
微结构气体探测器的发展动态与前景

张志永

核探测与核电子学国家重点实验室
中国科学技术大学

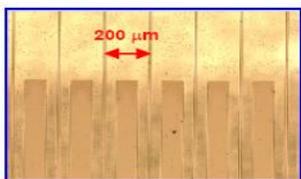
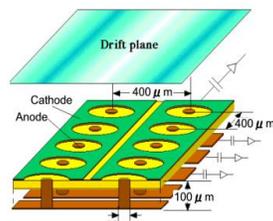
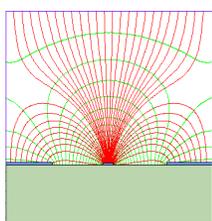
第十届全国先进气体探测器会议，2021-10

微结构气体探测器 (MPGD) 分类

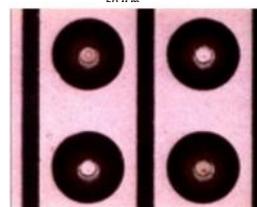


A. Oed
MSGC, 1988

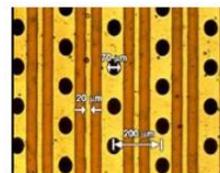
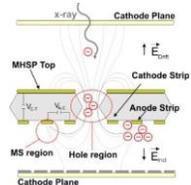
微条型



MSGC



microPIC

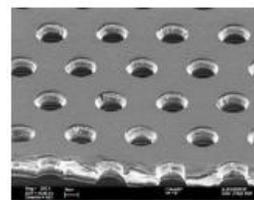
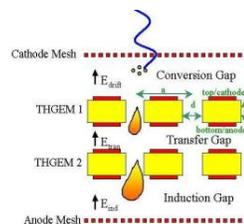
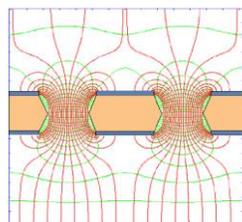


MHSP

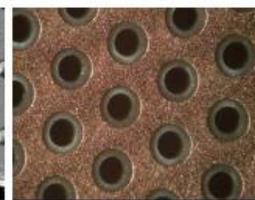


F. Sauli
GEM, 1997

微孔型

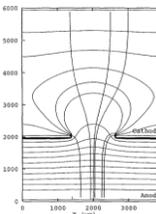


GEM



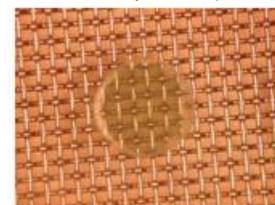
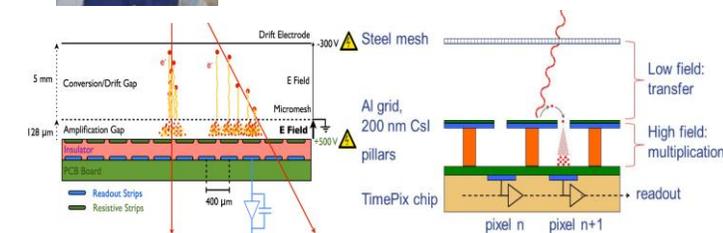
THGEM

微点、孔-条、微井、微槽

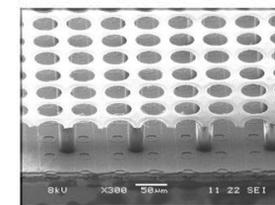


Y. Giomataris
Micromegas, 1996

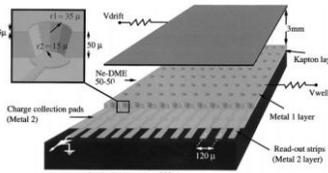
微网型



Micromegas



Ingrid



WELL

◆亚毫米电极、倍增结构：高计数率、高时空分辨、抗辐照、低离子和光子反馈

◆现代工业化加工技术：大面积、低造价

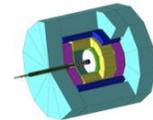
欣欣向荣的发展势态



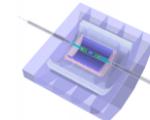
粒子物理实验大装置升级

- ATLAS, 缪子探测器, 1200 m² MM
- CMS, 端盖缪子探测器, 1000 m² of GEM
- ALICE, TPC 探测器, 130 m² GEM
- BES III 内径迹探测器升级, cylindrical GEMs
- 其他还有不少...

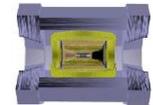
未来探测器谱仪预研基准方案



ILC



CEPC

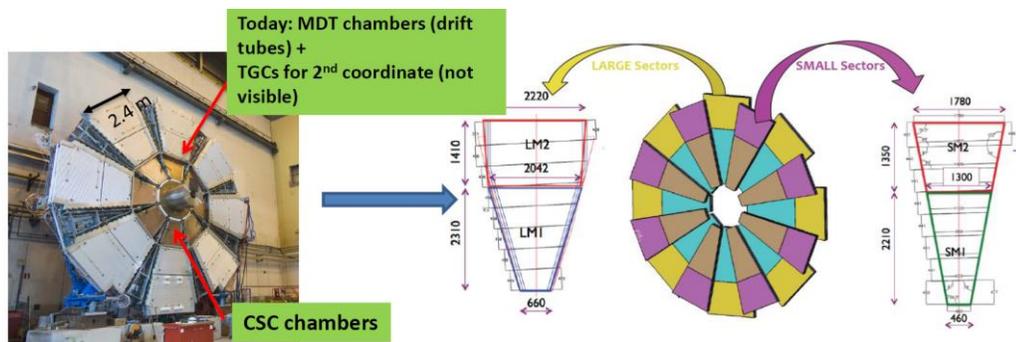


STCF

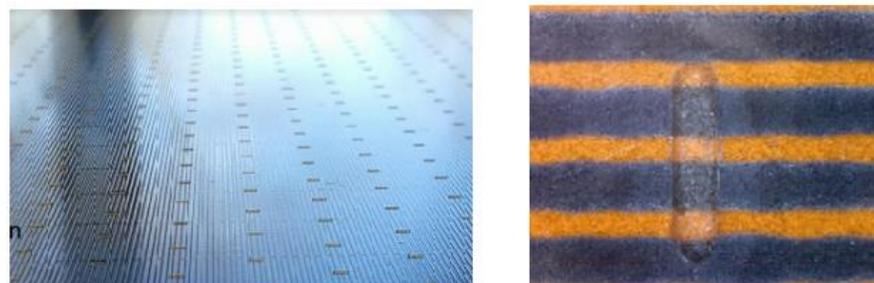
	内径迹	粒子鉴别	强子量能器
ILC	TPC(MM, GEM, InGrid)		DHCAL (MM, GEM, THGEM)
CEPC	TPC(GEM, MM)	RICH(THGEM, MM, DMM)	DHCAL (GEM, THGEM, RPWELL)
STCF	C-μRWELL	RICH(THGEM, MM, DMM)	

核与粒子物理实验仍是MPGD发展的核心驱动力!

大面积Micromegas：ATLAS 缪子探测器

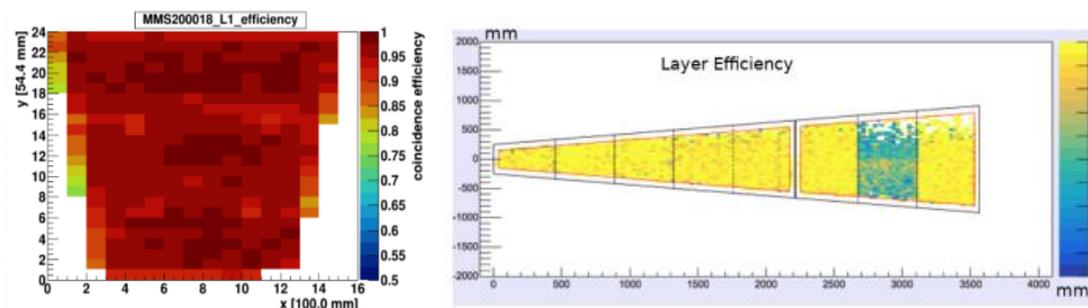
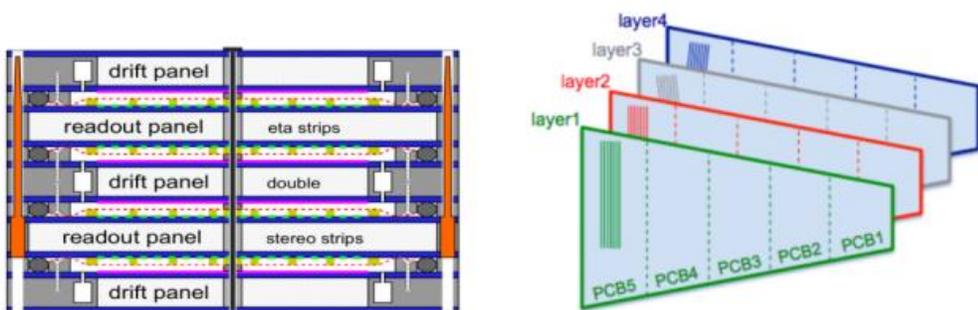


光刻膜制作支撑 $1\text{ mm} \times 330\ \mu\text{m}$ ，
厚度 $128\ \mu\text{m}$ ，间距 7 mm



- ◆ SW覆盖 $1.3 < \eta < 2.7$ 区域，预期计数率 $600 - 15\text{ k Hz/cm}^2$
- ◆ NSW MM总面积 1280 m^2 ，单个探测器达到 $\sim 2-3\text{ m}^2$

部分探测器打火频繁，单个探测器效率不均匀

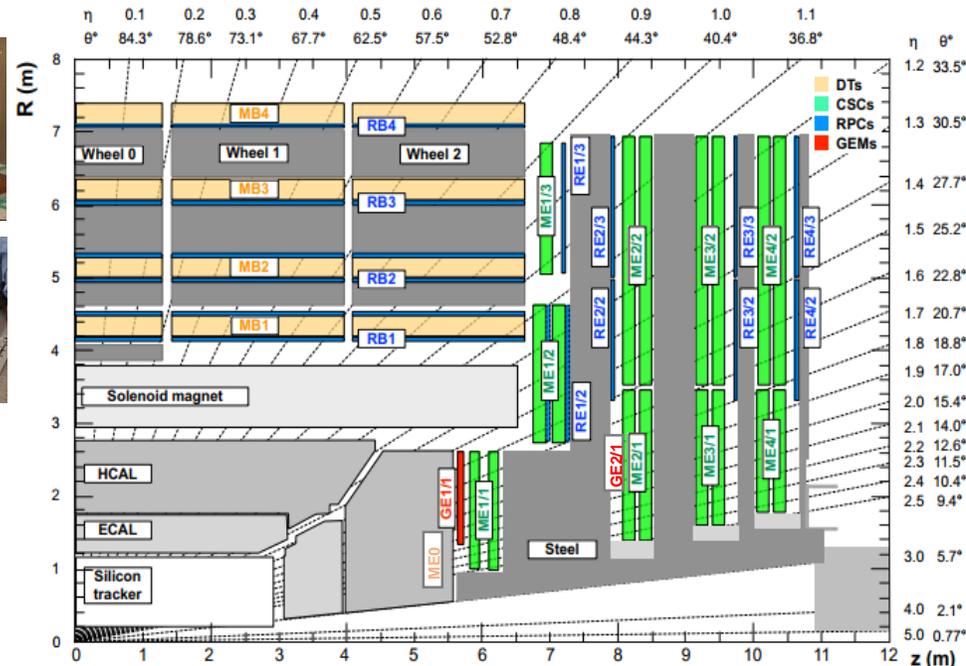
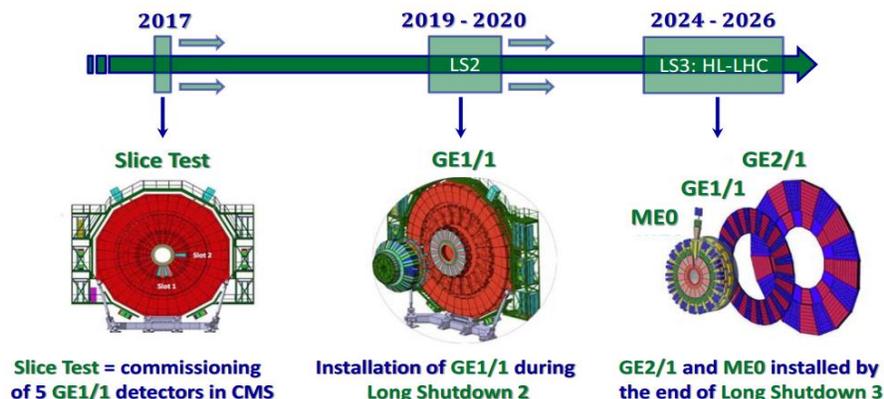


- ◆ 超出现有Bulk工艺能力 ($< 60\text{ cm}$) 采用floating mesh
- ◆ 阻性电极采用阻性条，阻值为数 $10\text{ k}\Omega/\text{cm}$

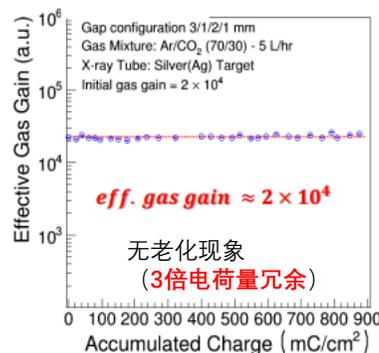
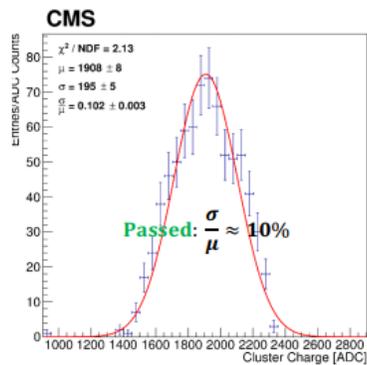
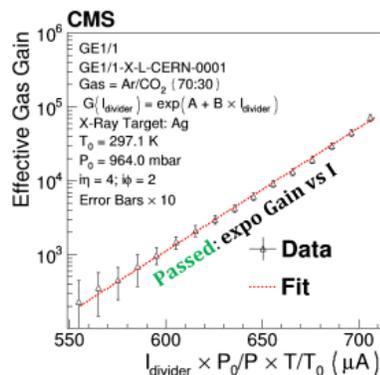
I. Gnesi 2020 JINST 15 C09019

大面积制作工艺、高性能阻性电极仍是重要挑战

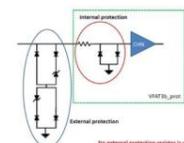
大面积GEM: CMS端盖缪子谱仪



- ◆ 覆盖 $1.5 < \eta < 2.8$, $\sim 50 \text{ kHz/cm}^2$ (ME0)
- ◆ 面积 350 m^2 , $\sim 1000 \text{ m}^2$ foil, 单个达到 $\sim 0.3 \text{ m}^2$
- ◆ 三层GEM, 增益 2×10^4 , 280 mC/cm^2 累积电荷量

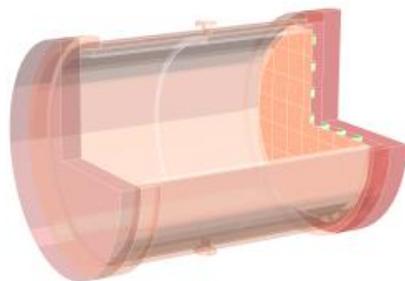
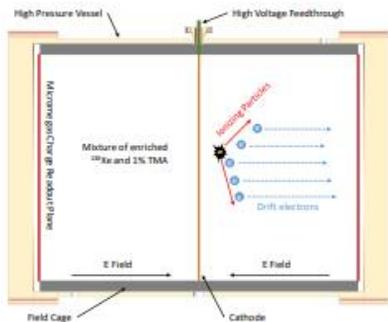


- ◆ CMS-GEM GE1/1目前按计划完成144个探测器生产, 计数率、增益、老化等性能符合预期
- ◆ 电子学VFAT第二版因打火引起通道损坏, 后续版本中设计保护电路后解决



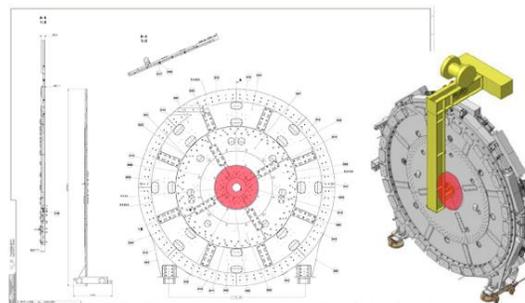
极端条件及个性化需求

PandaX-III 读出高压**低本底**TPC
 10bar Xe测量双贝塔衰变电子，排除本底



ATLAS Phase-II升级中

High- η tagger区域径迹测量
 距离束流管只有25cm，高达10MHz/cm²极端计数率

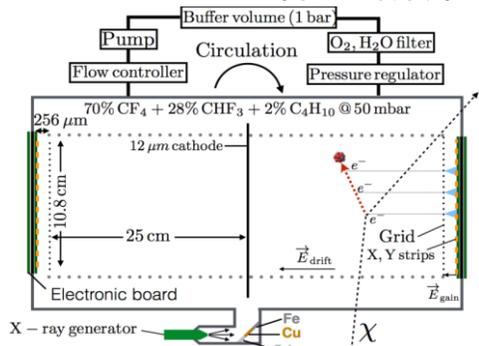


高亮度LHC升级中
 高计数率下达到30皮秒分辨，
 以应对超高的事例多重数

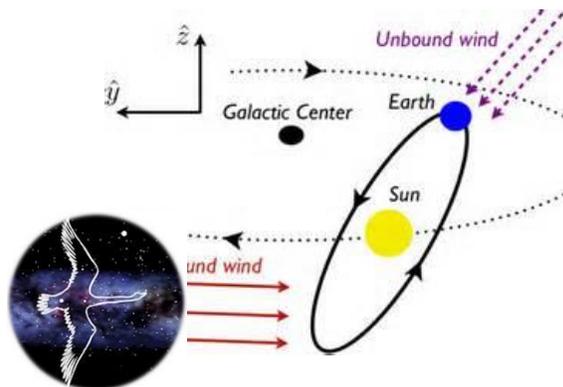


MIMAC 低气压**低本底**TPC

50mbar含氟气体探测暗物质方向性反冲核方向

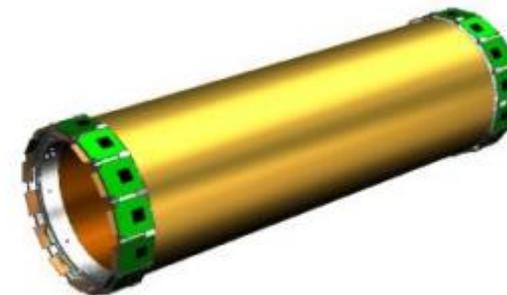
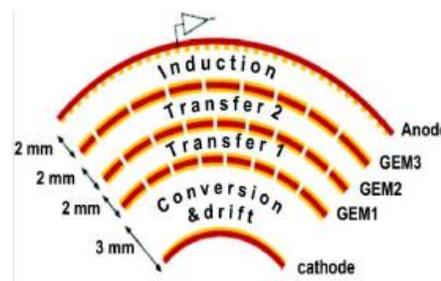


Y. Tao et al, NIMA Available online 4 May 2021, 165412



BES-III内径迹探测器

圆筒形GEM



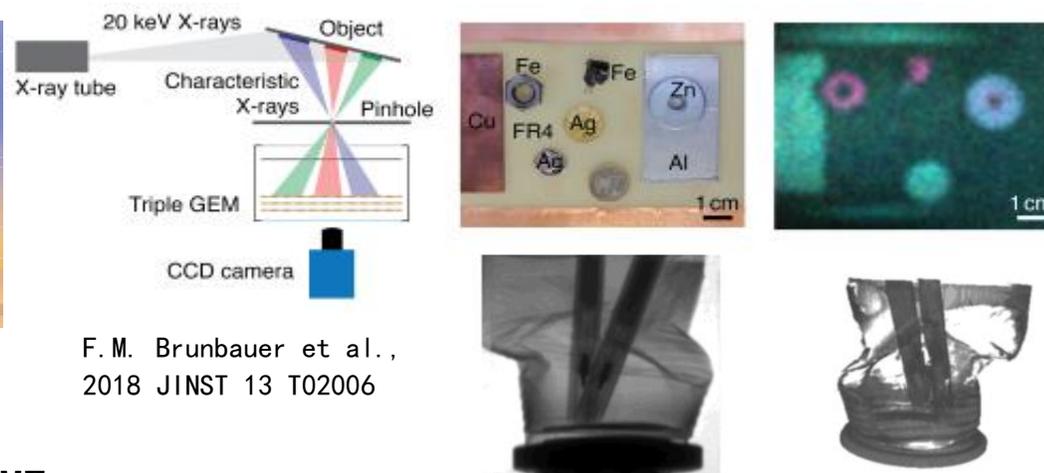
复杂多样化应用需求

缪子成像研究

大面积径迹探测，测量散射角度和透射吸收



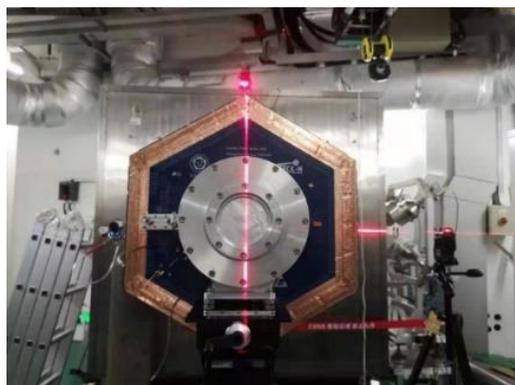
基于GEM光读出X-ray “彩色” 和3D成像 材料特征X-ray高分辨测量



F. M. Brunbauer et al.,
2018 JINST 13 T02006

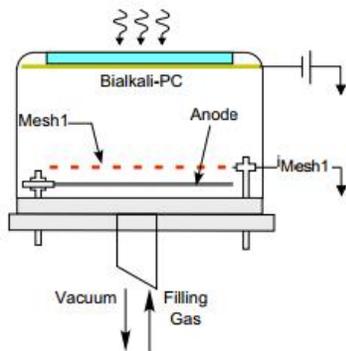
CSNS-Back-n 中子MTPC

高颗粒度像素读出TPC测量中子反应核数据



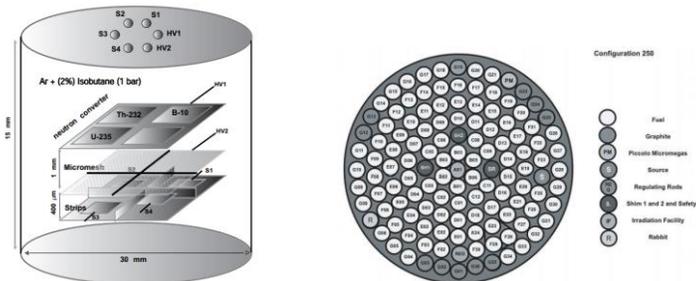
可见光灵敏gasPMT

单光电子测量、极低离子反馈率、无气体释放



基于Micromegas的中子探测

高辐照背景下宽中子能段，用于ADS堆芯内部中子测量



MPGD研究驱动与重心

◆ 平米量级、100微米分辨、100k - MHz/cm²等“不算苛刻”的性能需求在大工程建设中仍然具有挑战！

◆ 极端条件下要求达到极限性能

§ 低本底、高低气压：PandaX-III、MIMAC

§ 极低离子反馈：ALICE-TPC、CEPC-TPC、气体光电

§ 10 MHz/cm²计数率：ATLAS 二期 High- η tagger

§ \sim 30皮秒快时间测量：高亮度LHC升级

➔MPGD技术研发方向

§ 阻性电极

§ 新原理和新结构

§ 制造工艺方法

聚焦大面积高性能MPGD技术研发，挖掘MPGD极限性能，为应用开辟想象空间！

MPGD技术研发（约近五年）

- § 制造方法
- § 性能指标
- § 技术应用

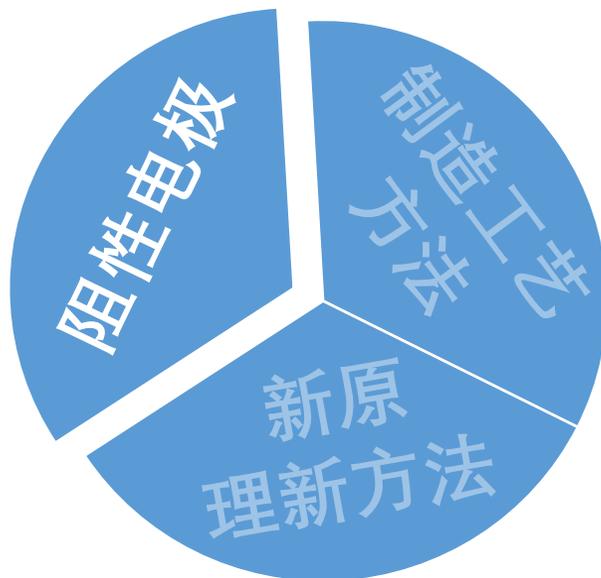


- § 热压接方法制作Micromegas
- § 新型微纳工艺制造GEM/THGEM

- § 紧凑型结构： μ RWELL、RWELL、MTHGEM
- § 快时间测量：FTM、PICOSEC-MM
- § 低离子反馈：MM-THGEM多层微网结构DMM、TMM

MPGD技术研发

- § 制造方法
- § 性能指标
- § 技术应用

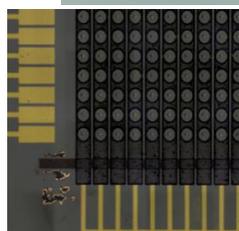


- § 热压接方法制作Micromegas
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- § 低离子反馈: MM-THGEM多层微网结构DMM、TMM

阻性电极技术

高性能阻性电极是大面积MPGD研制的关键：**抑制打火、提高增益与稳定性**



电子浆料

丝网印刷

10-20 μm , $\text{k}\Omega/\square$ - $100\text{M}\Omega/\square$

- 复杂结构
- 大面积制作
- △ 高温处理
- △ 阻值可控性
- △ 打火损伤

逐步隐退



镀锗薄膜

电子束或热蒸发

0.1-1 μm , $\text{M}\Omega/\square$ - $500\text{M}\Omega/\square$

- 阻值可控性：厚度
- 高纯材料 (Ge)
- 大面积制作
- △ 化学及热稳定
- △ 氧化失效：干燥保存

特定场景



类金刚石结构碳

磁控溅射 (石墨靶)

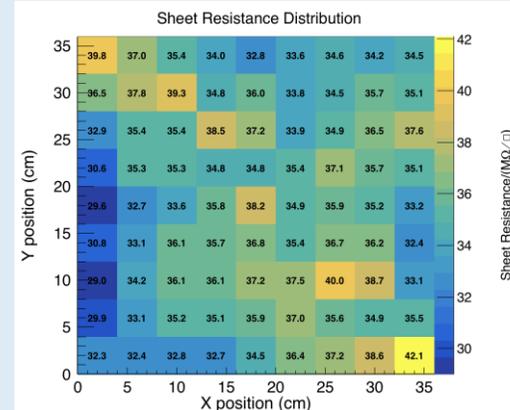
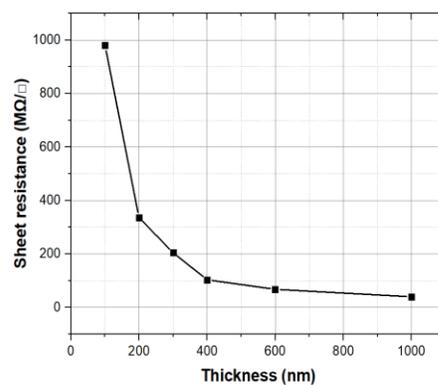
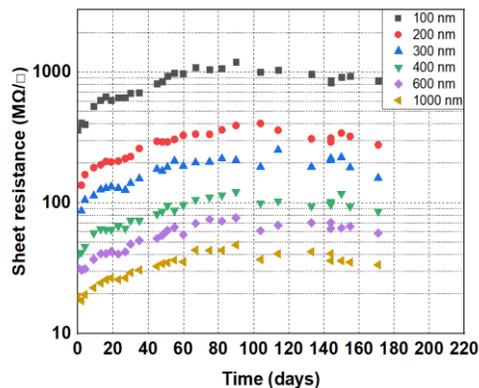
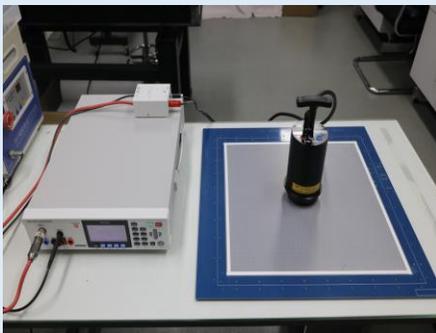
0.001-0.1 μm , Ω/\square - $\text{G}\Omega/\square$

- 阻值可控性：掺杂
- 高纯材料 (石墨靶)
- 柔性基材
- 化学及热稳定
- △ 大面积刚性基材 (如FR-4)
依赖于大型复杂设备

潮流趋势

高性能阻性电极：镀锗薄膜&DLC

■ 镀锗薄膜



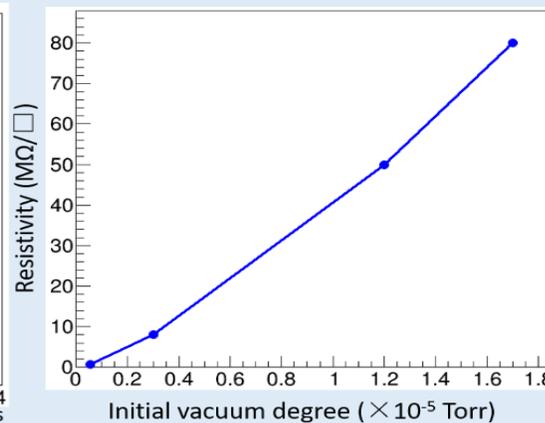
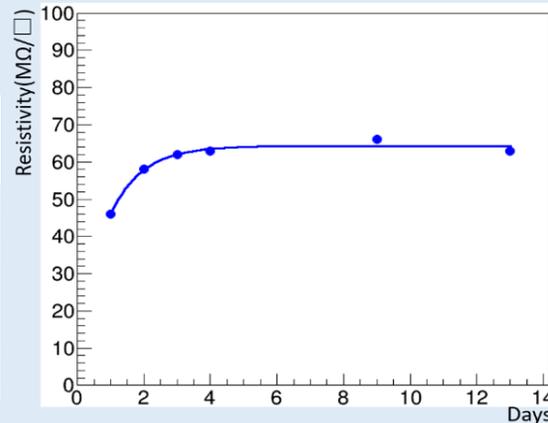
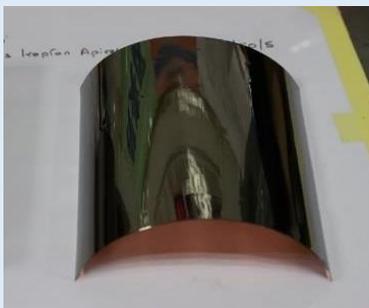
样品
Ge 40×40cm², DLC 15×15cm²

阻值达到及长期稳定性：
Ge~60天, DLC~4天

阻值可控：
Ge厚度反比,DLC真空度调控

均匀性可控：
RMS/MEAN~10%

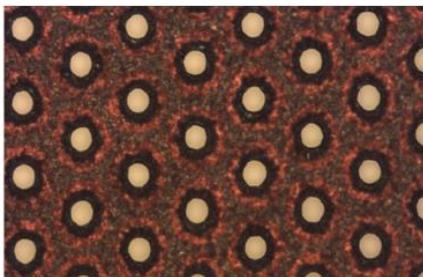
■ DLC



72 MΩ/□	62 MΩ/□	60 MΩ/□
64 MΩ/□	57 MΩ/□	63 MΩ/□
71 MΩ/□	59 MΩ/□	66 MΩ/□

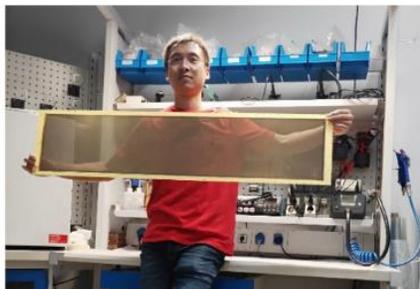
DLC引领MPGD发展的时代潮流

Eraldo Oliveri
CERN



DLC-无铜-THGEM
材料特征X-ray分析成像

Ming Shao
USTC



DLC-
THGEM

Fabio Sauli
CERN



DLC-GEM的X-ray
成像

Yongjie Sun
USTC



DLC-
MRPC

Ioannis Giomataris
Saclay



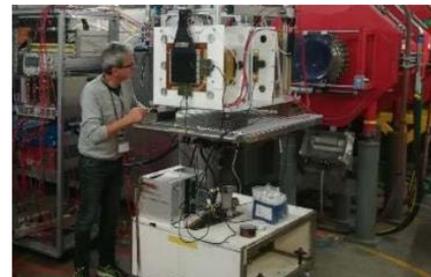
阻性ACHINO
用于暗物质探测器

Piotr Gasik
TUM



DLC-
THGEM

Giovanni Bencivenni
LNF-INFN



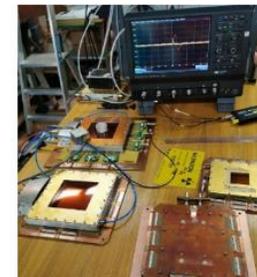
DLC-
μRWELL

Piet Verwilligen
INFN - Sezione di Bari



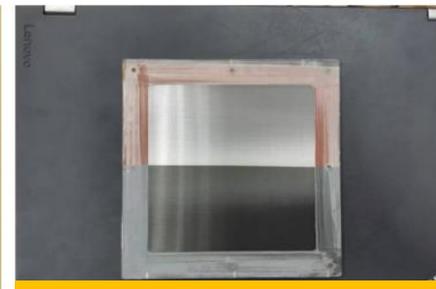
DLC-
FTM

Mauro Iodice
INFN Roma Tre



DLC-
Micromegas

Pollacco Emmanuel
Saclay

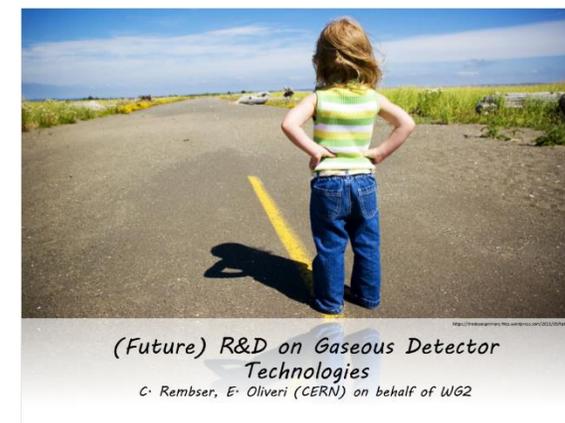
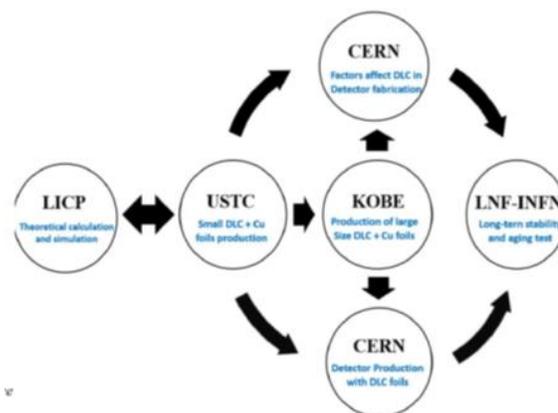
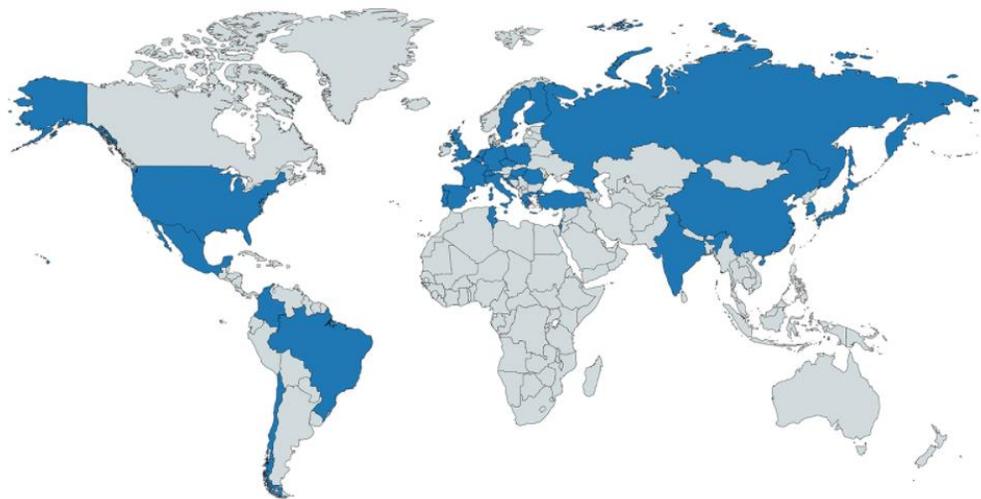


DLC dark mesh Micromegas
for optical readout

中科大与中科院兰州化学物理研究所合作研发DLC在国际国内MPGD研究中应用

DLC电极是MPGD未来需要重点发展的技术之一

CERN-RD51批准DLC阻性电极专题研究项目 (common project)



RD51是欧洲核子中心（CERN）2007成立的
致力于MPGD研究、生产和应用的国际研究
合作组：来自31个国家，89个机构
约450个参与成员

DLC新型电极技术在CERN的气体探测器技术
未来发展研讨会上得到了肯定！

MPGD技术研发

- § 制造方法
- § 性能指标
- § 技术应用

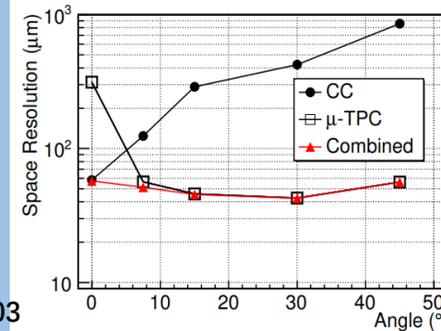
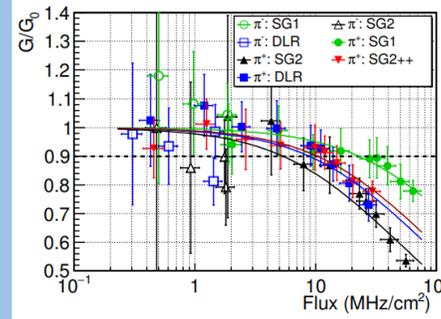
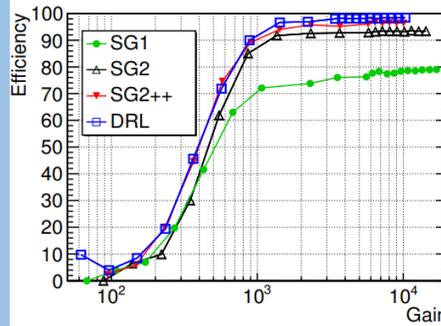
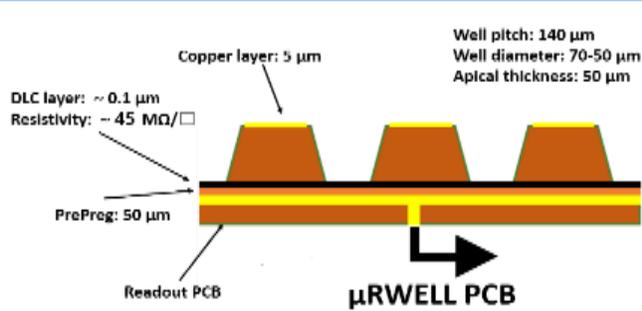


- § 热压接方法制作Micromegas
- § 新型微纳工艺制造GEM/THGEM

- § **紧凑型结构**: μ RWELL、RWELL、MTHGEM、槽型、孔针型
- § **快时间测量**: FTM、PICOSEC-MM
- § **低离子反馈**: MM-THGEM多层微网结构DMM、TMM

紧凑型结构: μ RWELL

- ◆ 井型概念很早就已出现
catWELL: F. Bartol et al., 1996
WELL, R. Bellazzini et al., 1999
- ◆ 得益于阻性电极(DLC)发展
RPWELL, A. Rubin et al., 2013
 μ RWELL, G. Bencivenn et al., 2015



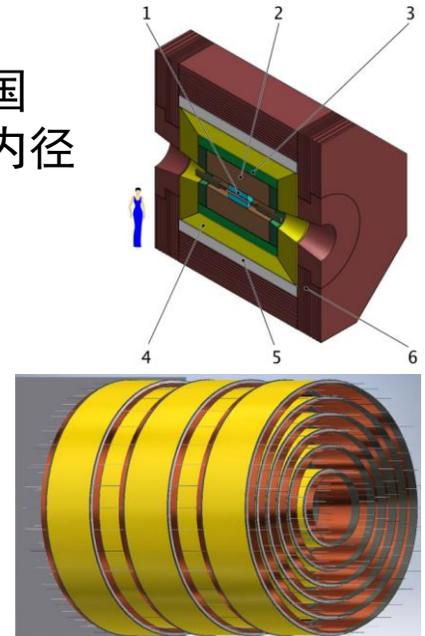
近年来快速发展:
98%探测效率, $>10\text{MHz}/\text{cm}^2$
计数率, $<50\ \mu\text{m}$ 位置分辨

Y. Zhou, et al., NIM-A, 927(2019) 31-36
G. Bencivenni et al 2020 J. Phys.: Conf. Ser. 1498 012003

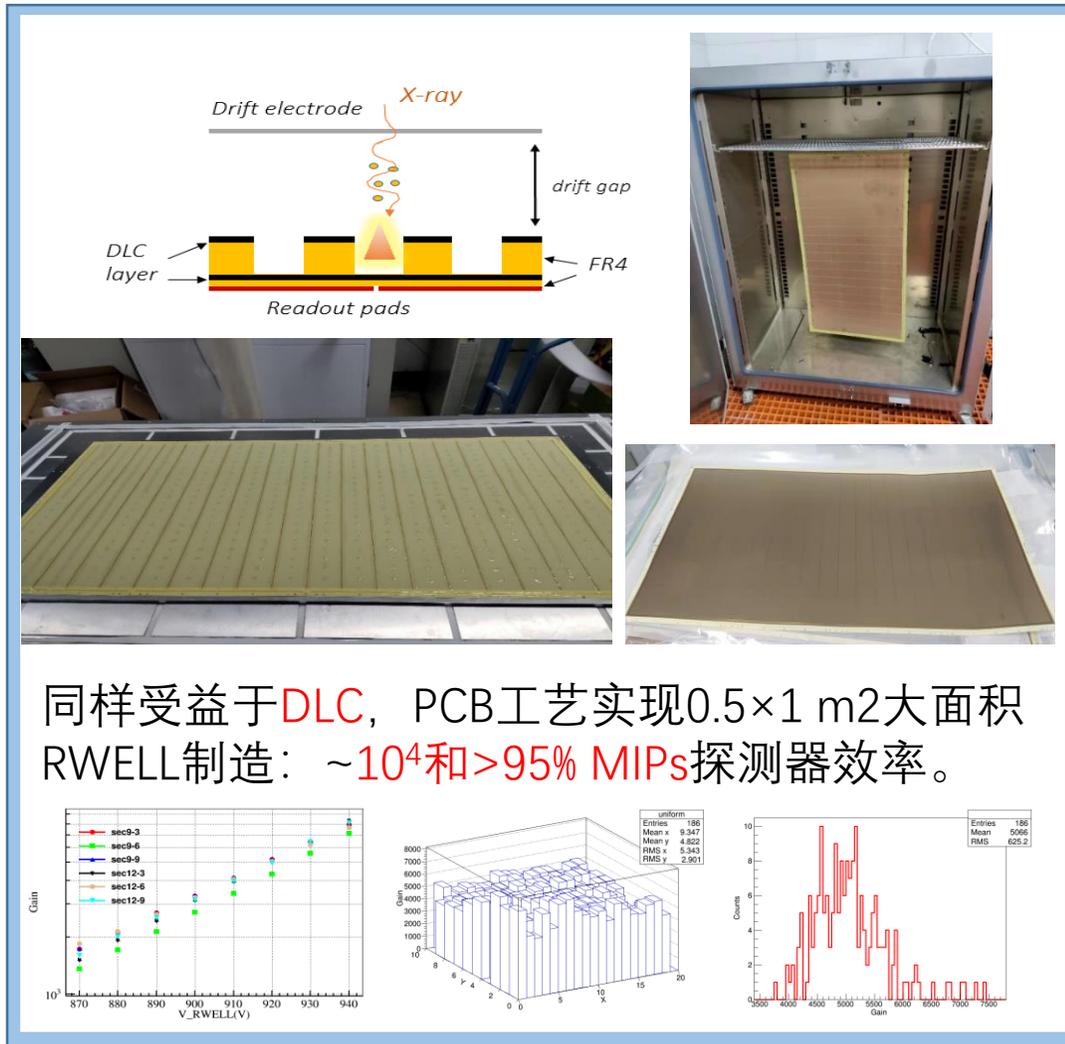
- 单级替代多级 (Vs GEM, THGEM)
- 取消电极张力 (Vs MM)
- 结构紧凑、易于大面积制作
- 可刚可柔、低物质质量、特殊形状

Cylindrical μ RWELL

- 下一代陶浆工厂 (中国 STCF 和俄罗斯 SCTF) 内径迹的共同选择
- EIC 桶部 Tracker 概念设计方案

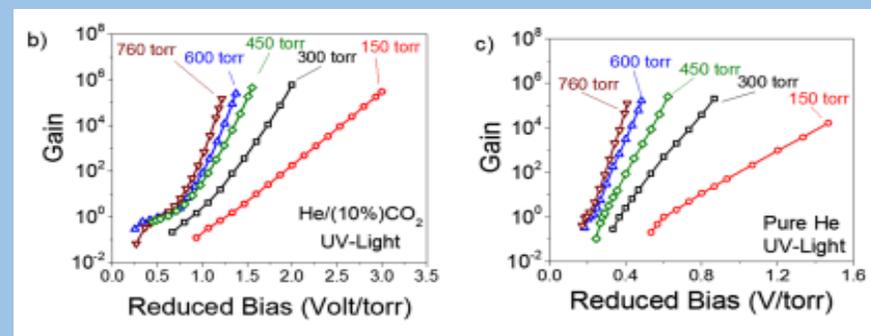
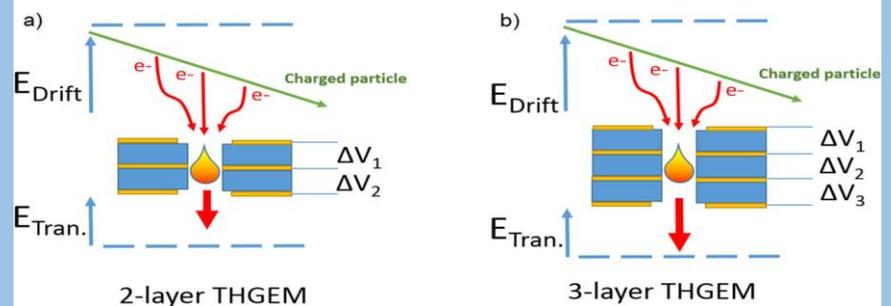


紧凑型结构：RWELL、MTHGEM



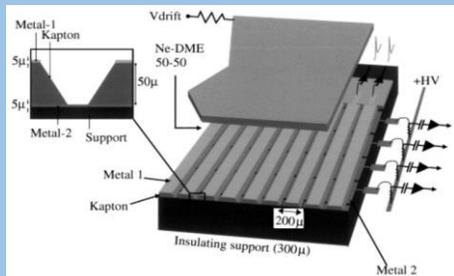
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 取消电极张力 (Vs MM)
 → 结构紧凑、易于大面积制作
 → 可刚可柔、低质量、特殊形状

MTHGEM, M. Cortesi et al., 2017



紧凑型结构：槽型、孔针型

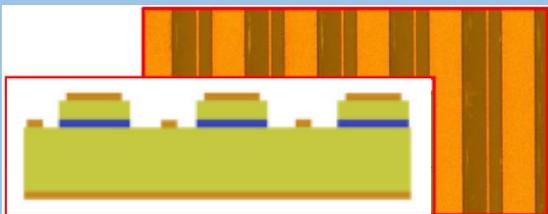
基于PCB工艺的槽型探测器



micro-groove概念

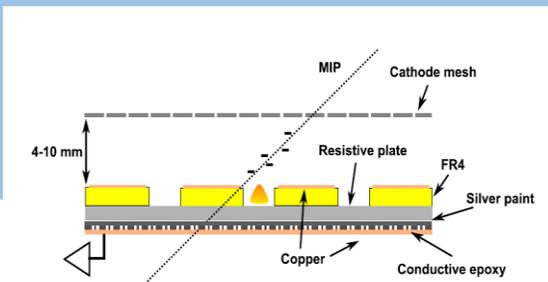
The micro-groove detector,
R. Bellazzini et al., 1999
WELL 也是这个人

给groove加上阻性层



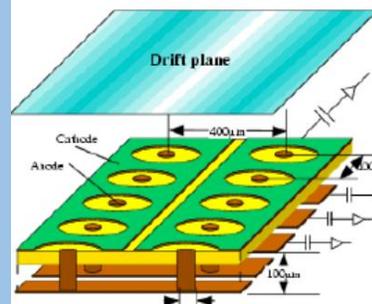
https://twiki.cern.ch/twiki/pub/Main/ThickGroove/Proceeding_Elba_15.pdf

把MSGC的微条放“坑”里

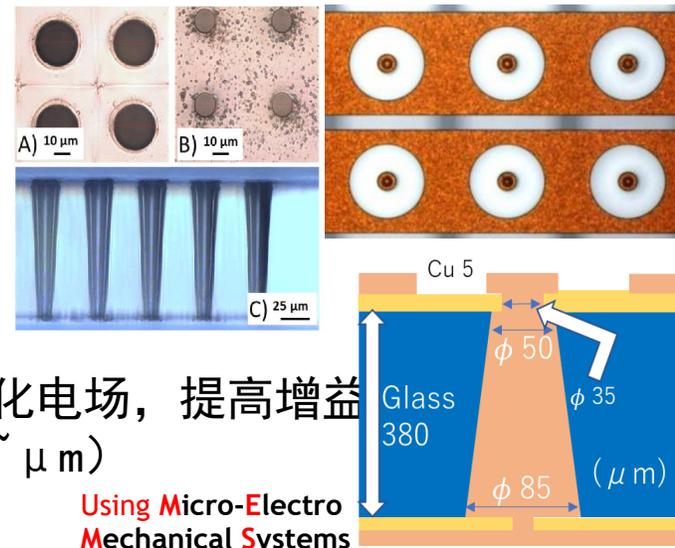


μ-PIC新工艺

常规PCB

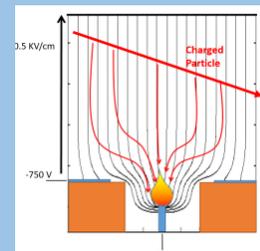
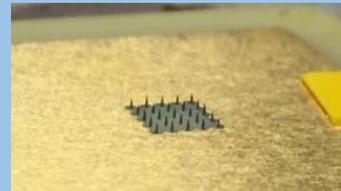
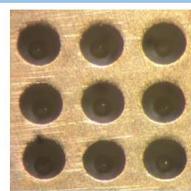
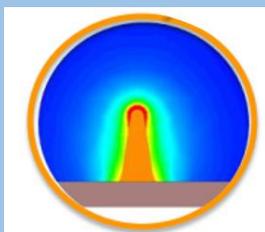
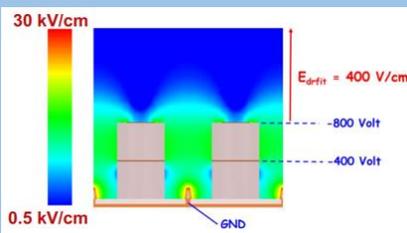


TGV (Through Glass Via)



- 高厚孔比：优化电场，提高增益
- 高刻蚀精度 ($\sim \mu\text{m}$)
- 无气体释放

First TIP-HOLE detector

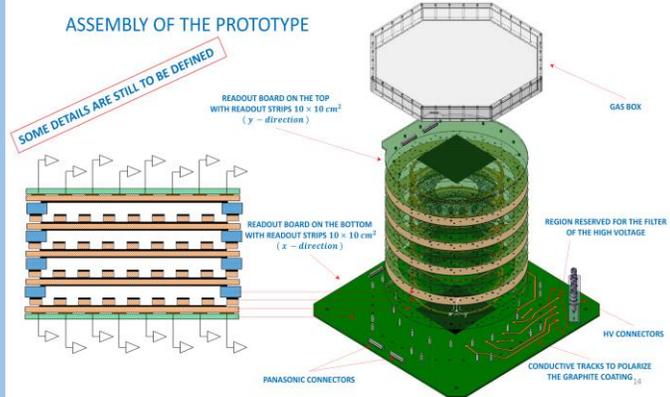
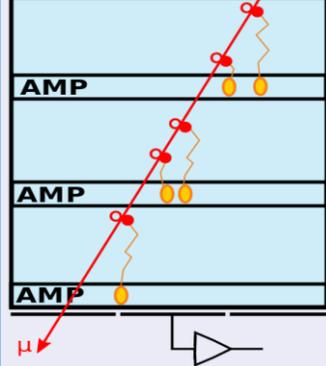


Marco Cortesi, 2019
下文里他还干的不
少事...

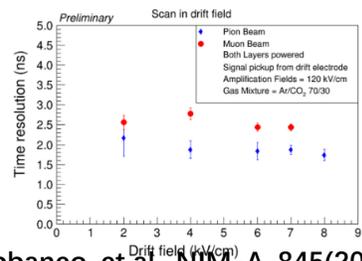
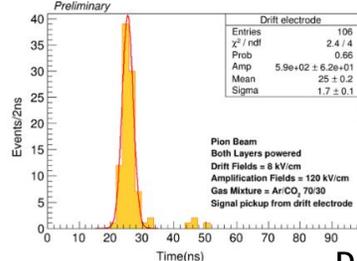
快时间测量：FTM、PICOSEC-MM

FTM

Fast Timing MPGD



- ◆ 多层全阻性井型探测器 (μ RWELL、RWELL)
- ◆ 期望集成MRPC的快时间和MPGD的高计数率

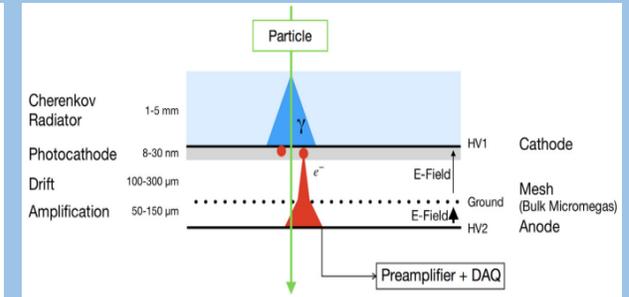
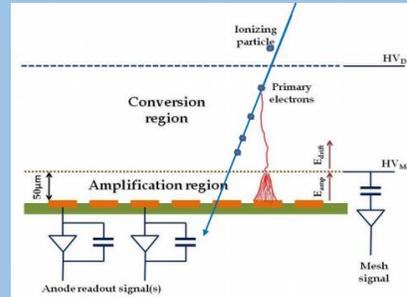


$\sigma : 1.7 \text{ ns}$

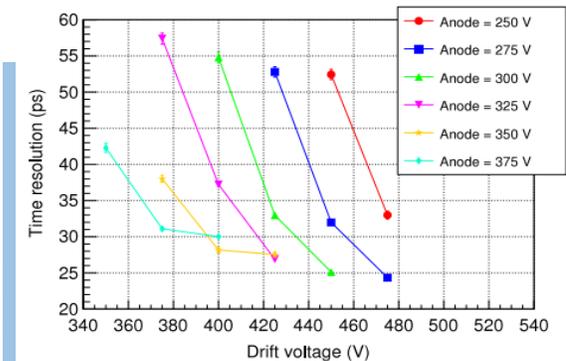
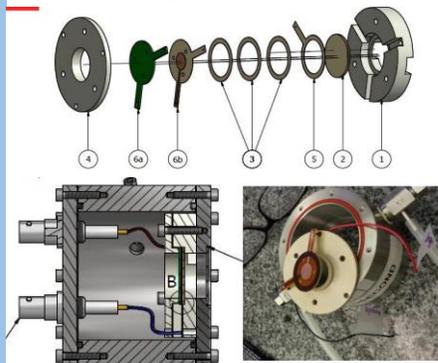
D. Abbaneo, et al., NIM-A, 845(2017) 313-317

性能并不乐观，存在一定的原理性问题

PICOSEC-MM



- ◆ 切伦科夫光电转换电信号
- ◆ 克服电离位置和电子漂移扩散造成的信号时间抖动



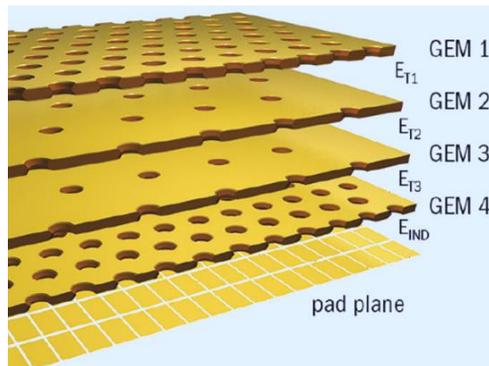
低离子反馈：需求与现行方案

◆ 高计数率TPC

ALICE 探测器升级, ILD, CEPC 预研等

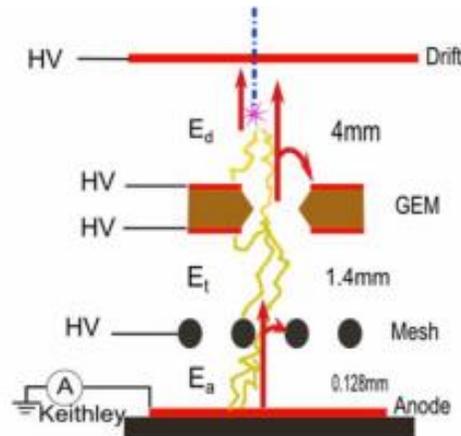
- 降低离子空间电荷对漂移电场的影响
- 高事例率连续读出 (non-gating)

ALICE-TPC



Quadruple GEM, IBF < 1%

CEPC-TPC



Gain \times IBF < ~ 5 , IBF < $\sim 0.1\%$

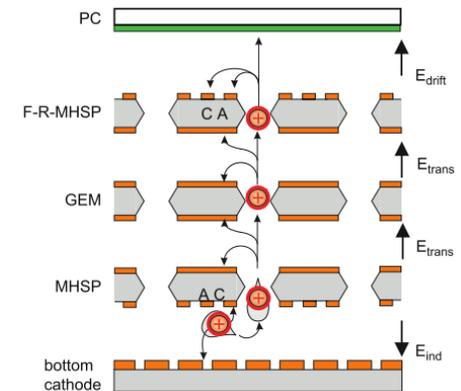
◆ 气体光电探测

	几何结构	抗磁干扰	大面积	位置灵敏	造价
传统型	受限	弱	难	弱	高
气体型	灵活	强	易	强	低

- UV light: CsI, $\sim \text{mC}/\text{cm}^2$
- Visible light: Bi-alkali, $\sim \mu\text{C}/\text{cm}^2$!

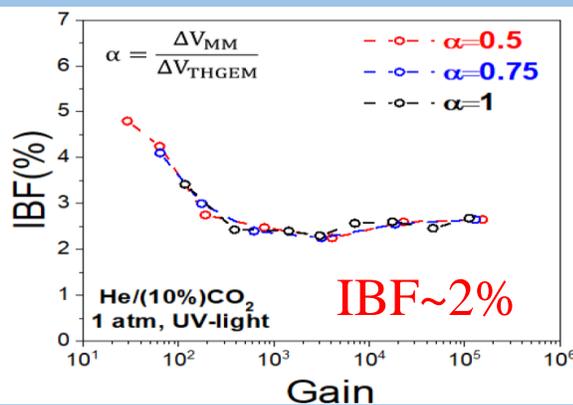
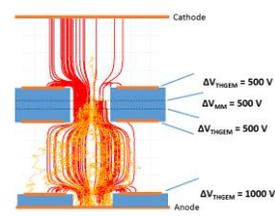
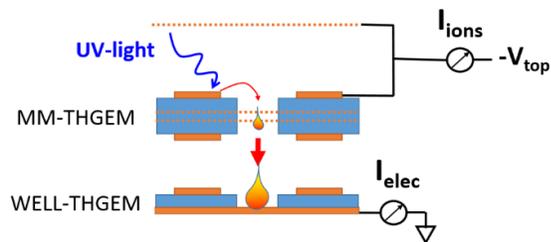
现行方案中的最好水平:
F-R-MHSP_GEM_MHSP
IBF: $\sim 0.03\%$

A. Lyashenko et al. , NIM A
598(2009) 116-120

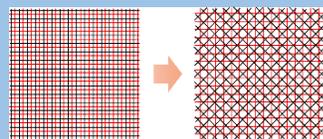
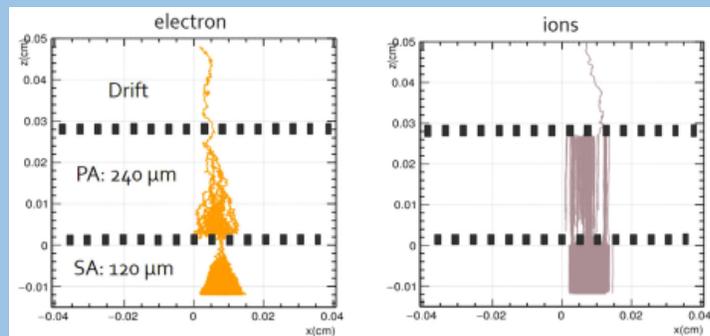
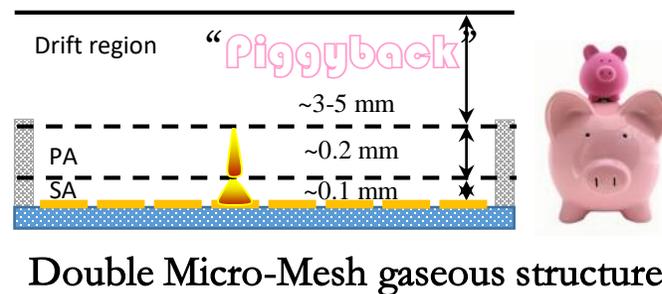


低离子反馈：新结构与提升

MM-THGEM



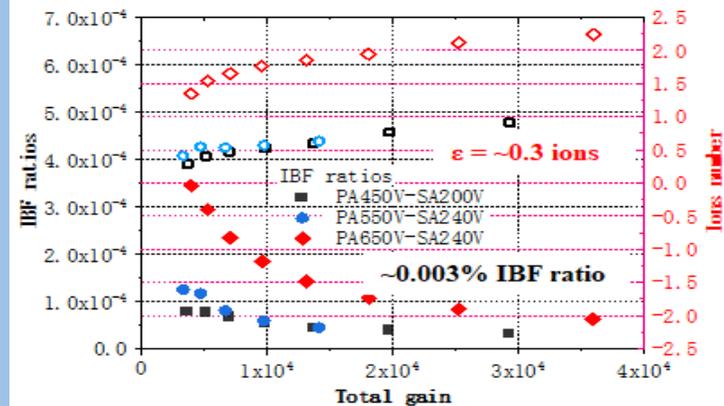
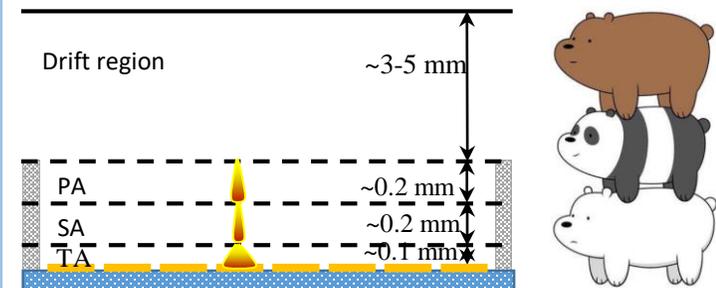
DMM



IBF~0.025%

Zhiyong Zhang et al., NIM-A 889 (2018) 78 - 82
Binbin Qi et al., NIM-A 976 (2020) 164282

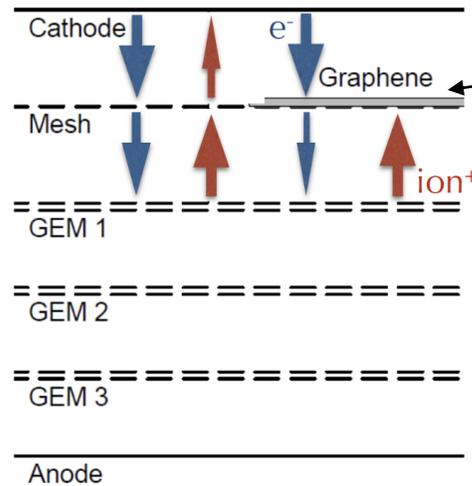
TMM



<0.003% 达到此类结构原理极限，
比已有报导提高1个量级！

低离子反馈：石墨烯热度

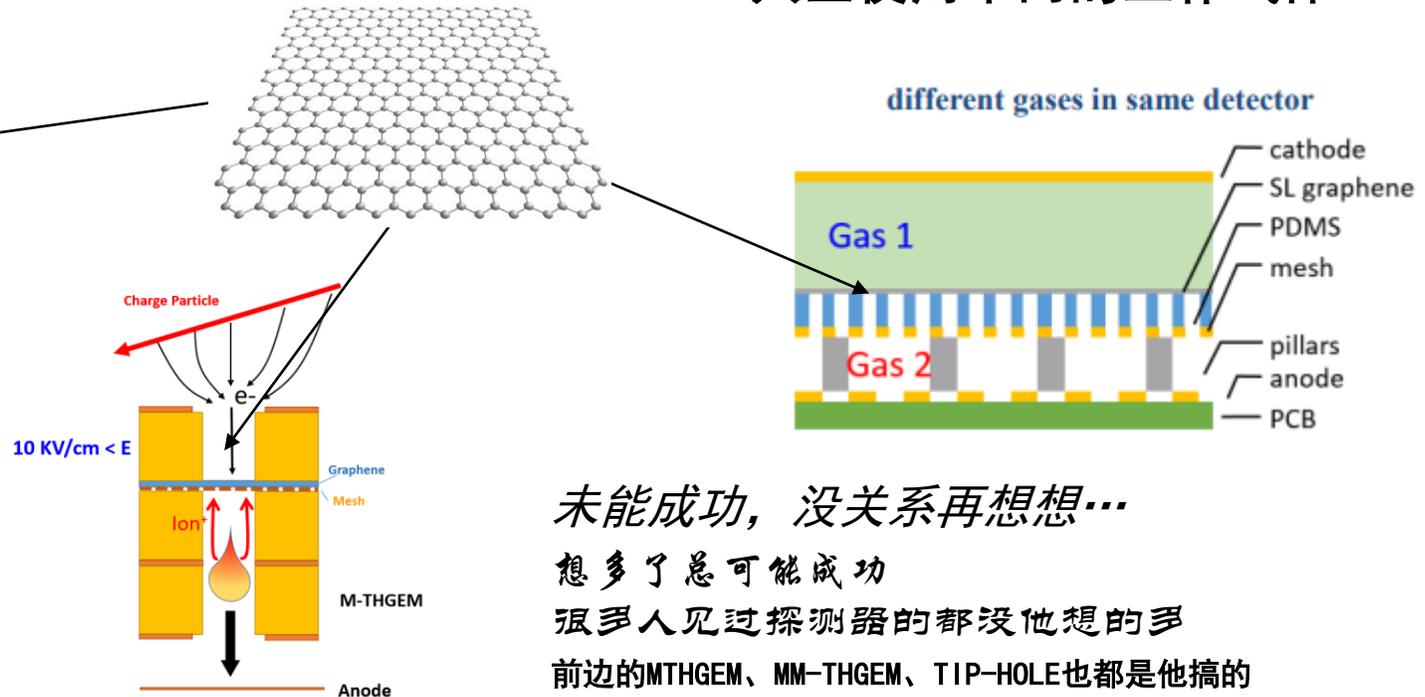
◆ 使用石墨烯通过电子，阻隔正离子



Marco Cortesi,
Michigan State University (MSU)

电子穿过石墨烯需要 $>10\text{kV/cm}$ 电场

◆ 通过石墨烯隔离气体分子实现漂移区和放大区使用不同的工作气体



未能成功，没关系再想想...

想多了总可能成功

很多人见过探测器的都没他想的

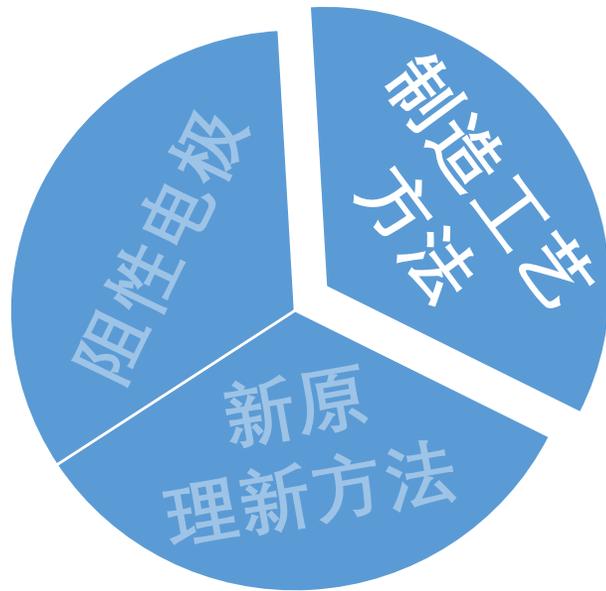
前边的MTHGEM、MM-THGEM、TIP-HOLE也都是他搞的

而且，即使现在不行，不代表以后不行

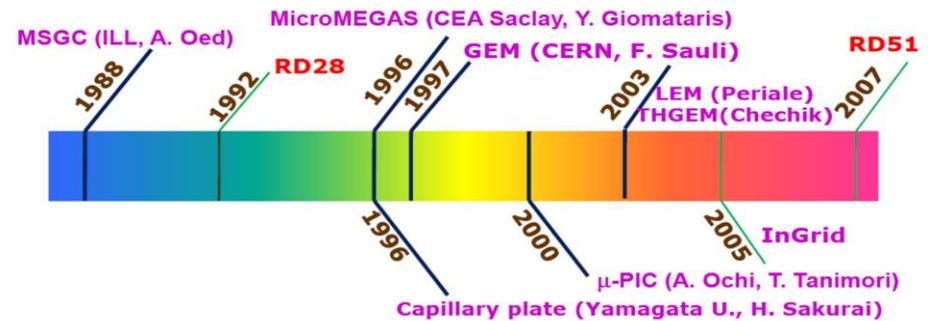
WELL概念出现到 μ RWELL、RWELL火热相隔了20年

MPGD技术研发

- § 制造方法
- § 性能指标
- § 技术应用



- § 热压接方法制作Microegas
- § 新型微纳工艺制造GEM/THGEM

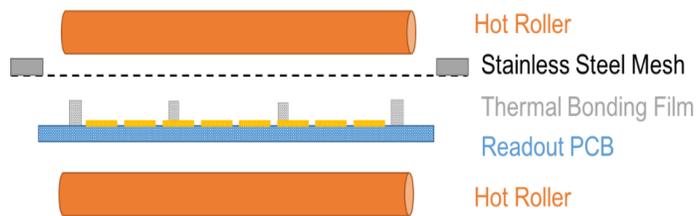


MPGD的发展离不开先进微纳加工技术支撑!

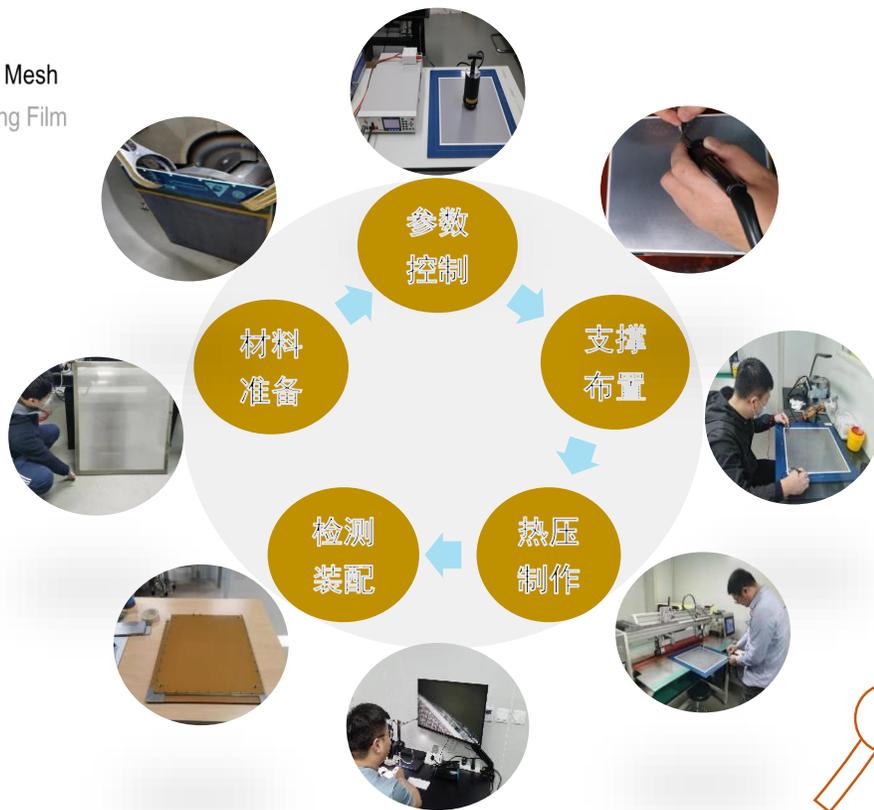
- § 紧凑型结构: μ RWELL、RWELL、MTHGEM
- § 快时间测量: FTM、PICOSEC-MM
- § 低离子反馈: MM-THGEM多层微网结构DMM、TMM

热压接方法制作Micromegas

中科大研发热压接探测器制作方法，
实现整套制造设备和工艺研发。



- 无刻蚀溶剂污染
- 容易在实验室操作
- 易于制作新结构
- 成本可控
- $\Phi 0.5-1\text{mm}$ 支撑垫片
- $5-10\text{mm}$ 支撑间距
 - 易于大面积制作
 - $< 1\%$ 支撑死区



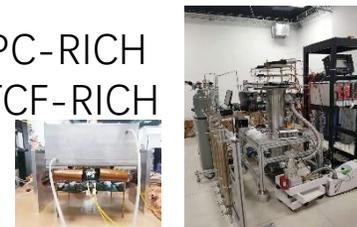
中国散裂白光中子源成像型
中子探测器



PandaX-III
TPC MM



CEPC-RICH
&STCF-RICH



缪子散射与透射
成像装置

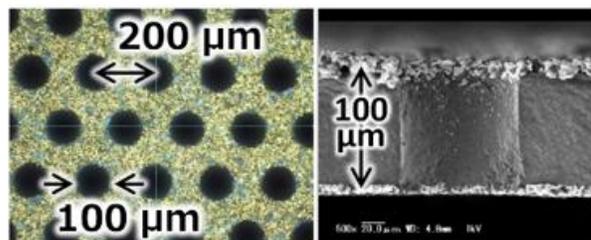
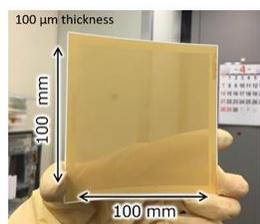
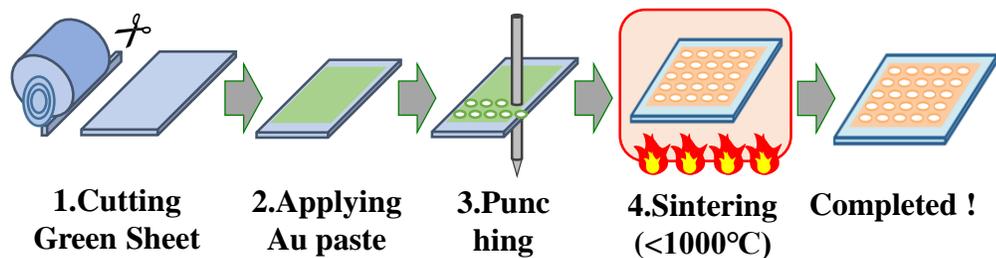


Jianxin Feng et al., NAM-A, 2021, 989(164958).

新型工艺制造GEM/THGEM

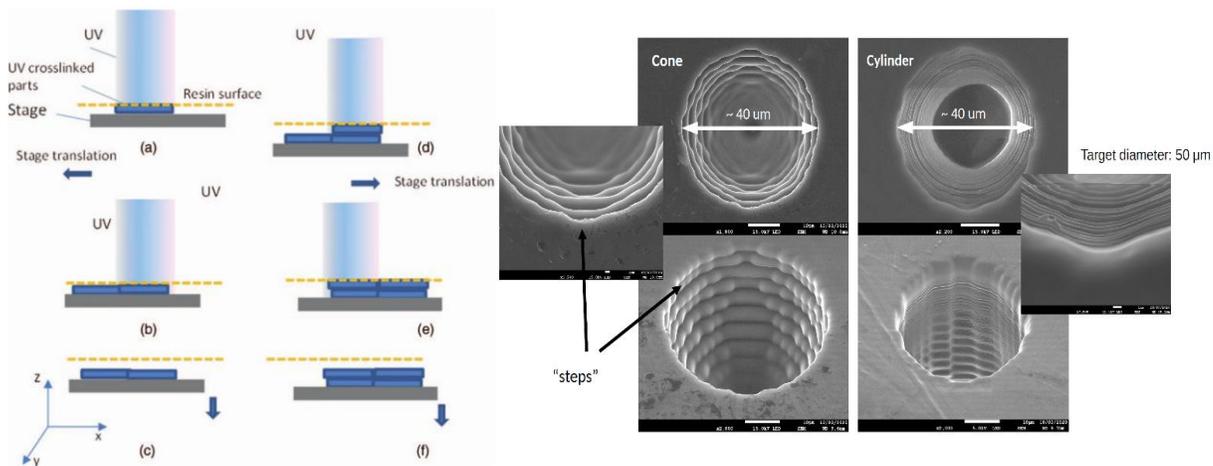
◆ 低温共烧陶瓷技术

Low Temperature Co-fired Ceramic, LTCC



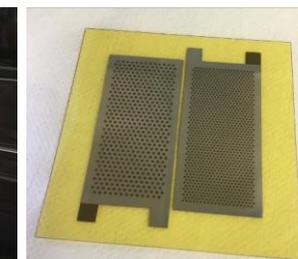
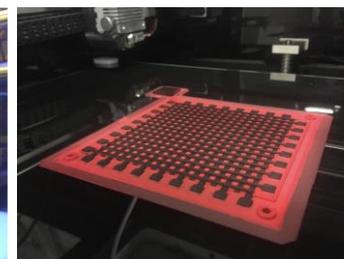
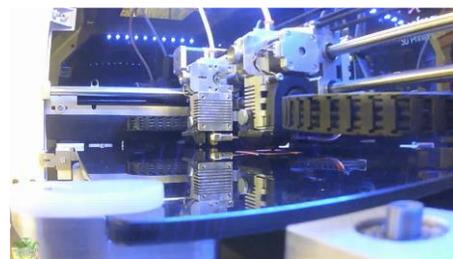
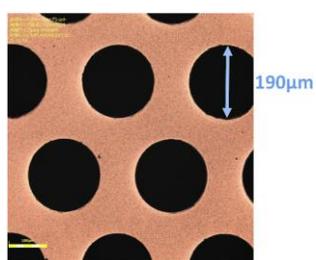
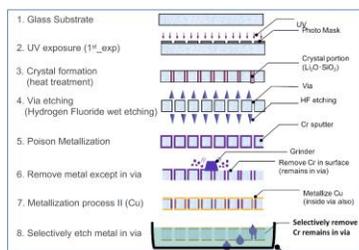
◆ 投影显微立体光刻技术(pμSLA)制作类GEM探测器

Projection micro-Stereolithography, pμSLA



◆ 使用微加工技术和可光刻玻璃制作大面积玻璃GEM

Photo Etchable Glass 3, PEG3



◆ 3D打印制作THGEM

小结

- ◆核与粒子物理实验需求仍然是MPGD发展的核心驱动：大面积、高分辨、高计数、低造价
 - 阻性电极 (Ge\ DLC)、新原理和新结构、先进制造工艺是提升MPGD性能的重要研究研究方向
- ◆性能极限不断突破
 - $\sim 3 \text{ m}^2$ 超大面积、 $>10 \text{ MHz/cm}^2$ 计数率 ($\mu \text{ RWELL}$)、10微米量级极限位置分辨、25ps超快定时 (PICOSEC-MM)、 $>10^6$ 高增益和 $<0.01\%$ 的极低离子反馈 (DMM&TMM)
- ◆同时伴随严峻挑战
 - 大面积Micromegas/GEM打火、高计数率 $\mu \text{ RWELL}$ 的大面积扩展、 PICOSEC-MM高光电效率和耐用光阴极、 DMM&TMM大面积制作等
- ◆MPGD的不断发展为其应用打开了更丰富的想象空间！

MPGD界的“奥斯卡”

DLC及基于DLC的新型探测器
(**μ RWELL**)

是近年来MPGD领域的流量新星



谢谢!