A novel solution to ion backflow of TPCs

——A double or triple micro-mesh gaseous structure (DMM&TMM)

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Outline

- Motivation
- Requirements for readout detector in CEPC TPC
- Double Micro-Mesh gaseous structure
  - Design, Fabrication and Performance
  - Optimization for CEPC TPC
- Triple Micro-Mesh gaseous structure
- Thermal bonding method for detector fabrication
- Summary

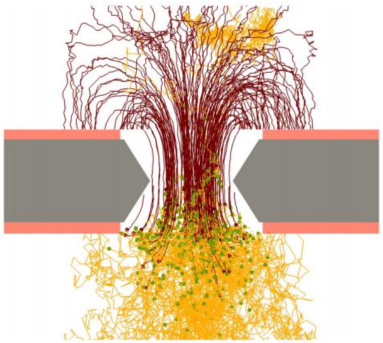
Motivation: high rate TPC

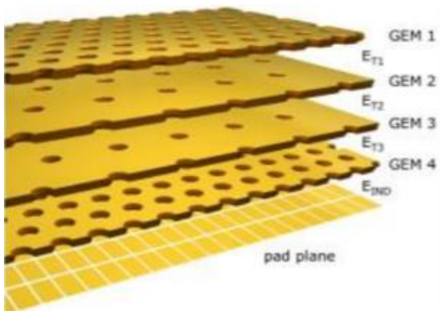
One example is Alice TPC upgrade:

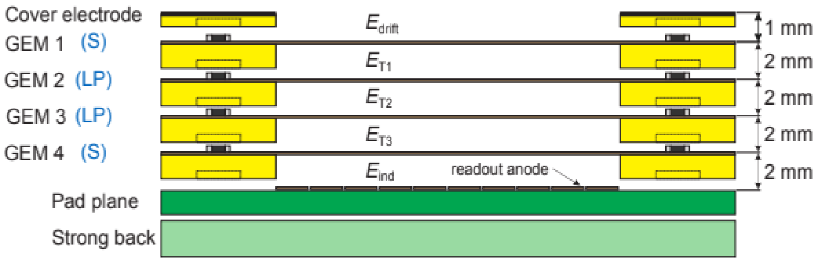
- Low IBF to minimize drift field distortion caused by ion space charge
- Continuous readout （without gating） to keep up with high event rate

➔MPGD is the only solution so far.

Quadruple GEM, IBF of < 1%







Opening structure

➔typically >20% IBF ratio

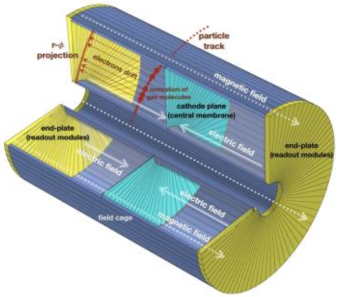
Different GEM geometries, Complex mechanical structure

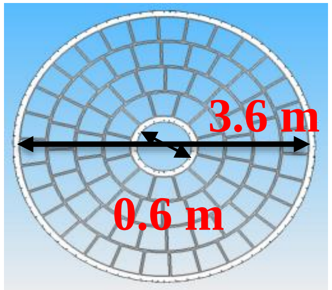
➔ very challenging for construction.

CEPC TPC

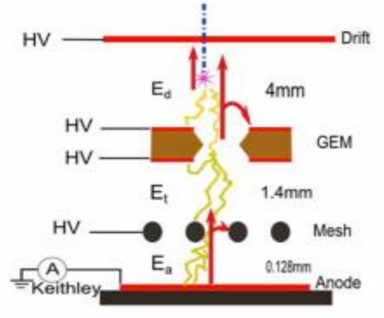
Requirements:

- Low IBF (IBF ratio< 0.1%)
  - IBF ×Gain <5 for Higgs, and <2 for Z
  - Drift field: 200V/cm
  - High electron collection ratio
- Mass production for future construction
  - Small module of ~170 mm × 210 mm in size
  - ~ 20 m^2 in total (two end-plates) , ~500 modules





Detector baseline: GEM + MM,
gain ×IBF<5, IBF ratio< 0.1% achieved



From CEPC CDR, arXiv:1811.10545 and Huirong's talk:
https://indico.cern.ch/event/889369/contributions/4051844/

A new option for TPC readout

The CEPC TPC working group (Huirong Qi et al.) have done great work on simulation and detectors :

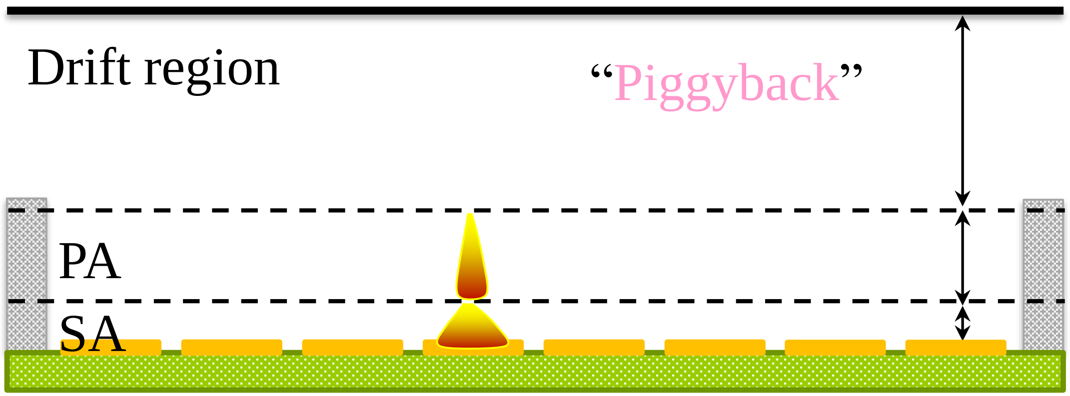
- *Physics requirements*
- *GEM +MM prototype and performance*
- *Calibration and correction method for high luminosity Z run*

https://indico.cern.ch/event/889369/contributions/4051844/

Here, we present a new option for TPC readout using Double (or Triple) MicroMegas, which may enhance the TPC performances on the aspects of **ultra-low IBF, low sparking probability, compact structure**, **rapid iterative updates for optimization in R&D and future production etc.**

DMM Design

- DMM: Double Micro-Mesh gaseous structure
  - Mesh-type : closing structure to strongly reduce IBF

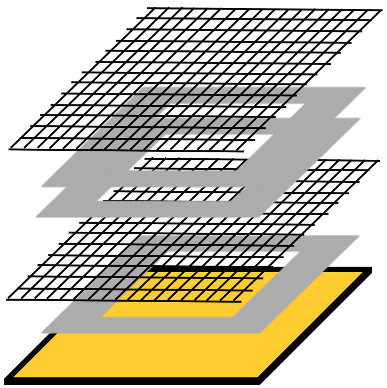


Stacked two meshes

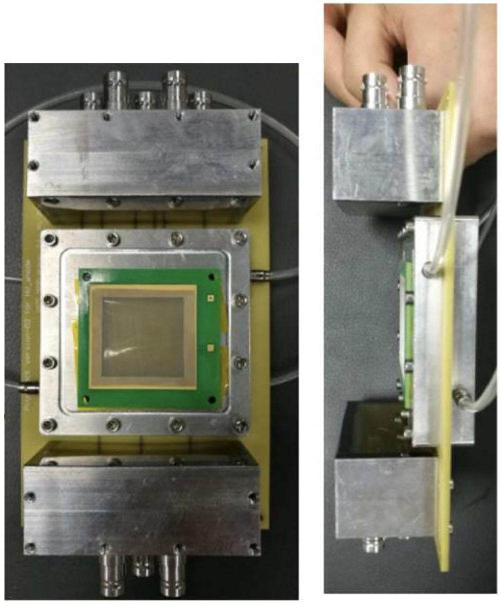
- Gap between the stacked meshes: 200-300um, serving as pre-amplification (PA)
- Gap between the bottom mesh and anode: 50-100um as secondary amplification (SA)
- Allows to achieve very high gain, and yet significantly reduce ion back-flow.

DMM Fabrication

- DMM is fabricated with the thermal bonding method developed at USTC, which provides a concise and etching-free process for manufacturing Micromegas detectors



The schematic diagram of DMM fabrication

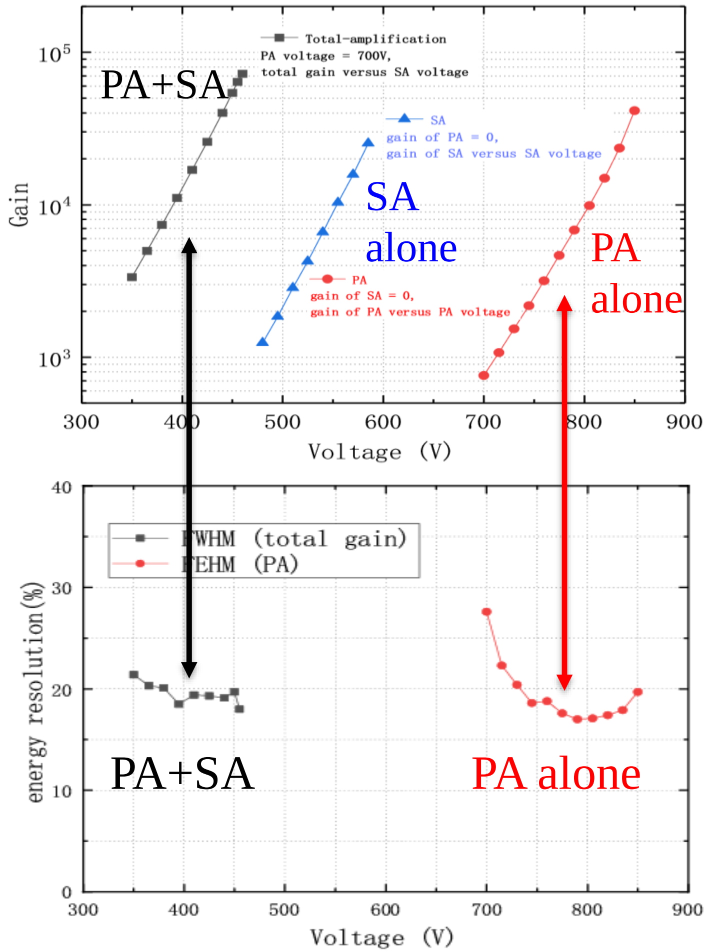


A small DMM prototype

Thermal bonding method will be introduced in the following.

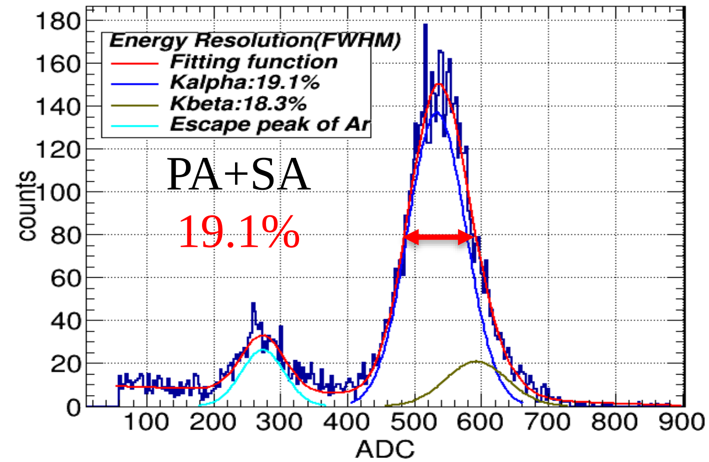
Good energy resolution ensures high electron collection

Gain: PA, SA and combined



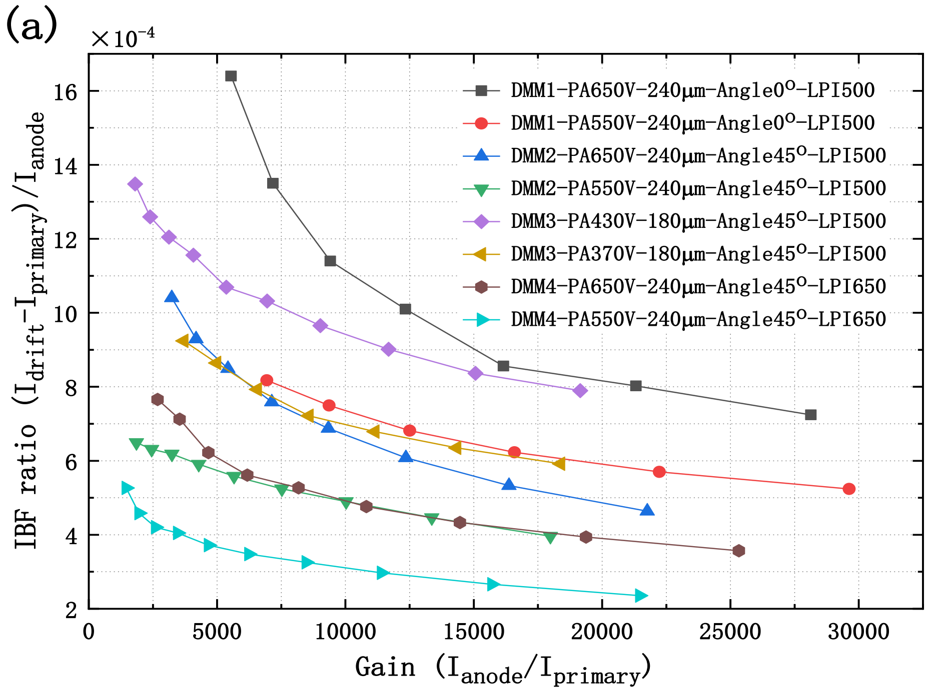
Resolution: PA and PA+SA combined

A typical ^{55}Fe energy spectrum



- Combined gain can reach up to 7×10^4 for 5.9 keV X-rays.
- Combined resolution remains almost constant and is close to PA-alone resolution, suggesting a **close-to-full collection of primary electrons** for the high-voltage configurations we used.

Optimization For DMM



To push IBF down to an extremely low level:

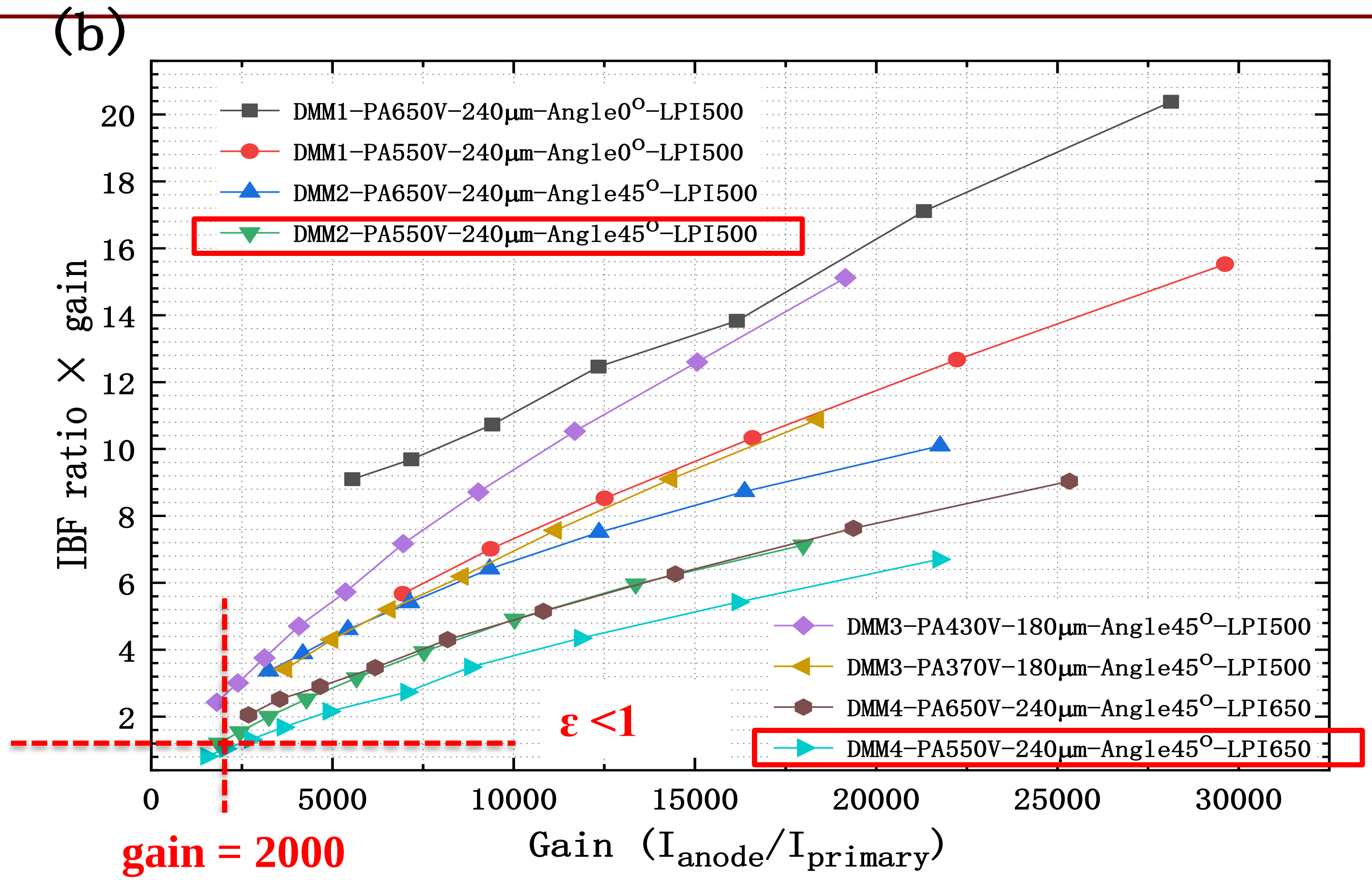
- ✓ low PA electric field
- ✓ large PA gap
- ✓ high mesh density
- ✓ crossing mesh setting

A IBF ratio down to ~0.025% was achieved .

More details:

- *A high-gain, low ion-backflow double micro-mesh gaseous structure for single electron detection， Nuclear Inst. and Methods in Physics Research A, 889 (2018) 78–82.*
- *Optimization of the double micro-mesh gaseous structure (DMM) for low ion-backflow applications，Nuclear Inst. and Methods in Physics Research A, 976 (2020) 164282.*
- *Also in backup slides*

In the view of IBF×Gain

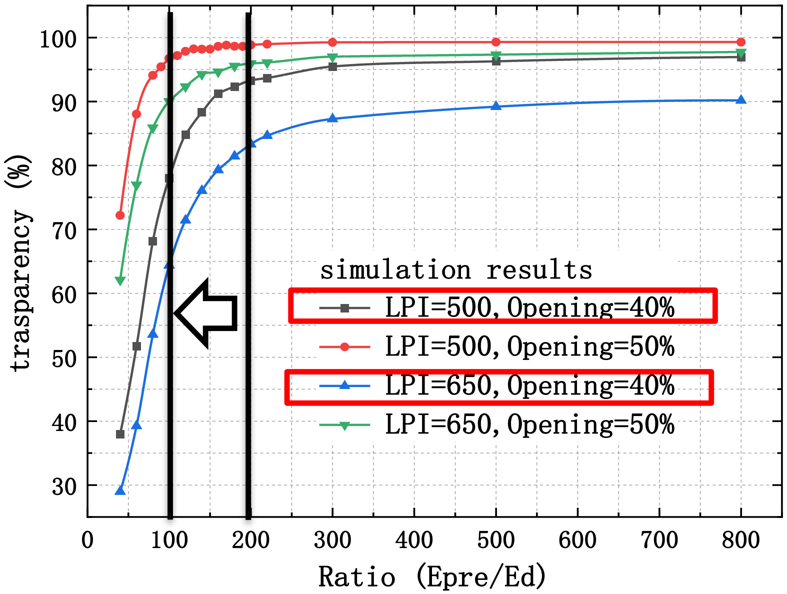


In general, we present a practical method to suppress the IBF as low as possible. for specific application of CEPC, specific optimizations are required.

DMM design optimization for CEPC TPC

Requirement of CEPC TPC:

- ☐ A proper drift field ~200 V/cm
- ☐ high collection efficiency



Simulation study on Electron transparency versus Electric ratio

The results presented above are achieved at:

- 40%mesh opening rate
- Epre/Ed = 200,
- Drift electric field of ~120V/cm

➔ Gain×IBF <1

⇩

Optimization and desired effect:

- 50%mesh opening rate
- Epre/Ed = 100
- Increasing PA gap
- Attempting to precisely align the meshes

➔Drift electric field >200V/cm

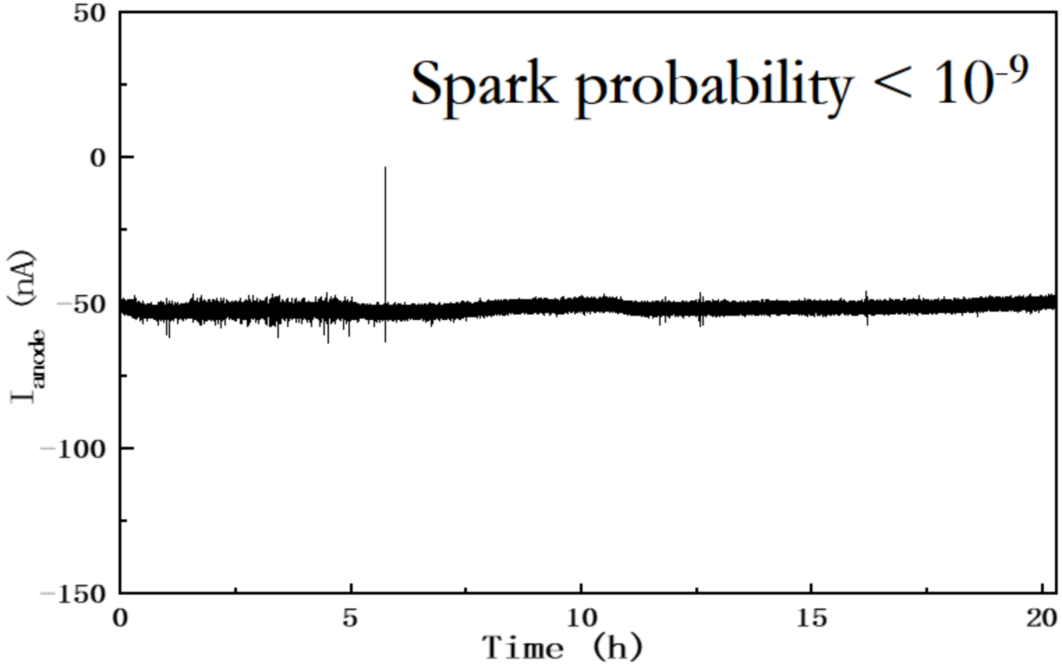
➔ Gain×IBF <2

➔ Electron collection >90%

Sparking probability test

DMM: 240μm- 45^0 - LPI650

X-ray irradiation by an 8.0 keV with a rate of ~50 kHz/cm^2 (recorded by the DMM) with an irradiation area of ~180 mm^2



Anode current of DMM at a gain of 5000, recorded over 20 h.
Each current spike represents one discharge.

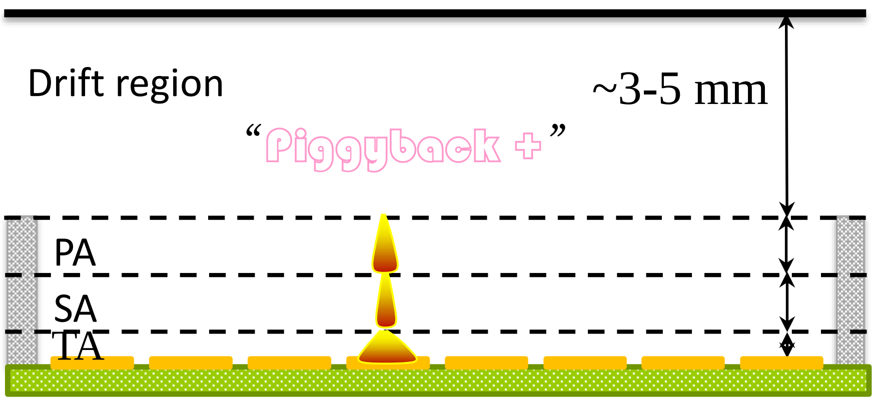
Lower the IBF with TMM

- For the case of DMM, when we switch off SA

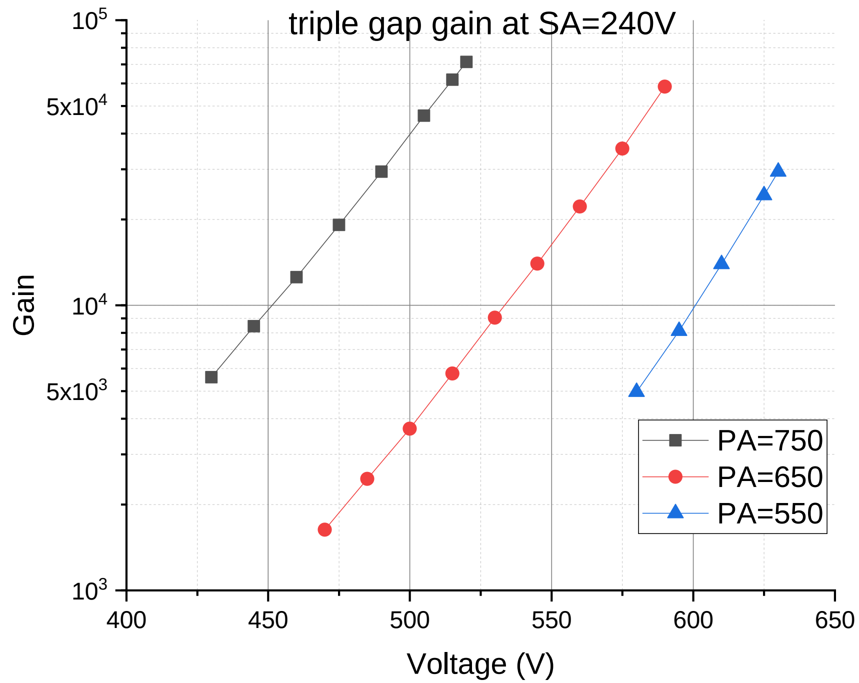
  ➔The PA only contributes ~0.3 for the ε factor, the SA dominates the total IBF

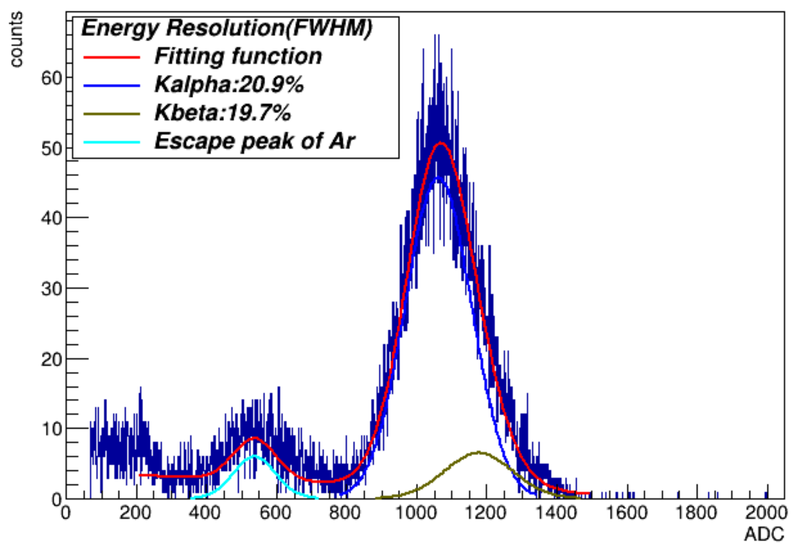
- So, adding another mesh on the DMM to suppress the SA ions is a easy option.

- One more mesh on the DMM
- More stable gain, lower IBF from second avalanche···



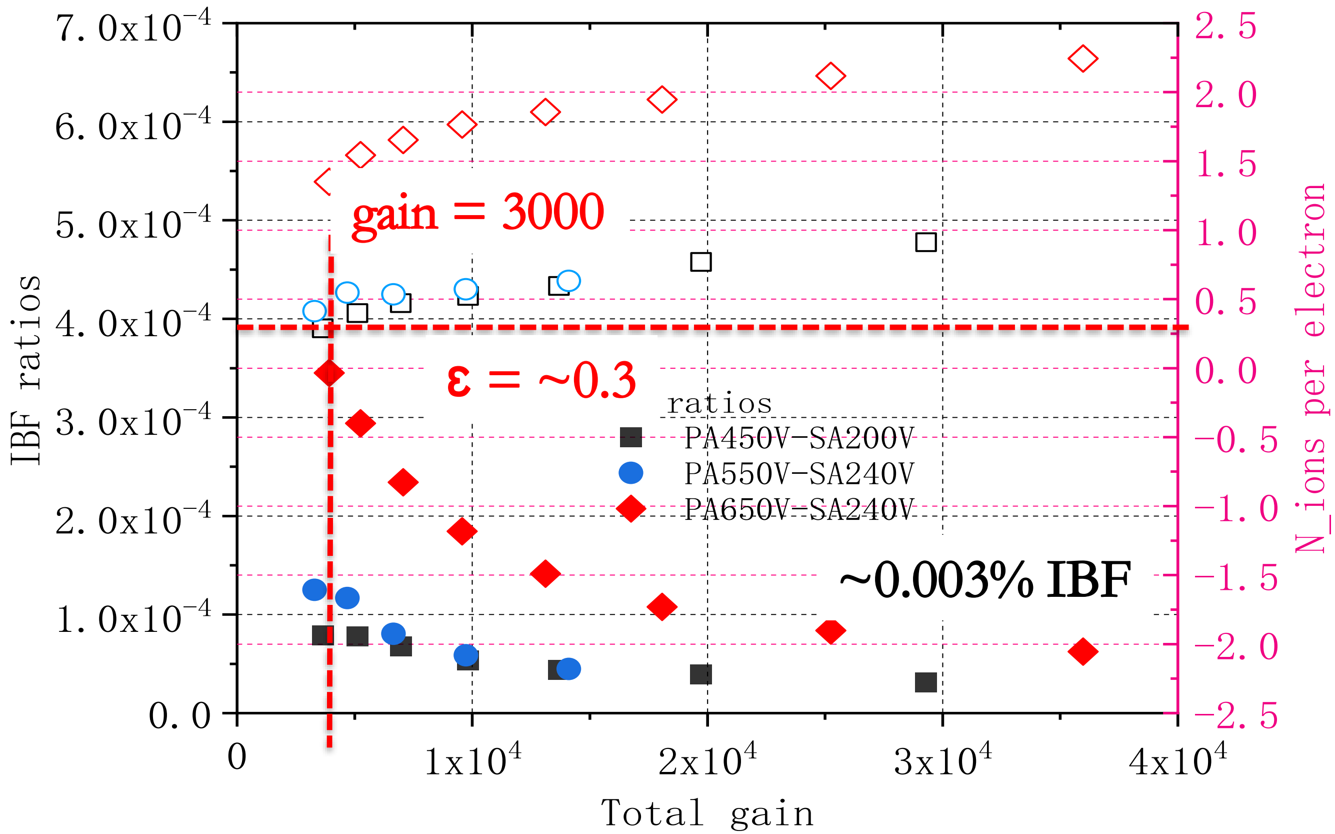
Gain and energy resolution





- Gas gain reaches up to 7×10^4 for 5.9 keV X-rays
- Energy resolution at ~21% (FWHM) indicates a high collection efficiency of the primary electrons

IBF measurement for TMM

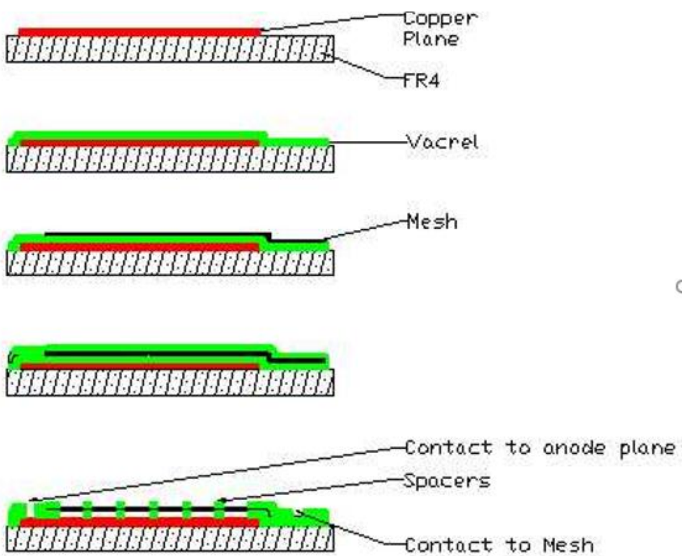


The back-flow ions (at **ε = ~0.3)** is mainly from PA, concluding that the IBF can not be further reduced by adding more meshes, the TMM reaches the lowest IBF level for the mesh-type structure.

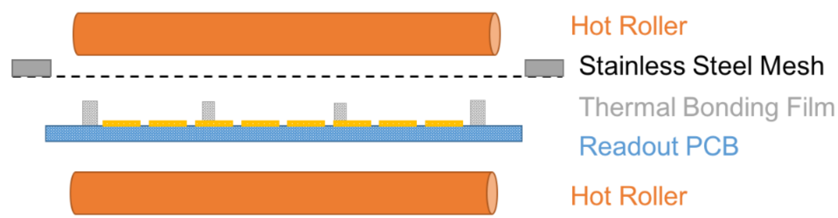
Fabricating method

Over the past decade, the thermal bonding method (TBM) has been developed at USTC. This method provides a concise, efficient and etching-free mass-productive process to fabricate Micromegas-like detector.

Micromegas in a Bulk



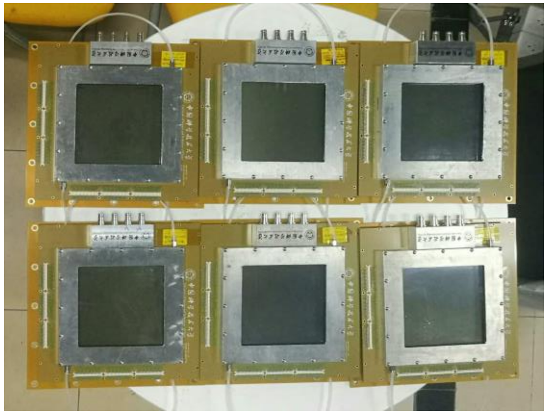
Thermal bonding processing



- No etching, no pollution
- Easy to handle at lab
- Easy to make new structures
- Cheap
- Φ0.5mm- Φ1mm spacers, ~1cm pitch
  - ➔easy to clean, especially for large area
  - ➔less than 1% spacer area

Mass production

A working room is built for Micromegas fabrication, mass-production for small area (<25cm×25cm) is realized, prototype with larger area 40cm×40cm are also verified.



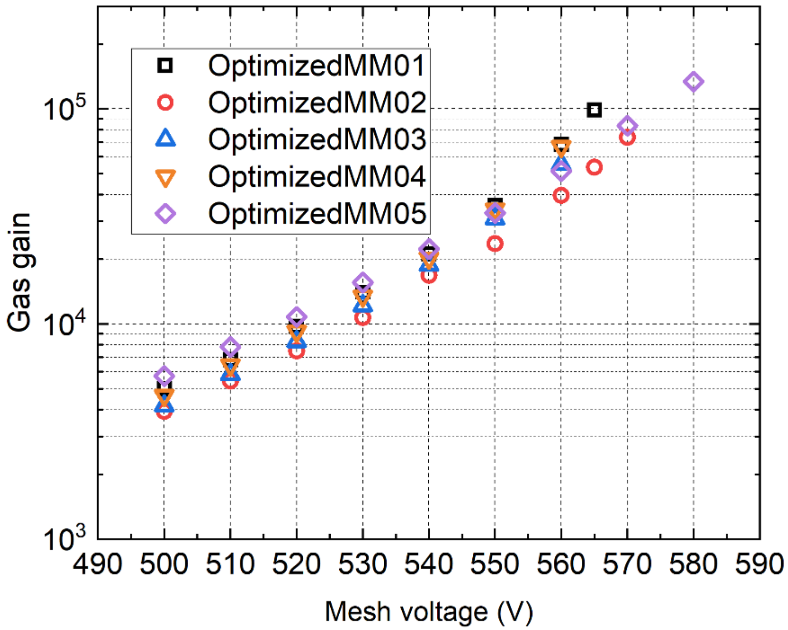
From raw material to complete detector

Several prototypes are produced, and the performances, such as gain, energy resolution and gain uniformity are tested using an X-ray source.

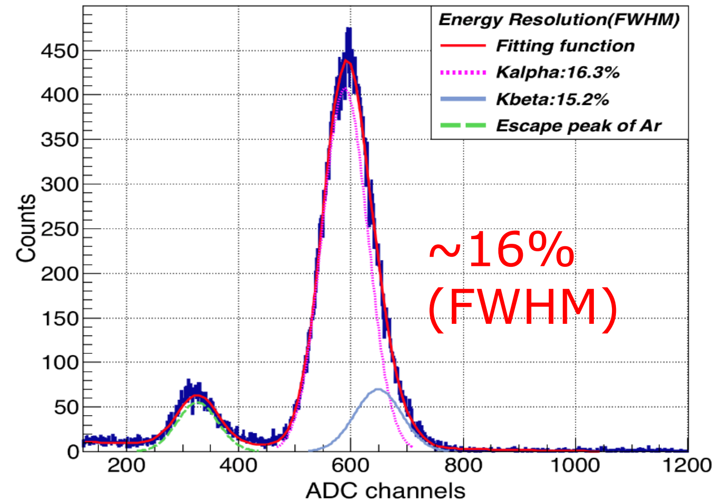
J. Feng, Z. Zhang, et al., A thermal bonding method for Manufacturing Micromegas detectors, available at https://arxiv.xilesou.top/abs/1910.03170.

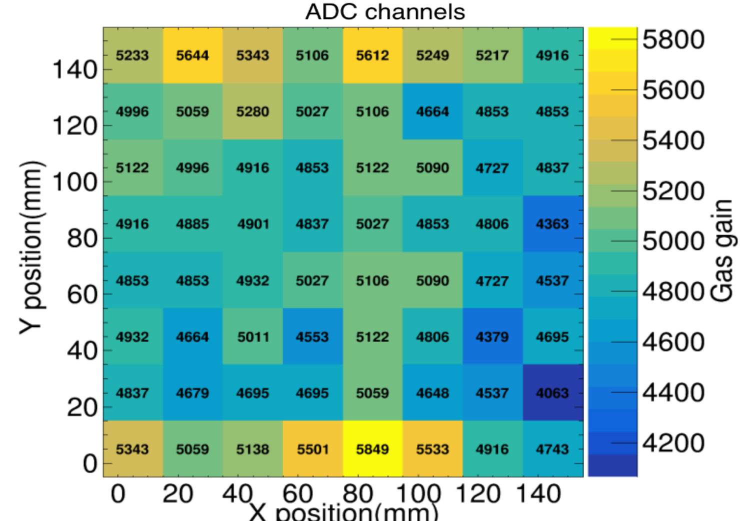
Performance of the TBM MMs

Test with 5.9 keV X-rays：



Very high gain ($>10^5$) using common Argon-based CO_2(7%) gas

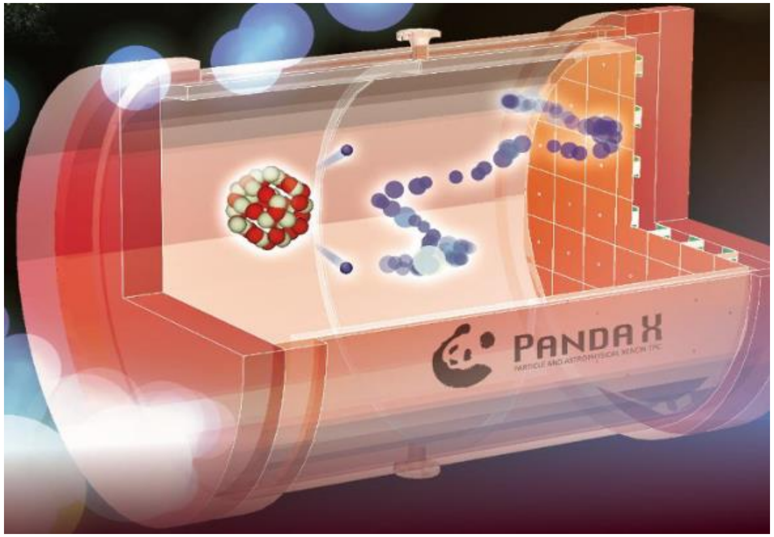


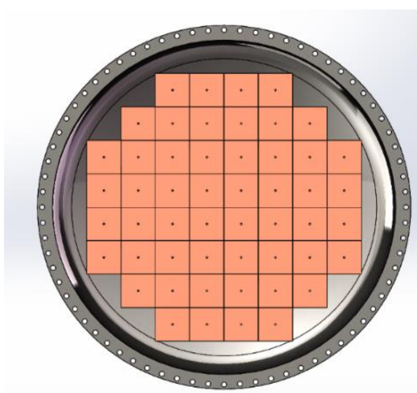


Gain non-uniformity (RMS/Mean)

6.3% @ gain =5000

An application example for PandaX-III





Requirements:

- 10 bar Xe-(1%)TMA (trimethylamine)
- Low radioactivity materials
- 52 20×20 cm^2 MMs for charge readout
- X-Y strip readout
- 3% resolution @ 2.5 MeV

  ➔high resolution & good uniformity

An application example for PandaX-III

Five detector versions, ~30 prototypes have been attempted to over come the key technical difficulties, shown better performance than the original micro-bulk technique.

Rapid R&D cycle using the TBM

12/2019 02/2020 04/2020 08/2020 11/2020

V1,V2 for narrow bonding region (dead area, 3 mm frame), V3-V5 for low radioactivity background & high energy resolution

Summary

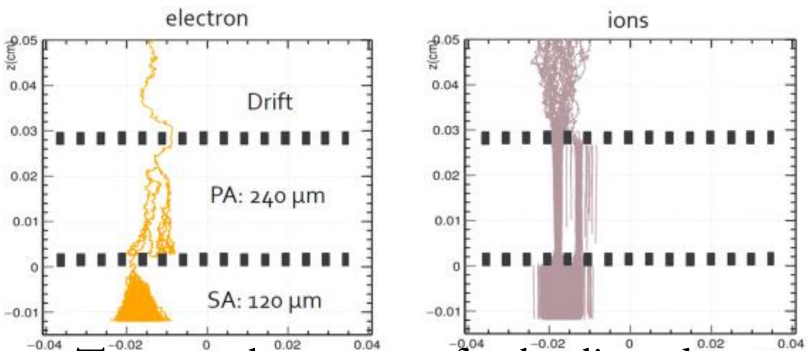
- Demonstrated the performance of DMM &TMM with prototypes:
  - High Gain: 7×10^4 for 5.9 keV X-rays.
  - IBF×Gain: down to <1(limit) for DMM , 0.3 (easy) for TMM
- A thermal bonding method for fabricating the detectors is presented and its performance was verified
- Predictable benefits using DMM (TMM) for CEPC-TPC
  - Promising to suppress the IBF×Gain to <1
  - Low sparking probability of $<10^{-9}$ with ~50 kHz/cm^2 8.0keV
  - Compact structure and narrow frame ensure low material and dead region
  - Lab-friendly fabrication method provides quickly iteration for R&D and production

Thanks for your attention !

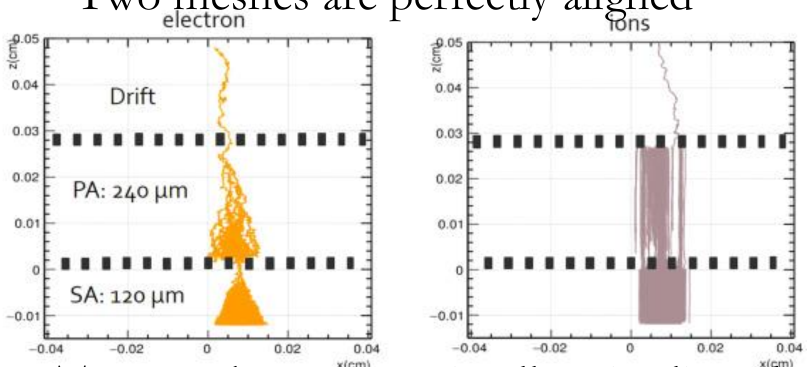
Back-up ⇨

Optimization for **Low IBF**

- Obviously, the IBF is depend on the geometry of the detector structure, in which the alignment, density, distance etc. of two meshes are crucial.



Two meshes are perfectly aligned



Two meshes are maximally mis-aligned

This reference investigation suggests to increase the ion cloud size (σ) and decrease the mesh pitch (l)
➔can be achieved by enlarging the distance and the wire density of the two meshes

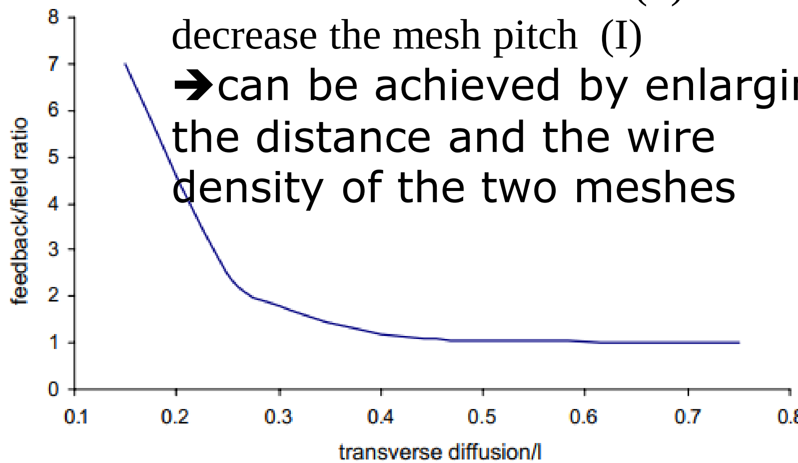
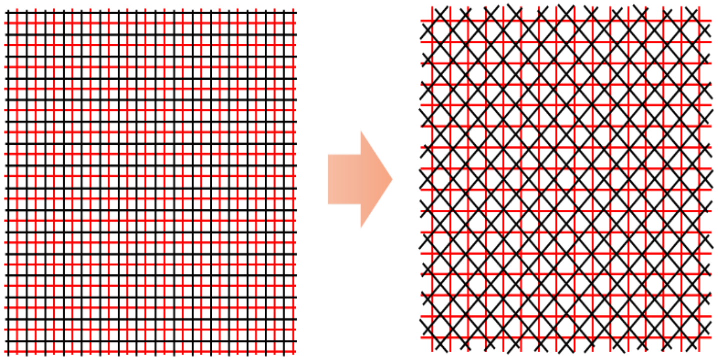


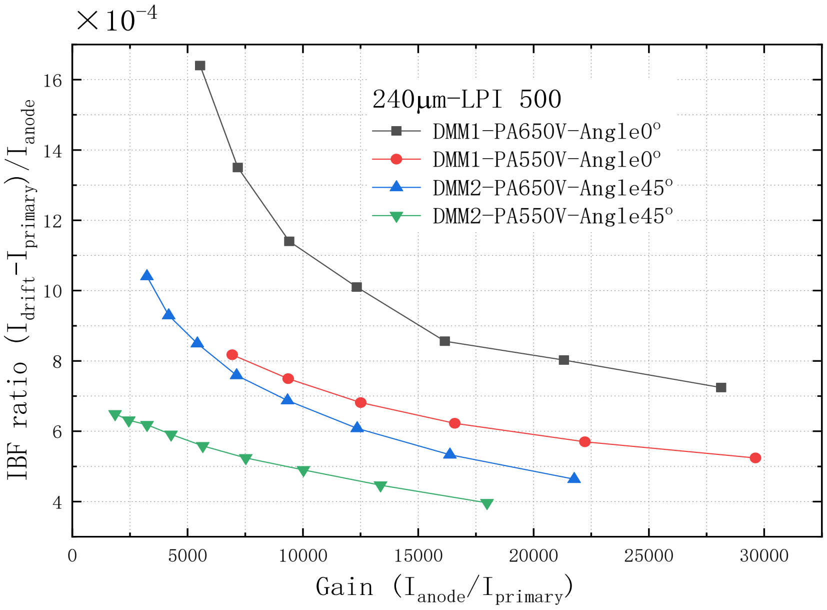
Fig. 4. Computed value of $\alpha\beta$ as a function of σ/l.

Colas P, Giomataris I, Lepeltier V. Ion backflow in the Micromegas TPC for the future linear collider, Nuclear Instruments and Methods in Physics Research Section A, 2004, 535(1-2): 226-230.

Optimization for Low IBF

Detectors	Cross Angle (°)	PA gaps (μm)	LPI
DMM1	0	240	500
DMM2	45	240	500
DMM3	45	180	500
DMM4	45	240	650

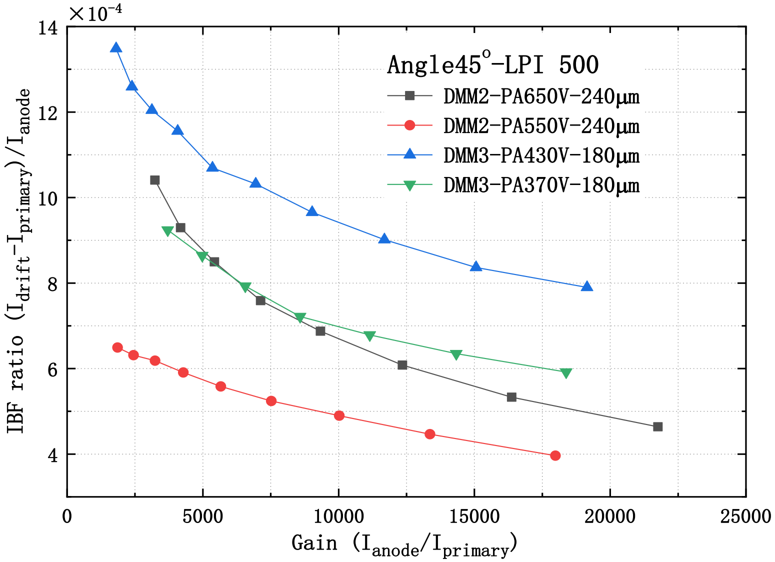




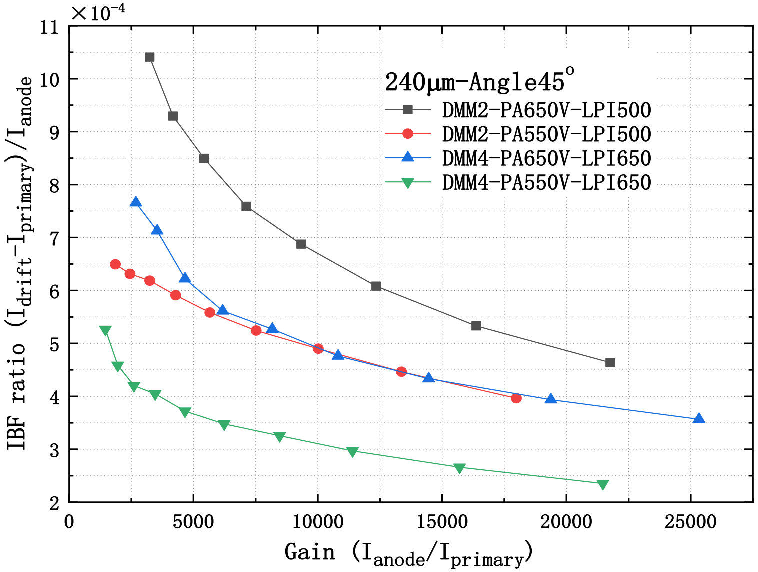
It's impractical to make any precise alignment of the two meshes. So setting the two meshes with a crossing angle is a practical way to ensure their mis-alignment.

Optimization for Low IBF

PA gap: from 180 to 240 μm   500 vs. 650 LPI (40% opening rate)



Larger gap increase the transverse diffusion of avalanche

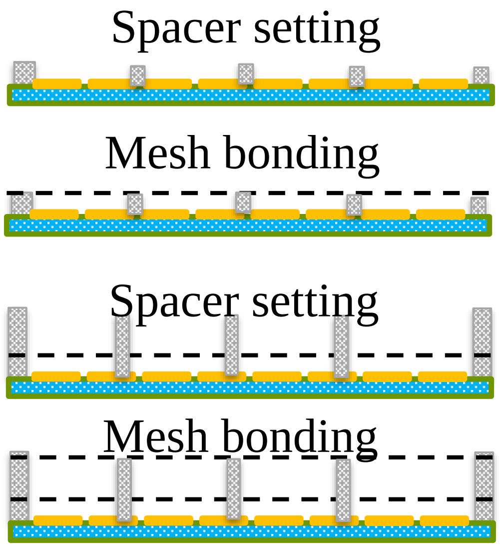


Higher mesh density decrease the mesh pitch

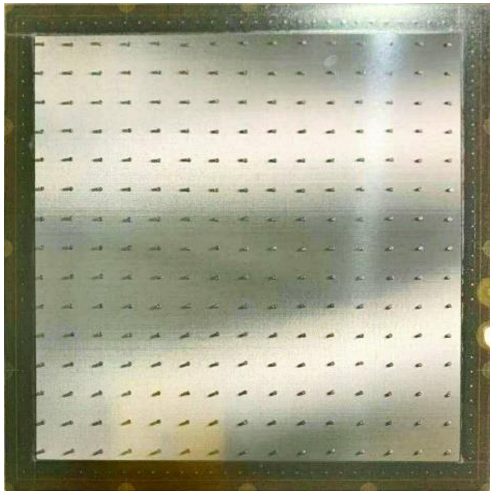
Both of these increase the σ/l value, optimizing the IBF as a consequent.

Fabrication process for DMM

- It is a crucial issue for the DMM (TMM) is to make a large area for real experiments
- Thermal bonding method open the door to make this complex fabrication



Thermal bonding for DMM

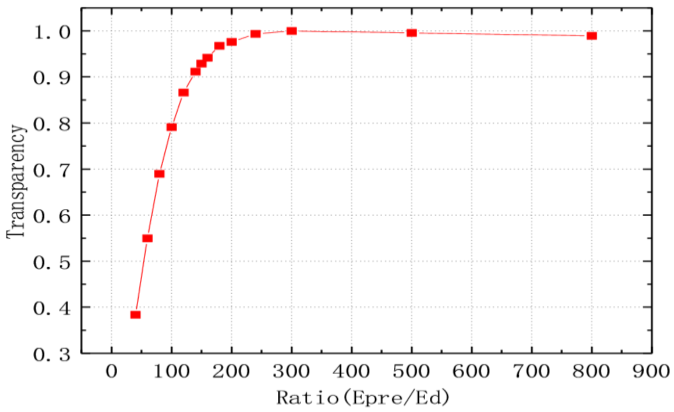


A 150mm ×150mm DMM prototype

Electron Transparency

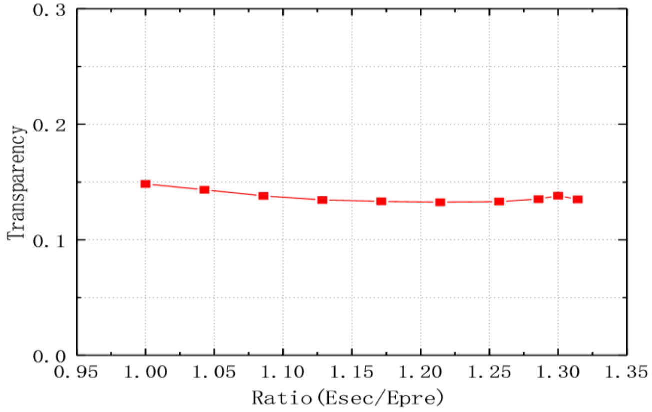
- Transparencies for electrons passing through PA and SA meshes are extracted by measuring PA, SA and total (PA and SA combined, DMM) gas gains
  - Combined gain = PA gain × SA trans × SA gain

PA relative transparency



E_{PA}/E_{drift} is set to 200 to maximize transparency most of the time.

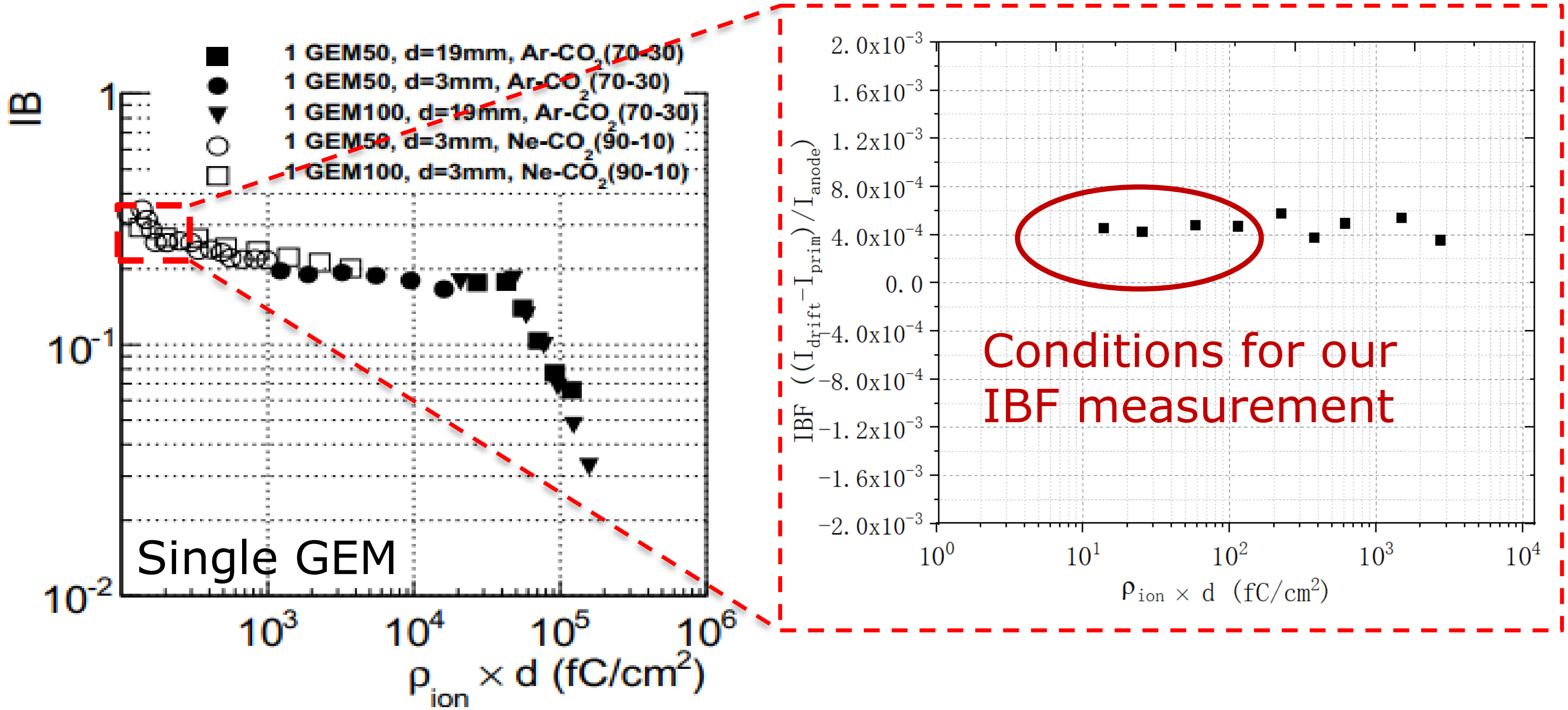
SA transparency



SA trans ~ 15% @ E_{SA}/E_{PA} ~ 1

Ion Space-Charge Effect

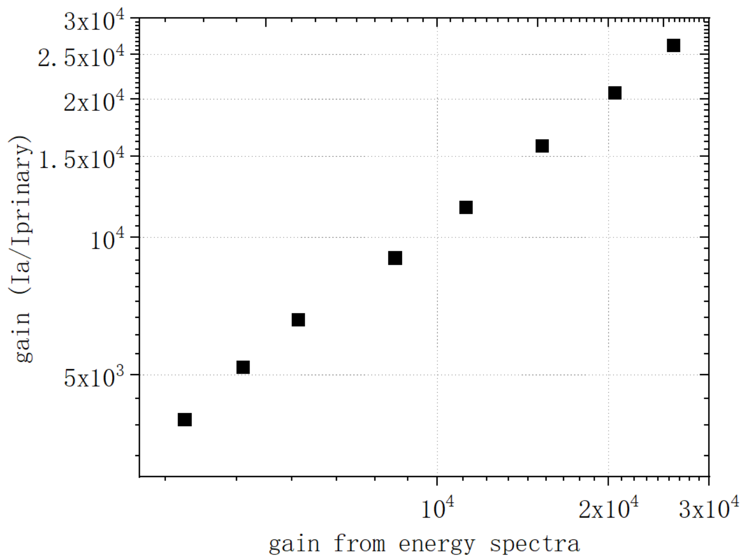
M Ball *et al* **2014** *JINST* 9 **C04025**



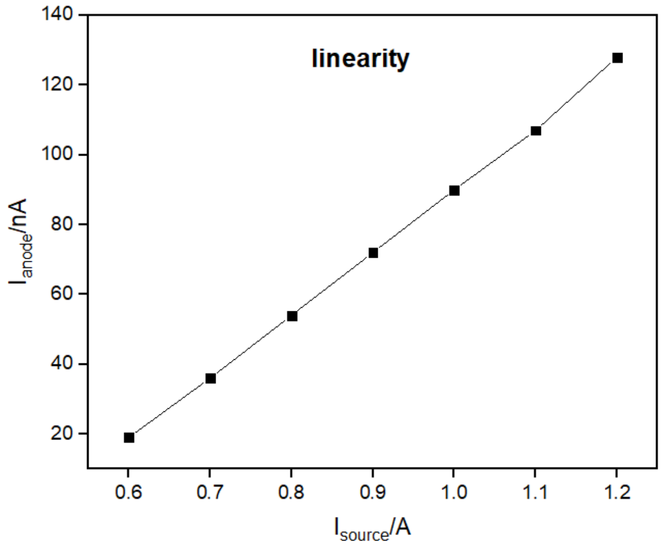
- Our IBF measurements are reliable in terms of ion space-charge effect (impact is negligible).

Validation of IBF Measurement

$Q_{full\text{-}energy\ peak}/Q_{Primary} = I_{Anode}/I_{Primay}$



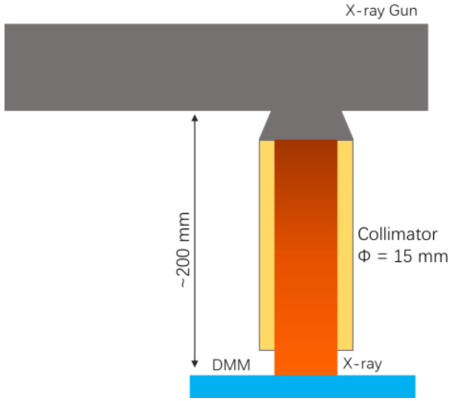
no gas gain saturation



- Gain measured with X-ray energy spectrum ($Q_{full\text{-}energy\ peak}/Q_{Primary}$) consistent with I_{Anode}/I_{Primay}
- I_{Anode} stays proportional to X-ray intensity in a rather wide range, suggesting no gas gain saturation in the IBF measurement.

- IBF ratios measured with 55Fe and X-ray tube are consistent

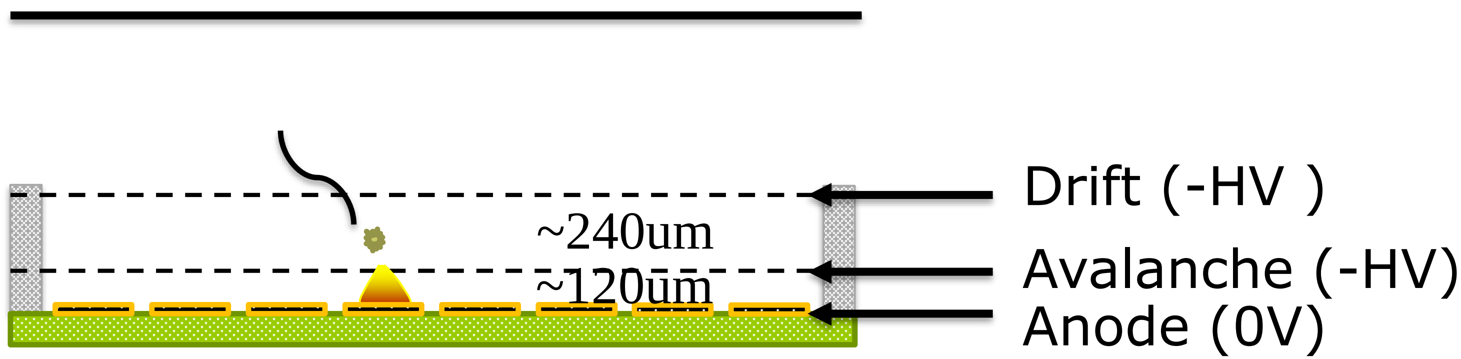
Performance Characterization



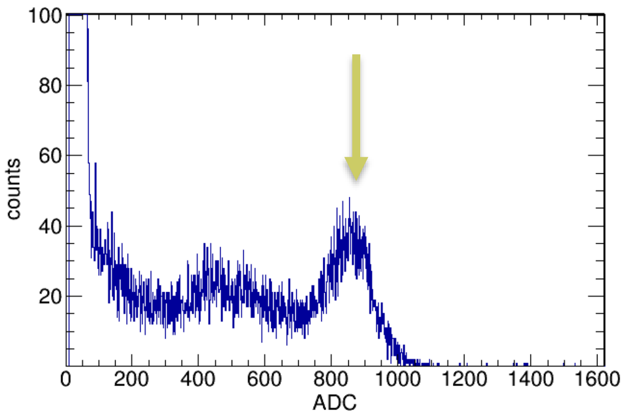
IBF measurement setting

- DMM with Ar (93%) + CO_2 (7%)
  - Electron transparency
  - Energy resolution and gas gain
  - Ion back-flow ratio
- DMM with Ne (80%) + CF_4 (10%) + C_2H_6 (10%)
  - Single photon electron response

Sec-amplification (SA)

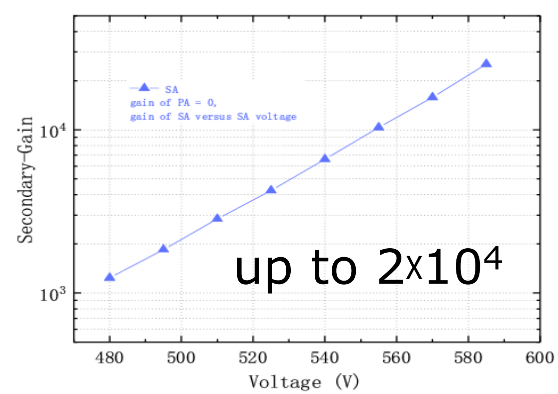


Full energy peak due to the lateral angle
photoelectrons and Auger electrons



The transparency should be similar to PA's, since their have the same mesh type.

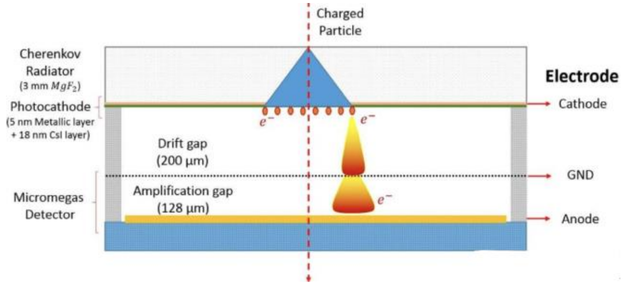
Gain VS avalanche voltages



Motivation : GPD

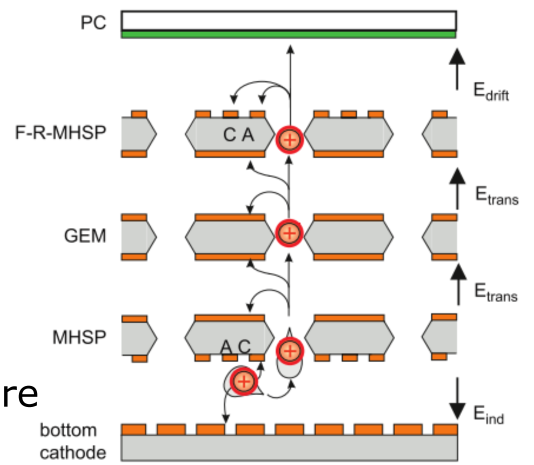
- Gaseous Photon Detectors (GPD) with MPGD
  - large area, high spatial and timing resolution, resistant to magnetic field, IBF suppression, low cost ···
- Challenges
  - High gain: to be sensitive to single photons
  - Very low IBF
    - UV light： CsI， ~mC/cm^2
    - Visible light： Bi-alkali, ~μC/cm^2 !

J. Va'vra et al., NIM A 387 (1997) 154-162.
T. Moriya et al., NIM A 732 (2013) 269-272.



PIC-SEC

F-R-MHSP+GEM+MHSP



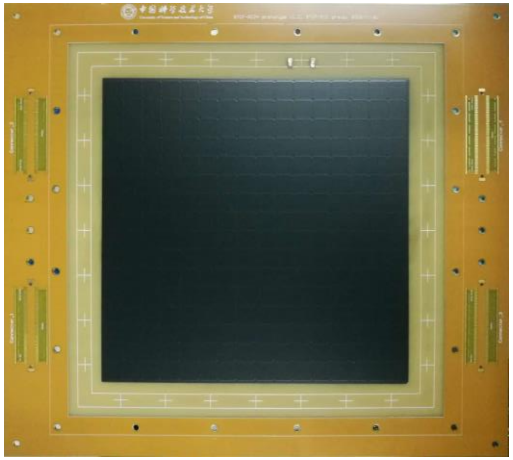
Gas-PMT

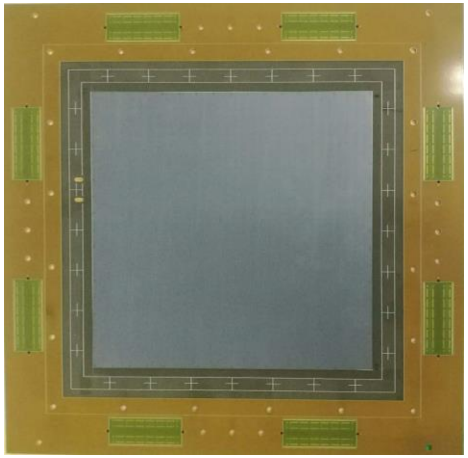
IBF: ~0.03%
Complex structure

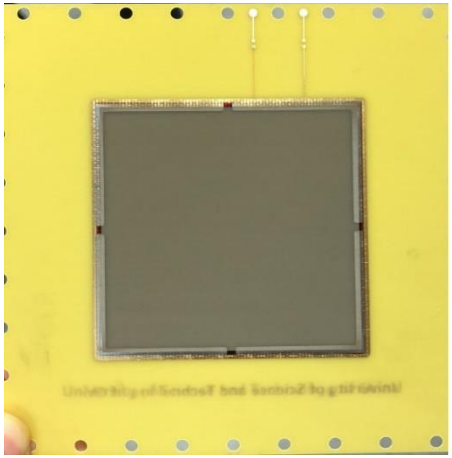
A. Lyashenko et al. , NIM A 598(2009) 116-120

Resistive anode for sparking-resistant

Pros & cons







resistive paste by screen printing: 10-20 μm

- o Complex pattern
- o Large area
- o Low Cost
- Δ High temperature curing
- Δ Controllability for resistivity
- Δ Sputtering up

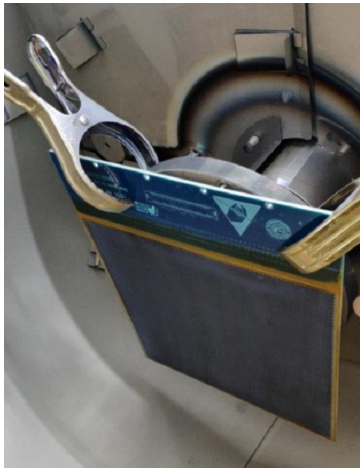
Ge film by thermal evaporation coating： 0.1-1 μm

- o Controllability for resistivity
- o Purity for low background applications
- o Large area
- Δ Complex pattern
- Δ Oxidation problem （keep in dry）

DLC deposited by magnetron sputtering:

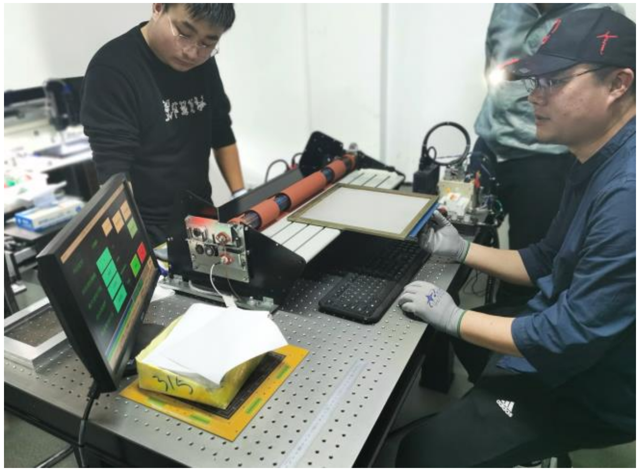
- o Controllability for resistivity
- o Purity for low background application
- o Robust

Fabrication process



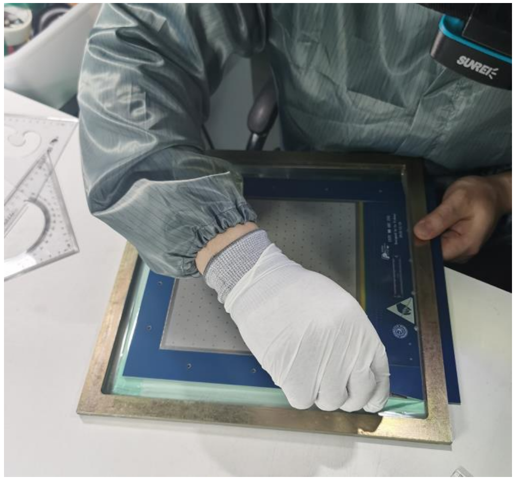
1:Ge coating

2:spacer setting

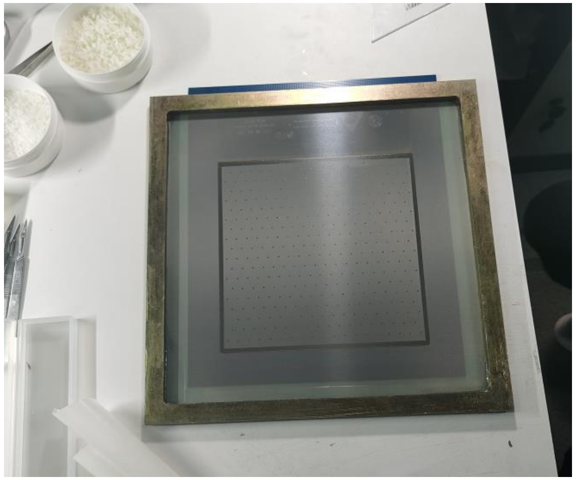


3: thermal bonding

6: assembling

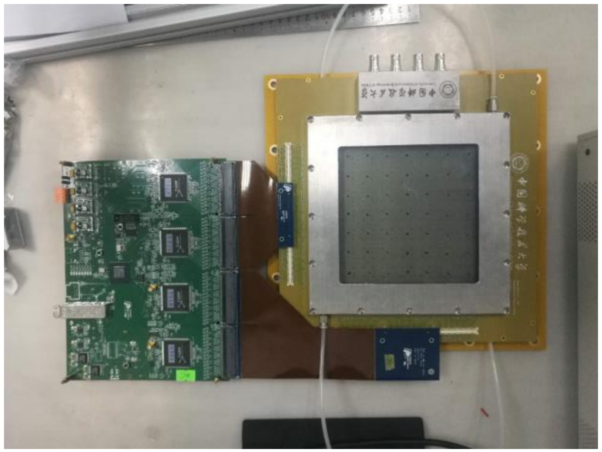


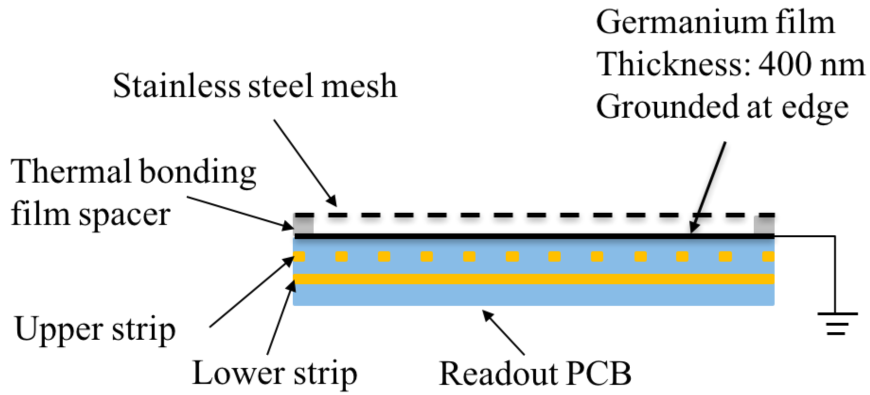
5: mesh cutting



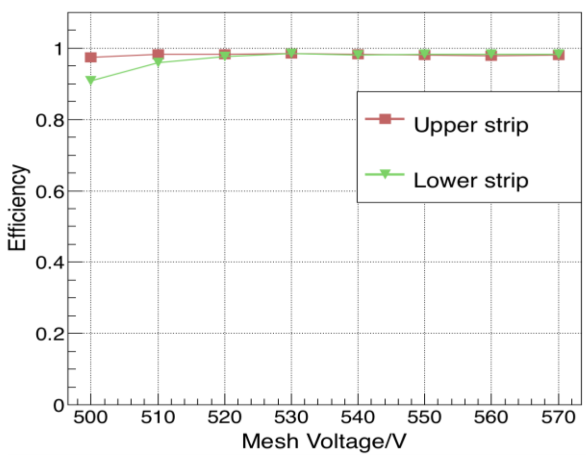
4: after bonding

Design and performance

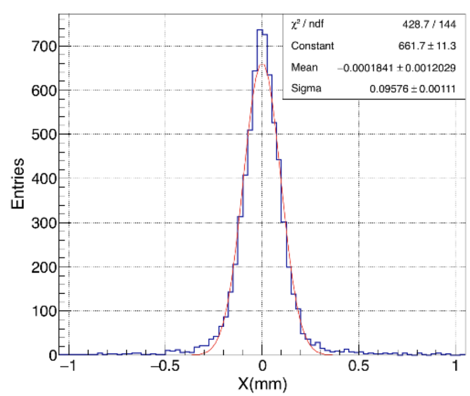


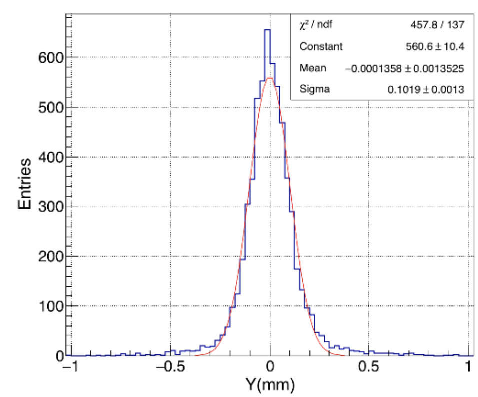


2D readout scheme



Detection efficiency





Distribution of deviation， which is corresponding to ~75 um spatial resolution