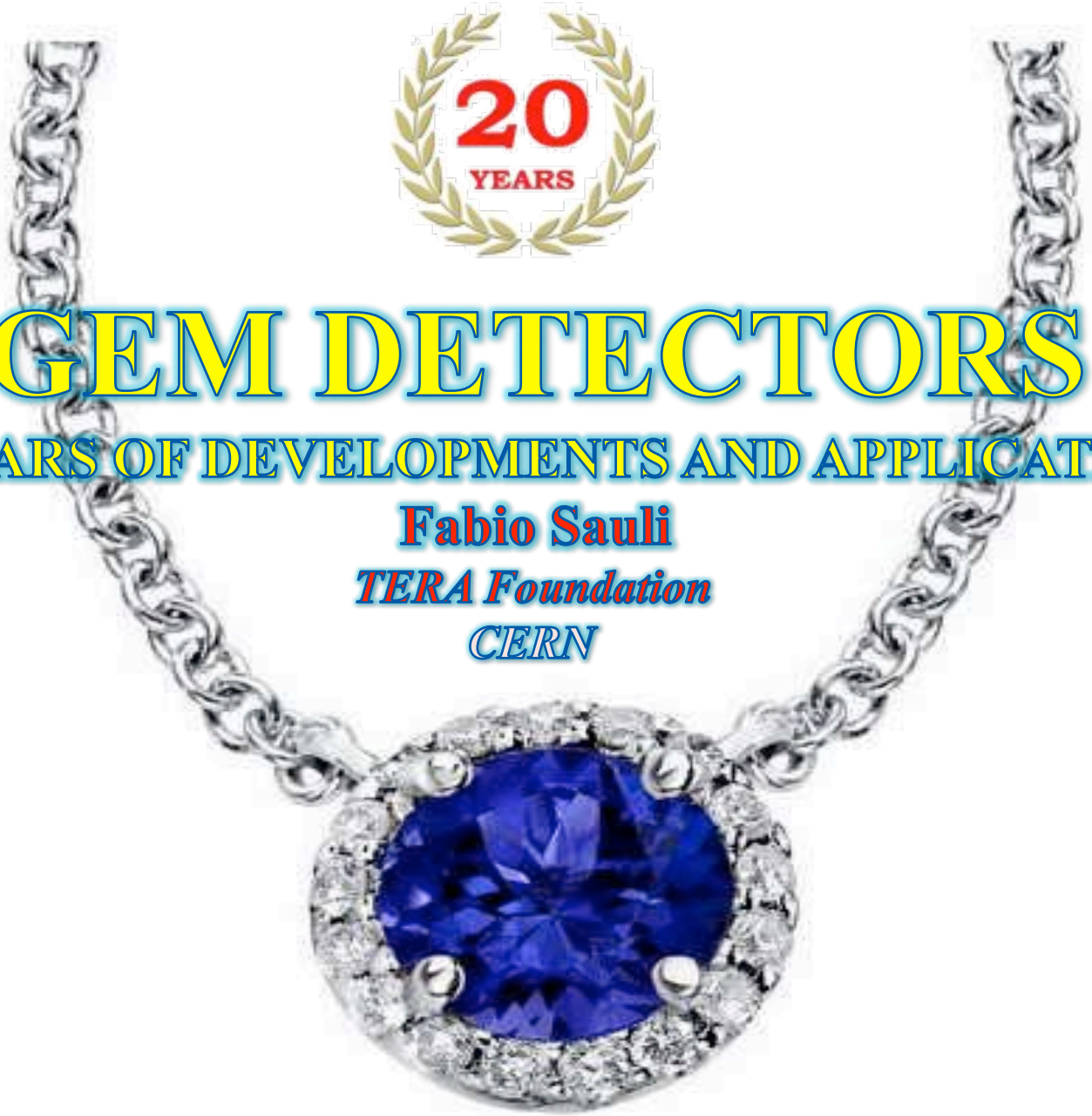


GEM DETECTORS

20 YEARS OF DEVELOPMENTS AND APPLICATIONS

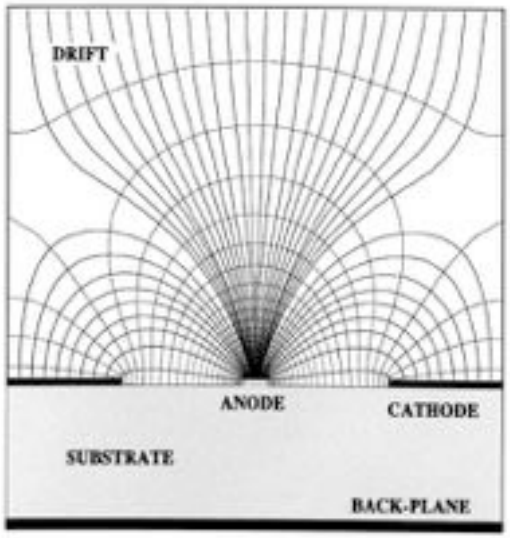
Fabio Sauli

TERA Foundation

CERN

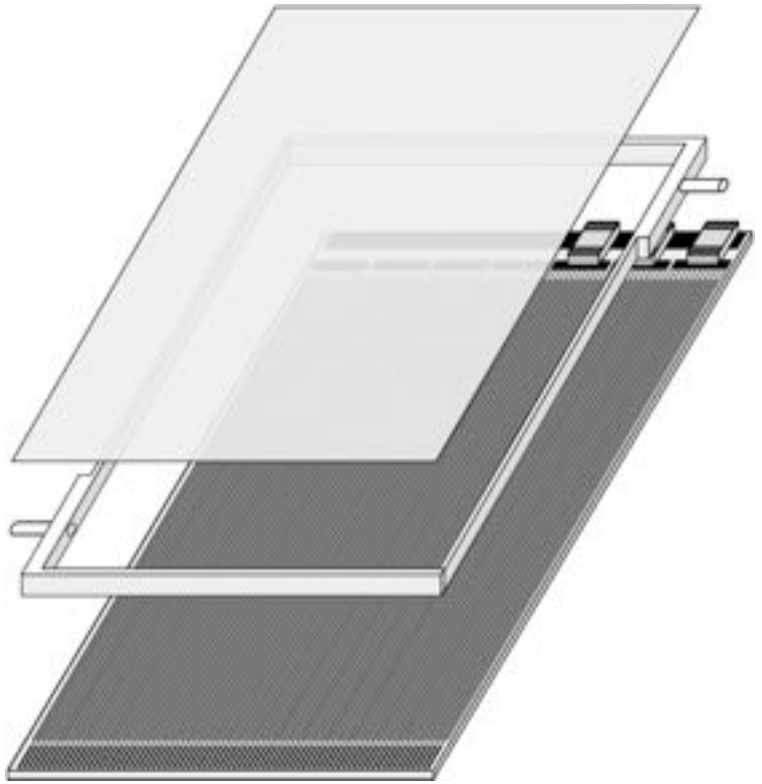
1988: MICRO-STRIP GAS COUNTER (MSGC)

THIN METAL STRIPS ON GLASS SUBSTRATE



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

LIGHT AND COMPACT DETECTOR CONSTRUCTION



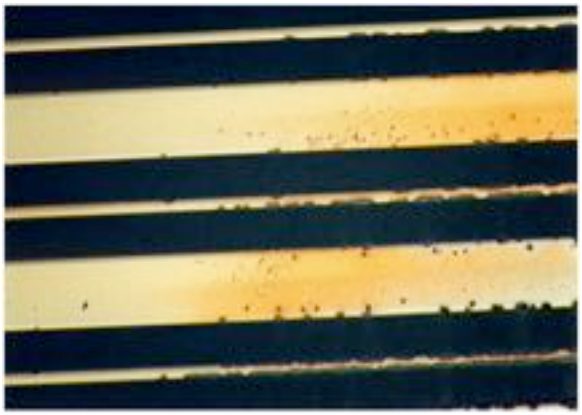
J. Bohm et al, Nucl. Instr. and Meth. A360(1995)34

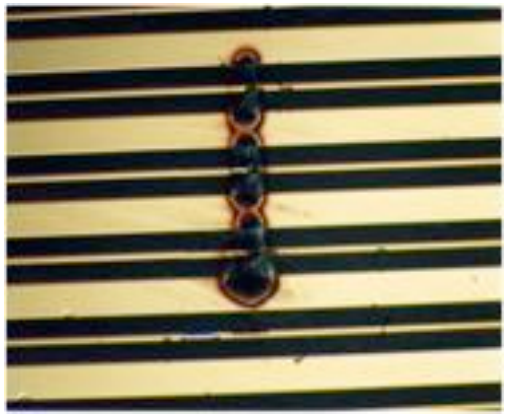
RATE CAPABILITY ~ 1 MHz/mm^2
POSITION ACCURACY ~ 40 µm
2-TRACK RESOLUTION ~ 500 µm

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

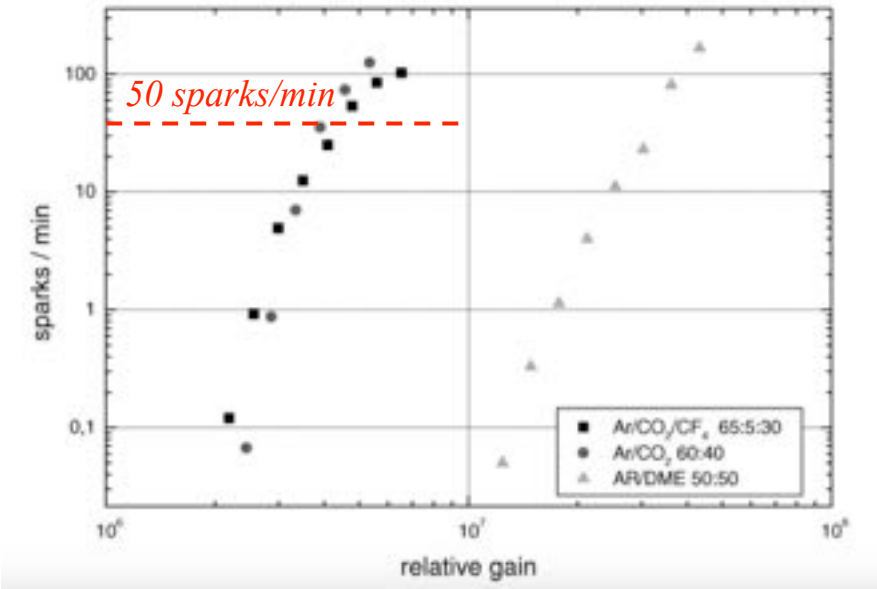
MSGC: DISCHARGE PROBLEMS

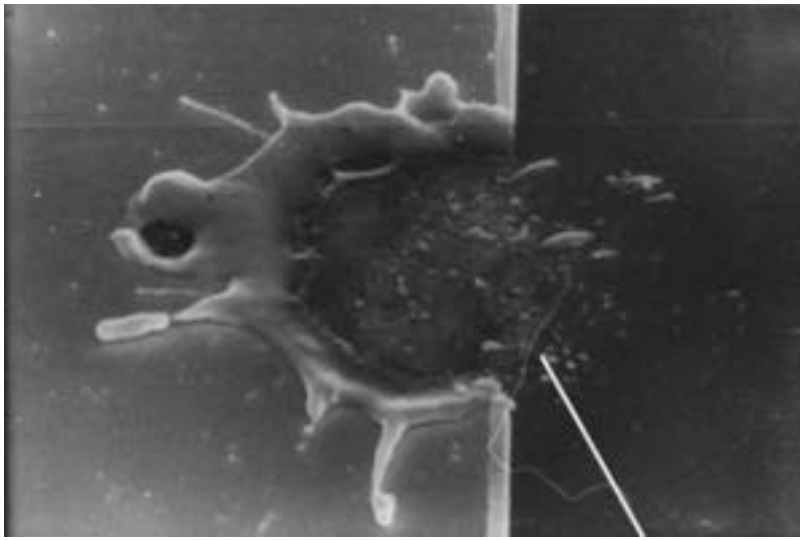
MILD OR SERIOUS
DISCHARGE PROBLEMS!





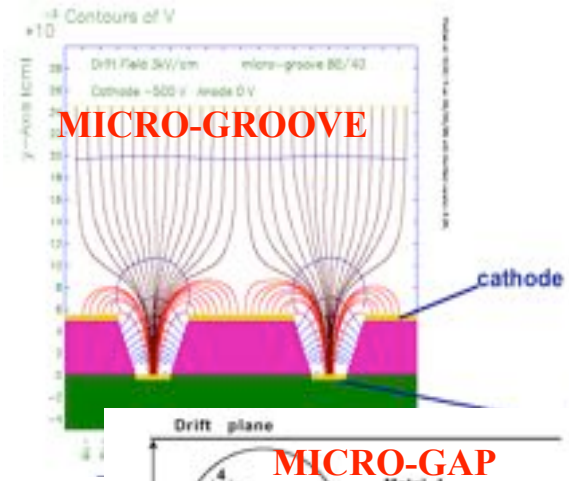
HERA-B MSGC INNER TRACKER

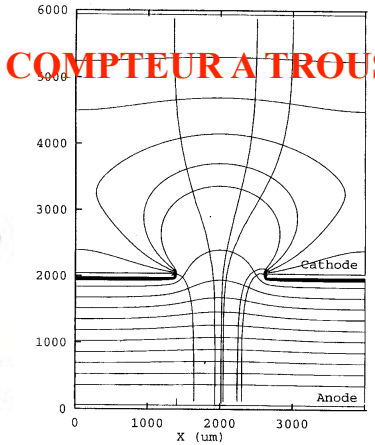


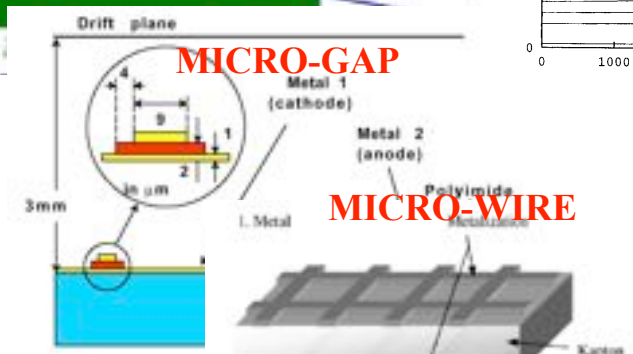


S. Keller et al, Nucl. Instr. and Meth. A419(1998)382

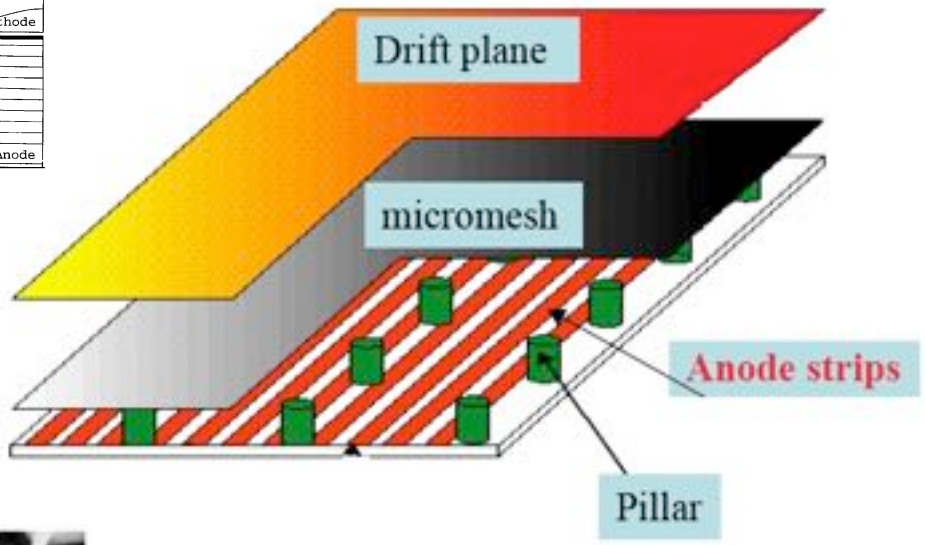
~ 1990 TO PRESENT: NEW DEVELOPMENTS







MICROMEGAS

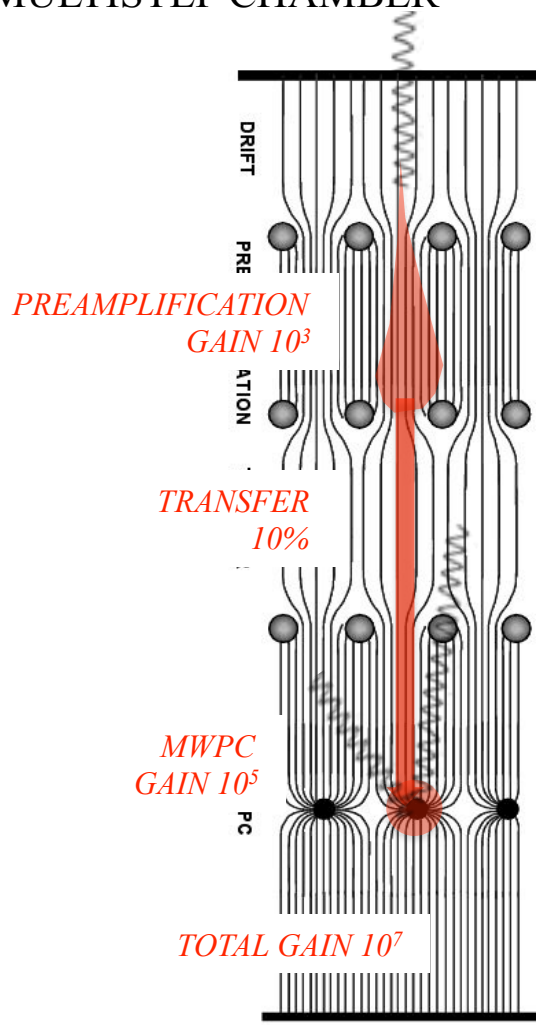


Y. Giomataris,
Nucl. Instr. and Meth. A419(1998)239

1978: THE MULTISTEP CHAMBER (MSC)

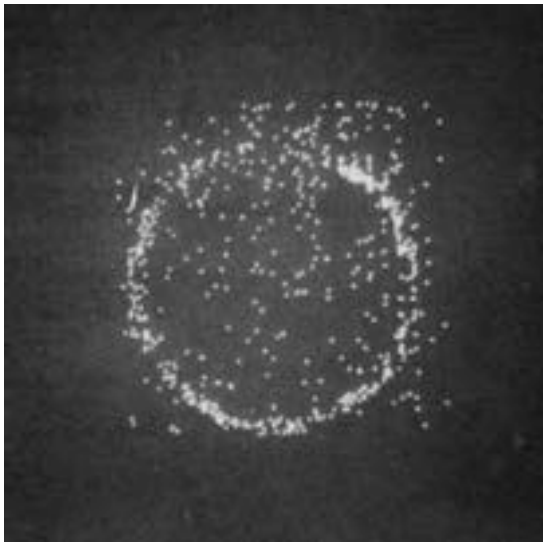
UV PHOTONS DETECTION (RICH): MWPC WITH PHOTOSENSITIVE GAS (TEA)

MULTISTEP CHAMBER



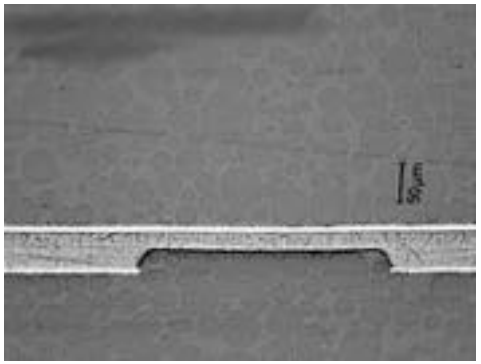
SINGLE ELECTRON DETECTION
SIMULATED CHERENKOV RING
(COLLIMATED UV SOURCE)

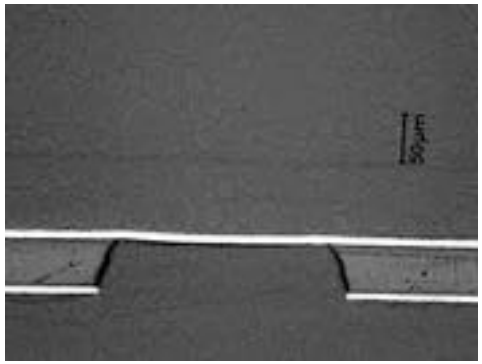
E605 RICH

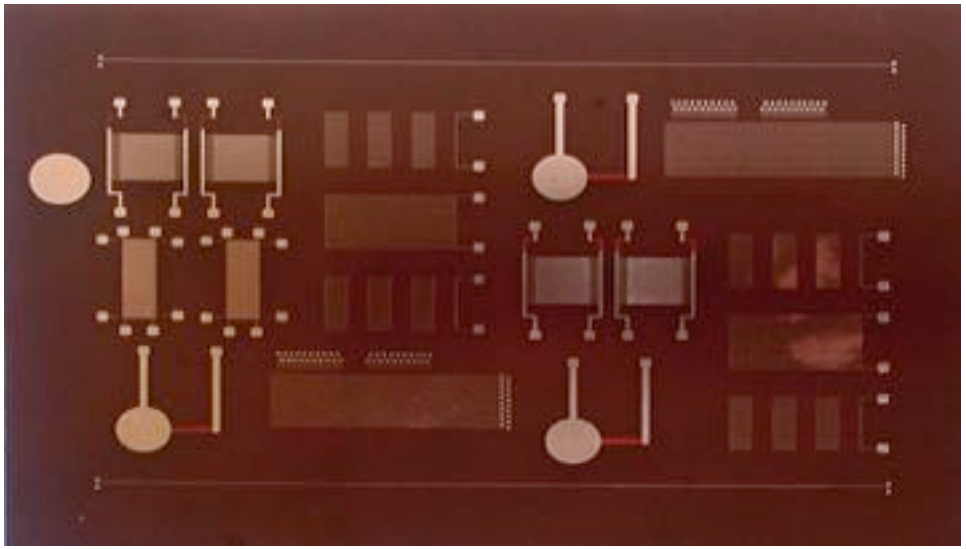


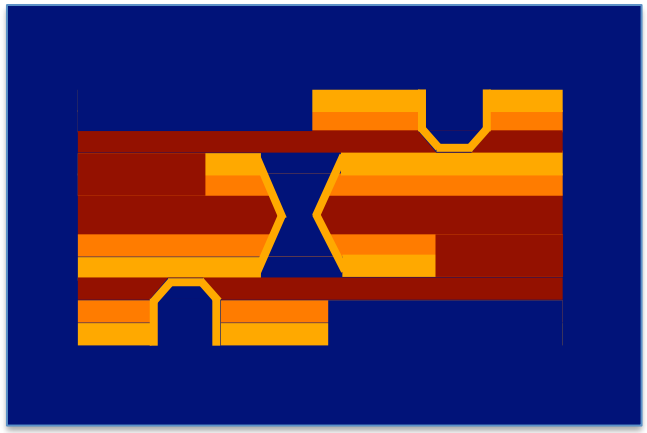
G. Charpak and F. Sauli, Phys. Lett. 78B(1978)723

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



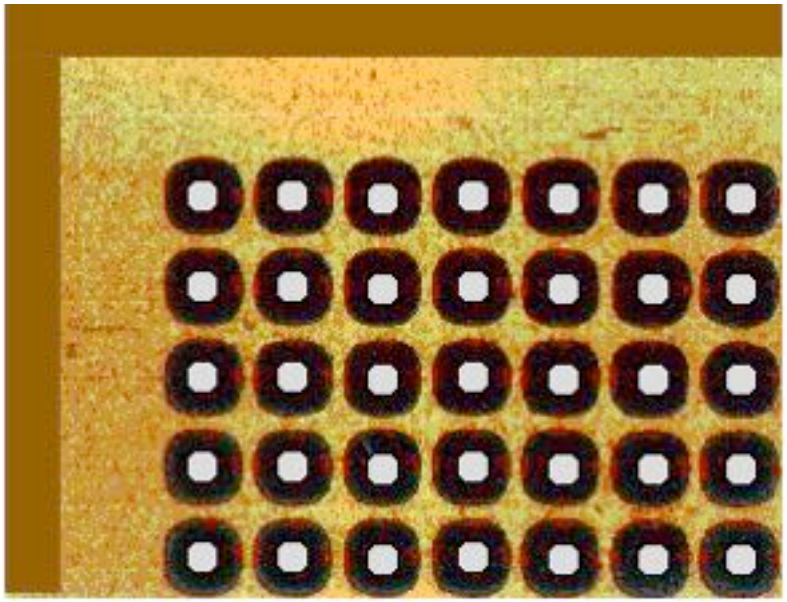


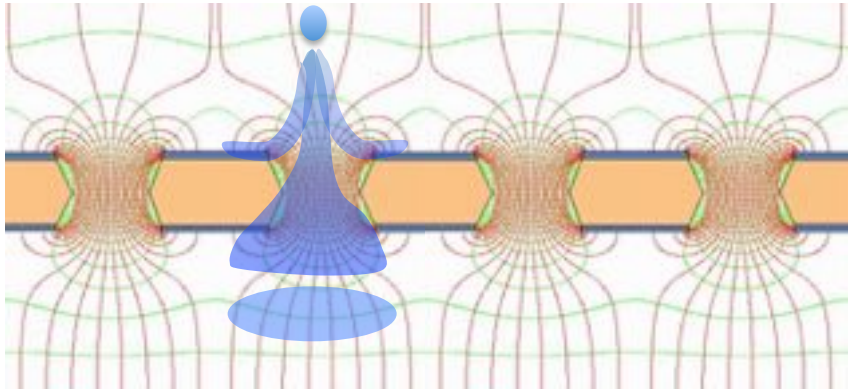




1996: MSC+μVIAS => GEM

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

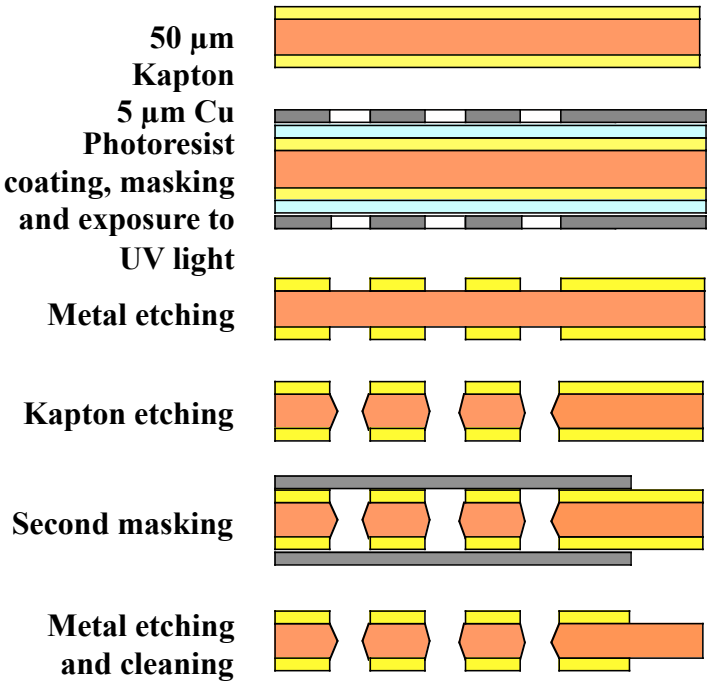




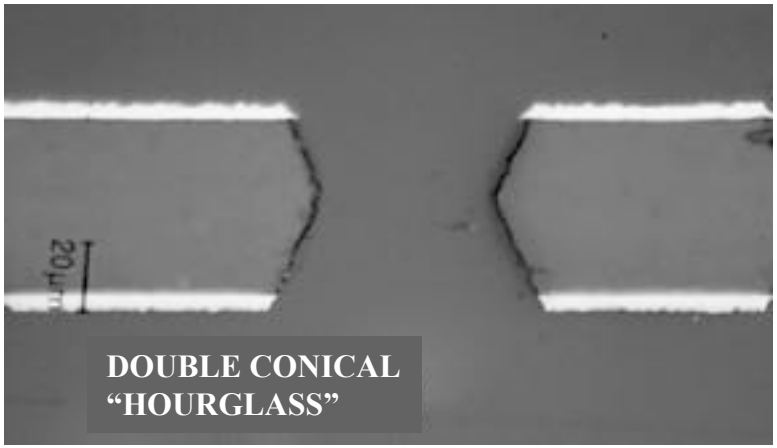
PRESENTED AT:
IEEE Nuclear Science Symposium & Medical Imaging Conference
Anaheim, CA November 3-9, 1996

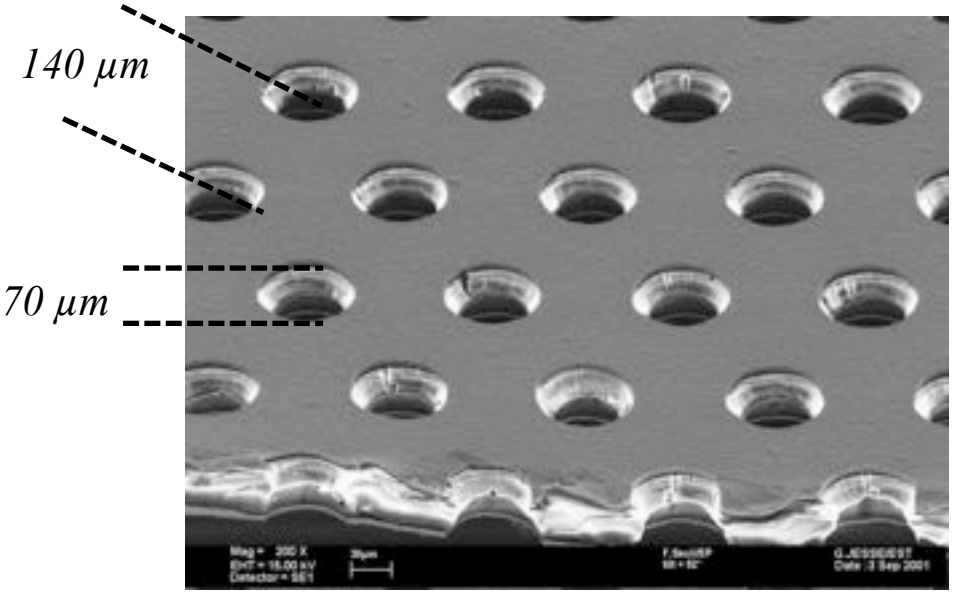
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

DOUBLE MASK PHOTOLITHOGRAPHY



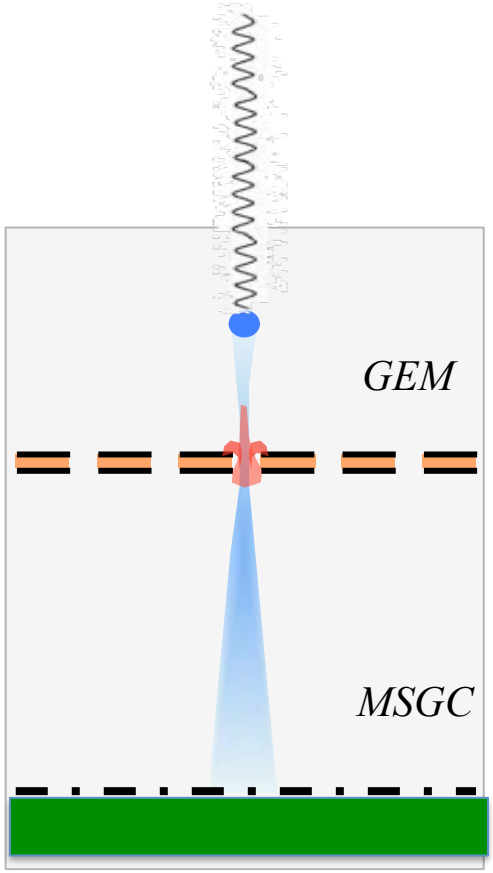
"STANDARD" GEM



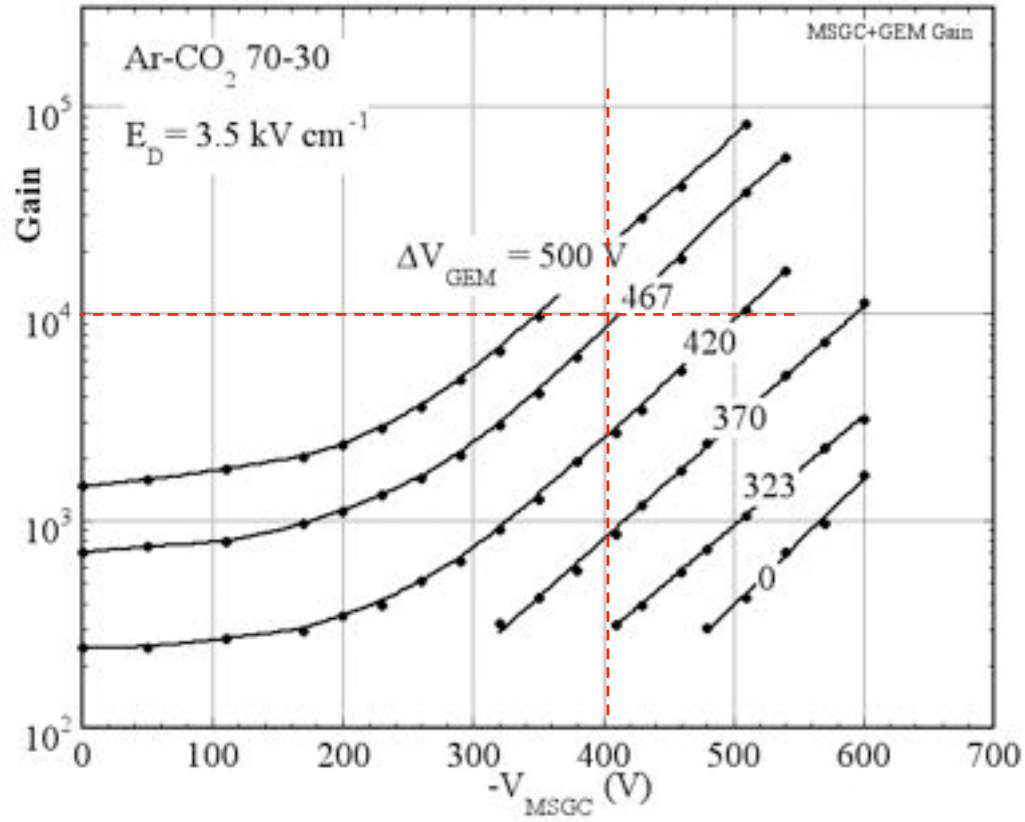


TWO-STEP DETECTOR

MSGC WITH GEM PREAMPLIFIER

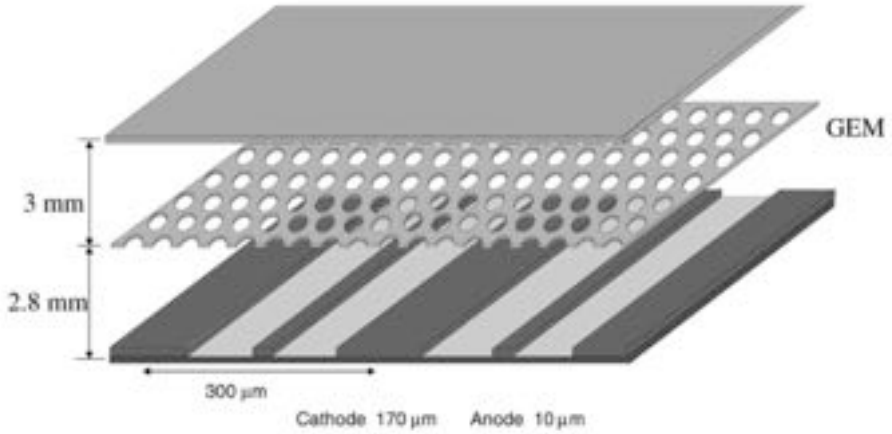


COMBINED GAIN CURVES

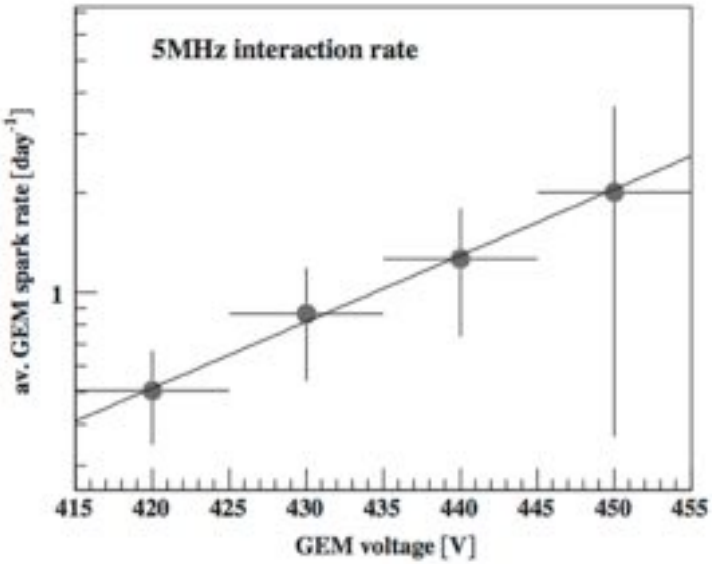


R. Bouclier et al, Nucl. Instr. and Meth. A396(1997)50

HERA-B MSGC+GEM

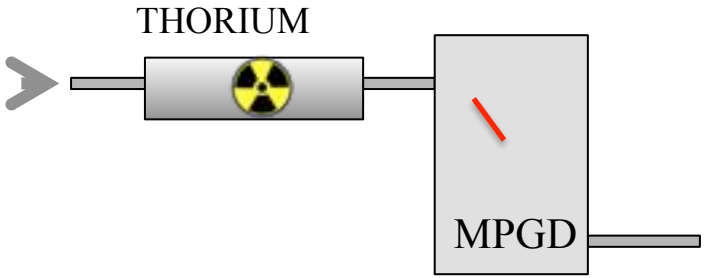


CERN's Printed Circuit Workshop (EST-DEM)

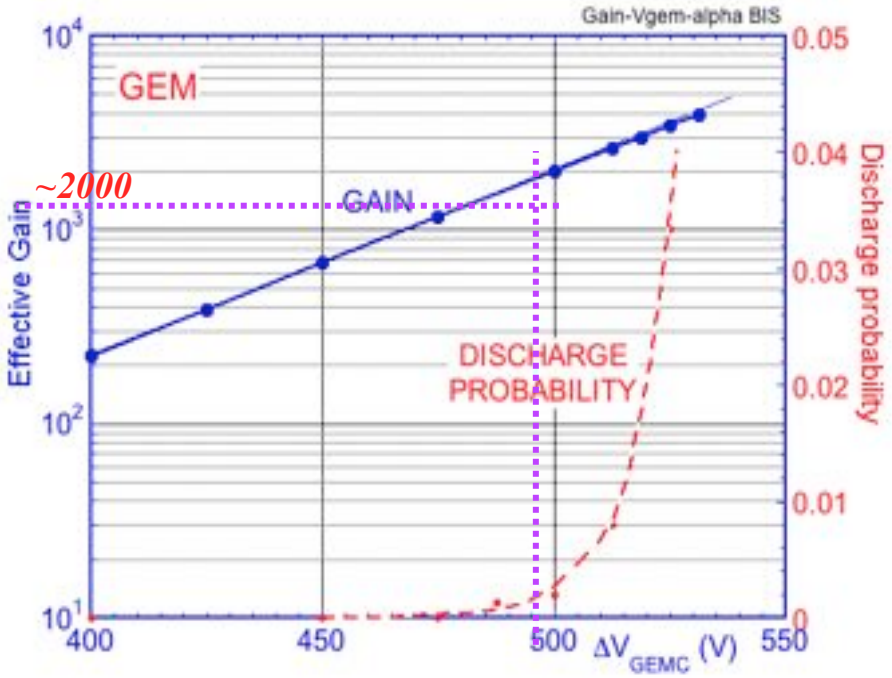


Bagaturia et al,
Nucl. Instr. and Meth. A490(2002)223

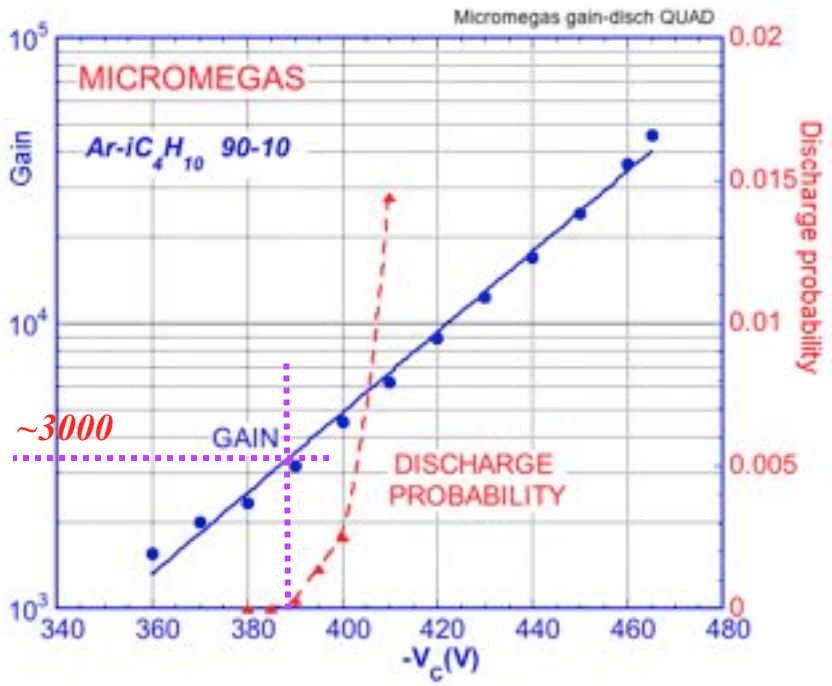
GASEOUS α SOURCE: $^{232}Th \rightarrow ^{232}Rn+\alpha$ (6.4 MeV) $\Delta E \sim 500$ keV $\sim 10^4$ e I^+



GEM:



MICROMEGAS:



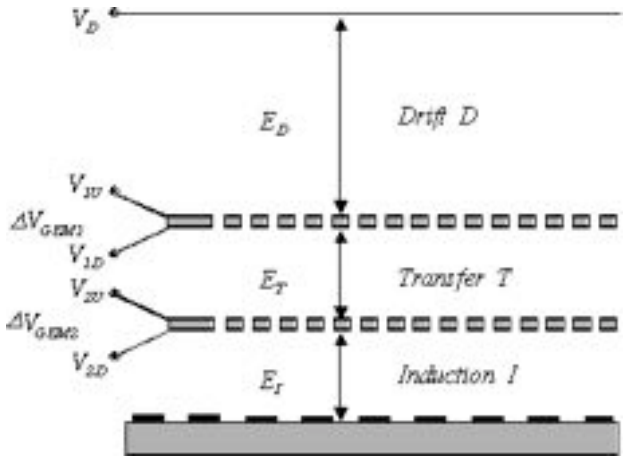
Q ~ $10^4.10^3 = 10^7$ e I^+

RAETHER LIMIT

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

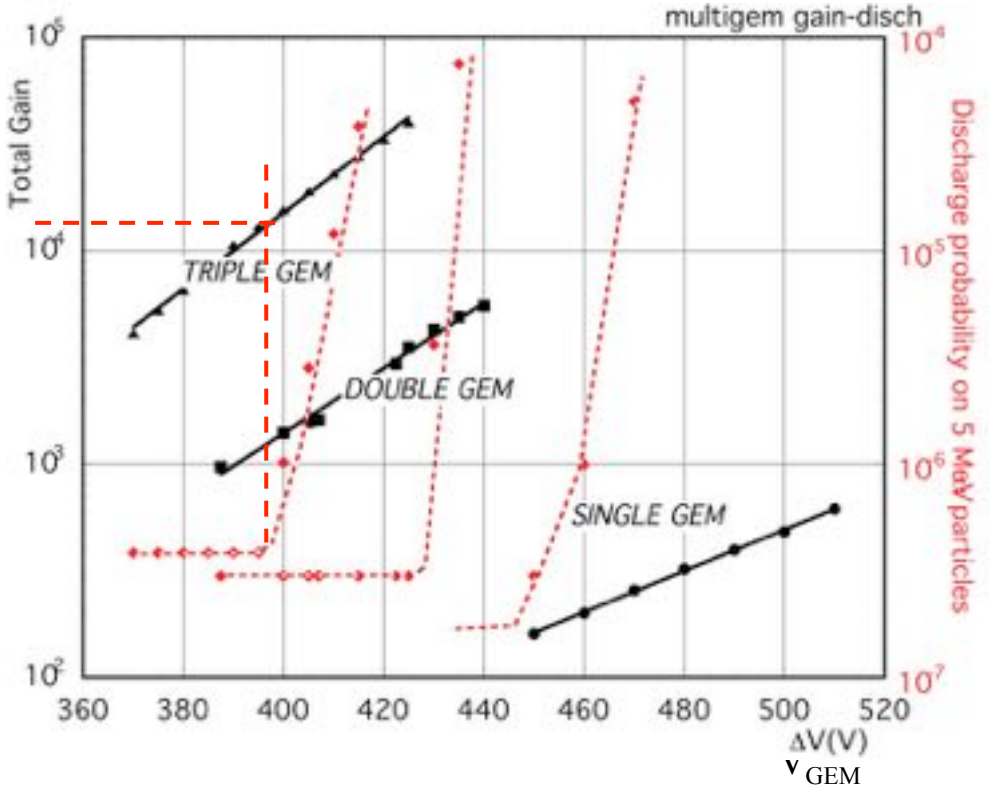
MULTI-GEM STRUCTURES

DOUBLE GEM



TRIPLE GEM

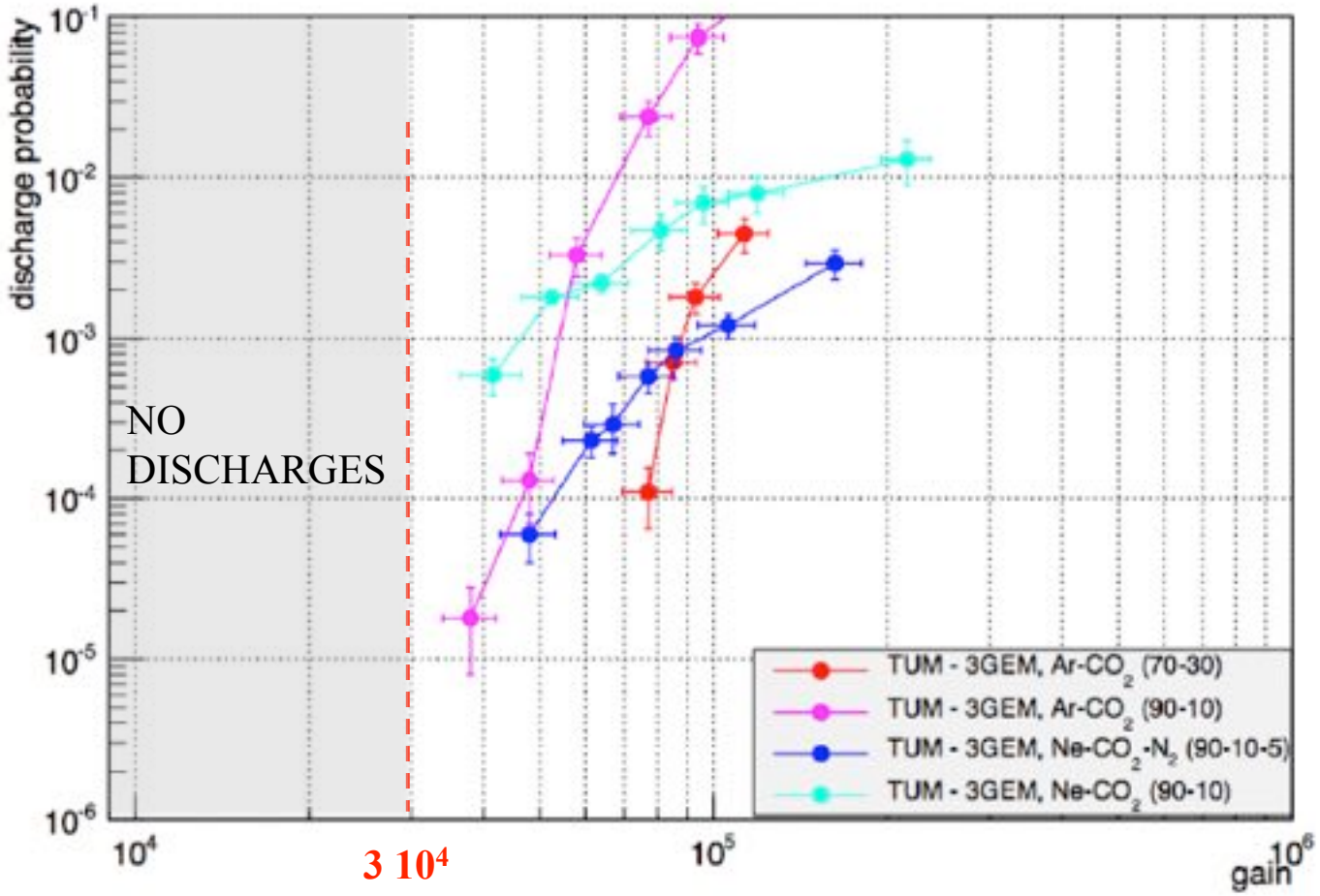
- HIGHER GAINS
- REDUCED ION BACKFLOW
- LOWER DISCHARGE PROBABILITY



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

DISCHARGE STUDIES - ALICE GEM TPC

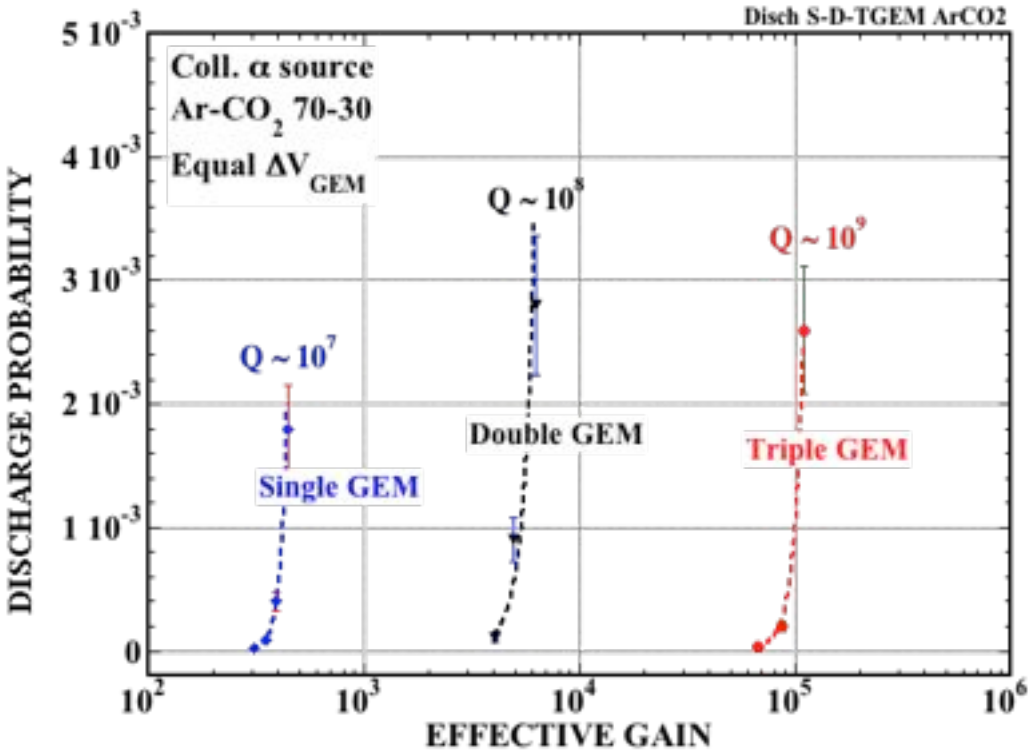
^{220}Rn INTERNAL α SOURCE TRIPLE GEM



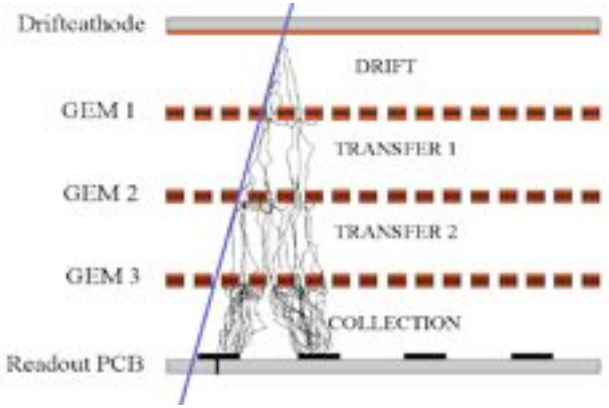
P. Gasik RD51Coll. Meeting (CERN 2016)

BACK TO MULTIGEM DISCHARGES

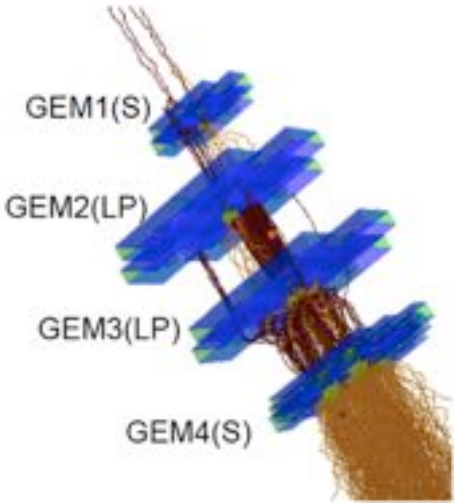
DISCHARGE PROBABILITY ON ~ MeV α



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



4-GEM SIMULATION (ALICE TPC)



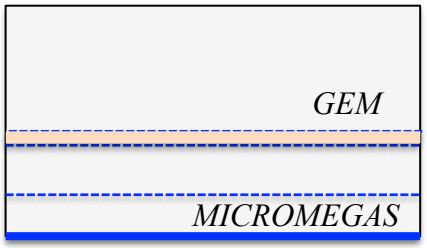
WHAT ABOUT THE RAETHER LIMIT?

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

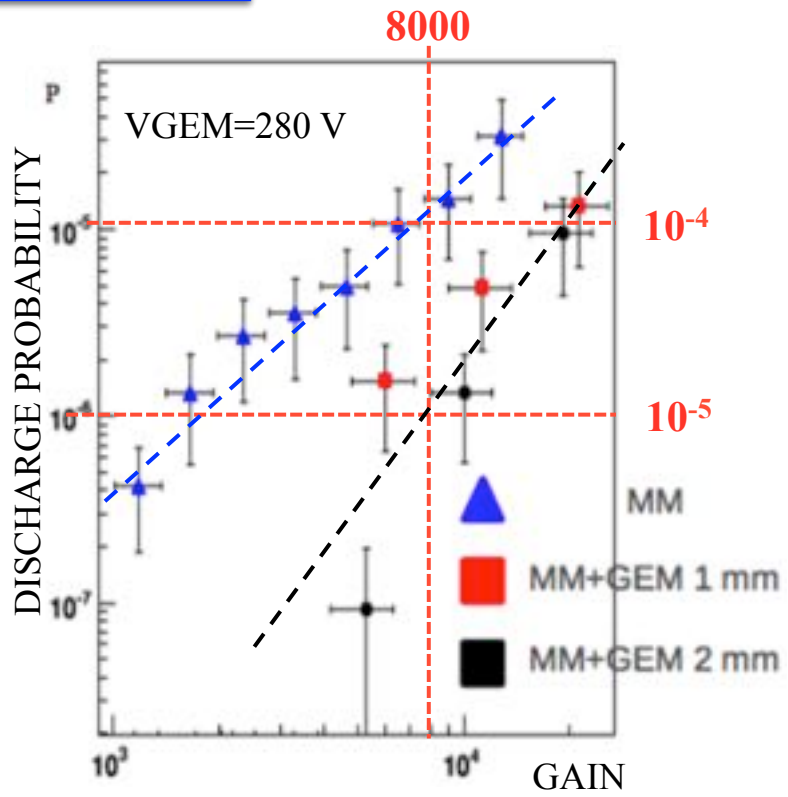
A. Buzulutskov et al, Nucl. Instr. and Meth. A433(1999)471

P. Bhattacharya, MPGD Workshop (Trieste 2015)

GEM + MICROMEGAS

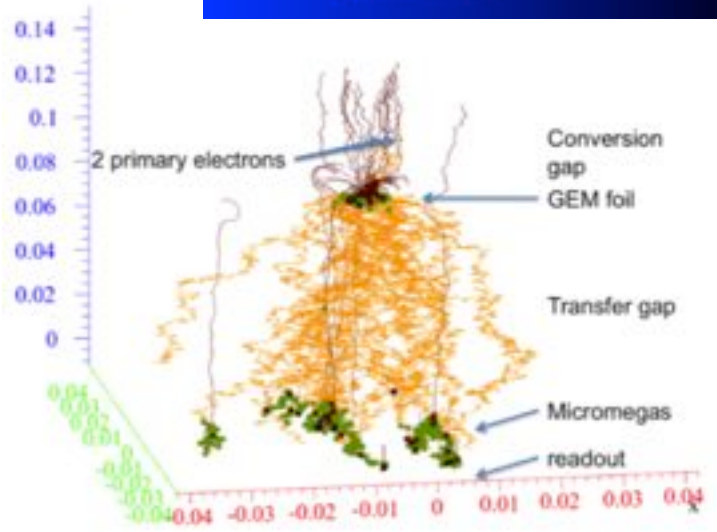


1 GeV π BEAM



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

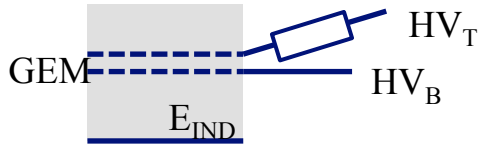
AVALANCHES SIMULATION
GEM+MICROMEGAS



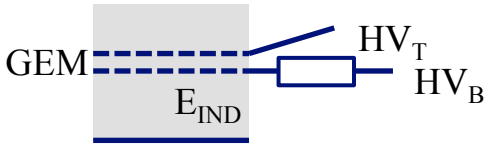
M. Vandenbroucke, JINST 7(2012)C05014

DISCHARGE PROPAGATION: LAST GEM TO ANODE

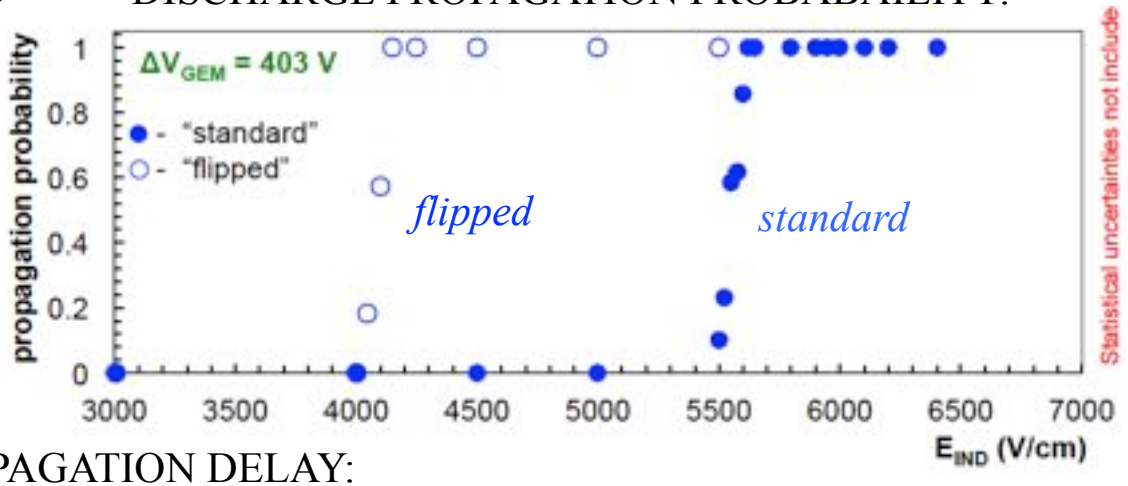
SECTORS POWERING: STANDARD



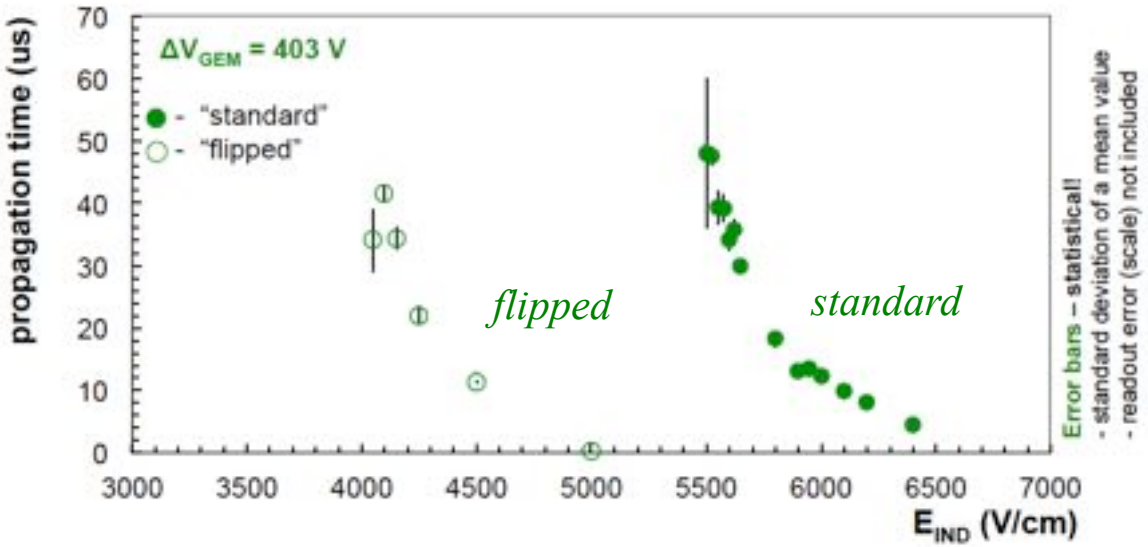
FLIPPED:



DISCHARGE PROPAGATION PROBABAILITY:



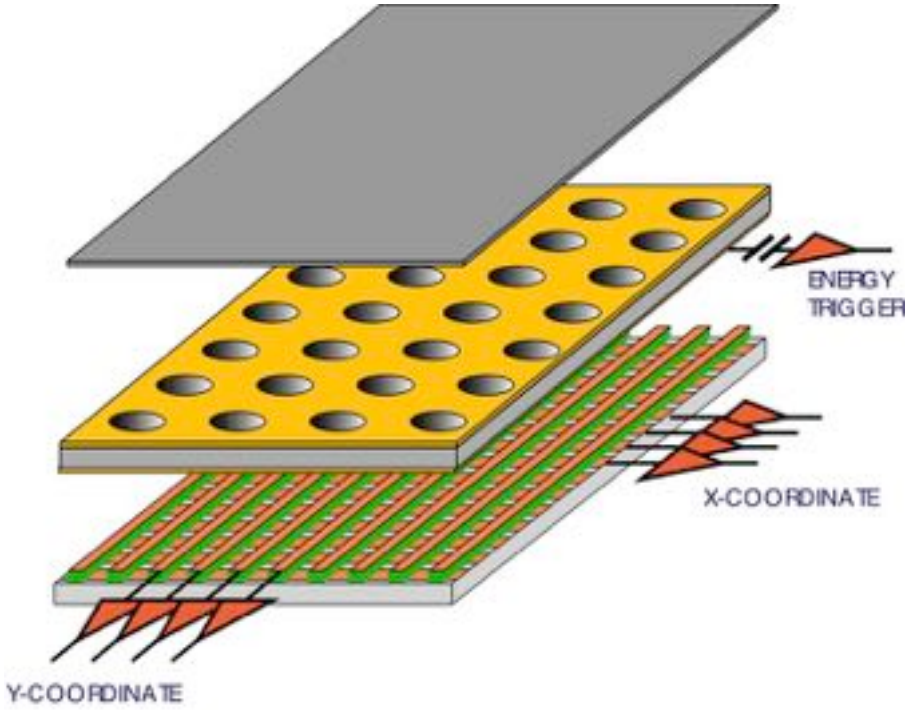
DISCHARGE PROPAGATION DELAY:



P. Gasik RD51Coll. Meeting (CERN 2016)

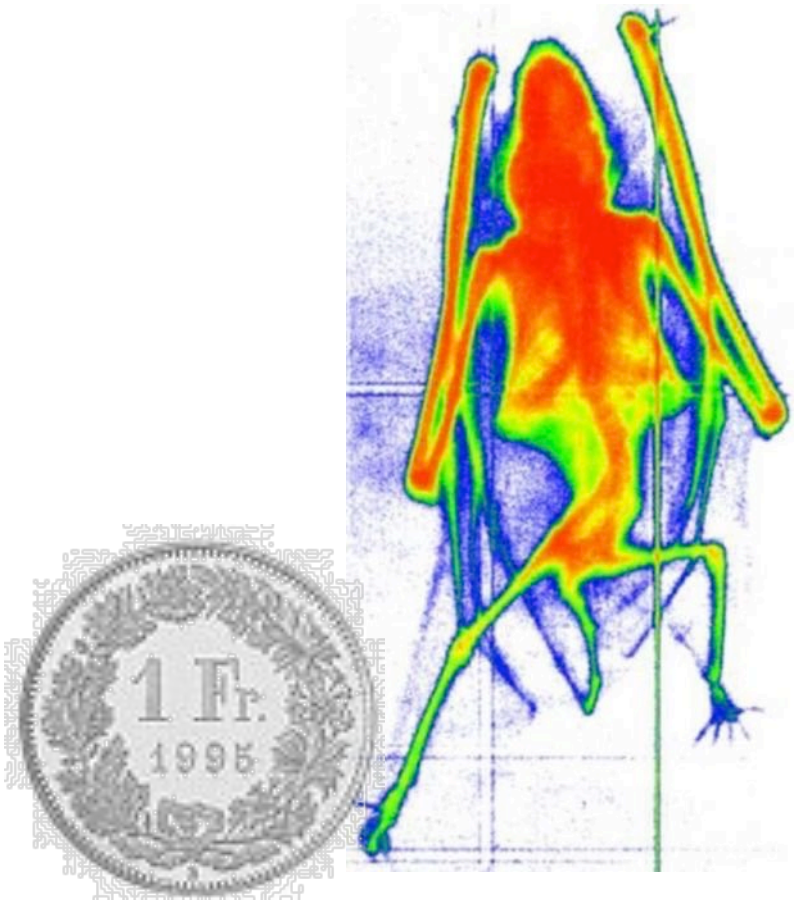
SINGLE GEM X-RAY DETECTOR

2-DIMENSIONAL CARTESIAN STRIPS READOUT



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

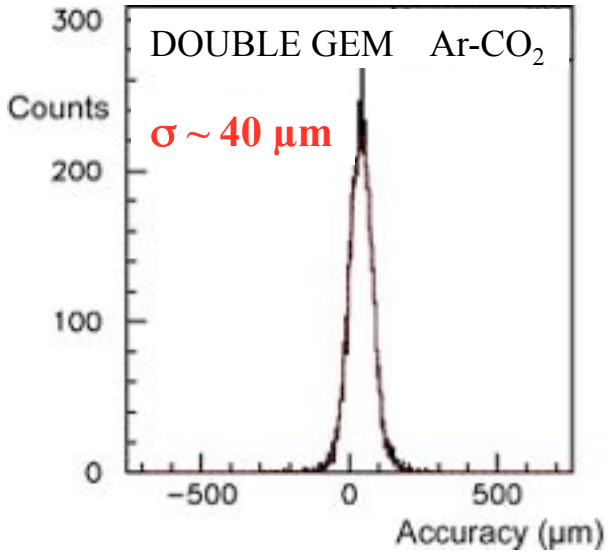
6 keV RADIOGRAPHY



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

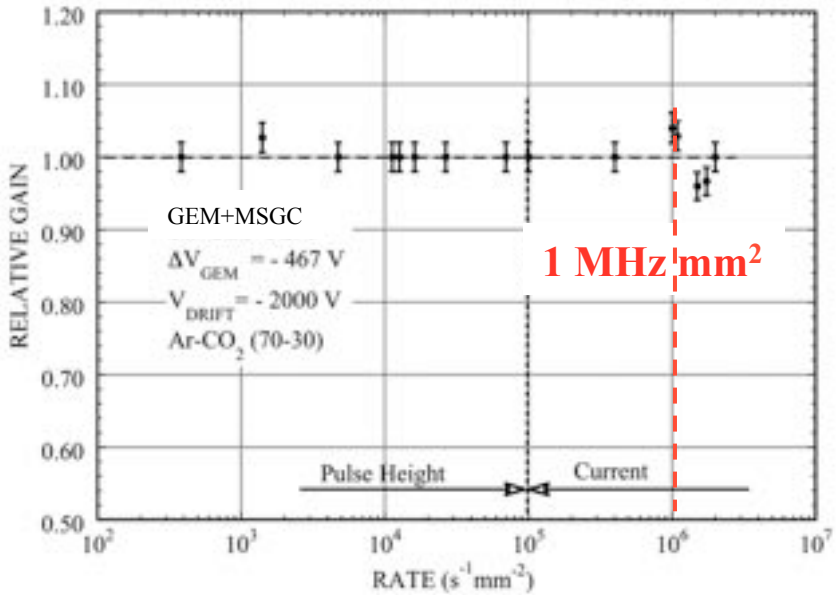
MAIN GEM PERFORMANCES: MIPS

LOCALIZATION ACCURACY



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

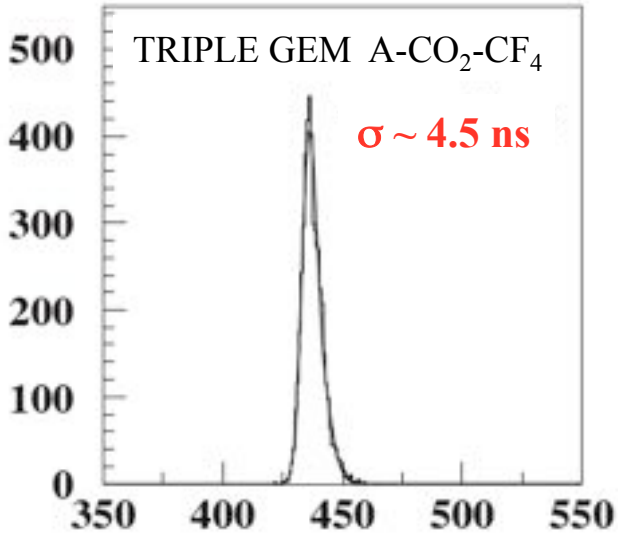
SINGLE GEM RATE CAPABILITY



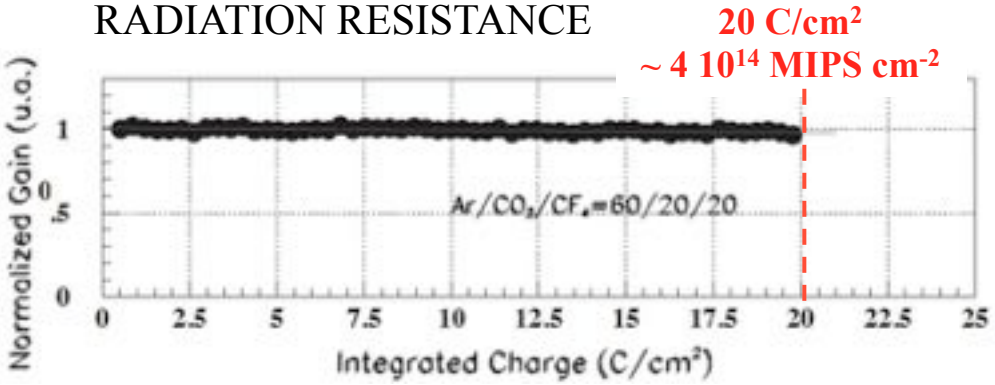
J. Benlloch et al, IEEENS-45(1998)234

TIME RESOLUTION: LHCB MUON TRIGGER

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



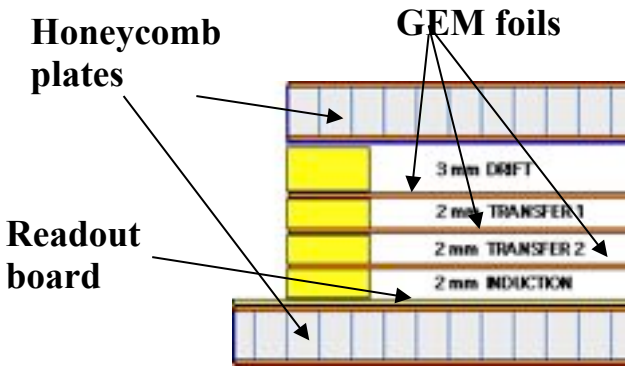
RADIATION RESISTANCE



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

TRIPLE GEMs FOR COMPASS TRACKER

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

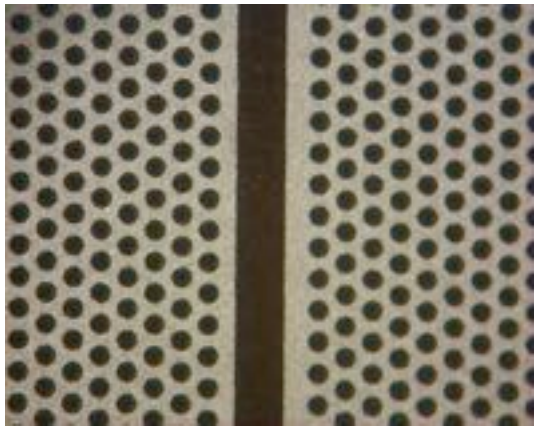


HV TESTING DURING ASSEMBLY

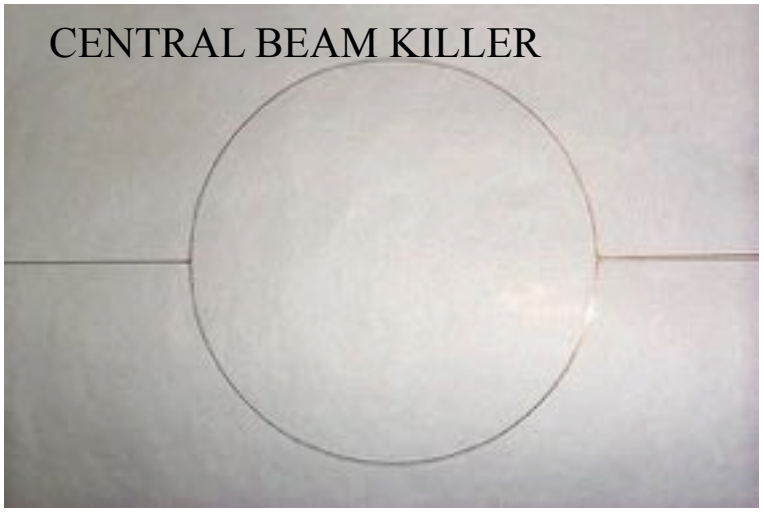
C. Altumbas et al,
Nucl. Instr. and Meth. A490(2002)177

GEM SECTORS AND READOUT PATTERNS

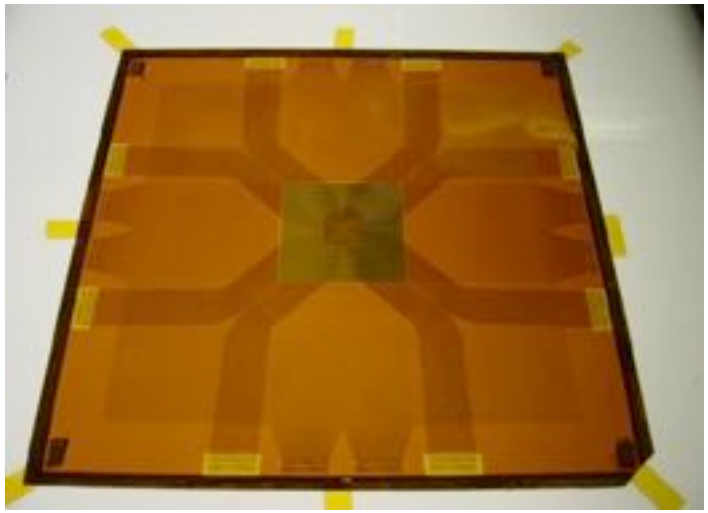
GEM SECTORS SEPARATION (200 μm)



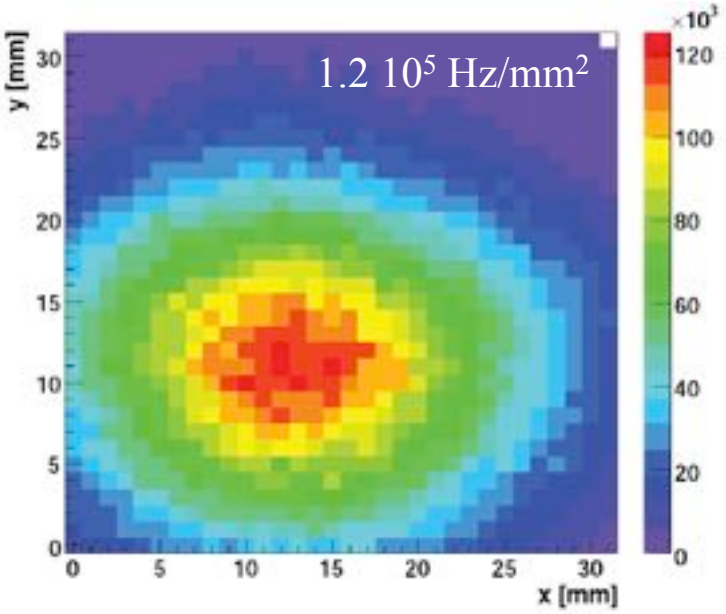
CENTRAL BEAM KILLER



1x1 mm^2 PIXELS AND STRIPS



MEASURED FLUX IN HADRON BEAM:

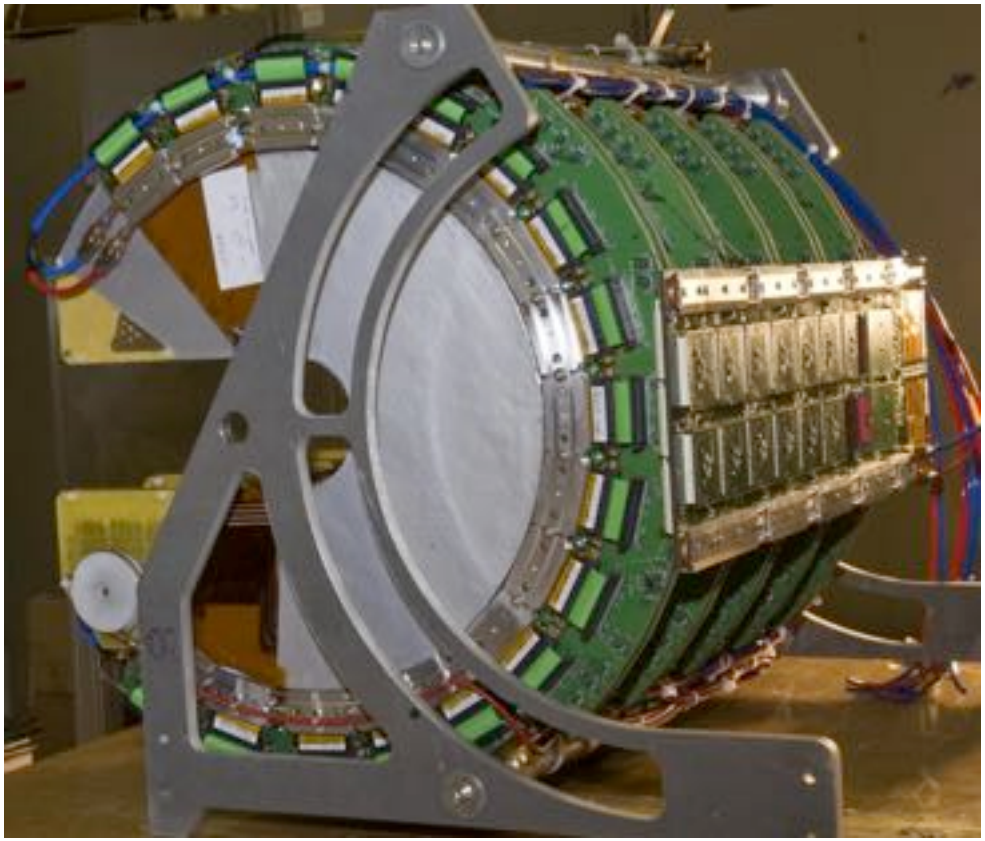


M. Krämer et al, 2008 IEEE Nucl. Sci. Symp. Conf. Rec.

TOTEM TRIPLE GEM FORWARD CMS TRACKER

SEMI-CIRCULAR MODULES

TEN-GEM TOTEM FORWARD SECTOR

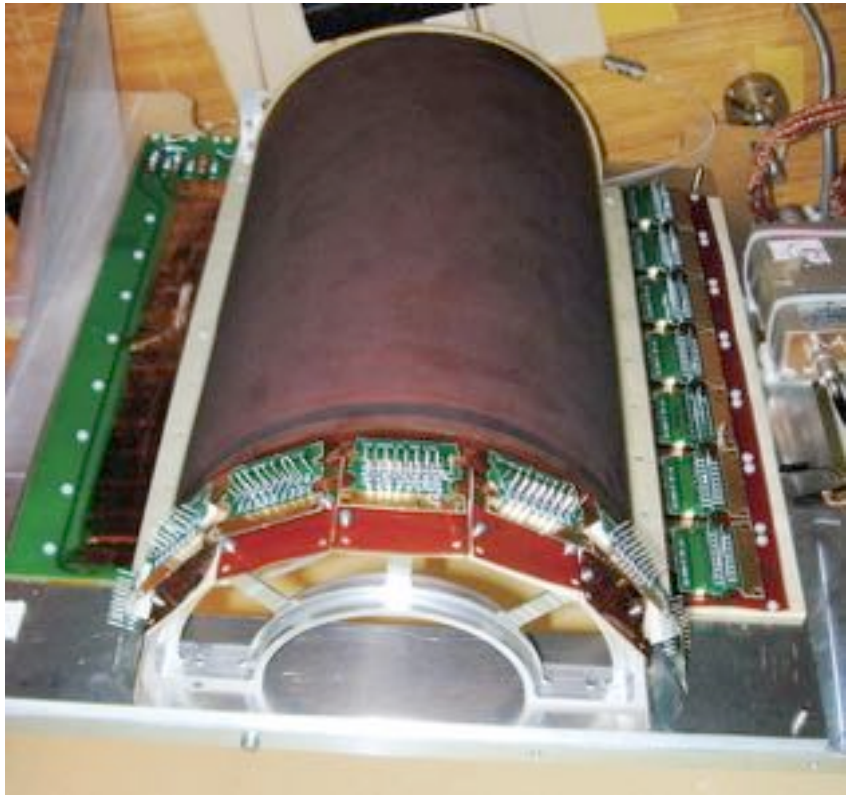


M.G. Bagliesi et al, Nucl. Instr. and Meth. A617(2010)134

CYLINDRICAL GEMS

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

TRIPLE-GEM PROTOTYPE



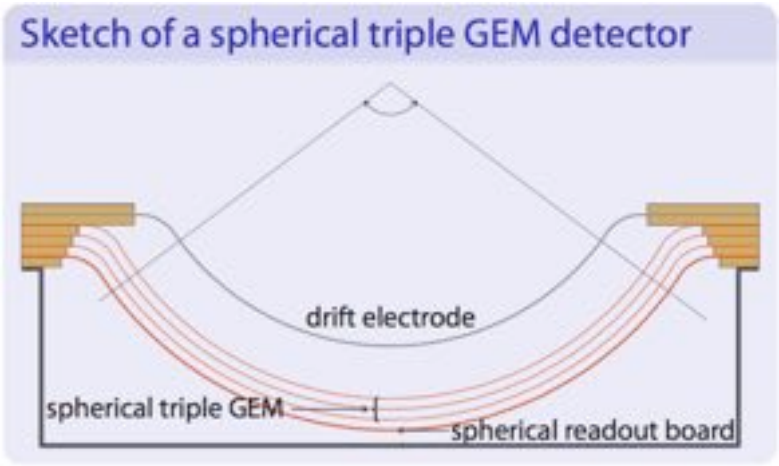
KLOE-2 INNER TRACKER

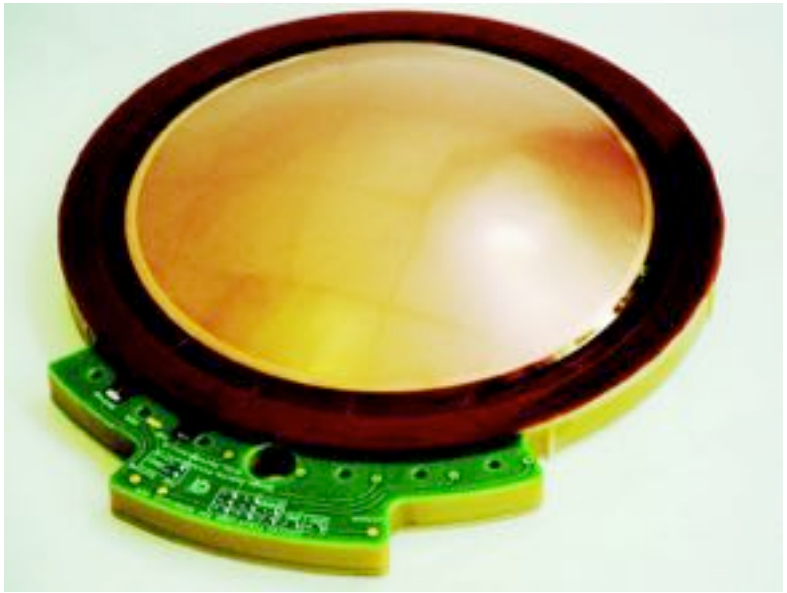
A. Balla et al,
Nucl. Instr. and Meth. A732(2013)221

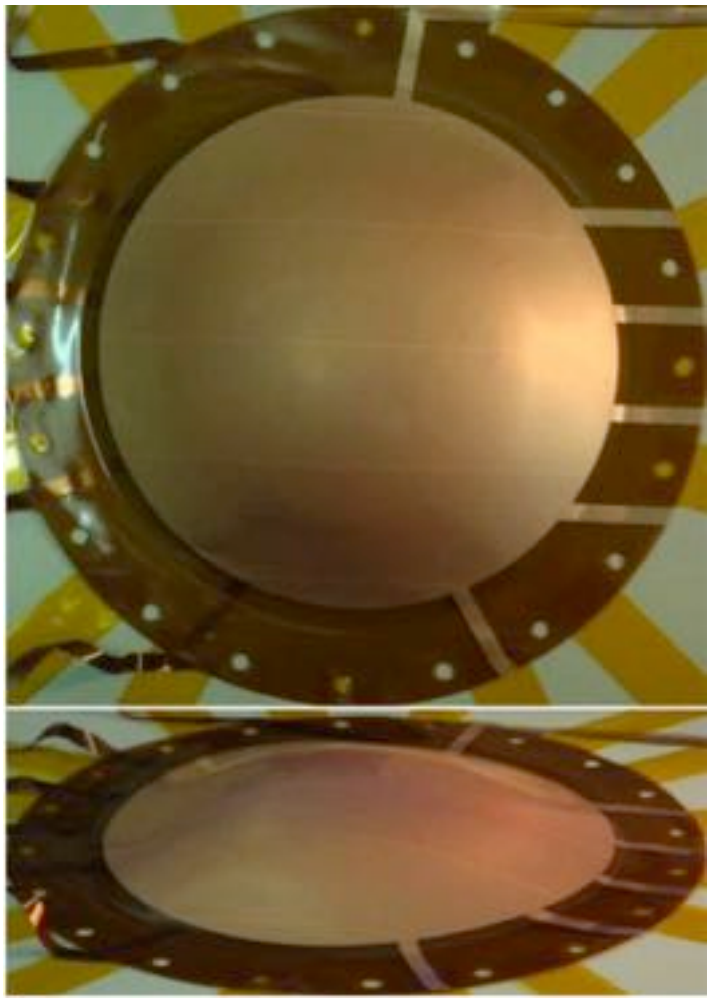
BES III DETECTOR at IHEP (Beijing)

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

"SPHERICAL" MULTIGEM AND READOUT BOARD



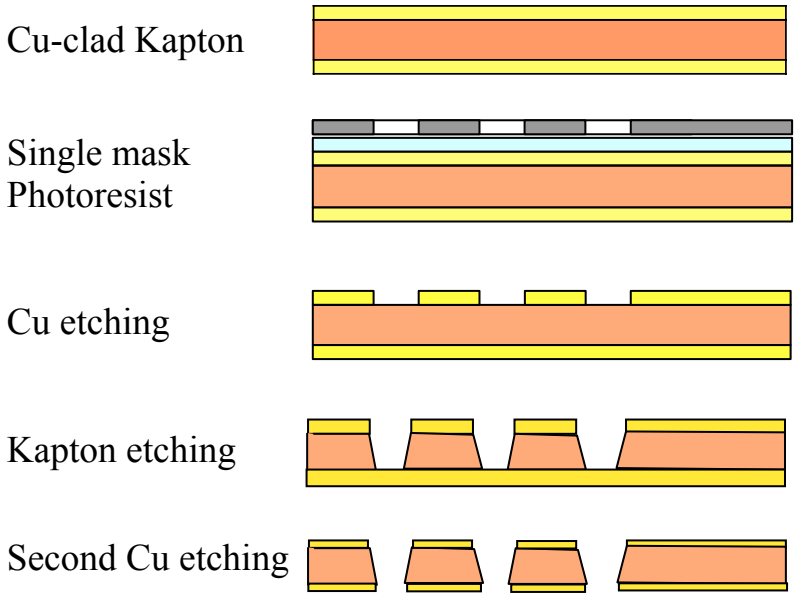




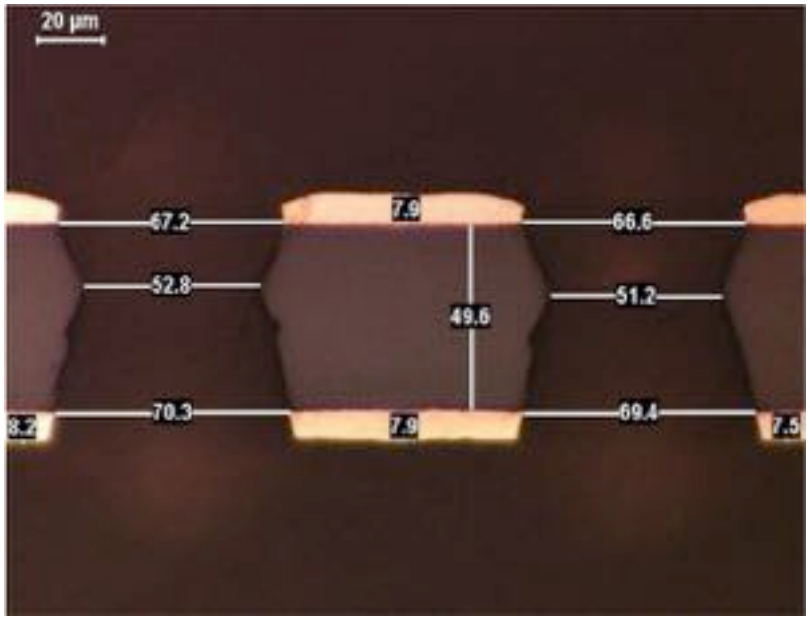
S. Duarte Pinto arXiv:1011.5528v1
IEEE 2011 Nucl. Sci. Symp. Conf. Rec.

GDD

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



"CYLINDRICAL" HOLES

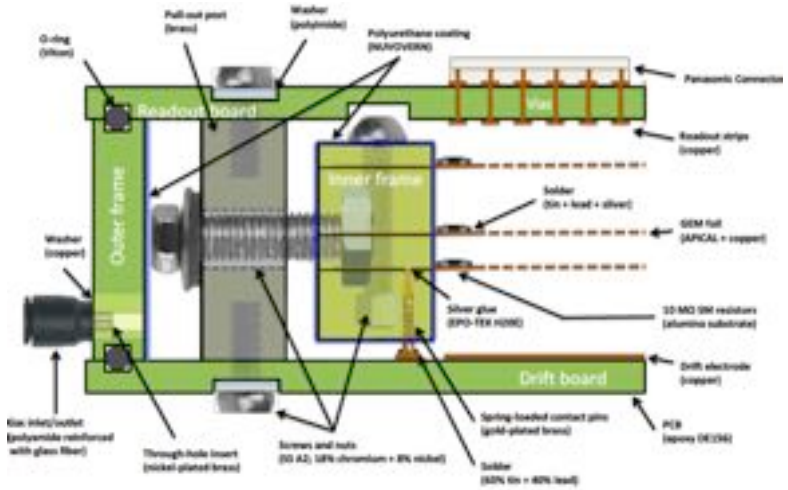


M. Alfonsi et al, Nucl. Instr. and Meth. A617(2010)151

Archana Sharma, CMS GEM Upgrade Project Manager

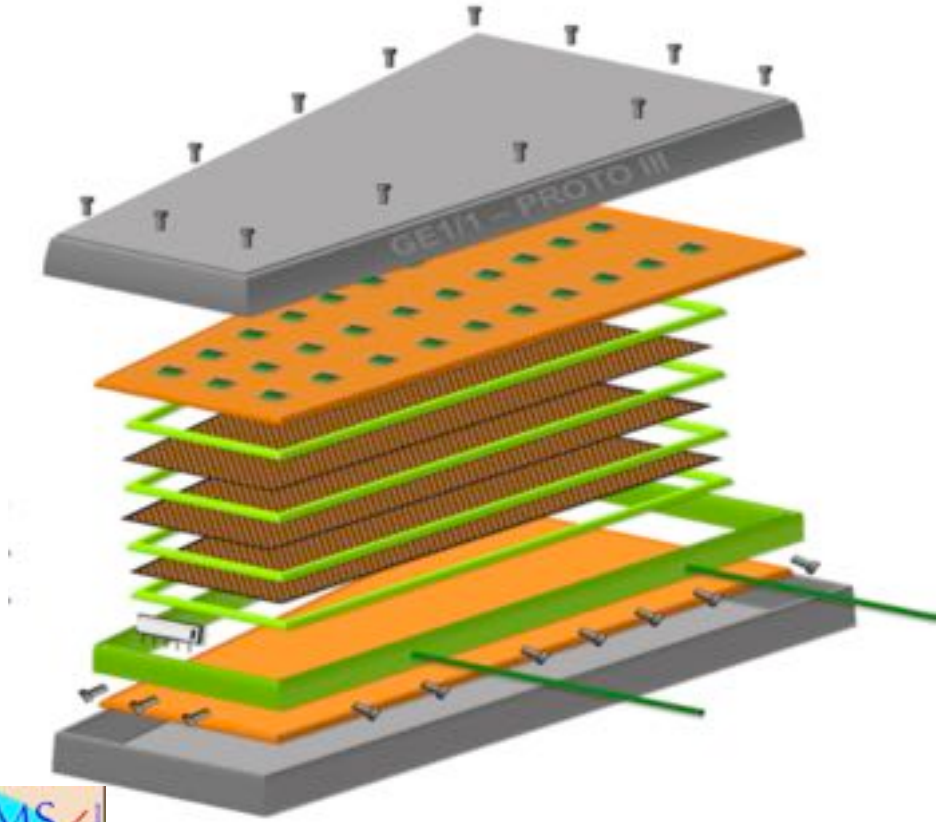
DISMOUNTABLE MECHANICAL ASSEMBLY
EDGE STRETCHED GEM FOILS
CERN-INFN-BONN

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



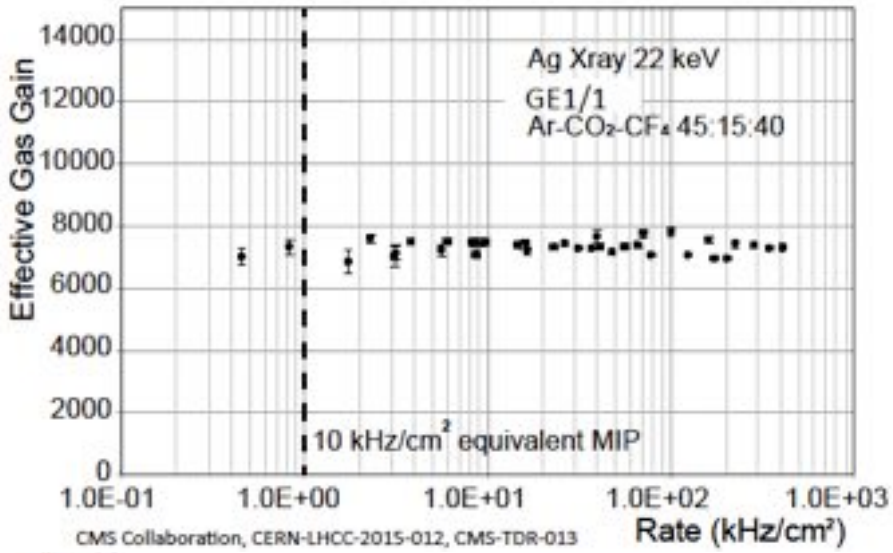
D. Abbaneo et al,
Nucl. Instr. and Meth. A732 (2013) 203

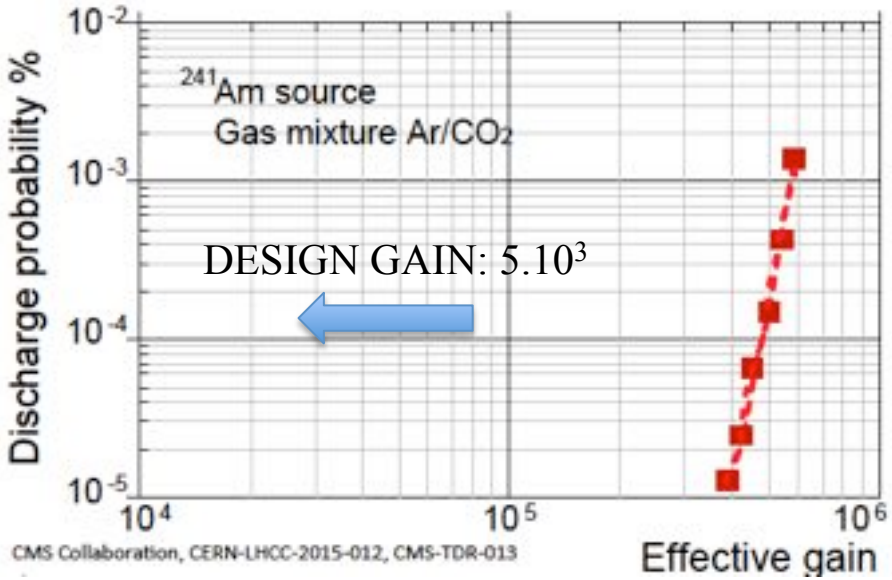
GEM MODULES: 100-120 cm x 22-45 cm
36 SUPERCHAMBERS IN EACH ENDCAP



B. Dorney, MPGD WORKSHOP (Trieste 2015)

LARGE PROTOTYPE IN TET BEAM

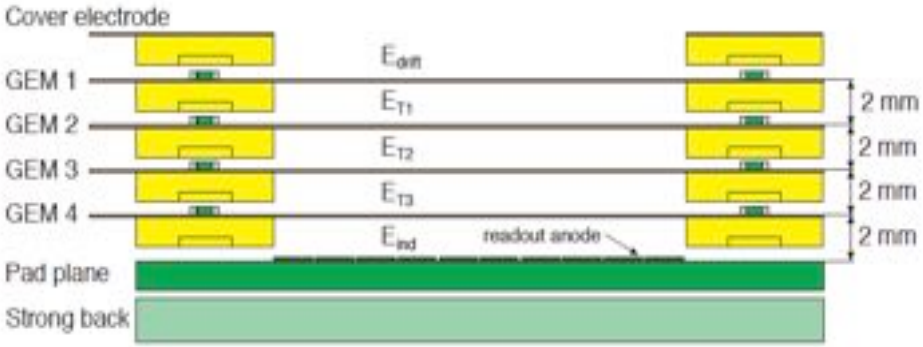


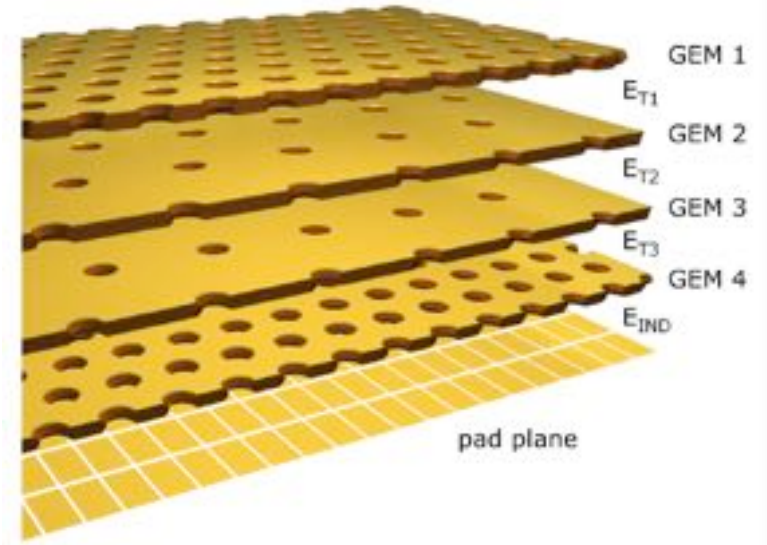


B. Dorney, MPGD Workshop (Trieste 2015)

Chilo Garabatos, Deputy Project Leader

QUAD-GEM WITH STAGGERED HOLES

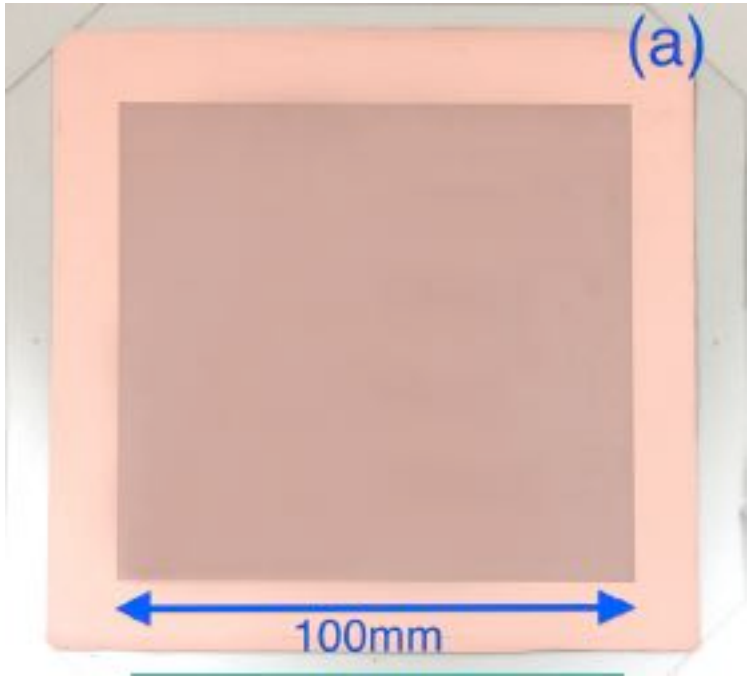


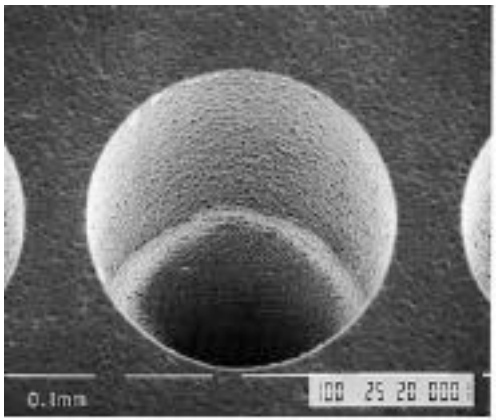


A. Deisting, MPGD Workshop (Trieste 2015)

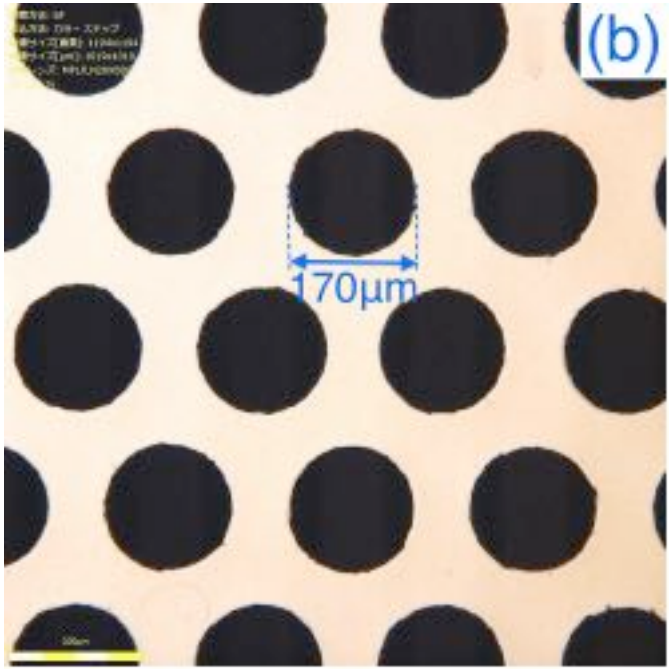
ALTERNATIVE GEM STRUCTURES

GLASS GEM





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

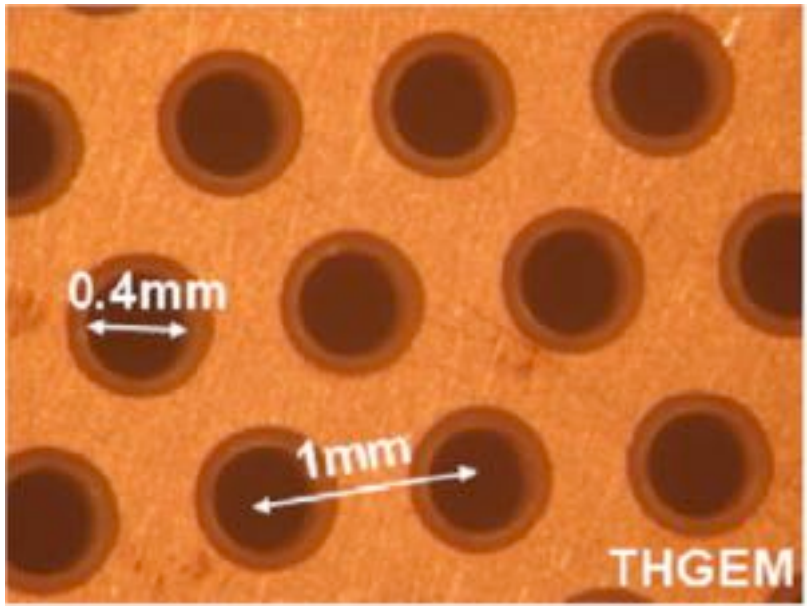


H, Takahashi et al, Nucl. Instr. and Meth. A724(2013)1

THICK ELECTRON MULTIPLIER (THGEM)

ALSO CALLED LARGE ELECTRON MULTIPLIER (LEM)

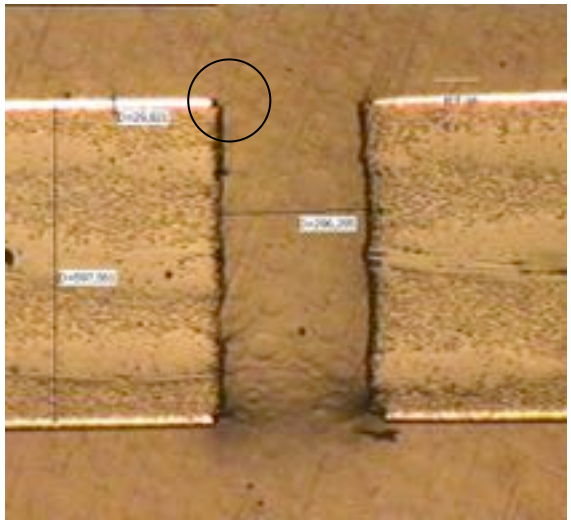
MECHANICAL DRILLING OF METAL-CLAD PC BOARD
- SELF-SUPPORTING
- HIGH GAIN (?)



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

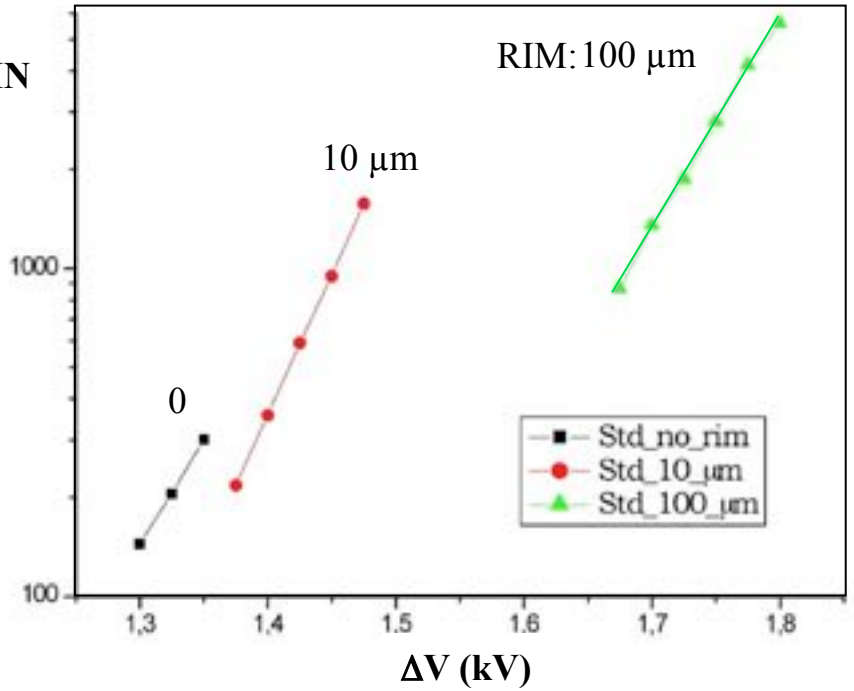
THGEM: GAIN AND CHARGING UP

DEVELOPMENTS FOR THE
COMPASS RICH-1 UPGRADE

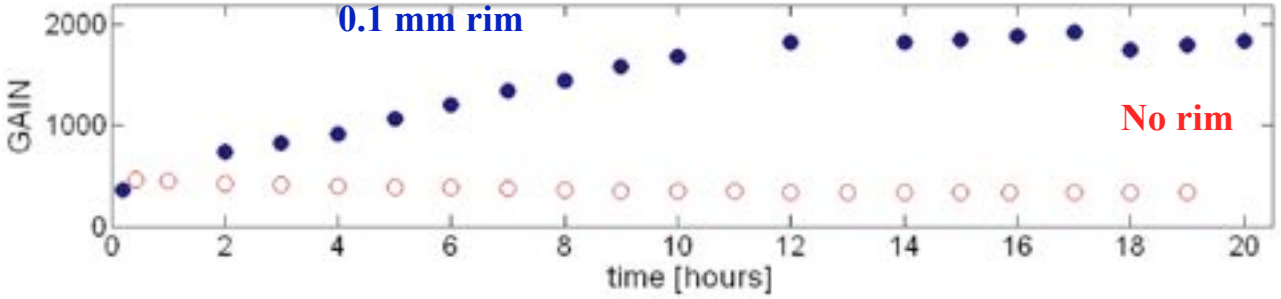


LARGE RIM:
- HIGH GAIN
- CHARGING UP

RIMLESS:
- LOW GAIN
- STABLE



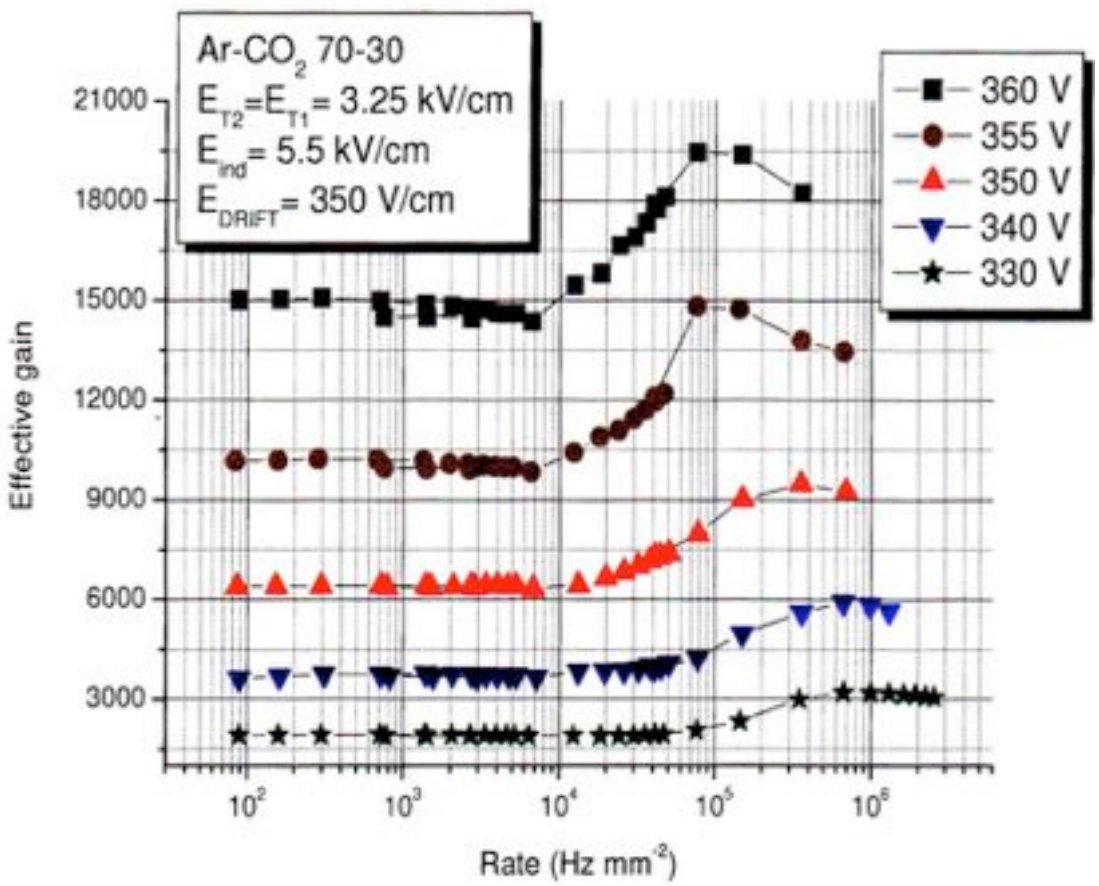
GAIN VS TIME (CHARGING UP EFFECT):



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

MULTIPLE
STRUCTURES

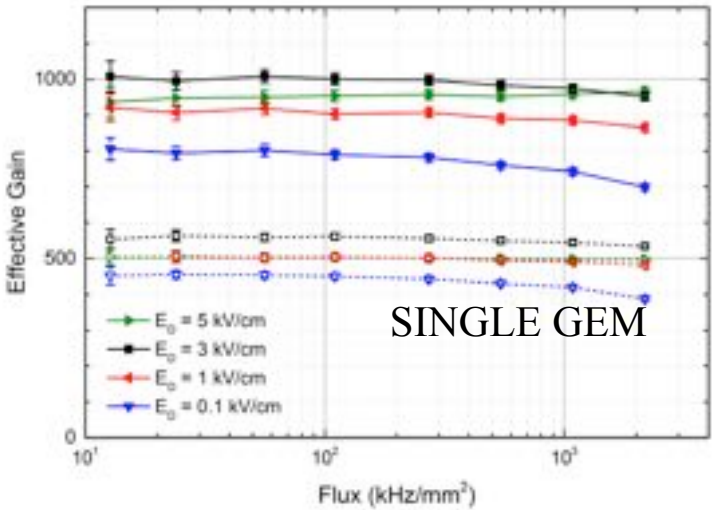
GAIN VS X-RAY RATE: TRIPLE GEM (2006)



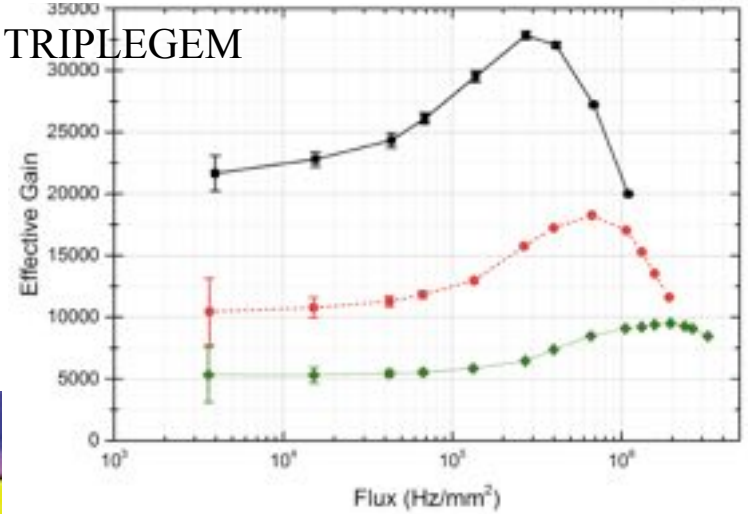
P. Everaerts, PhD Thesis Gent University (2006)

MULTIGEM GAIN AT VERY HIGH RATES

NEW MEASUREMENTS (2015)

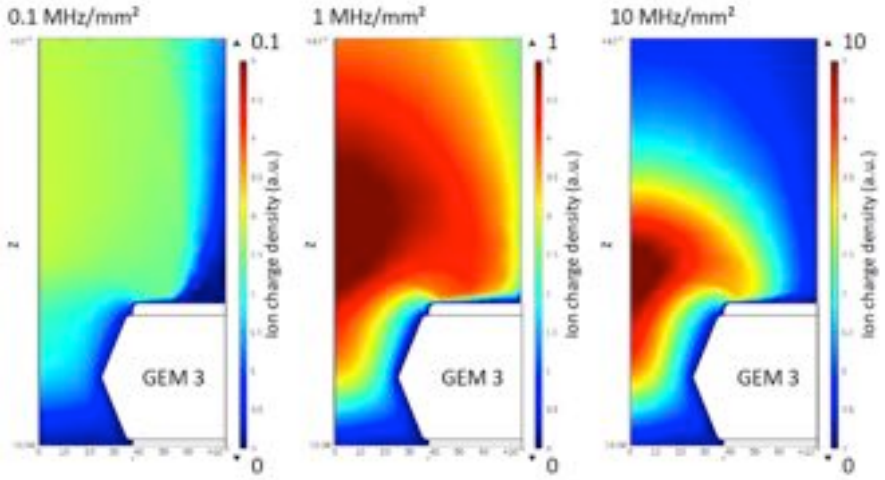


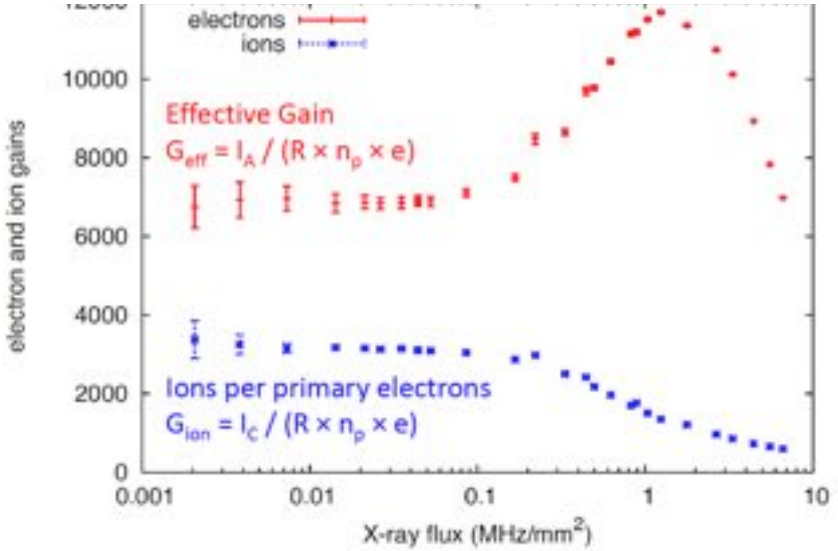
TRIPLEGEM



P. Thuiner, PhD TU Vienna (2016)

SIMULATION: CHARGE DENSITIES VS RATE





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

POSITIVE IONS BACKFLOW

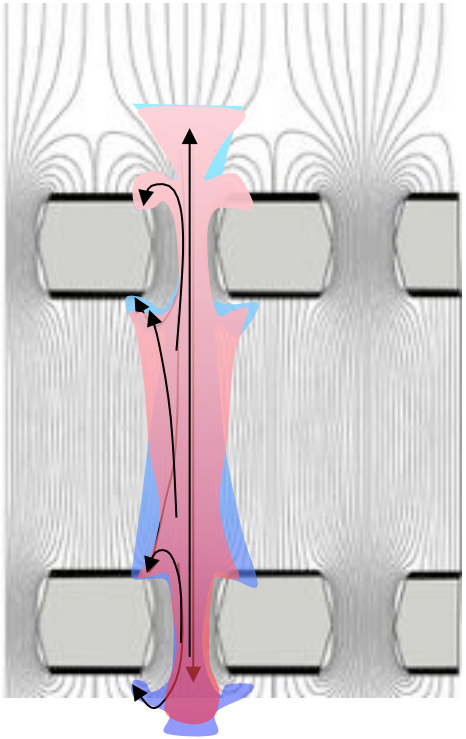
POSITIVE IONS BACKFLOW (OR FEEDBACK):

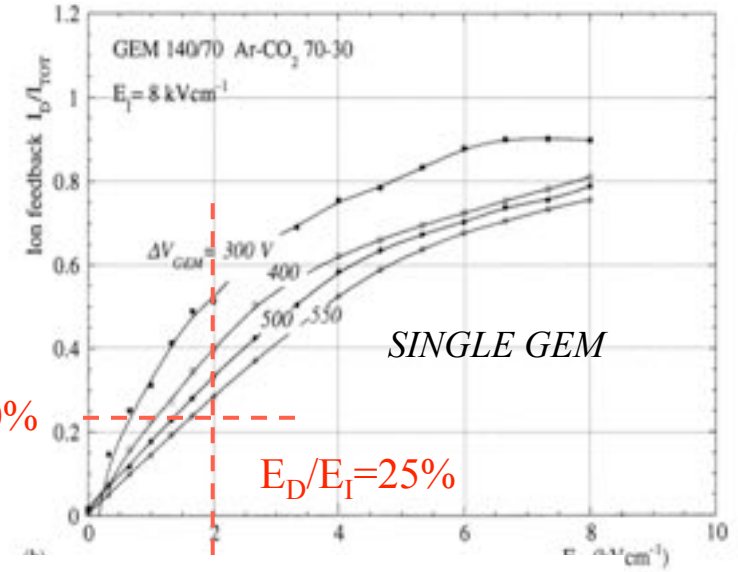
$$IBF = \frac{I_{DRIFT}}{I_{ANODE}}$$

THE WISH:
ONE IBF ION PER PRIMARY

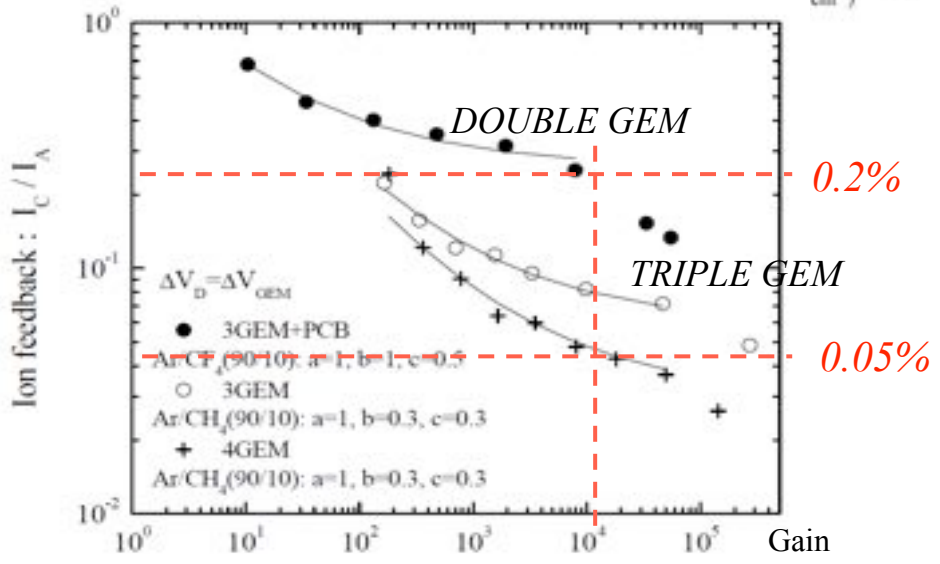
$$IBF \leq \frac{1}{GAIN} \approx 10^{-4}$$

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





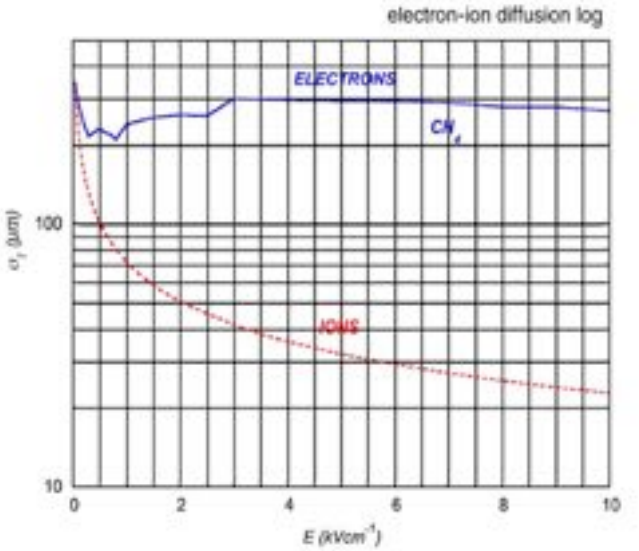
S. Backmann et a, l
Nucl. Instr. Meth. A438(1999)376



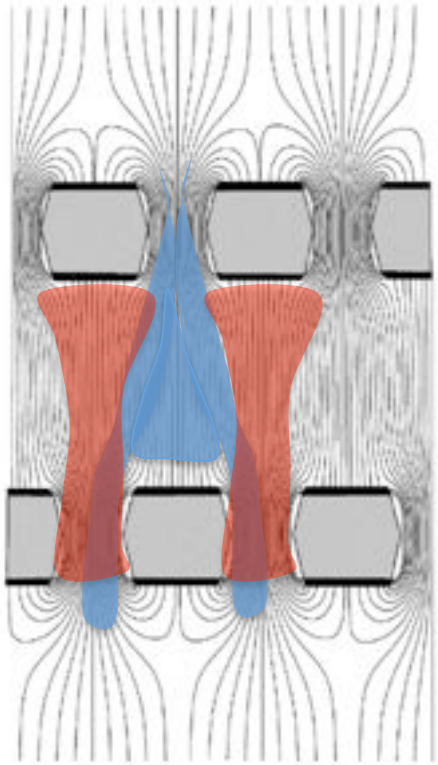
A. Bondar et al, Nucl. Instr. and Meth. A496(2003)325

ION BACKFLOW REDUCTION: OFFSET HOLES

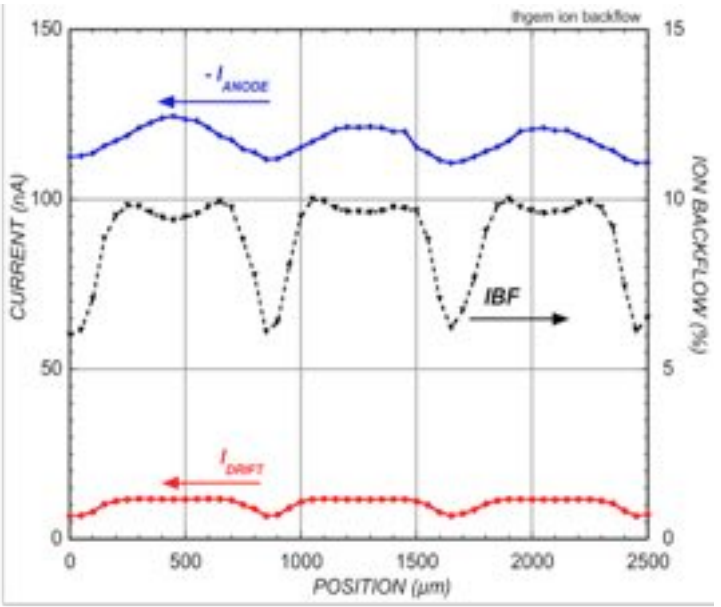
e^- I^+ TRANSVERSE DIFFUSION:



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

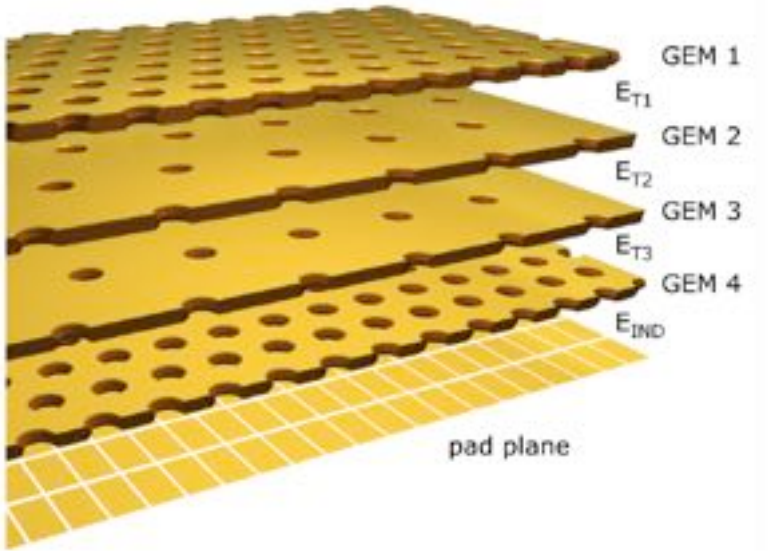


OFFSET SCAN:



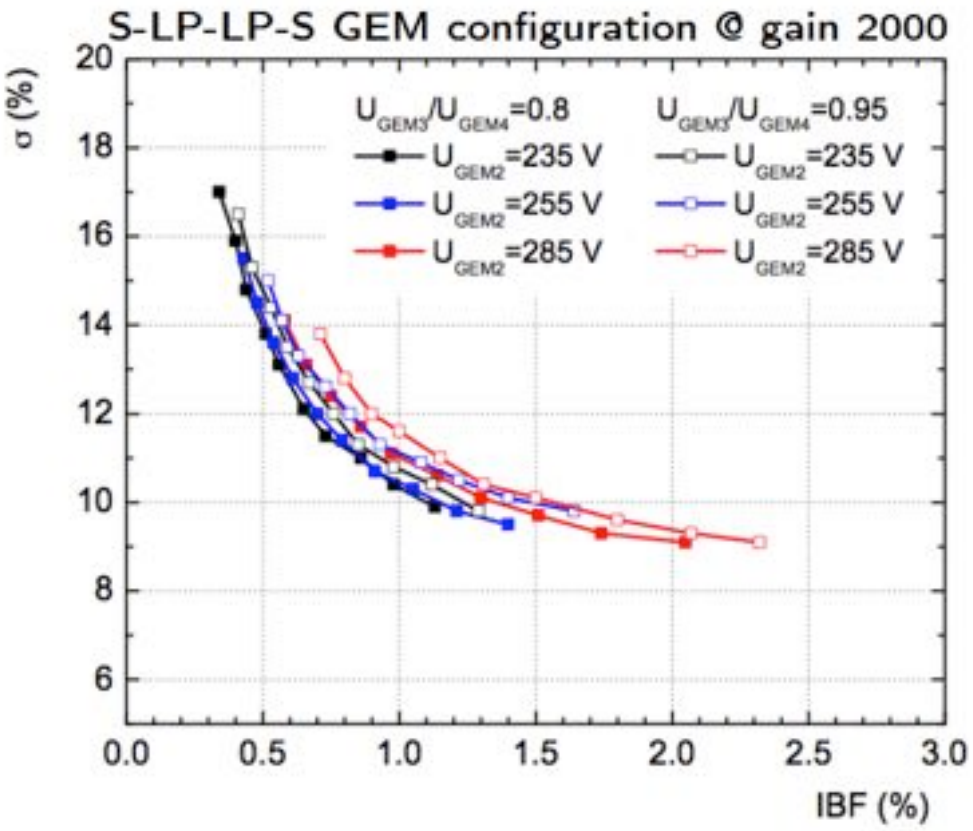
F. Sauli et al, Nucl. Instr. and Meth. A560(2006)269

FOUR GEMS WITH STAGGERED HOLES



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

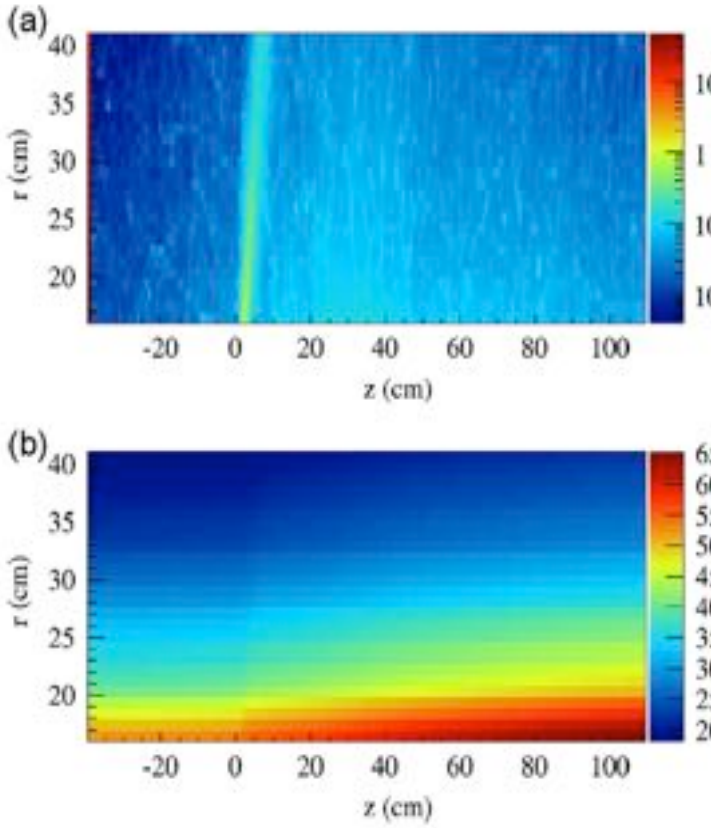
ENERGY RESOLUTION VS IBF:



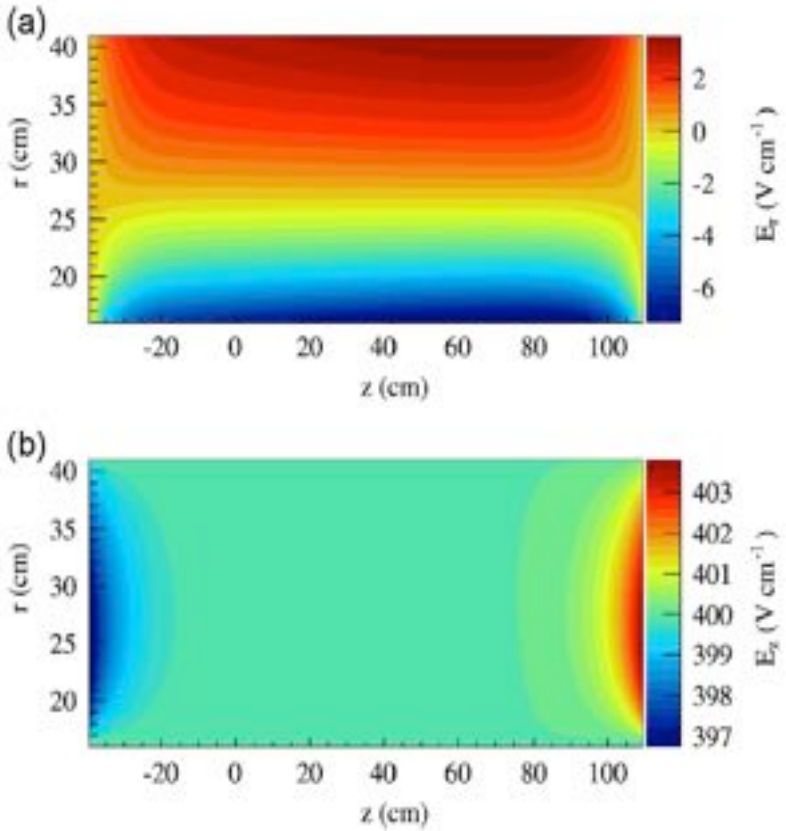
A.Deisting, MPGD Workshop (Trieste 20125)

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:

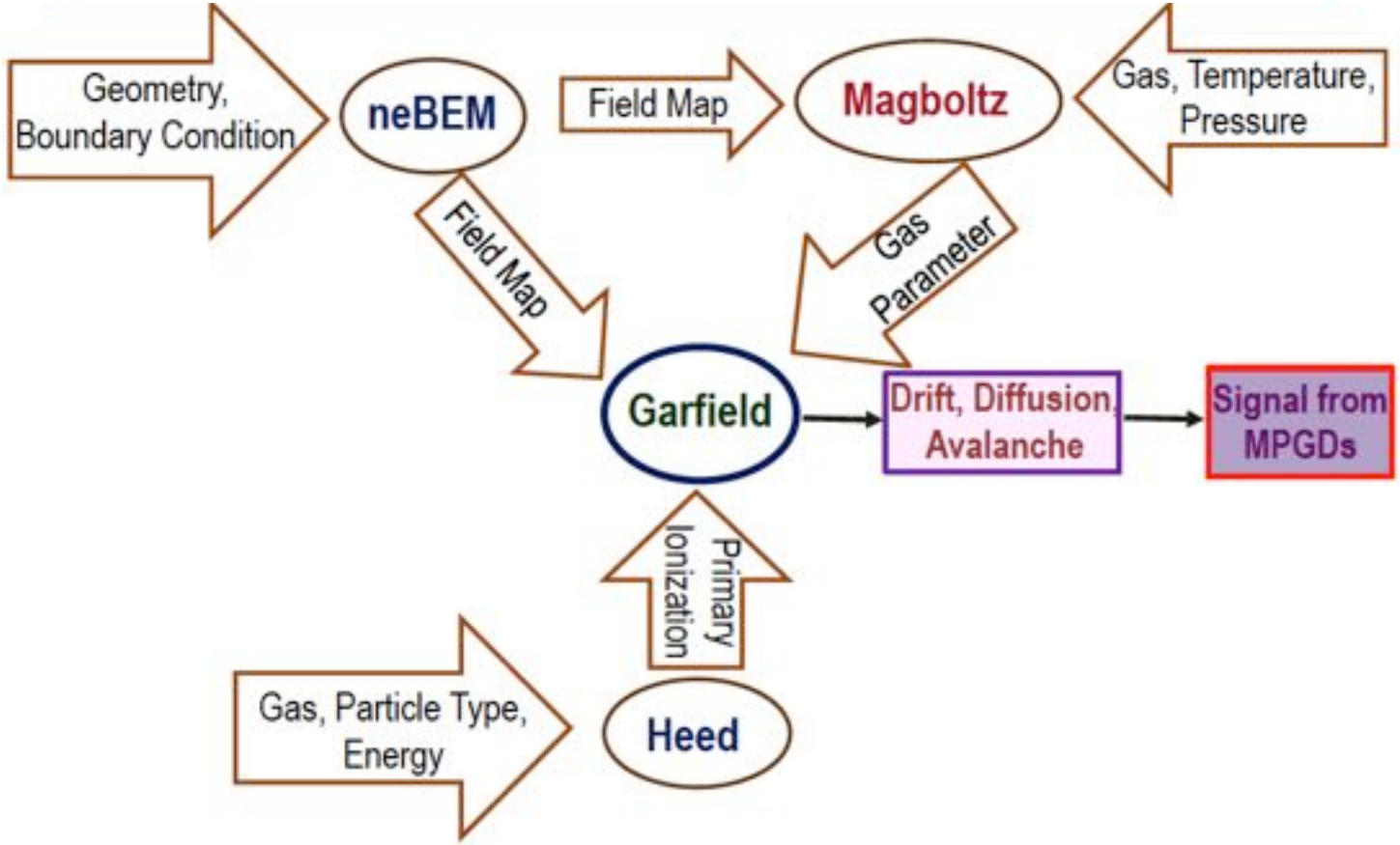


ELECTRIC FIELD DISTORTIONS:



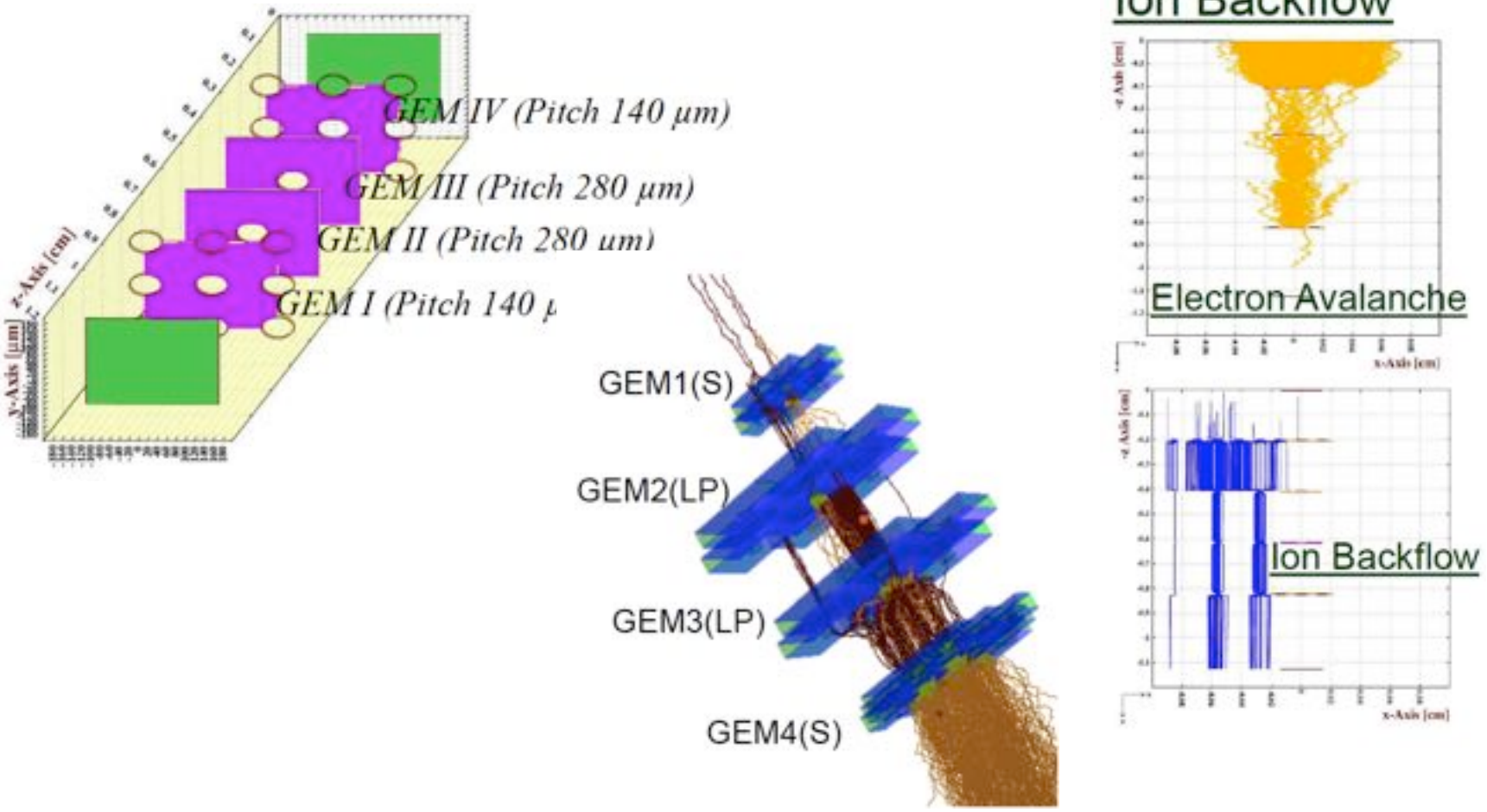
F.W. Bohmer et al,Nucl. Instr. and Meth. A719(2013)101

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



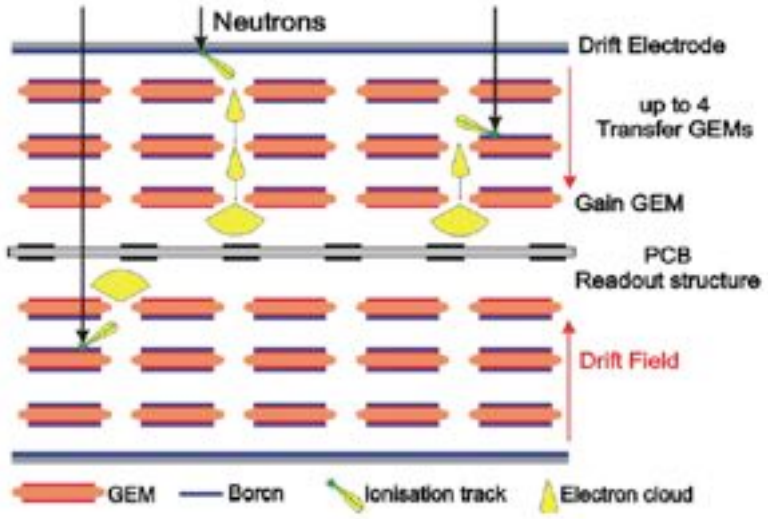
P. Bhattacharya, RD51 Collaboration

ALICE GEM TPC SIMULATION

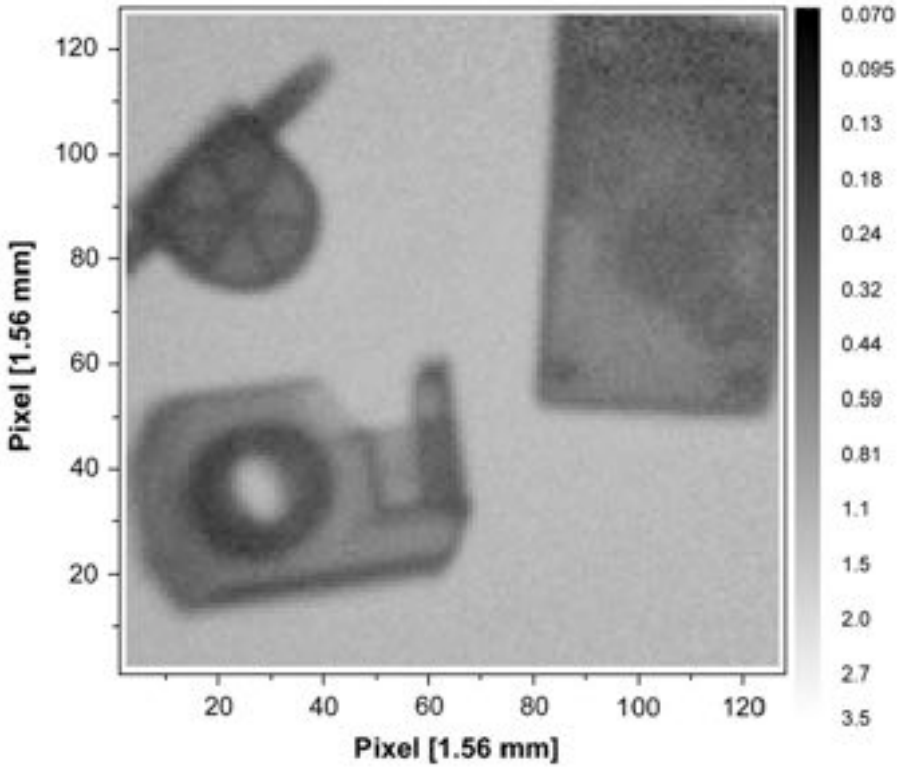


P. Bhattacharya, MPGD Workshop (Trieste 2015)

CASCADE: ^{10}B-COATED GEM ELECTRODES

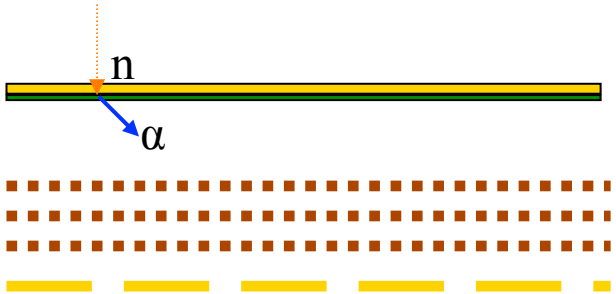


THERMAL NEUTRON RADIOGRAPHY

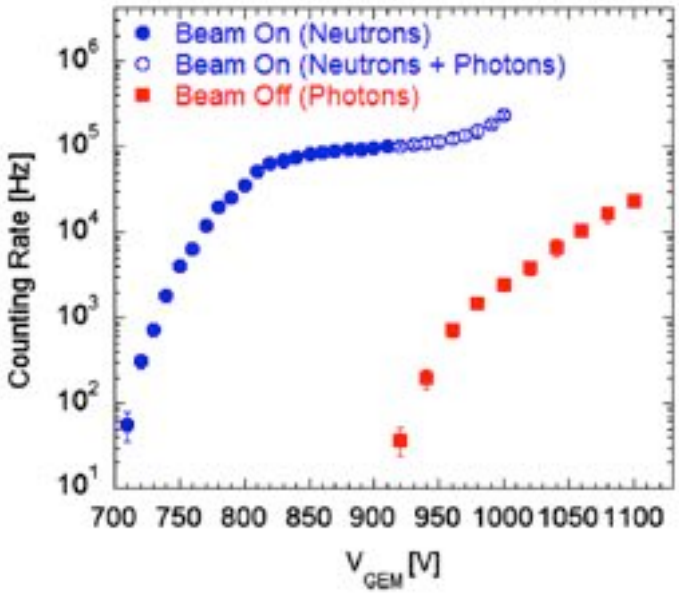


M. Klein and Ch. Schmidt, Nucl. Instr. and Meth. A628(2011)9

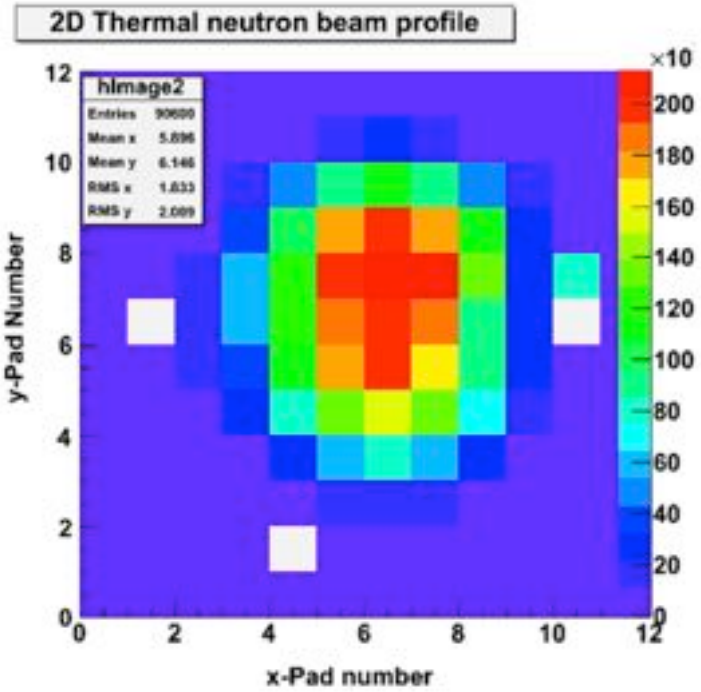
b-GEM:
TRIPLE GEM WITH ALUMINUM FOIL CATHODE COATED WITH 1 μm OF BORON CARBIDE
READOUT: 144 PADS, 8x8 mm^2



SENSITIVITY TO GAMMA BACKGROUND:



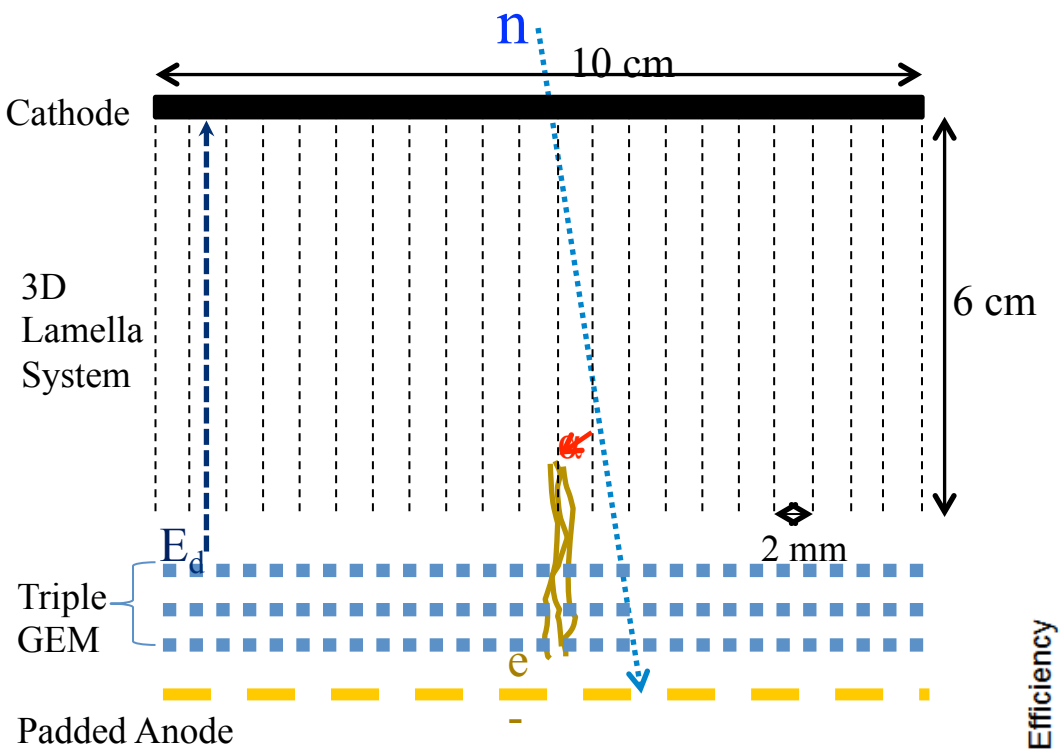
2-D THERMAL NEUTRON BEAM PROFILE



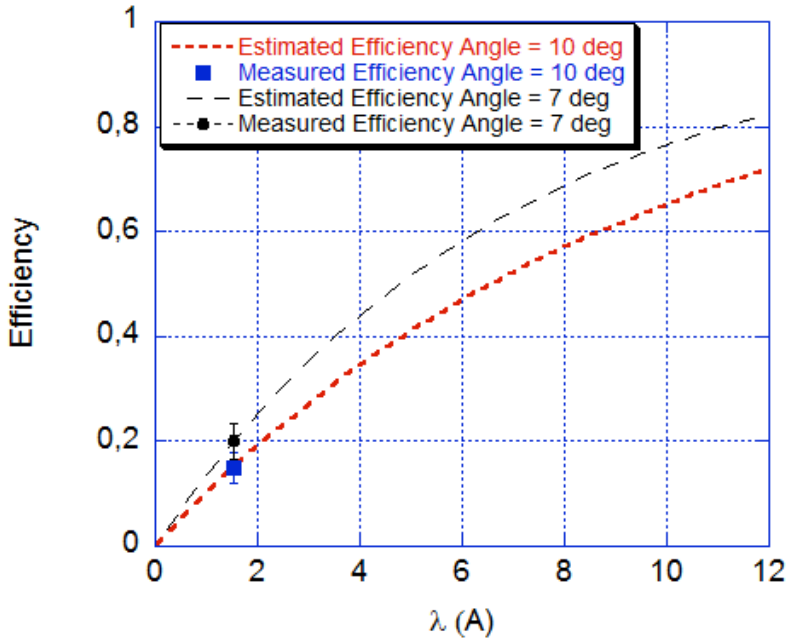
G. Croci et al, Nucl. Instr. and Meth. A732(2013)217

BORON ARRAY NEUTRON DETECTOR (BAND-GEM)

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



48 LAMELLAS PROTOTYPE

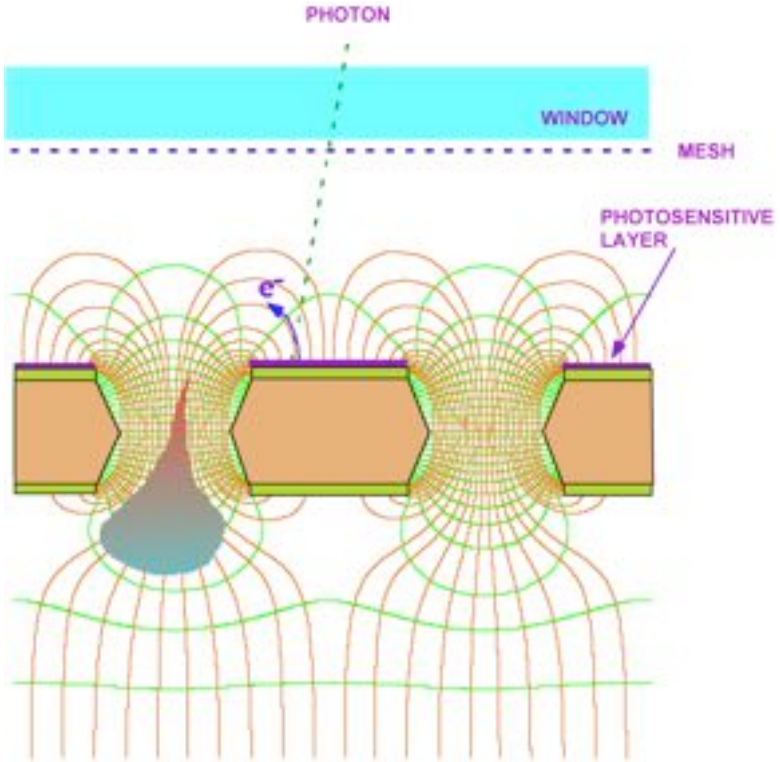


G. Croci et al, MPGD Workshop (Trieste 2015)

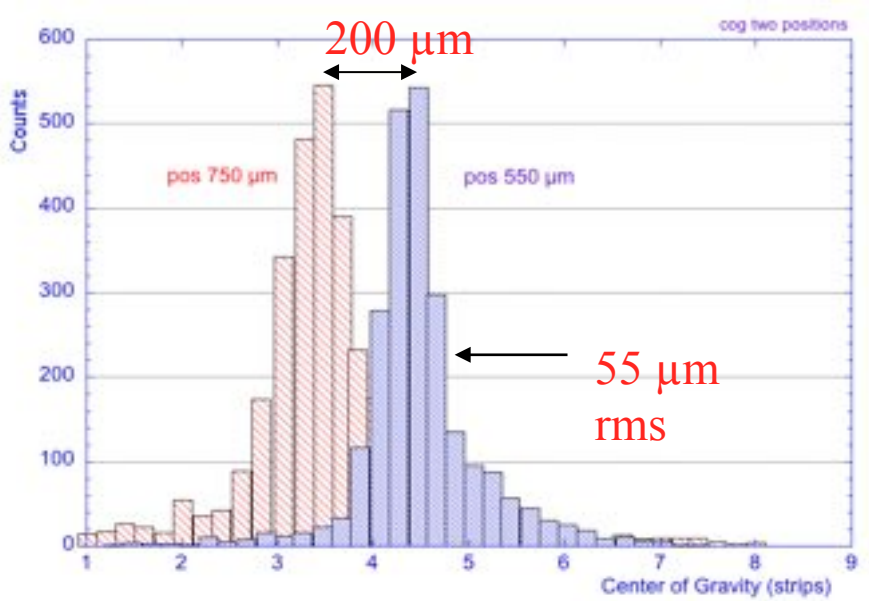
UV PHOTON DETECTION: CsI PHOTOCATHODES

REFLECTIVE CsI PHOTOCATHODE ON UPPER GEM ELECTRODE

- NO PHOTON FEEDBACK
- INSENSITIVE TO DIRECT IONIZATION



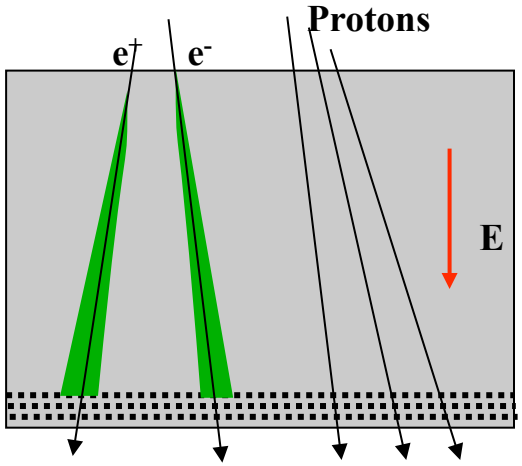
TRIPLE GEM
COLLIMATED SINGLE UV PHOTON SOURCE
POSITION ACCURACY

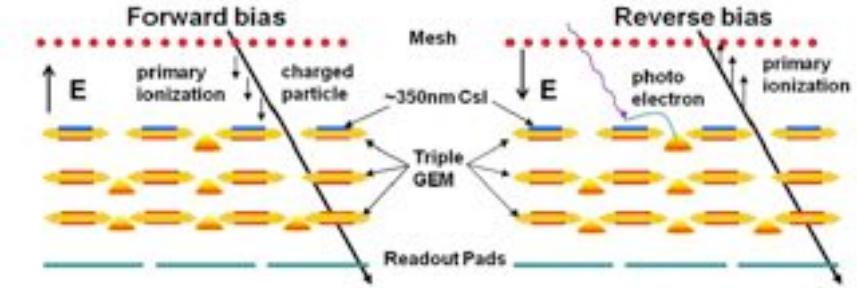


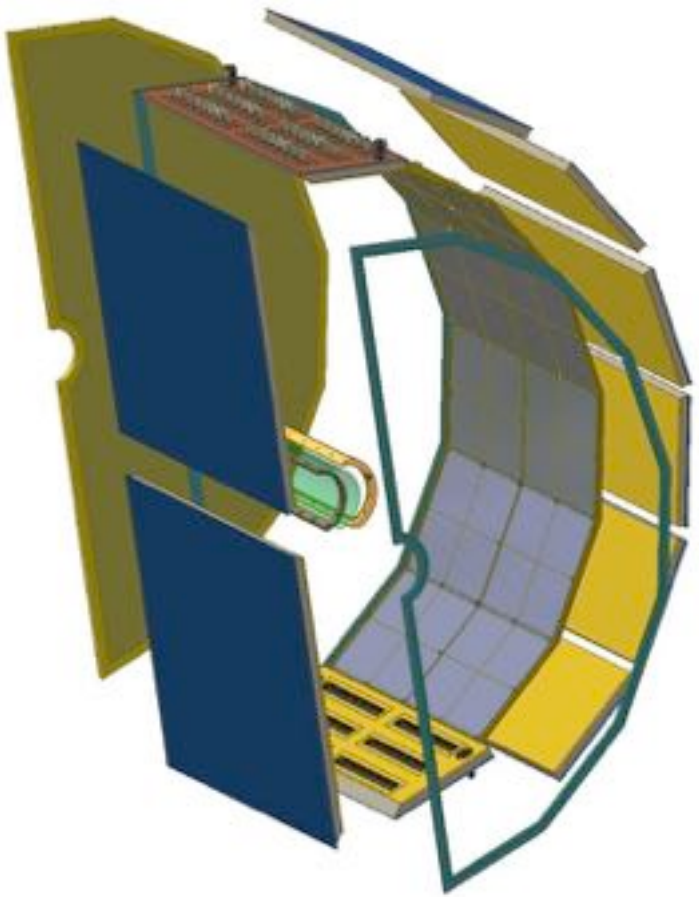
GDD

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

"INVERSE FIELD" TPC





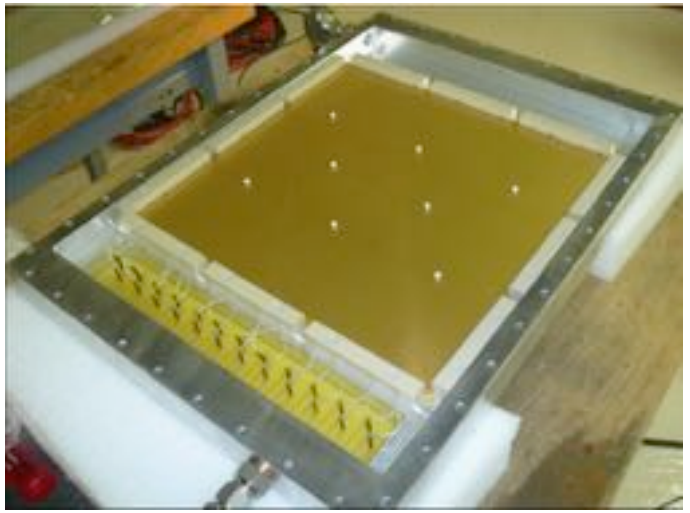


C. Aidala et al, Nucl. Instr. and Methods A502(2003)200

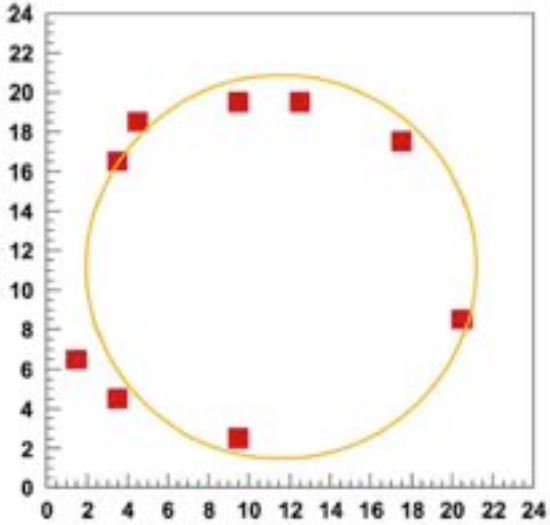
Z. Fraenkel et al, Nucl. Instr. and Methods A546(2005) 466

THICK GEM CsI-COATED 30x30 cm^2

TRIPLE THGEM PROTOTYPE



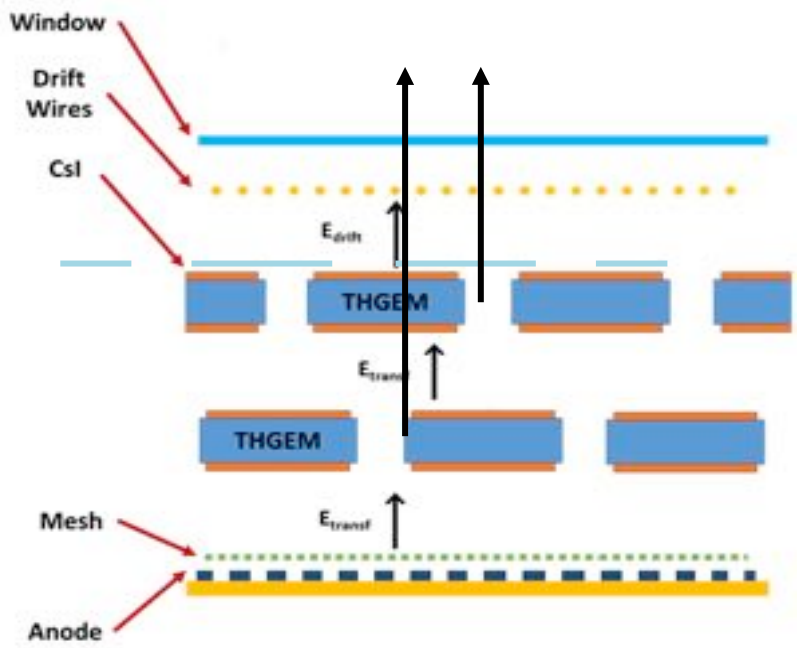
SINGLE EVENT (6 GeV π^- BEAM)



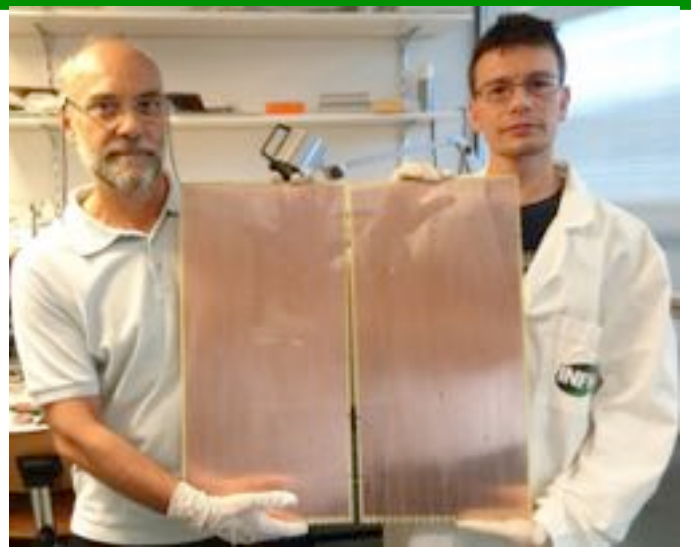
M. Alexeev et al, Nucl. Instr. and Meth. A732(2013)264

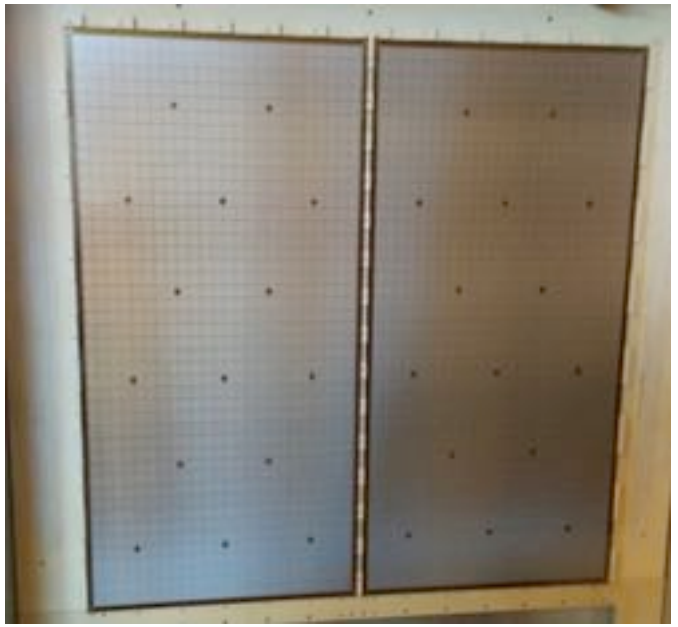
COMPASS RICH-1 MPGD UPGRADE

DOUBLE STAGGERED THGEMS+MICROMEGAS



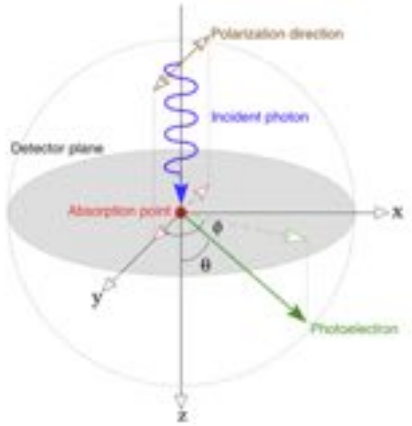
M. Alexeev et al, MPGD Workshop (Trieste 2015)

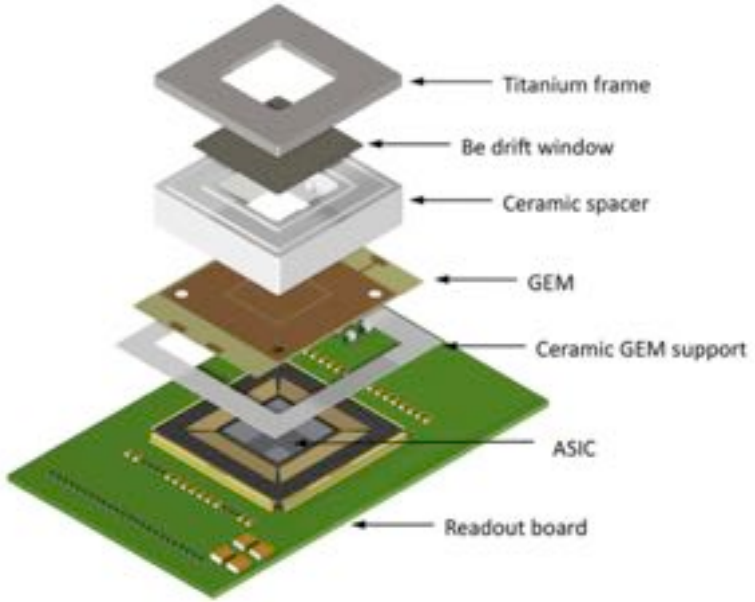




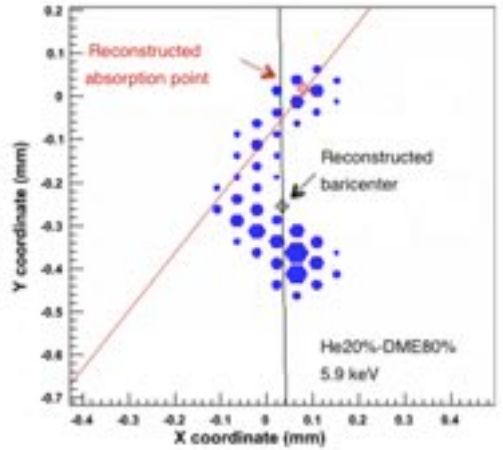
GEM APPLICATIONS: POLARIMETRY

SOFT X-RAY POLARIMETRY

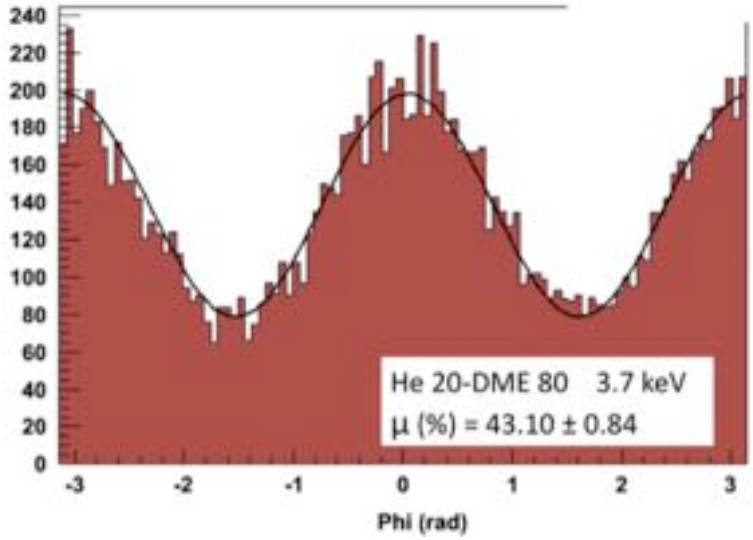




5.9 keV PHOTOELECTRON (80 µm pixels pitch):



MEASURED ANGULAR MODULATION:

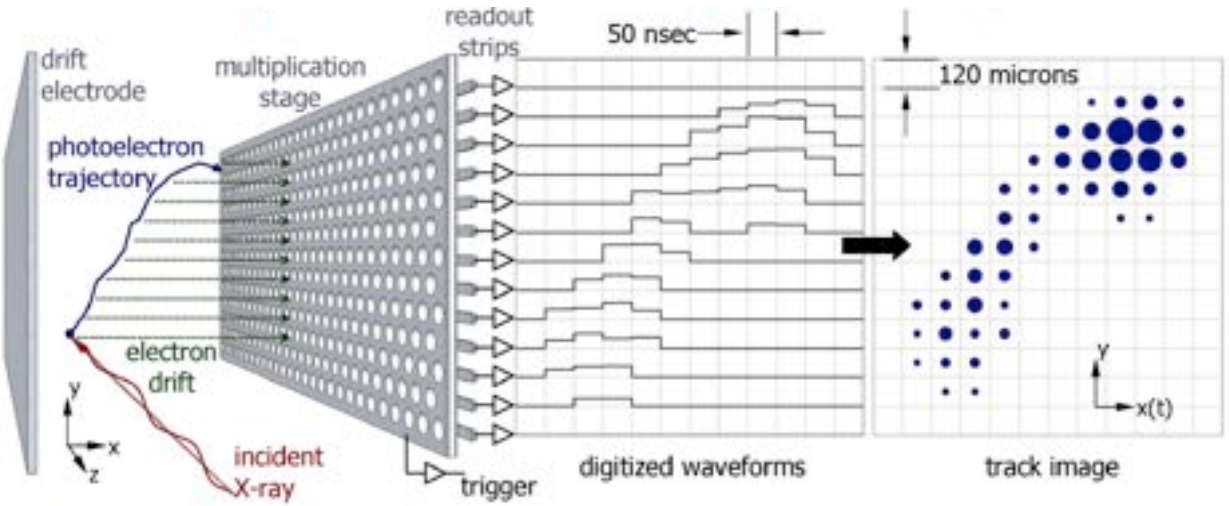


R. Bellazzini et al, Nucl. Instr. and Meth. A720(2013)173

GEMS MISSION CANCELLED BY NASA (2012)

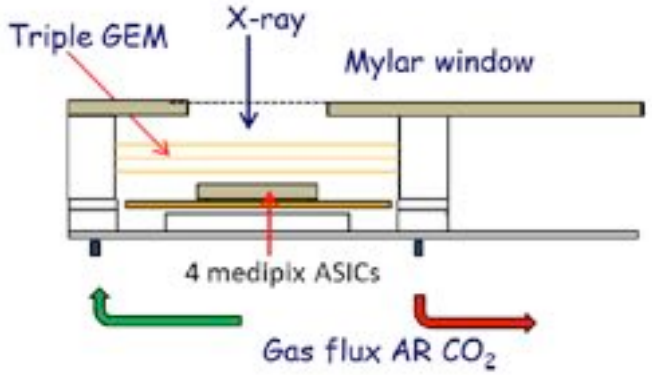
NEW MISSION (2017):
POLARIMETRY FOR RELATIVISTIC
ASTROPHYSICAL X-RAY SOURCES (PRAXyS)

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

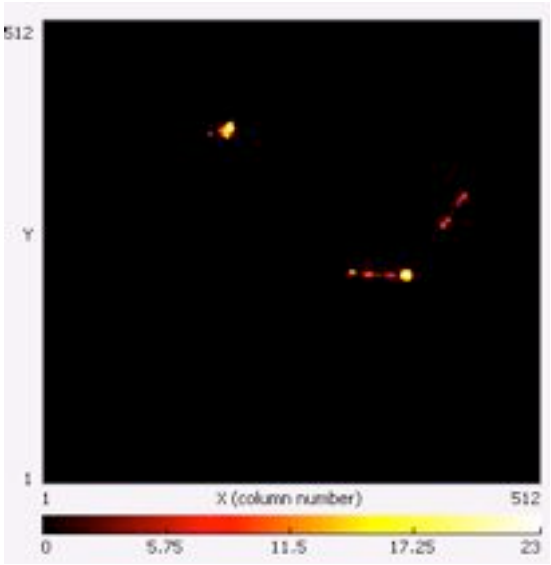


Toru Tamagawa, MPGD Workshop (Saragoza 2013)

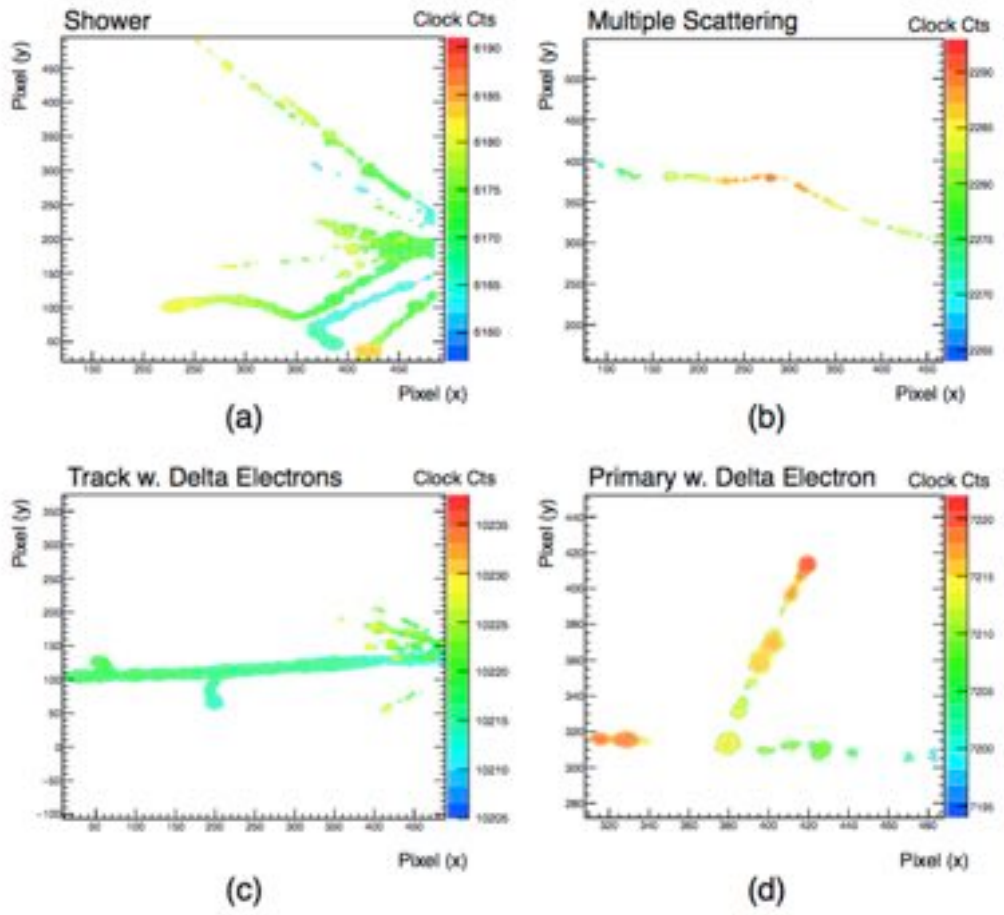
TRIPLE-GEM WITH MEDIPIX READOUT
256x256 pixels, 55x55 μm^2



COMPTON ELECTRON:

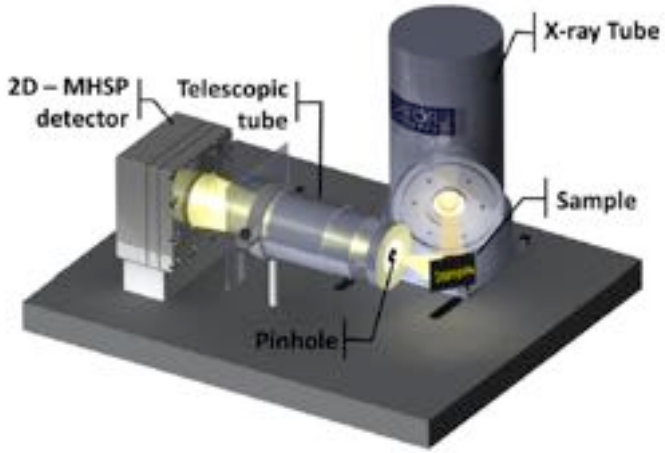


RECORDED EVENTS:

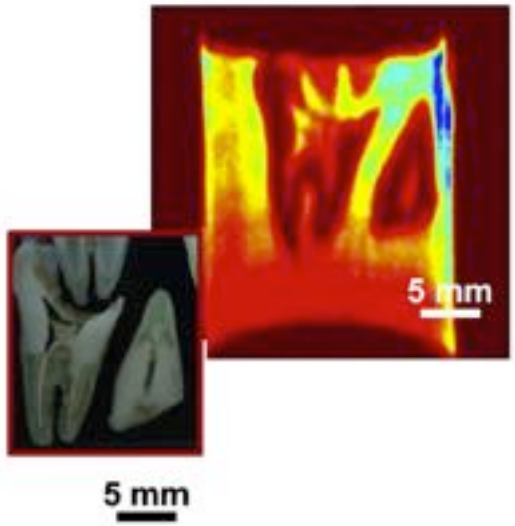


F. Murtas et al, JINST10(2015)P11003

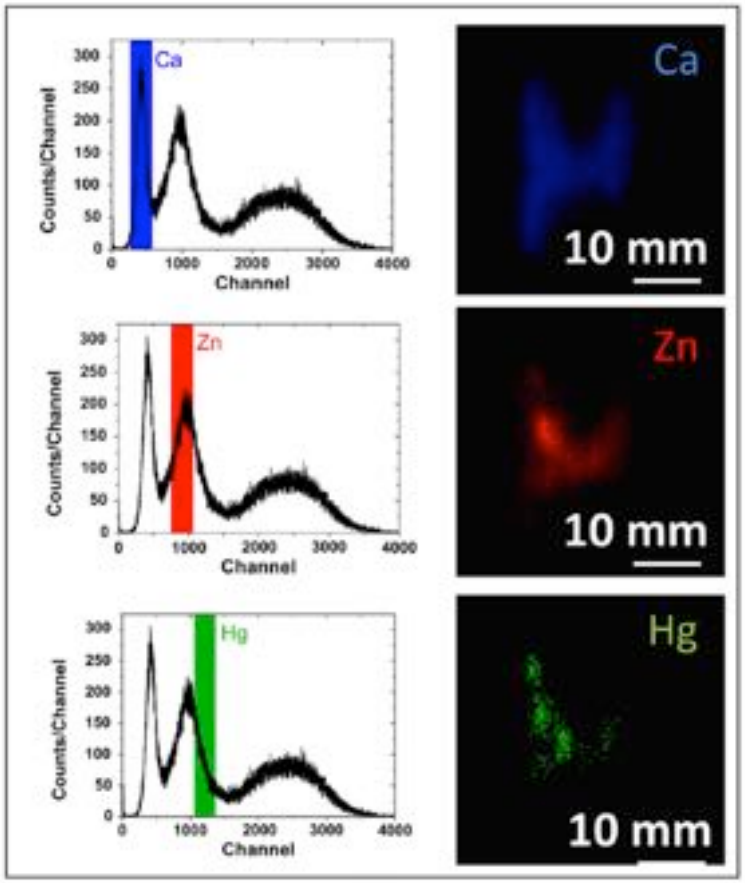
28x28 mm^2 MICRO-HOLE AND STRIP PLATE (MHSP)
WITH RESISTIVE LINES 2-D READOUT



X-RAY TRANSMISSION IMAGE:

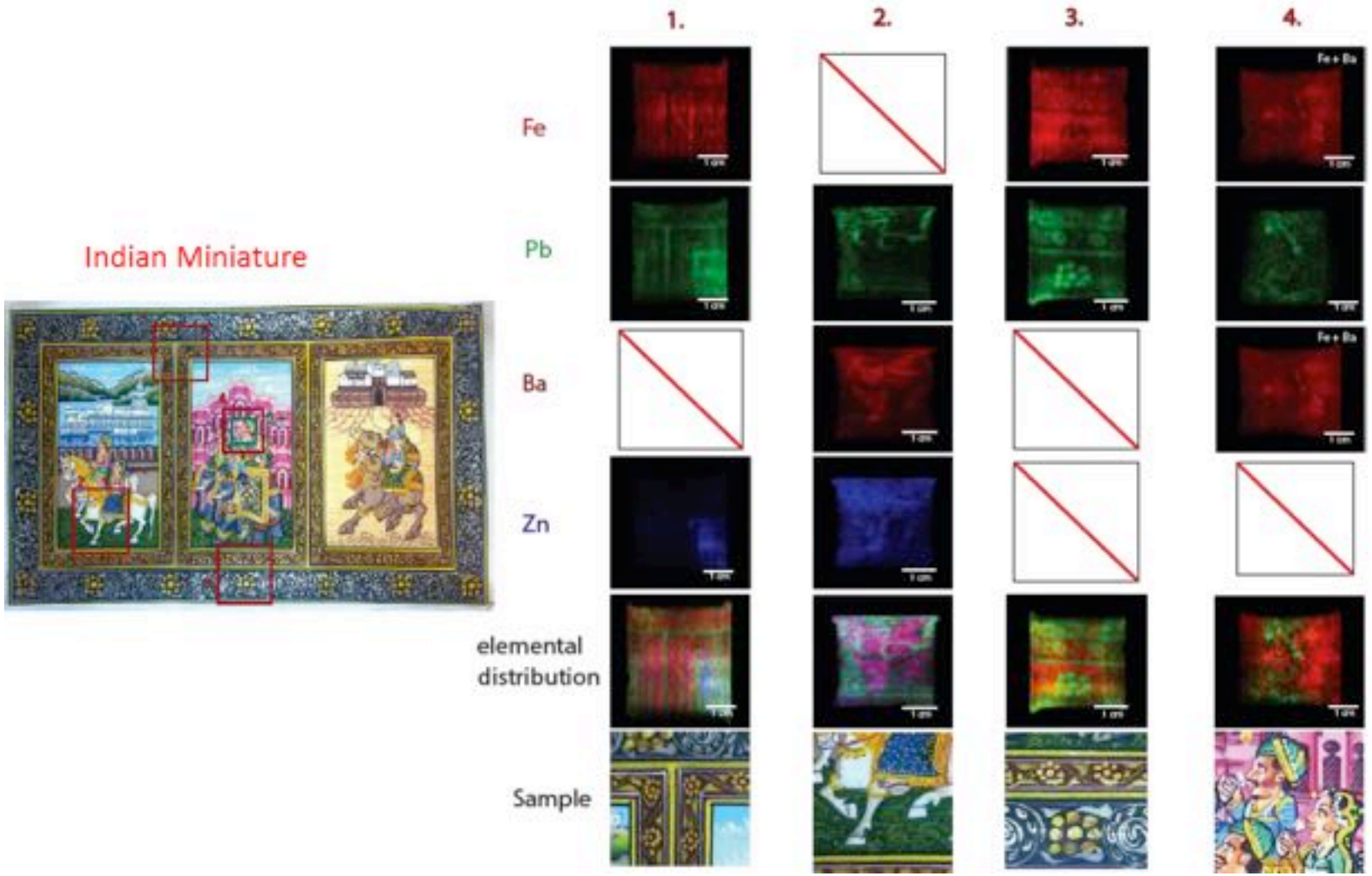


ELEMENTAL ANALYSIS:



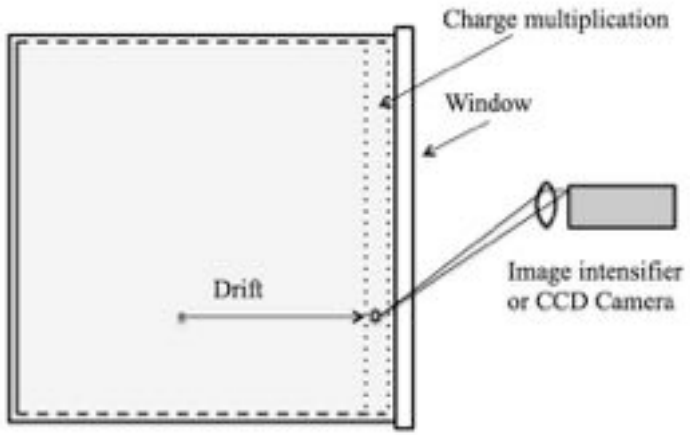
A.L.M. Silva et al, Spectrochimica Acta B86(2013)115

ENERGY-RESOLVED X-RAY FLUORESCENCE

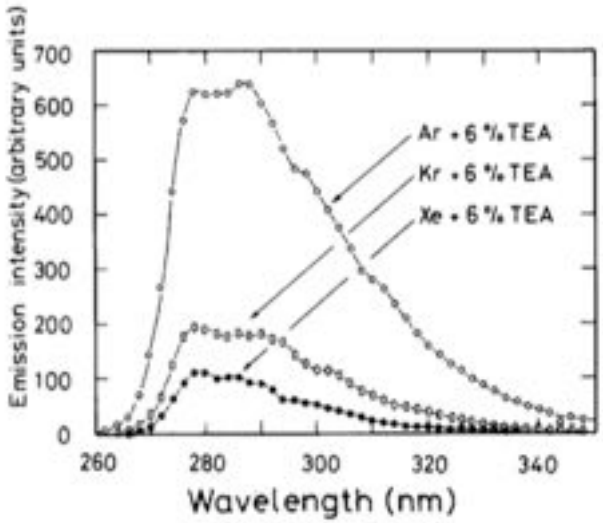


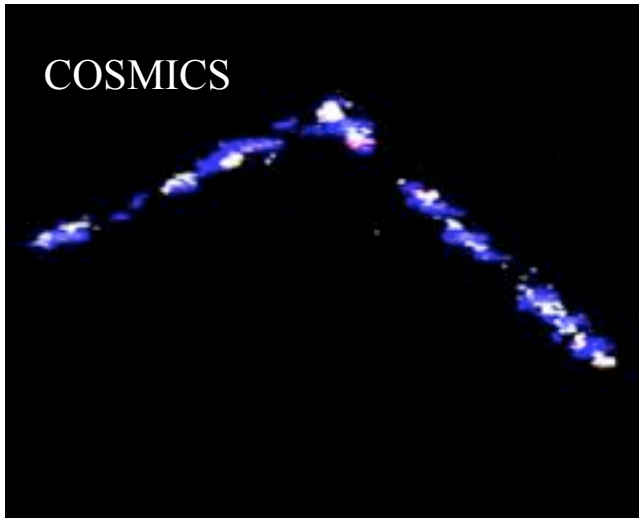
J. Veloso, RD51 Special Workshop on Photon detection (CERN, 2015)

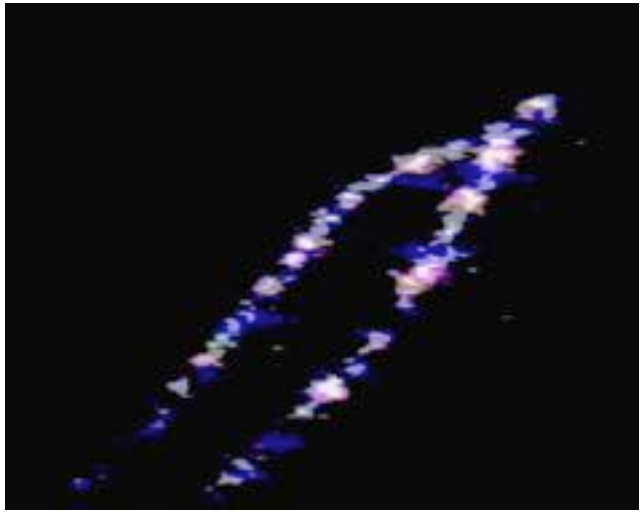
IMAGING CHAMBER (1987)



TRIETHYLAMINE (TEA):
INTERNAL WAVELENGTH SHIFTER

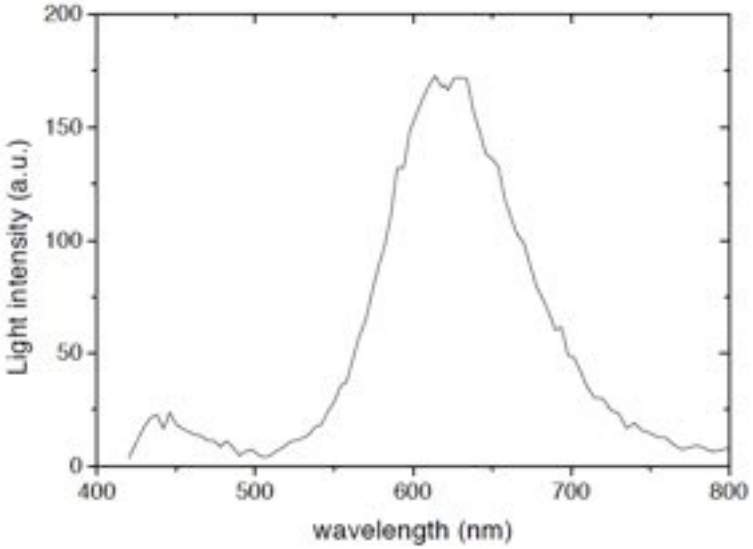


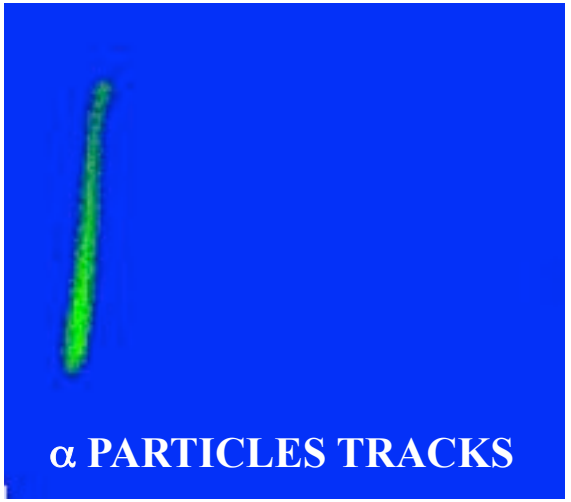




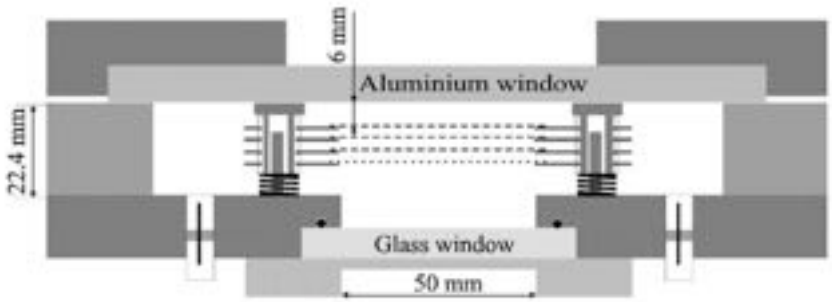
G. Charpak, J.-P. Fabre, F. Sauli and M. Suzuki, Nucl. Instr. and Meth. A258(1987)177

CARBON TETRAFLUORIDE SCINTILLATION:

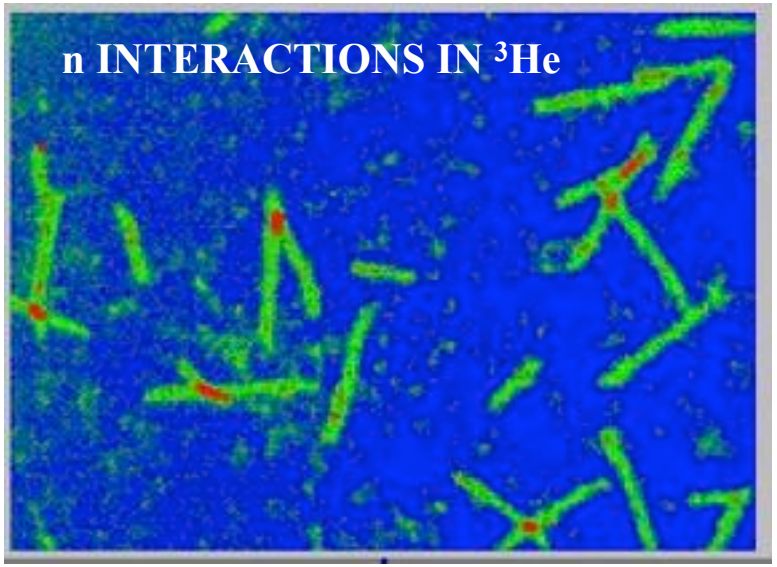




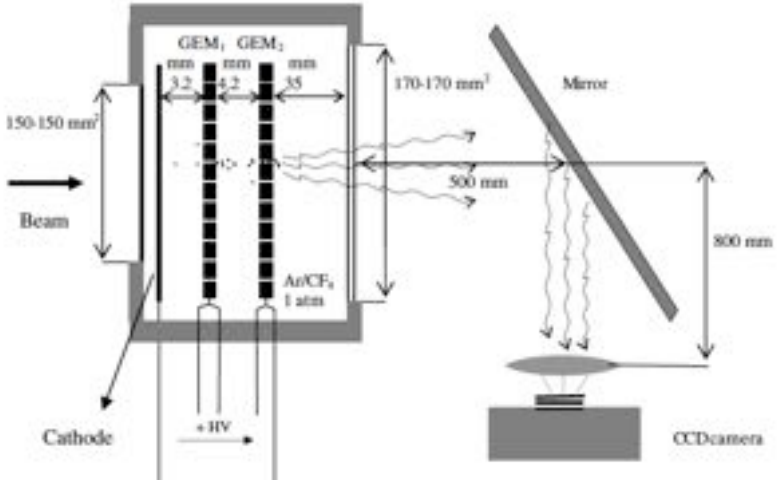
He-CF_4 GAS FILLING

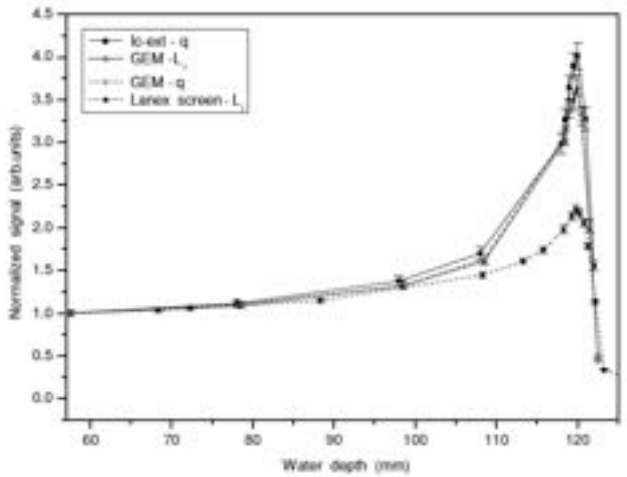


F.A.F. Fraga, et al, Nucl. Instr. and Meth. A478(2002) 357



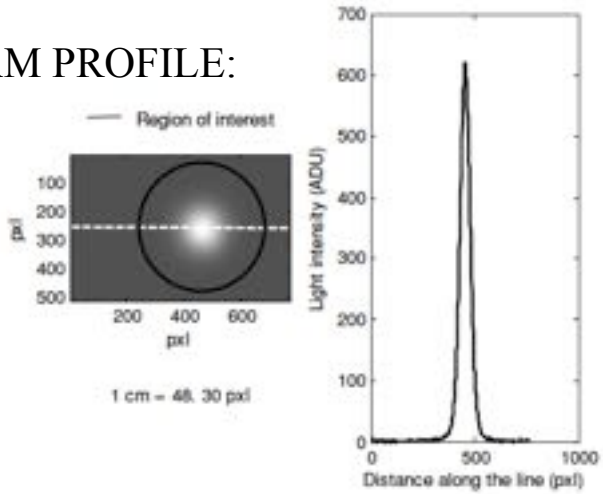
DOUBLE GEM WITH OPTICAL DETECTION



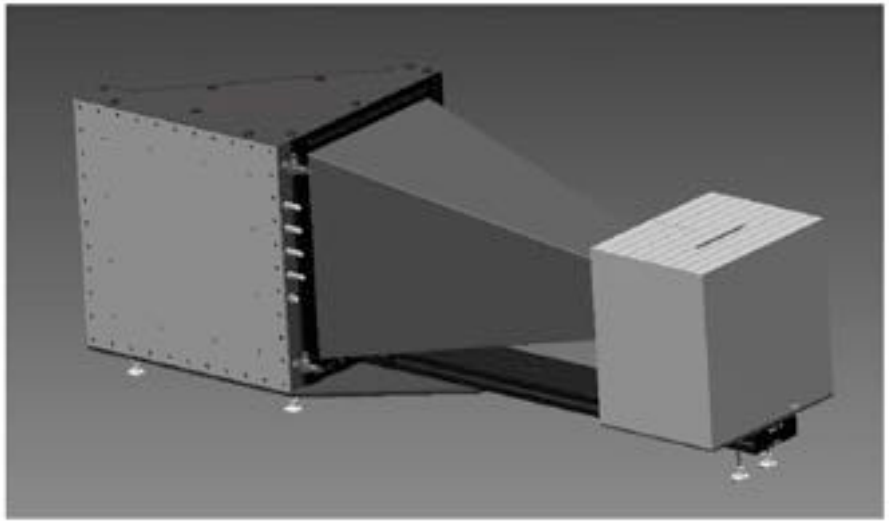


E. Seravalli et al, Phys. Med. Biol. 53(2008)4651

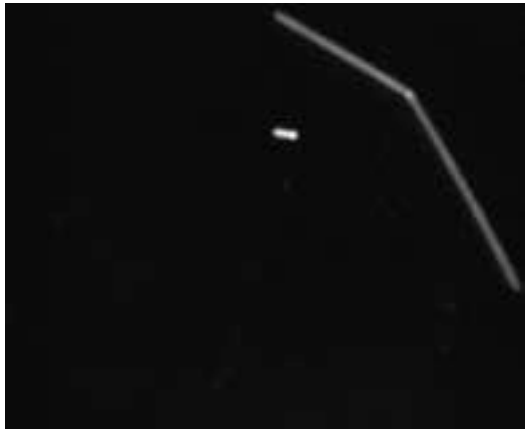
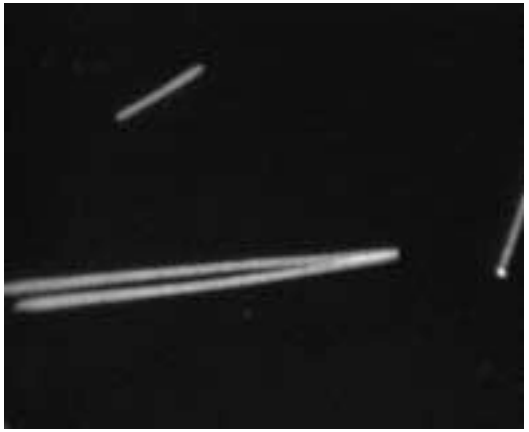
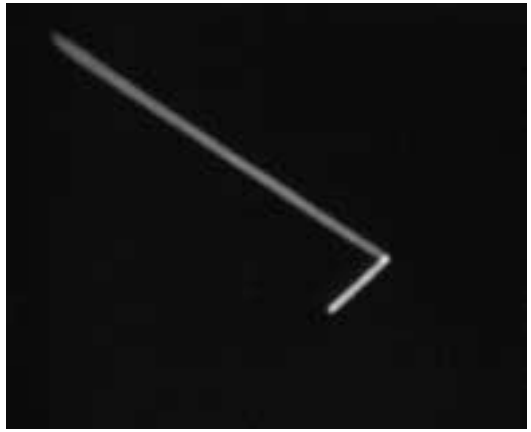
BEAM PROFILE:

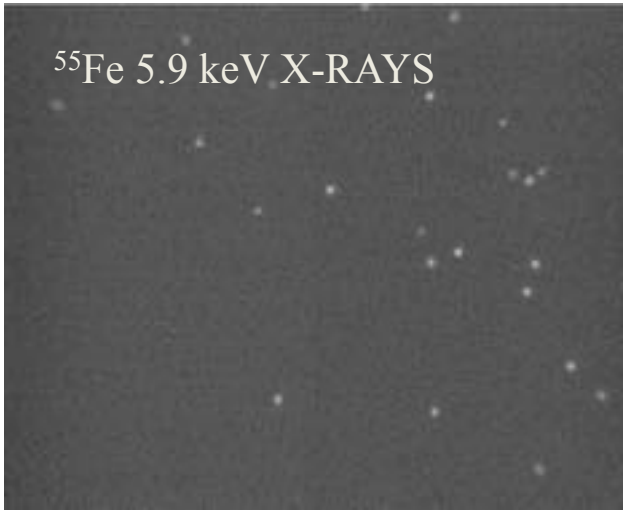


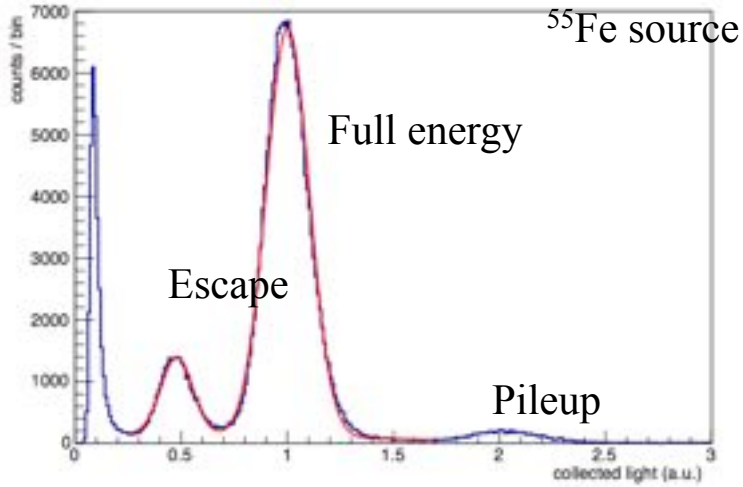
Phenix Medical OptiGEM Dose Imaging Detector User Manual



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

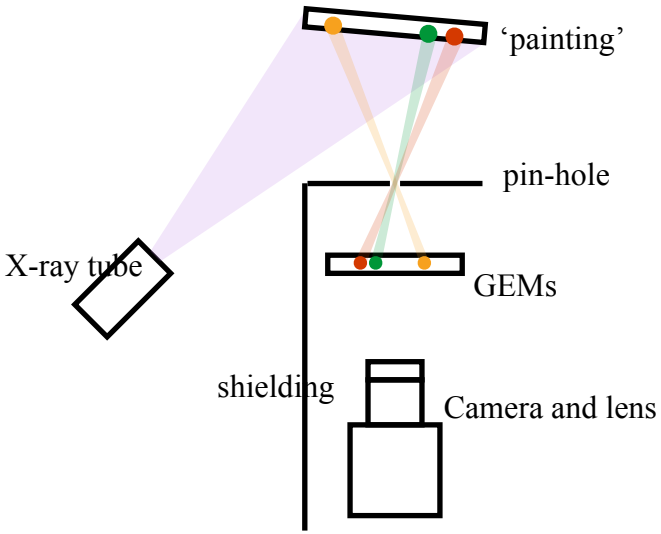




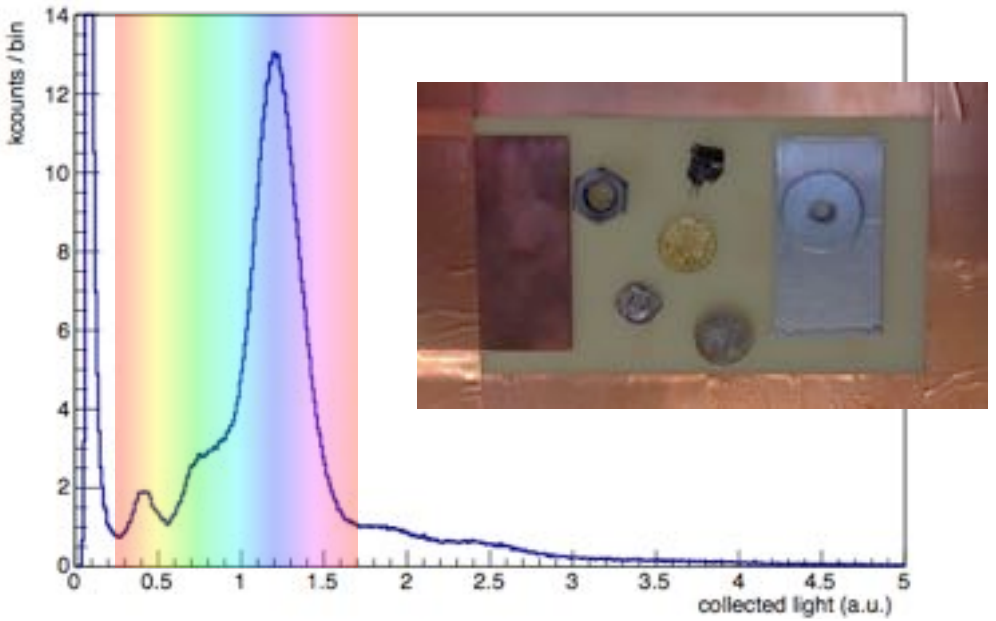


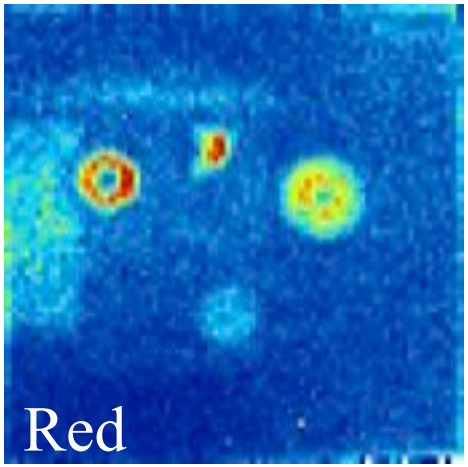


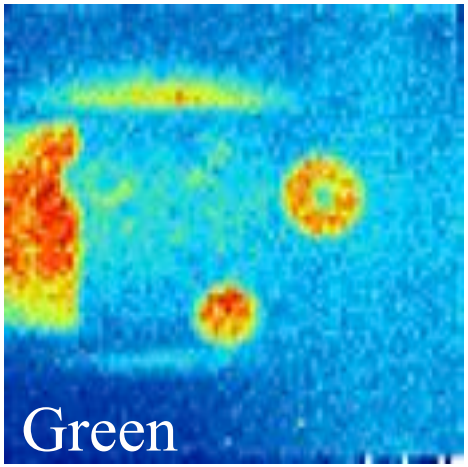
F. Resnati , EP Detector Seminar (CERN, April 29, 2016)

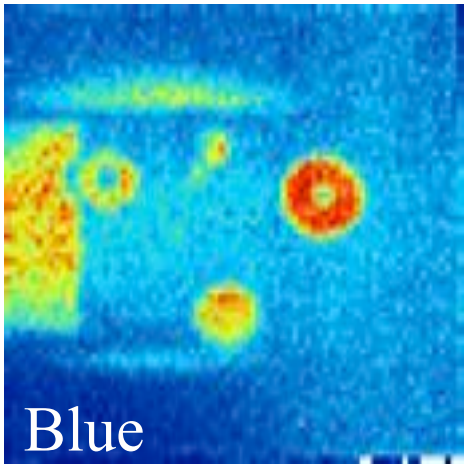
ENERGY RESOLVED FLUORESCENCE ANALYSIS





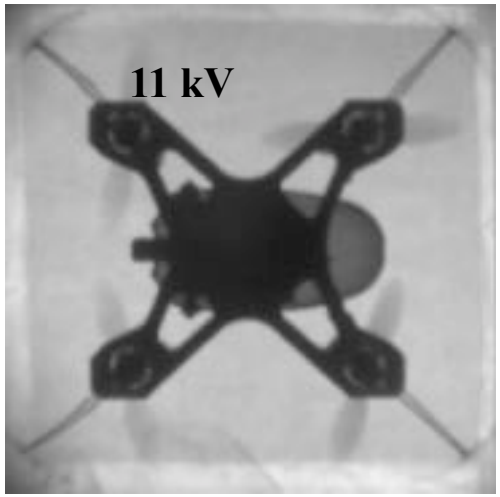


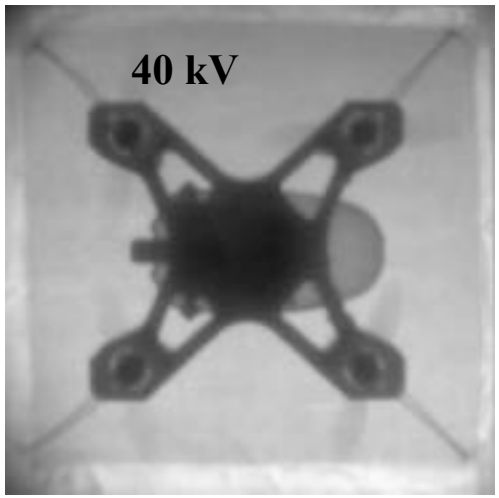




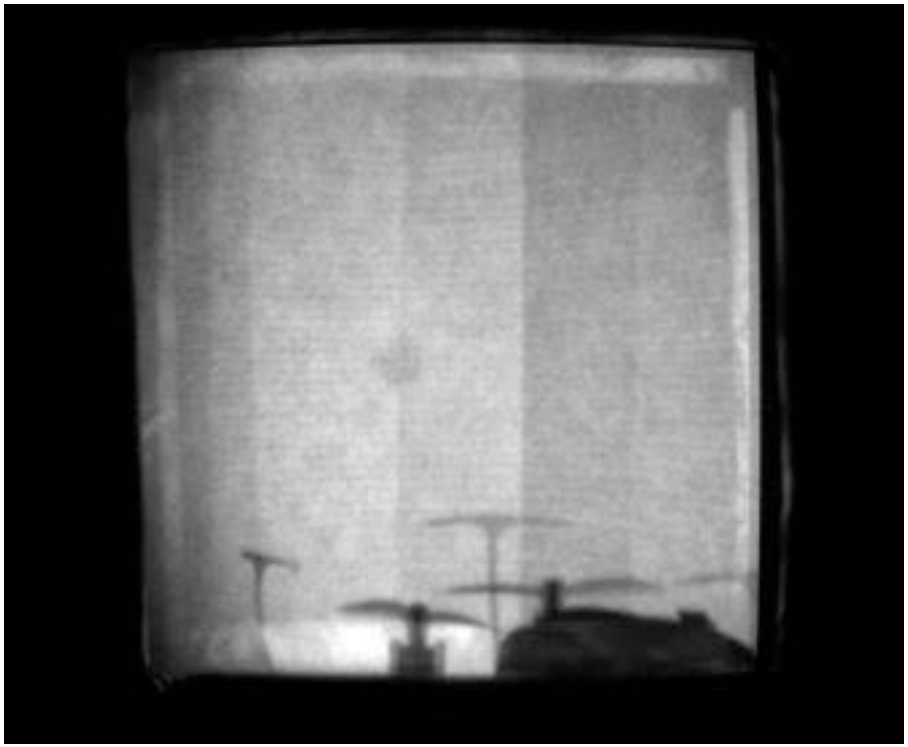
F. Resnati, MPGD Workshop (Aveiro, 2016)

SMALL DRONE-IN-THE BOX



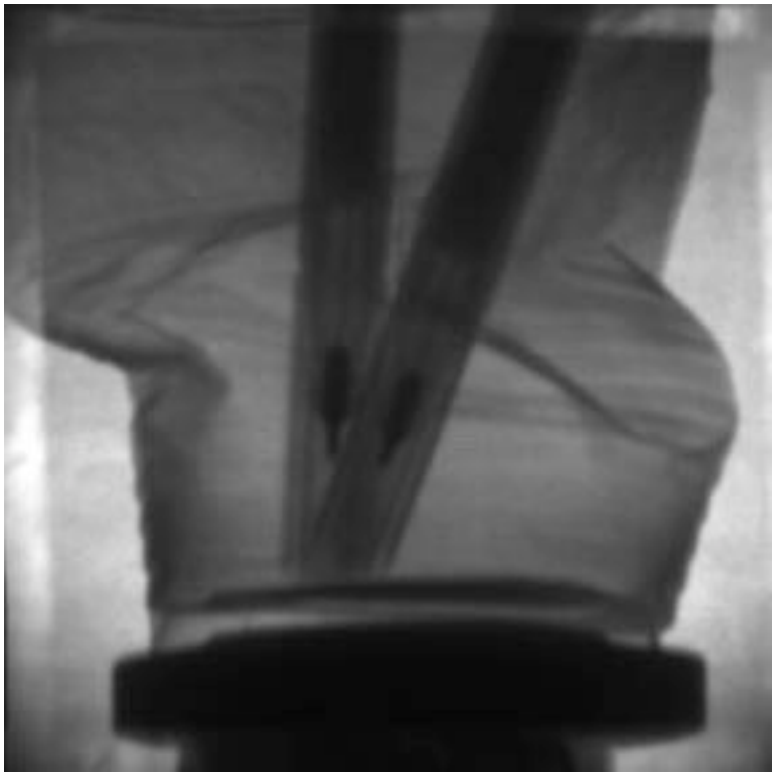


JUMPING DRONE RADIOGRAPHY (30 keV)



F. Resnati, MPGD Workshop (Aveiro, 2016)

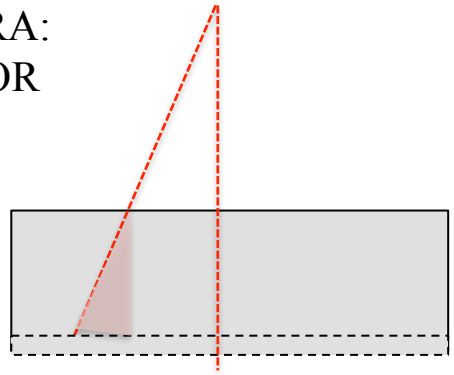
IMAGE -> SINOGRAMS -> FILTERED BACK PROJECTION -> 3D IMAGE



F. Resnati, MPGD Workshop (Aveiro, 2016)

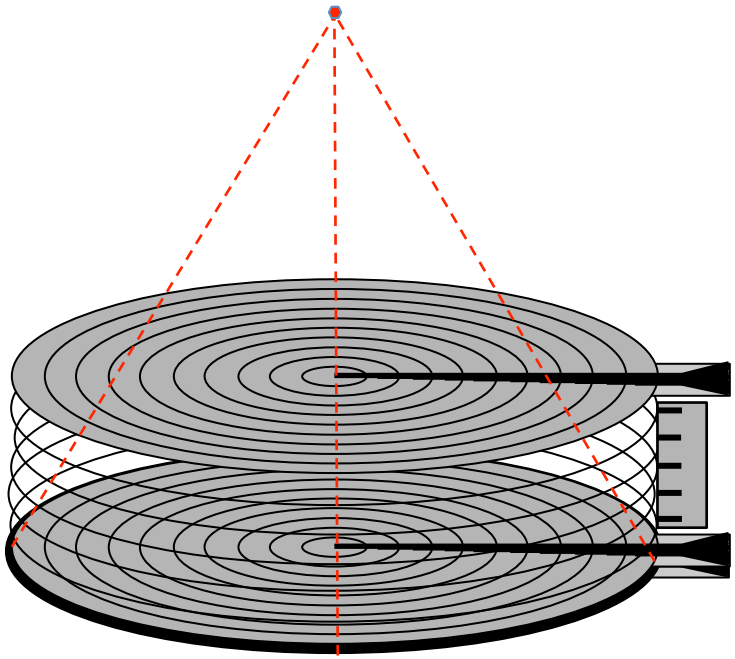
CORRECTION OF THE PARALLAX ERROR

PINHOLE CAMERA:
PARALLAX ERROR



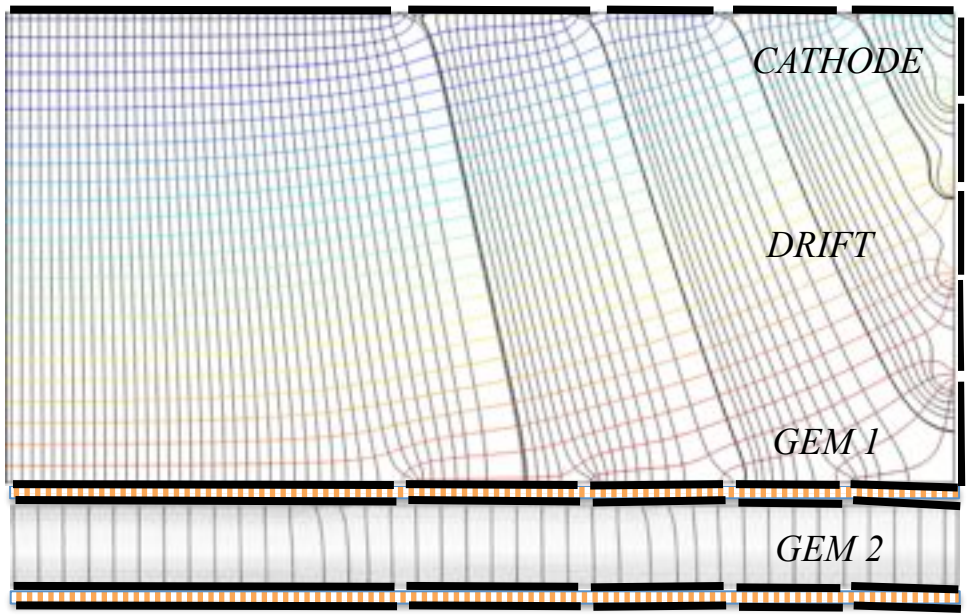
PLANISPHERICAL GEM

CONCENTRIC GRADED POTENTIAL RINGS
ON CATHODE AND GEM ELECTRODES



F. Sauli, PCT Patent WO99/21211

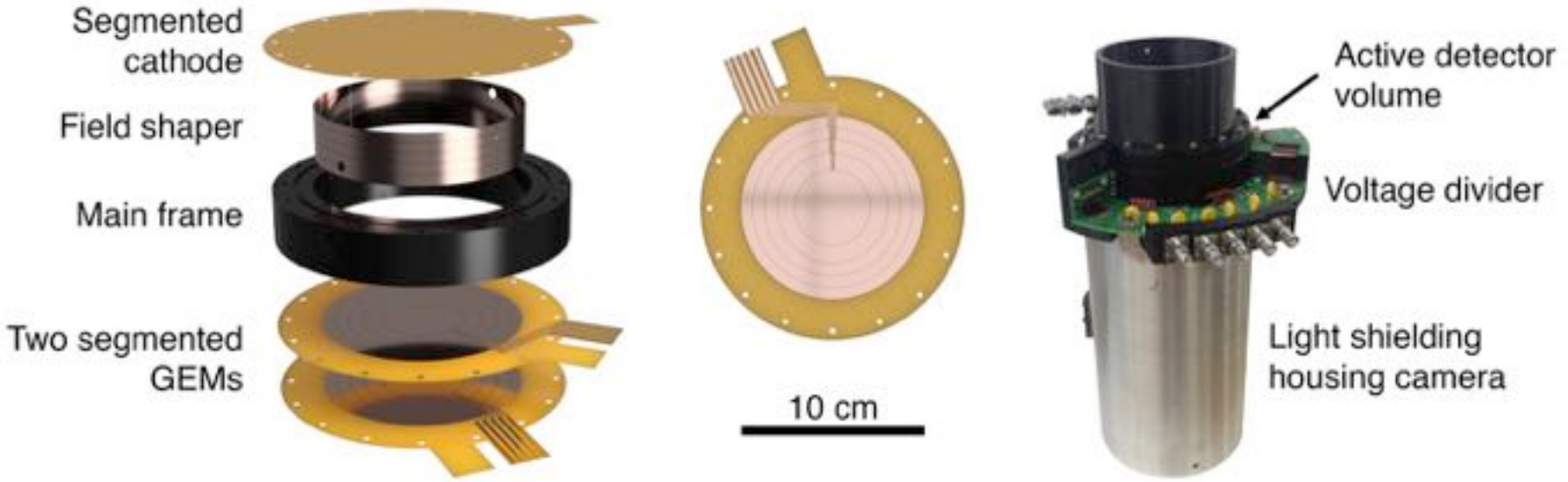
RADIAL CONVERSION AND DRIFT:



Computed with COMSOL Multiphysics

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

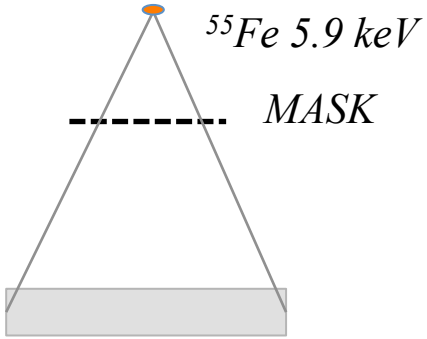
10 cm Ø 10 cm FOCUS (ADJUSTABLE)



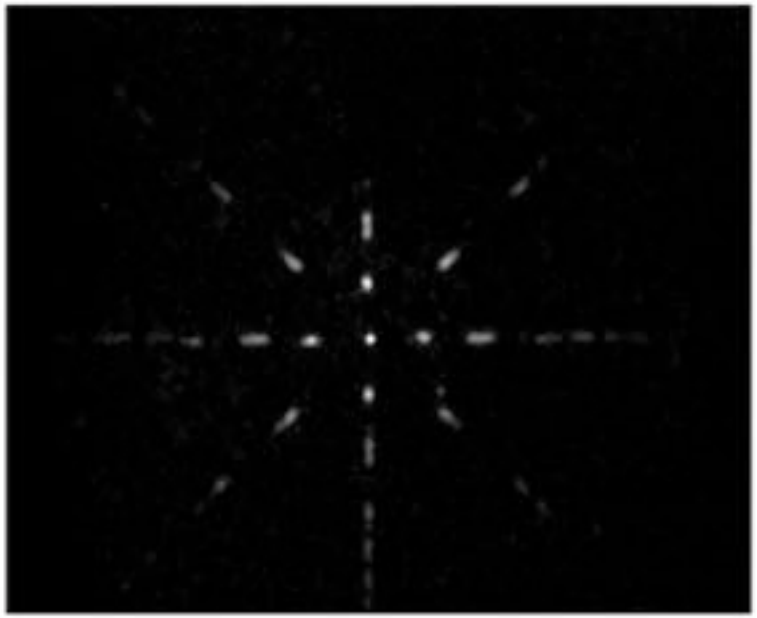
... F. Brunbauer.....M. Van Stenis.....

PLANISPHERICAL GEM

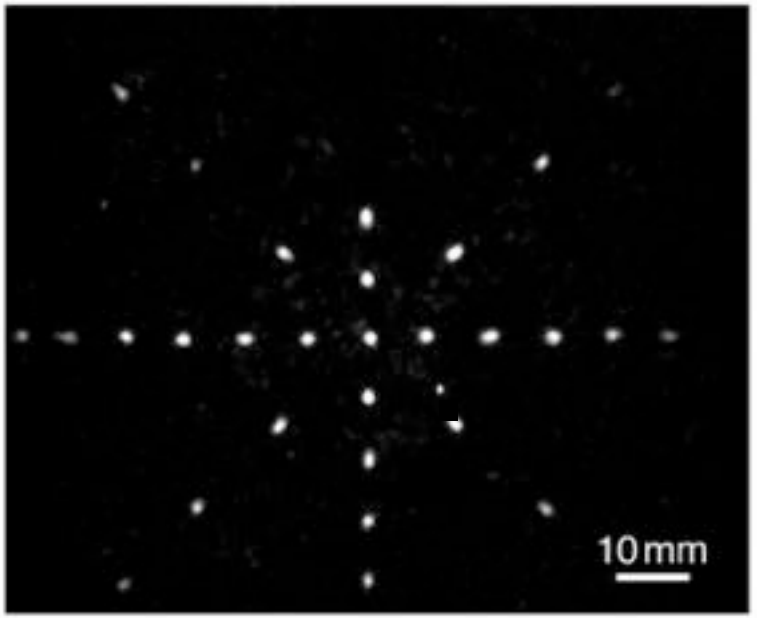
MASK WITH 1 mm Ø HOLES PATTERN



UNIFORM DRIFT FIELD



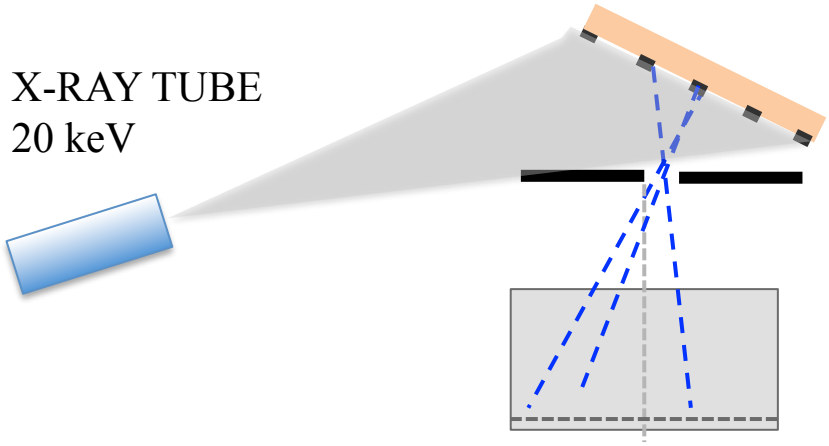
RADIAL DRIFT FIELD

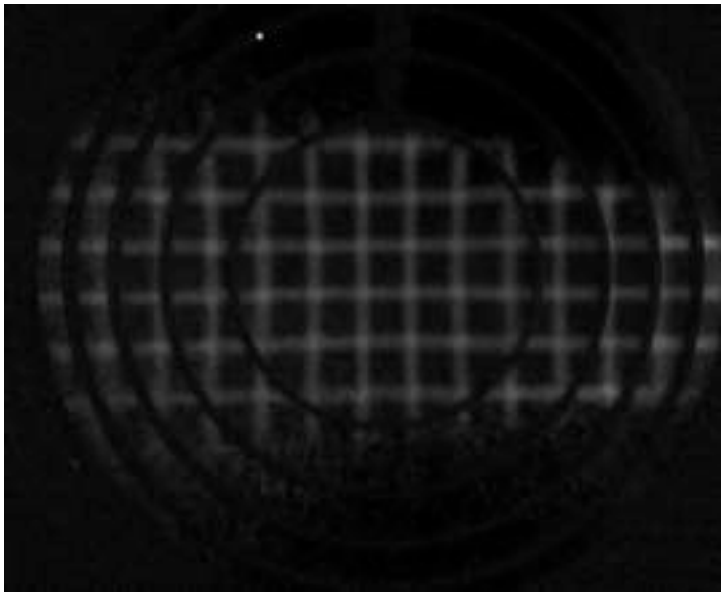


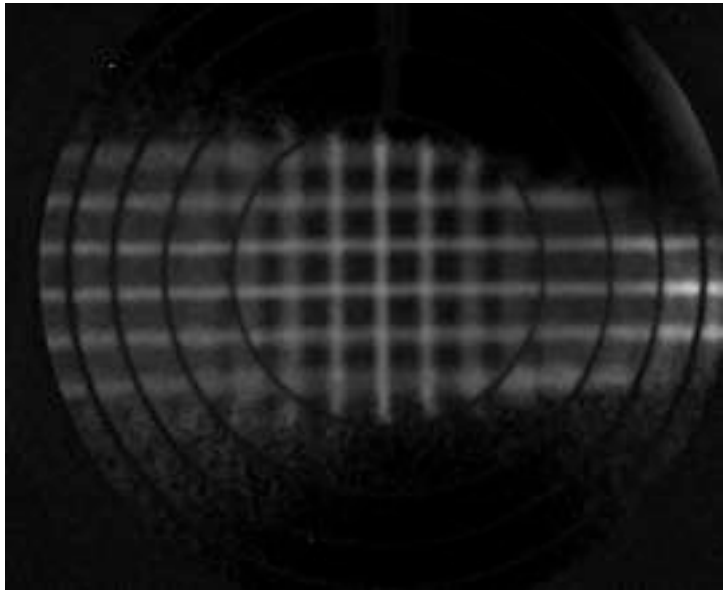
F. Sauli, MPGD Workshop (Aveiro 2016)

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

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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.