DMM & TMM: the Double and Triple Micro-Mesh gaseous structures for high gain and low ion-backflow applications

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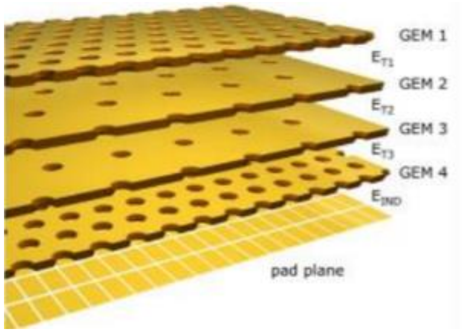
Outline

- Motivation
- Double Micro-Mesh gaseous structure
  - Design and Fabrication
  - Performance Characterization
  - Optimization for further IBF suppression
  - Consideration for CEPC-TPC
- Triple Micro-Mesh gaseous structure
  - Design and performance study
- Summary

Motivation: TPC

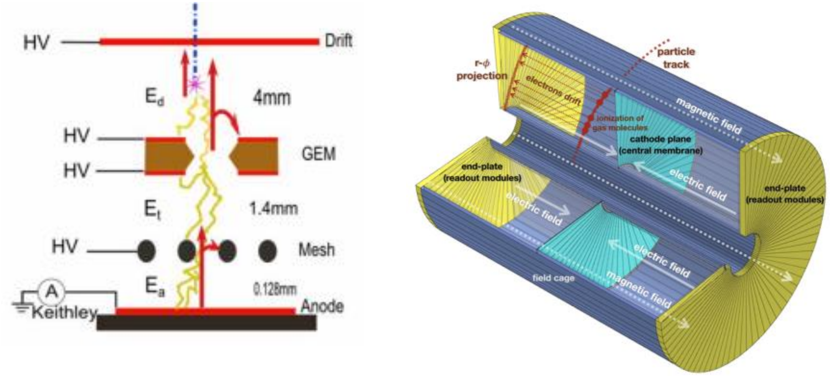
- Application of TPC in high-rate environments: ALICE upgrade, ILD, CEPC …
  - Very low IBF is the key: to minimize drift field distortion caused by ion space charge
  - Continuous readout to keep up with high event rate

ALICE



Quadruple GEM, IBF < 1%

CEPC



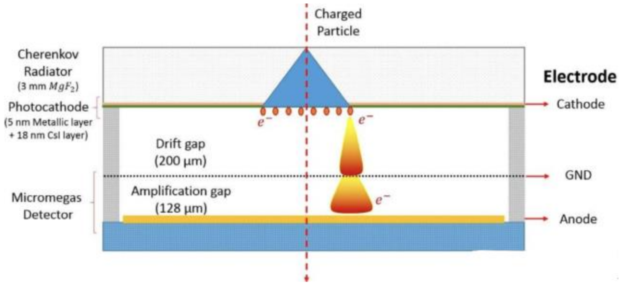
GEM+MM, Gain × IBF<5
IBF <~ 0.1% required

MPGD is the only solution so far. The IBF still need to be further reduced.

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.

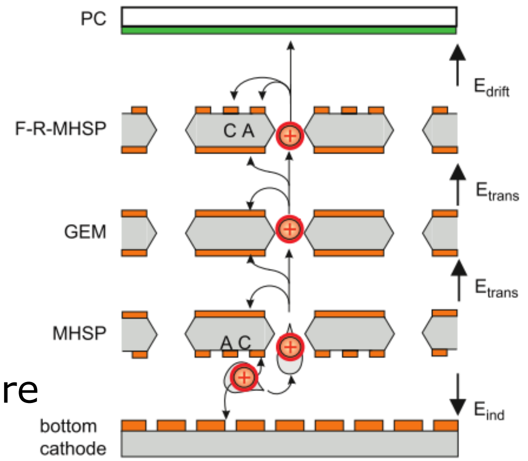


PIC-SEC

Gas-PMT

IBF: ~0.03%
Complex structure

F-R-MHSP+GEM+MHSP

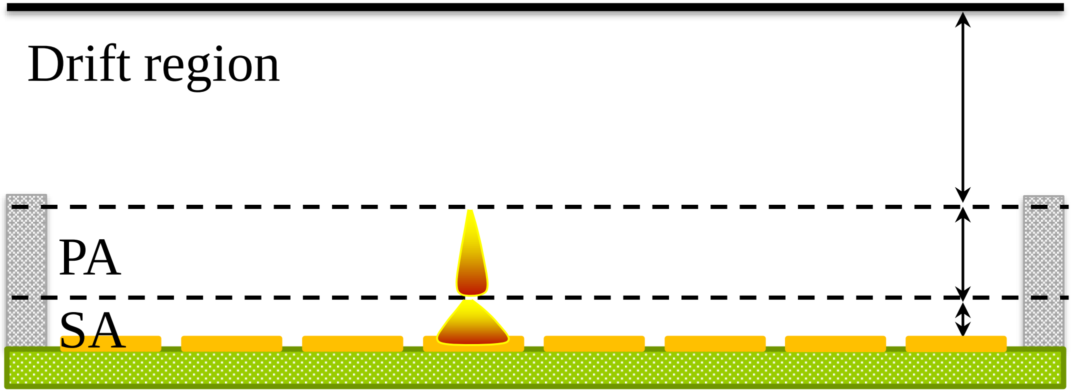


A. Lyashenko et al. , NIM A 598(2009) 116-120

DMM Design

- DMM: Double Micro-Mesh gaseous structure
  - Hole-type → mesh-type : to strongly reduce IBF
  - Double mesh: cascading avalanche for high gain

"Piggyback"

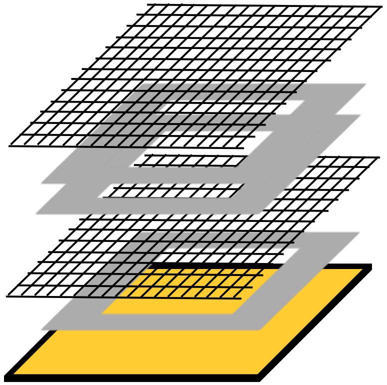


Stacked two meshes

- 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



PA Mesh

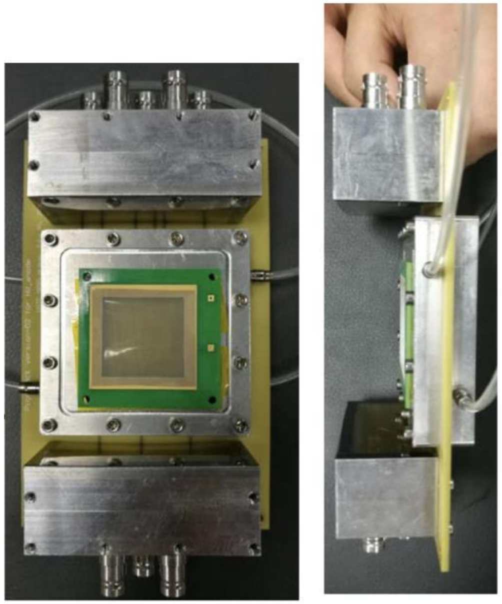
Thermal bonding film χ 2

SA Mesh

Thermal bonding film χ 1

Anode PCB

The schematic diagram of DMM fabrication

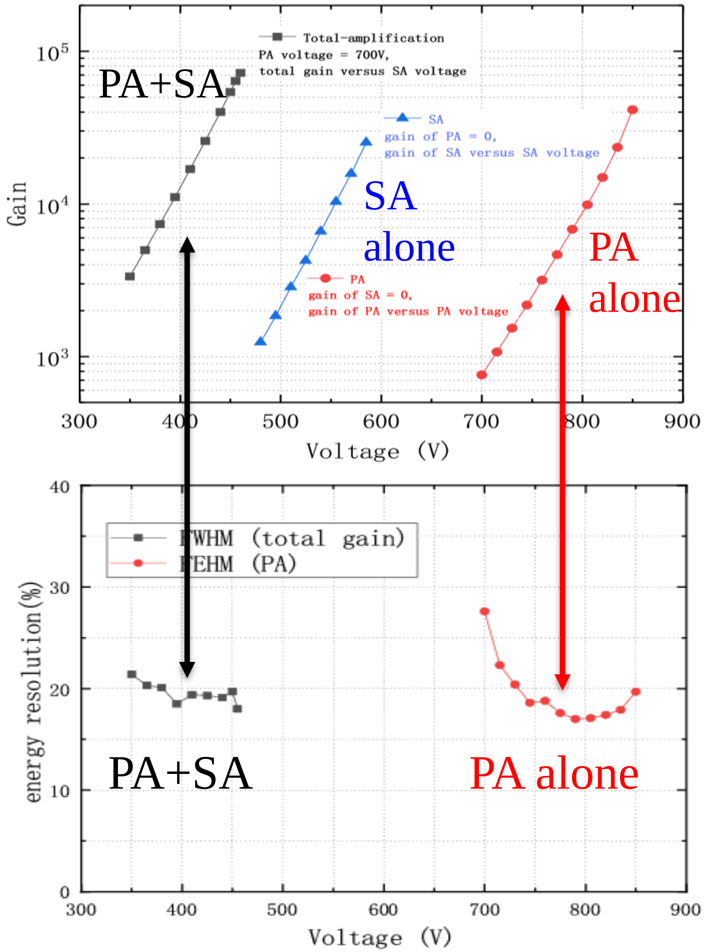


A 2.5cm×2.5cm DMM prototype

More details on thermal bonding method, see backup slides

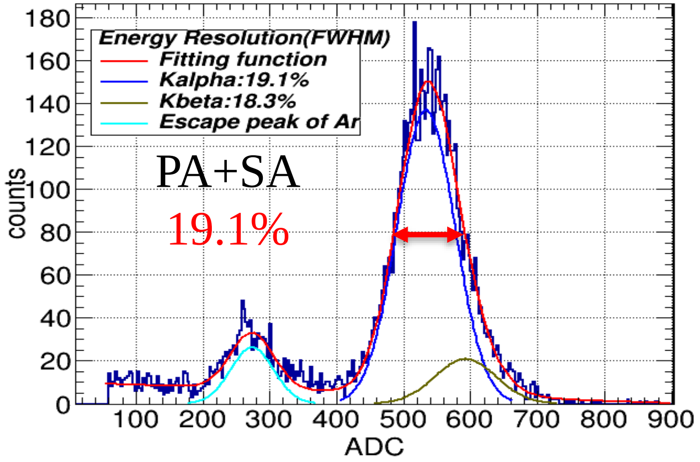
Gas Gain and Energy Resolution with ^{55}Fe

Gain: PA, SA and combined



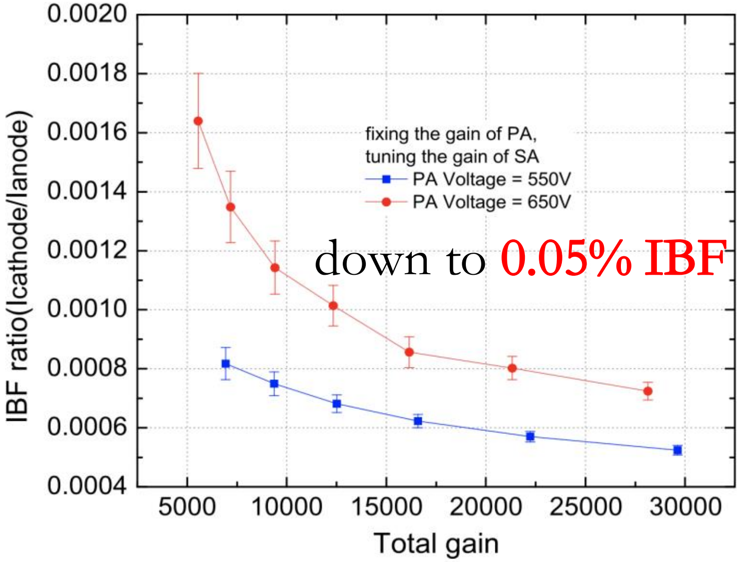
Resolution: PA and PA+SA combined

A typical ^{55}Fe energy spectrum

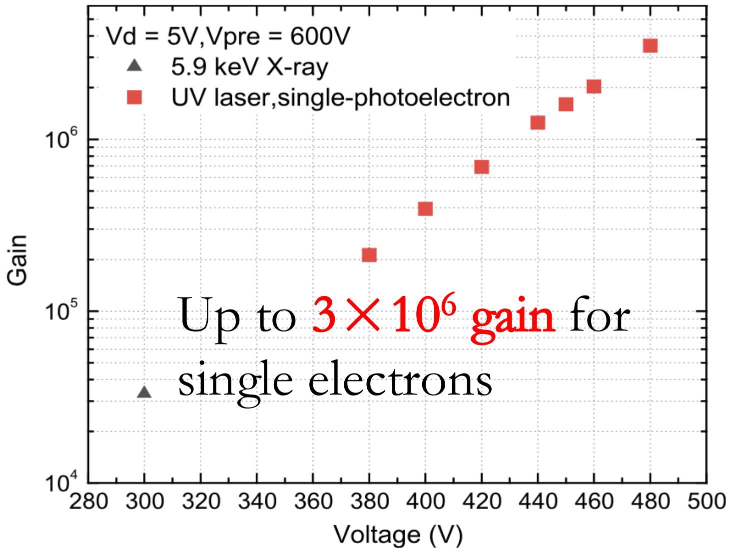


- Combined gain can reach up to 7×10^4 for 5.9 keV X-rays.
- Combined resolution remains almost constant and is close to PA-alone resolution, suggesting a close-to-full collection of primary electrons for the high-voltage configurations we used.

Previous results and validation



down to 0.05% IBF



Up to 3×10^6 gain for single electrons

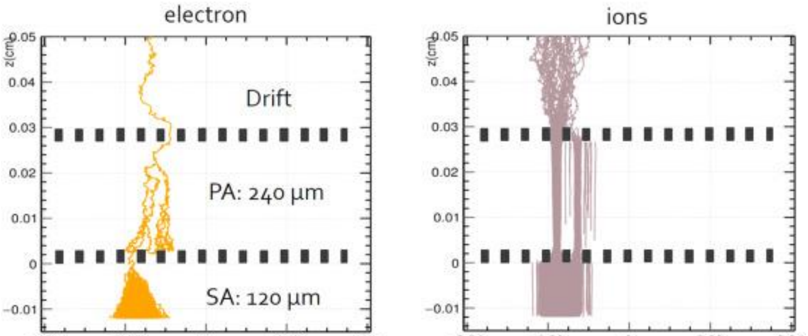
- Gain measured with X-ray energy spectrum ($Q_{\text{full-energy peak}}/Q_{\text{Primary}}$) is consistent with $I_{\text{Anode}}/I_{\text{Primary}}$.
- No ion space charge effect is confirmed in the DMM test.

More details:

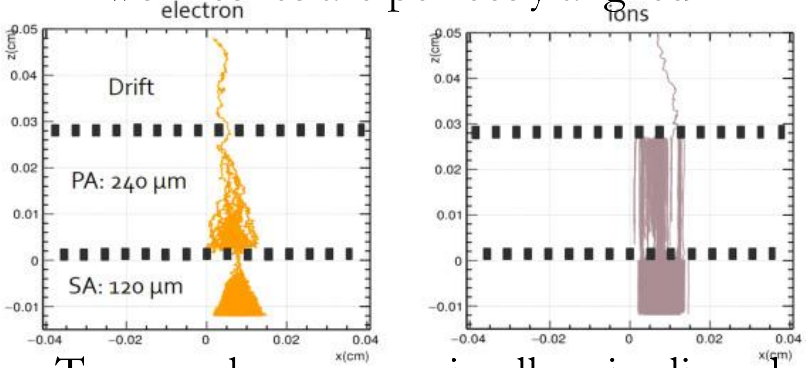
- *A high-gain, low ion-backflow double micro-mesh gaseous structure for single electron detection， Nuclear Inst. and Methods in Physics Research A, 889 (2018) 78–82.*
- *Optimization of the double micro-mesh gaseous structure (DMM) for low ion-backflow applications，Nuclear Inst. and Methods in Physics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

Can we further lower the 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 (I)

➔can be achieved by enlarging the distance and the wire density of the two meshes

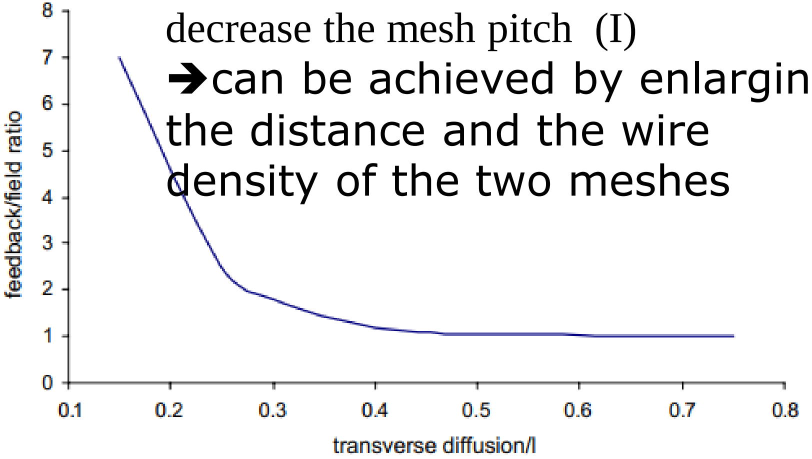
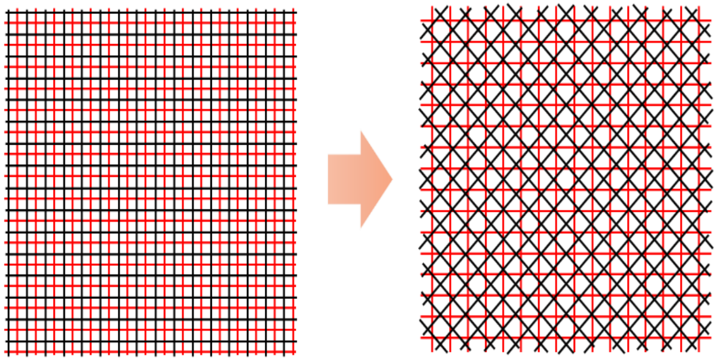


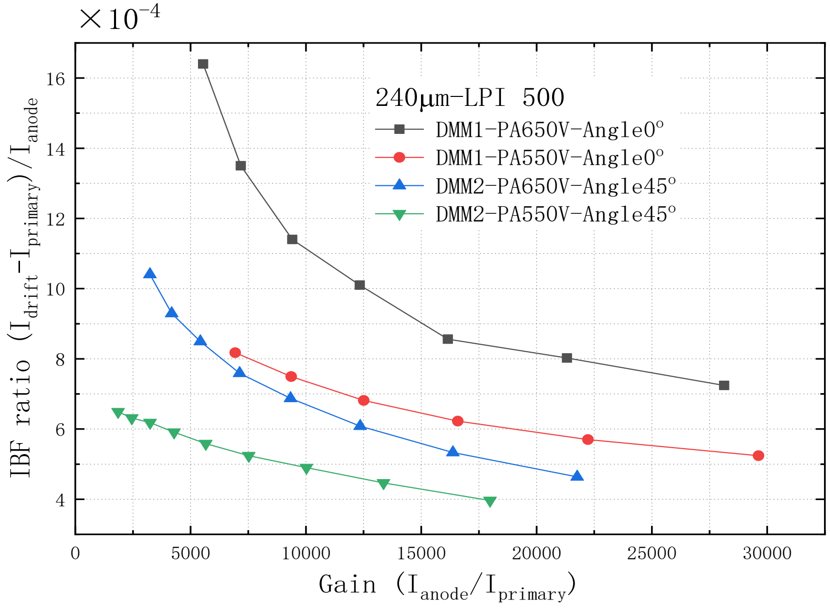
Fig. 4. Computed value of $\alpha\beta$ as a function of σ/l.

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

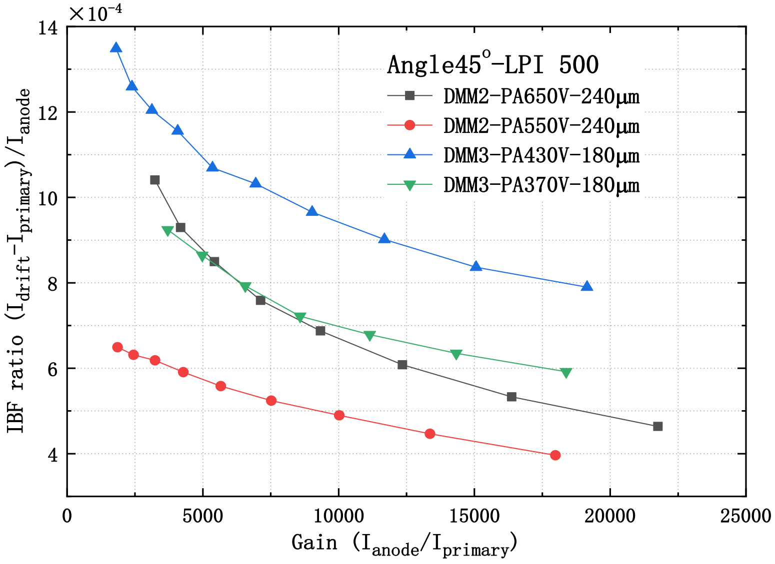


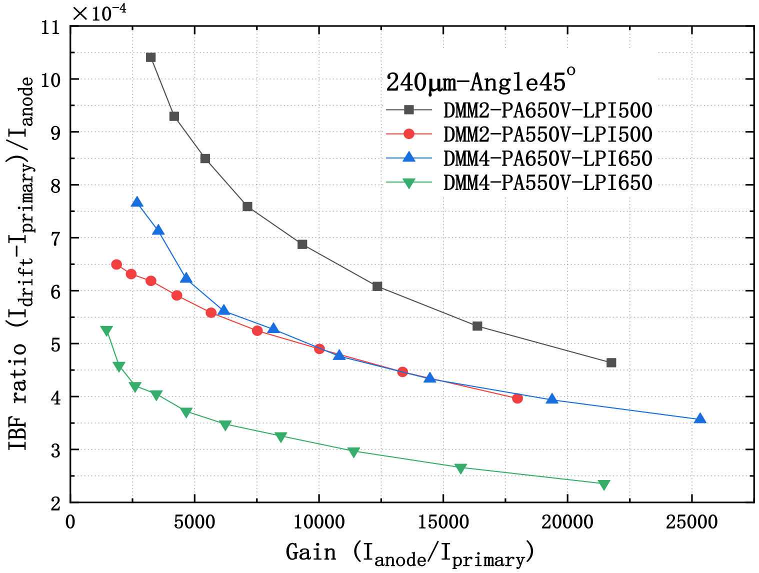


It's impractical to make any precise alignment of the two meshes. So setting the two meshes with a crossing angle is a practical way to ensure their mis-alignment.

Optimization for Extremely Low IBF

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



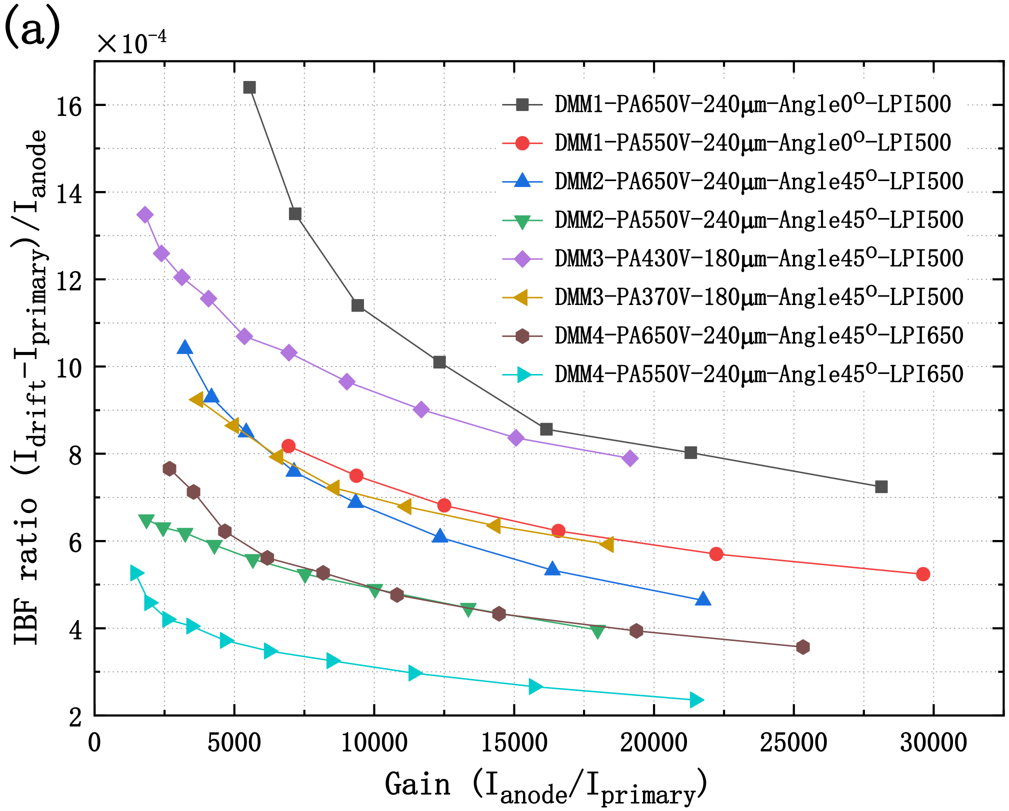


Larger gap increase the transverse diffusion of avalanche

Higher mesh density decrease the mesh pitch

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

Optimization Outcome For DMM

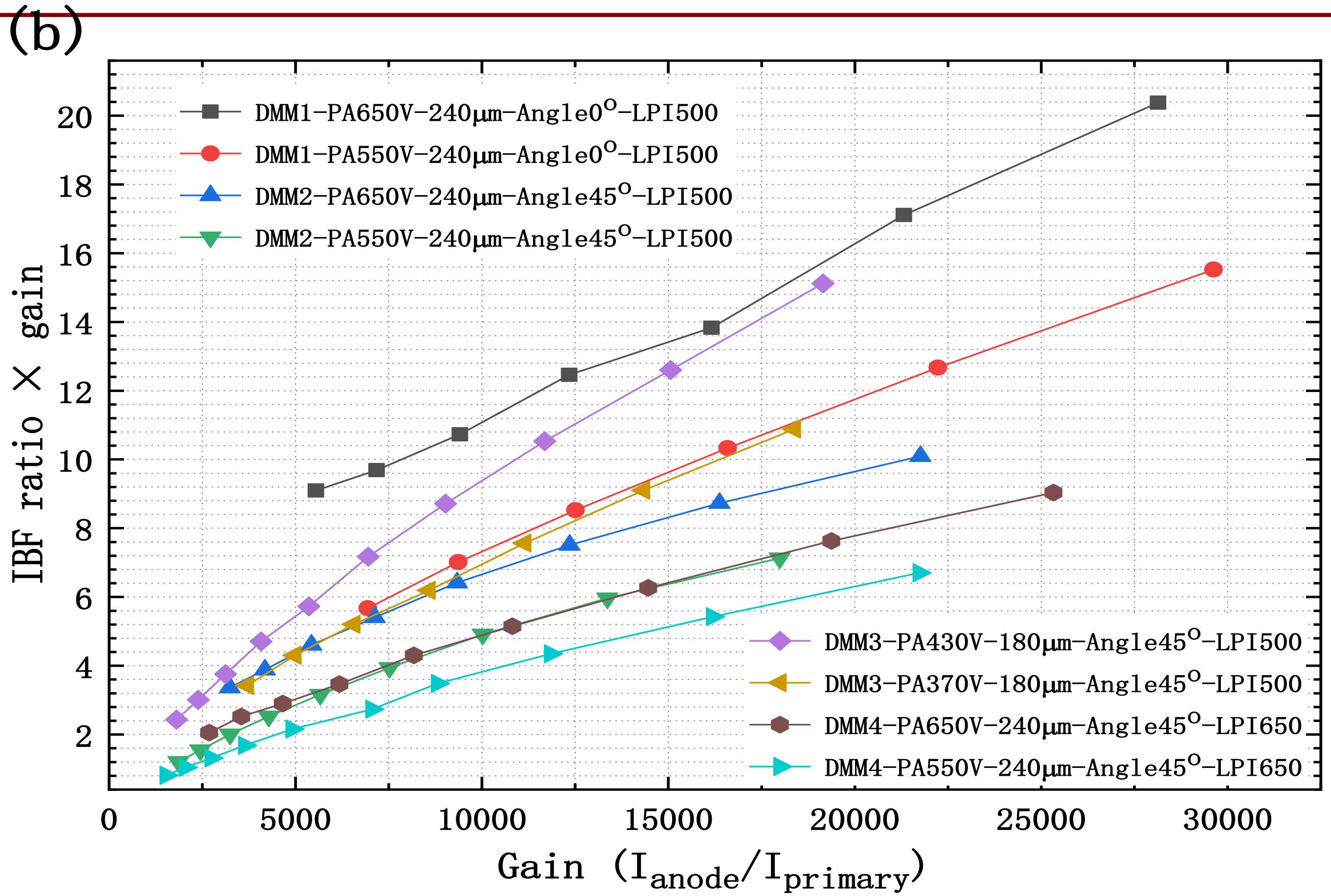


To push IBF down to an extremely low level:

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

A IBF ratio down to ~0.025%, which has been improved with a factor of 2 compared with that before optimization.

Consideration for the CEPC-TPC



In general, we present a practical method to suppress the IBF as low as possible. for specific application of CEPC, trade-off optimization in different parameters are required.

Consideration for the CEPC-TPC

- To adapt the usage of CEPC-TPC
  - Drift field: 200-300 V/cm
  - Electron collection
- Towards to large area
  - To develop the Fabrication process
  - To improve the Non-uniformity

From CEPC CDR

arXiv:1811.10545

The TPC has a cylindrical drift volume with an inner radius of 0.3 m an outer radius of 1.8 m, and a full length of 4.7 m. The central cathode plane is held at a potential of 50 kV, and the two anodes at the two end-plates are at ground potential. The cylindrical walls of the volume form the field cage, which ensures a highly homogeneous electrical field of 300 V/cm between the electrodes. The drift volume is filled with Ar/CF4/iC4H10 in the ratio of 95%/3%/2%.

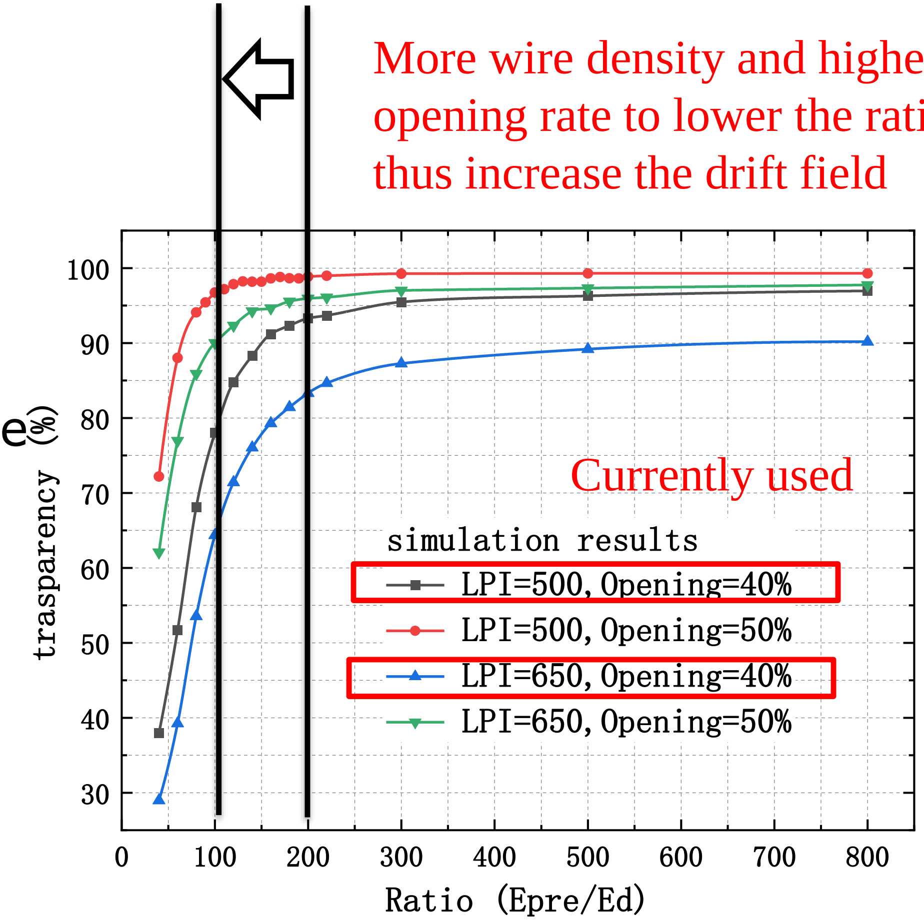
50kV/（4.7m/2）= ~210V/cm, is not consistent with 300 V/cm

Drift field and Electron Transparency

Requirement for drift and collection of primary electrons:

- ☐ A proper drift field ~200-300 V/cm
- ☐ high collection efficiency

The results presented above are achieved at Epre/Ed = 200 to ensure a maximum electron collection, the PA voltages are 650V and 550V, which are corresponding to drift electric field of 135V/cm and 115V/cm

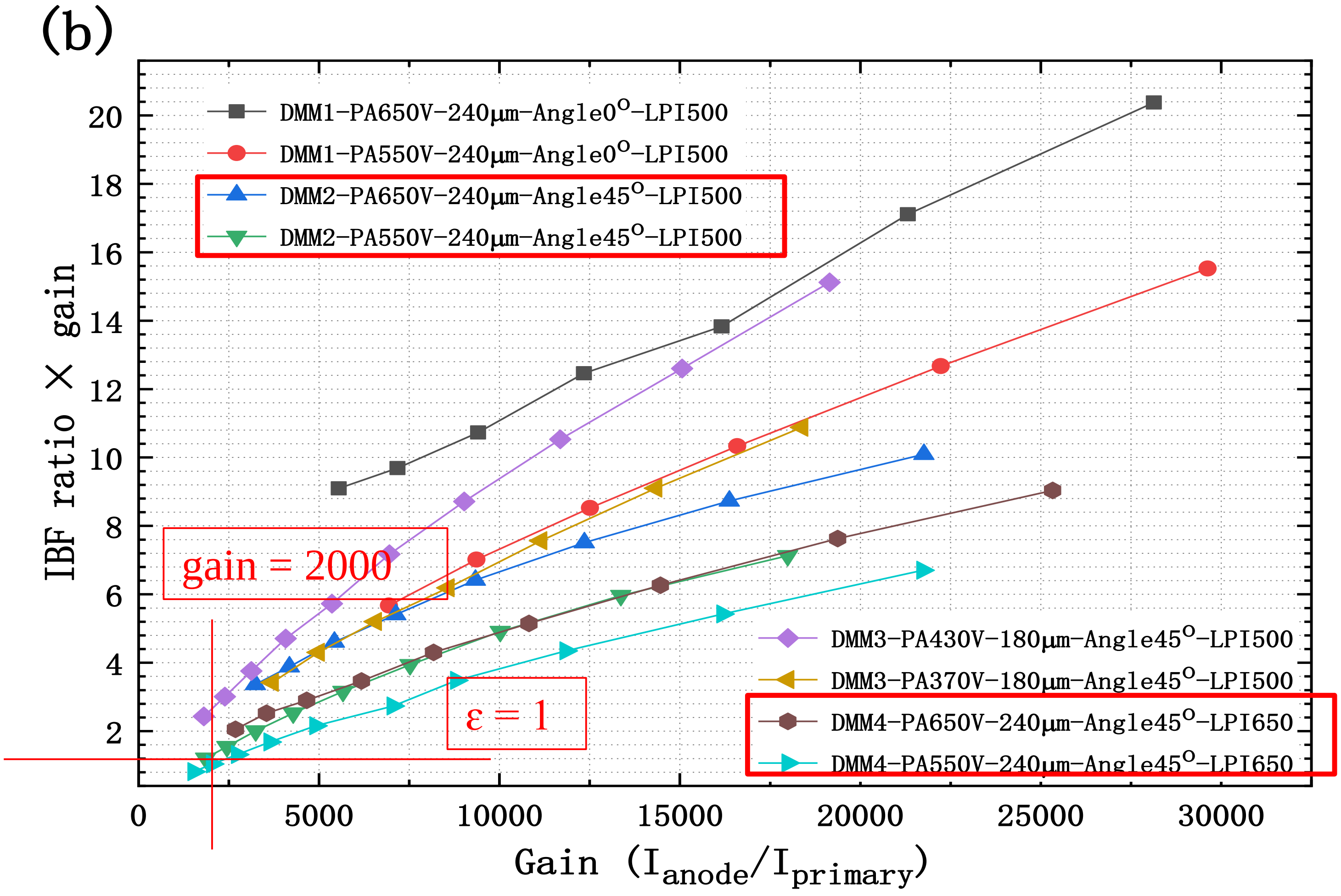


More wire density and higher opening rate to lower the ratio, thus increase the drift field

Currently used

Simulation study on Electron transparency with different mesh density

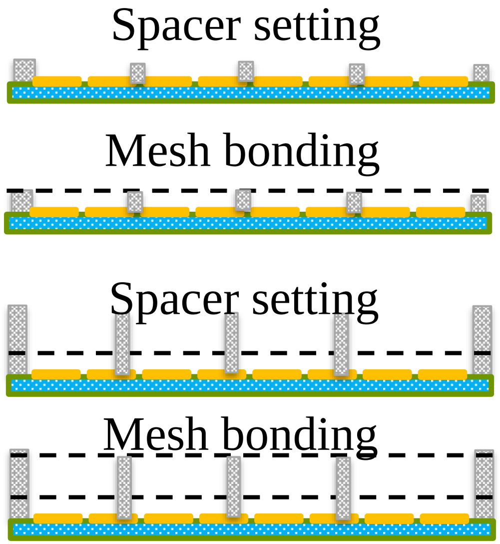
Drift field and Electron collection



It is possible to reduce the product of IBF and gain to < 1, while maintaining > 200V/cm drift field and >90% electron transparency by increasing the opening rate of the mesh.

Fabrication process

- 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



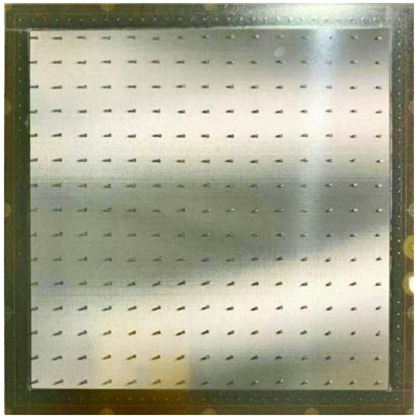
Spacer setting

Mesh bonding

Spacer setting

Mesh bonding

Thermal bonding for DMM

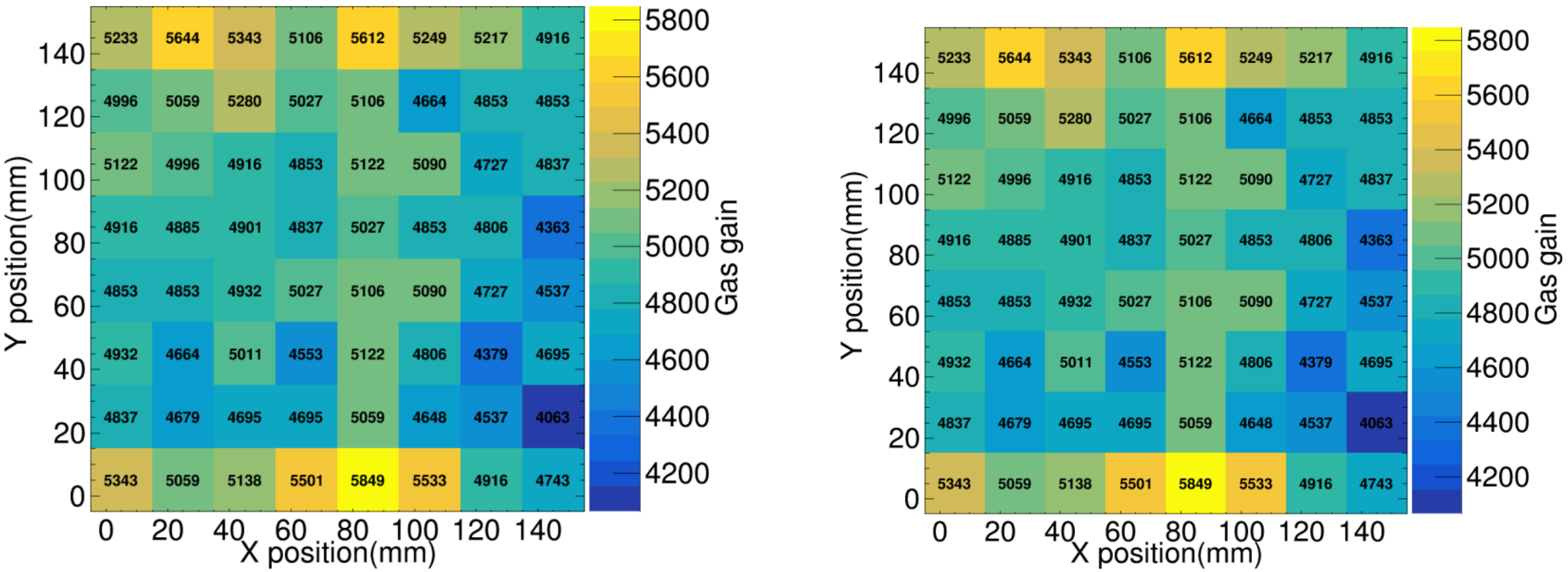


A 150mm ×150mm DMM prototype manufactured last year,

But we found severe non-uniformity, which needs to be overcome before further attempting.

To improve the non-uniformity (single MM)

Thanks to the flexibility of the TBM, it is convenient to optimize the detector structure by tuning the conditions such as temperature, pressure in the thermal-bonding process. The temperature and pressure are increased in order to fully squeezing the adhesive layers so as to press the spacer to the thickness of its middle substrate layer ~100um.



5233	5644	5343	5106	5612	5249	5217	4916
4996	5059	5280	5027	5106	4664	4853	4853
5122	4996	4916	4853	5122	5090	4727	4837
4916	4885	4901	4837	5027	4853	4806	4363
4853	4853	4932	5027	5106	5090	4727	4537
4932	4664	5011	4553	5122	4806	4379	4695
4837	4679	4695	4695	5059	4648	4537	4063
5343	5059	5138	5501	5849	5533	4916	4743

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5343	5059	5138	5501	5849	5533	4916	4743

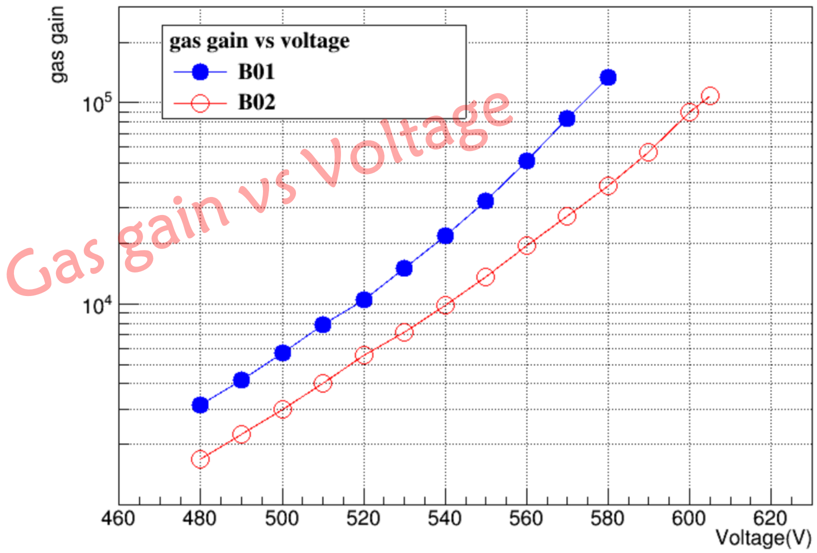
Gain non-uniformity (RMS/Mean)

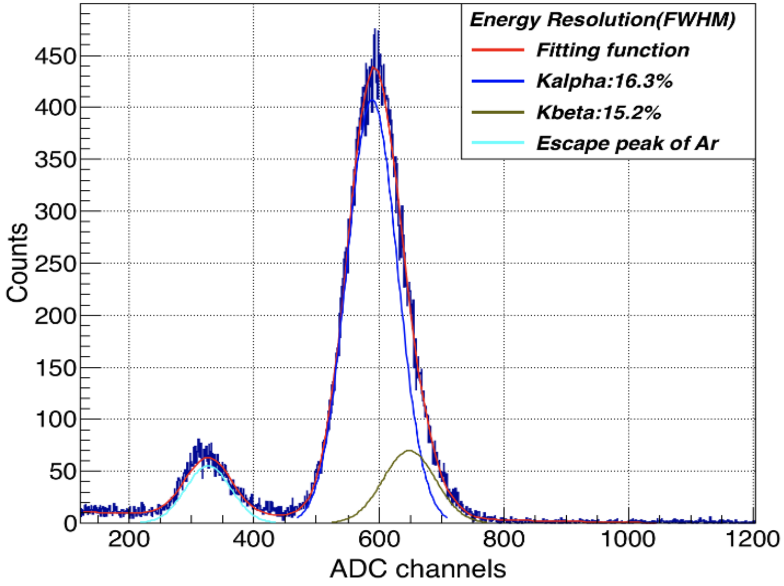
6.3% @ gain =5000

5.5% @ gain =1000

Gas gain and Energy resolution (single MM)

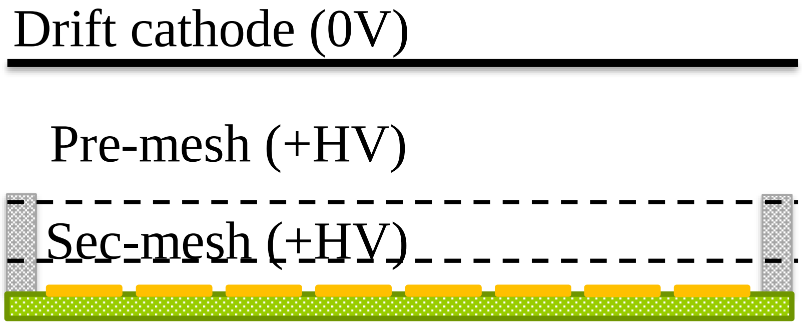
Very high gain (>10^5) , and excellent energy resolution of ~16% (FWHM) , test with 5.9 keV X-rays





Can the IBF be lower?

- For the case of DMM, when we set PA at 550V and switch off SA, the $I_{drift}/I_{primary}$ was measured at ~1.3



Drift cathode (0V)

Pre-mesh (+HV)

Sec-mesh (+HV)

Anode (same to Sec-mesh)

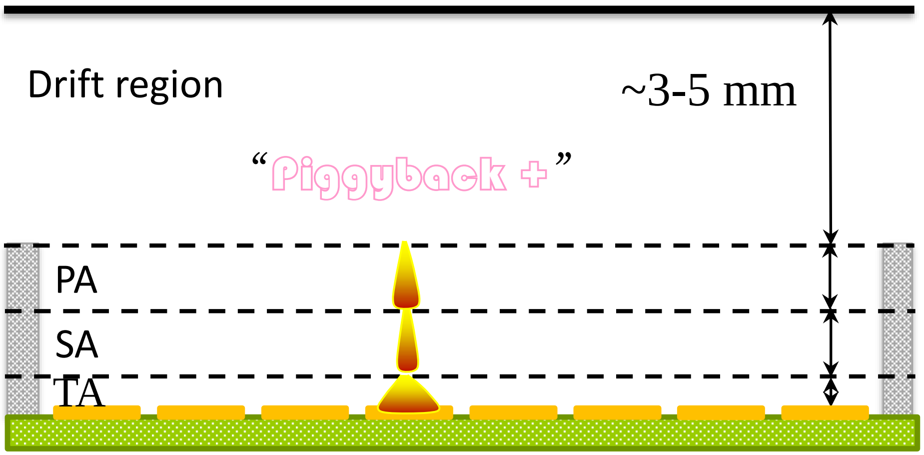
➔The PA only contributes ~0.3 for the ε factor, the SA dominates the total IBF

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

➔Let’s go to TMM

TMM Design

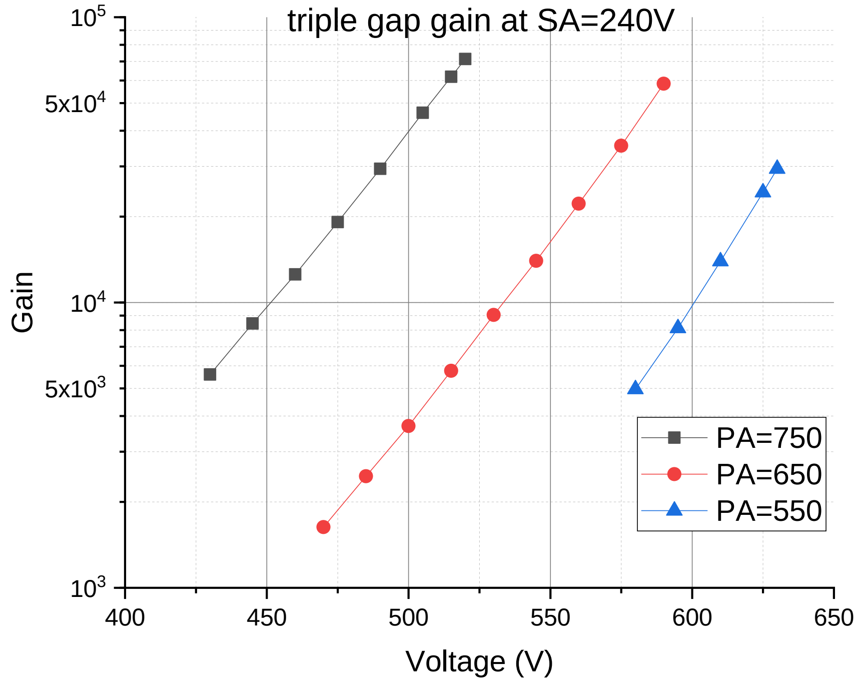
- TMM: Triple Micro-Mesh gaseous structure
  - One more mesh on the DMM
  - More stable gain, lower IBF from second avalanche···

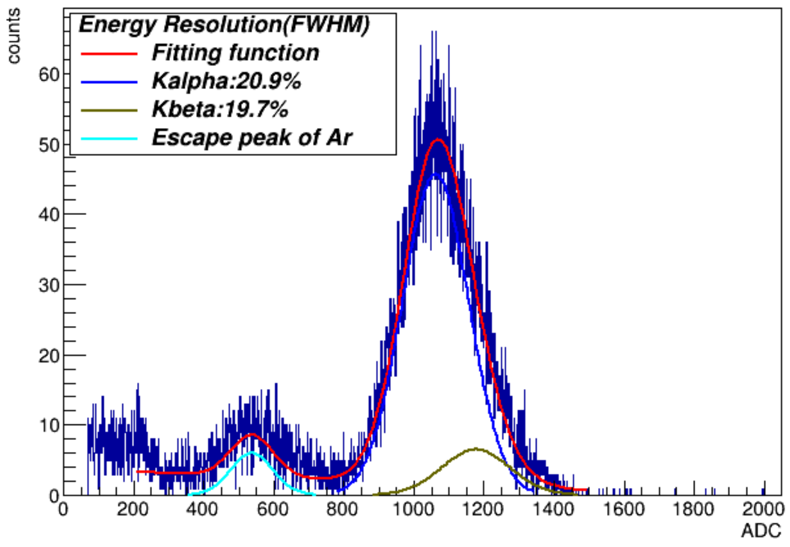


Stacked three meshes

- Gap between the 1st and 2nd meshes: 200-300um, serving as pre-amplification (PA)
- Gap between the 2nd and 3rd meshes : 200-300um as secondary amplification (SA)
- Gap between the bottom mesh and anode: 50-100um as secondary amplification (TA)

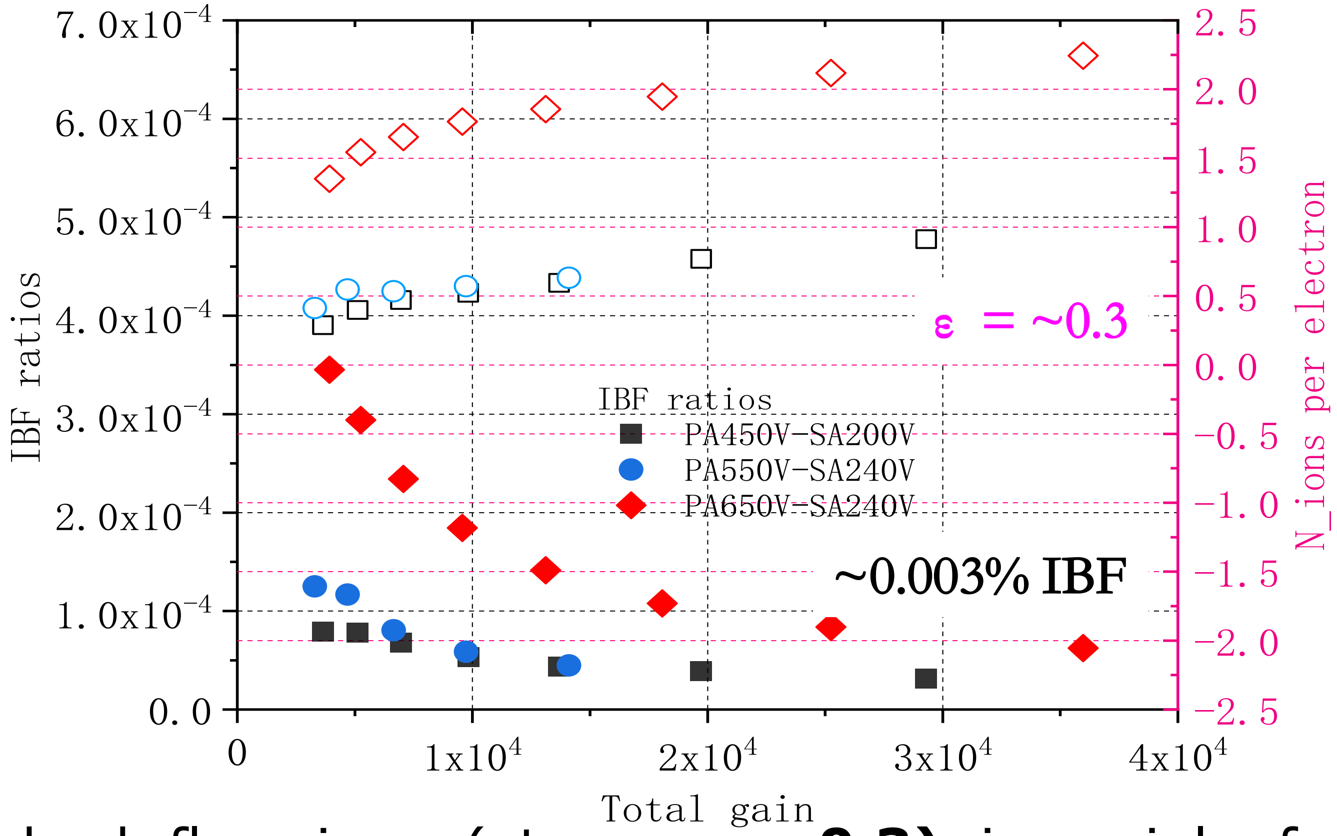
Gain and energy resolution





- 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

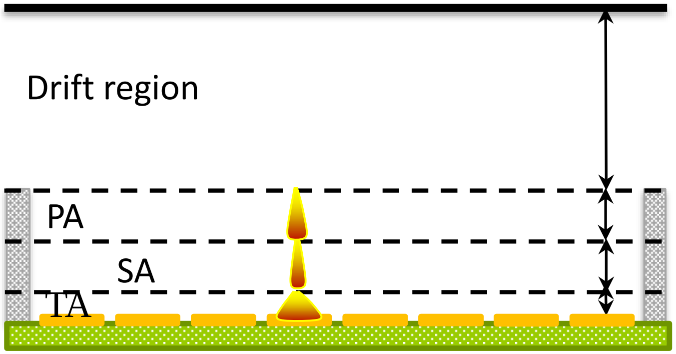
IBF measurement for TMM

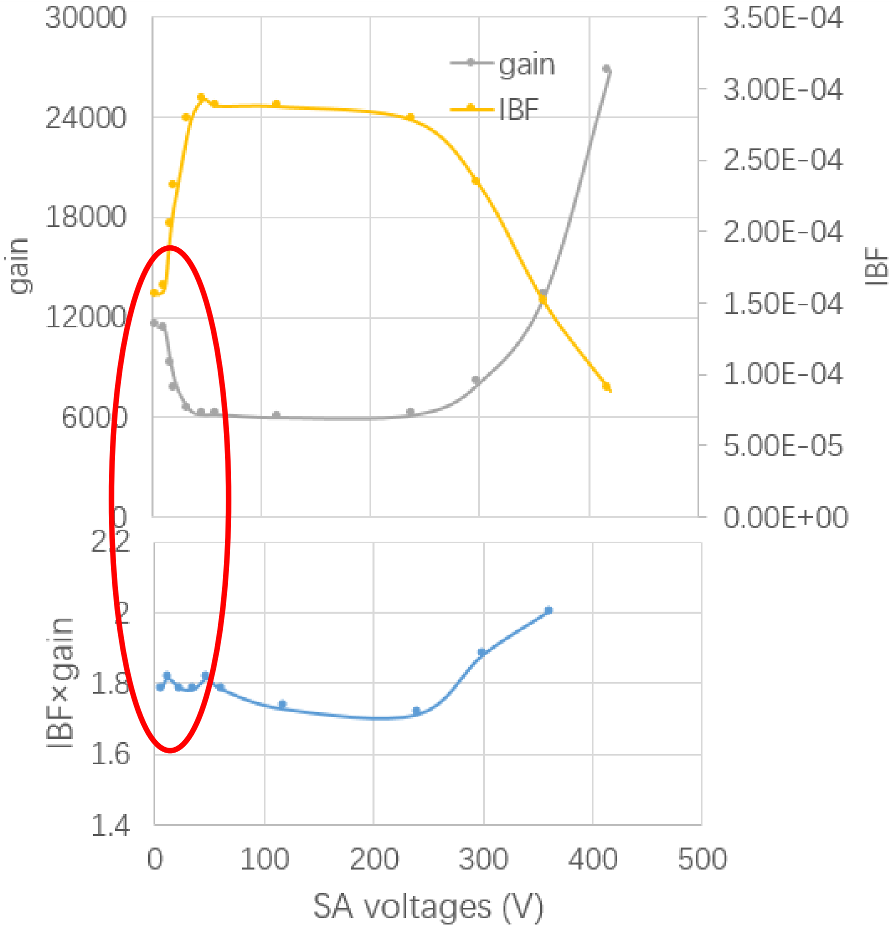


The back-flow ions (at **ε = ~0.3)** is mainly from PA, concluding that the IBF can not be further reduced by adding more meshes, the TMM reaches the lowest IBF level for the mesh-type structure.

To optimize

Combined gain = PA gain × SA trans × SA gain × TA trans × TA gain





PA and TA voltages are fixed at 650V and 530V, this plot shows the combined gain, IBF and their product change with the variation of SA voltages

Summary

- Demonstrated the performance of DMM &TMM with small-size prototypes:
  - Gain: 7×10^4 for 5.9 keV X-rays and 3×10^6 for single electrons.
  - IBF ratio: down to ~ 0.03% for DMM, ~ 0.003% for TMM
- Potential application in CEPC-TPC
  - Verified the feasibility to larger area
  - If it is necessary to limit the product of IBF and Gain to <1

    DMM is a promising option after careful adjustment, while TMM is confirmed.

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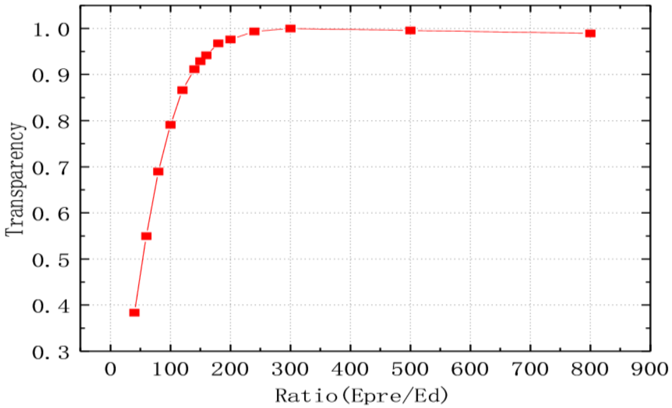
Thanks for your attention !

Back-up

Electron Transparency

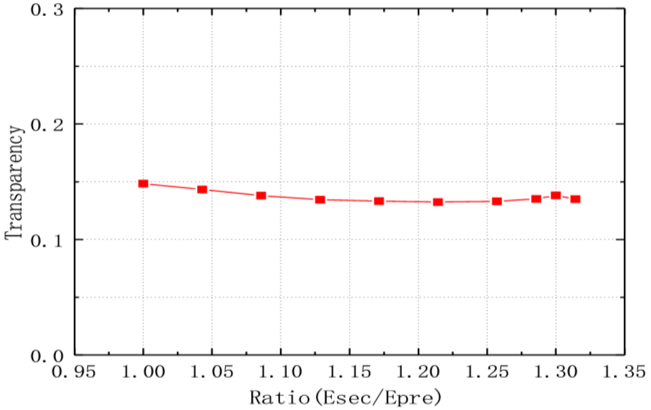
- Transparencies for electrons passing through PA and SA meshes are extracted by measuring PA, SA and total (PA and SA combined, DMM) gas gains
    - Combined gain = PA gain × SA trans × SA gain

PA relative transparency



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

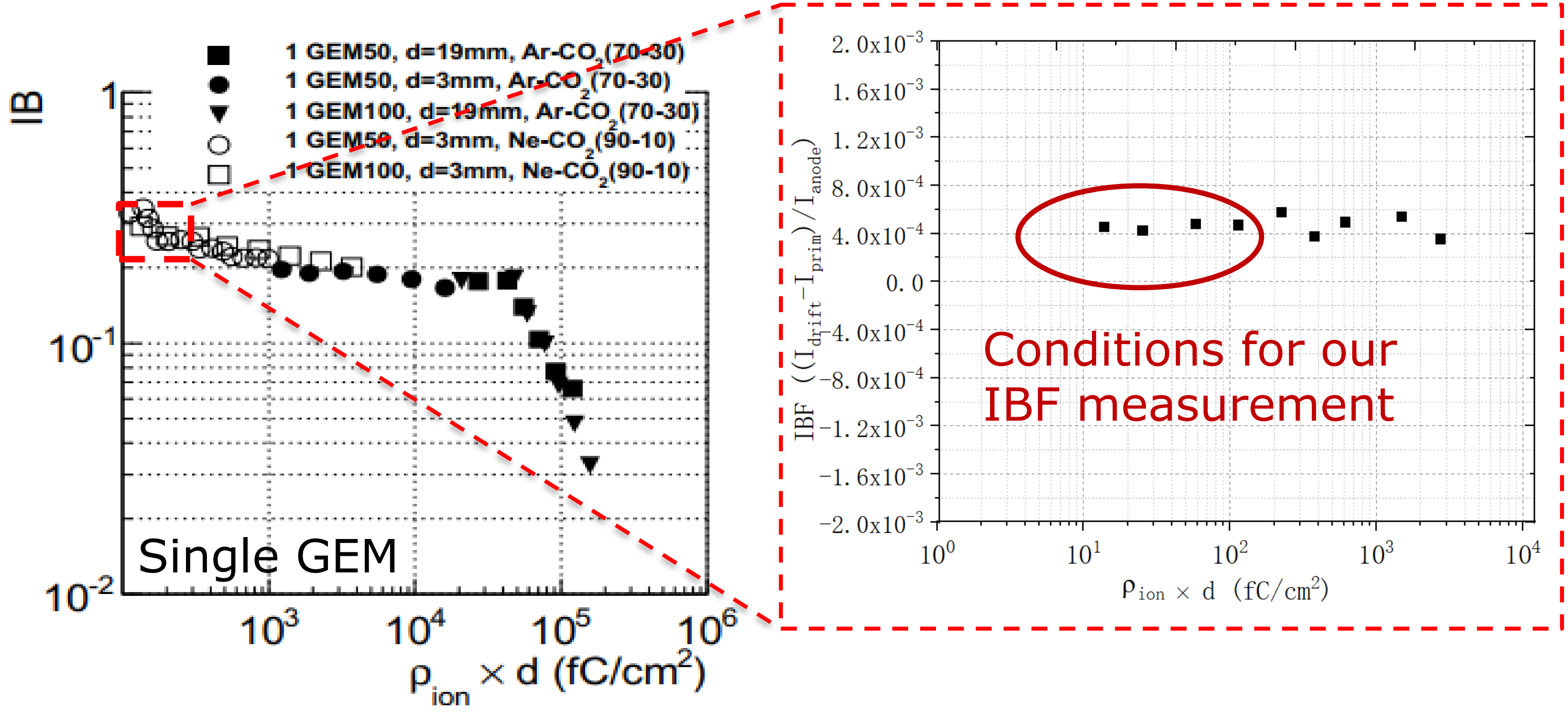
SA transparency



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

Ion Space-Charge Effect

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

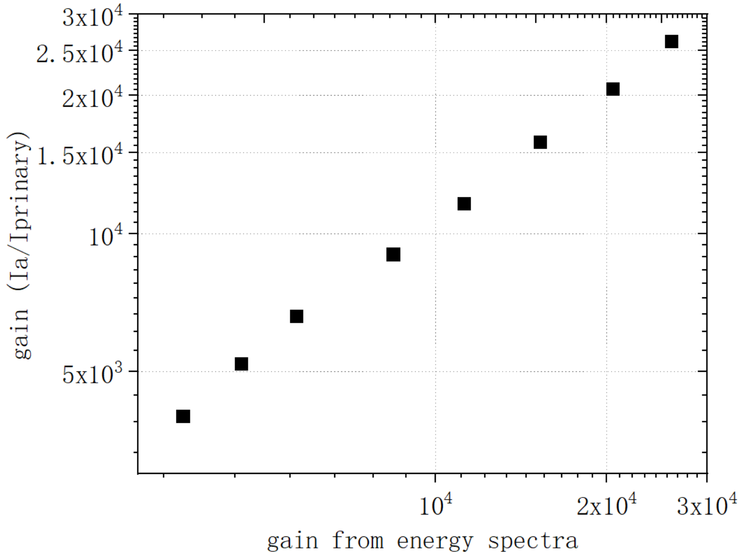


Conditions for our IBF measurement

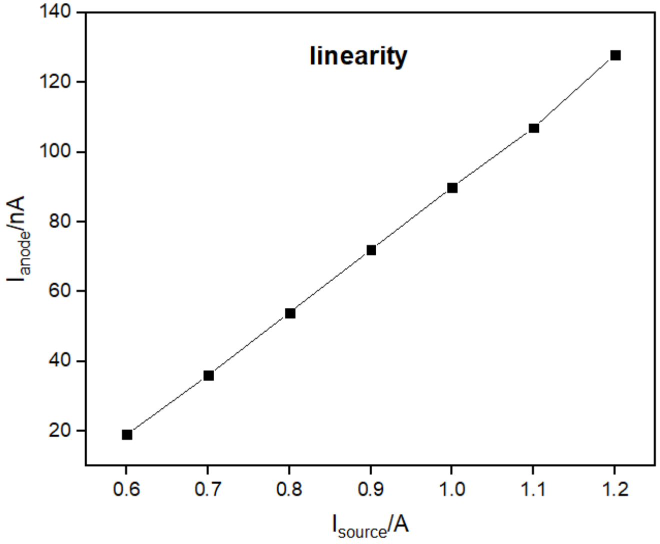
- Our IBF measurements are reliable in terms of ion space-charge effect (impact is negligible).

Validation of IBF Measurement

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



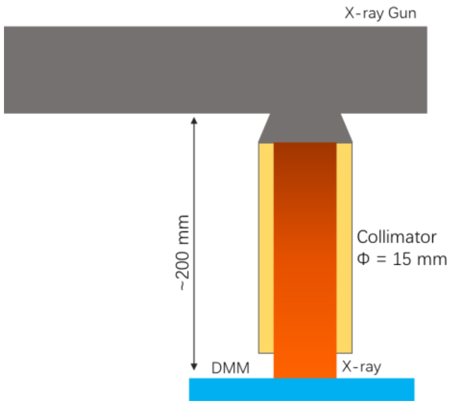
no gas gain saturation



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

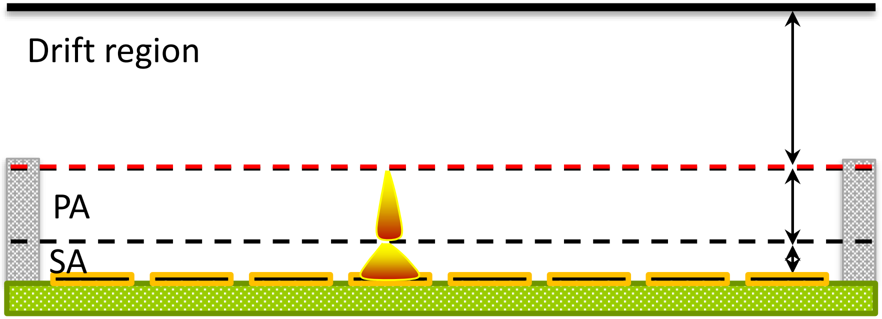
- IBF ratios measured with 55Fe and X-ray tube are consistent

Performance Characterization

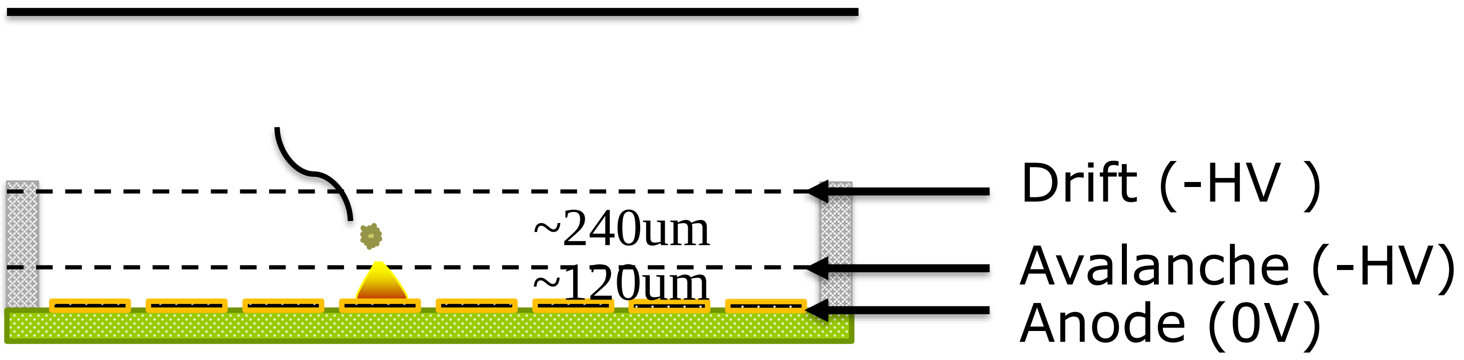


IBF measurement setting

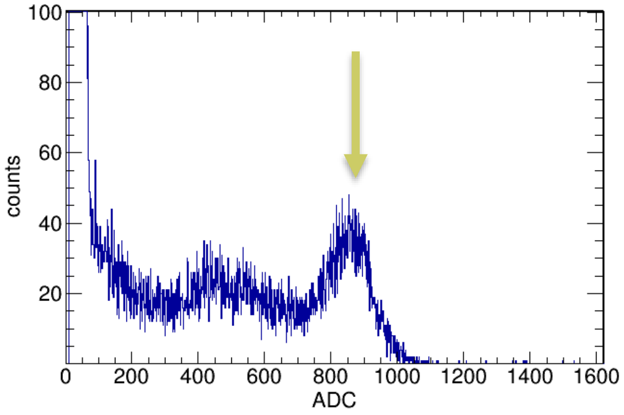
- DMM with Ar (93%) + CO_2 (7%)
  - Electron transparency
  - Energy resolution and gas gain
  - Ion back-flow ratio
- DMM with Ne (80%) + CF_4 (10%) + C_2H_6 (10%)
  - Single photon electron response



Sec-amplification (SA)

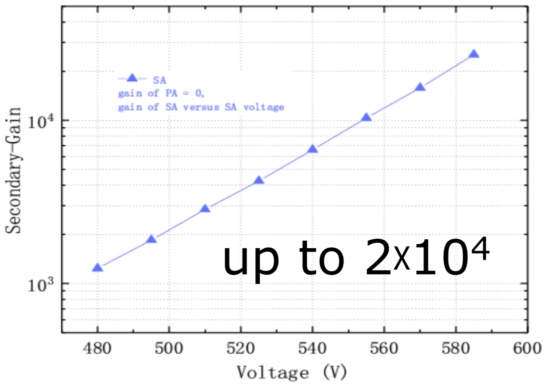


Full energy peak due to the lateral angle
photoelectrons and Auger electrons



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

Gain VS avalanche voltages



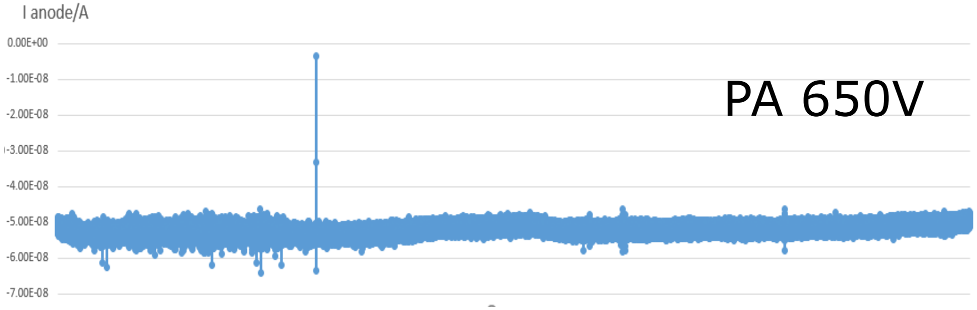
up to 2x10^4

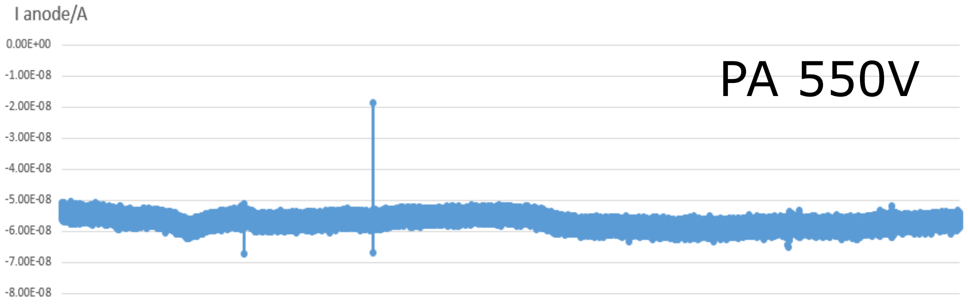
Long-Term Stability

DMM: 240μm- 45^0 - LPI650

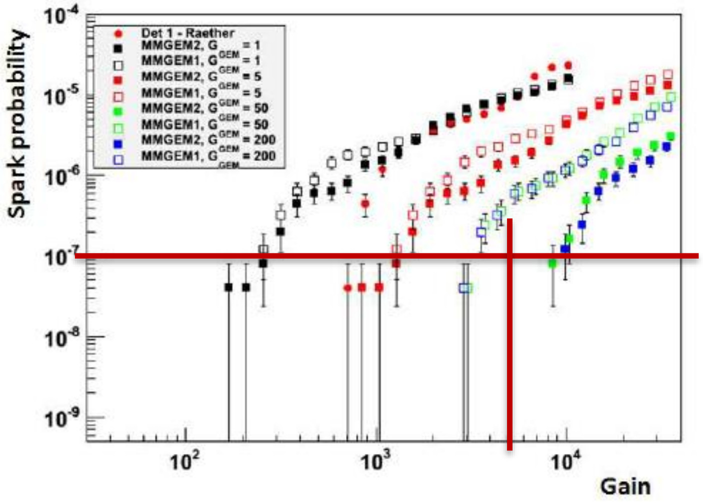
~24 hours of X-ray irradiation,

Gain ~ 5000





Reference for comparison



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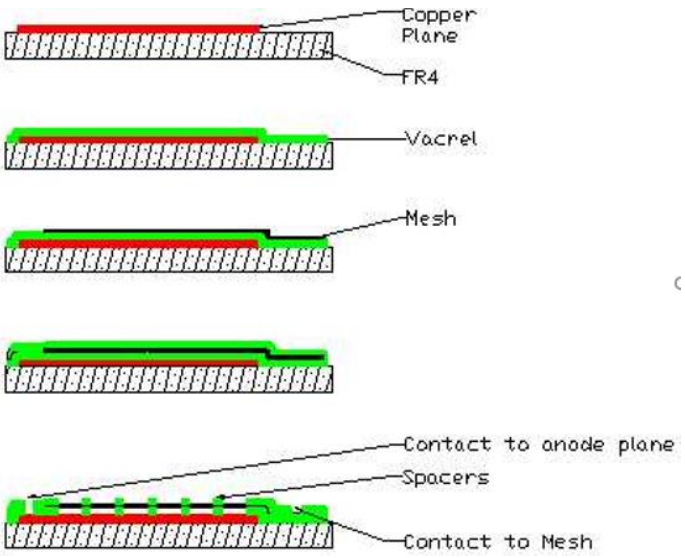
Spark probability < 10^{-9}

The thermal bonding method

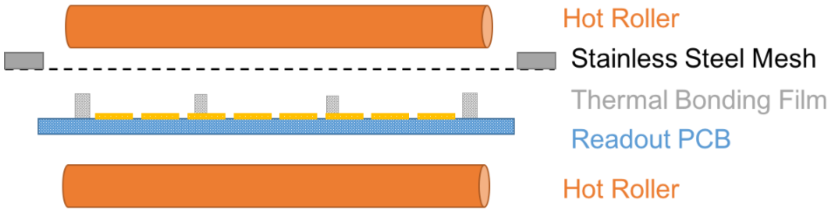
Thermal-bonding method

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

Micromegas in a Bulk

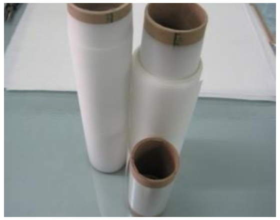
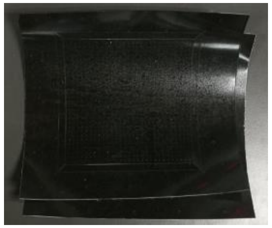


Thermal bonding processing

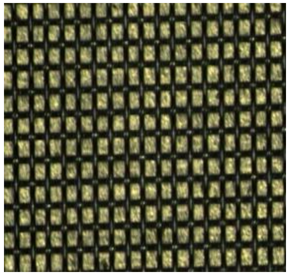


- No etching, no pollution
- Easy to handle at lab
- Easy to make new structures
- Cheap
- Φ0.5mm- Φ1mm spacers, ~1cm pitch
  ➔easy to clean, especially for large area
  ➔less than 1% spacer area

Materials and Specifics

Thermo-bond films with a dry (hot-melt type) adhesive on both sides.
A variety of specifications to choose.

Abundant types to choose:
Thickness: 20-40μm, Density: 260-640 LPI
Opening rate: 30-70%, Tension: up to 30N/cm

Resistive paste

Pure germanium

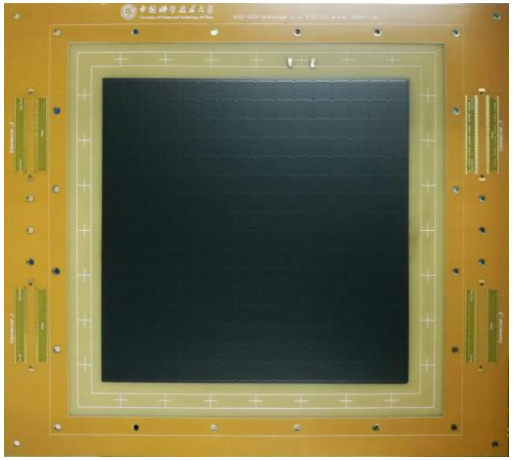
Graphite target

Resistive anode:

- Resistive paste printing: kΩ/□ - 200MΩ/□
- Germanium coating: MΩ/□ - 200MΩ/□
- DLC: Ω/□ - GΩ/□

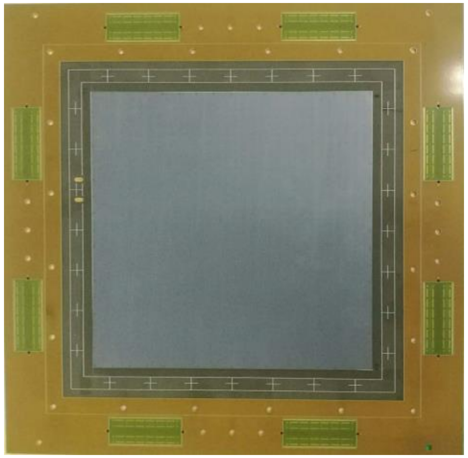
Resistive anode

Pros & cons



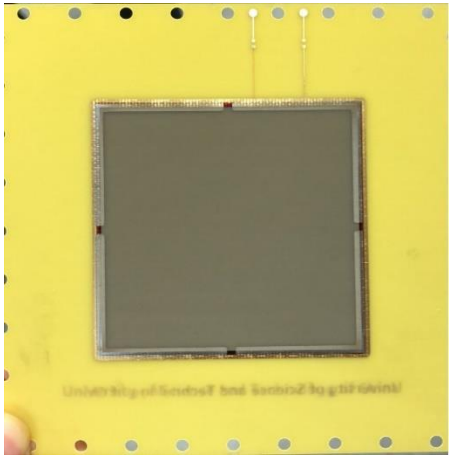
resistive paste by screen printing: 10-20 μm

- 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

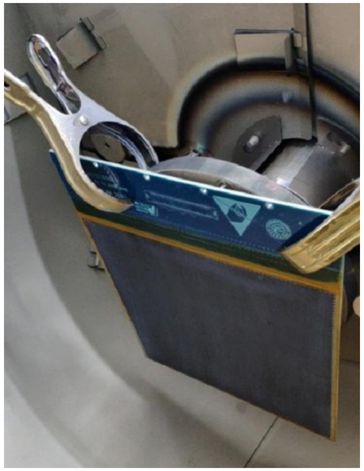
- o Controllability for resistivity
- o Purity for low background applications
- o Large area
- Δ Complex pattern
- Δ Oxidation problem （keep in dry）
- ? Irradiation hardness & aging



DLC deposited by magnetron sputtering:

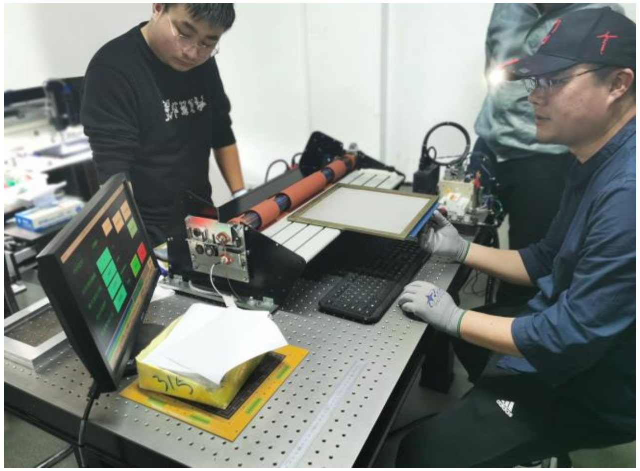
- o Controllability for resistivity
- o Purity for low background application
- o Robust

Fabrication process



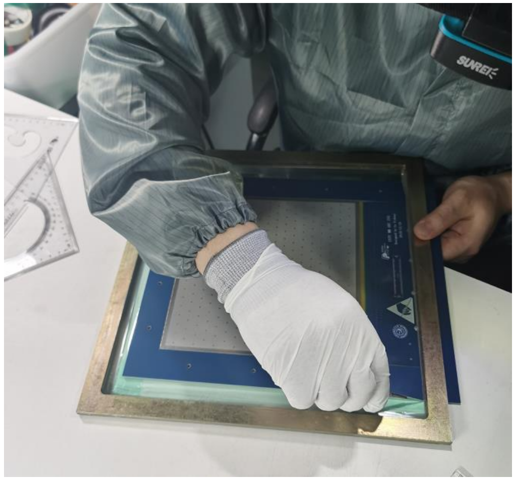
1:Ge coating

2:spacer setting

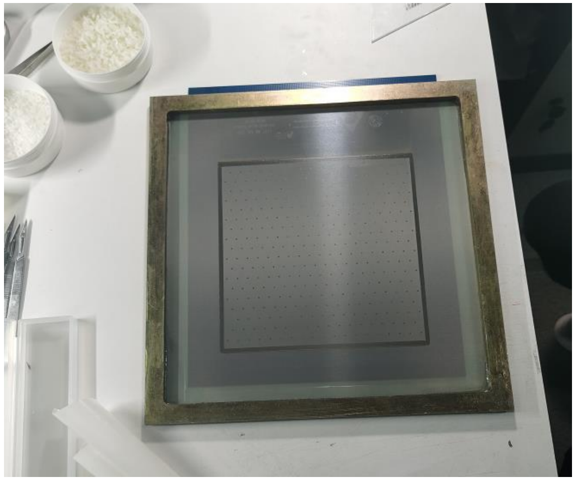


3: thermal bonding

6: assembling



5: mesh cutting

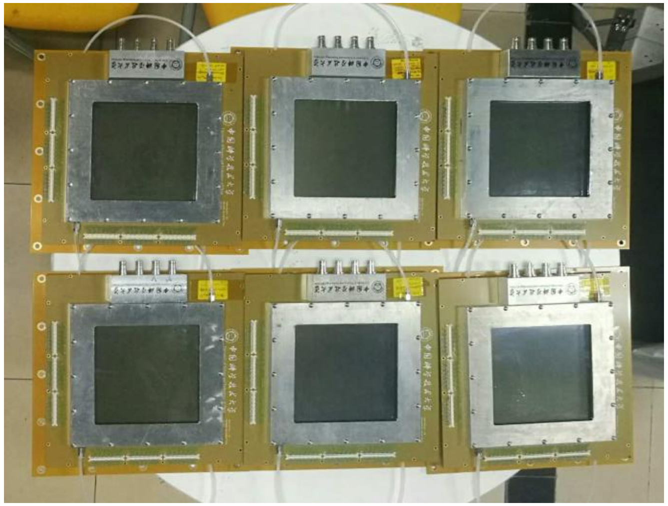


4: after bonding

Mass production

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

From materials to full detectors



Several 15cm×15cm prototypes are produced to verify the method, basic performances, such as gain, energy resolution and gain uniformity are tested using X-ray source.