

# 微结构气体探测器

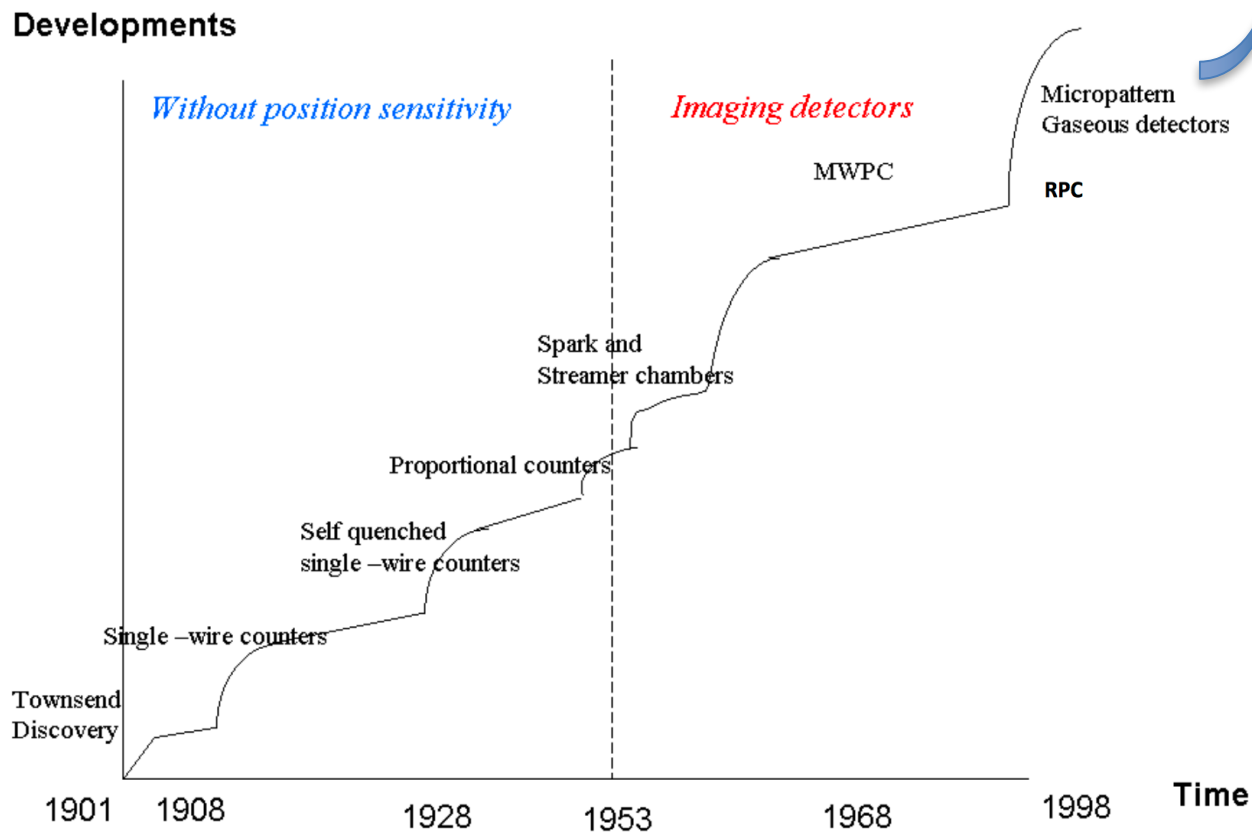
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2017年11月14日

# 气体探测器发展史

- 微结构气体探测器（**M**icro-**P**attern **G**aseous **D**etector：**MPGD**）是当今气体探测器发展的主流和前沿。



# 什么是微结构气体探测器？



micro pattern gas detector



All

Images

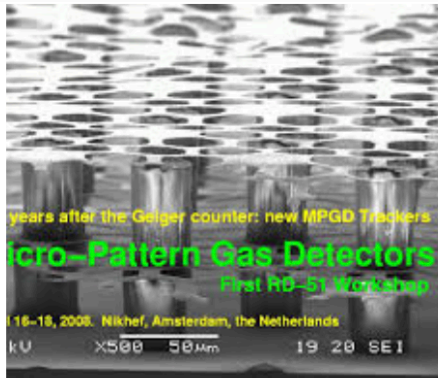
Videos

News

More

Settings

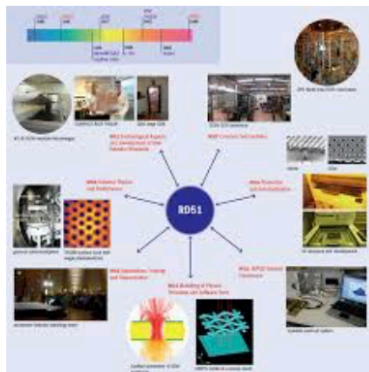
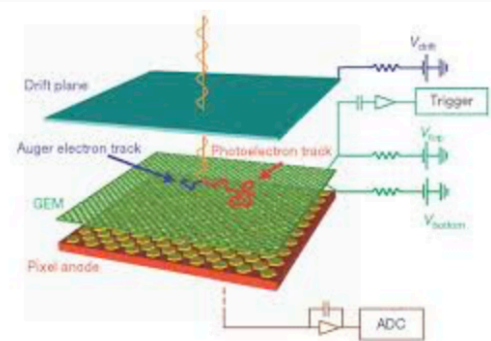
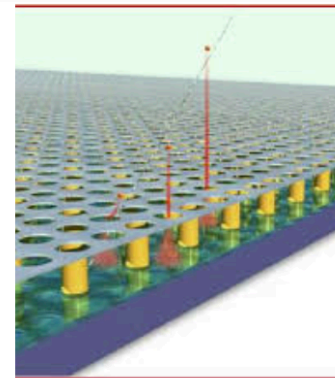
Tools



### Micro-pattern gas detectors: layout and features

Gas-avalanche detector containing a gas layer as signal generator with a CMOS readout pixel array

- particle track image (projection)
- 3D track reconstruction
- no sensor leakage current compensation
- low parasitic capacitance (less than 10fF)
- micro-discharges in avalanche gap



### Gas Electron Multiplier (GEM) Detector

- It is micro pattern gas detector(MPGD)
- Consists of GEM foil that is made up of kapton foil coated with copper on both sides and has array of holes which are equidistant usually 140µm
- High voltage is applied across foils, which creates avalanche of electrons through holes
- Provides good efficiency and spatial resolution
- Provide a gain of 10<sup>4</sup> with gas mixture of Ar/CO<sub>2</sub>

Triple GEM configuration: Most popular and reliable

### X-Ray Polarimetry with Micro Pattern Gas Detectors

The micro-pattern gas detector scheme

### Current Trends in Micro-Pattern Gas Detectors (Technologies)

Semiconductor industry technology:

- Photolithography
- Etching
- Coating
- Doping

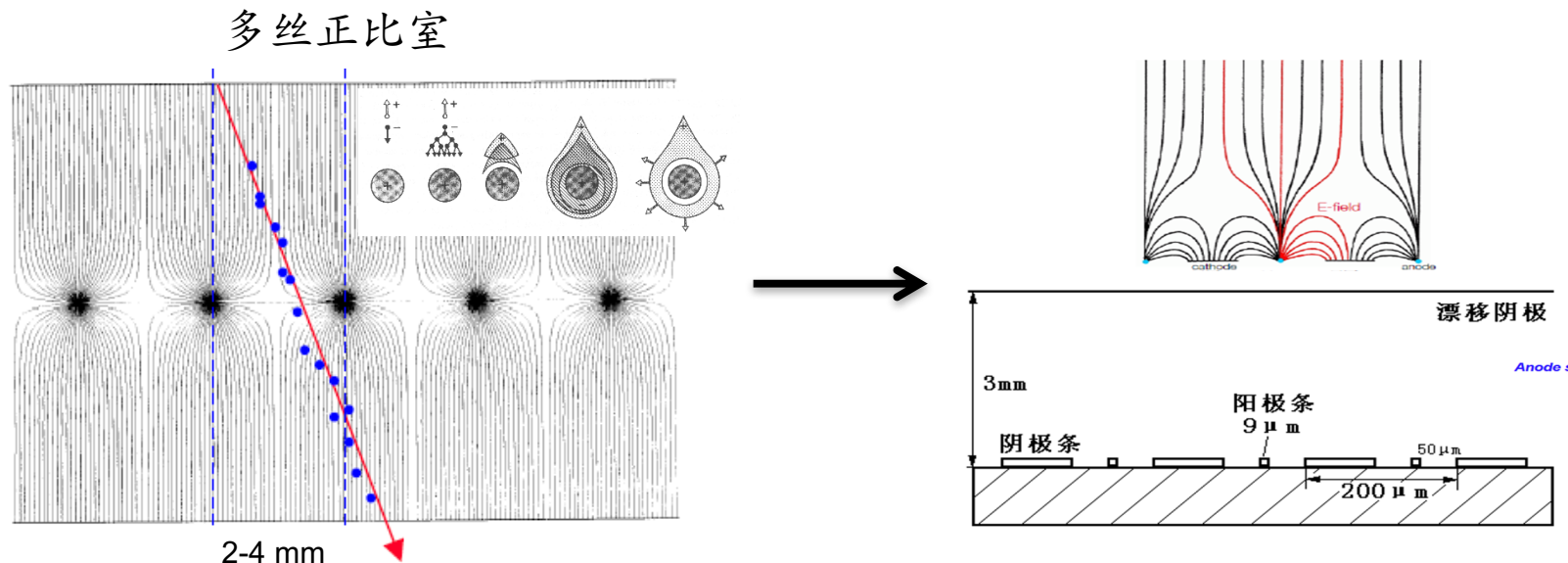
Operational instabilities:

- Rate Capability > 10<sup>10</sup> cm<sup>-2</sup> s<sup>-1</sup>
- Residual Resistance < 10µm
- Track Resolution < 10µm
- Discharges
- Polymers (outgassing, ageing)

MWPC      MSGC

电极距离极小(<1mm)的高颗粒度气体探测器

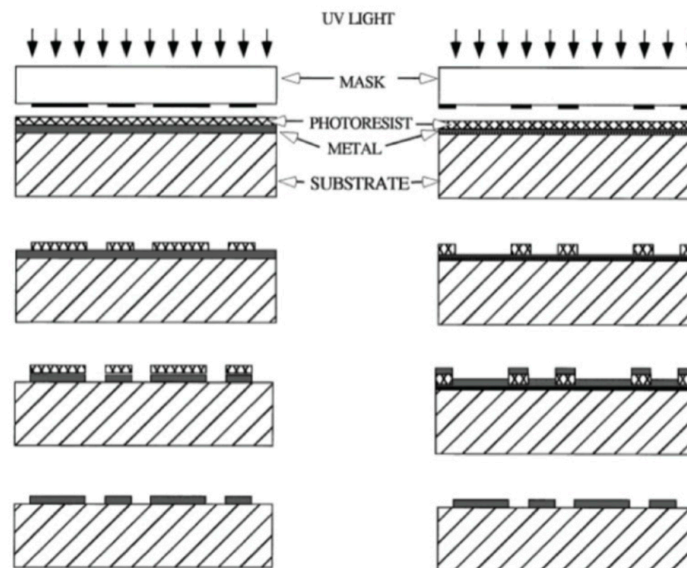
# 为什么要“微结构”？



- 传统丝室计数率能力低、位置分辨不够高，不能满足新一代高计数率高精度实验的要求（LEP→LHC）。
- 缩小电极之间的距离能克服以上不足 → 微结构
  - 加快离子收集速度 → 高计数率能力
  - 提高探测颗粒度 → 高位置分辨

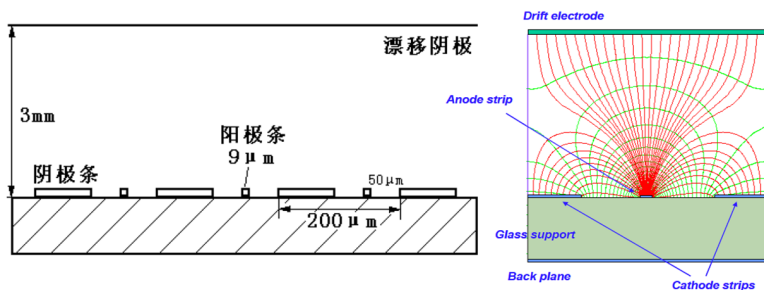
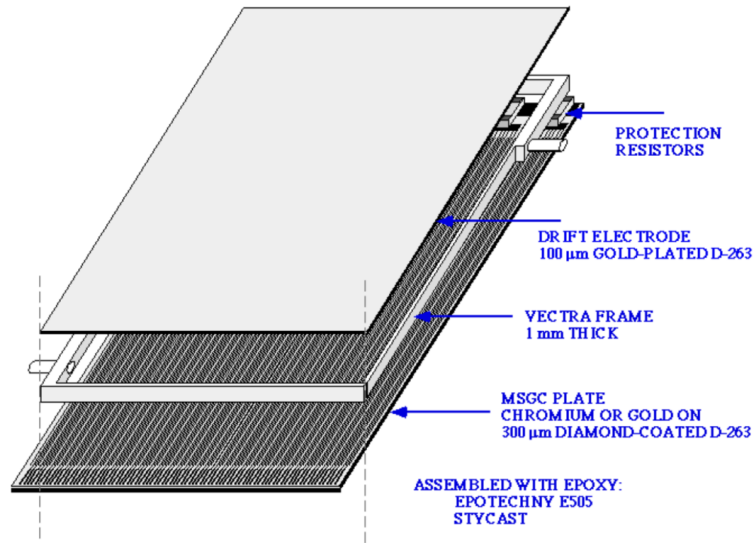
# 如何实现“微结构”

- 真正的突破：1988年，A. Oed 将微电子制造中的光刻工艺引入气体探测器制作中，并制作出了第一个微结构气体探测器 → 微条室 (MSGC)



光刻工艺的引入引发了微结构气体探测器的蓬勃发展

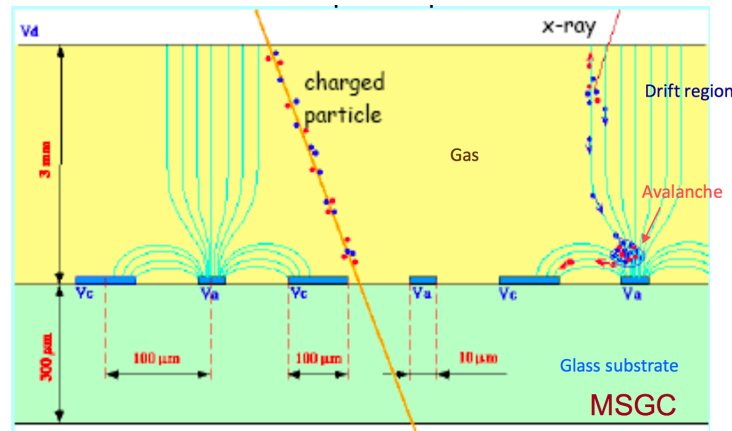
# 微条室



- 条状的阳极 ( $5\sim 10\mu\text{m}$ 宽) 和阴极 ( $50\sim 100\mu\text{m}$ 宽) 在同一平面上交替排列，间距很小 ( $50\sim 200\mu\text{m}$ )，阳极条宽度很小，在附近区域形成强电场。
- 漂移电极与阴极阳极平面之间形成转换漂移区 ( $2\sim 6\text{mm}$ )。
- 入射粒子在漂移区产生的原初电离电子沿电力线向阳极漂移，在阳极附近的强电场区发生雪崩放大。
- 雪崩产生的电子和大部分正离子分别被阳极和阴极快速收集，并感应出快信号。

# 性能特点

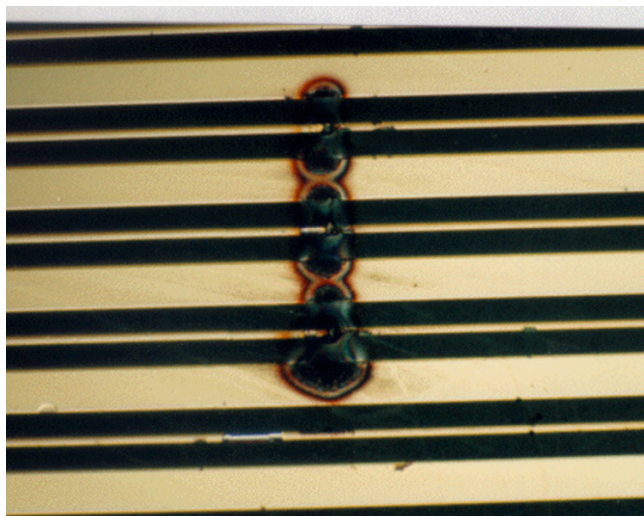
- 位置分辨高，可达 $30\text{-}50\ \mu\text{m}$
- 双径迹分辨可达 $\sim$ 几百 $\mu\text{m}$
- 计数率能力  $> 10^6\ \text{Hz}/\text{cm}^2$ 
  - 正离子漂移至阴极被收集的时间仅几十ns
- 正离子容易在绝缘基材表面上堆积，导致局部放电，所以气体增益不能太大( $\sim < 10^4$ )



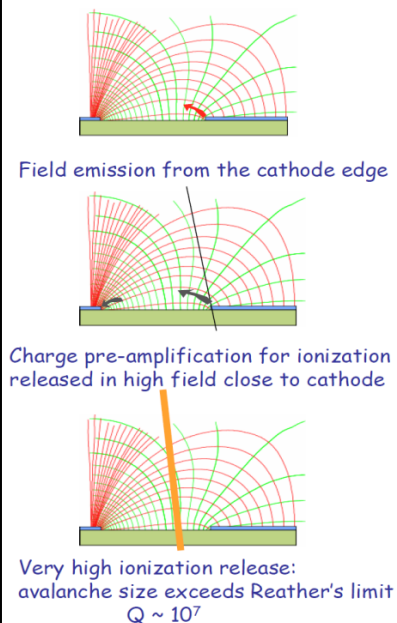
缺点：易放电，稳定性不高，气体增益不能太高

# 放电和老化

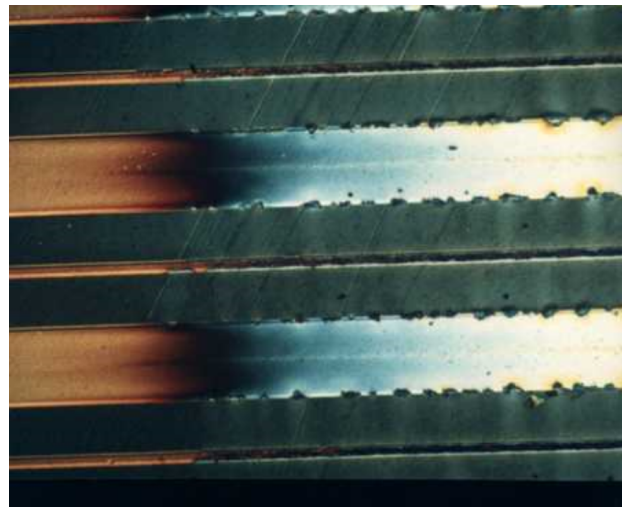
极具破坏性的放电现象



MSGC: Discharge mechanisms



导致探测性能持续下降的老化现象



阳极和阴极同处绝缘基材上，彼此距离很近，大量正离子容易堆积绝缘体表面，产生放电。当电离较强或气体增益较高时，气体放大很容易转变为流光模式直至火花放电。这些放电现象会造成电极的永久性损坏，很难预防和控制。

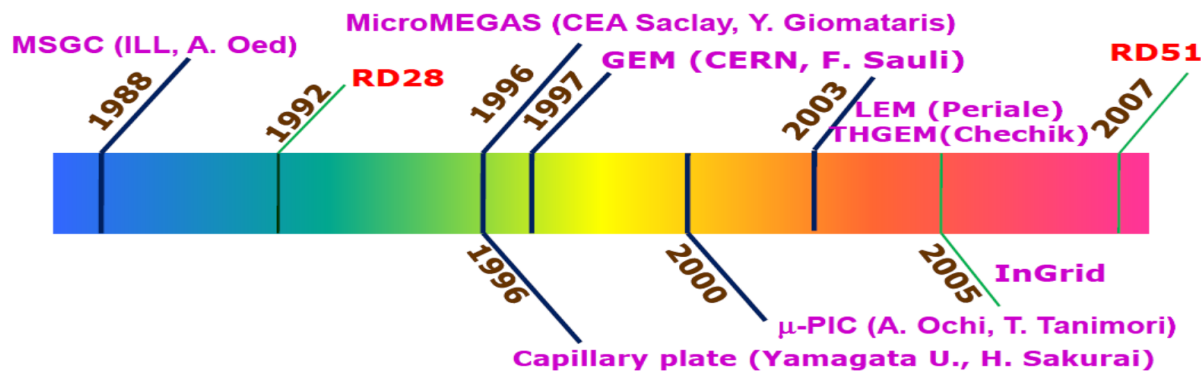
气体分子离解，产生自由基，最终在电极表面形成沉积物，导致性能变坏。微条气体室的气体放大有效区域很集中，使得老化效应更显著。

**由于以上原因，微条气体室未能在大型实验中得到广泛应用。**



# MPGD发展历程

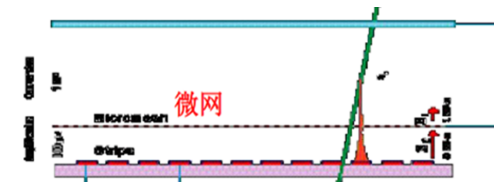
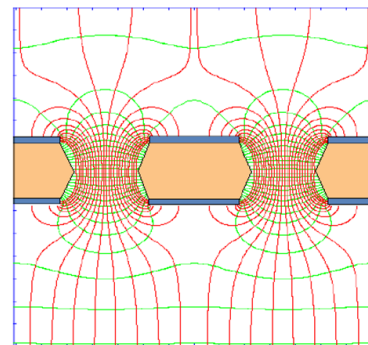
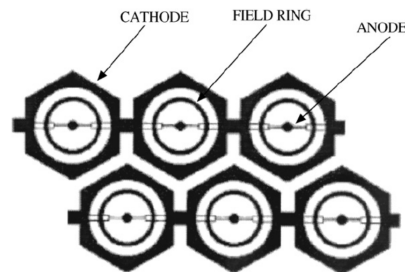
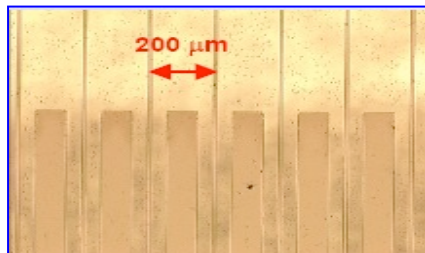
- 高计数率下的老化效应和强电离诱导的打火损伤限制了微条室的应用。
- 但二十多年来，微电子工艺和印刷版电路技术的进步极大促进了微结构气体探测器的发展。
- 各种新的微结构概念不断涌现，相关技术不断发展。
- 2007年成立RD51合作组
- 目前比较主流和成熟的技术
  - MicroMegas、GEM、THGEM



注：此图显示的只是所有开发的微结构气体探测器的一部分

# 特点和分类

- **结构特点**：通常包括原初电离产生和电子漂移的区域（转换漂移区）、气体放大区和信号读出电极。
- **性能特点（趋势）**：高计数率能力、高位置分辨、好的时间分辨和能量分辨、抗辐照、离子和光子反馈小、大面积、低造价
- **主要类型**：条型、点型、孔型、平行面型



# 微网结构气体探测器

## MicroMEGAS

(Micro-MEsh Gaseous Structure)

Y. Giomataris



1996年

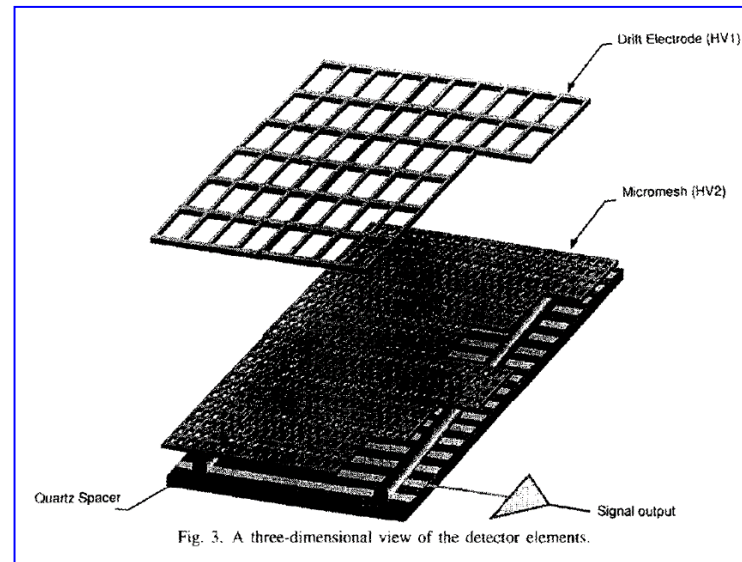
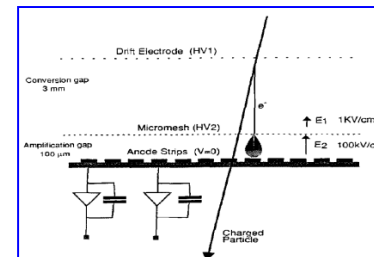
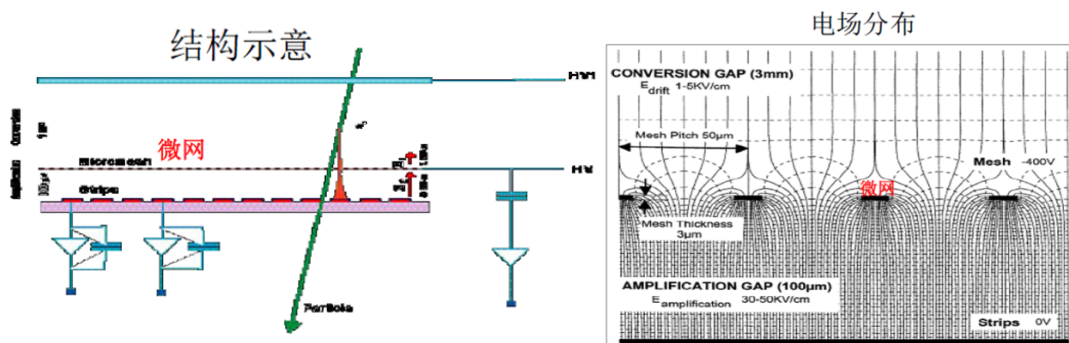
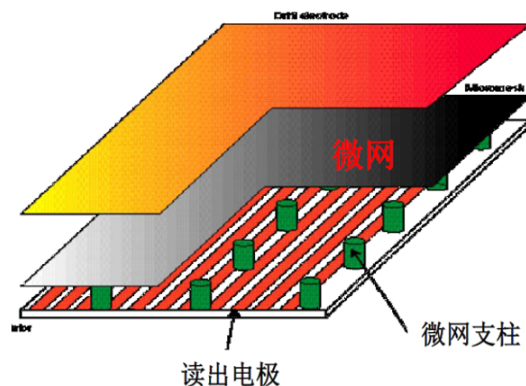
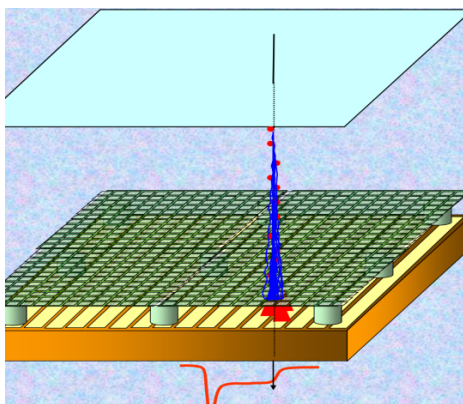


Fig. 3. A three-dimensional view of the detector elements.

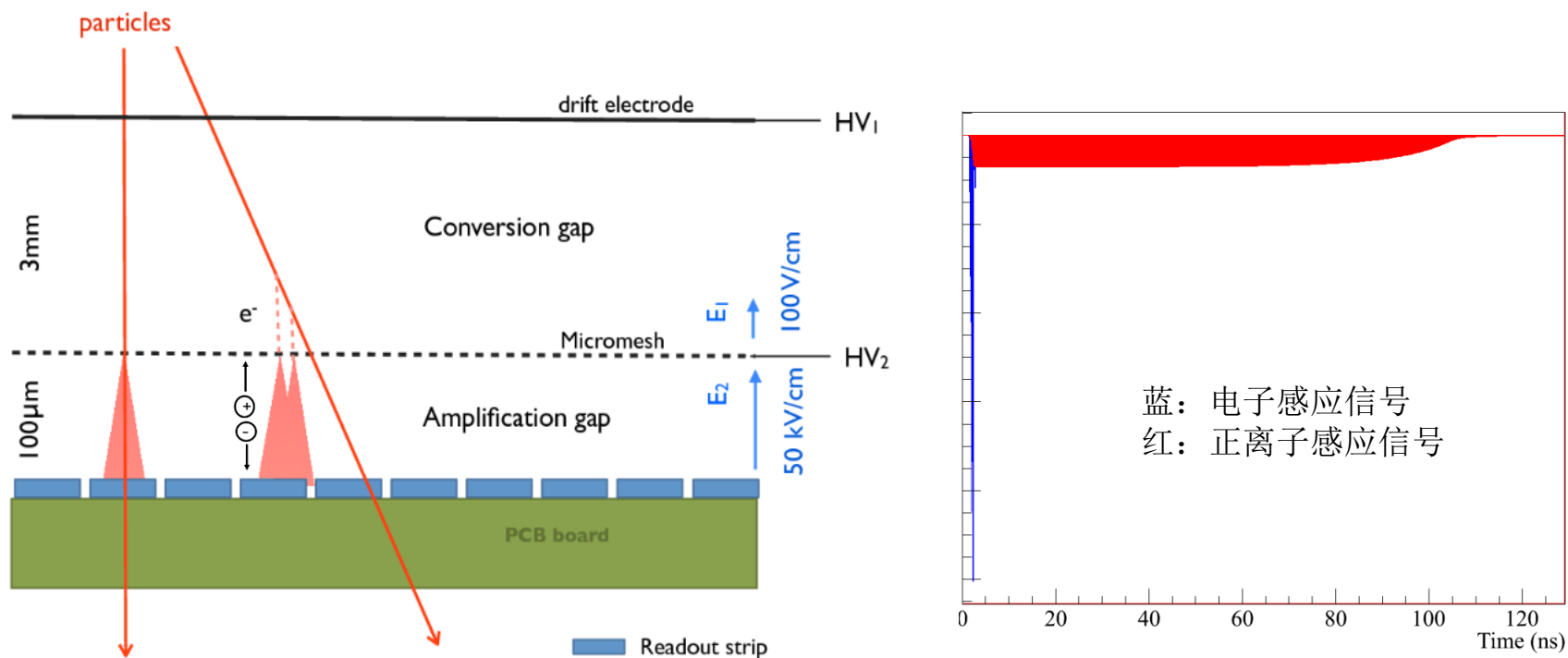


# 基本结构和原理



- 关键部件是一个具有无数微孔(尺度:几十到上百 $\mu\text{m}$ )的金属丝网结构。
- 漂移电极和金属微网之间形成转换漂移区(3~5mm)
- 金属微网和读出电极之间间隙很窄(几十到上百 $\mu\text{m}$ ), 电场强度很大, 形成气体放大区。
- 入射粒子在转换漂移区产生的电离电子向微网漂移, 穿过微网进入气体放大区, 发生电子雪崩放大。
- 雪崩产生的电子和正离子分别被读出电极和微网迅速收集, 同时感应出快信号。

# 输出信号

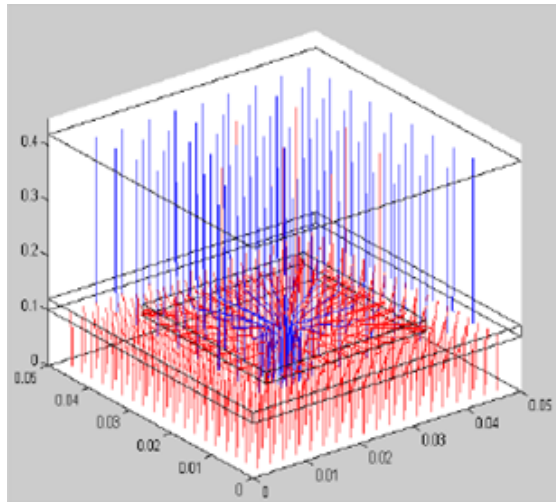


- 雪崩过程产生的电子在气体放大区的强电场作用下，以极快的速度向阳极漂移，在漂移过程中感应出一个幅度极大宽度很窄的电流信号，但由于大量电子是在靠近阳极的区域产生的，因而这个电流信号的电荷量很小。与此同时，雪崩过程产生的正离子以较慢的速度向微网漂移，感应出一个幅度较小但较宽的电流信号，并携带了总感应信号的大部分电荷量。
- 以上图像没有考虑转换漂移区的原初电离的空间分布。实际上在此区域所有电离电子漂移到放大区需要一定的时间 ( $T = \text{转换漂移区厚度} / \text{漂移速度}$ )，考虑到这一点，总的电子感应信号的宽度应为 $T$ ，而不会如右图中显示的那样窄。

# 电子透过率

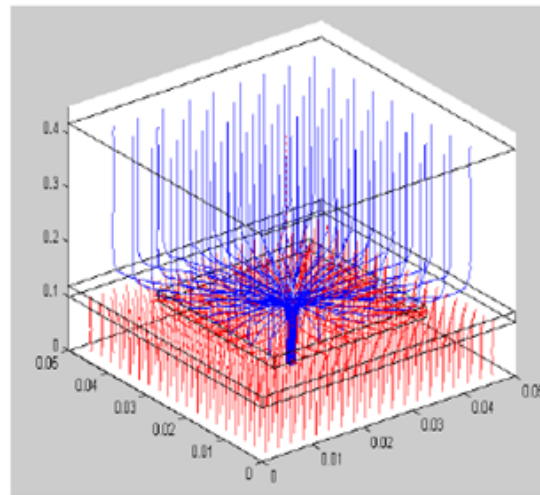
- 原初电离产生的电子在漂移区向微网漂移，在通过微网的过程中，一部分电子被微网收集，其它电子则透过微网，进入气体放大区。透过微网的电子占原初电子的比例称为电子透过率。
- 电子透过率取决于气体放大区的电场强度 ( $E_{\text{mesh}}$ ) 与漂移区电场强度 ( $E_{\text{drift}}$ ) 的比值。通过设置适当高的电场比值，可以获得足够高的电子透过率。

$$E_{\text{mesh}}/E_{\text{drift}} = 21$$



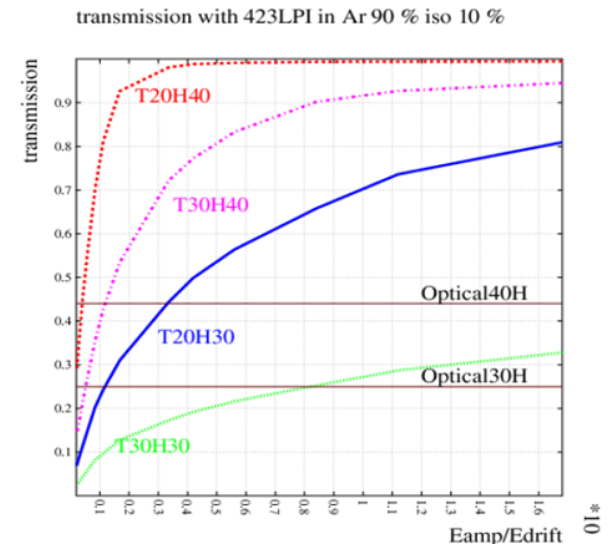
漂移区的电力线大部分落在微网上

$$E_{\text{mesh}}/E_{\text{drift}} = 840$$

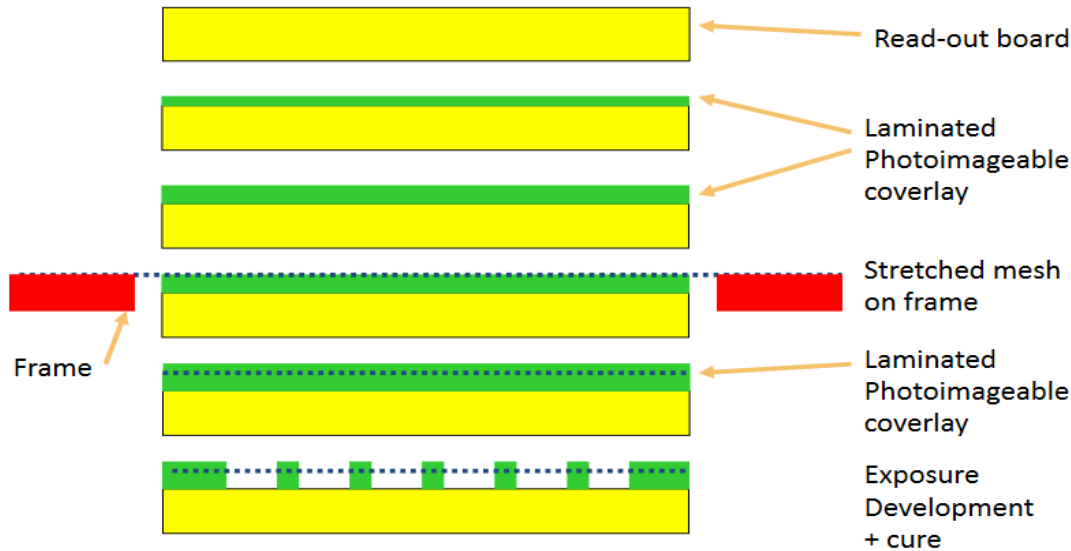


漂移区的电力线大部分穿过微网的小孔

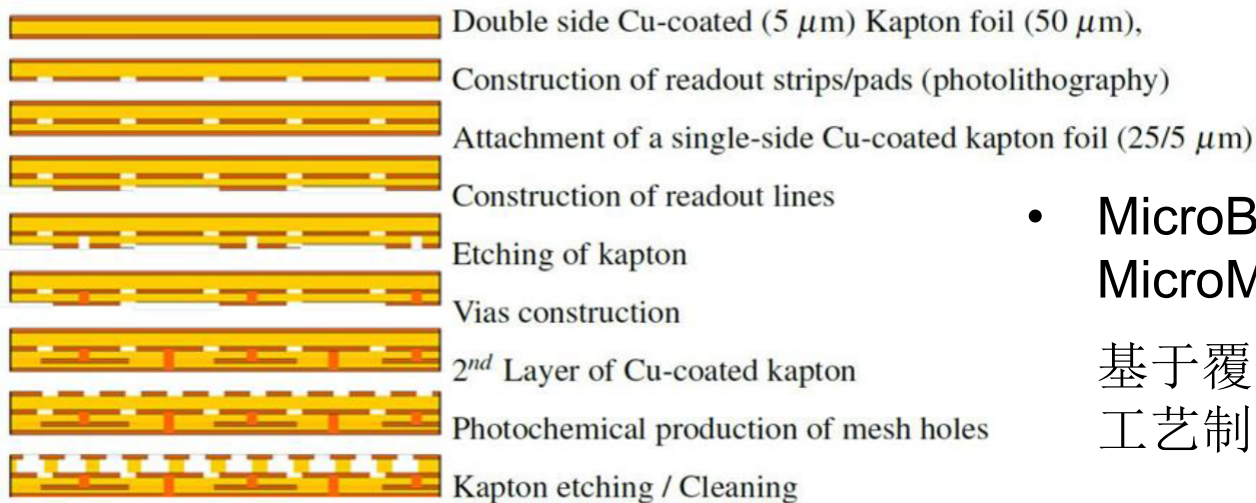
电子透过率与  $E_{\text{mesh}}/E_{\text{drift}}$  的关系



# MicroMEGAS制作工艺

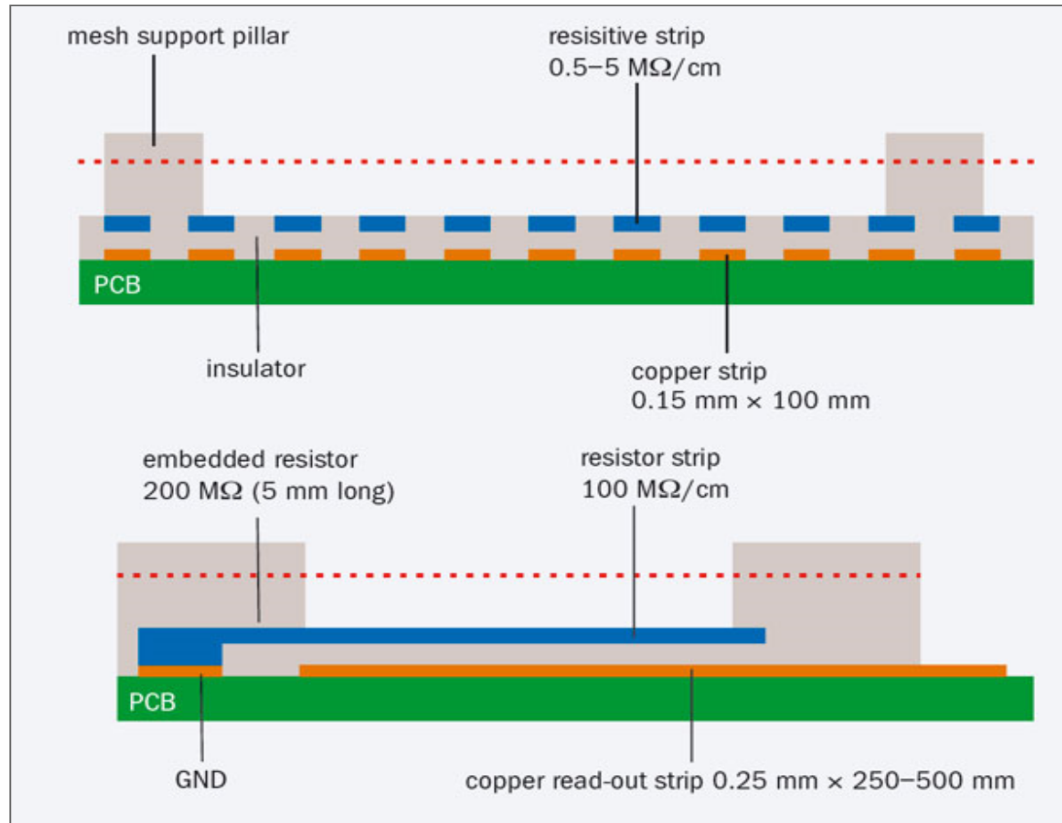


- Bulk（一体化）  
MicroMEGAS工艺：  
采用光刻工艺，PCB  
和金属网一体化制作，  
不再分别装配。



- MicroBulk（微型一体化）  
MicroMEGAS工艺：  
基于覆铜Kapton膜，采用光刻  
工艺制成。

# MicroMEGAS放电问题的解决



通过在读出阳极上平行地放置一层阻性电极可以有效地抑制放电过程的能量释放，从而大大增强了MicroMEGAS对放电的承受能力。



# 气体电子倍增器

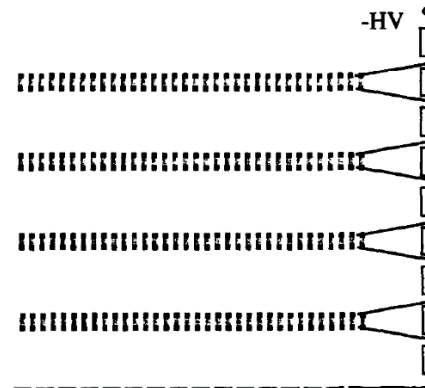
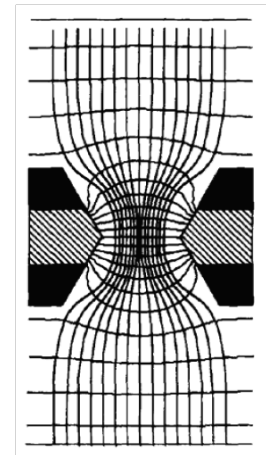
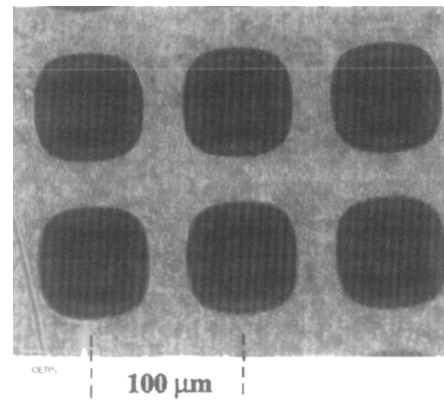
## GEM

(Gas Electron Multiplier)

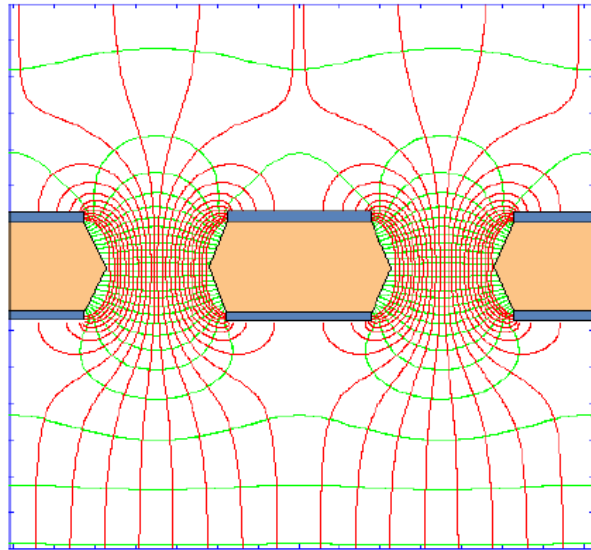
F. Sauli



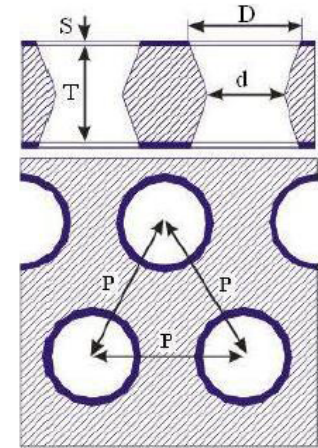
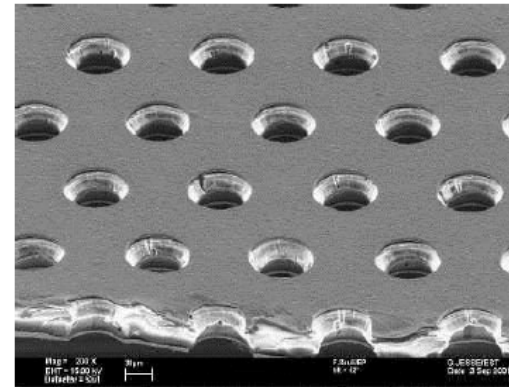
1997年



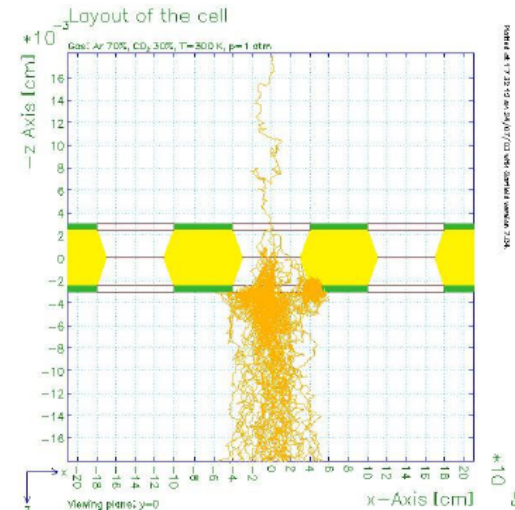
# 基本原理



聚酰  
亚胺  
薄膜

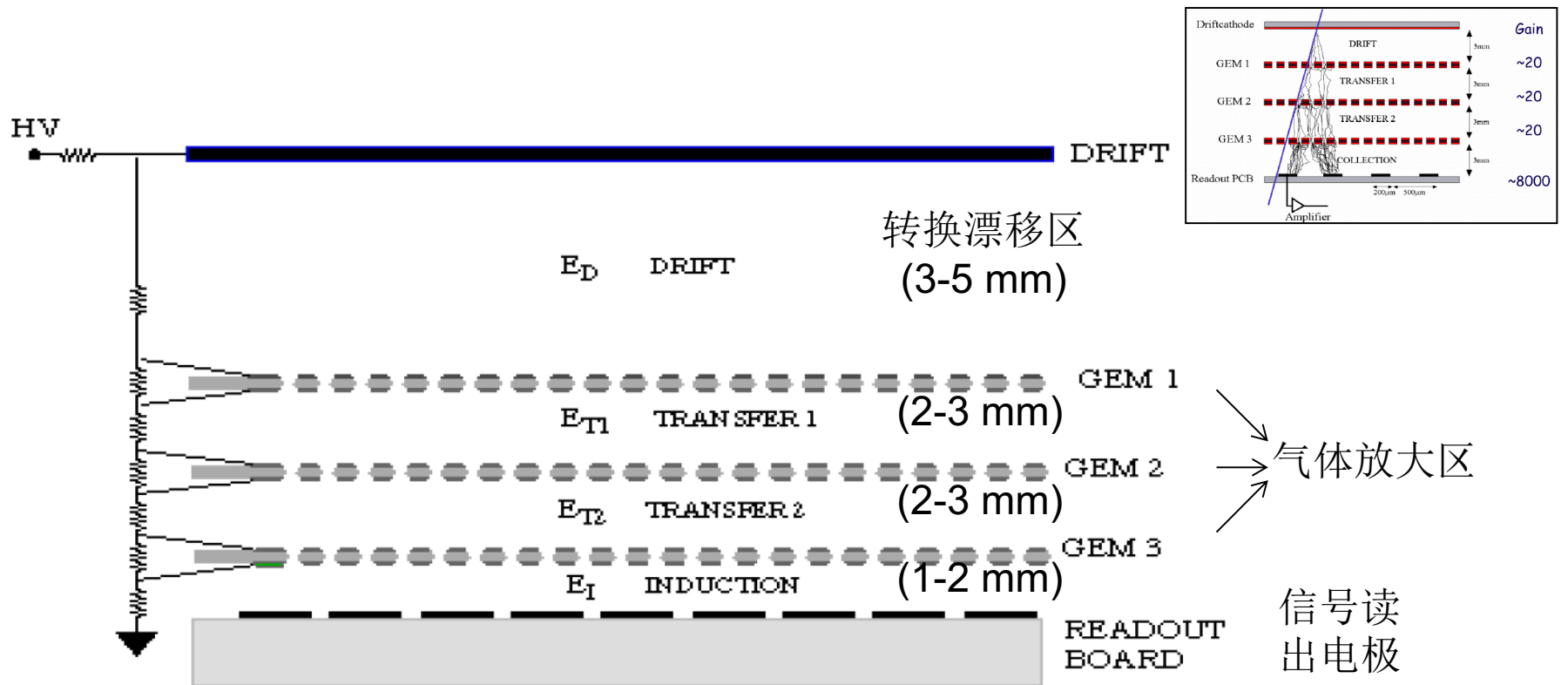


薄膜上下表面镀有薄层铜膜，分布有高密度的小孔，孔径在 $50\text{--}70\ \mu\text{m}$ ，上下铜膜加上电压后，孔中心的电场强度可达 $100\text{kv}/\text{cm}$ ，电子经过小孔时在强电场下发生雪崩放大，实现对原初电子的倍增，放大倍数为 $10^2\text{--}10^3$ 。由于雪崩放大过程被局限在微孔内，计数承受能力可以很高，同时采用微条电极读出可以获得很好的位置分辨。



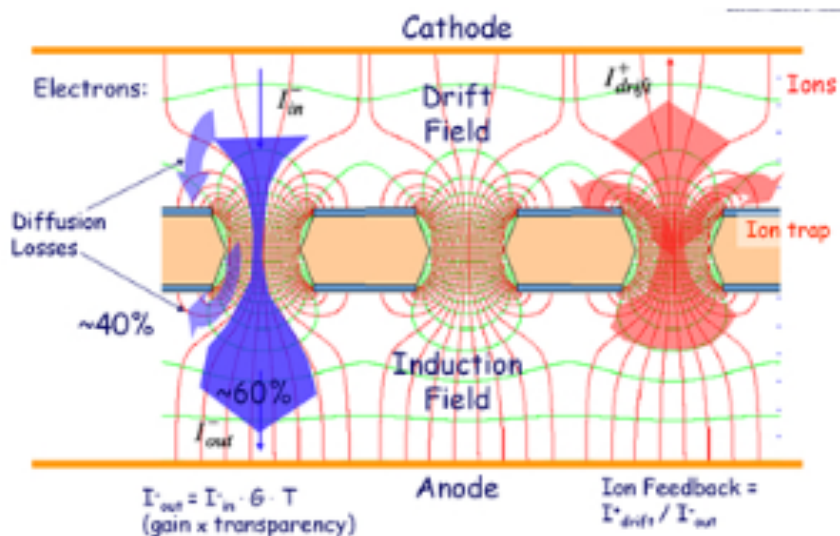
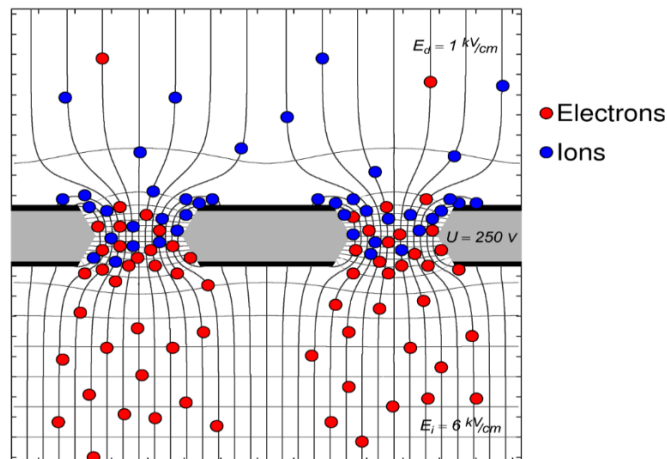
$S = 5\ \mu\text{m}$   
 $D = 80\ \mu\text{m}$   
 $T = 50\ \mu\text{m}$   
 $d = 60\ \mu\text{m}$   
 $P = 140\ \mu\text{m}$

# 基本结构



- 通常采用多层GEM的结构，这样每层GEM可以工作在较低的气体增益下，同时能获得较高的总气体增益，满足探测要求。
- 阳极输出信号由电子在最后一张GEM膜与阳极之间的漂移感应产生。

# 电荷运动

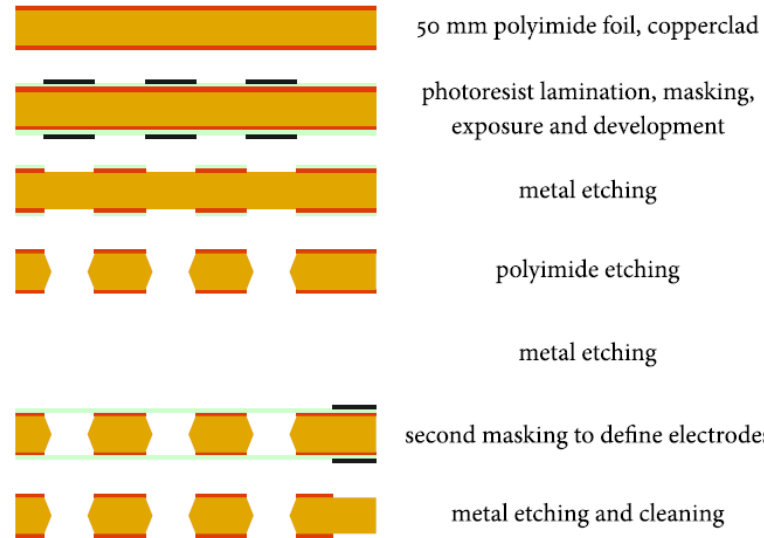


- 当漂移区的电场不是很强时，漂移区的电力线绝大部分穿过**GEM**膜上的小孔进入后续区域，而不会落在**GEM**膜的金属上表面，这时几乎所有原初电离产生的电子都能进入小孔进行雪崩放大。极少部分的原初电子由于扩散偏离原初的电力线最终被上表面收集，从而损失掉。
- 在**GEM**孔中雪崩产生的电子大部分沿电力线往下漂移并最终被阳极收集，一小部分由于扩散效应被**GEM**膜下表面的铜膜电极收集，从而损失掉。雪崩产生的正离子一部分被**GEM**上表面铜膜电极收集，另一部分沿电力线往上漂移并最终被漂移阴极收集（离子反馈）。通过适当的电压配置，可以减小离子反馈。
- 阳极上的输出信号完全由电子在从**GEM**膜下表面漂移到阳极的过程中感应产生，正离子对输出信号没有贡献。

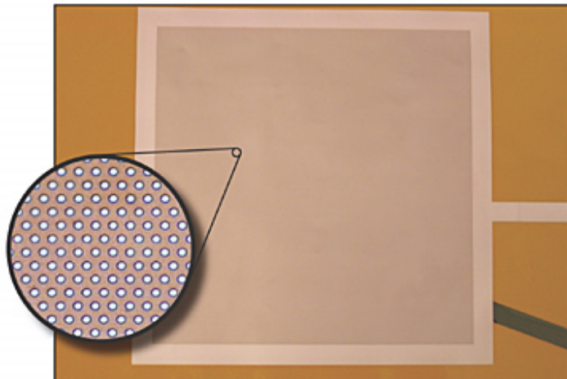
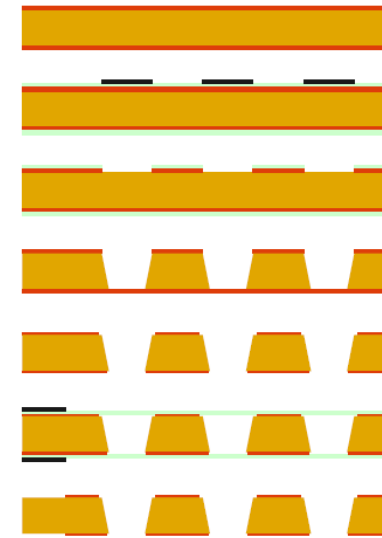
# GEM膜的制作



DOUBLE MASK



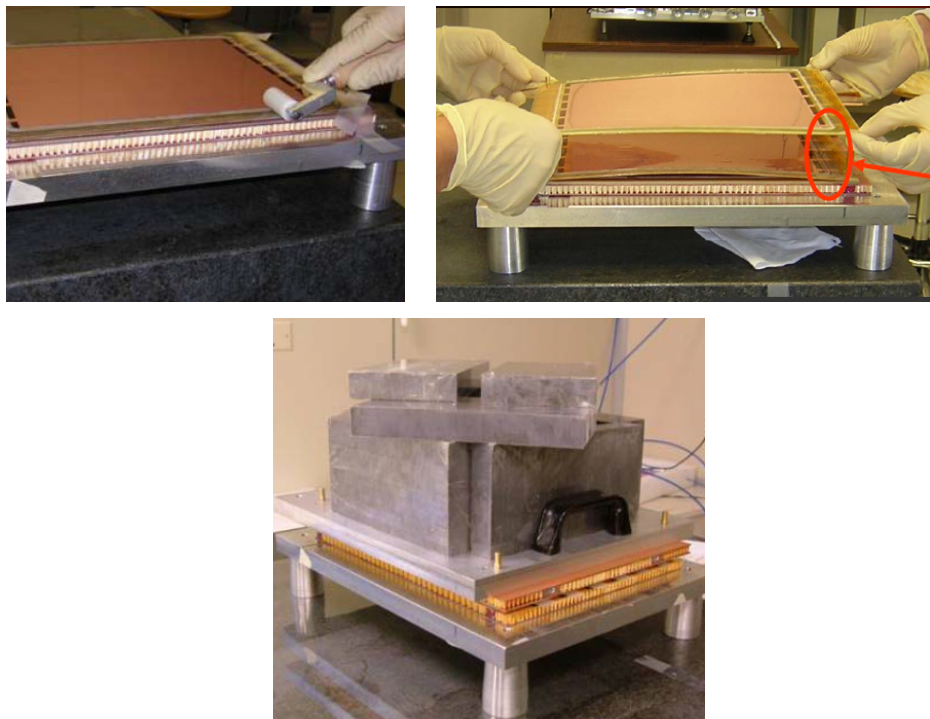
SINGLE MASK



- **Double-Mask技术**
  - 受上下掩模对齐精度的限制，GEM膜最大制作尺寸为40cm\*40cm
- **Single-Mask技术**
  - 摆脱了掩模对齐的问题，最大GEM膜可达2m\*60cm，主要限制因素为GEM膜基材的尺寸。

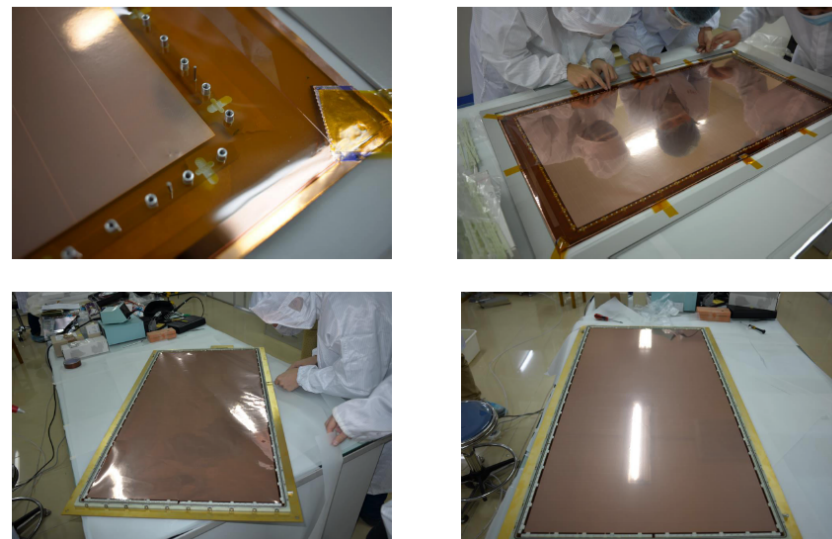
# GEM探测器制作工艺

## 胶粘法



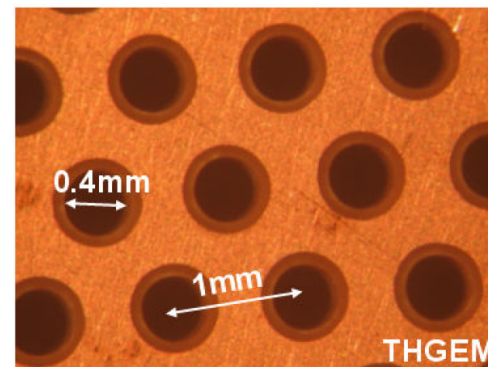
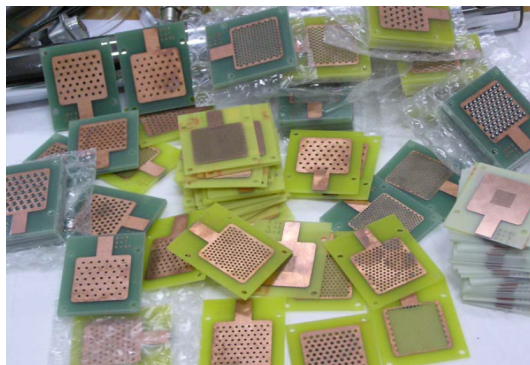
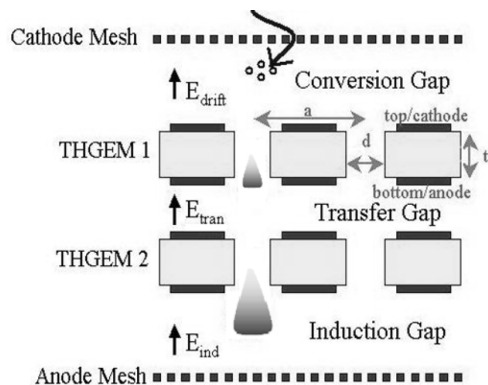
用胶将GEM膜固定在框架上

## 自拉伸法



用机械拉伸的办法将GEM膜  
固定在框架中

# 厚GEM (THGEM)

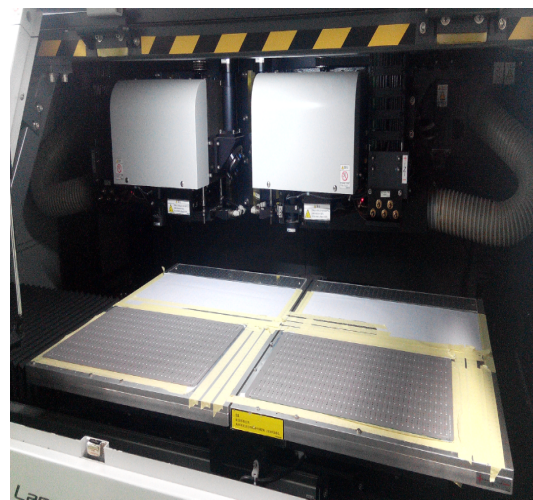


PCB基材，结构性能好，位置分辨~亚毫米，单层增益可达 $\sim 10^4$

目前最常用且最可靠的制作方法：机械打孔



尝试新方法：激光打孔



# 发展现状

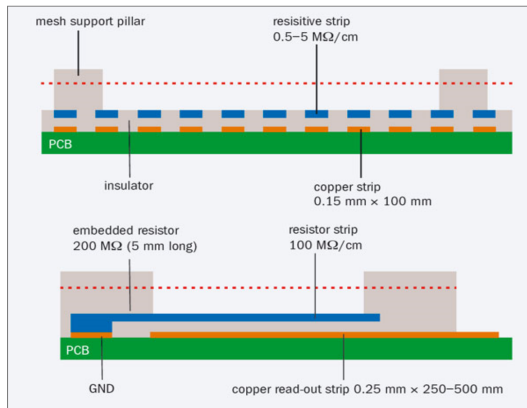
- 阻性电极
- 大面积工艺
- 特殊形状
- 离子/光子反馈抑制
- 新材料
- 新颖结构
- 读出方式
- 工业化



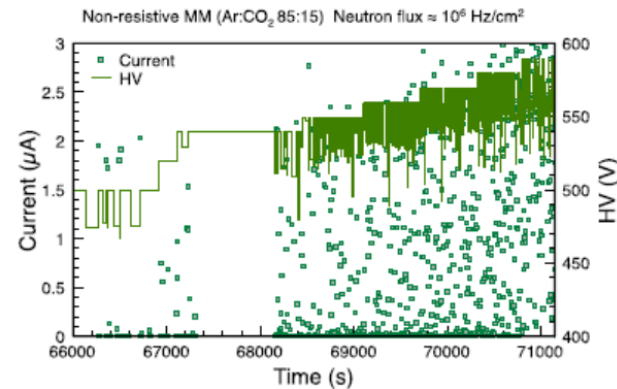
# 阻性电极 (I)

- 放电打火是微结构气体探测器的“公敌”。
- 阻性电极是抑制放电的有效手段。

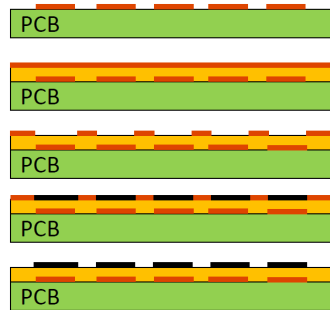
阻性MicroMegas



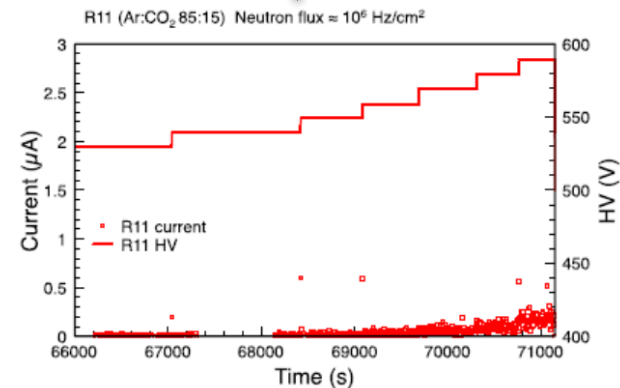
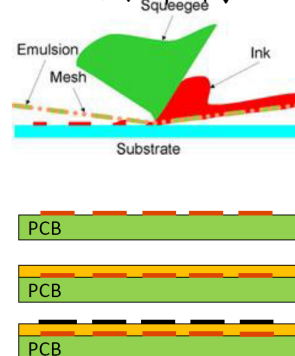
阻性电极的效果



光刻腐蚀



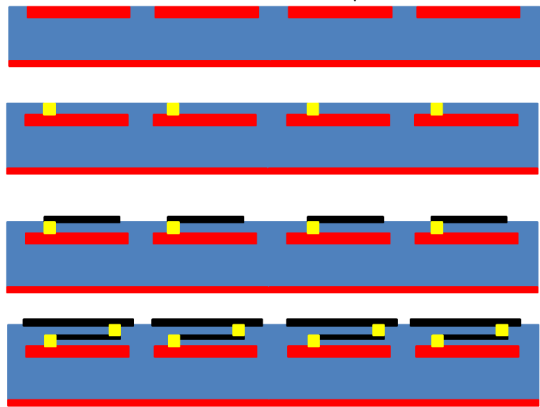
丝网印刷



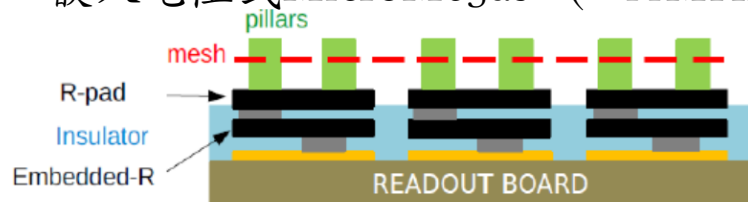
# 阻性电极 (II)

- 阻性电极已成为微结构气体探测器的一个共同趋势，相关技术也成为研究热点。
  - 阻性膜（光刻、丝网印刷、蒸镀、溅射…），嵌入电阻（双层结构，高计数率），阻性板

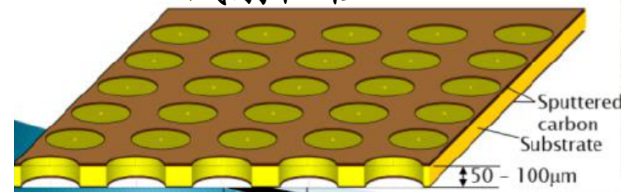
嵌入电阻制作技术



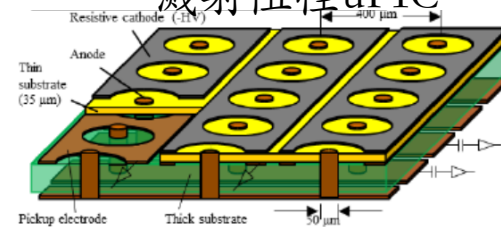
嵌入电阻式MicroMegas ( $>11\text{MHz}/\text{cm}^2$ )



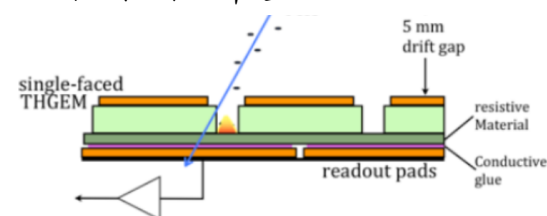
溅射阻性GEM



溅射阻性uPIC



阻性板井型THGEM

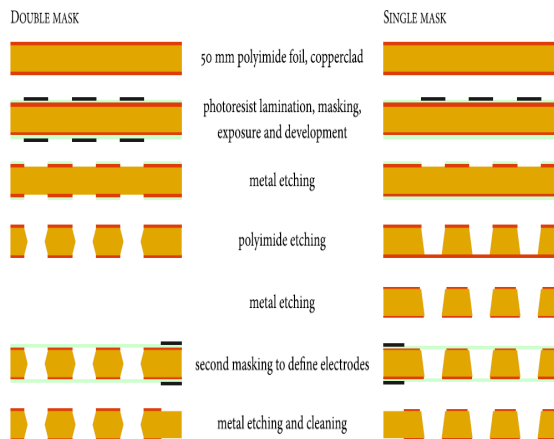


# 大面积工艺 (I)

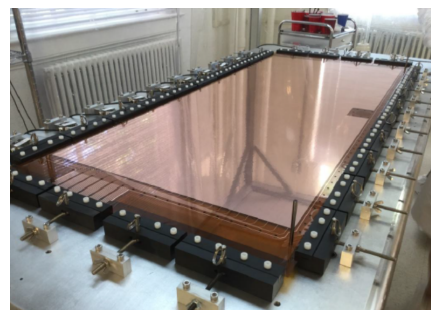
- 实现大面积制作是推动微结构气体探测器应用的重要方面

— 大面积元件，大面积装配

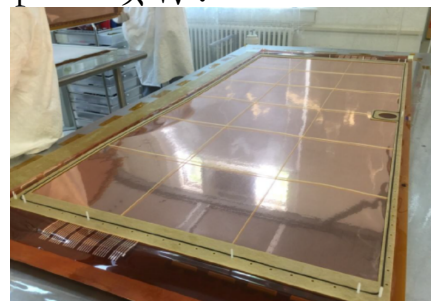
GEM膜制作 → 大面积



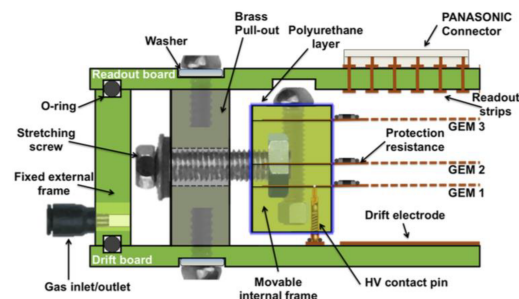
传统GEM制作方法(拉伸+粘胶, LHCb等), 低质量, 大面积需内部支撑, 不可拆卸, 费时费工。



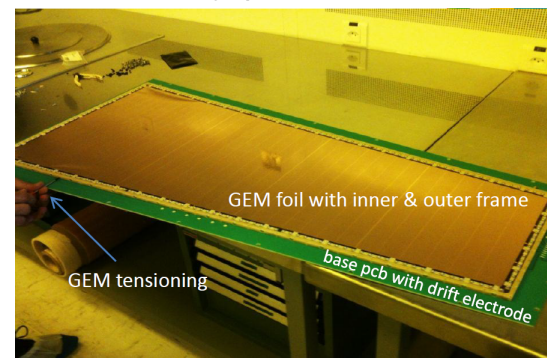
pRad项目: 0.6m\*1.2m



自拉伸(Self-stretching) 大面积GEM装配技术 (CMS升级), 无胶, 无内部支撑, 可拆卸可修复, 制作效率高, 物质较少。



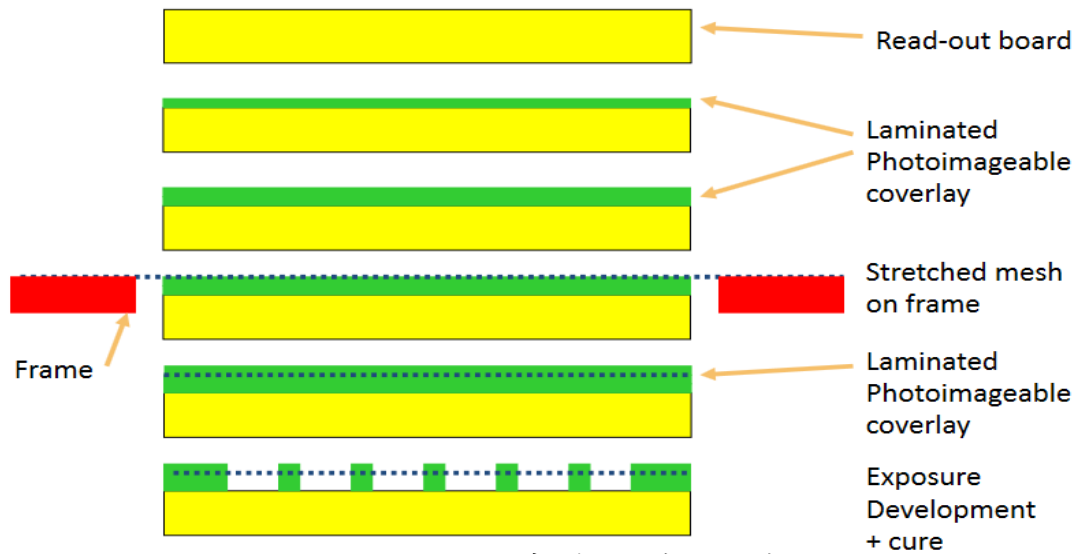
~0.4m\*1m



- Double-Mask技术:** 受上下掩模对齐精度的限制, 最大制作尺寸为40cm\*40cm。
- Single-Mask技术:** 摆脱了掩模对齐问题, 可达2m\*60cm, 限制因素为GEM膜基材尺寸。

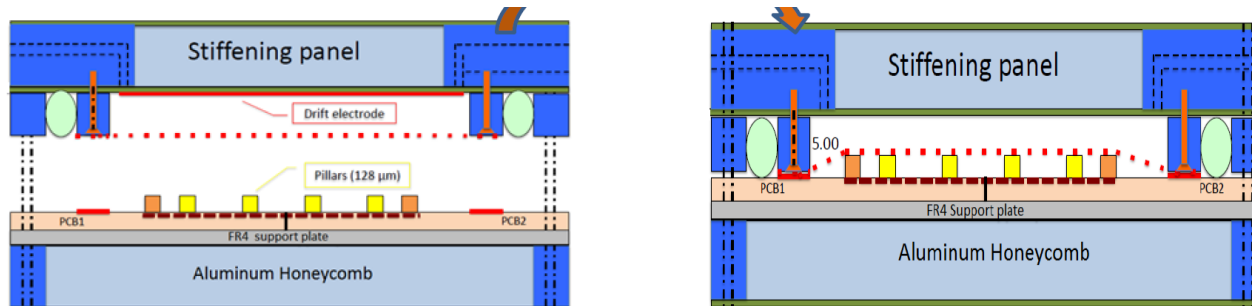
# 大面积工艺 (II)

## 一体化 (Bulk) MicroMegas 工艺

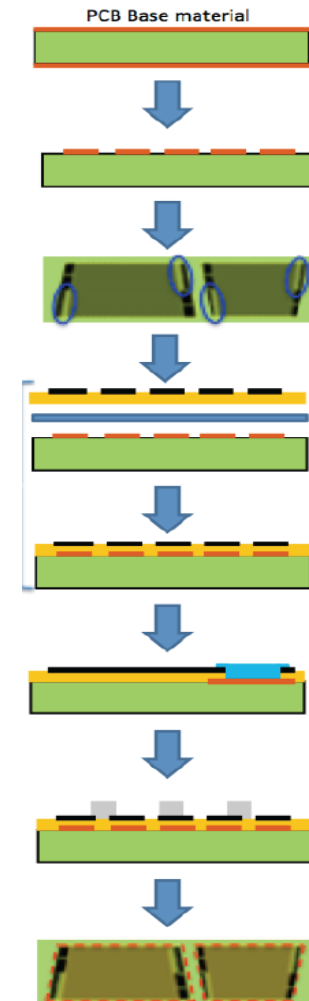


微网下如有杂物极难去除

## 浮动微网 (Floating mesh) 技术 (ATLAS升级, ~3m<sup>2</sup>)

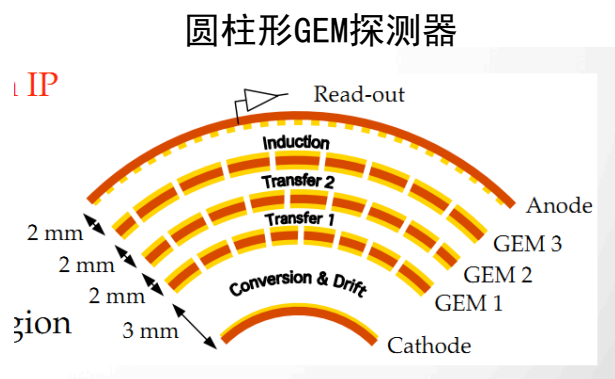


## ATLAS-MicroMegas读出板制作 (涉及PCB拼接工艺)



# 特殊形状

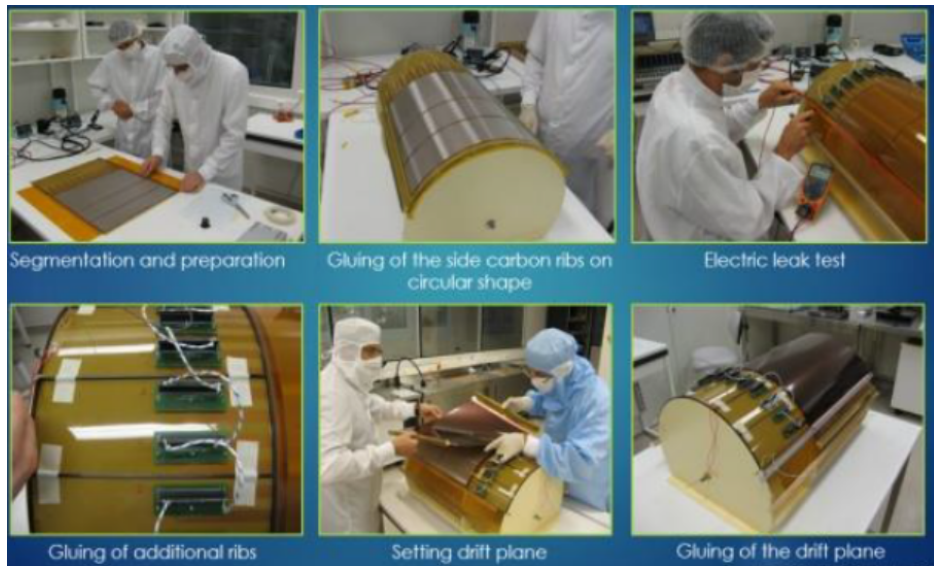
- 圆柱形制作是微结构气体探测器应用中的一个突破



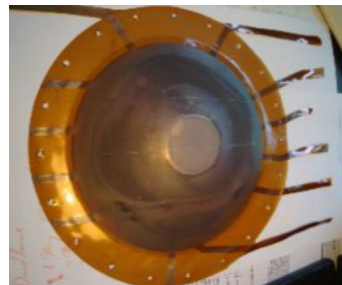
KLOE-2圆柱GEM径迹室



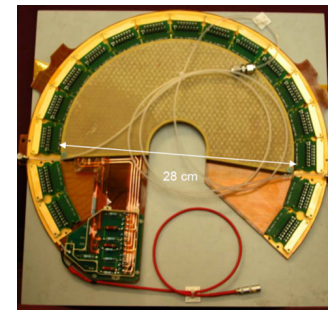
CLAS12圆柱MicroMegas径迹室



球形GEM

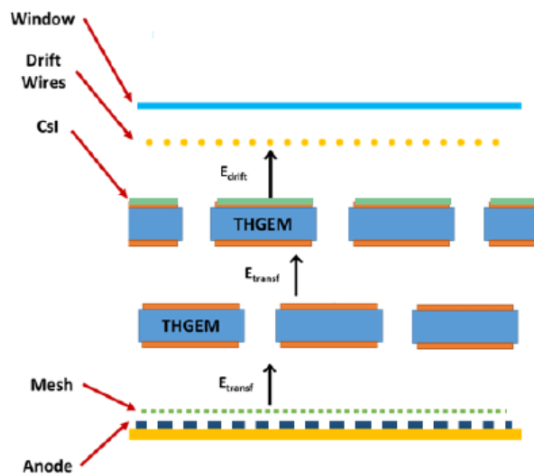


TOTEM-GEM

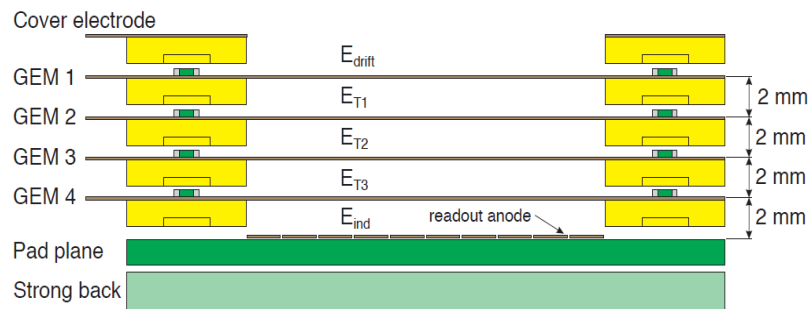


# 离子反馈抑制

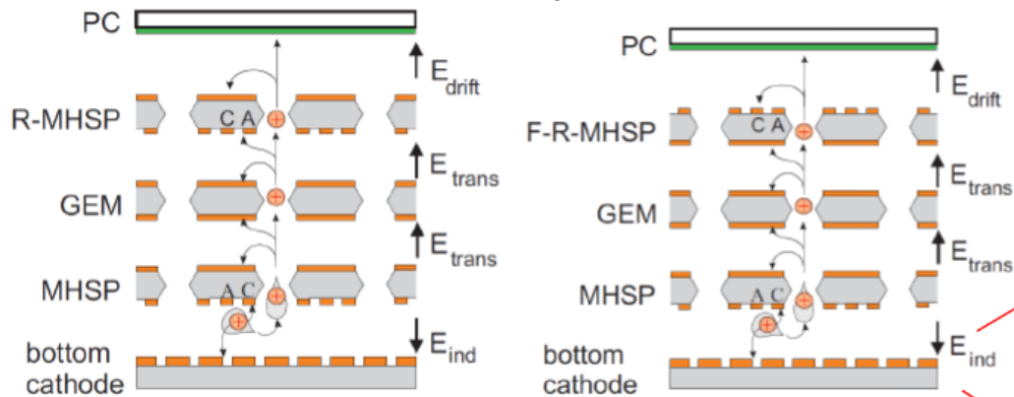
COMPASS-RICH: THGEM (staggered)  
+MicroMegas, IBF<1%



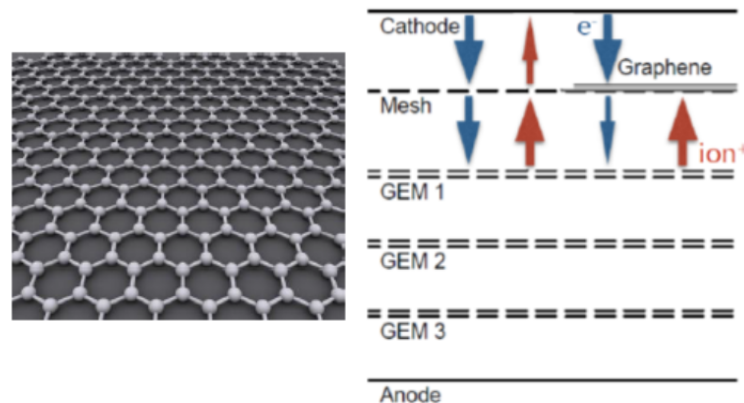
ALICE-TPC: 4GEMs (with  
different pitches), IBF<1%



Micro-Hole & Strip Plate, IBF<10<sup>-4</sup>

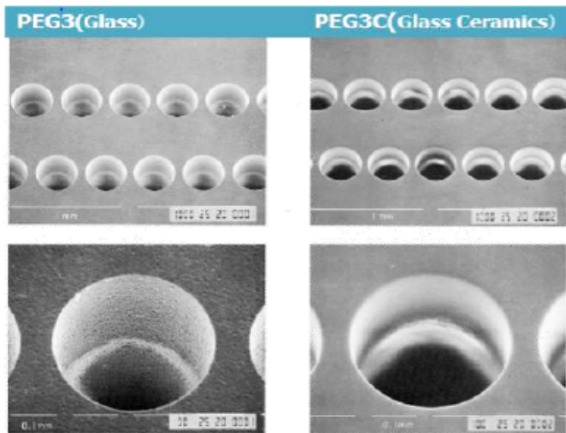


石墨烯, 未成功

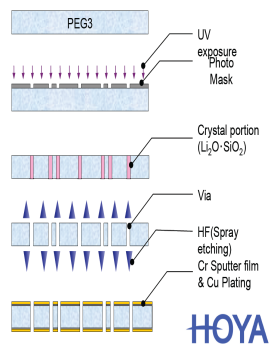


# 新材料

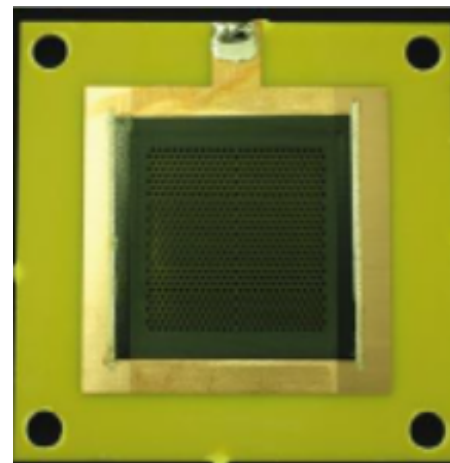
GEM/THGEM: 玻璃、陶瓷, 无出气, 密封式应用, 或其他



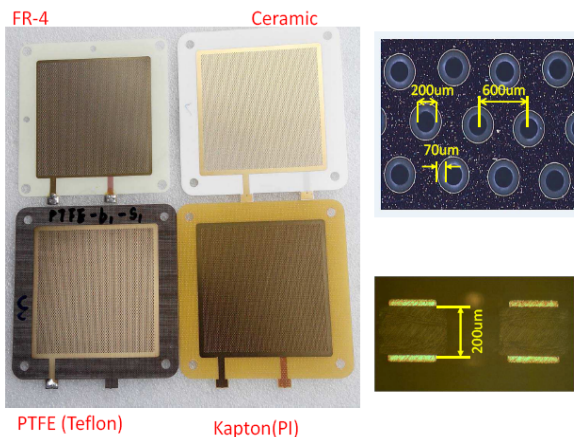
1. Glass Substrate (PEG3)
2. UV exposure (1<sup>st</sup>\_exp)
3. Crystal formation (heat treatment)
4. Via etching (hydrogen fluoride wet etching)
5. Cr sputter & Cu plating



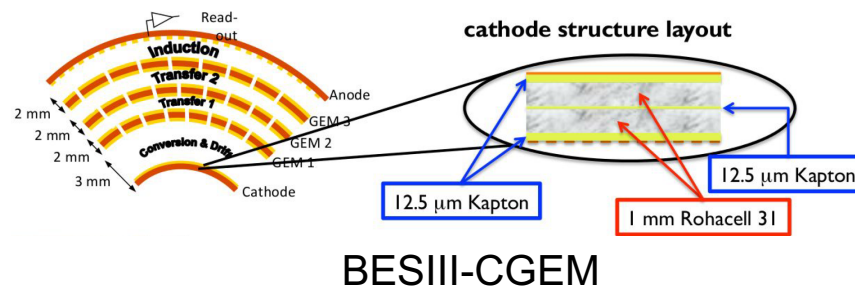
THGEM: 阻性Kapton,  $G \sim 10^5$ , 高增益应用



THGEM: 寻找合适中子探测和低本底实验的基材

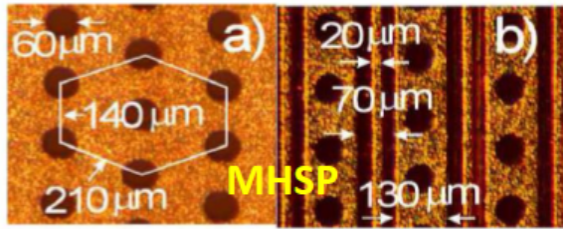


Rohacell: 非常轻, 支撑强度好, 可以替代传统蜂窝板。

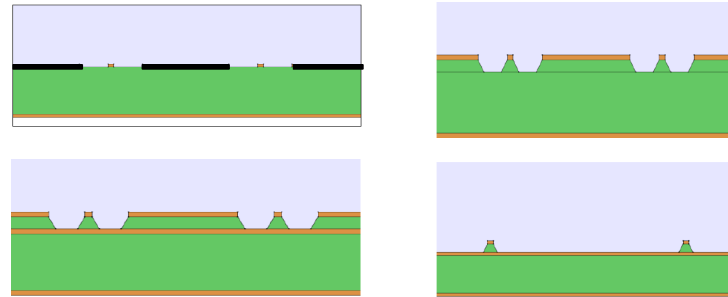


# 新颖结构 (I)

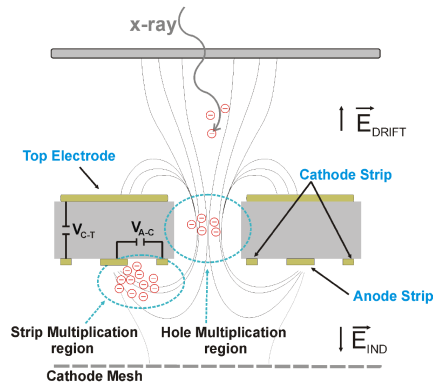
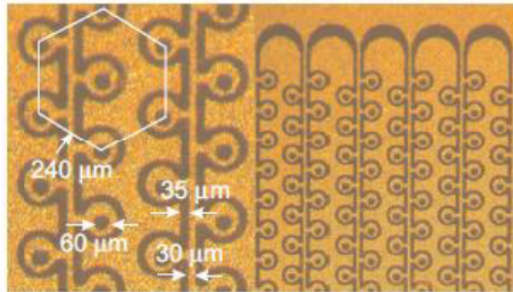
MHSP (IBF抑制)



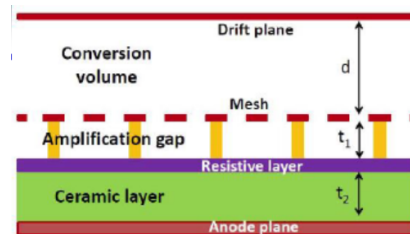
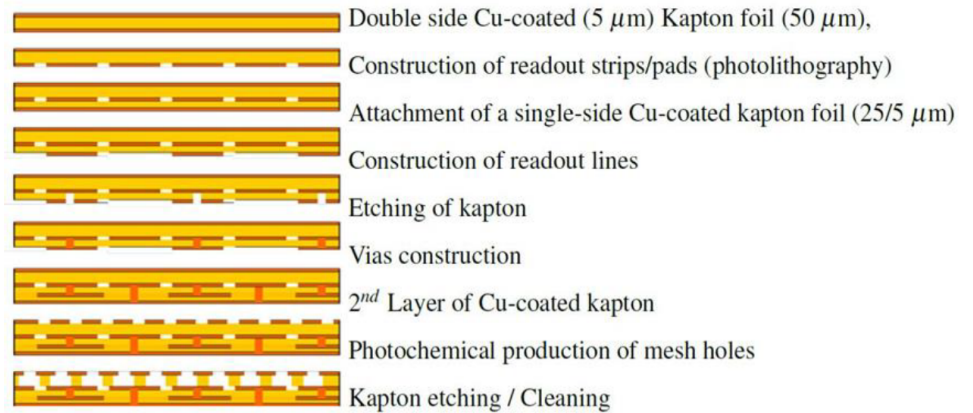
新型微条结构



COBRA (低工作电压, 高增益)



MicroBulk-MM (低质量、放射本底小, 能量分辨好)

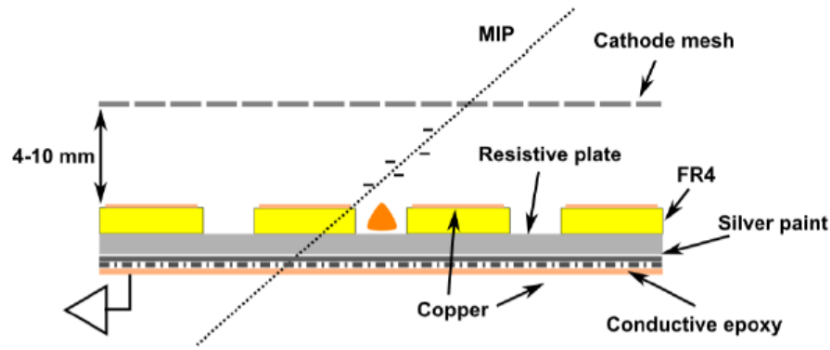


Piggy-Back MicroMegs (高增益, 防打火)

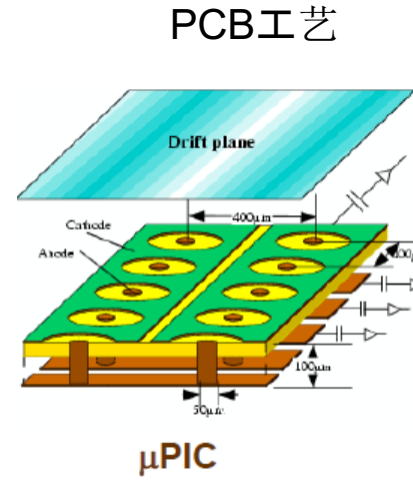


# 新颖结构 (II)

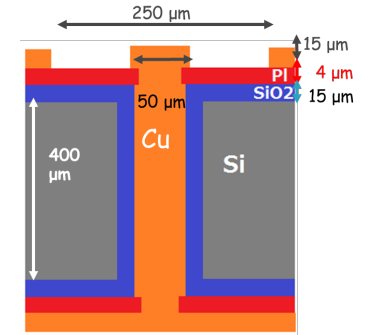
## 阻性井型THGEM



## uPIC



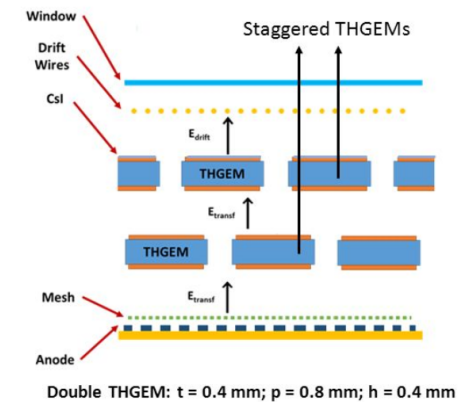
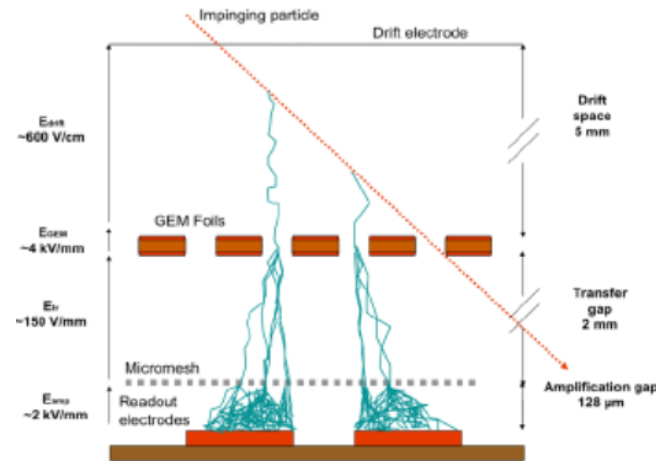
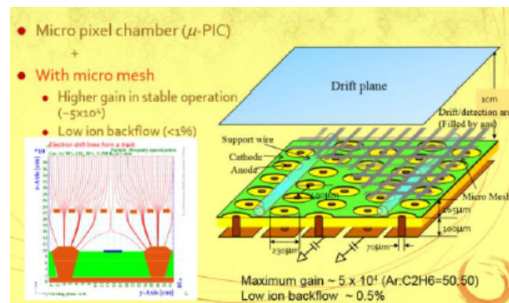
## MEMS工艺



## 混杂结构: MM+uPIC

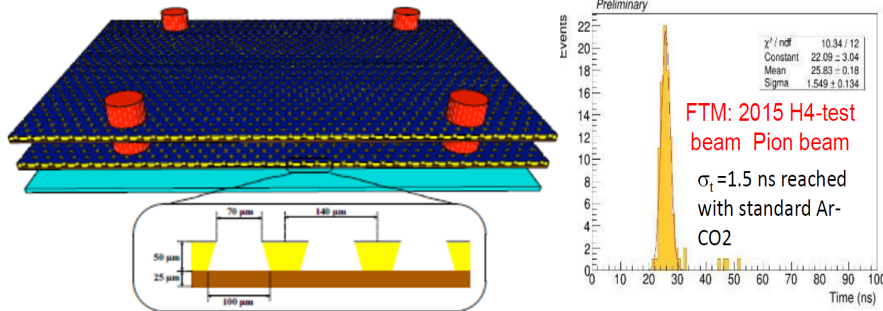
## 混杂结构: GEM+MM

## 混杂结构: THGEM+MM

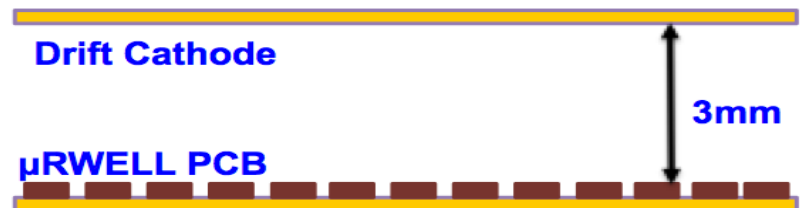


# 新颖结构 (III)

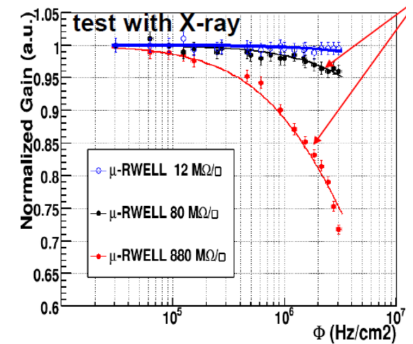
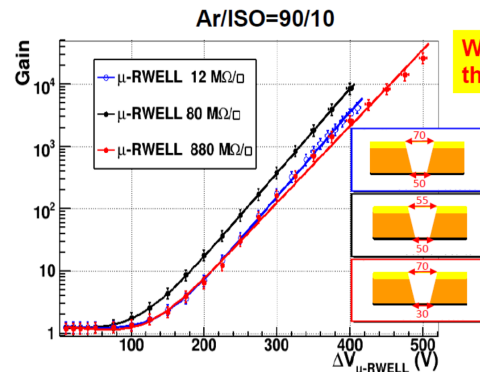
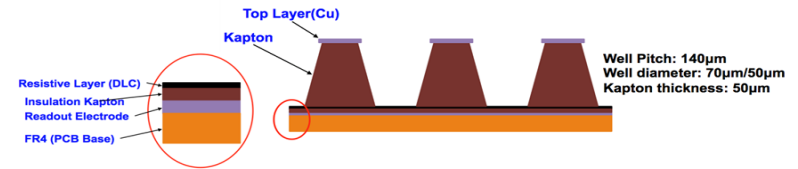
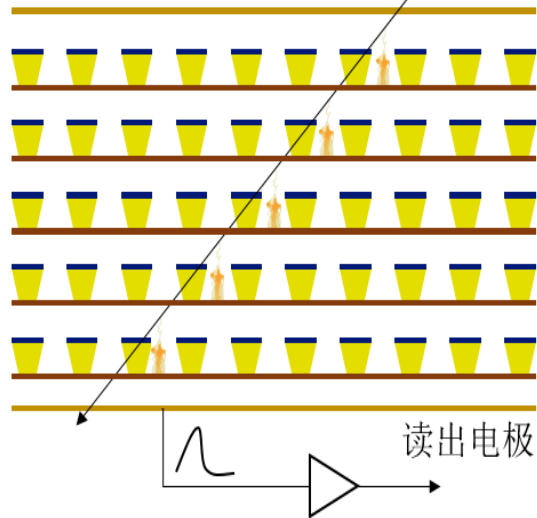
**多层阻性微结构(FTM):** R&D for CMS Muon upgrade, 高时间分辨



**阻性微井型结构(uRWELL):** R&D for CMS and LHCb Muon upgrade, 结构紧凑, 无胶, 无内部支撑, 装配简单高效, 适合大面积应用

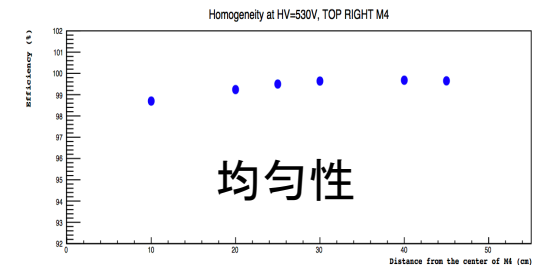
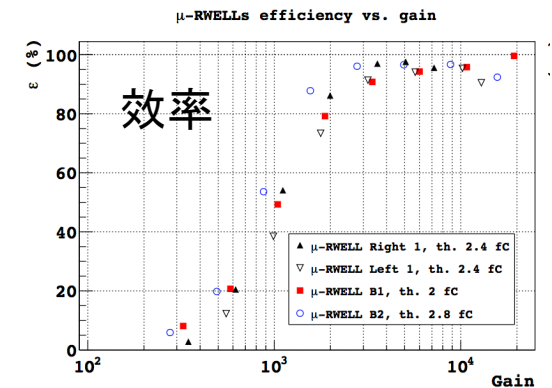
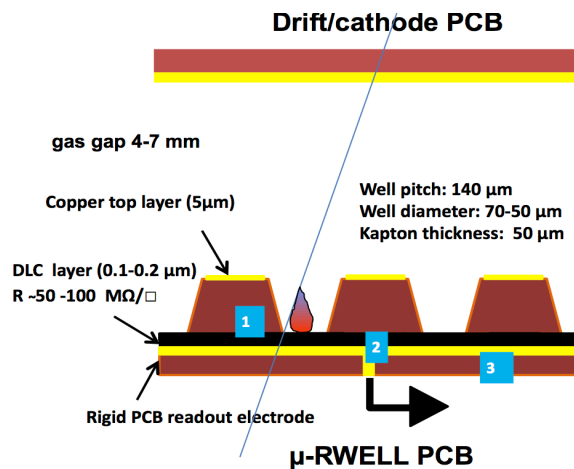


顶层漂移电极



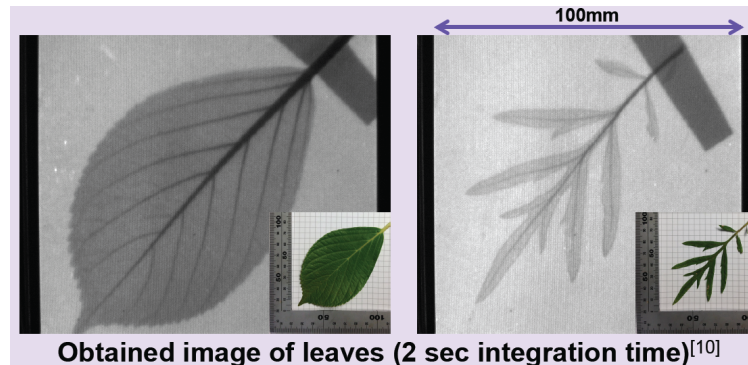
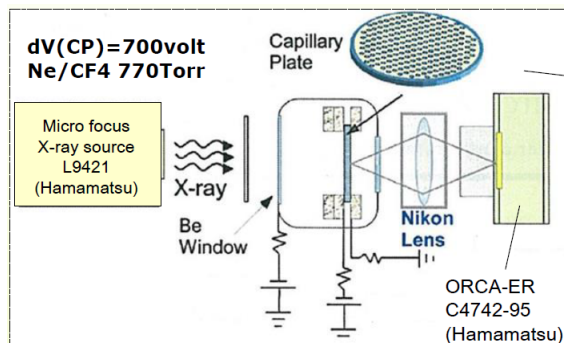
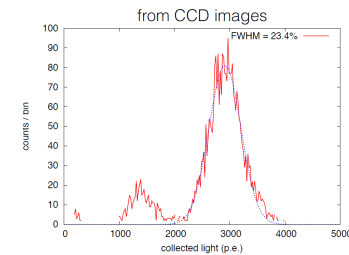
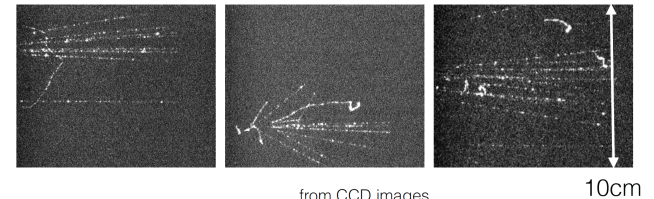
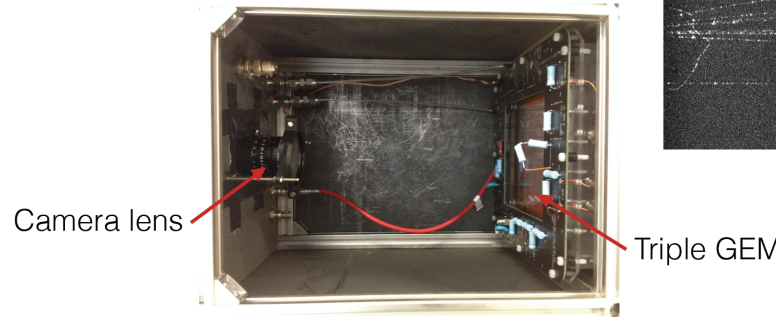
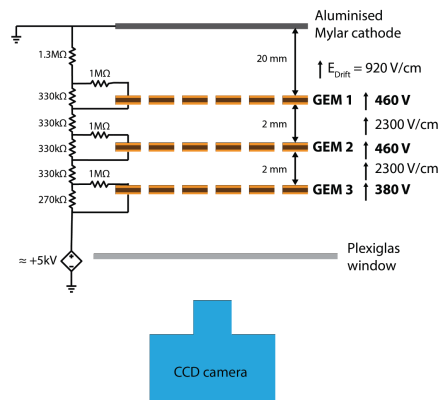
# uRWELL

- GEM(微孔) + MicroMegas(阻性阳极)的结合
  - 井型微孔气体放大 + 阻性电极放电保护
- 3层GEM膜 → 单层GEM膜，造价显著降低
- GEM膜直接粘贴在PCB上 → 无需拉伸和张网，装配极大简化
- 低计数率( $\sim 100 \text{ kHz/cm}^2$ )的技术方案已日趋成熟，并能实现大面积制作，非常有应用前景!



# 光读出方式

- 通过探测微结构中雪崩过程产生的闪烁光可以实现直接成像和能量测量(3d: 位置+能量)。



- 某些实验中的 TPC读出
- X、gamma、中子成像
- 材料分析
- ...

# 工业化

## GEM

### •Techtra

- Polish company
- Making GEM since 10 years
- Licensed by CERN
- Setting up equipment for large GEM production since 1 year
- 30cm x 10cm GEMs already produced
- First delivery of 30 GEMs last week

### •UPLUS/Mecharomics

- Korean company
- Making GEM since a few months
- Licensed By CERN
- 30cm x 30cm GEMs already produced (characterization in progress)
- Willing to ramp up to large size

### •Tech-etch

- US company
- Making GEM since 15 years
- Many small and medium sizes GEM have been produced
- Recently involved in STAR experiment (80 GEMs 40cmx40cm)
- Willing to ramp up to large size
- Licensed by CERN

### •Scienergy

- Japanese company
- Making GEM since 6 years
- Top quality laser drilled GEM up to 30cm x 30cm
- Licensed by CERN

## MICROMEAS

### •ELTOS

- Resistive 10cm x 10cm BULK Micromegas → OK
- Large single side read-out boards and drift (2mx0.5m) → OK
- Screen printing of large area → in progress
- Pillars on large area → OK

### •ELVIA (see Fabien talk in WG6)

- Resistive 40cm x 40cm BULK Micromegas → OK
- Embedded resistor BULK detectors → in progress (see Damien talk WG6)
- Large single side read-out boards and drift (2mx0.5m) → OK
- Screen printing of large area → in progress
- Pillars on large area → OK

## THGEM

### •ELTOS

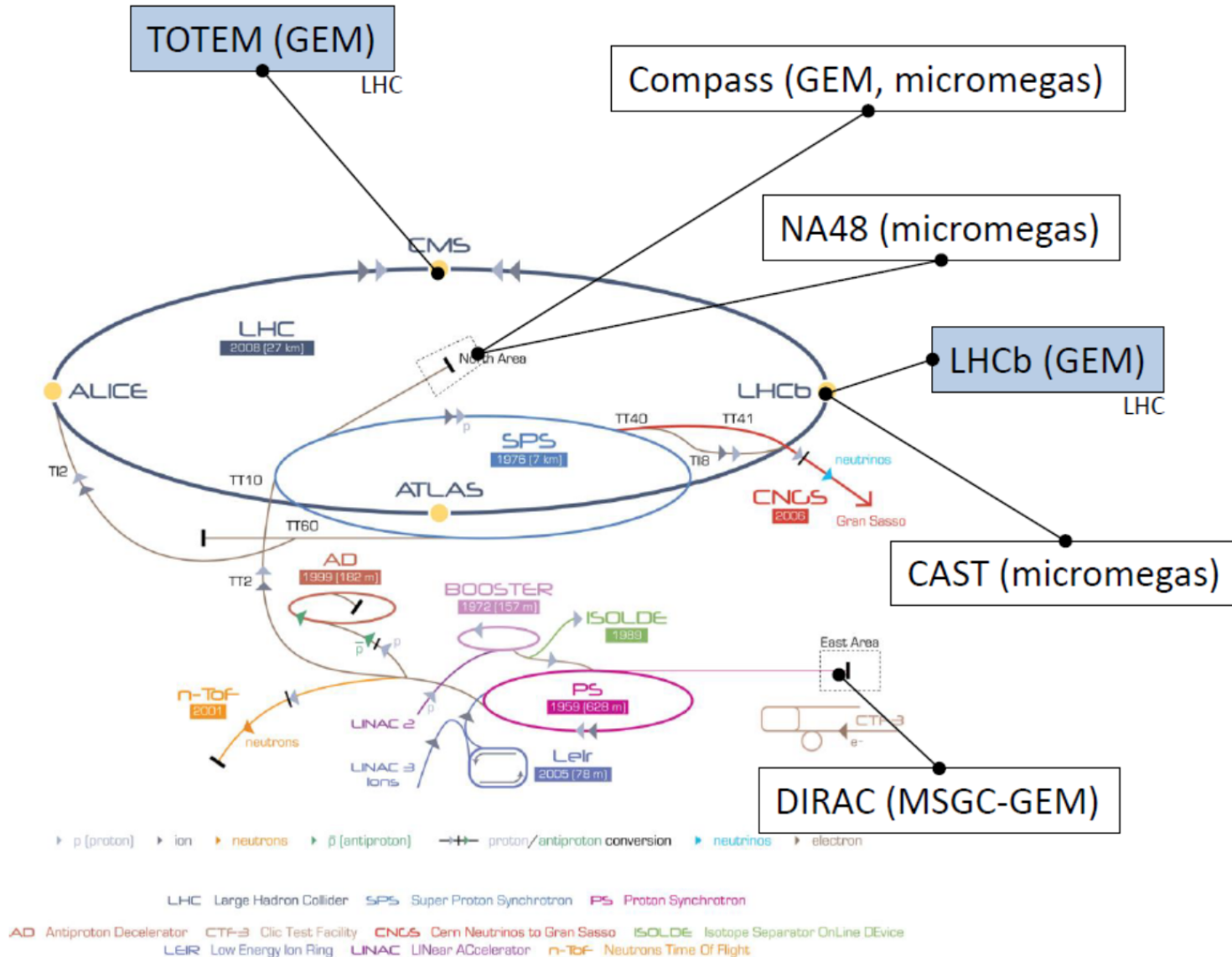
- 10 holes/ sec drilling machine
- They have produced 60cm x 60cm just for mechanical purpose
- They have produced 80cm x 40cm working THGEM
- They are able to produce RIMs.
- The final cleaning should still be performed by the user or CERN
- Long polishing or PU coating are not yet available in industry
  
- Mass production costs are still difficult to predict (cleaning technology transfer should be organized)

### •Print Electronics

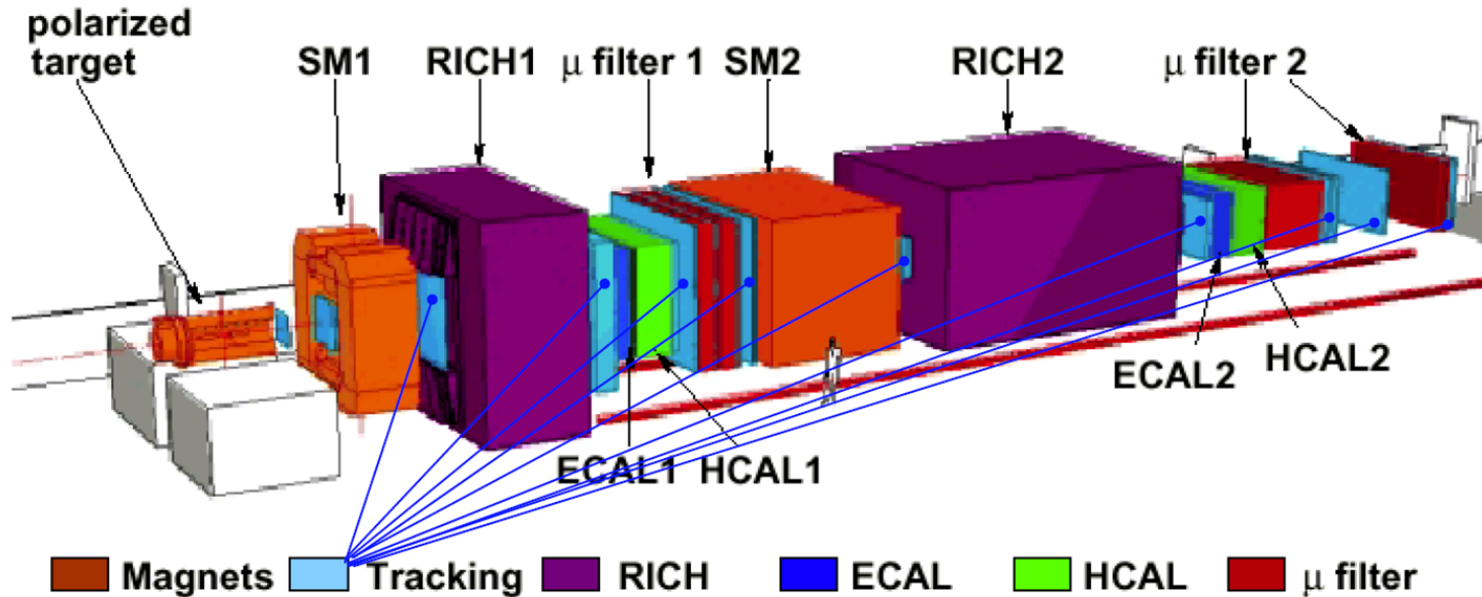
- Israel
- Many pieces made for Weismann institute
- Little information on the capabilities

From Rui De Olivera

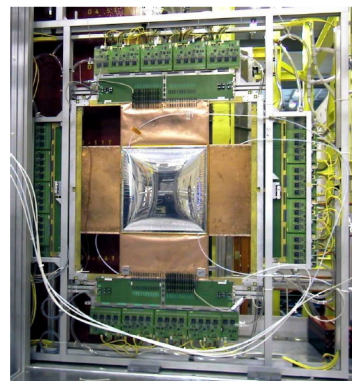
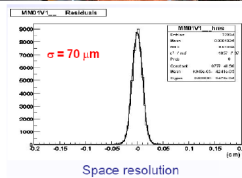
# 应用：径迹/触发探测器



# COMPASS



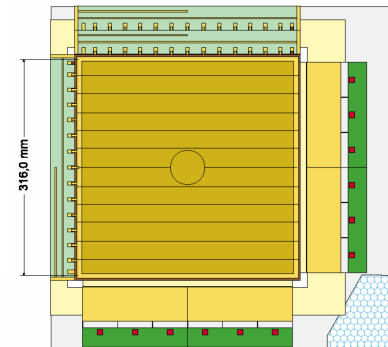
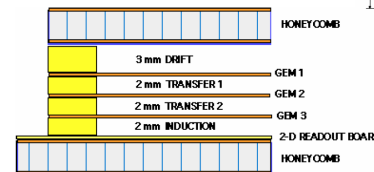
CAMPASS实验中的Micromegas探测器：上游径迹室  
自2002一直在运行，效率>97%，空间分辨~70 $\mu$ m



COMPASS Triple GEM

- Active Area 30.7 x 30.7 cm<sup>2</sup>
- 2-Dimensional Read-out with 2 x 768 Strips @ 400  $\mu$ m pitch
- 12+1 sectors GEM foils
- Central Beam Killer 5 cm  $\varnothing$  (remotely controlled)
- Total Thickness: 15 mm
- Honeycomb support plates
- Thickness in active area 0.7%  $X_0$

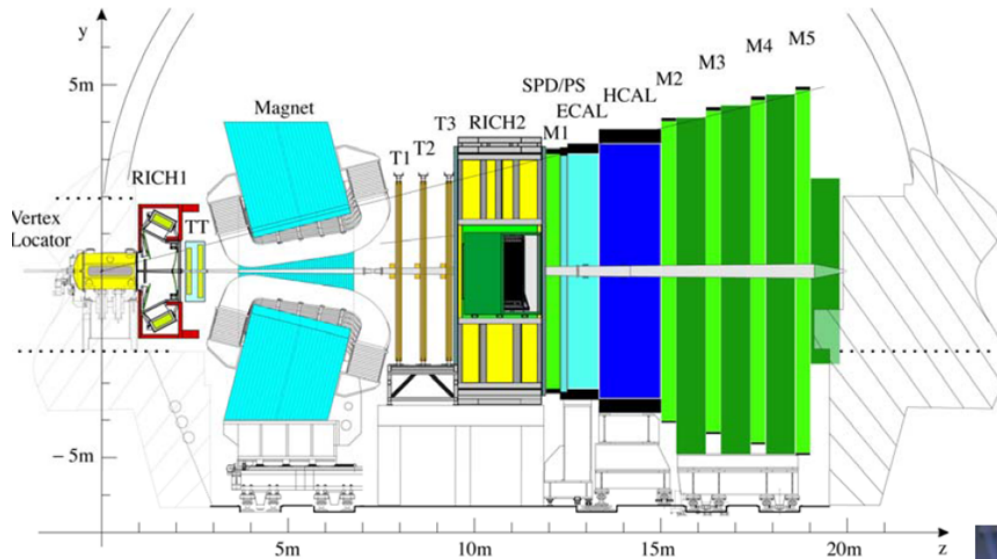
共22个GEM室



空间分辨~70 $\mu$ m  
效率>97%

# LHCb

## Fast TripleGEM Detectors for LHCb Muon Trigger

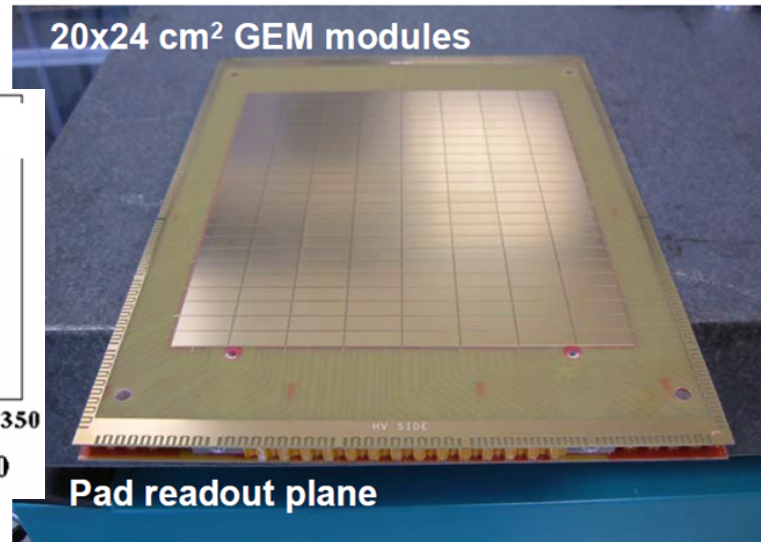
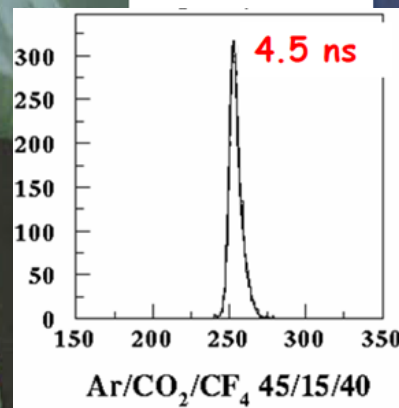
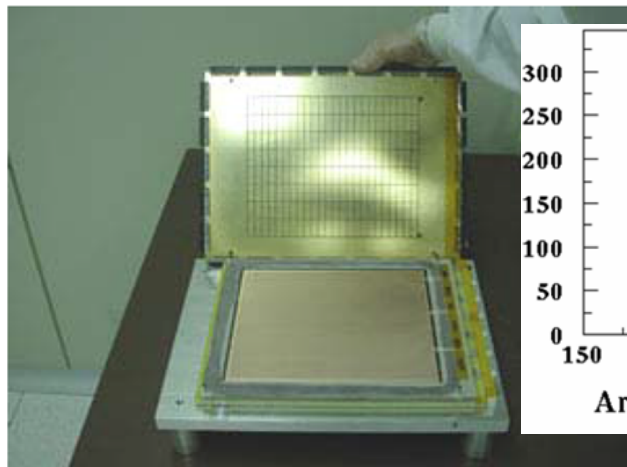


12 double TGEM detectors operated with fast gas mixture ( $\text{Ar-CO}_2\text{-CF}_4$ )

Rate -  $5 \text{ kHz mm}^{-2}$

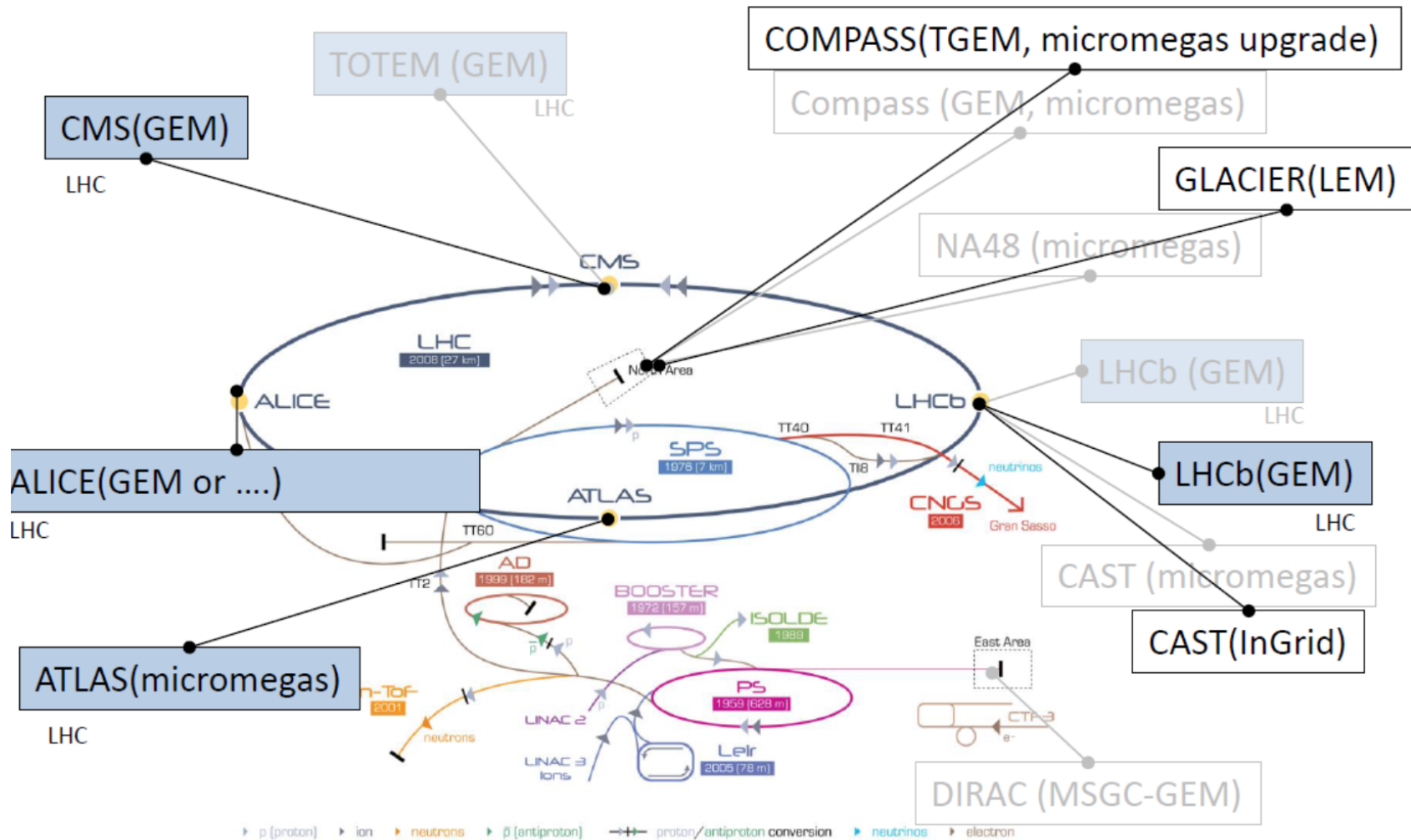
Time resolution  $4.5 \text{ ns rms}$

Radiation hard up to integrated charge of  $18 \text{ mC mm}^{-2}$  (10 LHCb years)





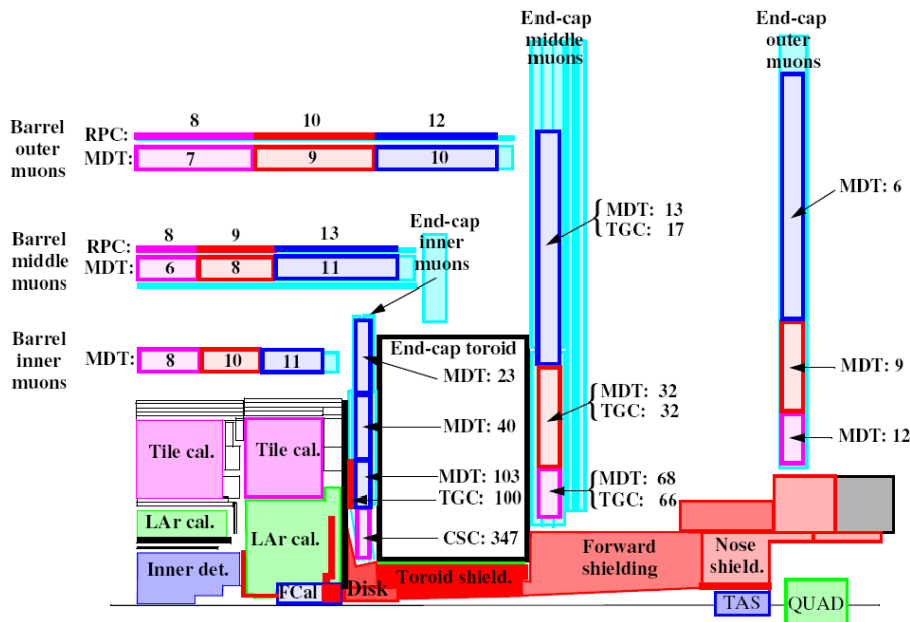
# 更大规模的应用（进行或计划中）



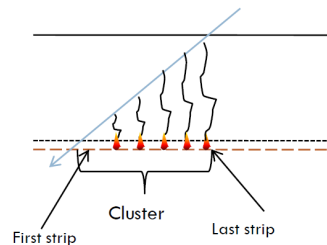
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF-3 Clic Test Facility CNCS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice  
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-Tof Neutrons Time Of Flight

# ATLAS-MicroMegas



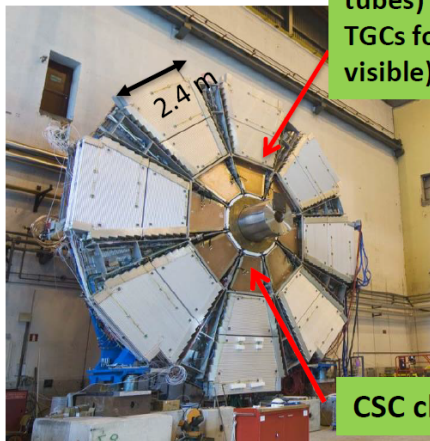
uTPC读出方式  
(保持大倾斜角下的位置分辨性能)



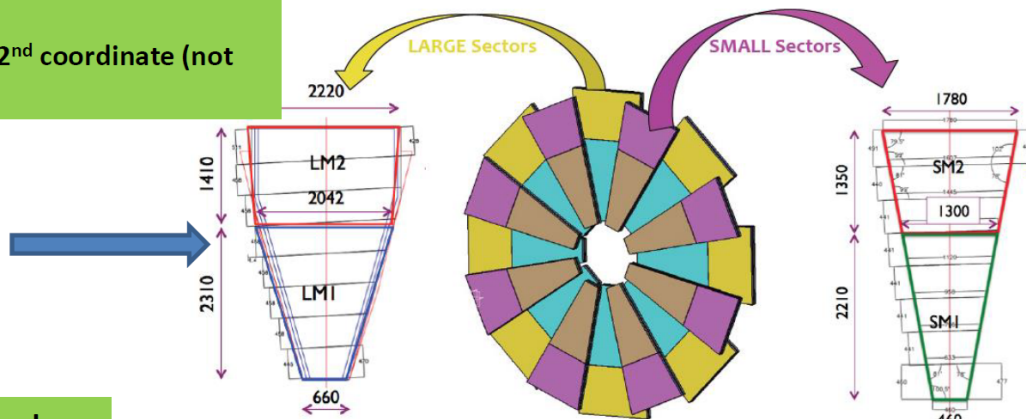
Sector	Nbr sectors Nbr chambers/sector MM layers/chambers	MM layer area (containing rectangle)	Total Nbr MM layers (w/o spares)	Total MM PCB area	Manufacturing plan
Small	8x2=16	From ~0.68m <sup>2</sup> (696x980)	512	0.88x512 = 450m <sup>2</sup>	Yrs 2015 +2016
	4 4x2=8	To ~1m <sup>2</sup> (1420x730)			
Large	8x2=16	From ~0.96m <sup>2</sup> (1036x930)	512	1.5x512 = 768m <sup>2</sup>	Yrs 2015 +2016
	4 4x2=8	To ~1.9m <sup>2</sup> (2300x835)			

**1200 m<sup>2</sup> of Resistive bulk  
128 MM Detectors**

Today: MDT chambers (drift tubes) + TGCs for 2<sup>nd</sup> coordinate (not visible)

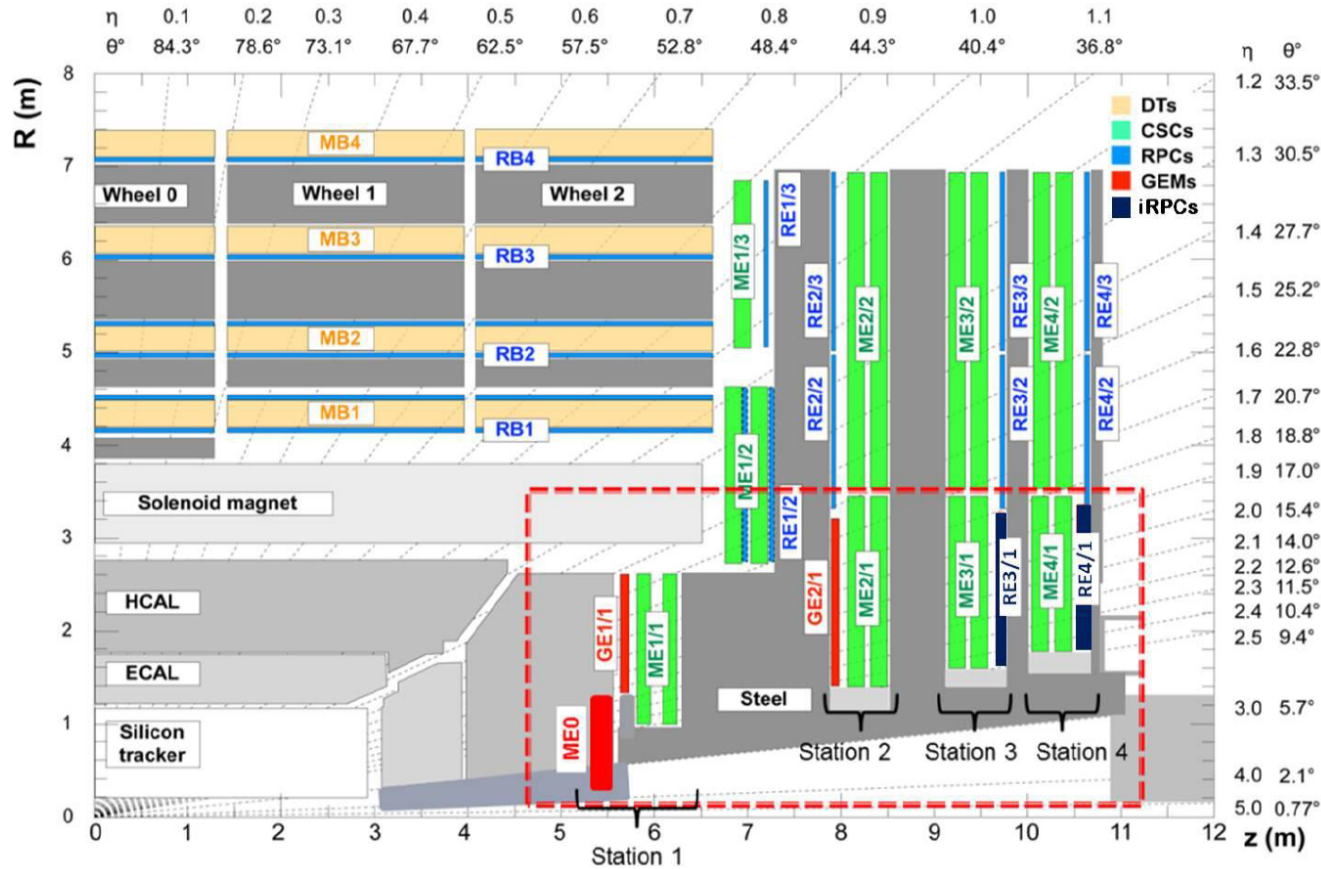


CSC chambers



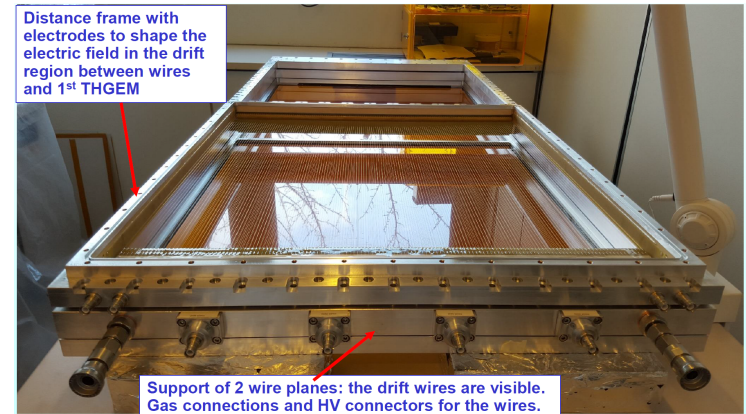
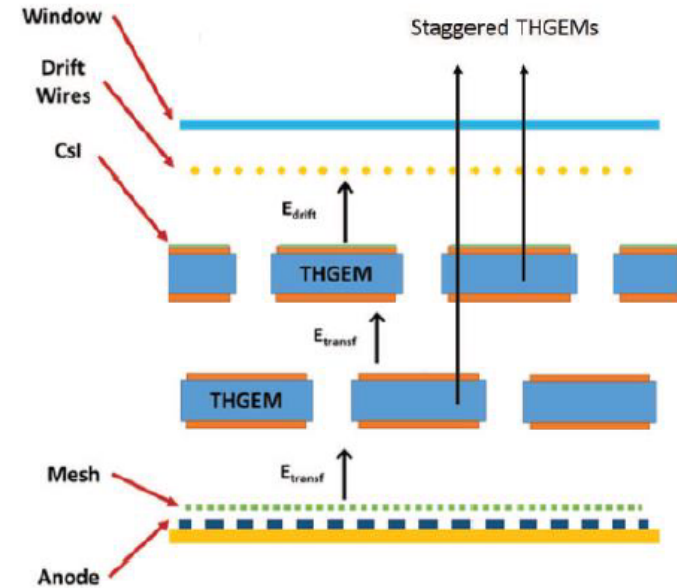
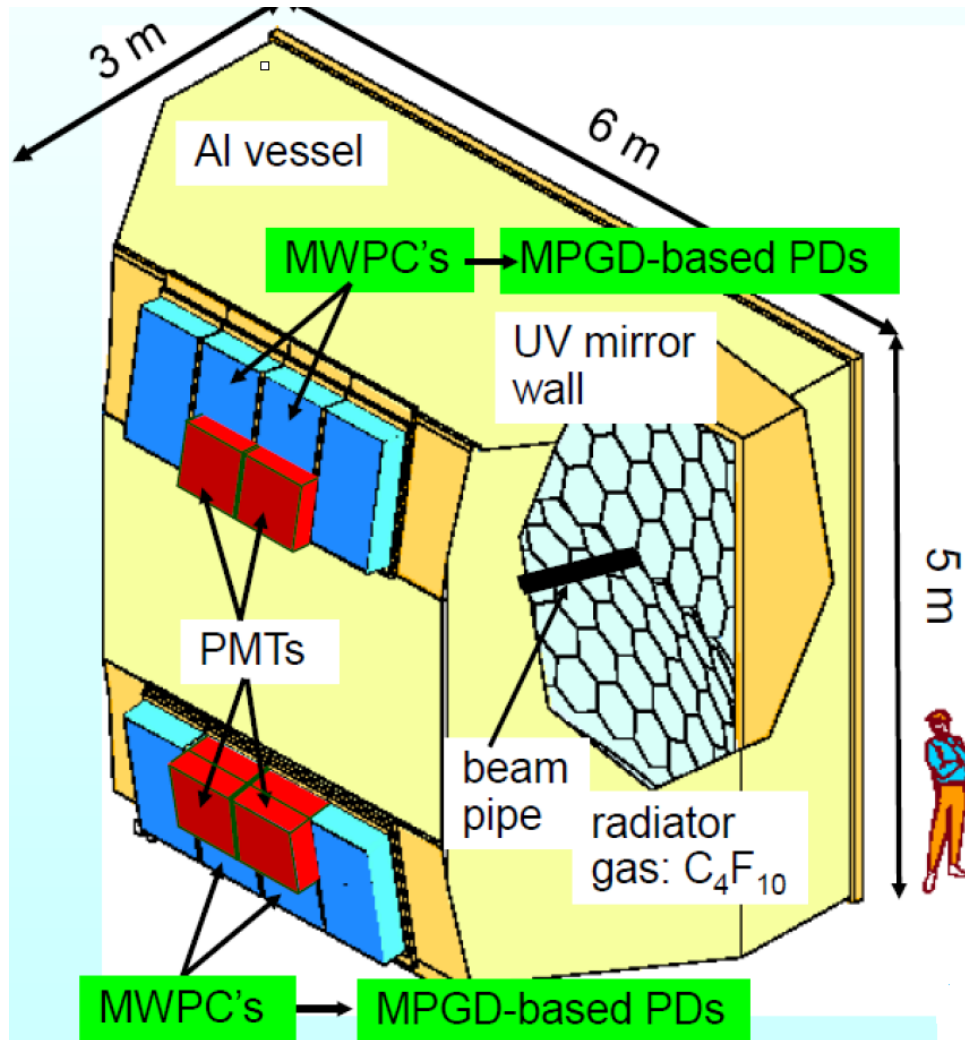
精确 $\eta$ 方向位置测量+ $\phi$ 方向位置测量+触发

# CMS-GEM



Station	Nbr of modules	Module area (containing rectangle)	Total Nbr of modules (w/o spares)	Total GEM foil area (3ple GEMs)	Manufacturing plan
1	18x2x2=72	~0.43m <sup>2</sup> (440x990)	72	0.43x72x3= 93m <sup>2</sup>	Yrs 2014+2015
2	36x2=72 (long) 36x2=72 (short)	~2.4m <sup>2</sup> (1251x1911) ~1.6m <sup>2</sup> (1251x1281)	144	(2.4+1.6)x72x3= 864m <sup>2</sup>	Yrs 2015+2016

# COMPASS-RICH



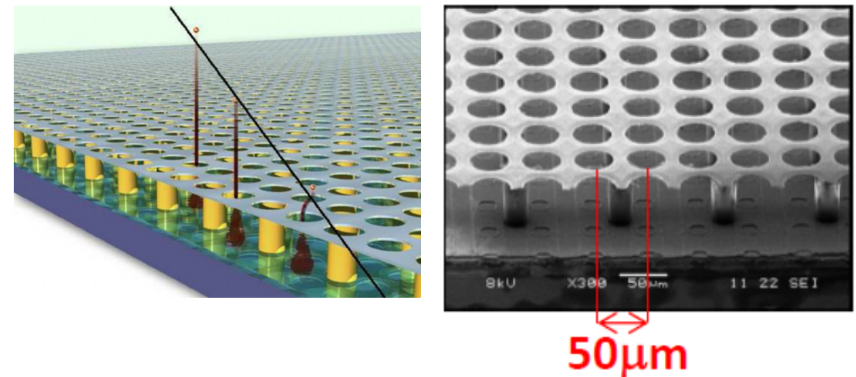
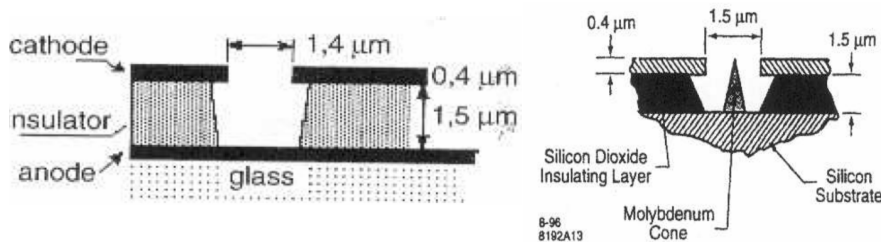
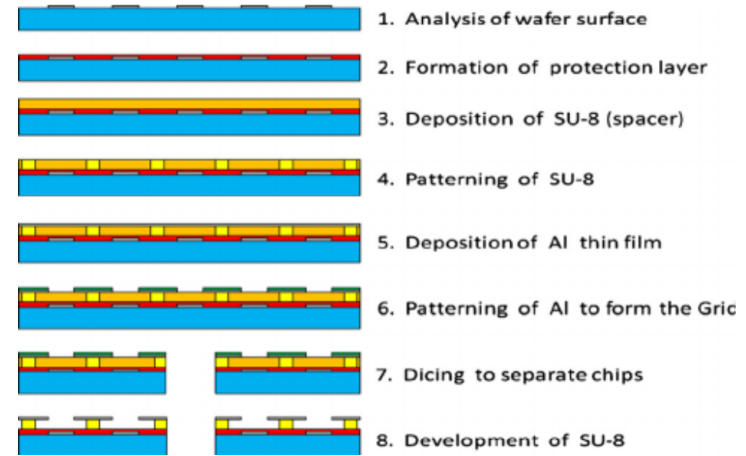
# 还有很多很多很多...

- 重离子物理
  - STAR, Nuclotron BM, SuperFRS, CBM ...
- 天体粒子物理：X、gamma极化测量仪
  - PRAXyS, HARPO, SMILE-II ...
- 暗物质探测
  - DARWIN, PANDA-X, NEWAGE, CAST, IAXO ...
- 中微子探测
  - T2K, SHiP, WA105, DUNE ...
- 中子探测
  - ESS NMX, LOKI-SANS, SPIDER, n\_TOF ...
- 光探测
  - COMPASS, PHENIX, SPHENIX, EIC ...
- ...

# 推动极限

- 极高集成度
- 极高颗粒度
- 极高时间分辨 ( 下一页)

GridPix = InGrids+Timepix

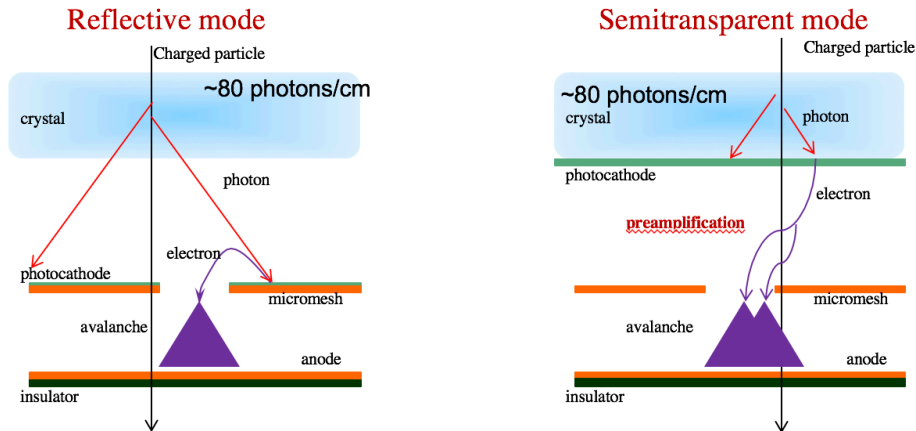


- 增益十分有限 (~30), 电极极易损害, 可靠性是一个大问题。
- 有必要这么高的颗粒度吗?(已经显著小于 $\delta$ 电子、光电子射程)

探测器(MM) 生长在读出芯片之上, 达到硅像素探测器的集成度和颗粒度。

# 时间分辨前沿：PICSEC-MM

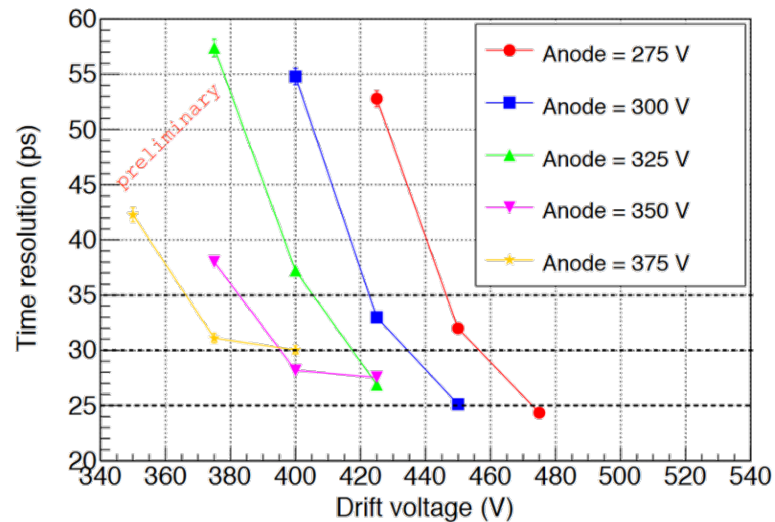
## 探测器原型 (PICSEC合作组)



## Picosec Collaboration

- CEA (Saclay): T. Papaevangelou, I. Giomataris, M. Kebbiri, F.J. Iguaz, T. Gustavsson, D. Desforge, M. Pomorski, O. Maillard, C. Guyot, P. Schwemling
  - CERN: J. Bortfeldt, F. Brunbauer, C. David, J. Franchi, M. Lupberger, H. Muller, E. Oliveri, F. Resnati, L. Ropelewski, M. van Stenis, T. Schneider, L. Sohl, P. Thuiner, R. Veenhof, S. White<sup>1</sup>
  - LIP: M. Gallinaro
  - NCSR Demokritos: G. Fanourakis
  - NTUA Athens: Y. Tsiolitis
  - University of Santiago de Compostela: D. Gonzalez-Diaz
  - University of Science and Technology of China: Y. Zhou, Z. Zhang, J. Liu, B. Qi, X. Wang
  - University of Thessaloniki: I. Manthos, K. Paraschou, S. Tzamarias, D. Sampsonidis
- <sup>1</sup>Also University of Virginia

## 束流测试结果



- 最终目标：实现大规模应用中高计数率 ( $\sim > 1\text{MHz}/\text{cm}^2$ ) 下时间分辨  $< \sim 50\text{ps}$ !
- 高计数率能力+精确定时+适中定位

# 发展趋势

- 主要受高能物理需求（大面积、抗辐照、高计数率、高分辨…）驱动，但也越来越受到高能物理领域外的影响（低质量、高低压、极低放射本底、高灵敏度、便携…）。
- 两个方向并行
  - 开发新的探测器生产技术，发明新的探测器方案。
  - 改善现有探测器的稳定性，为特定应用改良已有探测器设计。
- 应用领域越来越广，早已超越了核与粒子物理领域
- 冲击性能极限：极高集成度、极高分辨…



# 结语

- 微结构气体探测器是气体探测器继多丝正比室后的第二次革命。
- 经过二十多年的发展，微结构气体探测器已成为气体探测器的主流，并具备了多种成熟的技术方案。
- 微结构气体探测器起源于粒子物理领域，但已远超越了这一领域。
- 微结构气体探测器将继续发展，以不断适应新的需求和挑战。