Status and future Developments of MPGDs for low-energy nuclear physics applications at FRIB

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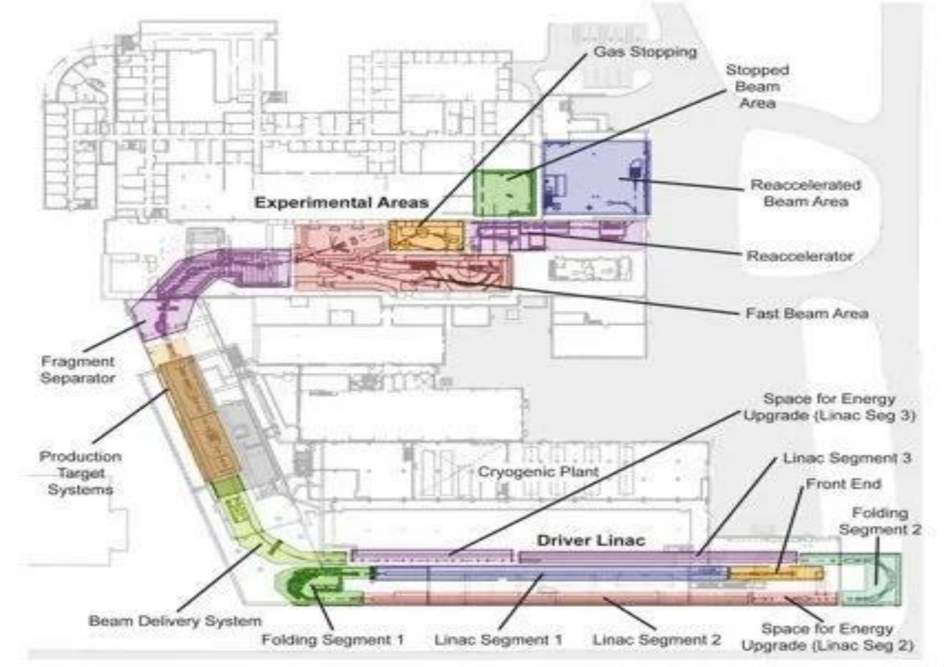
Facility For Rare Isotope Beams (FRIB)

- FRIB is a US DOE Office of Science scientific user facility (one of 28) intended to provide beams of rare isotopes – located on MSU campus

- FRIB started in 2008 and reached the last project milestone in January 2022, five months ahead of schedule and on budget
- Experiments began in May 2022.
- FRIB is open to researchers from around the world based on scientific merit: Program committee approximately once per year
- FRIB's key feature is 400 kW beam power
  - 8 pμA or 5 x 10^{13} ^{238}U /s
  - 42 pμA or 2.6 x 10^{14} ^{48}Ca /s
- Experiments with fast (200 MeV/u), stopped (trapped), and reaccelerated beams (0.6 to 10 MeV/u)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives

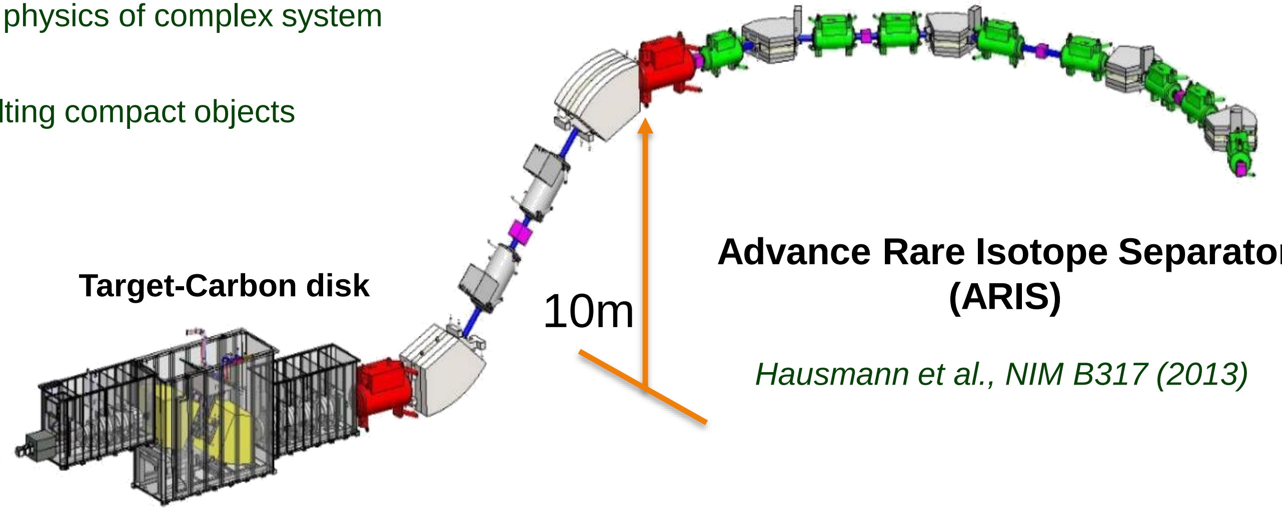
FRIB provides access of 80% of all atoms predicted to exist in nature

- Isotope harvesting capability from beam dump water



FRIB Enables Scientists to Make Discoveries in Four Areas

- **Properties of atomic nuclei**
  Study of predictive model of nuclei & their interactions, Many-body problem & physics of complex system
- **Astrophysics: Nuclear Processes in the Cosmos**
  Origin of the elements, energy generation in stars, stellar evolution & the resulting compact objects
- **Use atomic nuclei to tests of laws of nature**
  Effects of symmetry violations are amplified in certain nuclei
- **Societal applications and benefits**
  Medicine, energy, material sciences, national security, etc. etc.



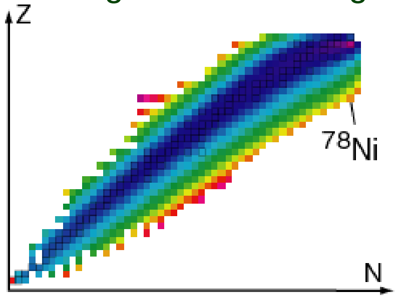
Advance Rare Isotope Separator (ARIS)

Hausmann et al., NIM B317 (2013)

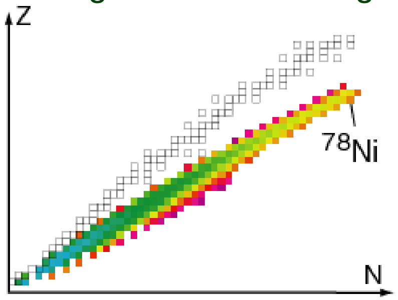
Example:
^{78}Ni from ^{86}Kr at 200 MeV/u

Three-stage separation, approximately 90 m long

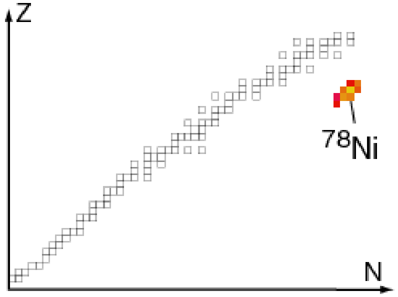
Fragments after target



Fragments after wedge

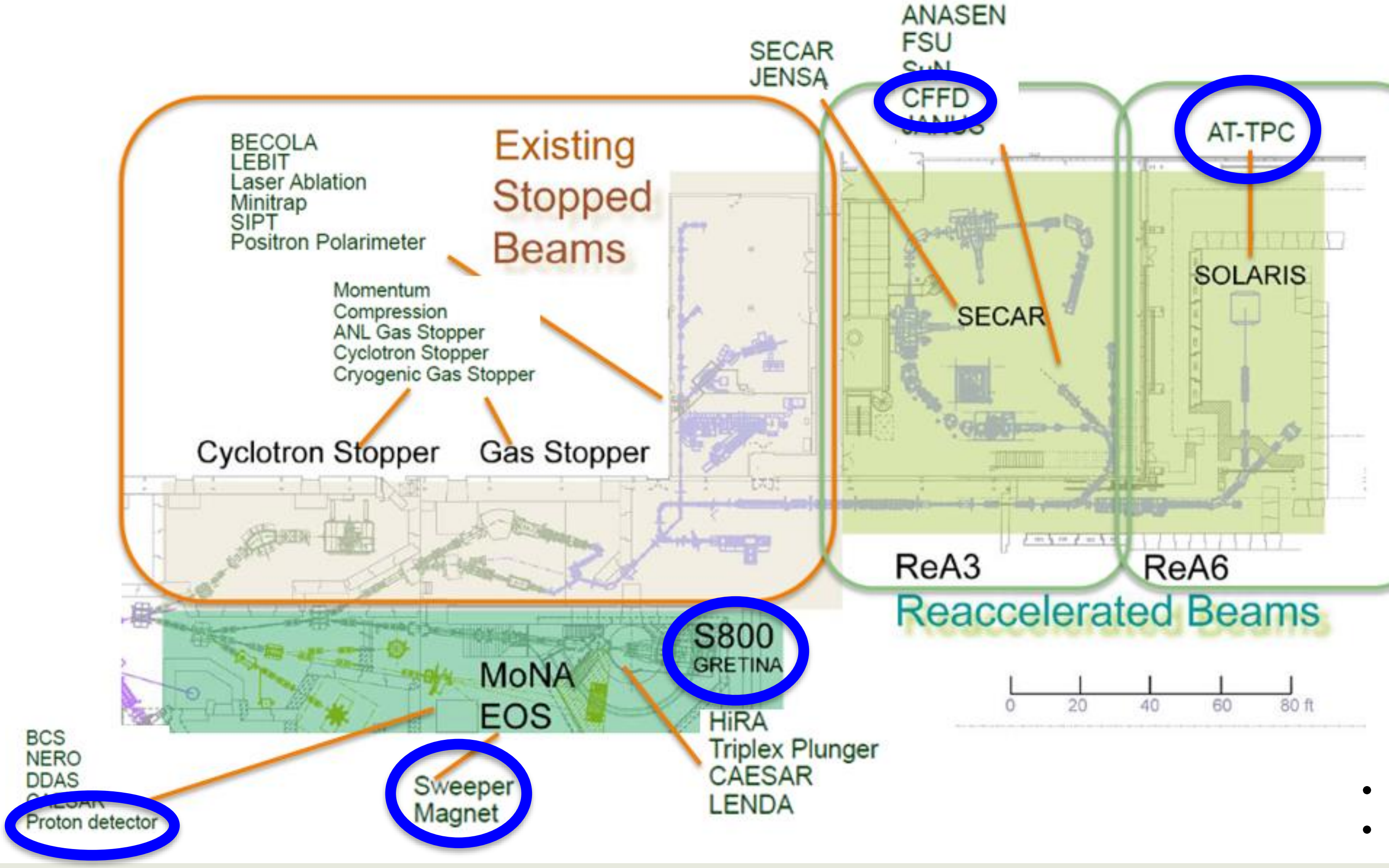


Fragments at focal plane

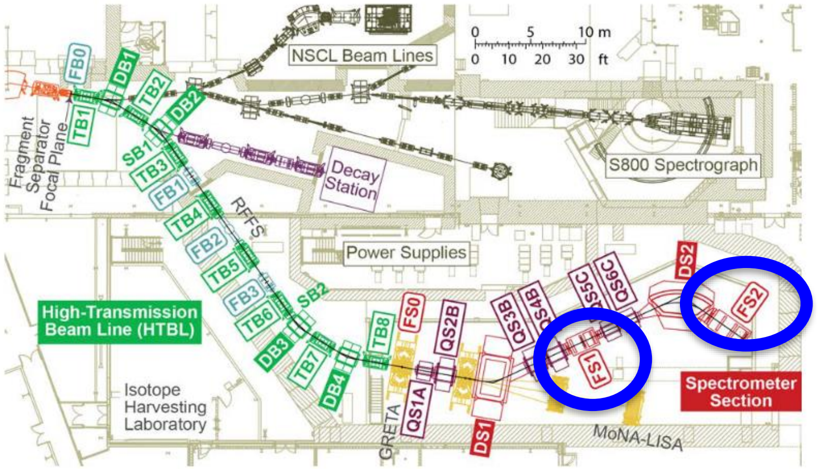


Science Opportunities at FRIB
with Fast, Stopped, Reaccelerated Beams

Different devices based on MPGD readouts: Tracking (drift chamber), TPCs, Fission Fragment detector …



High Rigidity Spectrometer (HRS)
Under construction



- FRIB is part of the RD51 collaboration since 2019
- FRIB charter member of the DRD1 collaboration

MPGD R&D for Nuclear Physics

The 2023 Long Range Plan for Nuclear Science, Section 9.8: Detector R&D

… *micropattern gaseous detectors (MPGDs)*, which are rapidly becoming the choice for cost-effective instrumentation of large-area detection and for continuous tracking of charged particles with minimal detector material. *More than 50 US research institutions are involved in MPGD development or activities for experiments in different fields of physics that would benefit directly from a novel US-based MPGD facility*. Several of these institutions are members of the European Organization for Nuclear Research (CERN)-based RD51 collaboration, which focuses on the advancement of MPGD technologies. *Although the US institutions have benefitted from the facilities at CERN, the community is growing swiftly and no such facility in the United States can accommodate this need* …

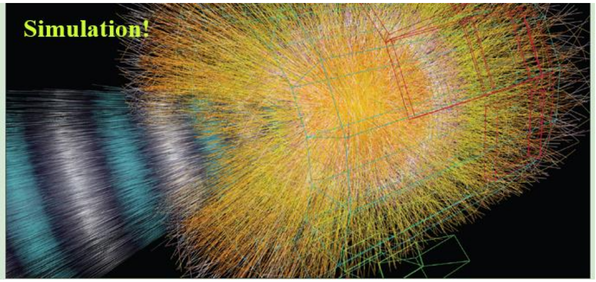
Approved by DOE & NSF Nuclear Science Advisory Committee (NSAC) on 10/4/2023

Tracking system for RIBs: requirements

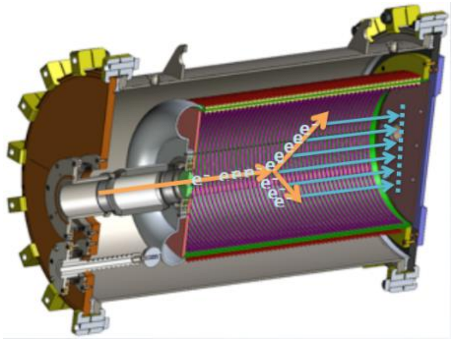
High-E Particle Physics

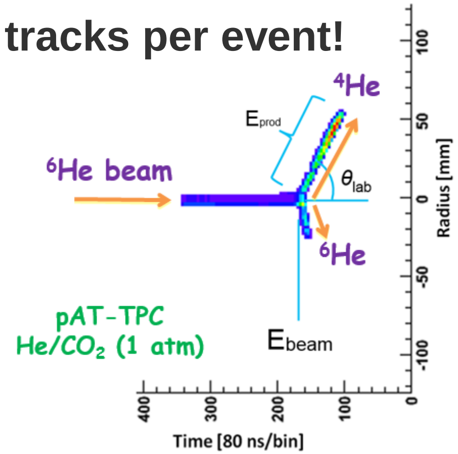
-) High gain (MIPs, Photons, etc.)
-) High Multiplicity
-) Specificity
-) High rate
-) Large & complex
-) IBF → mostly from the gas avalanche readout
-) …

LHC-ALICE ➔ Tens of thousand tracks per event!



pAT-TPC (NSCL) ➔ few tracks per event!





Ayyad et al. Eur. Phys. J. A (2018) 54: 181

Low-E Nuclear Physics

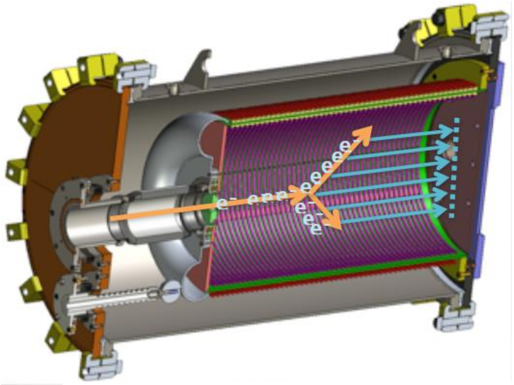
-) Modest gain (heavy charged particles)
→ different specific ionization density
-) Low Multiplicity
-) Versatility (one setup many experiments)
→ large dynamic range (different pressure)
→ active target mode (pure elemental gas)
-) Low/moderate rate
-) Small setup, simple
-) IBF → mostly from the beam particles
-) …

Applications: Reaccelerated Beams

Goal: Study of inverse-kinematic nuclear reactions

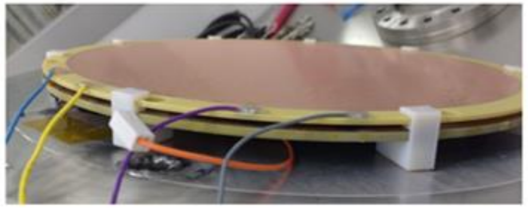
pAT-TPC

- Active volume 25 liters (L = 50 cm, Ø = 25 cm)
- Cylindrical pad plane (1,000 pads)

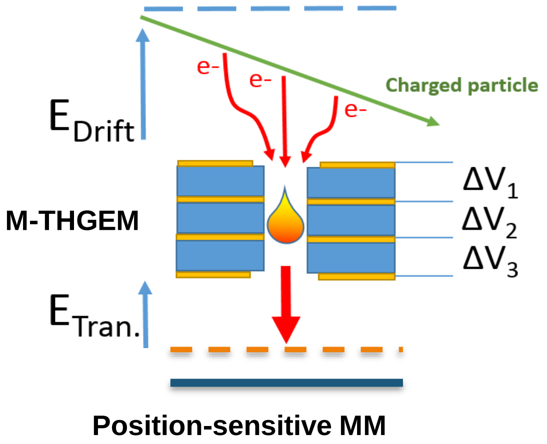


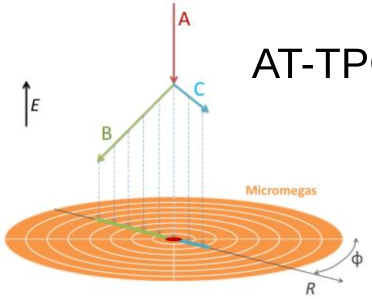
Full scale AT-TPC

- Active volume 200 liters (L = 100 cm, Ø = 50 cm)
- 10,240 triangular pads
- Placed inside 2 Tesla solenoid



Hybrid readout: Micromegas + THGEM-like structures





AT-TPC Readout pad → GET electronics

Cortesi *et. al.* EPJ Web of Conferences 174, 01007 (2018)

Ayyad et al. Eur. Phys. J. A (2018) 54: 181

Filling Gas/Target

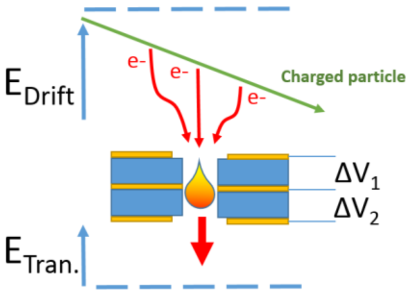
- **H_2 as proton target**
- **D_2 as deuteron target**
- **^{3}He as helion target**
- **^{4}He as alpha-particle target**
- **Others: CF_4, CO_2, etc.**

-) Purity (no quencher)
→ High Reaction Yield
-) Low-Pressure Operation
→ Large Dynamic Range

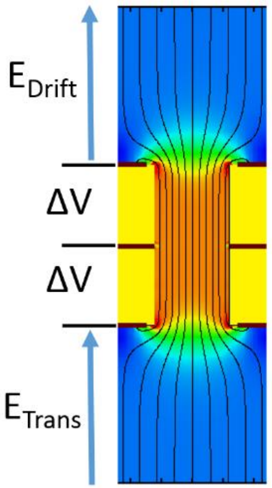
Gas Gain, Energy Resolution, Spatial Resolution, Counting Rate Capability, Stability etc…

Multi-Layer THGEM (M-THGEM)

Manufactured by multi-layer PCB technique out of FR4/G-10/ceramic substrate

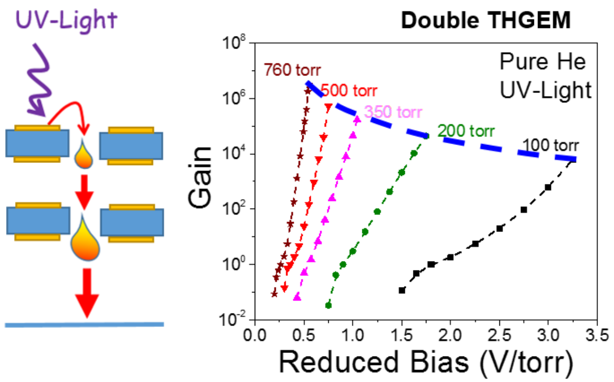


2-Layer M-THGEM

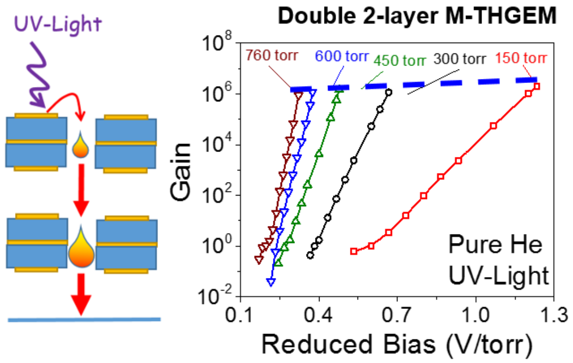


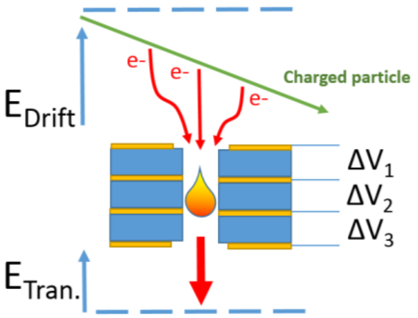
Low pressure

10x10cm² THGEM
(thickness = 0.6 mm, hole = 0.5 mm, pitch = 1 mm)

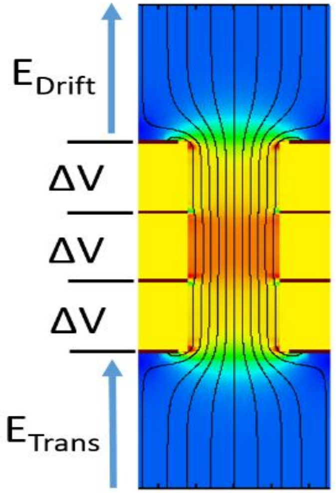


10x10cm² M-THGEM
(thickness = 1.2 mm, hole = 0.5 mm, pitch = 1 mm)





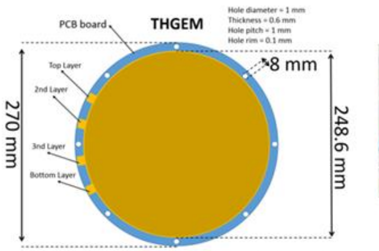
3-Layer M-THGEM

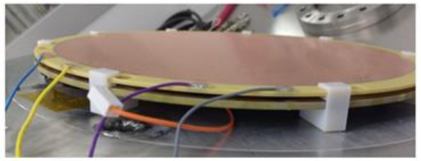


AT-TPC & pure gases

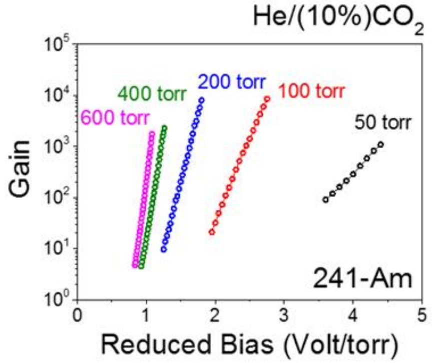
- -) No loss of charge ➔ high gain @ low voltage
- -) Robust avalanche confinement
  ➔ lower secondary effects
- -) Long avalanche region
  ➔ high gain @ low pressure
- -) Field geometry stabilized by inner electrodes
  ➔ reduced charging-up

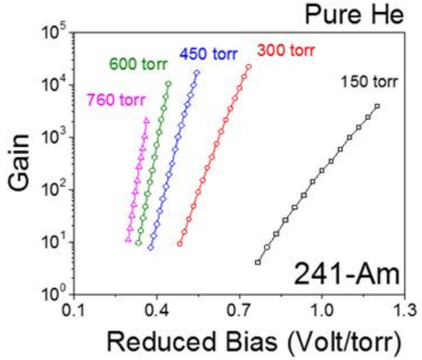
Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)





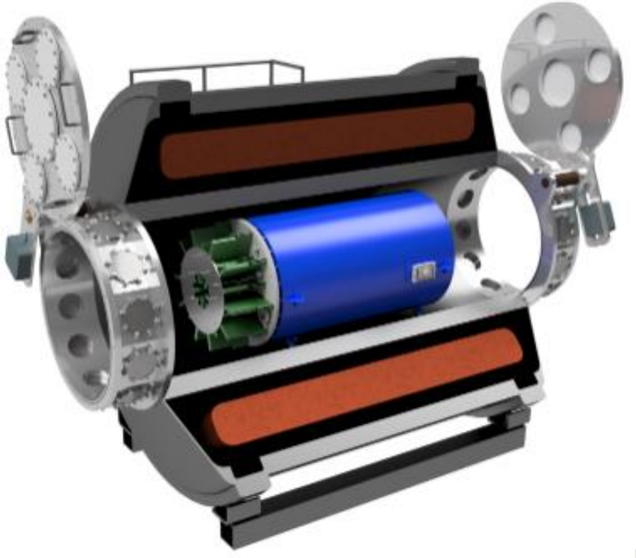
Single 3-layer M-THGEM



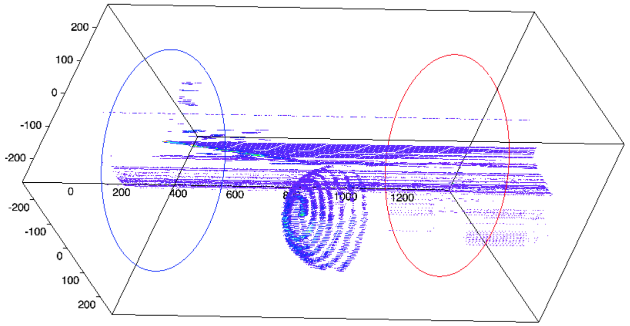


AT-TPC in pure elemental gas: recent results

SOLARIS (up to 4 Tesla)

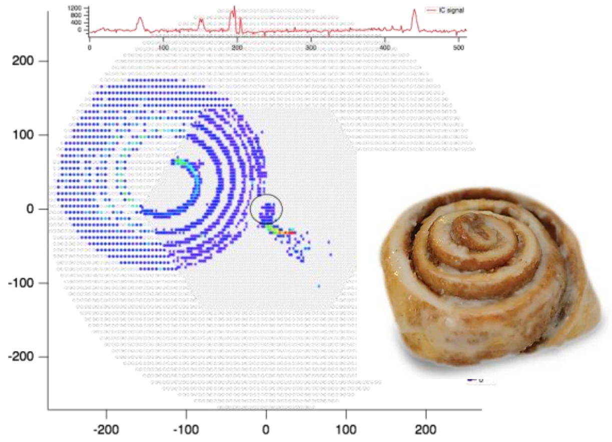


E20009 → pure D_2 (760 Torr)
$^{10}Be(d,p)^{11}Be$

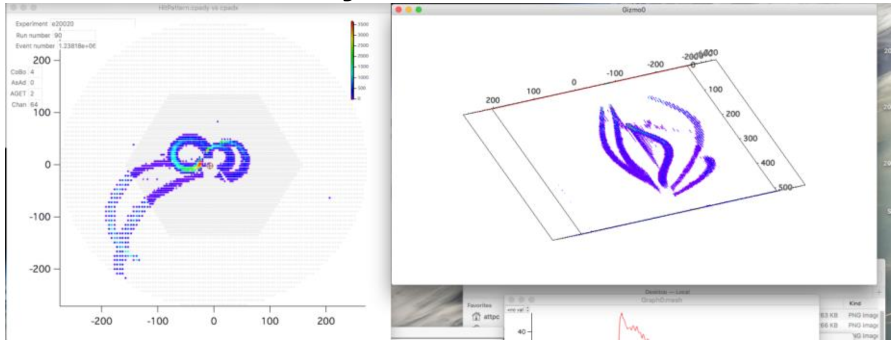


The cinnamon roll: 8 MeV p (5 m range)

Spokesperson: Daniel Bazin

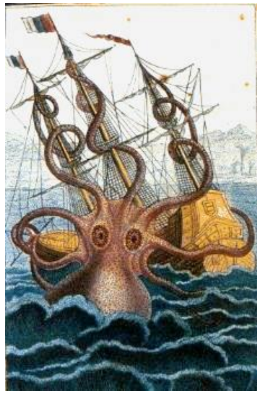


E20020 → pure He (700 Torr)
4 α decay of ^{16}O



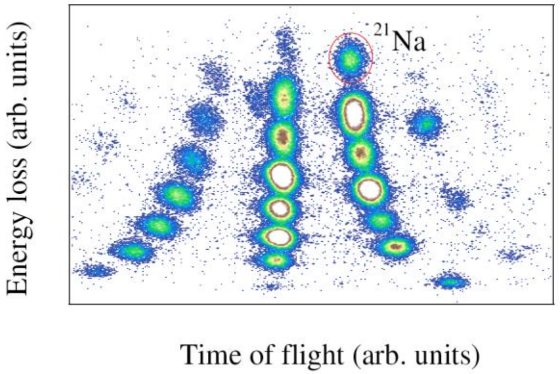
The big Kraken: 5 α-particle tracks

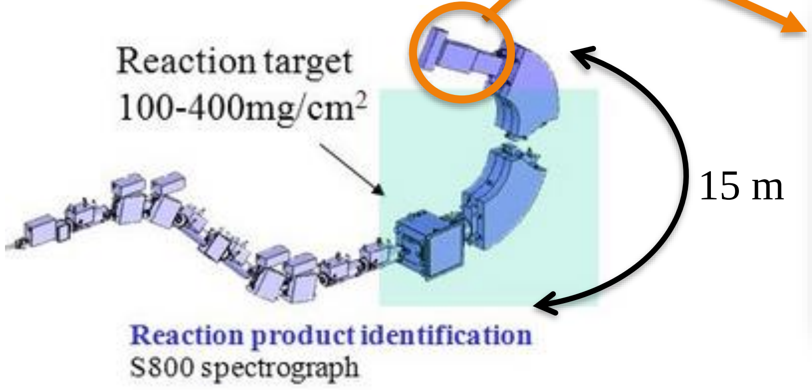
Spokesperson: Clementine Santamaria



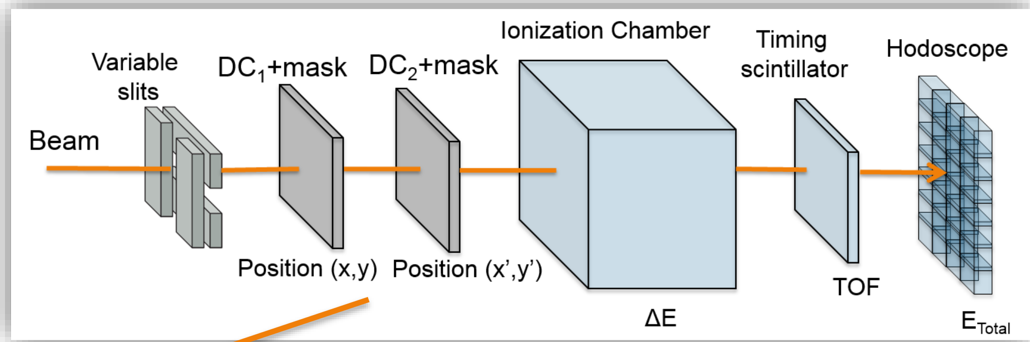
Fast-beam experiment with the S800

PID: Bρ-dE-ToF





Focal Plane detector system for heavy-ion PID

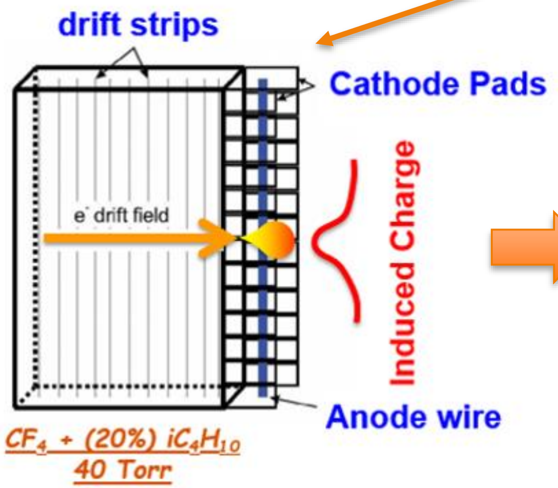


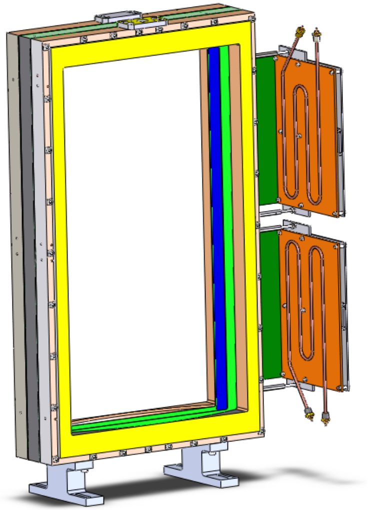
Cathode Readout Drift Chamber (CRDC):

Position and angles

Two CRDCs, 1 m apart, with 30x60 cm^2 effective area filled with CF4/(20%)iC_4H_{10}

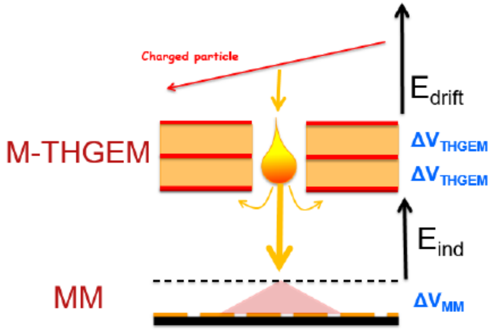
- -) *Slow detector → low rate (<5KHz)*
- -) *Position resolution → <1 mm FWHM*
- -) *Aging problems*



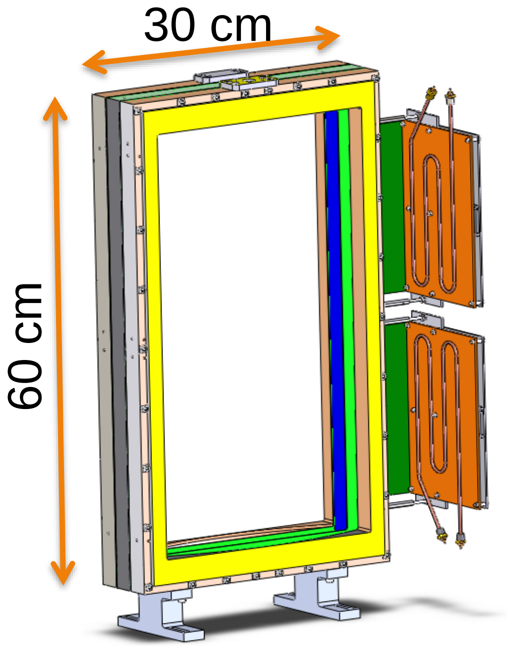


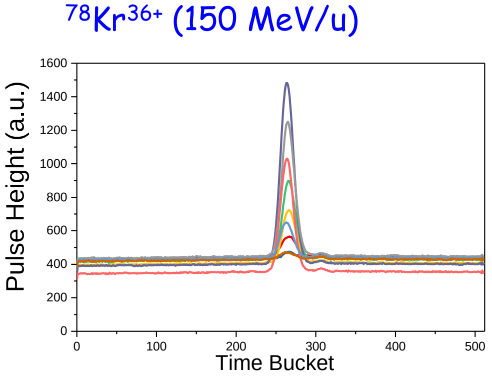
MPGD-based Readout

Position-sensitive Micromegas readout + 2L M-THGEM-based pre-amplification stage + GET front-end electronics



New MPGD-based Tracking System Performance





DAQ Based on the GET electronics fully integrated into the FRIBDAQ

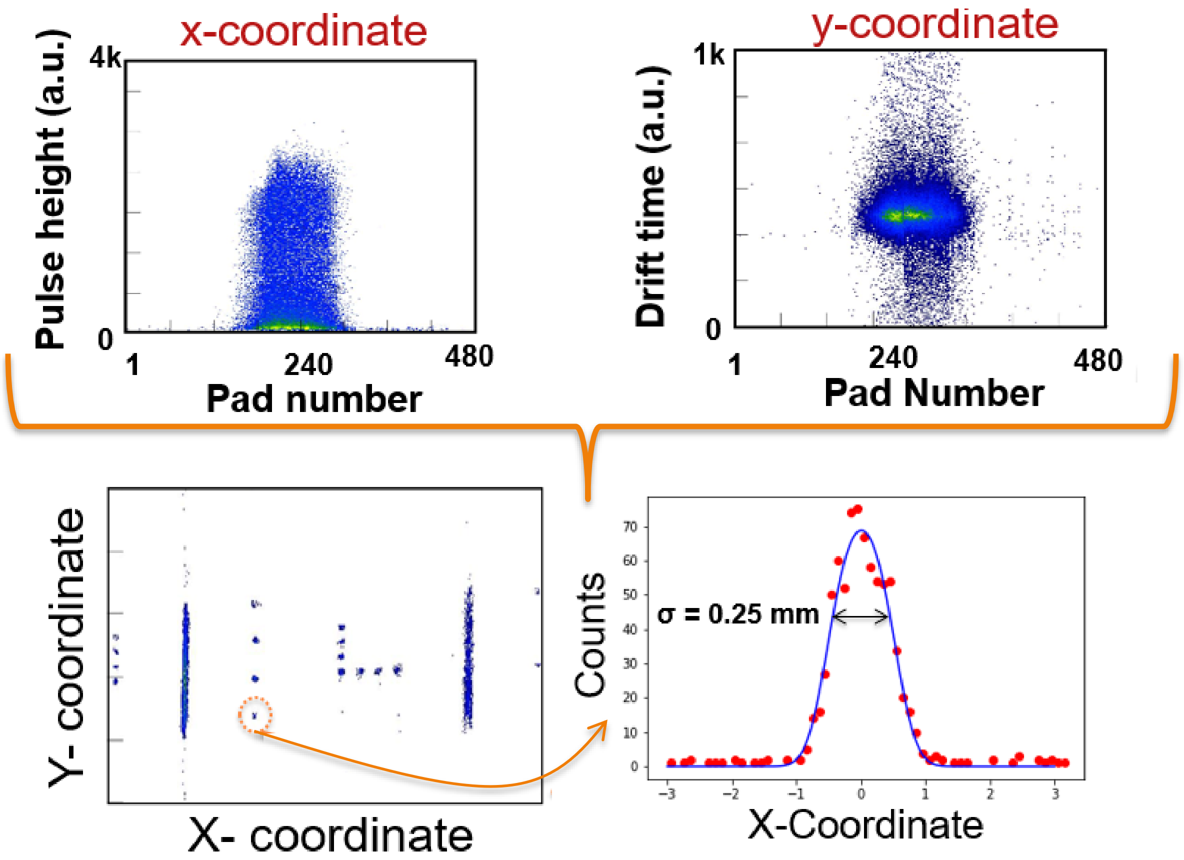
- Number of samples (up to 512 time "buckets")
- Clock "sampling" frequency (time/sample)
- Peaking time; gain

M. Cortesi *et al.*, 2020 JINST 15 P03025

HITMAKER:
baseline + parabolic fit

-) Pulse Height
-) Peak location (time)

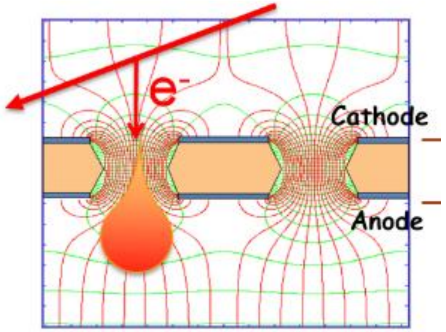
X ➔ charge distribution (center of the gravity)
Y ➔ Arrival time (external trigger)



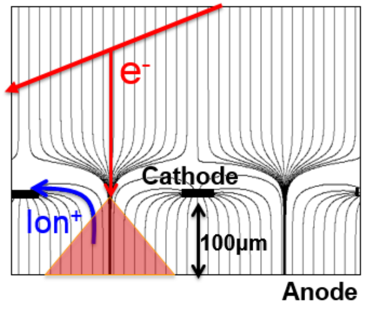
-) **Simple & robust Assembly ➔ No aging problems expected**
-) **Better ions-backflow suppression**
-) **High detector gain @ low pressure (MM+THGEM) ➔ large dynamic range**
-) **High counting rate (up to 20 kHz) ➔ faster electronics + Multi-hit capability**
➔ expected up to 3 time lower dead time
-) **High granularity: 480 pads along the 60 cm dispersed beam coordinate**
all pad are readout individually ➔ better position resolution (0.25 mm σ)

WAR FOR THE THRONE

Love in the time of … MPGDs

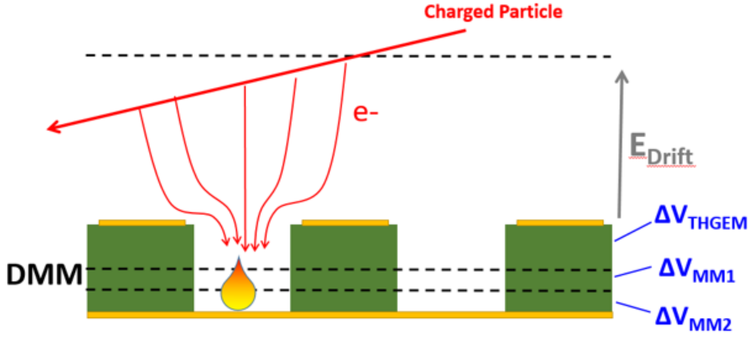


Hole-type Multi-layer
as mechanical support



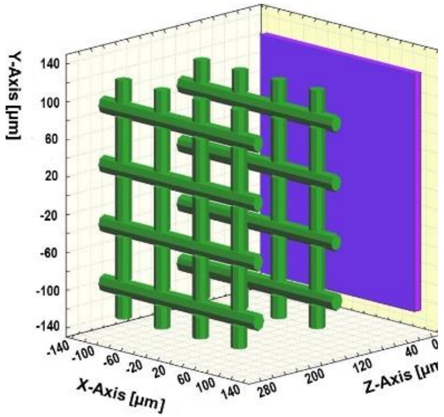
Amplification in Meshes

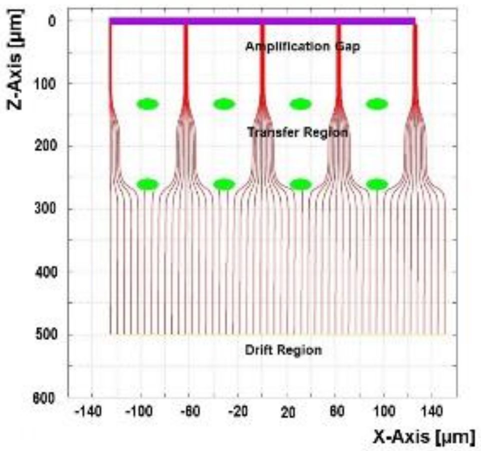
De Olivera & Cortesi 2018 JINST P06019

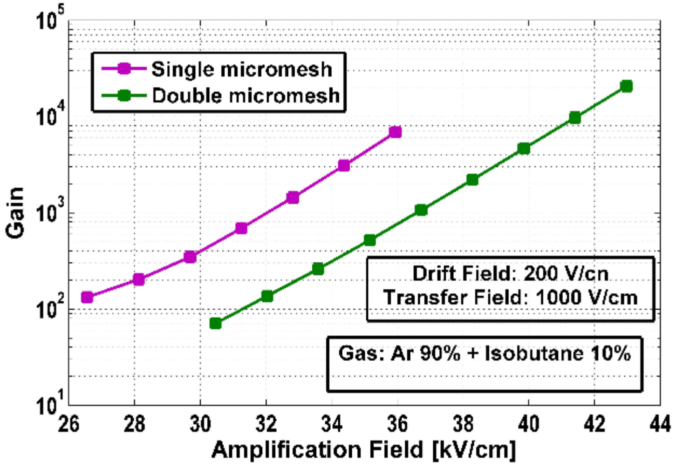


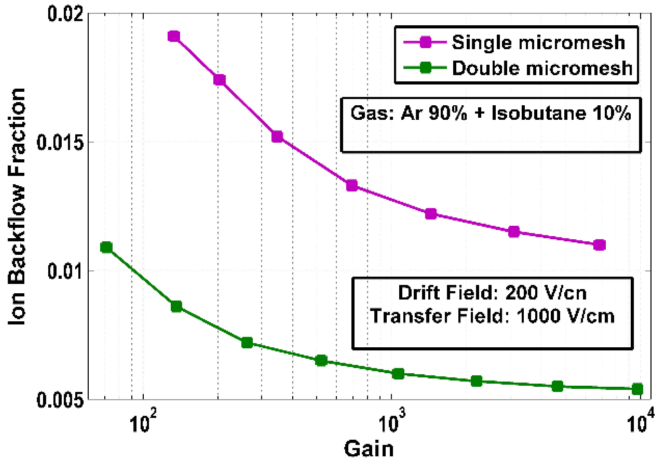
Multi-Mesh THGEM

P. Bhattacharya et al 2015 JINST10 P09017







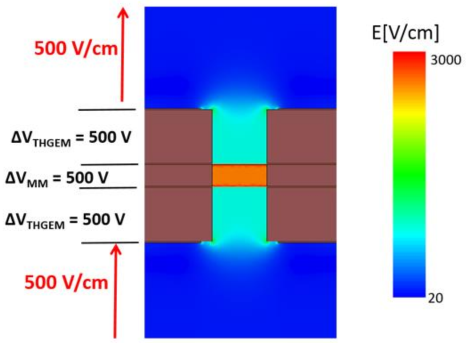


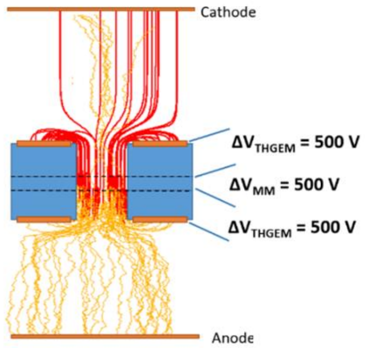
DMM → larger gain, lower IBF, Mechanical stability of DMM over large area?

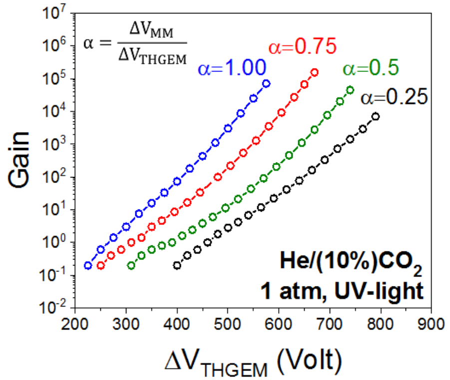
The Multi-Mesh THGEM: performance

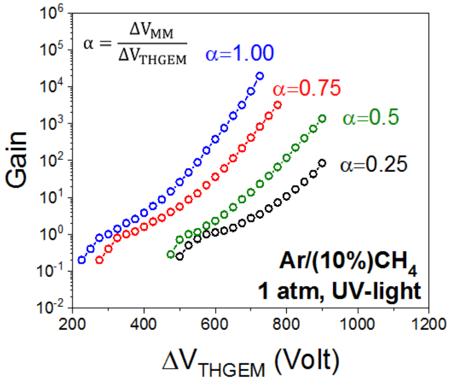
De Olivera & Cortesi 2018 JINST P06019

Maxwell-Garfield Simulations



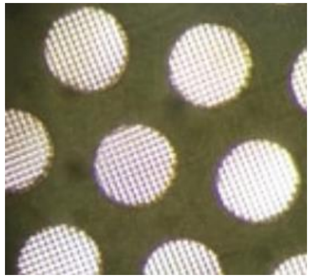


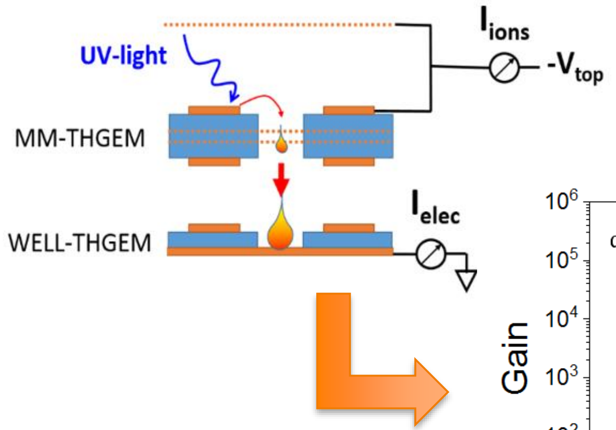




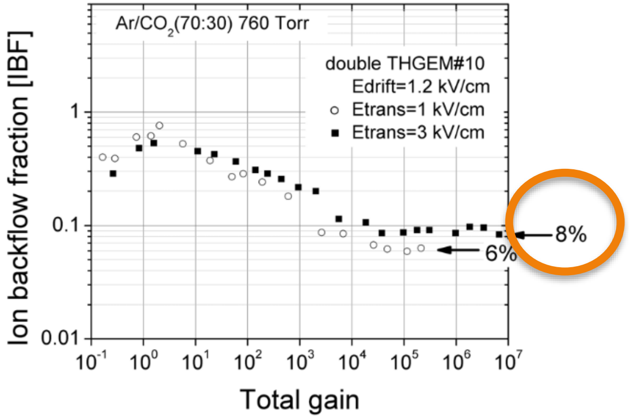
Advantages:
-) Uniform avalanche field
-) Lower Ion backflow
-) DMM over large area

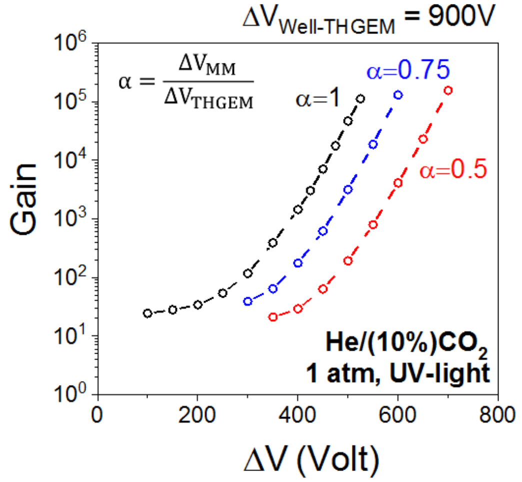
Disadvantages:
-) Loss of e- transfer efficiency
➔ moderate E resolution

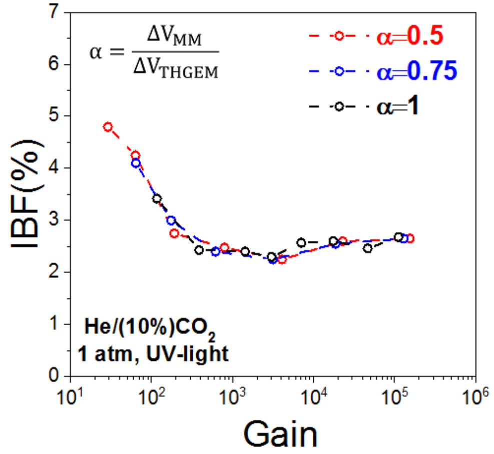




C. Shalem et al. NIM A558 (2006) 475-489





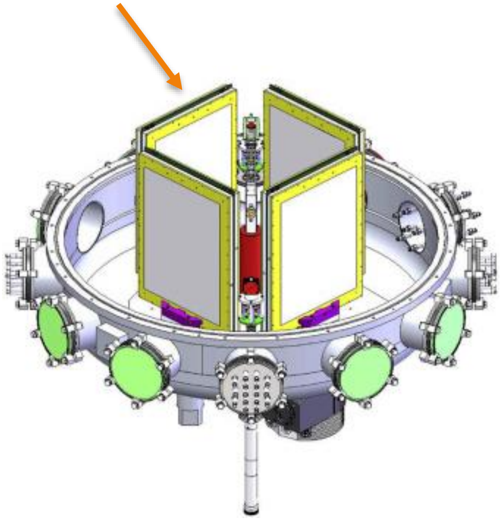


-) High effective (single photoelectron) gain (> 10^5) with single element
-) Higher gain with small pre/post avalanche multiplication (α=1)
-) Higher stability and higher max achievable gain at lower operational voltage

MM-THGEM for Fission Fragment Study

- Goal: Understand Fusion-Fission and quasi-Fission reaction mechanisms → production of super-heavy elements

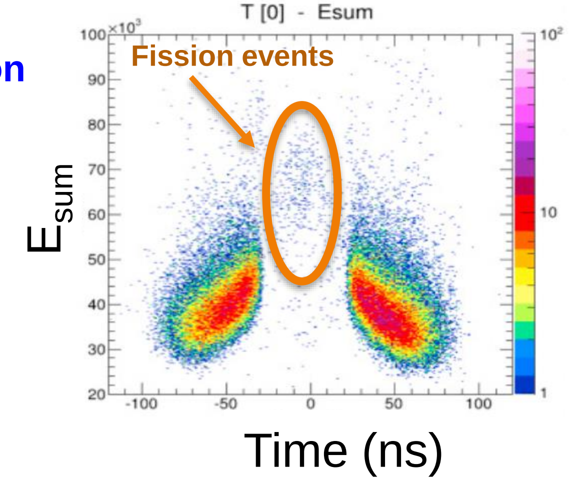
Heavy-ion Imaging system:
Velocity vector
→ Mass/Angle distribution

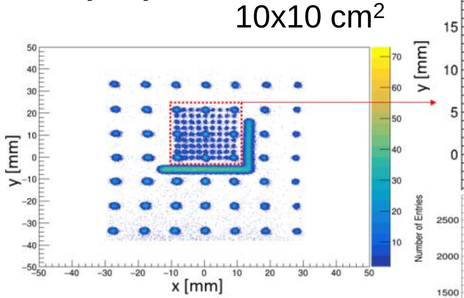


PPAC Problems
-) Large area → Fragile, difficult to maintain
-) Poor spatial resolution ~ 4 mm (FWHM)
-) Modest rates (up to a few kHz)

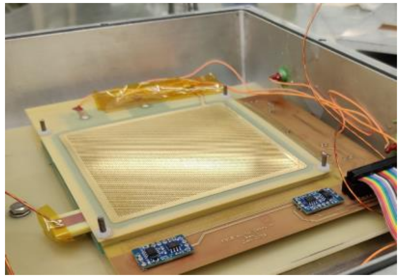
→ Test new technology to improve resolution

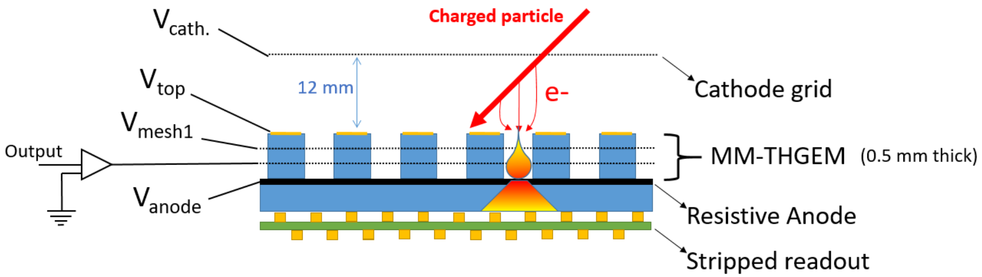
PPAC-based tracking system



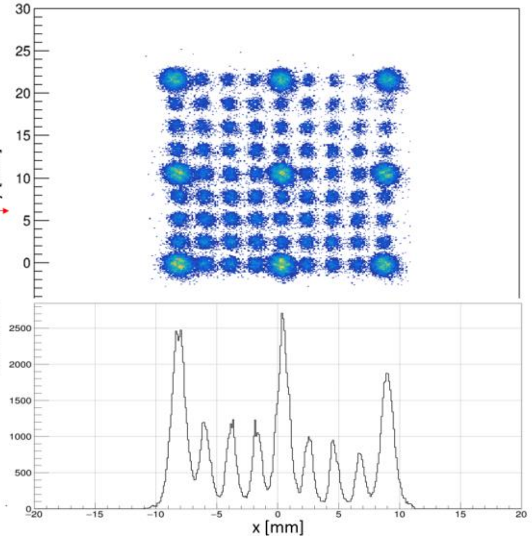


MM-THGEM imaging detector prototype (10x10 cm^2)

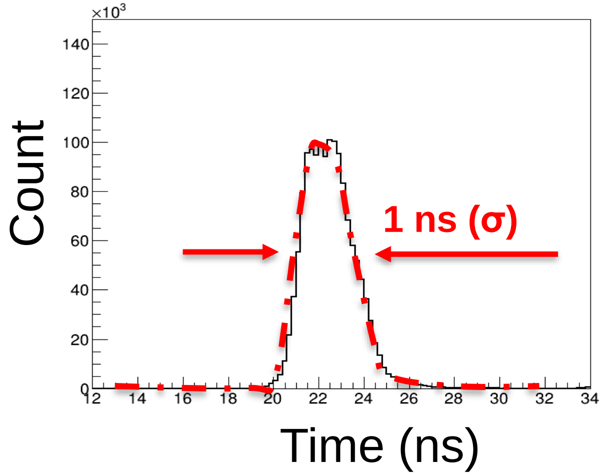




Isobutane (7 Torr)



Performance:
-) Spatial Resolution < 0.5 mm (σ)
-) Time resolution ~ 1 ns (σ)



Summary

-) Exciting New Science opportunities from World-Class Equipment with Radioactive Isotope Breams

-) MPGD mostly driven by HEP applications while RIBs experiments have different requirements
→ **new MPGD architectures!**

-) R&D on new/upgrade of existing detector systems:
focal-plane Bρ measurements, (AT-)TPC, FF study, low-material budget tracking …

-) **M-THGEM: first MPGD specifically conceived for applications in Low-E NP**
→ stable high-gain operation at different pressure in pure elemental gas!

-) Presented preliminary results of a derived multi-layer structures, MM-THGEM

MM-THGEM, M-THGEM applications beyond NP: optical readout or rare event searches,
negative-ion TPC, gaseous photomultiplier, neutron imaging detection,
charge/light multiplier double-phase LAr/LXe TPC

M-THGEM-like scheme: the TIP-Hole structure

AT-TPC approved experiments:

E15328-NSCL:

Measurement of ANC of ^{12}N(p,γ)^{13}O relevant for the r-process study
Spokesperson: J. Pereira (NSCL).

E534-RCNP:

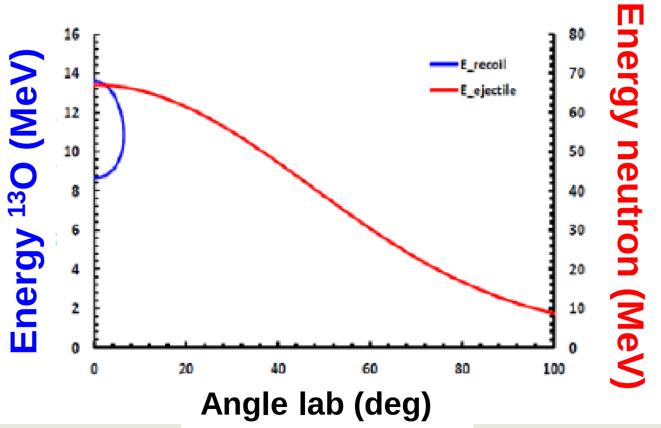
Spectroscopy of ^{18}C: single-neutron transfer ^{17}C(d,p)
Spokesperson: B. F. Dominguez (University of Santiago de Compostela).

E535-RCNP:

Study of the ^{13,15}B(d,^{3}He)^{12,14}Be transfer reactions
Spokesperson: Augusto Macchiavelli (LBL).

Requirements ***→ Deuterium target: Stop the reaction products in the AT-TPC***

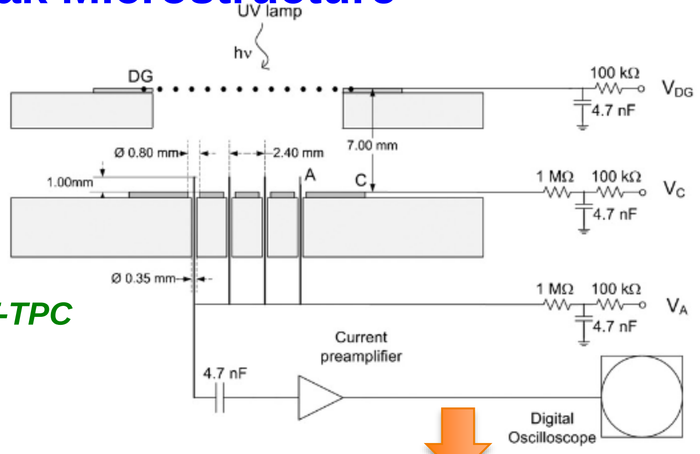
Example: study of ^{12}N(d,n)^{13}O reaction to constrain ^{12}N(p,γ)^{13}O via asymptotic normalization coefficient (ANC) method with 15 MeV/u ^{12}N beam on deuterium or deuterated target.

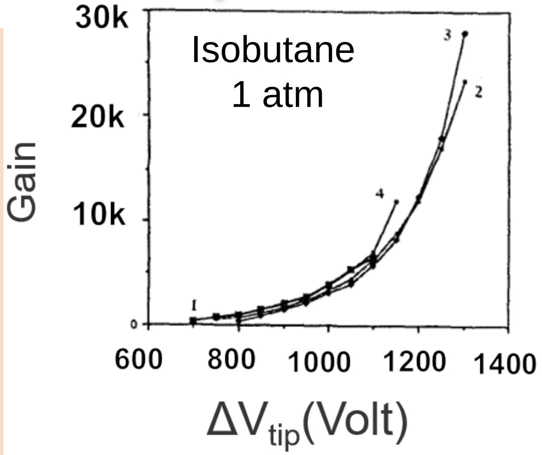


Cannot detect the neutron!
Kinematic variables and PID derived by tracking & stopping the recoiled ^{13}O
→
AT-TPC operated in iC$_4$D$_{10}$ @ atmospheric pressure

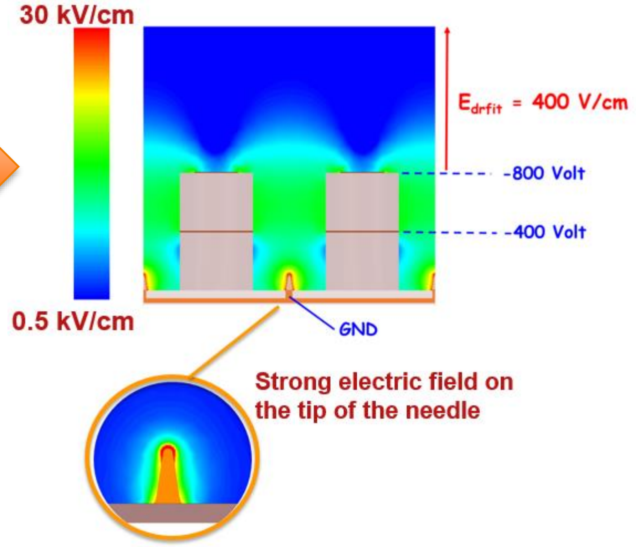
Lombardi et al. 1996 IEEE Conf. Rec., pg. 603-607

Leak Microstructure





M-THGEM + Tip anode



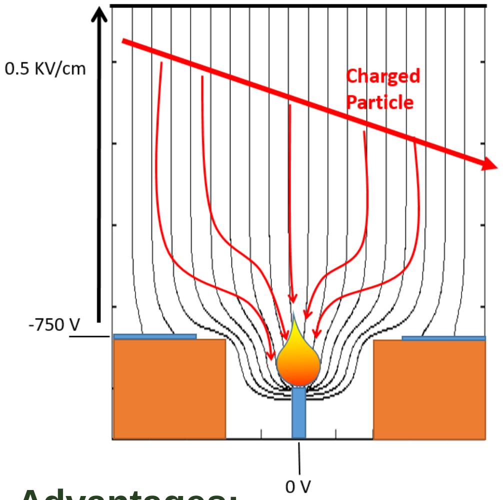
New Concept: Electrons focused in the hole-type structure, pre-amplified along the multi-layer THGEM and multiplied by gas-avalanche process in the proximity of the anode tip.

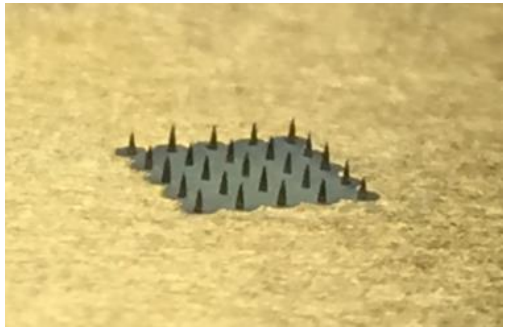
TIP-Hole prototype

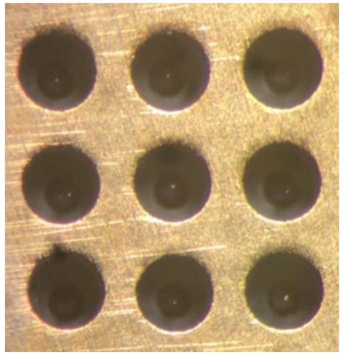
The first "homemade" prototype successfully operated at different pressures in P10

5x5 needles TIP-HOLE detector

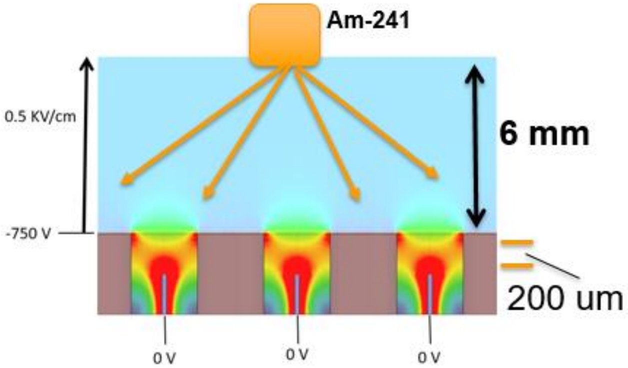
J. Randhawa & AT-TPC (MSU) undergraduate students







Tattoo Needle (Nickel): Size 00

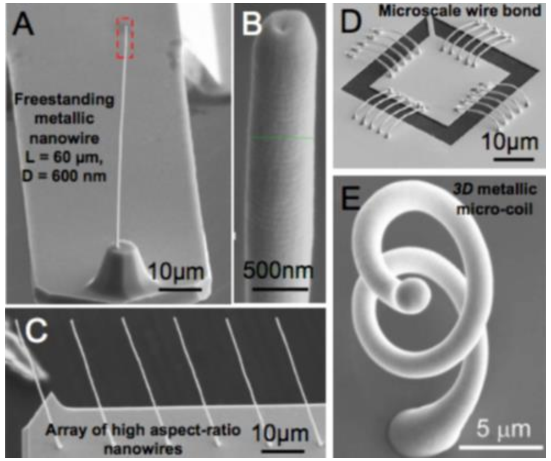


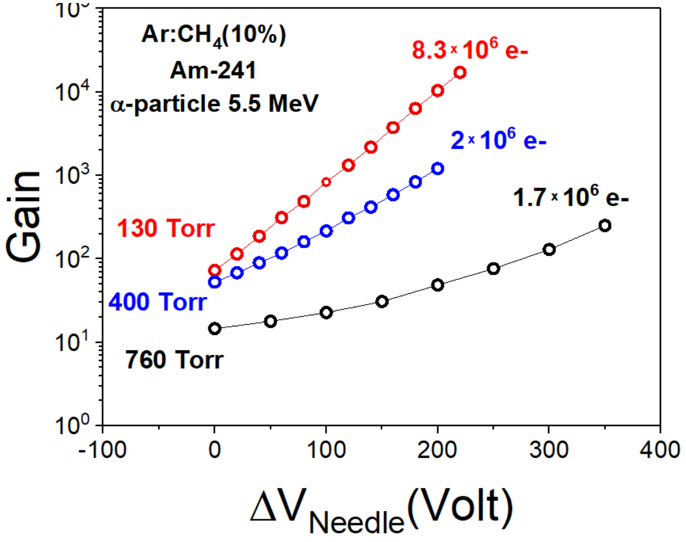
Advantages:

-) Multi-stage amplification ➔ large gain at low pressure

-) High amplification in pure quencher (iC_4H_{10}, propane, …)

-) Close geometry ➔large versatility



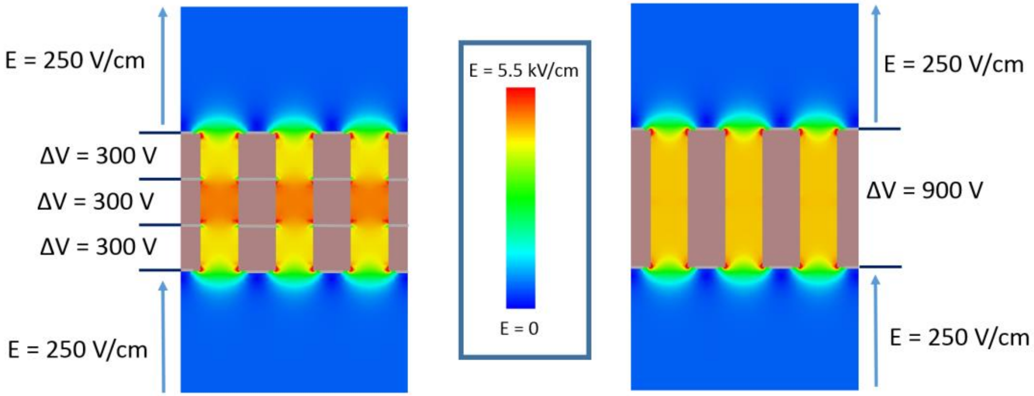


Path Forward ➔ develop large-area production technology

-) room temperature 3D printing technology for PCB

-) Microvia PCB fabrication technique

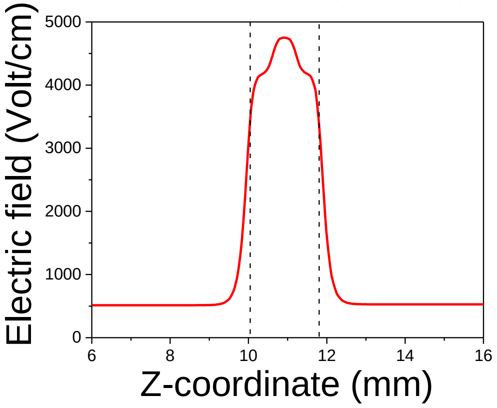
Three-Layer M-THGEM vs Single-layer THGEM



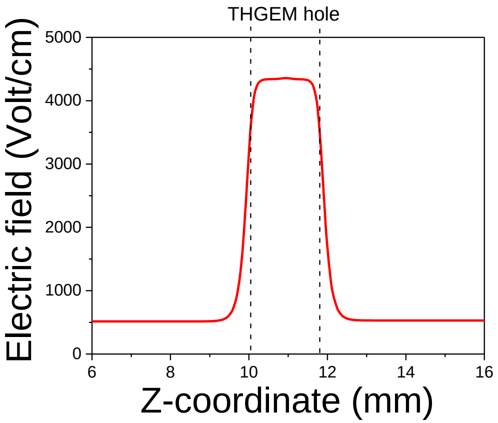
-) Amplification "condensed" in the inner volume of the hole
-) Lower energy released during discharges & lower probability to damages

Lower photon-mediated secondary effects in pure elemental gas at low pressure

M-THGEM hole



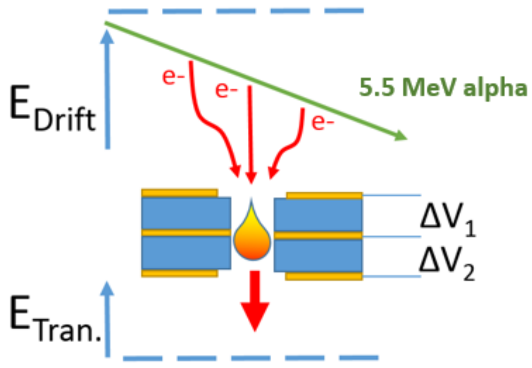
THGEM hole



Long-term gain stability of Ceramic M-THGEMs

Two-layer ceramic M-THGEM

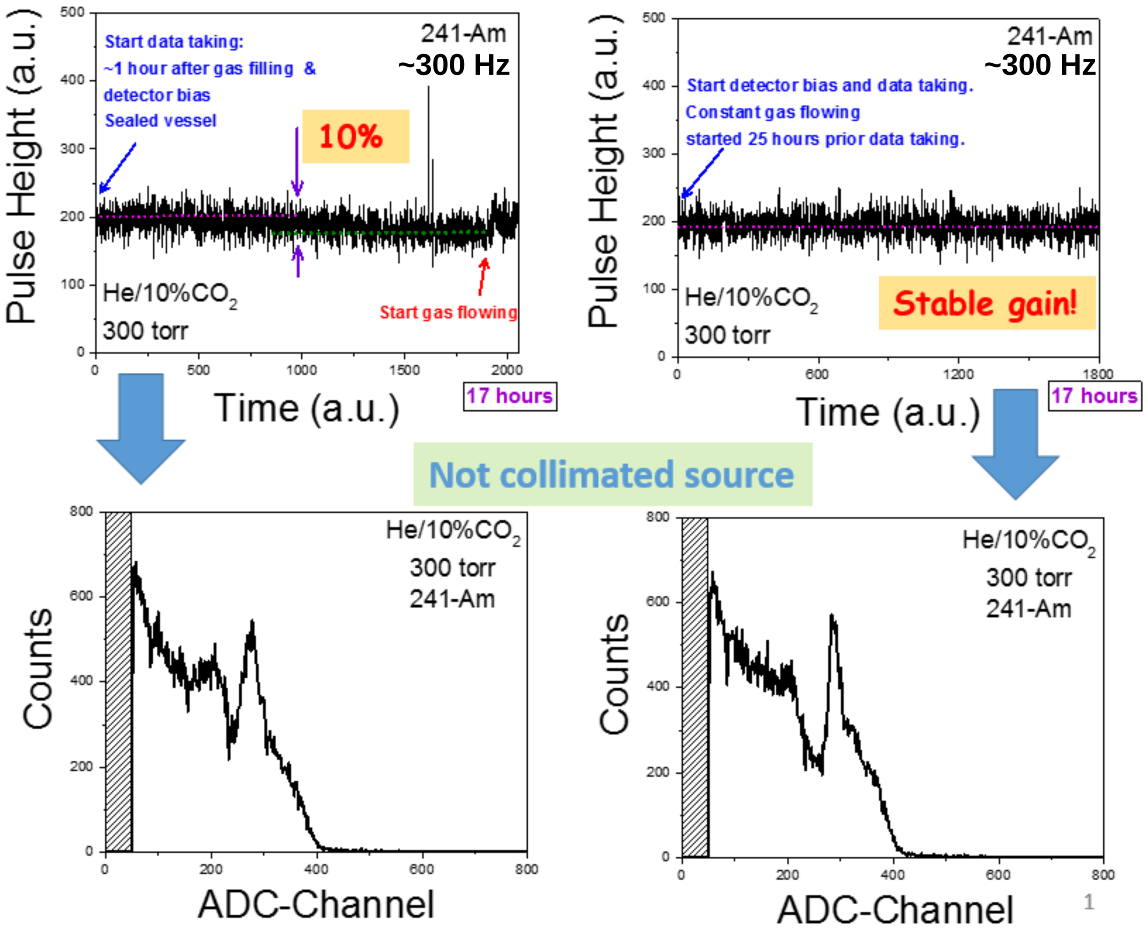
10x10 cm² prototype
12 mm drift ➔ E_{Drift} = 1 kV/cm
3 mm trans. ➔ $E_{trans.}$ = 0.33 kV/cm
$\Delta V_{M\text{-}THGEM}$ = 480 Volt
Counting rate ≈ 700 Hz



2-layer THGEM

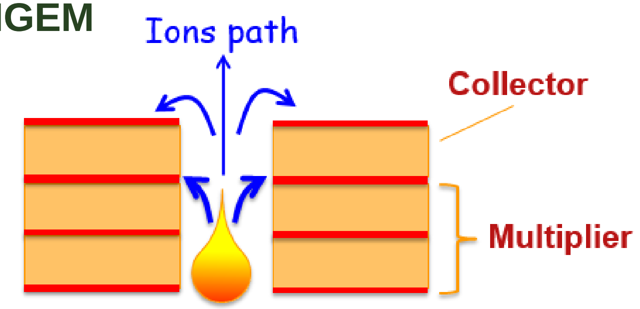
No significant charging up effect at low rate!

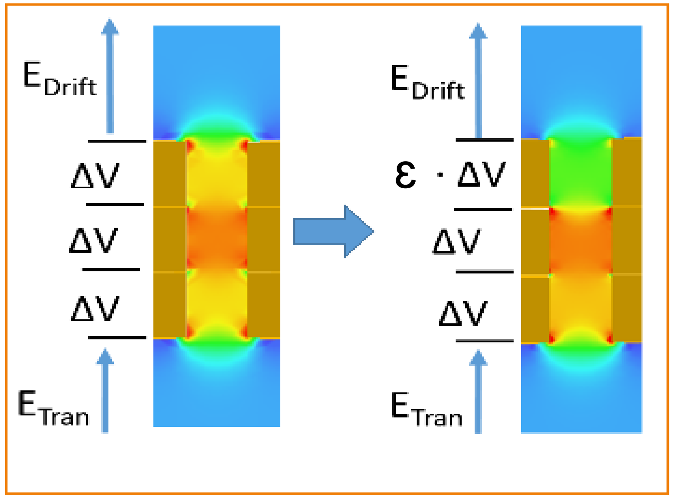
Each point is the average of ≈150 recorded pulse (1 pulse/sec)



Asymmetric bias mode

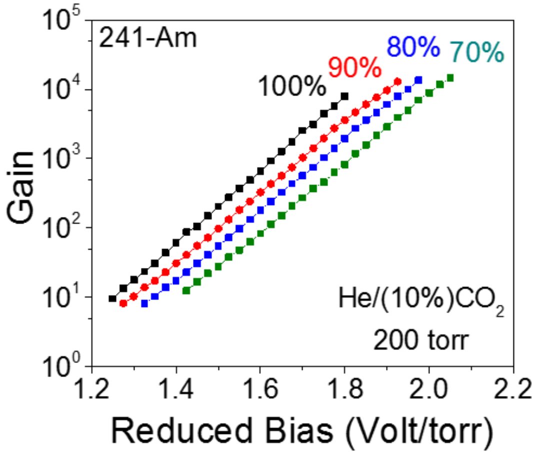
3-layer M-THGEM

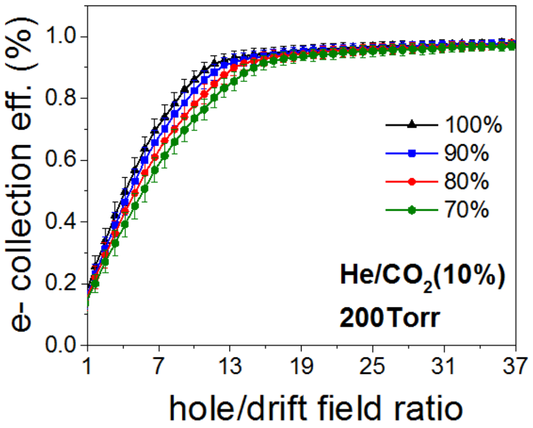


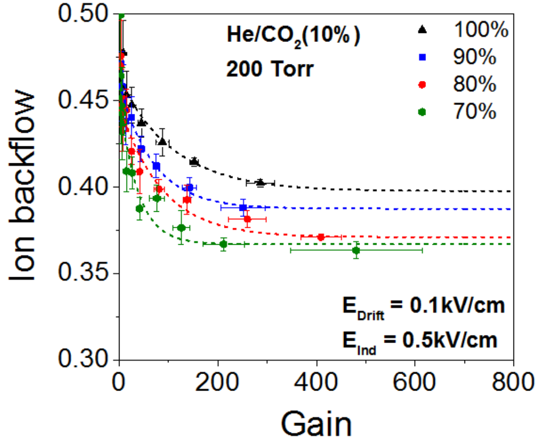


Strategy ➔ Stop ions in asymmetric setup
Problems: energy resolution? Effective gain?

Garfield – Stefan Rost







Same Max achievable Gain!

No significant loss of e- collection efficiency

Lower ion backflow with cascade configurations