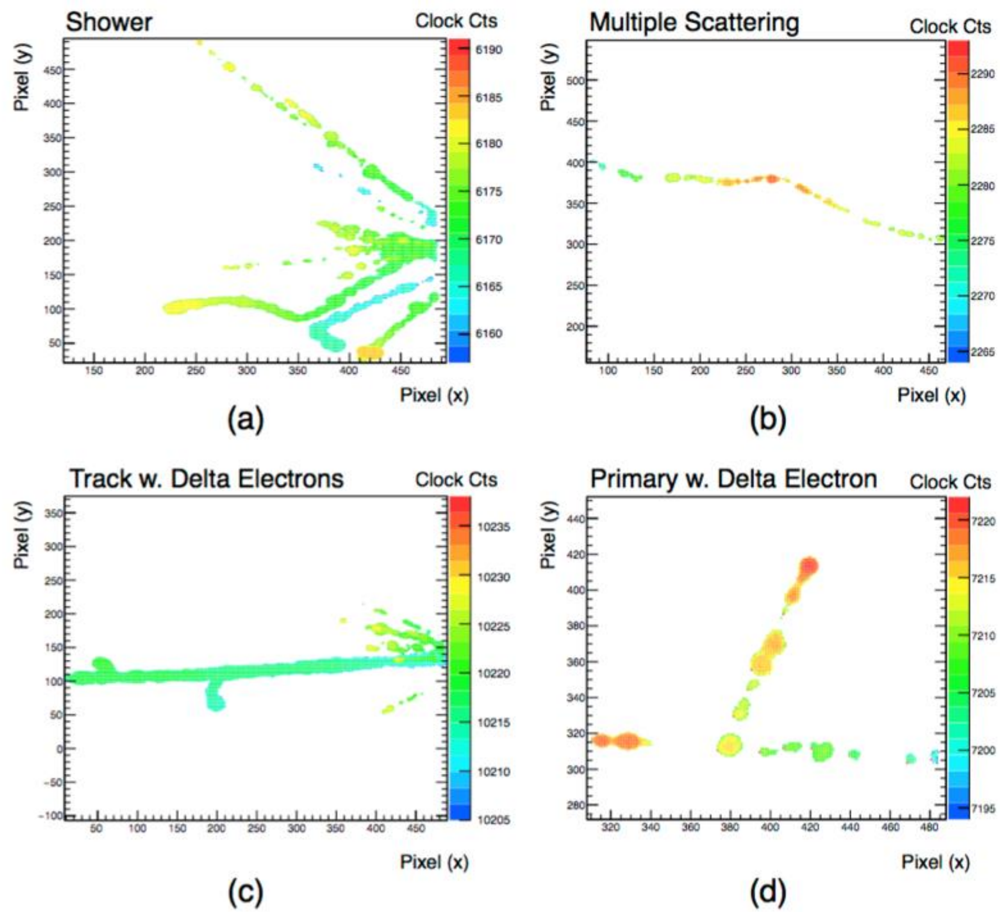

*Toru Tamagawa, MPGD Workshop (Saragoza 2013)*

TRIPLE-GEM WITH MEDIPIX READOUT

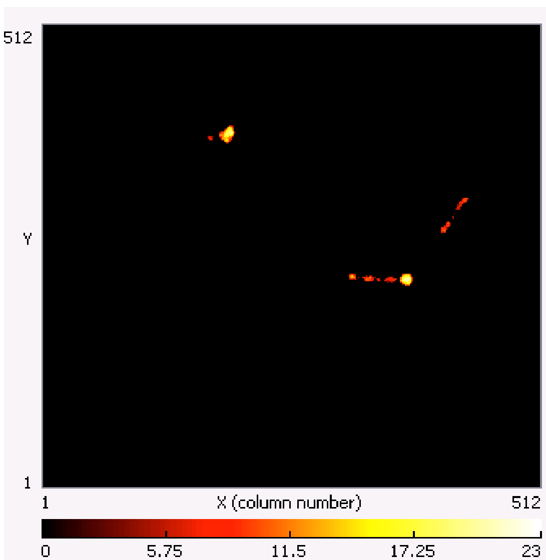
256x256 pixels, 55x55 μm$^2$




RECORDED EVENTS:

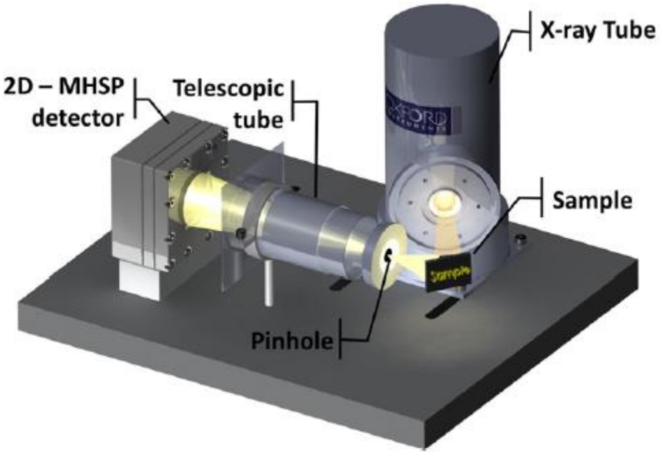



COMPTON ELECTRON:

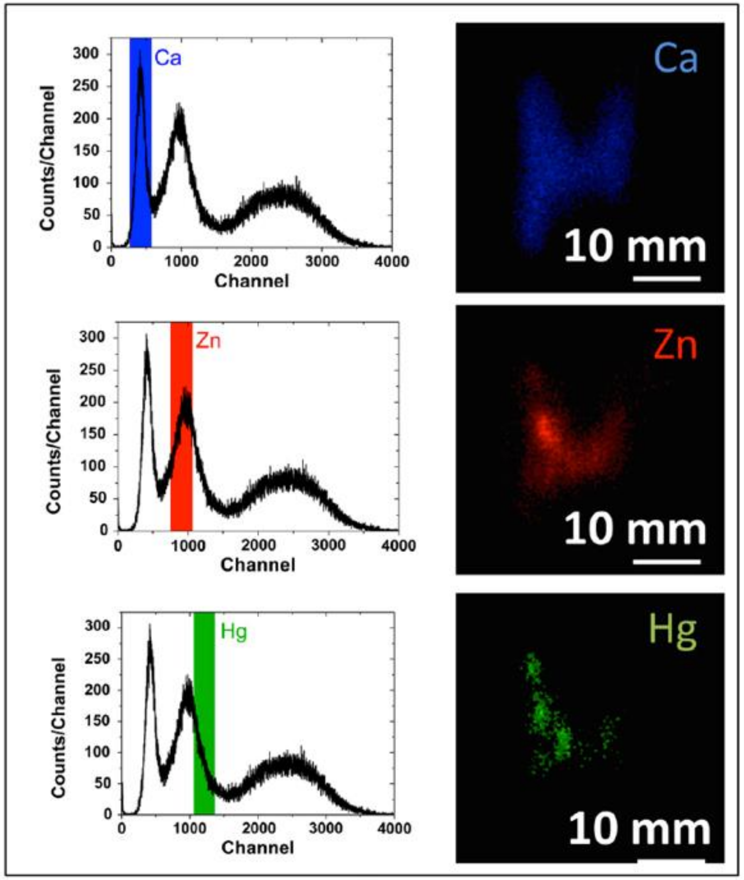



*F. Murtas et al, JINST10(2015)P11003*

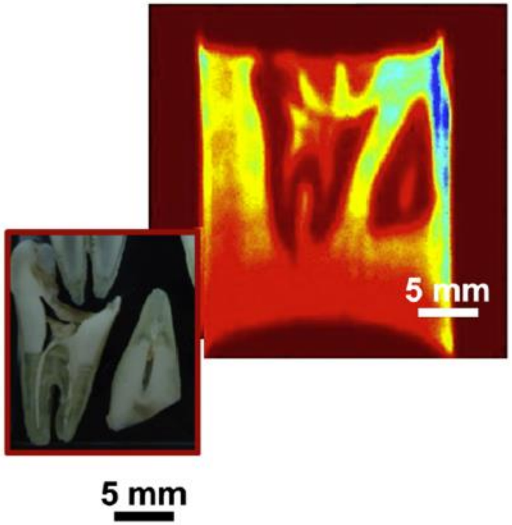
28x28 mm$^2$ MICRO-HOLE AND STRIP PLATE (MHSP)
WITH RESISTIVE LINES 2-D READOUT




ELEMENTAL ANALYSIS:



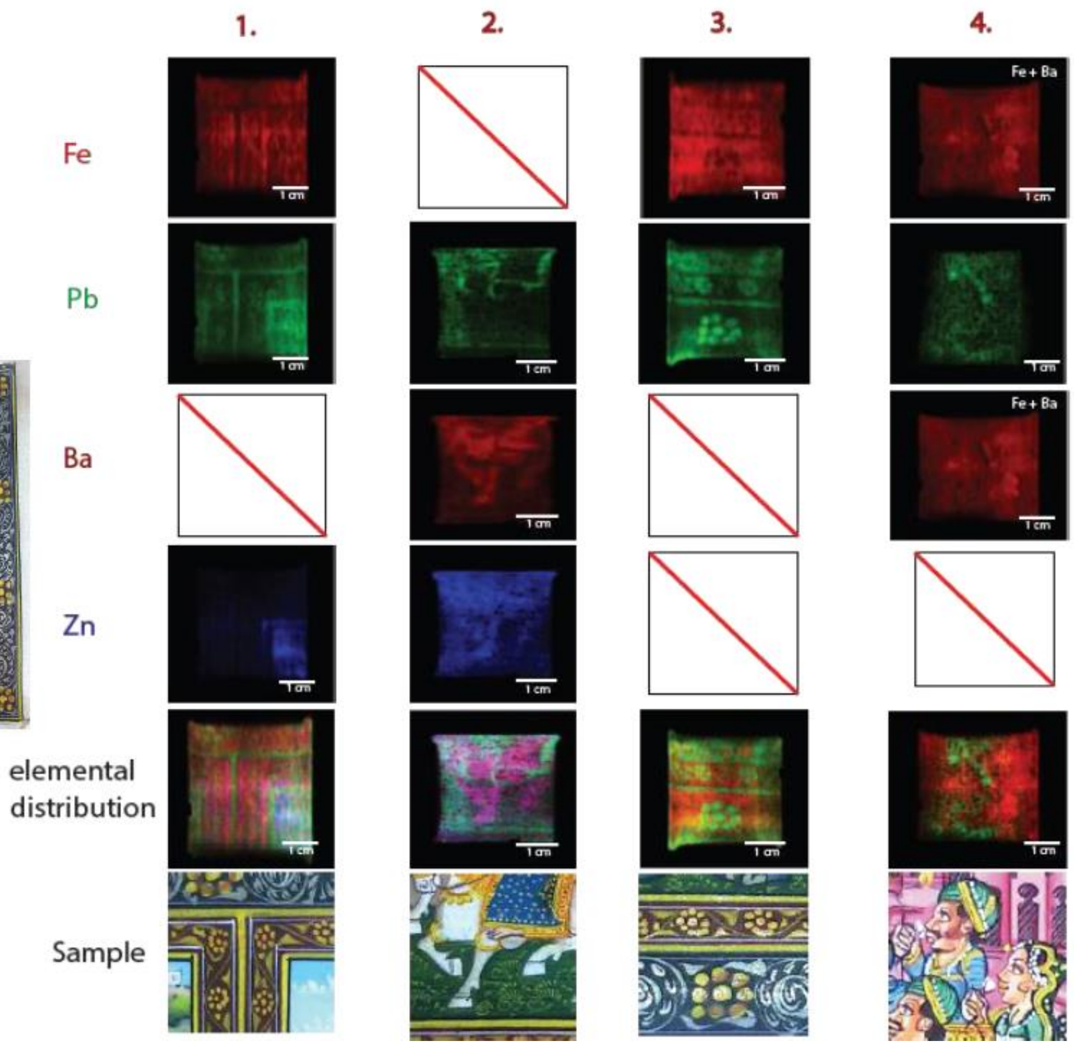

X-RAY TRANSMISSION IMAGE:




*A.L.M. Silva et al, Spectrochimica Acta B86(2013)115*

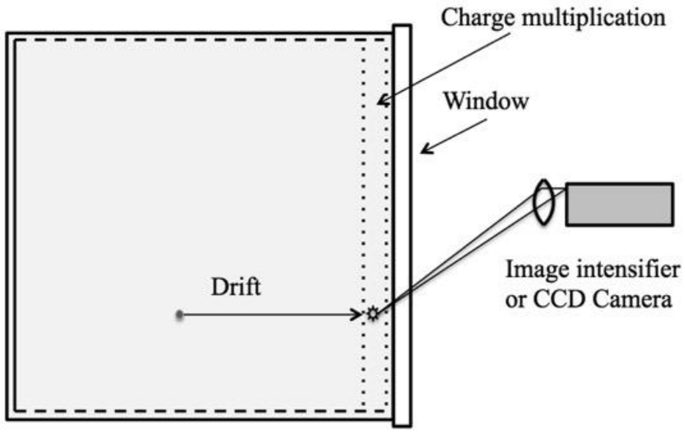
# ENERGY-RESOLVED X-RAY FLUORESCENCE

Indian Miniature

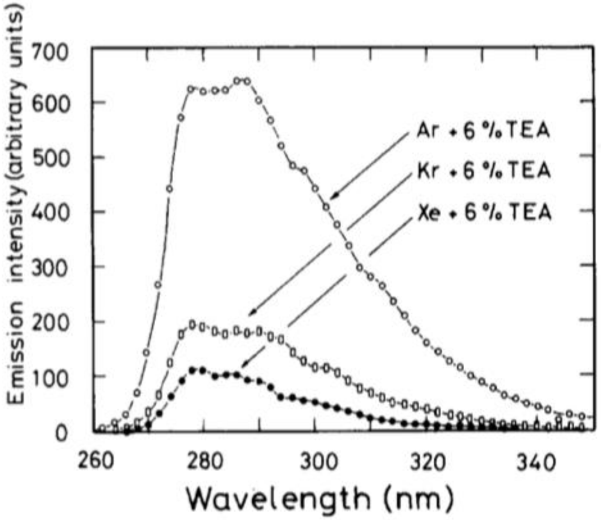


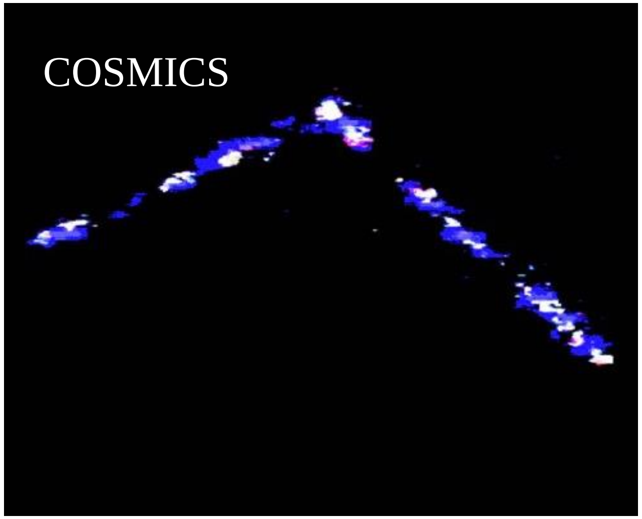

J. Veloso, RD51 Special Workshop on Photon detection (CERN, 2015)

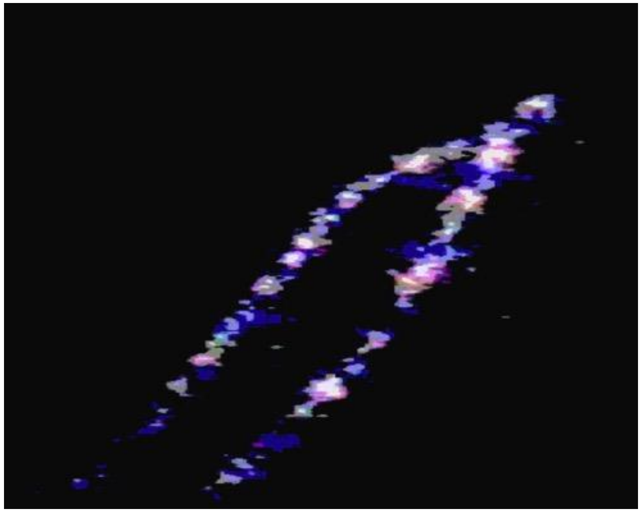
IMAGING CHAMBER (1987)




TRIETHYLAMINE (TEA):
INTERNAL WAVELENGTH SHIFTER



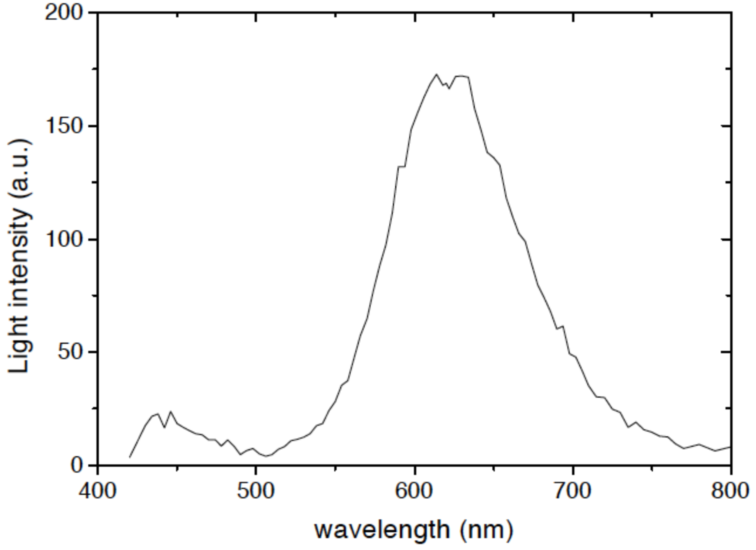



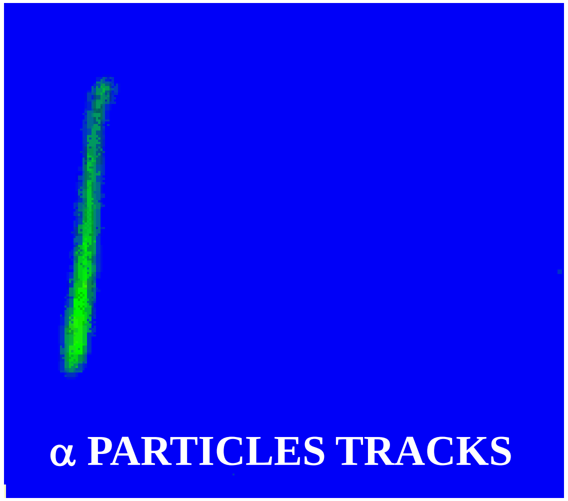



*G. Charpak, J.-P. Fabre, F. Sauli and M. Suzuki, Nucl. Instr. and Meth. A258(1987)177*

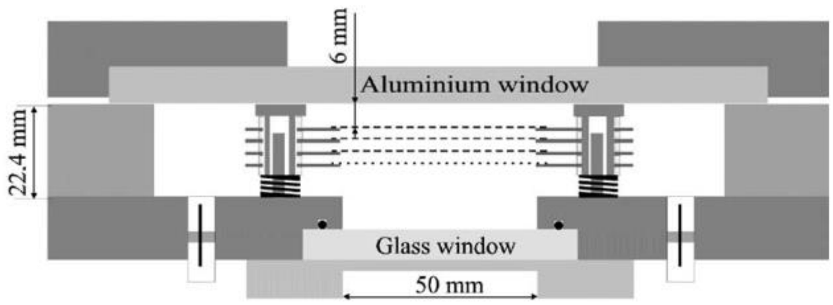
# OPTICAL IMAGING (2002)

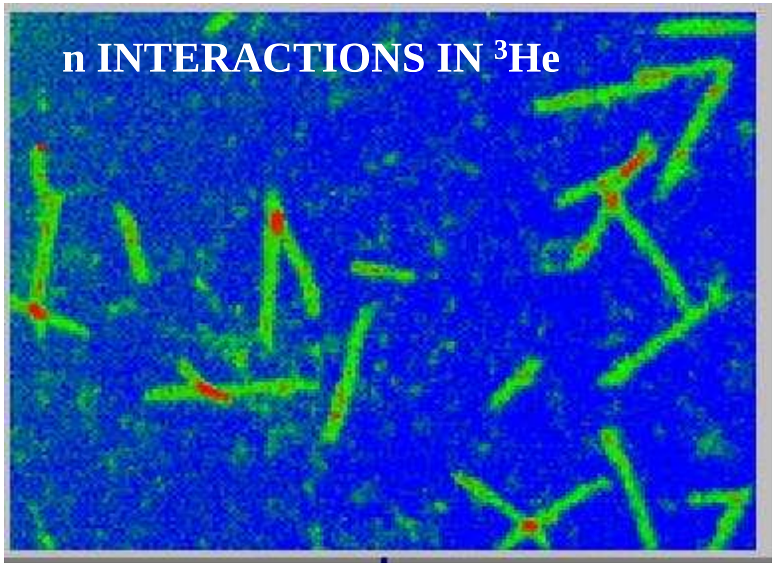
CARBON TETRAFLUORIDE SCINTILLATION:



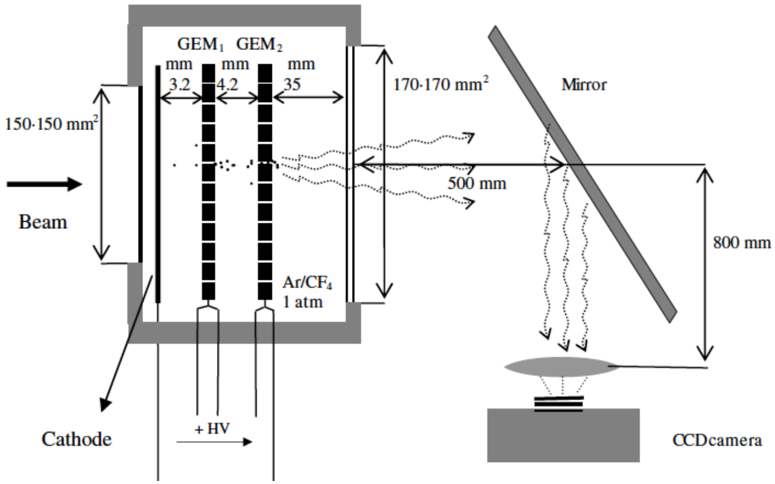

He-$CF_4$ GAS FILLING



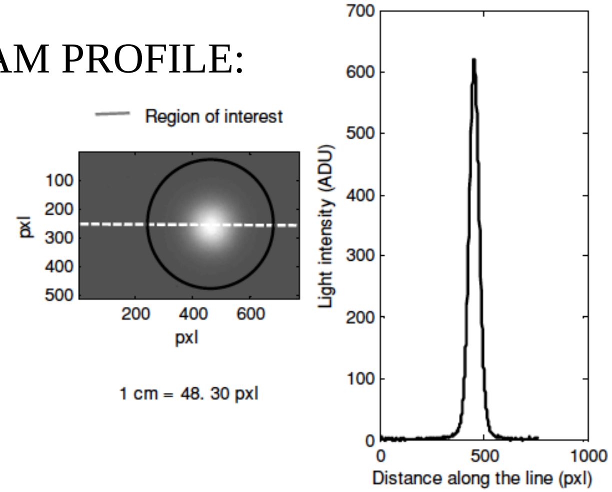



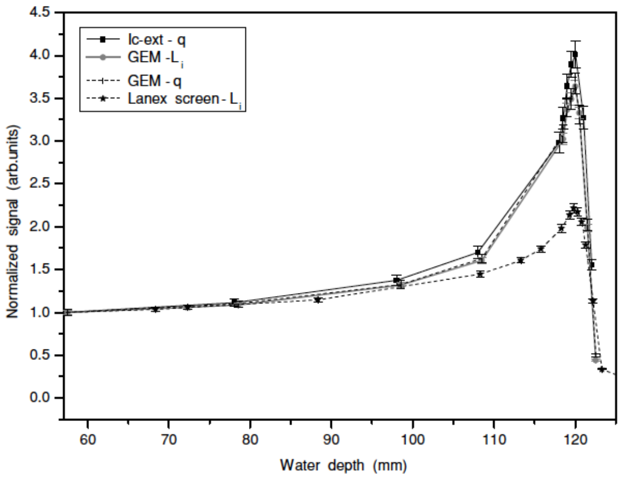

*F.A.F. Fraga, et al, Nucl. Instr. and Meth. A478(2002) 357*

## DOUBLE GEM WITH OPTICAL DETECTION



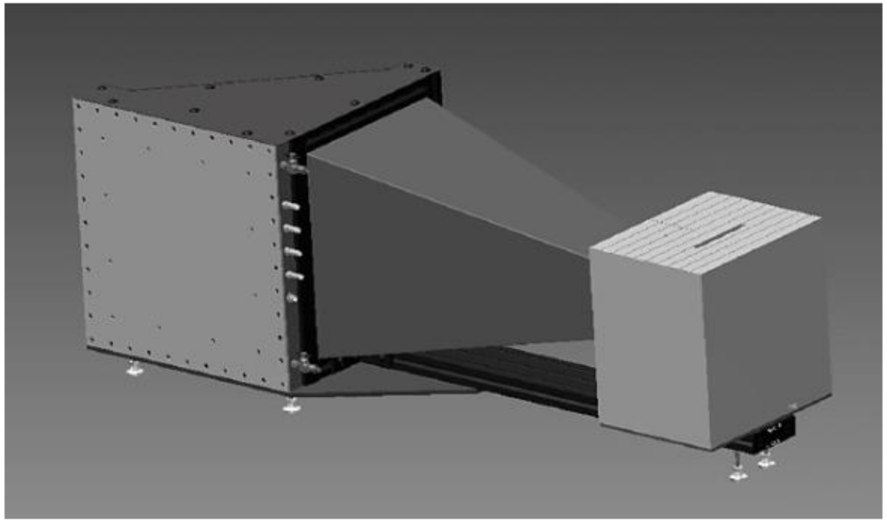

## BEAM PROFILE:



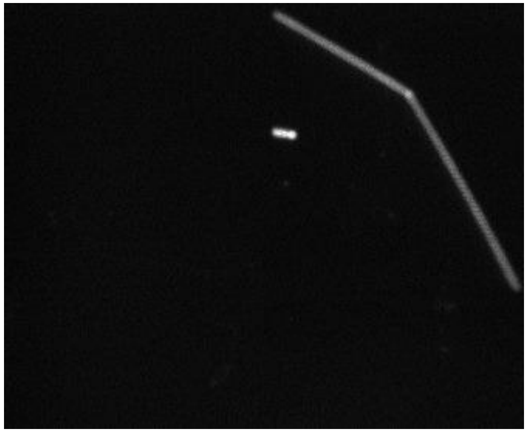

*E. Seravalli et al, Phys. Med. Biol. 53(2008)4651*

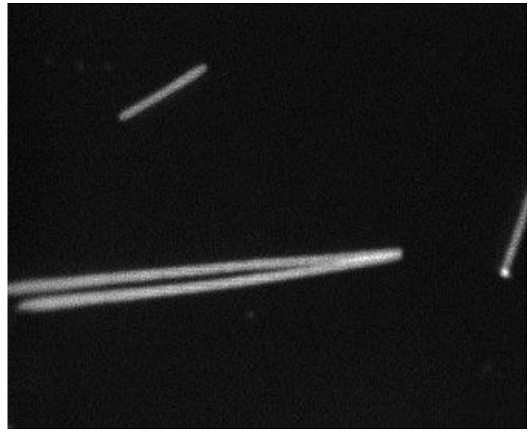
**Phenix Medical OptiGEM Dose Imaging Detector User Manual**

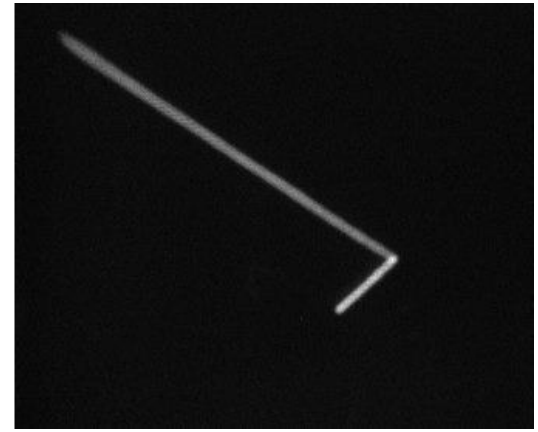


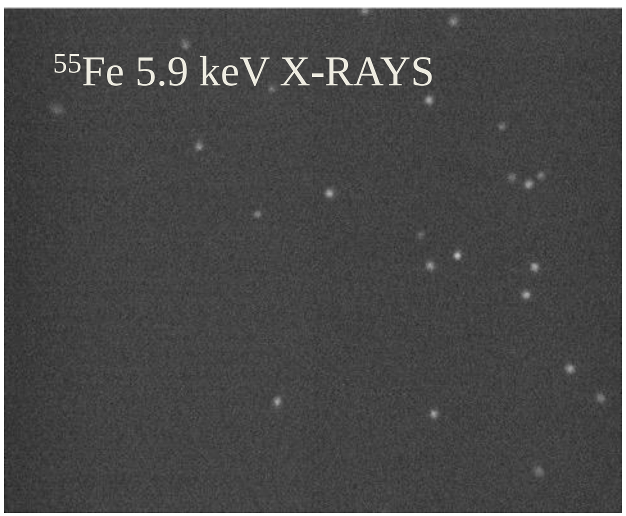
# OPTICAL IMAGING

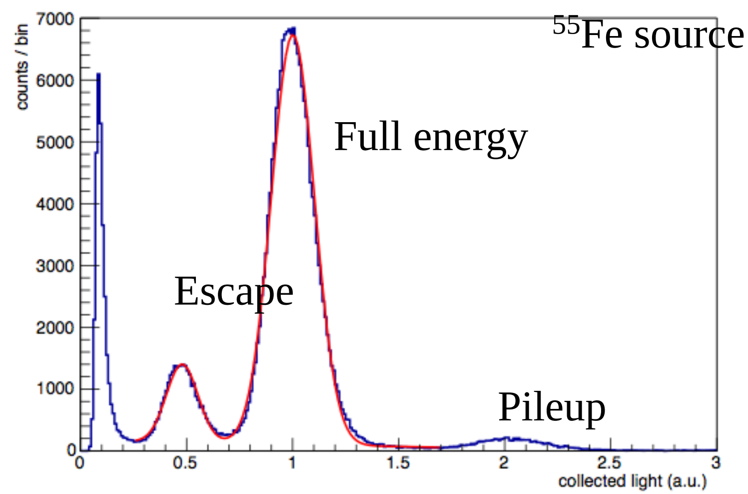
α PARTICLES FROM $^{220}$Rn and $^{216}$Po





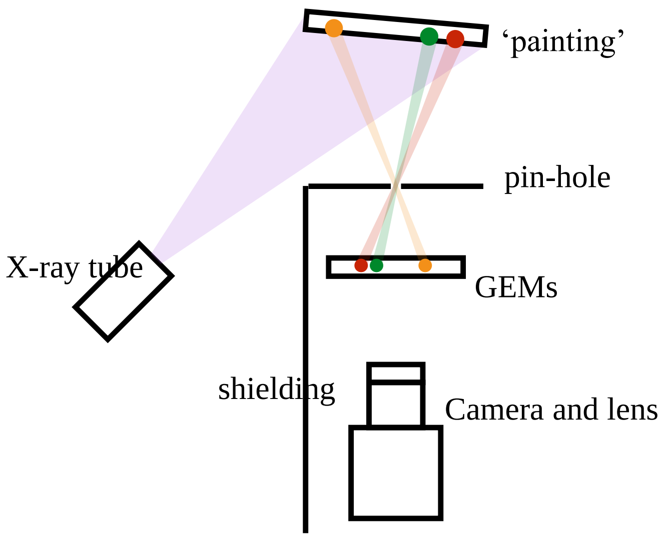


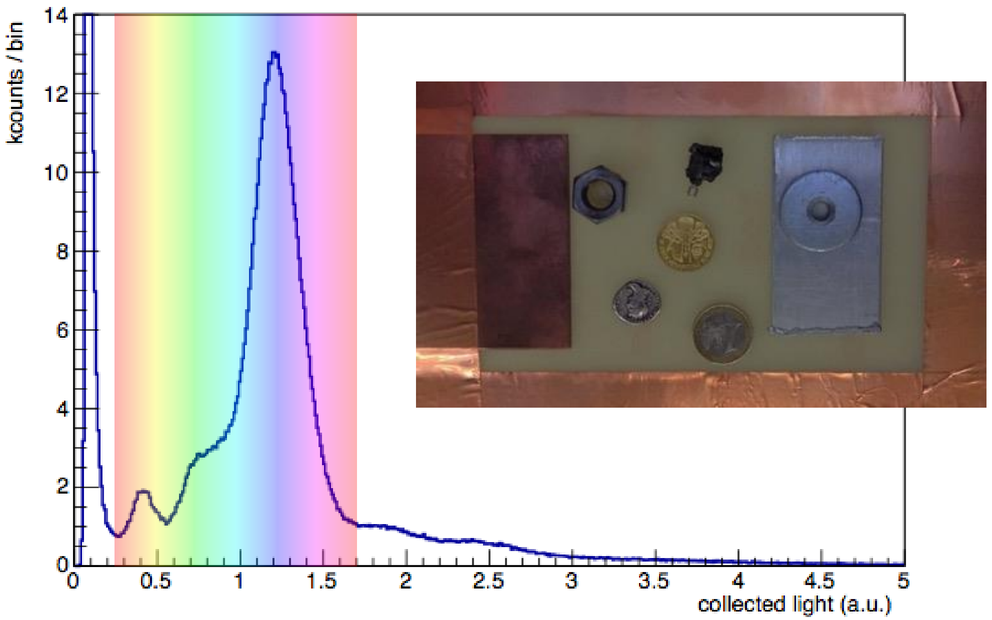


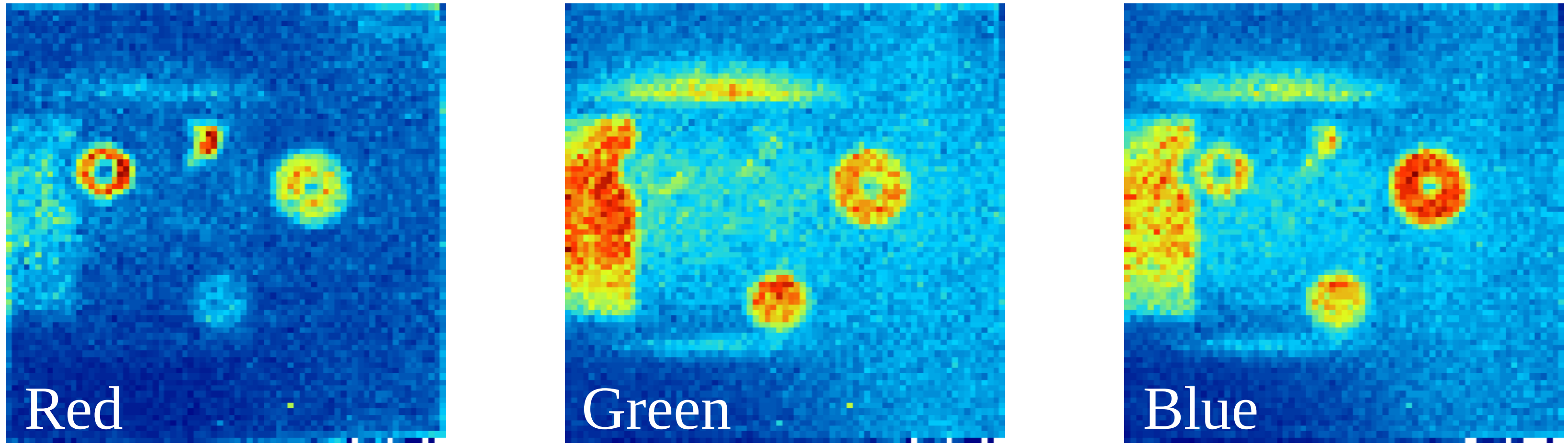




*F. Resnati , EP Detector Seminar (CERN, April 29, 2016)*

# ENERGY RESOLVED FLUORESCENCE ANALYSIS

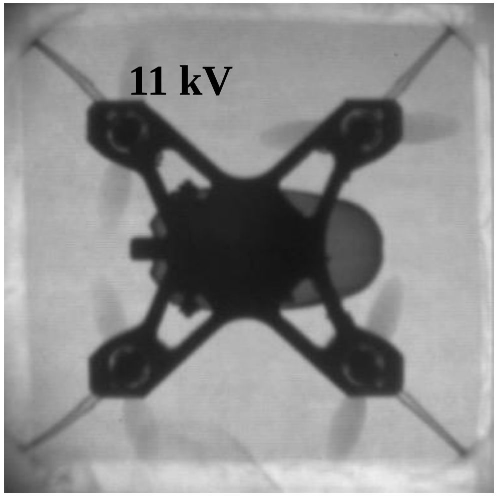


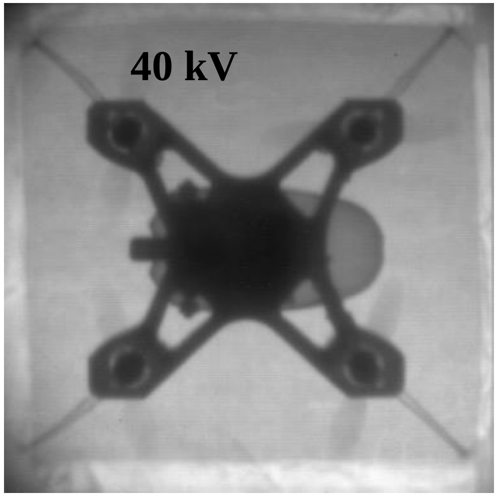



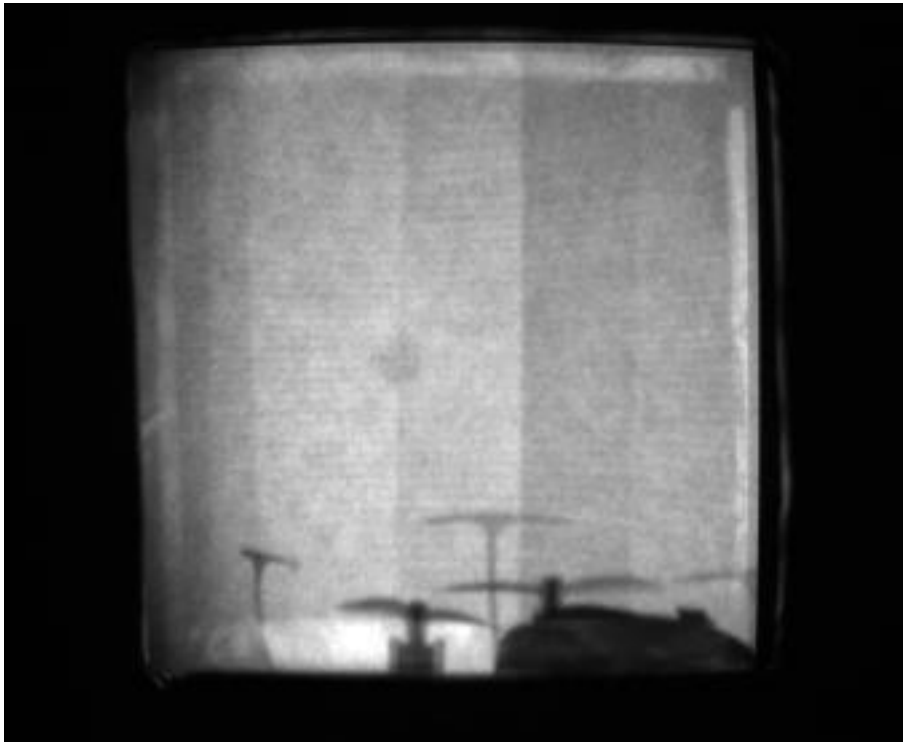

F. Resnati, MPGD Workshop (Aveiro, 2016)

SMALL DRONE-IN-THE BOX



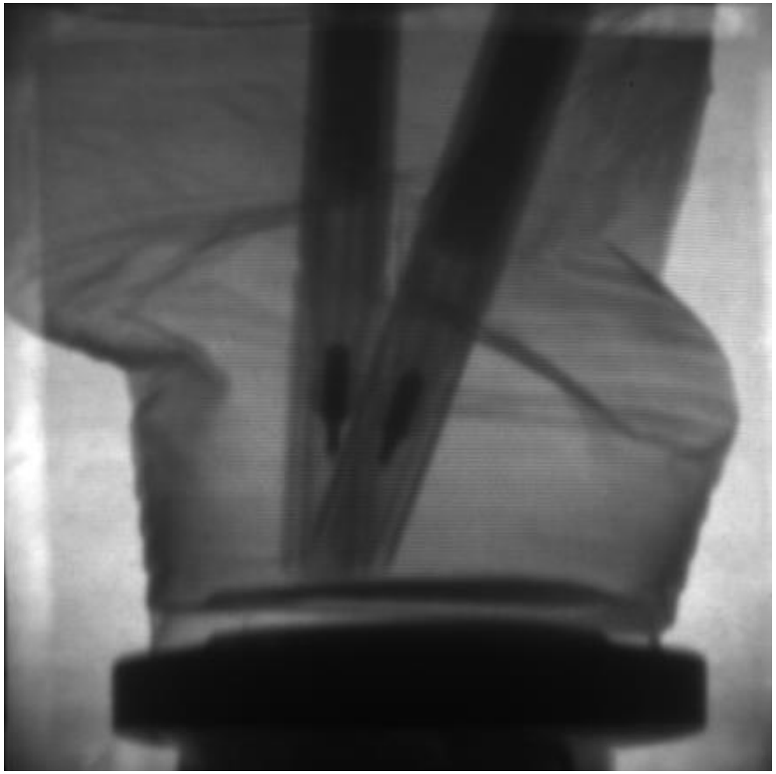

JUMPING DRONE RADIOGRAPHY (30 keV)



*F. Resnati, MPGD Workshop (Aveiro, 2016)*

# X-RAY TOMOGRAPHY

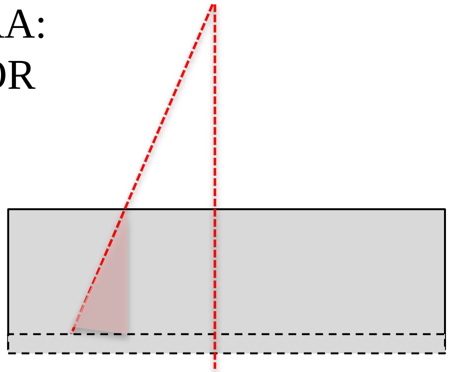
IMAGE -> SINOGRAMS -> FILTERED BACK PROJECTION -> 3D IMAGE



GDD

*F. Resnati, MPGD Workshop (Aveiro, 2016)*

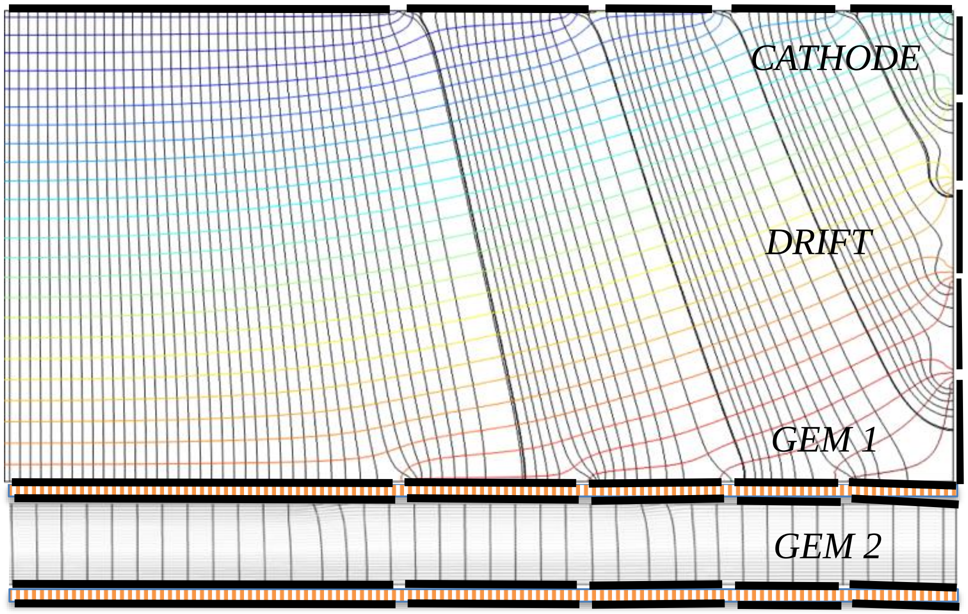
PINHOLE CAMERA:
PARALLAX ERROR



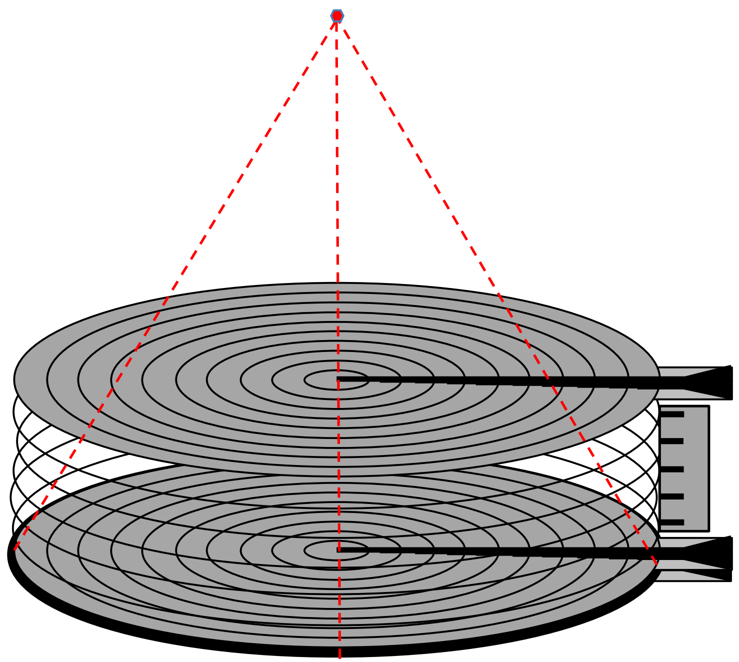
PLANISPHERICAL GEM

CONCENTRIC GRADED POTENTIAL RINGS ON CATHODE AND GEM ELECTRODES

RADIAL CONVERSION AND DRIFT:



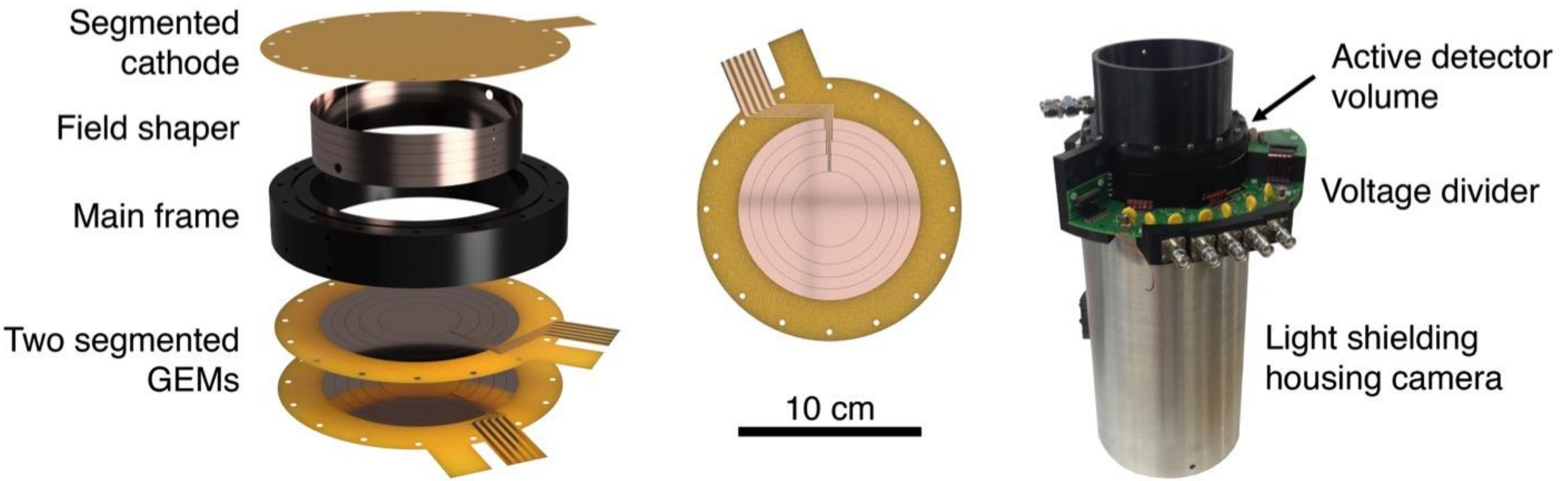

*Computed with COMSOL Multiphysics*



*F. Sauli, PCT Patent WO99/21211*

CAD-CAM DESIGN
3-D PRINTING OF MOST PARTS
SEGMENTED GEMS MANUFACTURED AT CERN (R. De Oliveira)

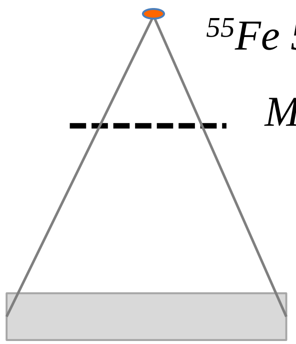
10 cm Ø    10 cm FOCUS (ADJUSTABLE)



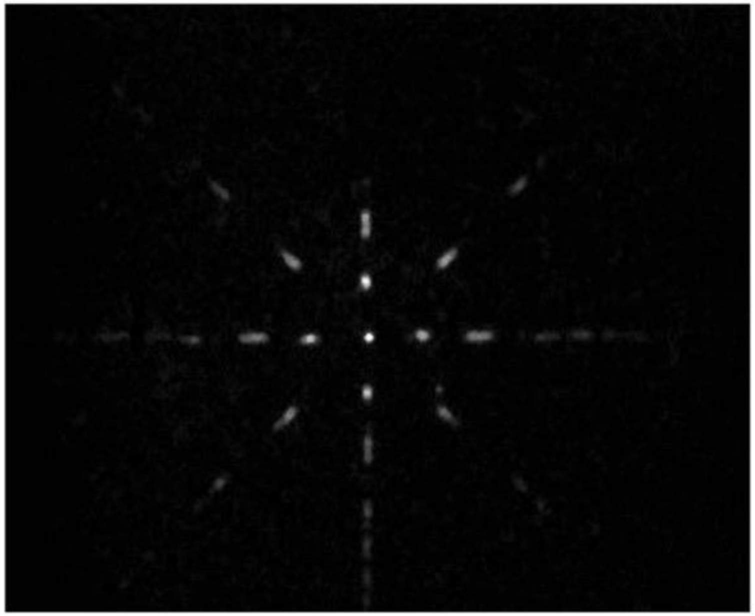

... F. Brunbauer.....M. Van Stenis.....

# PLANISPHERICAL GEM

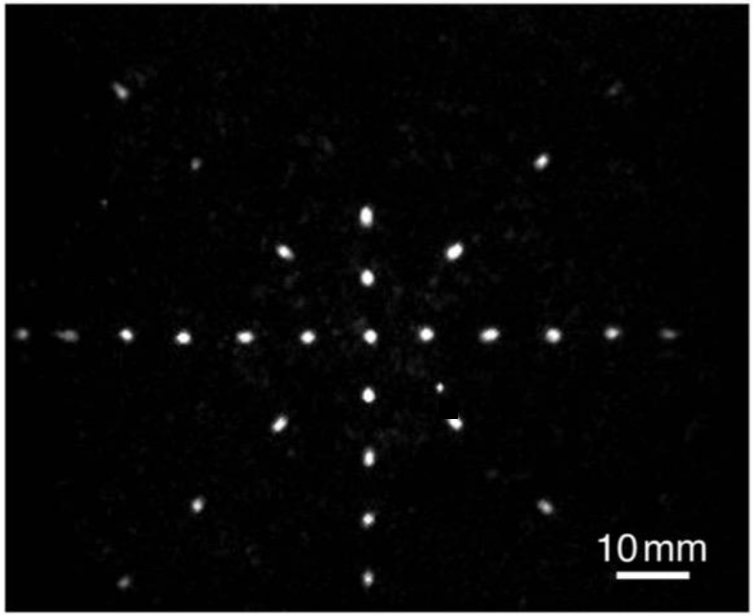
MASK WITH 1 mm Ø HOLES PATTERN




UNIFORM DRIFT FIELD



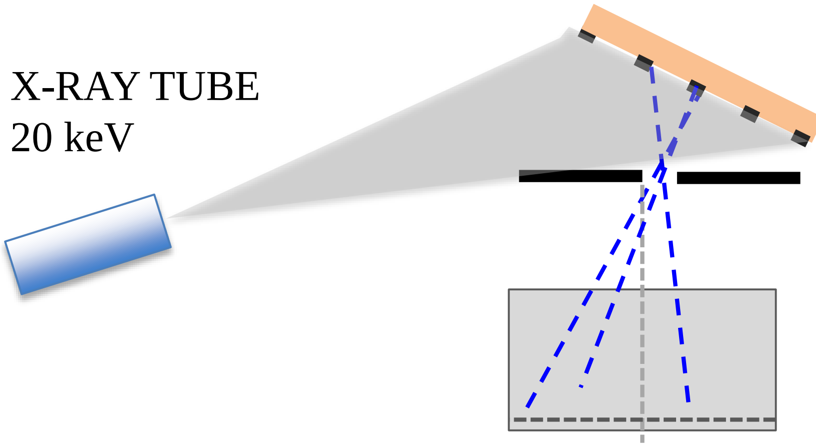
RADIAL DRIFT FIELD

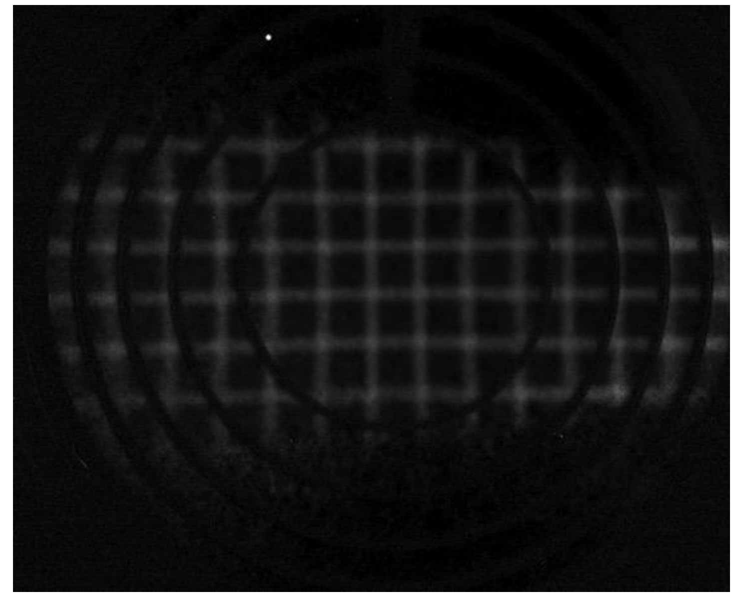


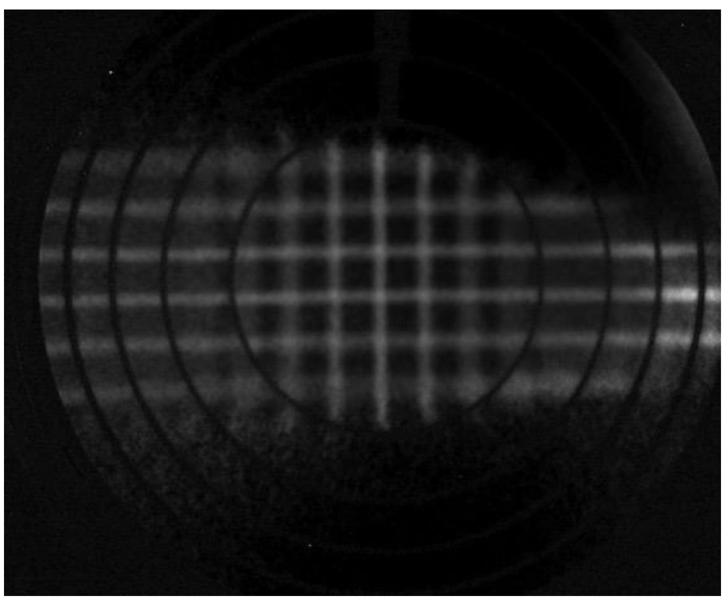

*F. Sauli, MPGD Workshop (Aveiro 2016)*

FLUORESCENCE IMAGE OF A COPPER MESH 1mm STRIPS AT 5 mm PITCH

X-RAY TUBE
20 keV







*Florian Brunbauer, October 20*

# AND IF YOU WISH TO KNOW MORE.....

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journal homepage: www.elsevier.com/locate/nima

ELSEVIER

## The gas electron multiplier (GEM): Operating principles and applications

Fabio Sauli

*CERN, Geneva, Switzerland*

ARTICLE INFO

Available online 7 August 2015

*Keywords:*
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GEM
Gaseous radiation detectors

ABSTRACT

Introduced by the author in 1997, The Gas Electron Multiplier (GEM) constitutes a powerful addition to the family of fast radiation detectors; originally developed for particle physics experiments, the device and has spawned a large number of developments and applications; a web search yields more than 400 articles on the subject. This note is an attempt to summarize the status of the design, developments and applications of the new detector.


**Thanks for your attention!**