A progress report on development of Multi-layer THGEM readout structures

Marco Cortesi
Detector System, Group Leader
cortesi@frib.msu.edu

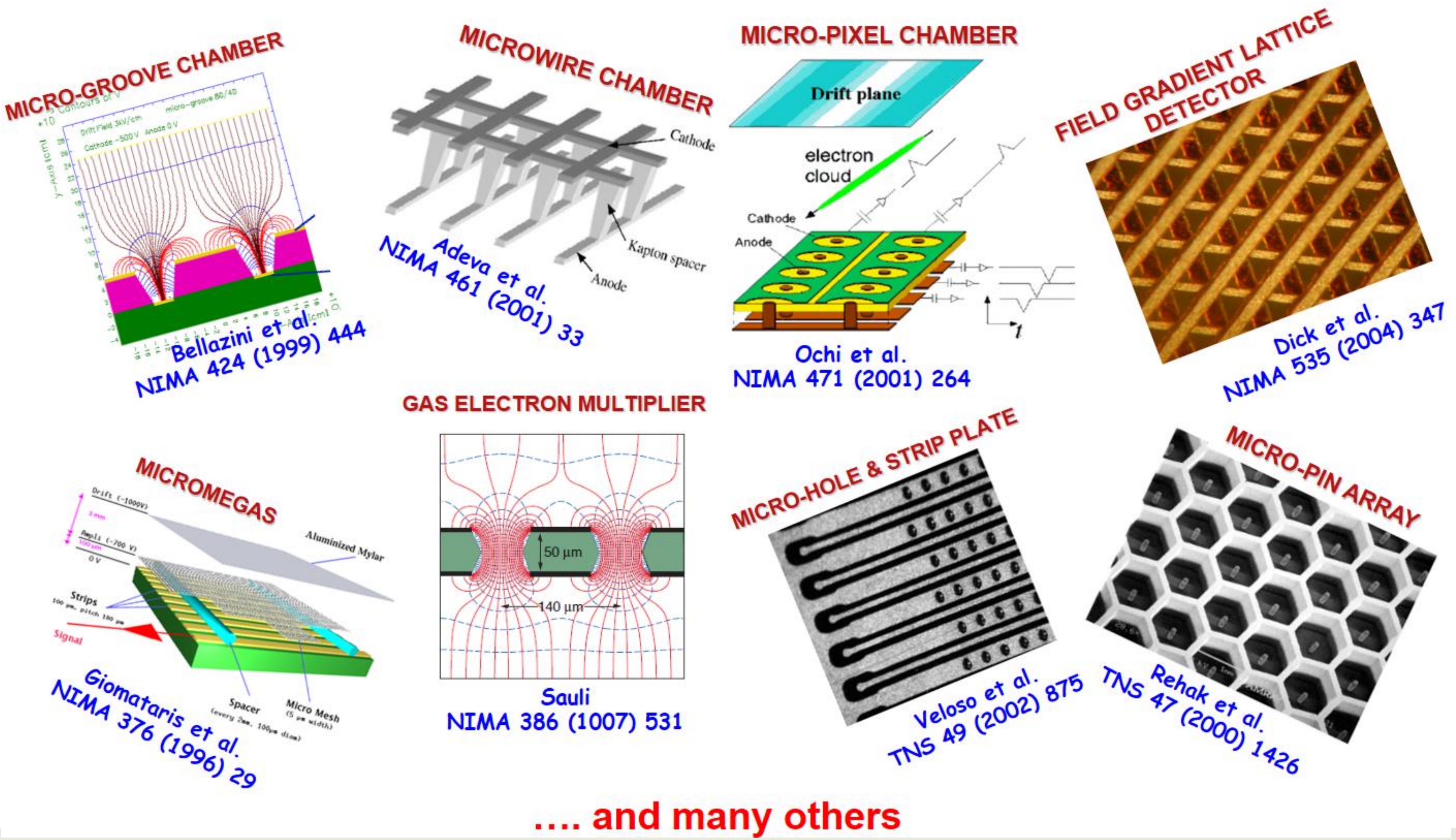
29 November 2023

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

Dec. 13 2023
Wednesday 5 PM

Dec. 14 2023
Thursday 9 AM

Micro-Pattern Gaseous Detector: a HEP R&D domain

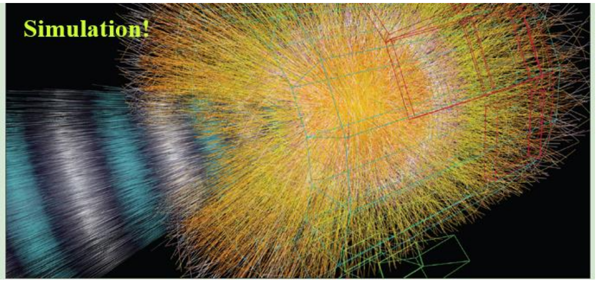


Tracking system for RIBs: requirements

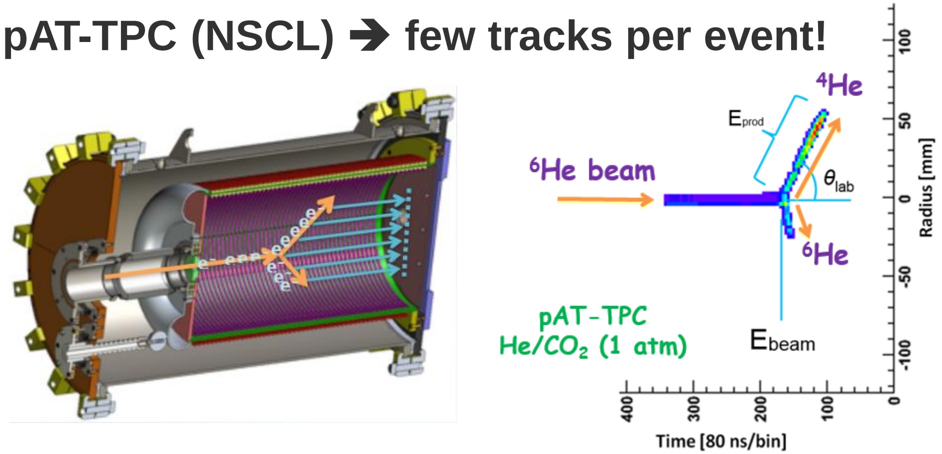
High-E Particle Physics

-) 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
-) …

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* …

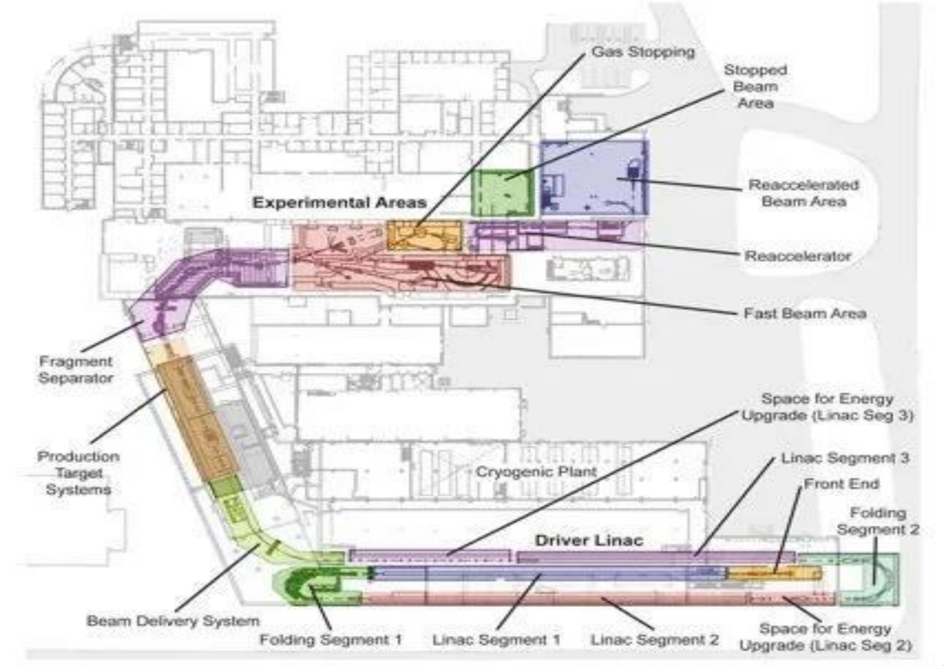
Approved by DOE & NSF Nuclear Science Advisory Committee (NSAC) on 10/4/2023

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

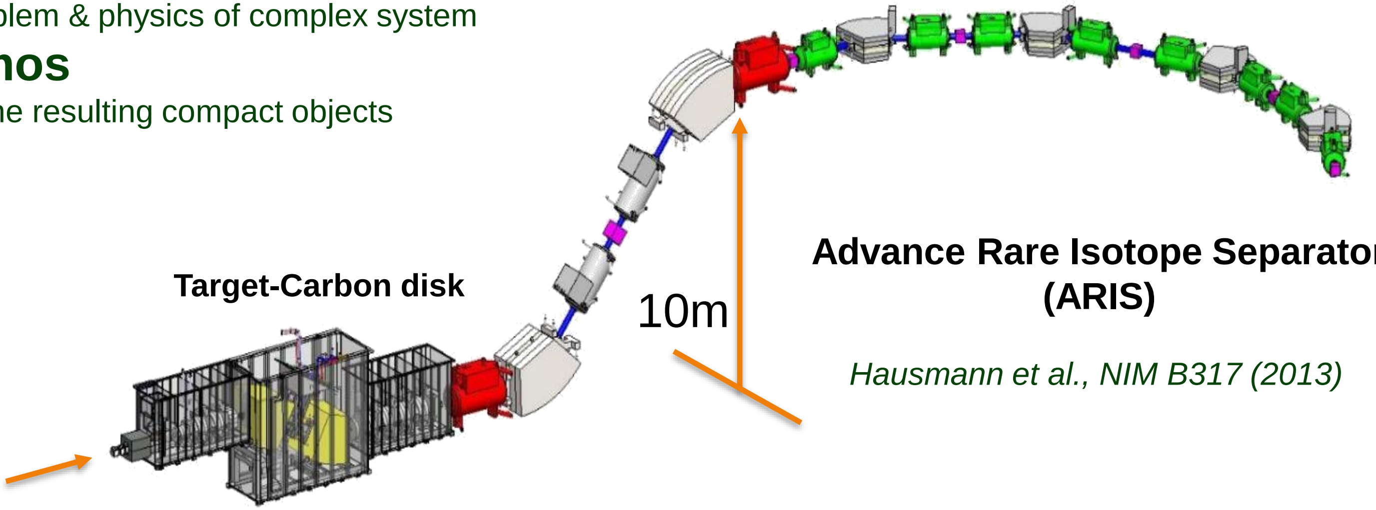
FRIB provides access of 80% of all atoms predicted to exist in nature

- Isotope harvesting capability from beam dump water



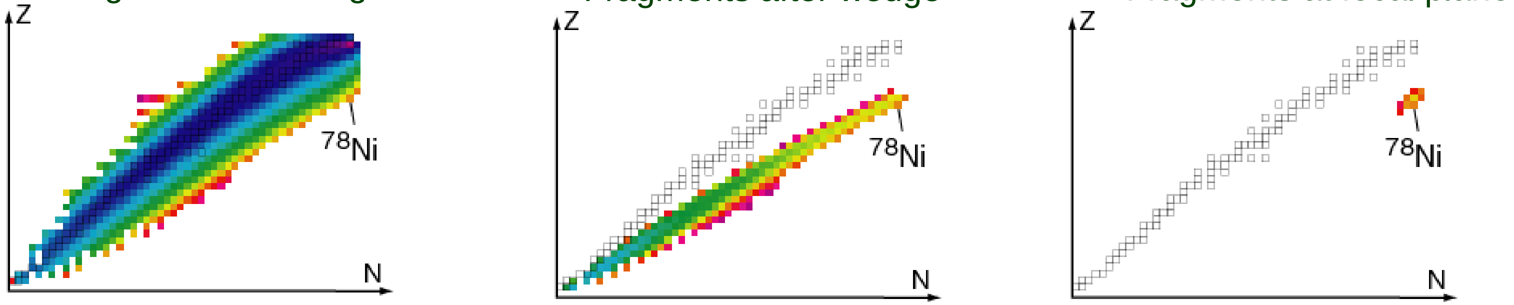
FRIB Enables Scientists to Make Discoveries in Four Areas

- **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.



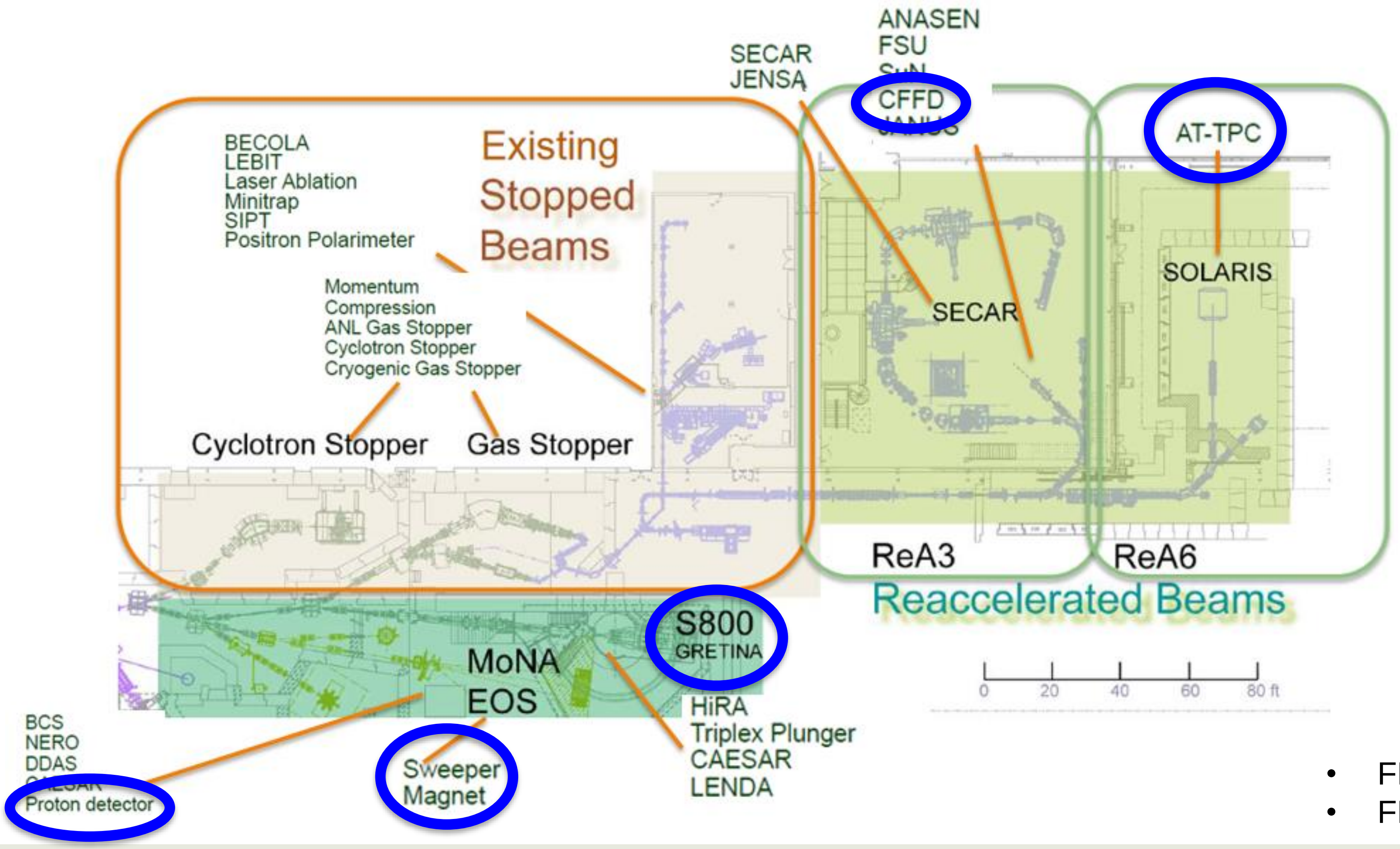
Example:
^{78}Ni from ^{86}Kr at 200 MeV/u

Three-stage separation, approximately 90 m long

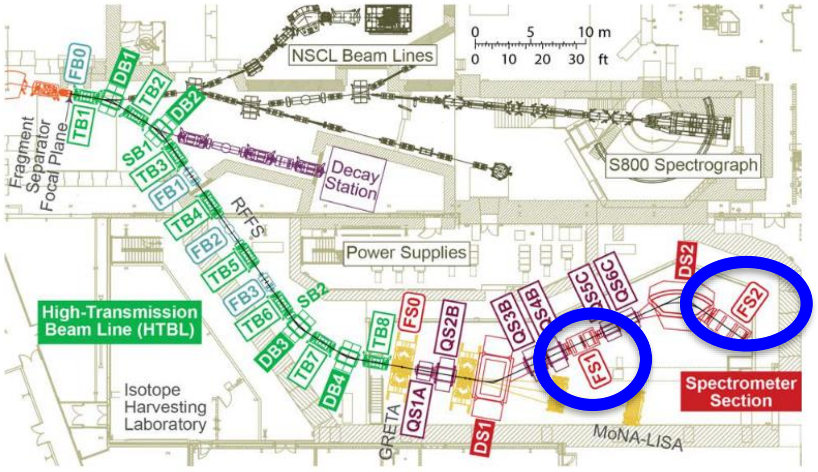


Science Opportunities at FRIB
with Fast, Stopped, Reaccelerated Beams

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



High Rigidity Spectrometer (HRS)
Under construction

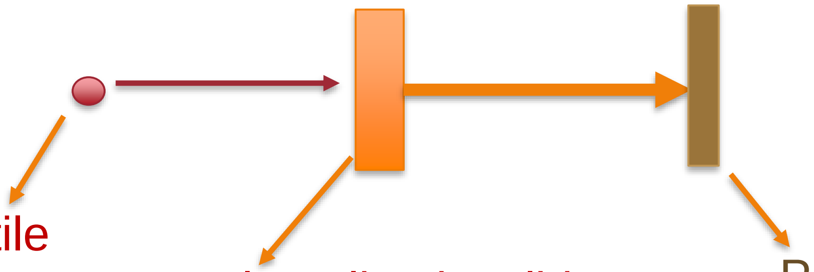


- FRIB is part of the RD51 collaboration since 2019
- FRIB charter member of the DRD1 collaboration

Inverse Kinematic with gaseous detector targets

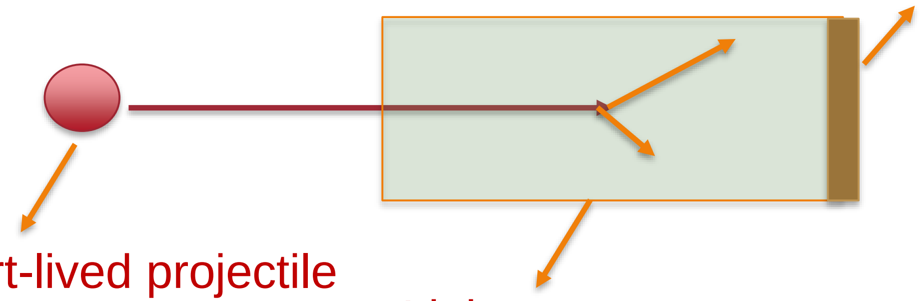
Goal: Study of inverse-kinematic nuclear reactions with resolutions equal to the one achieved in direct kinematics with high-resolution spectrometers + higher efficiency & thicker targets

Direct Kinematic



- -) Thin Targets (low luminosity, low straggling, good ΔE/E)
- -) Thick Targets (high luminosity, high straggling, poor ΔE/E)
- -) Small acceptance angle
- -) low energy event trapped in the target

Inverse Kinematic (AT-TPC) → ***gas is simultaneously the target and the tracking medium***



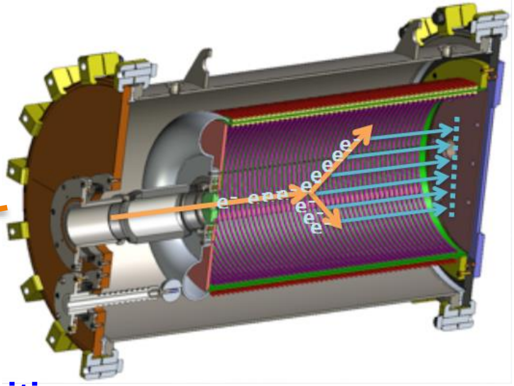
- -) 4π acceptance of reaction products
- -) Energy loss like thin target = excellent ΔE/E
- -) Very high effective thickness ➔ high luminosity
- -) Detection efficiency ~100% (+ low energy events)
- -) Event-by-event reconstruction in 3 dimensions
- -) Different target pressure ➔ Large dynamic range

Active-Target TPC @ Facility for Rare Isotope Beams (FRIB)

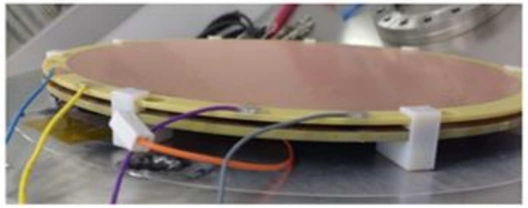
Cylindrical configuration:
Use with solenoid
➔ Magnetic field for PID

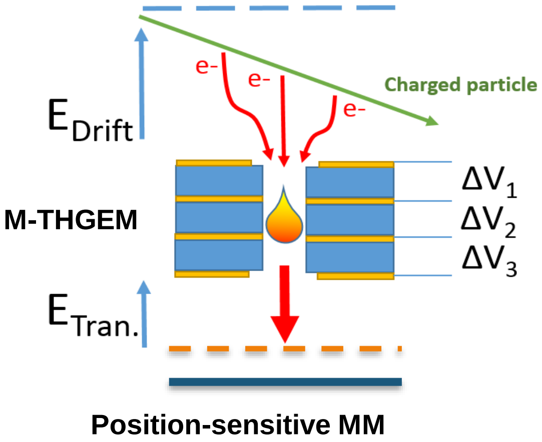
Problem:
Need to suppressed beam!
➔ Smart-ZAP

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



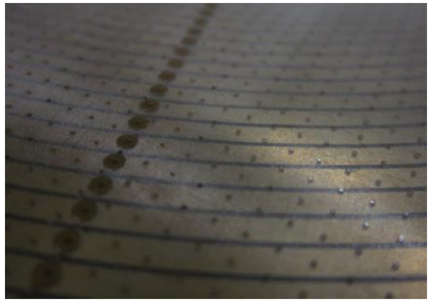
Full scale AT-TPC
- Active volume 200 liters (L = 100 cm, Ø = 50 cm)
- 10,240 triangular pads
- Placed inside 4 Tesla solenoid

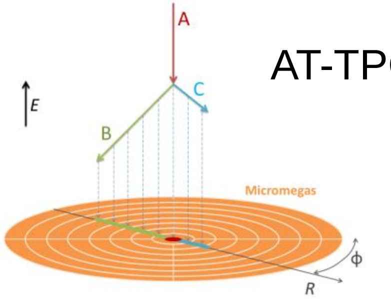




Field Cage

Position-sensitive micromegas pad





AT-TPC Readout pad → GET electronics

Gain Provided mainly by M-THGEM
Position-sensitive MM for track encoding

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

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

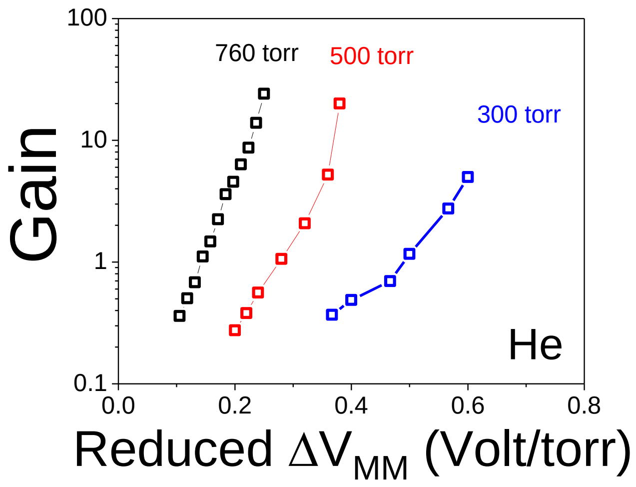
Stability issues in pure elemental gas

- **H_2 as proton target**
  - 1 neutron pickup (p,d)
  - 2 neutron pickup (p,t)
  - p-scattering
- **D_2 as deuteron target**
  - 1 neutron transfer (d,p)
  - 1 proton pickup (d,^{3}He)
  - Inelastic scattering (d,d')
- **^{3}He**
  - 1 proton transfer (^{3}He,d)
- **^{4}He as alpha-particle target**
  - Inelastic scattering (^{4}He, ^{4}He'),
  - Isoscalar Giant Resonances excitations …
  - Alpha-induced reactions for astrophysical p-process
- **Etc. . .**

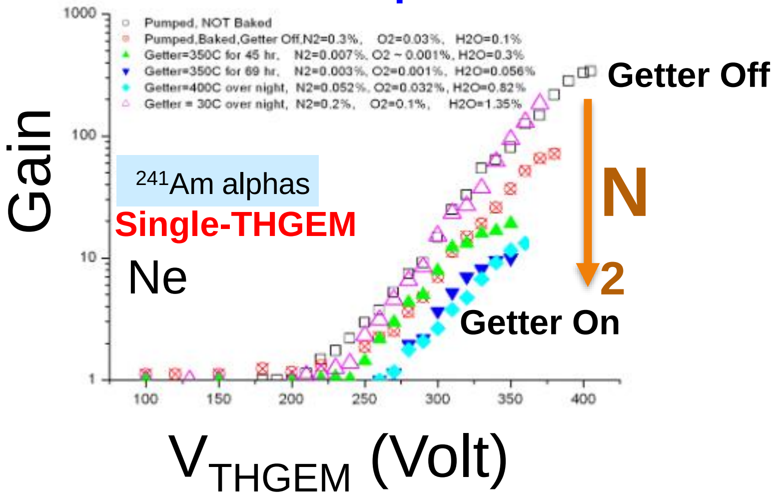
-) Purity (no quencher) → High Reaction Yield
-) Low-Pressure Operation → Large Dynamic Range

Endcap Detector Performance:
Gas Gain, Energy Resolution, Spatial Resolution, Counting Rate Capability, Stability etc…

Micromegas in pure He

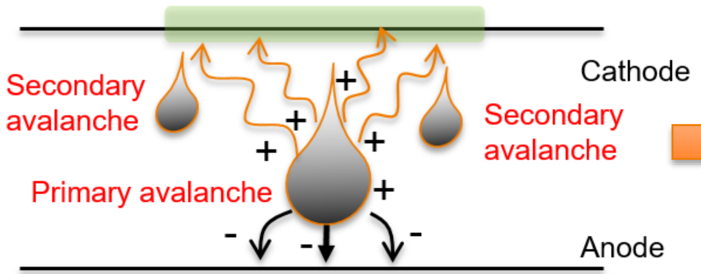


THGEM in pure Ne



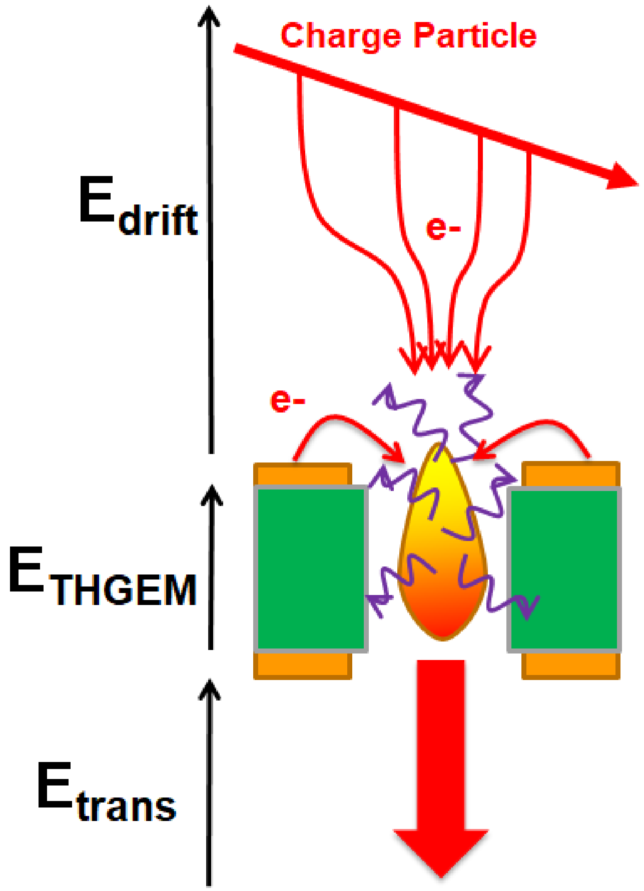
Miyamoto et al. 2010 JINST 5 P05008

Photon-feedback



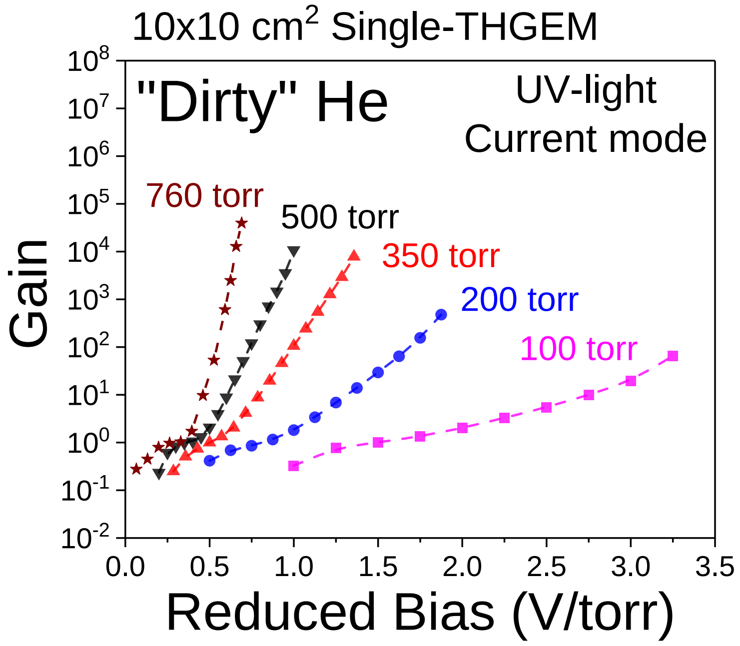
Problem:
Photo-mediated secondary effects induce a transition from the proportional mode to streamer (sparks) in poor quenched gas mixtures!

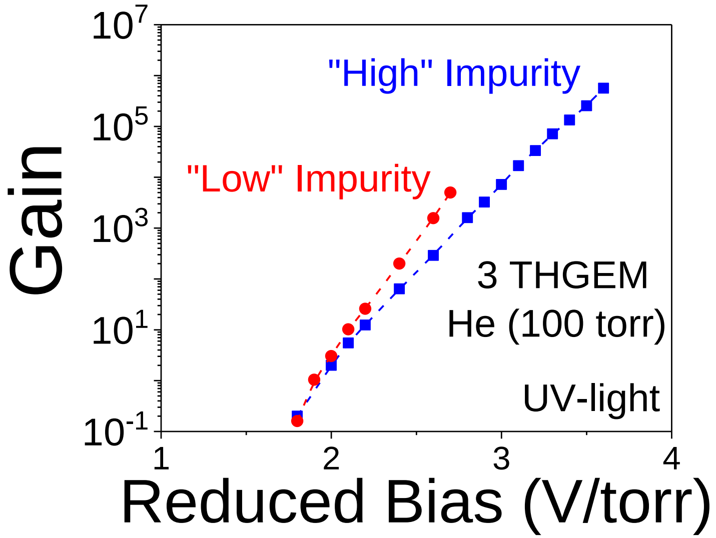
Stability issue for hole-type multipliers in pure elemental gas



The Problem:

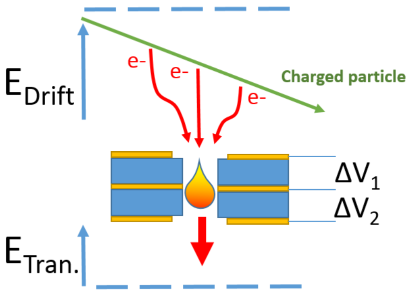
Drop of GEM-like max. achievable gain in pure elemental gas
➔ loss of electron avalanche confinement (within the holes) that results in photo-mediated secondary effects
➔ transition from proportional mode to streamer



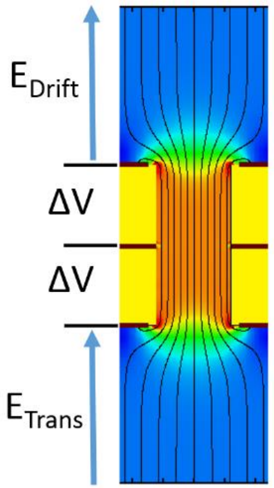


Multi-Layer THGEM (M-THGEM)

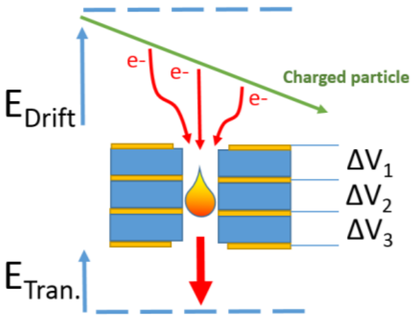
Manufactured by multi-layer PCB technique out of FR4/G-10/ceramic substrate



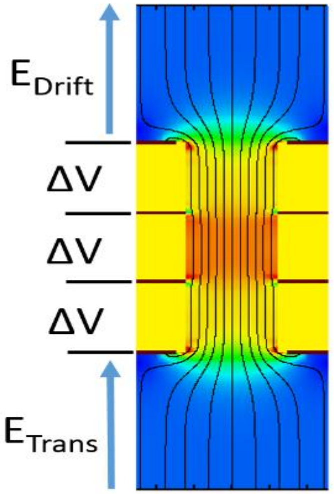
2-Layer M-THGEM



Low pressure



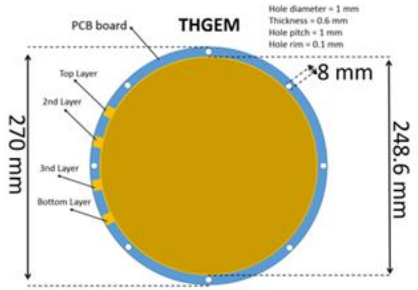
3-Layer M-THGEM

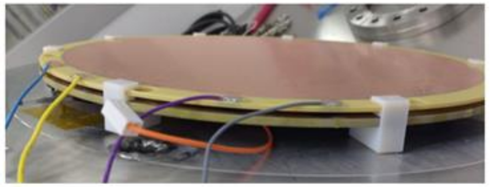


AT-TPC & pure gases

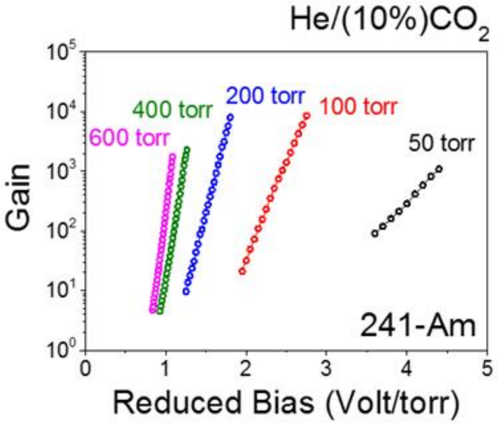
- -) No loss of charge ➔ high gain @ low voltage
- -) Robust avalanche confinement ➔ lower secondary effects
- -) Long avalanche region ➔ high gain @ low pressure
- -) Field geometry stabilized by inner electrodes ➔ reduced charging-up

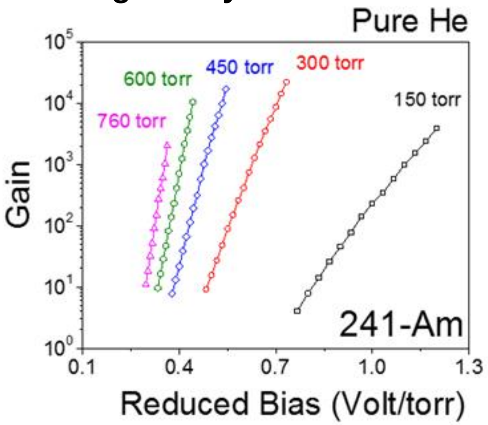
Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)



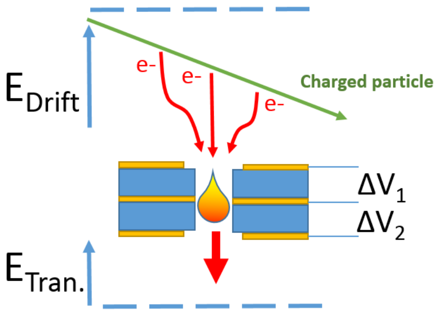


Single 3-layer M-THGEM

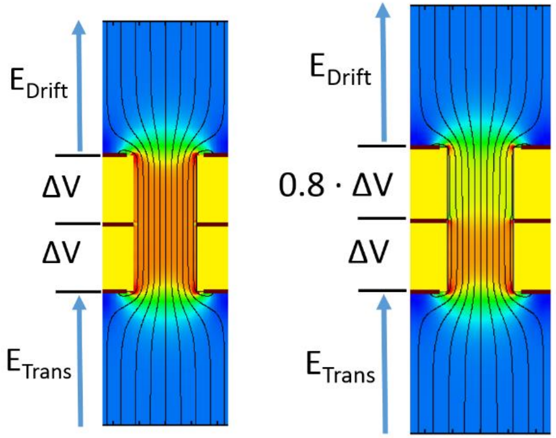


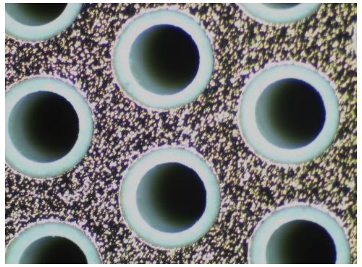


2-Layers M-THGEM (field configuration)



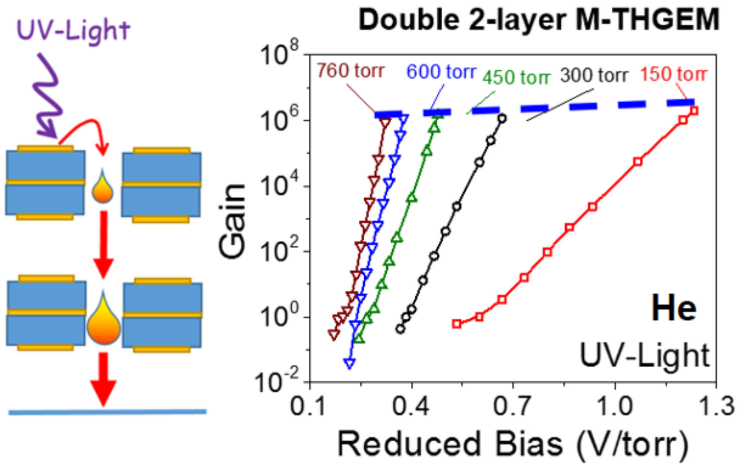
2-Layer M-THGEM



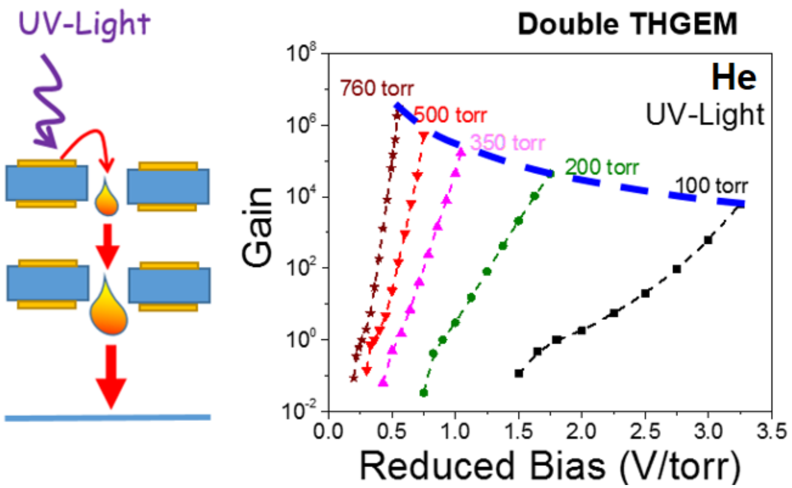


Asymmetric Bias Operation mode:
-) The first THGEM act as a "collector"
no/negligible multiplication
-) Avalanche occurs into the 2nd stage

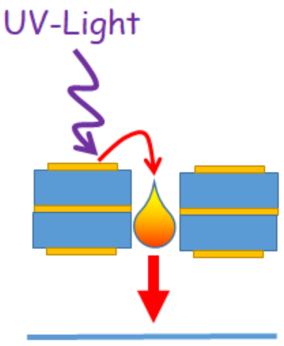
10x10cm² M-THGEM
(thickness = 1.2 mm, hole = 0.5 mm, pitch = 1 mm)

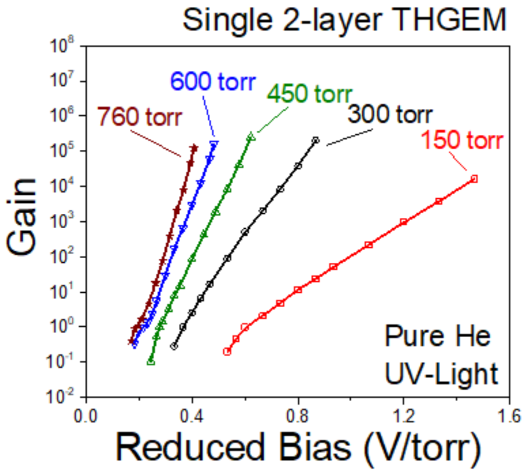


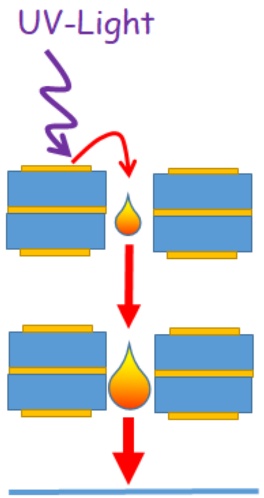
10x10cm² THGEM
(thickness = 0.6 mm, hole = 0.5 mm, pitch = 1 mm)

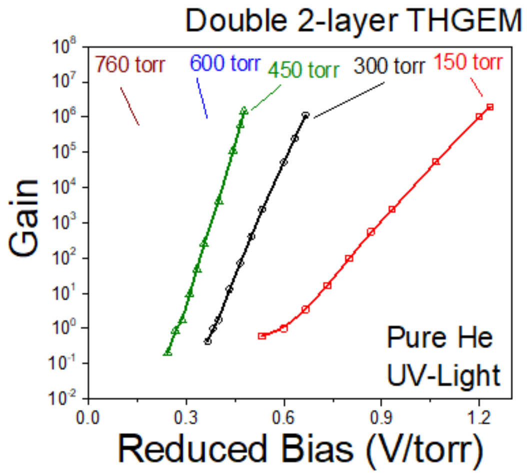


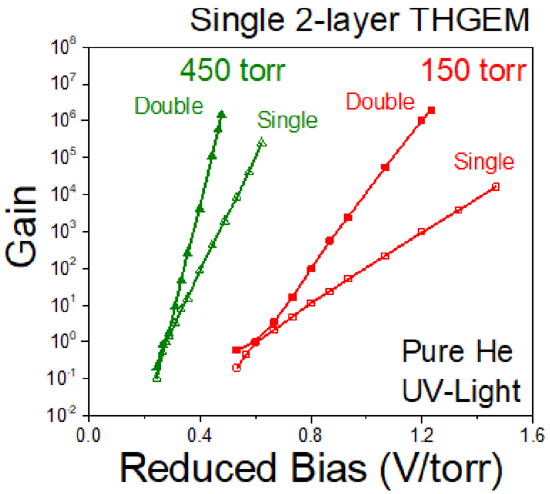
2-Layers M-THGEM (single vs double)



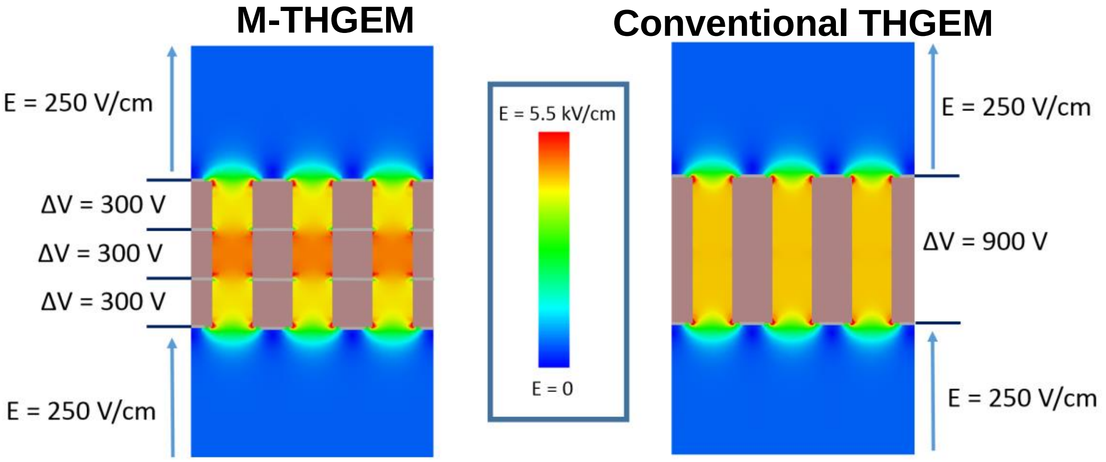


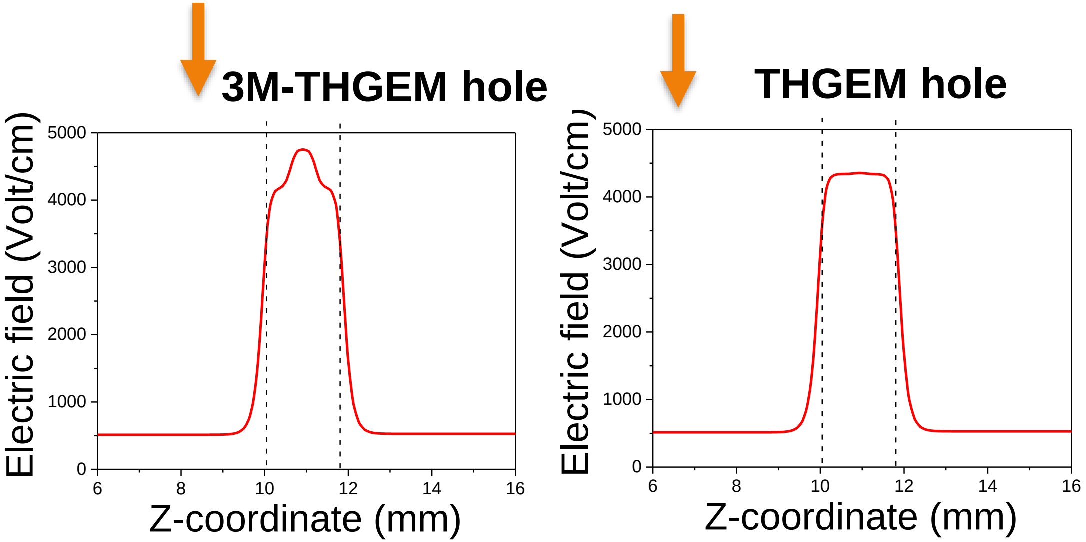






3-Layers M-THGEM (field configuration)





E-field strength computed along the hole axis

-) Gas avalanche process "confined" in the inner volume of the hole

⇓

Better suppression of photon-mediated secondary effects in pure elemental gas

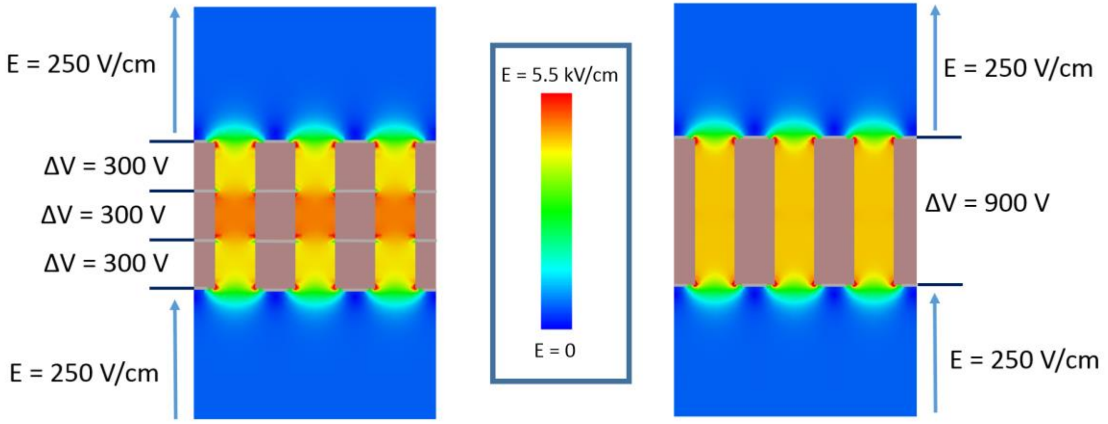
-) Multi-stages & voltage bias breakup

⇓

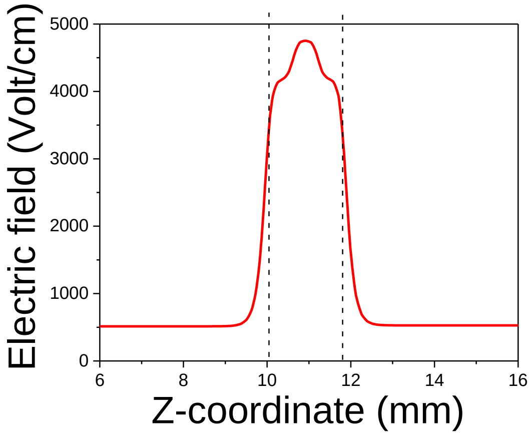
Lower energy released during discharges & lower probability of damages

3-Layers M-THGEM (results)

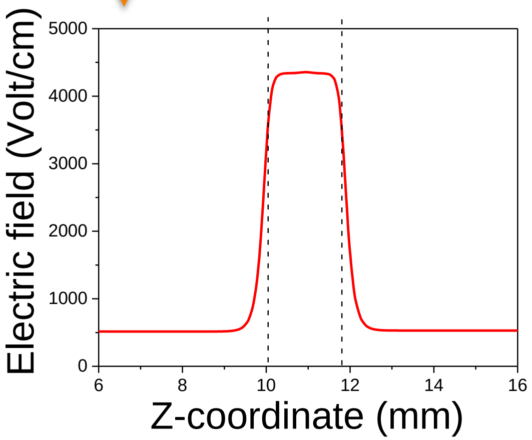
M-THGEM **Conventional THGEM**



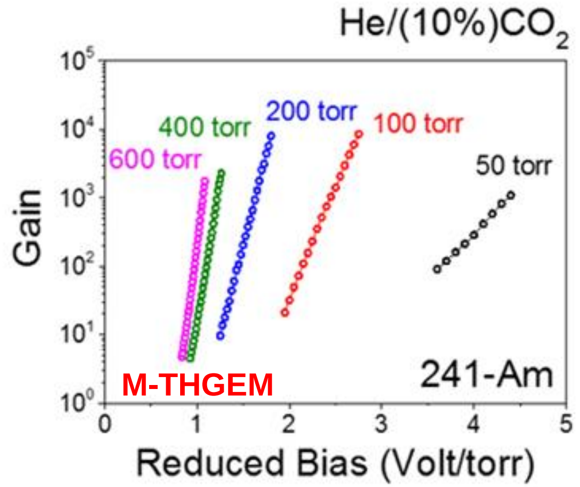
3M-THGEM hole

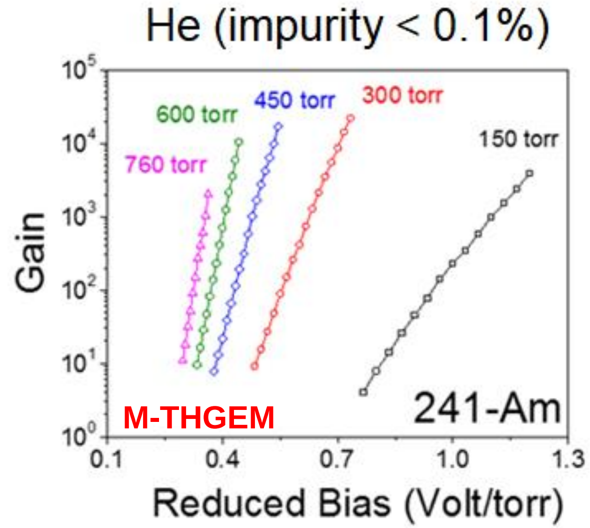


THGEM hole

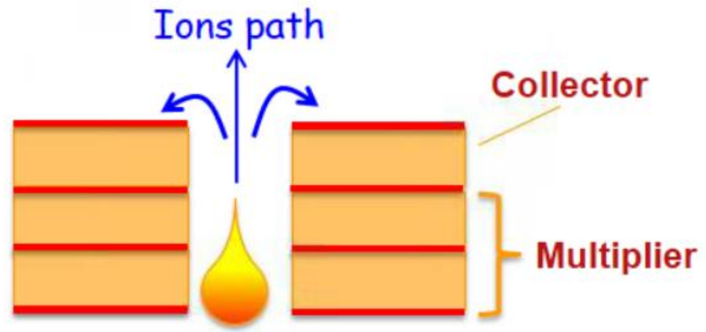


E-field strength computed along the hole axis

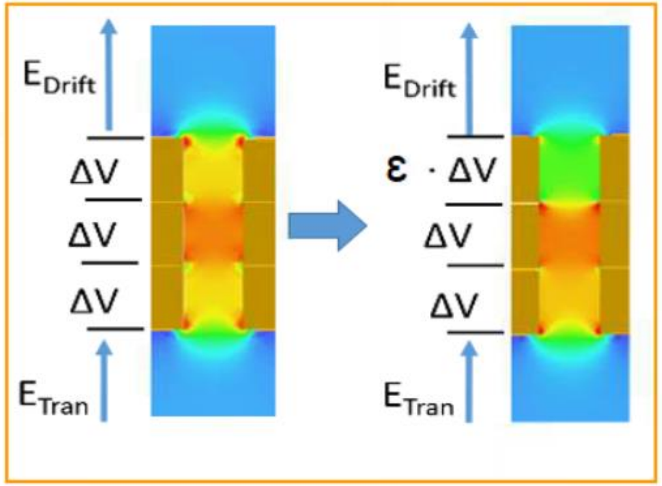




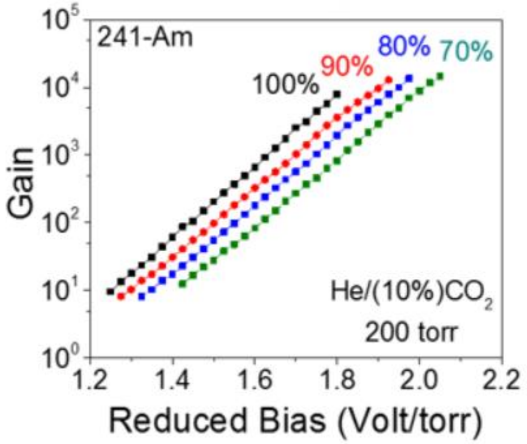
Asymmetric mode of operation



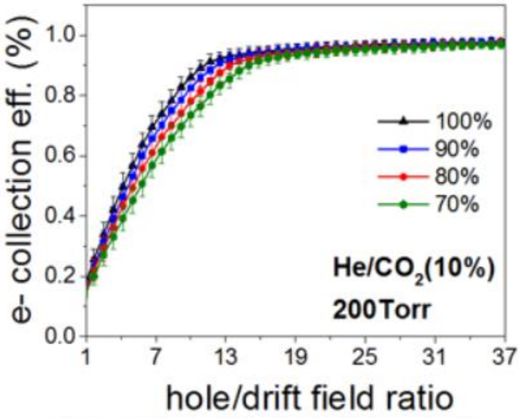
Problems: energy resolution? Effective gain?



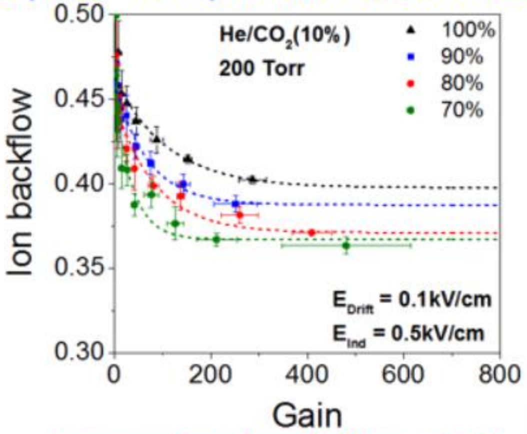
Garfield – Stefan Rost MSc Thesis



Same Max achievable Gain!



No significant loss of e- collection efficiency

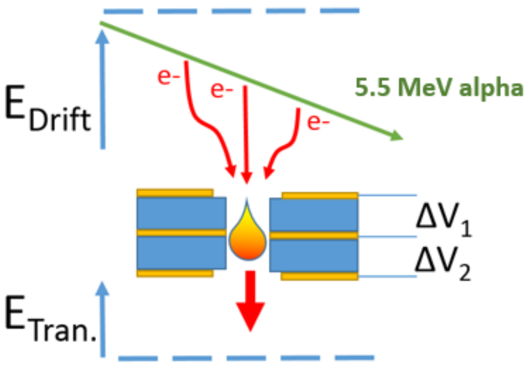


Lower ion backflow with cascade configurations

Long-term gain stability of Ceramic M-THGEMs

Two-layer ceramic M-THGEM

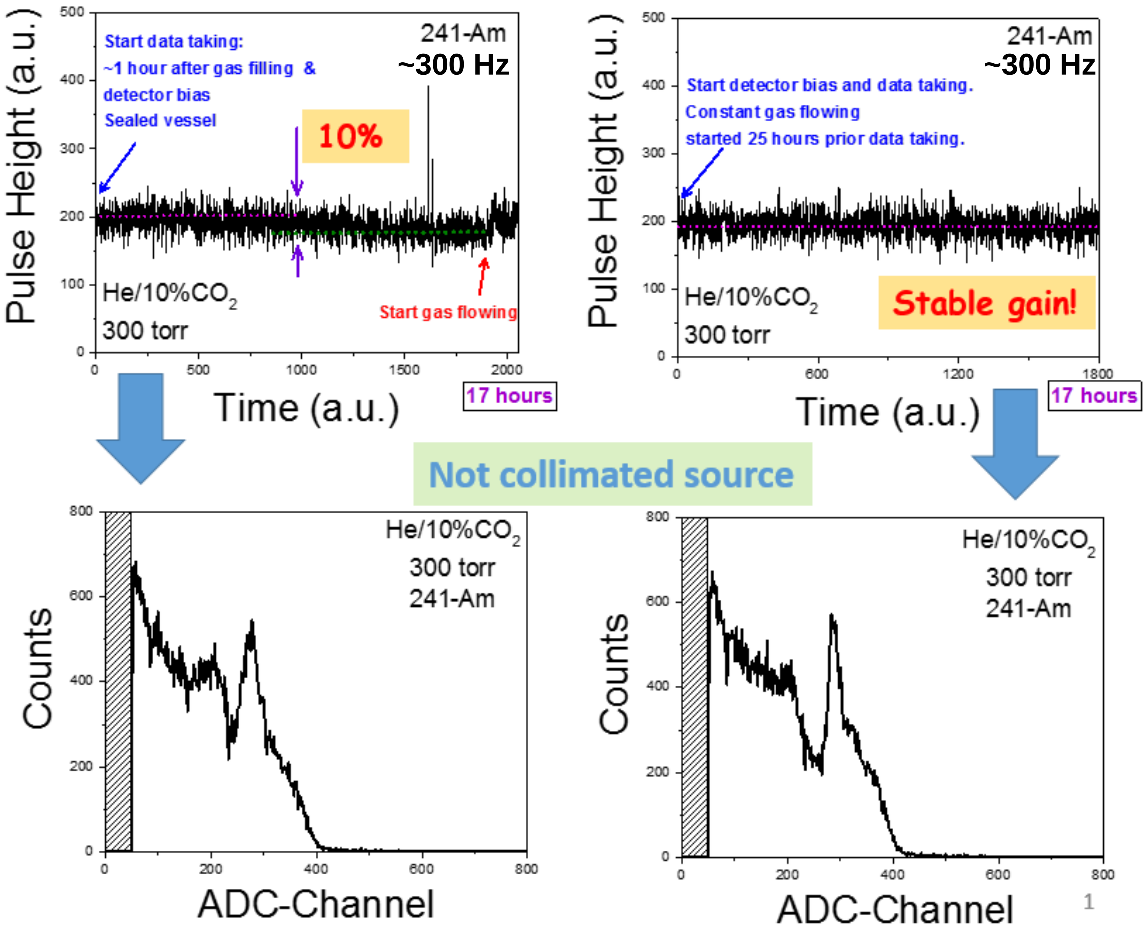
$10 \times 10\ cm^2$ prototype
12 mm drift ➔ E_{Drift} = 1 kV/cm
3 mm trans. ➔ $E_{trans.}$ = 0.33 kV/cm
$\Delta V_{M\text{-}THGEM}$ = 480 Volt
Counting rate ≈ 700 Hz



2-layer THGEM

No significant charging up effect at low rate!

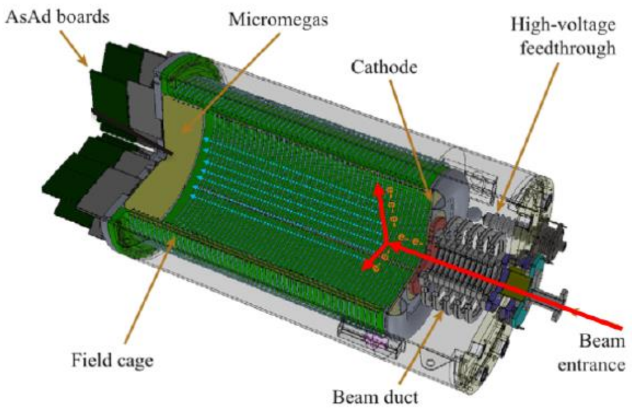
Each point is the average of ≈150 recorded pulse (1 pulse/sec)



AT-TPC with Reaccelerated Beams

Goal: Study of inverse-kinematic nuclear reactions with resolutions equal to the one achieved in direct kinematics with high-resolution spectrometers + higher efficiency & thicker targets

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



Why Gas-filled AT-TPC for low-energy nuclear physics?

-) 4π acceptance of reaction products

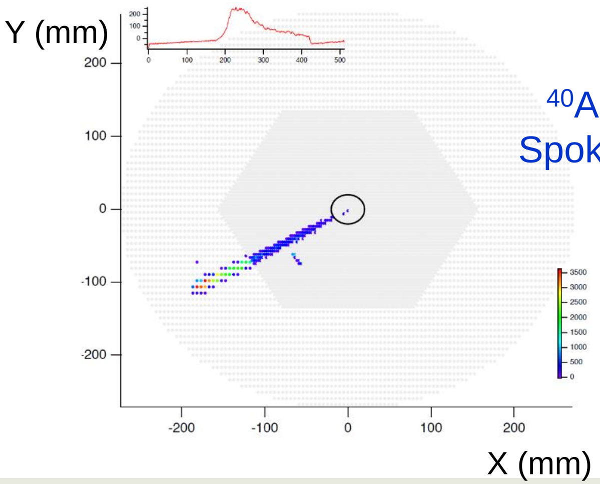
-) Energy loss like thin target = excellent resolution

-) Very high effective thickness ➔ high luminosity

-) Detection efficiency ~100% (+ low energy events)

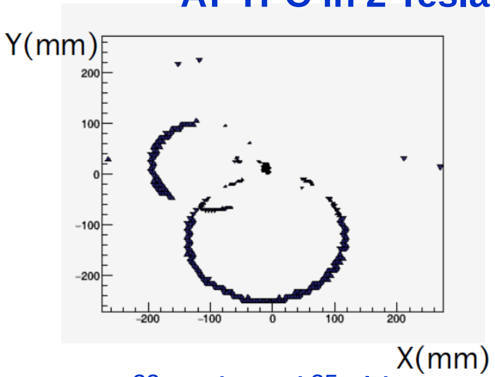
-) Event-by-event reconstruction in 3 dimensions

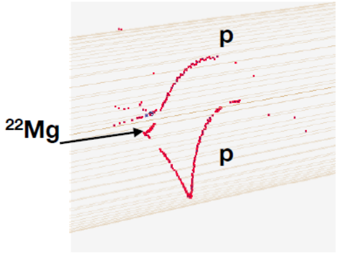
-) Full excitation function with mono-energetic beam



^{40}Ar(p,p') in pure H_2
Spokeperson: D. Bazin

AT-TPC in 2 Tesla magnetic field



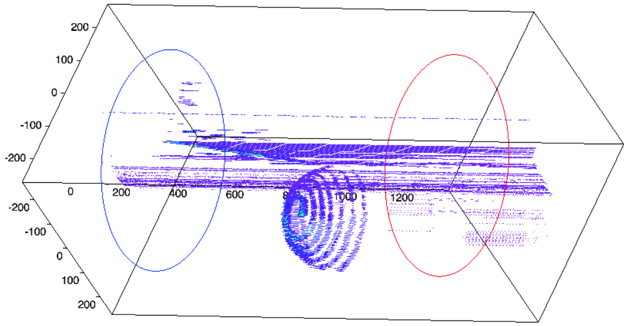


^{22}Mg(α,2p)^{25}Al in He:CO_2(10%)
Spokeperson: Y. Ayyad

AT-TPC in pure elemental gas: recent results

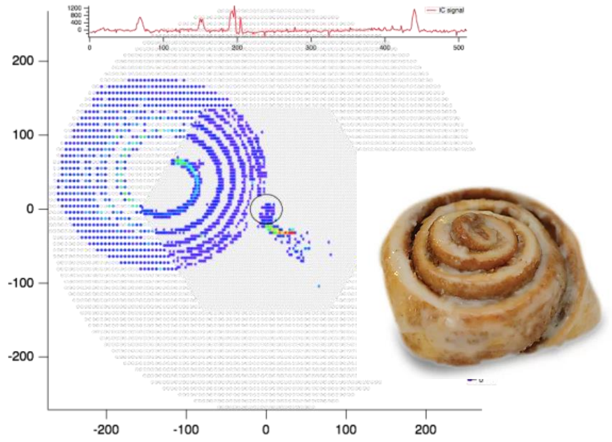
SOLARIS (up to 4 Tesla)

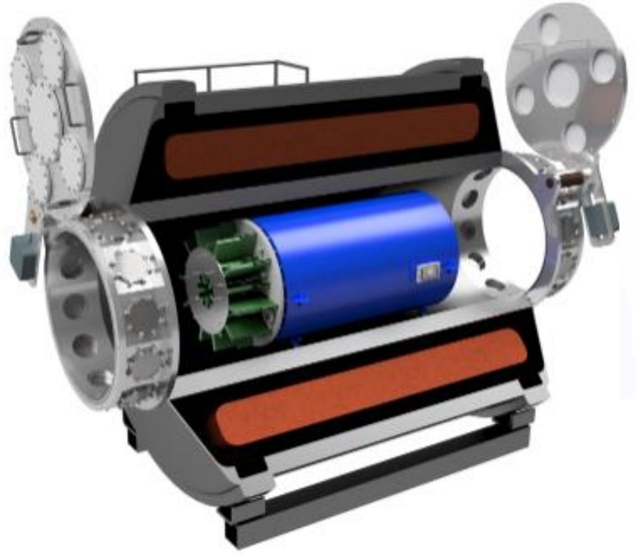
E20009 → pure D_2 (760 Torr)
$^{10}Be(d,p)^{11}Be$

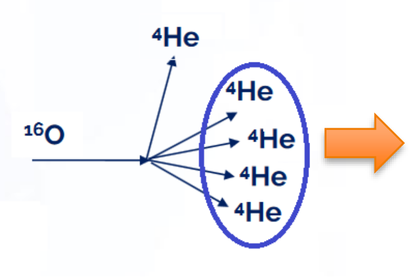


The cinnamon roll: 8 MeV p (5 m range)

Spokesperson: Daniel Bazin

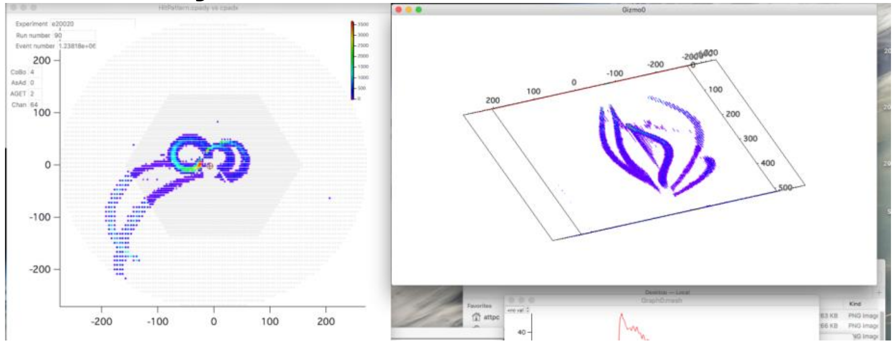


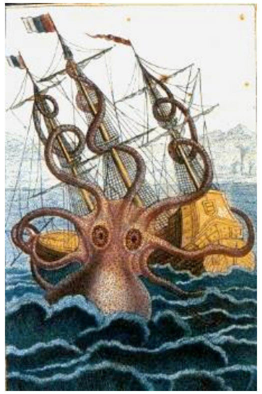




E20020 → pure He (700 Torr)
4 α decay of ^{16}O

Spokesperson: Clementine Santamaria





The big Kraken: 5 α-particle tracks

Applications to exotic decays: The X17 Boson

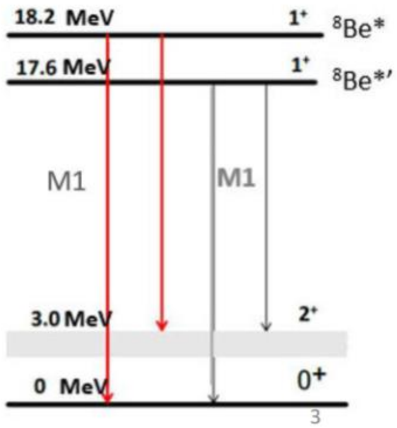

PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

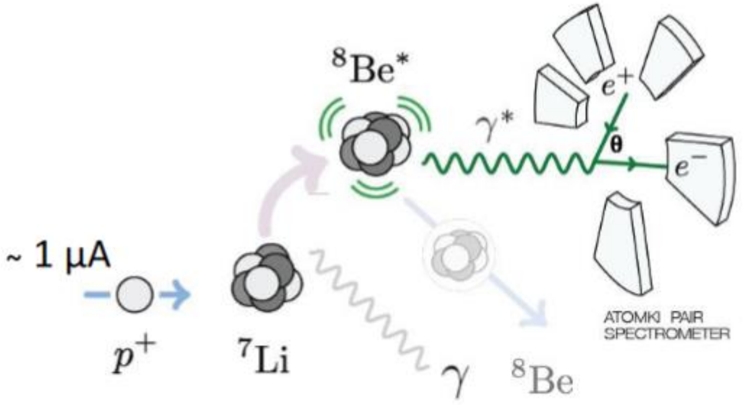
Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

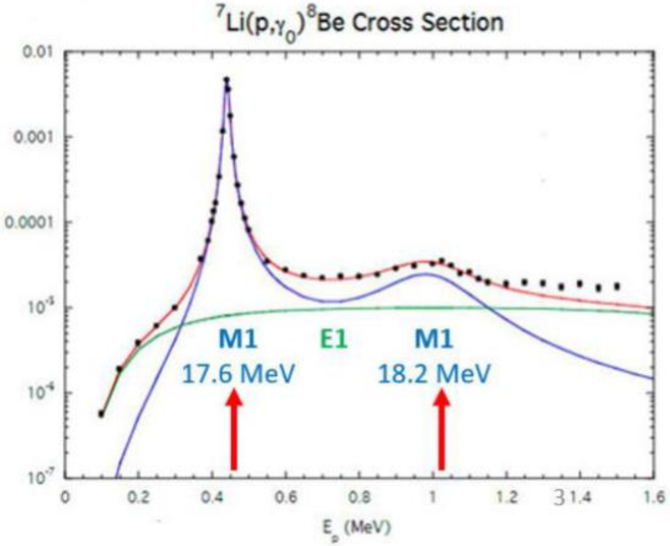
A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

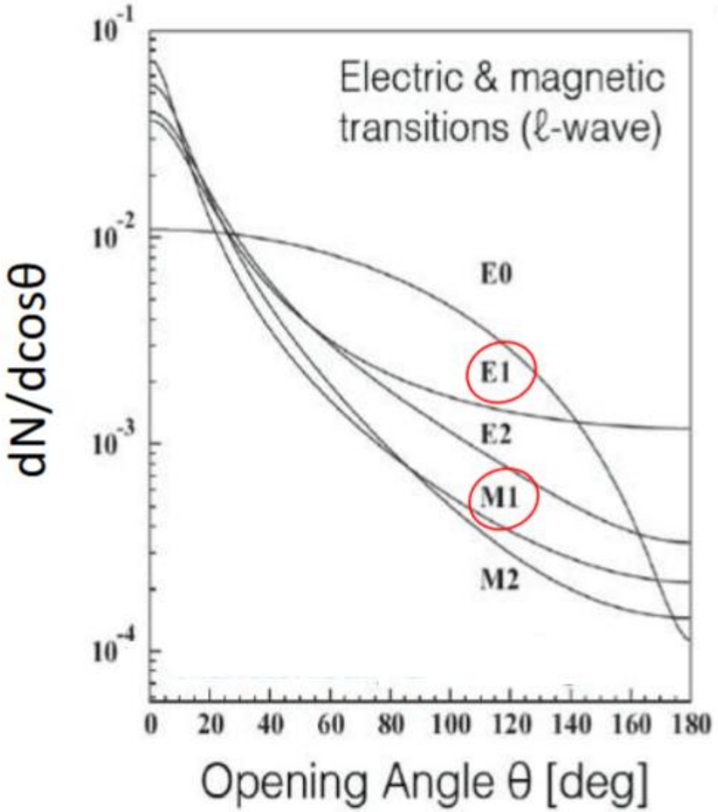
A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)







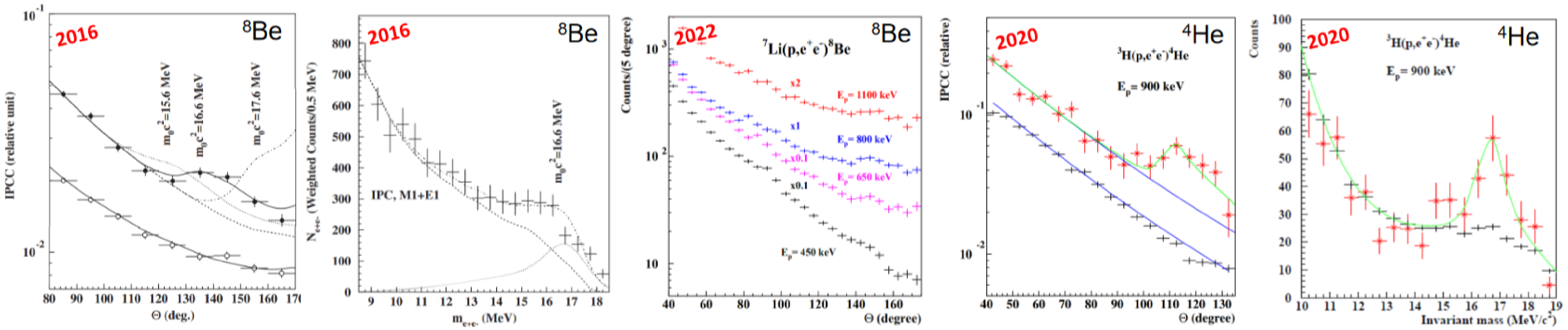
P. Schlüter et al, Physics Reports 75 (1981), pp 327-392.

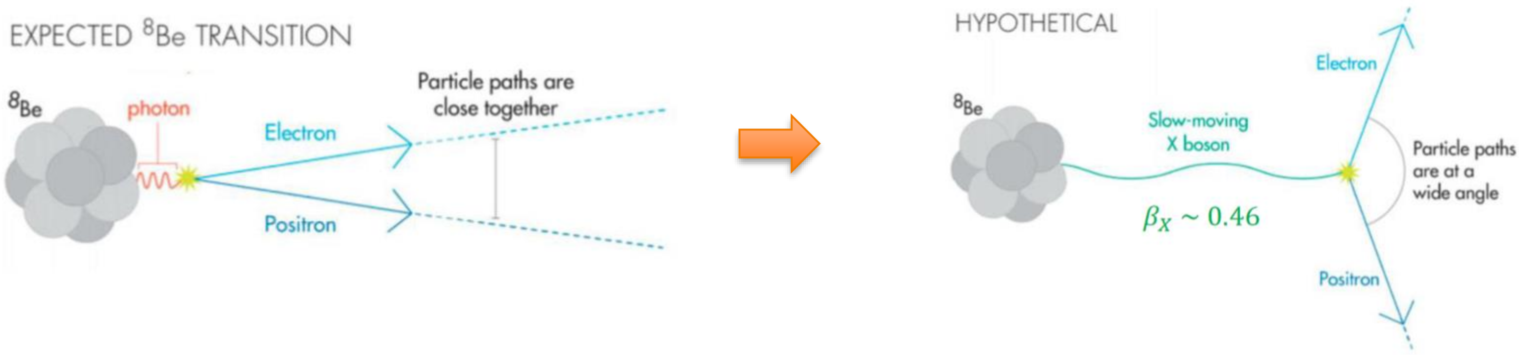


-) Photo-production in ^{8}Be* via p+^{7}Li
-) Fraction of the photons converted into e+e- by IPC
-) Measure angular distribution of the e+e- pair

Decay and Internal Pair Creation (IPC): ATOMKI's Anomaly

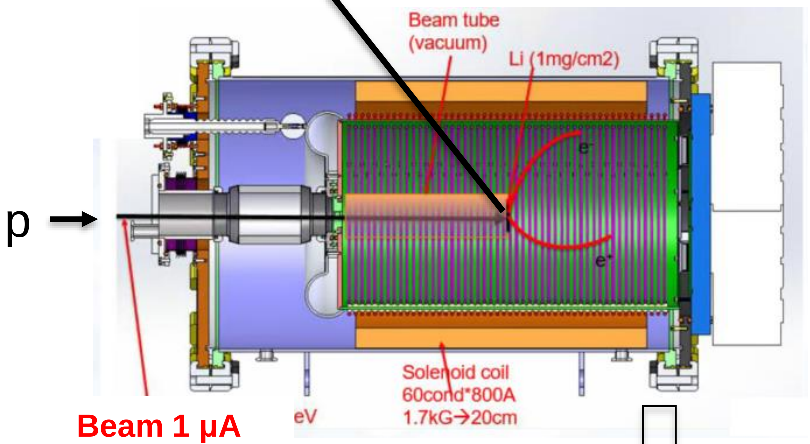
A.J. Krasznahorkay et al., Phys. Rev. Lett. 116 (2016) 042501
A.J. Krasznahorkay et al, J. Phys.: Conf. Ser. 1643 (2020) 012001





TPC with solid target for X17 boson search

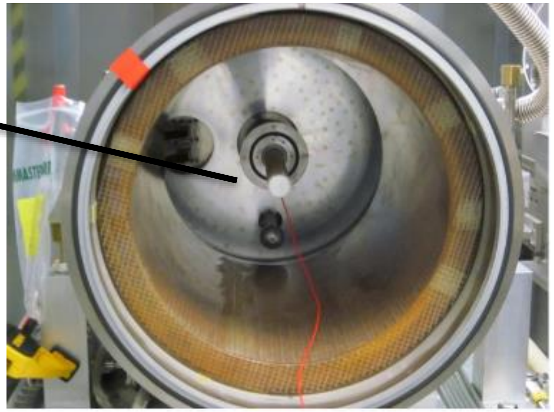
Target:
-) 400 µg/cm Lithium Hydroxide (LiOH)
-) 10 µg/cm Lithium Fluoride (LiF)

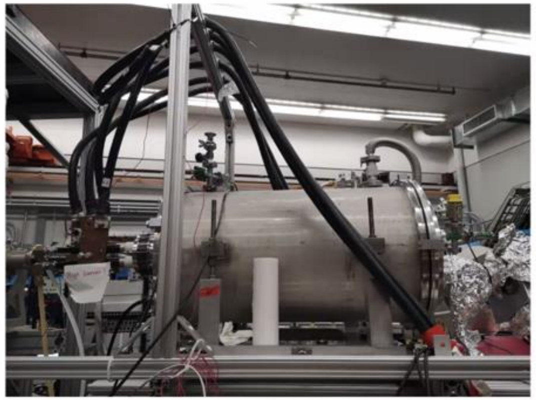


Beam 1 µA protons 1 MeV

M-THGEM+Micromegas

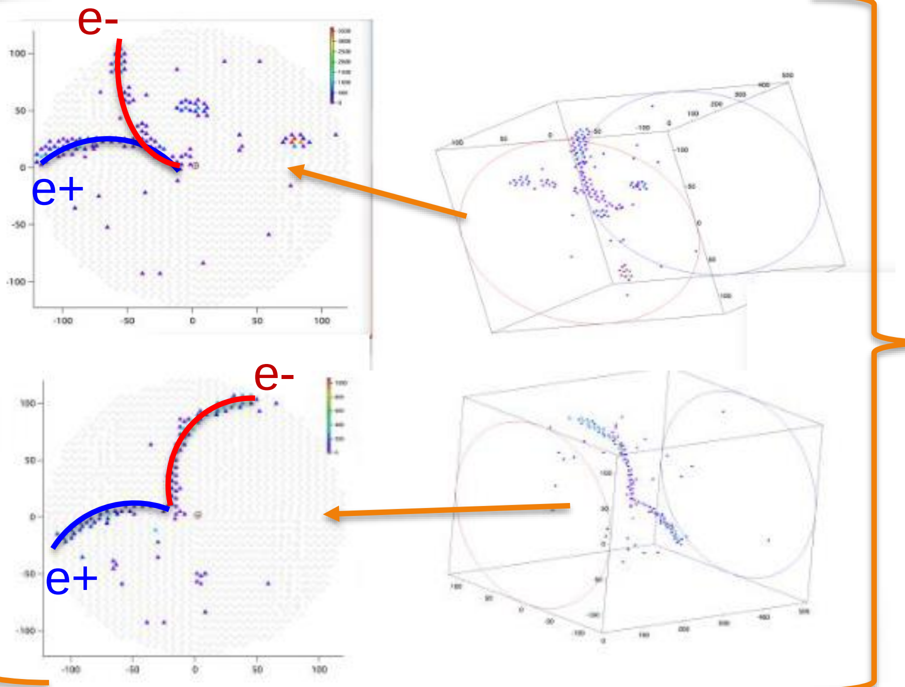
Gas filling: P10 @ 1 atm



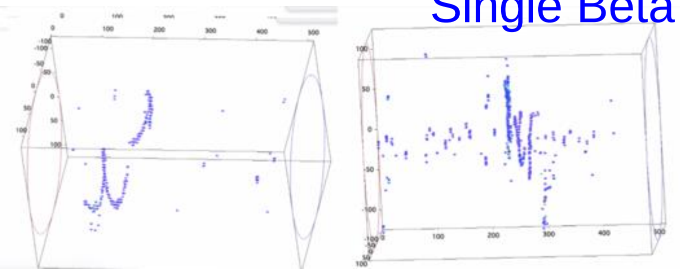


TwinSol – Notre Dame University (Indiana)

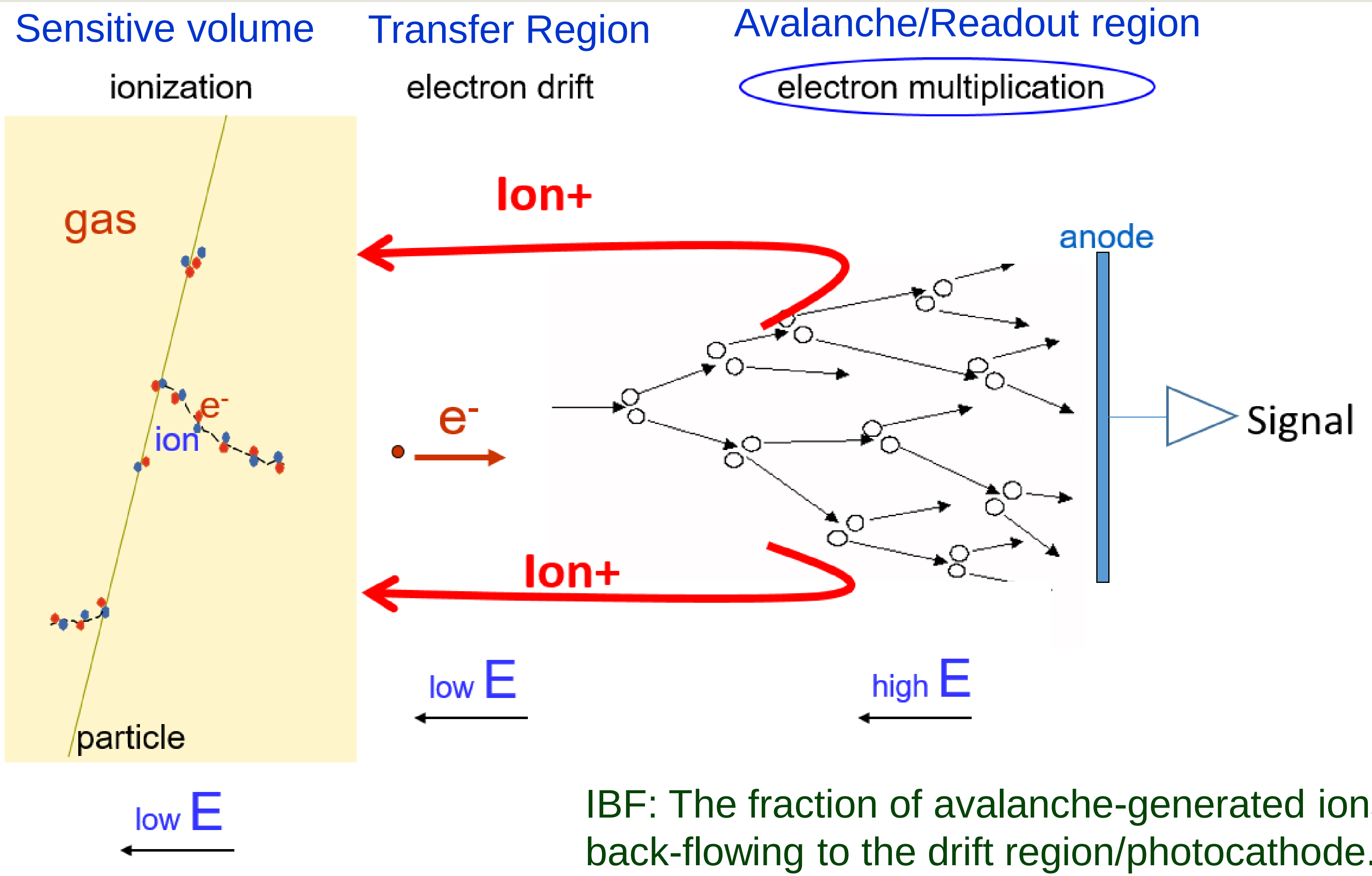
Courtesy W. Mittig (AT-TPC collaboration)



Single Beta Background



The IBF problem in Gas Avalanche Detectors

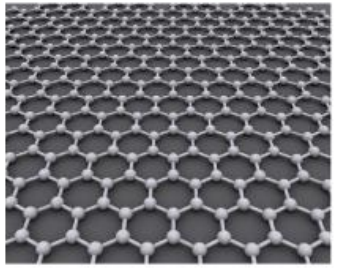


IBF: The fraction of avalanche-generated ions back-flowing to the drift region/photocathode.

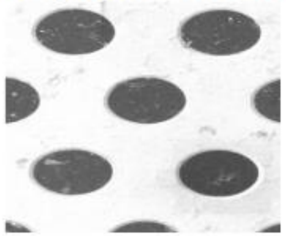
IBF suppression with Graphene

Franchino et al., NIMA 824 (2016) 571–574

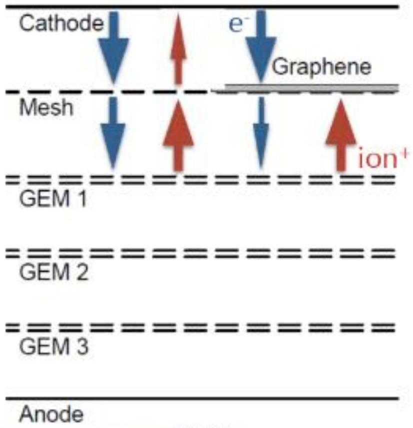
RESNATI **ION BLOCKING w GRAPHENE ON GEM**

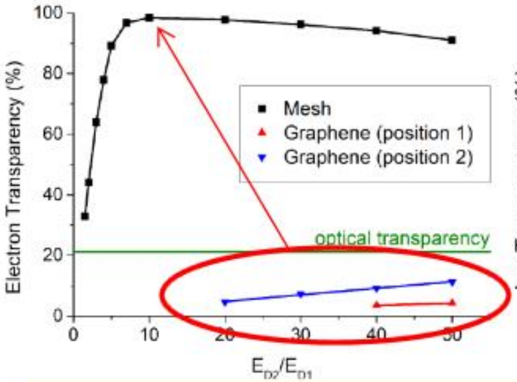


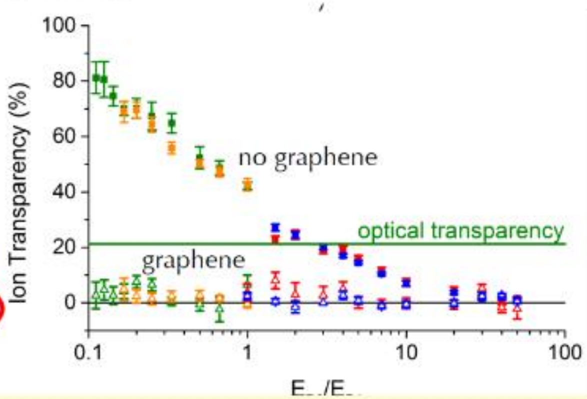
Graphene on "GEM"

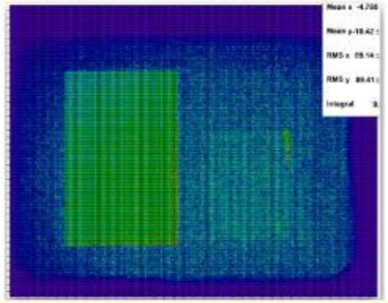


Graphene: opaque to ions and
UNDER SOME CONDITIONS:
transparent to electrons



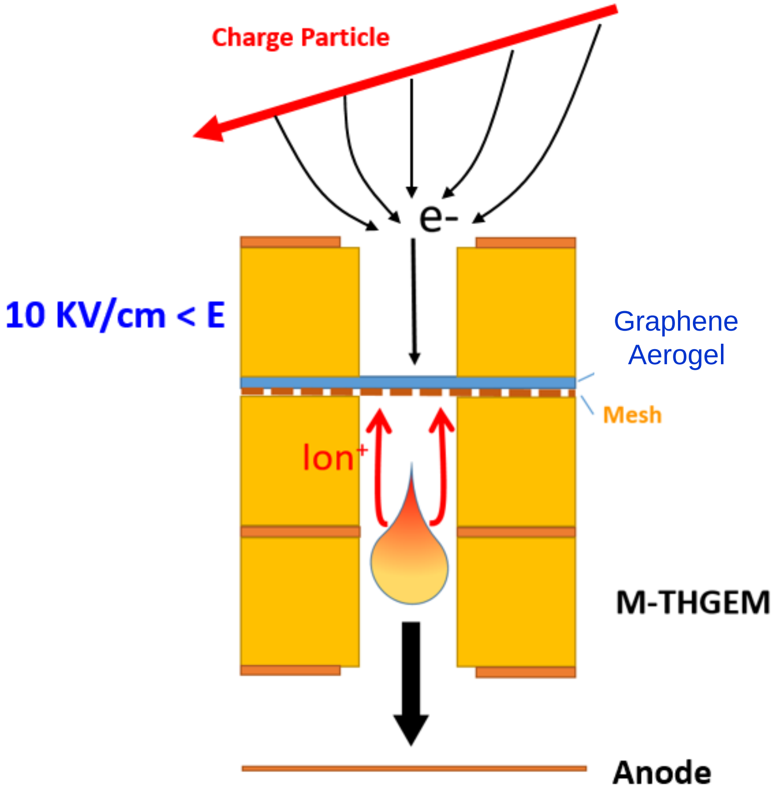




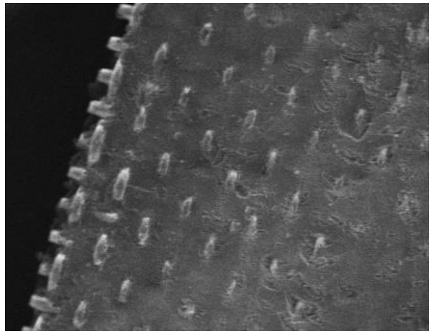
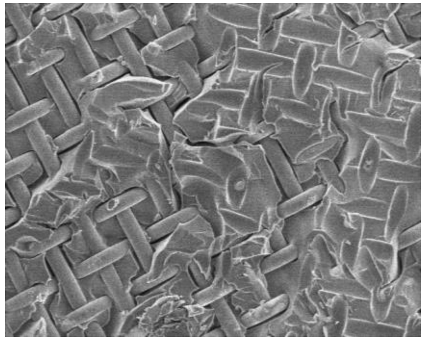


Coating GEM w GRAPHENE: need to increase e- Energy > 10kV/cm. Did not succeed to transmit e- via 3-layer Graphene.

IBF suppression using M-THGEM + charge filter



<u>The Idea:</u>
Create a passive charge filter (graphene/aerogel deposited on a mesh) sandwiched between multiplication layers inside the M-THGEM structure, transparent to electrons but opaque to ions:
-) First stage hole-type structure ➔ e- collection
-) Second stage hole-type structure ➔ gas avalanche process

First prototype: 200 um thick aerogel – 40 nm C evaporated on both side

Applications @ FRIB: position-sensitive, large-area GPM for MoNA-LISA Detector Array, High-Rate Tracking
<u>Personal Goal:</u> Destroy Hamamatsu dominance over Photon Detection technology (A "Serious" Joke)

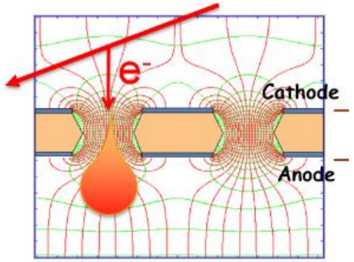
Collaborators: MoNA Group (P. Gueye and T. Baumman), W. Halpering group @ NWU

WAR FOR THE THRONE

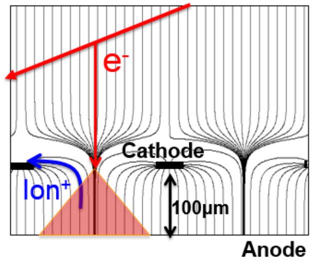
Love in the time of … *MPGDs*

Marco Cortesi (FRIB)

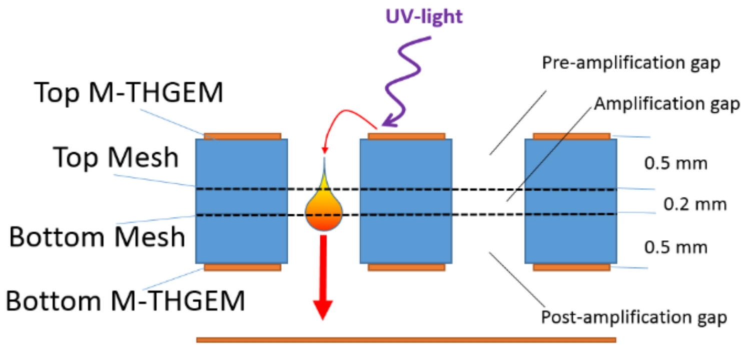
Rui de Oliveira (CERN)



Hole-like
Multi-layer
Mechanical support



Amplification in Meshes



Multi-Mesh THGEM

Example of “Hybrid”-MPGD configurations

S. Kane et al. NIM515 (2003) 261–265

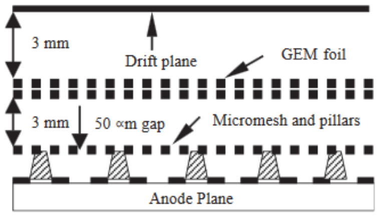
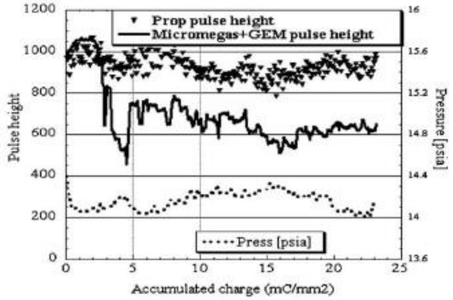
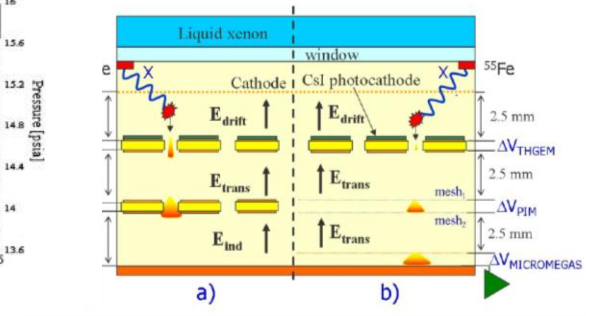


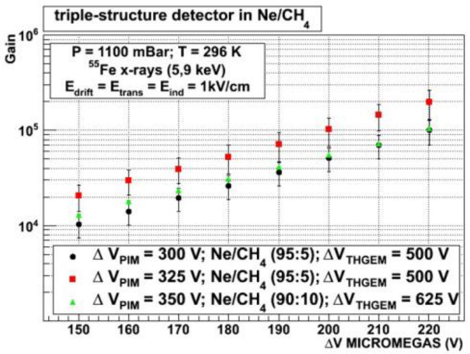
Fig. 2. MICROMEGAS + GEM detector.



Increase Micromegas stability at high gain

S. Duval et al. 2011 JINST 6 P04007

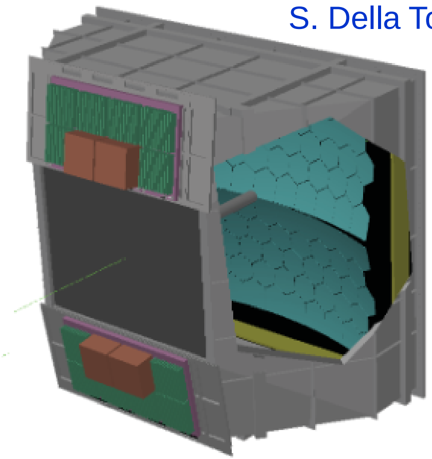


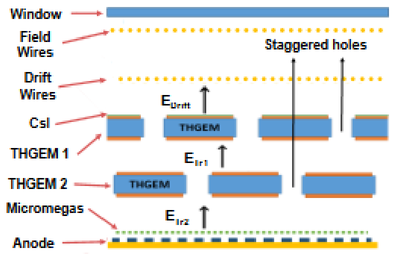


Low IBF & high gain

The MPGD-Based GPM for the upgrade of COMPASS RICH-1

S. Della Torre, MPGD2019, La Rochelle 2019



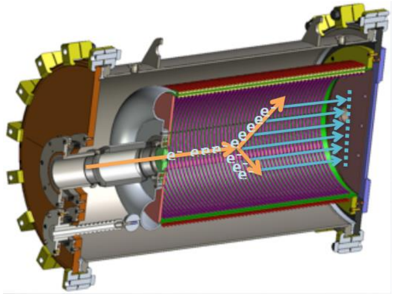


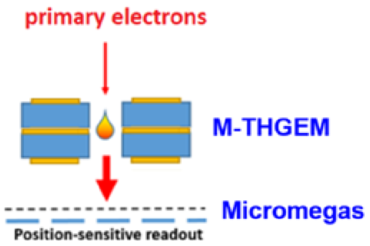
Technological achievement - for the FIRST TIME:

- **single photon detection is accomplished by MPGDs**
- **THGEMs used in an experiment**
- **First resistive MM used in an experiment**
- **For the first time MPGD gain > 10k in an experiment**

AT-TPC for low-E nuclear physics/astrophysics experiments

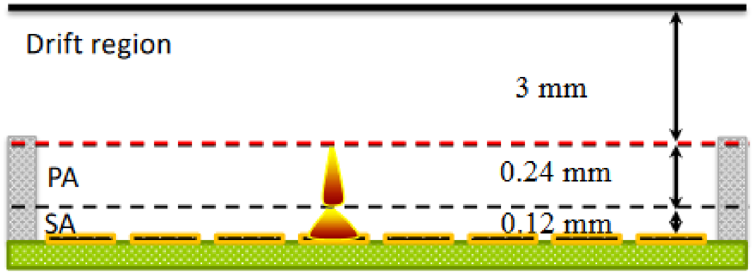
M. Cortesi, MPGD2019, La Rochelle 2019

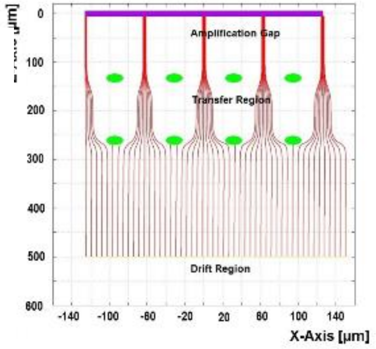




First MPGD operated in “pure” elemental gas & used in several NP experiments in different irradiation conditions

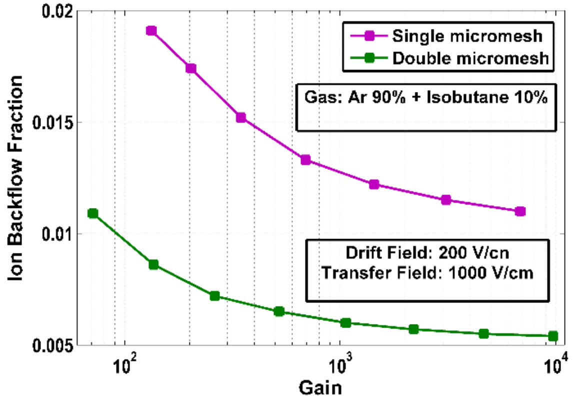
The idea: M-THGEM as support for the Double-MicroMegas

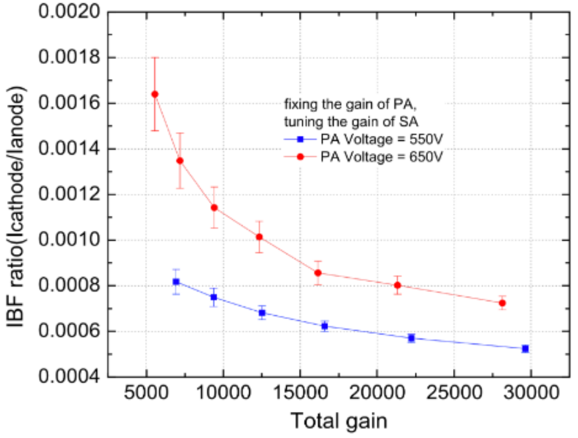




Problem: mechanical stability of DMM over large area

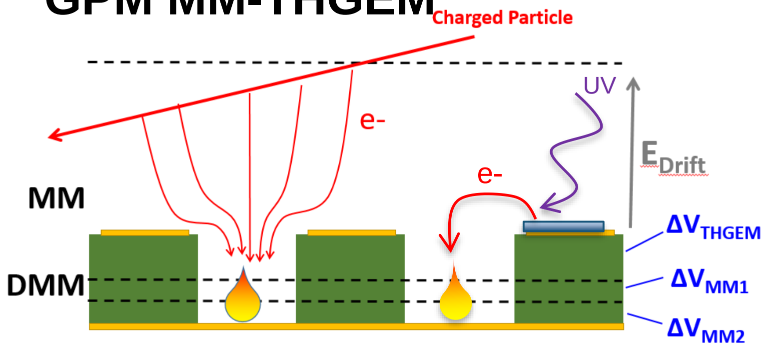
P. Bhattacharya et al 2015 JINST10 P09017

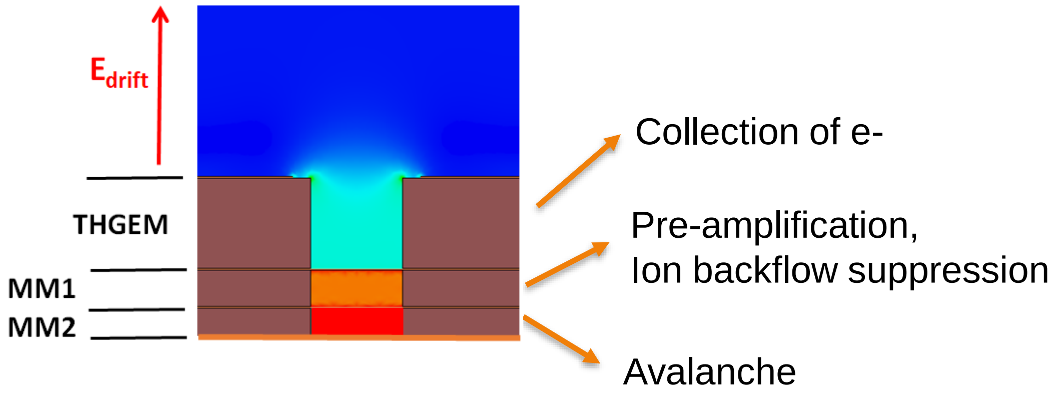




More recent results ➔ IBF ~10^{-4} (B. Qi t al. NIMA 976 (2020) 164282)

GPM MM-THGEM





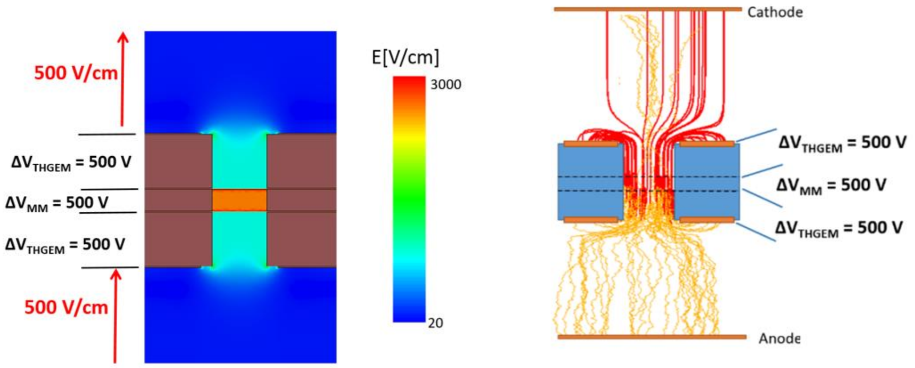
Features:

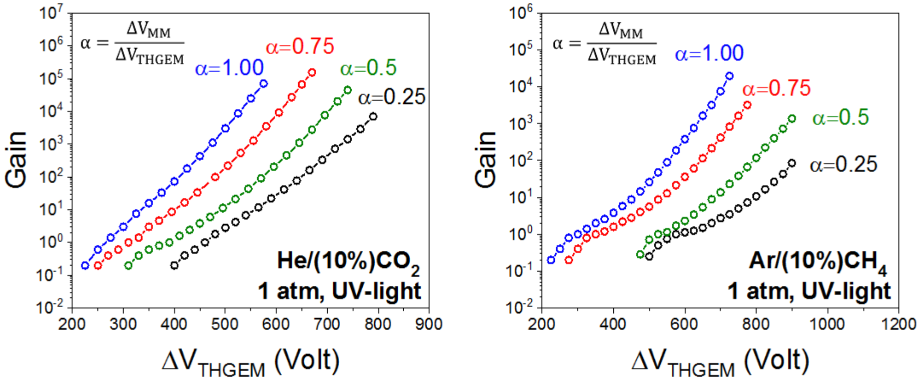
-) M-THGEM as mechanical support for the meshes
-) Reduced ion backflow
-) Uniform field ➔ Good energy resolution
-) Photocathode on the THGEM top surface for GPM

The Multi-Mesh THGEM: performance

De Oliviera & Cortesi 2018 JINST P06019

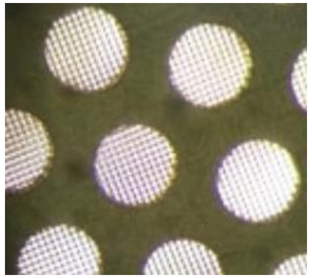
Maxwell-Garfield Simulations

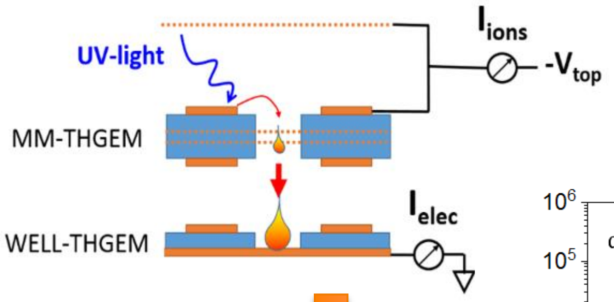




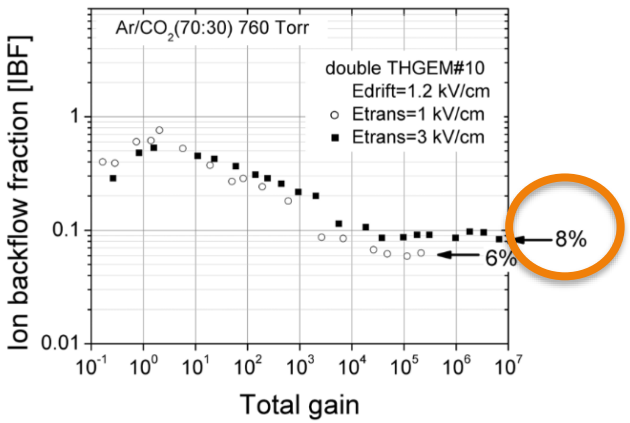
Advantages:
- -) Uniform avalanche field
- -) Lower Ion backflow
- -) DMM over large area

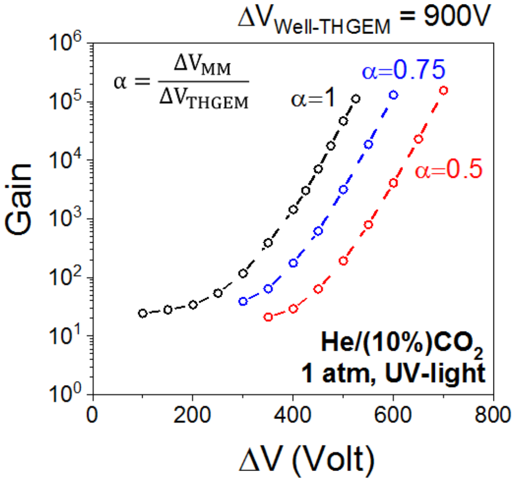
Disadvantages:
- -) Loss of e- transfer efficiency
  ➔ moderate E resolution

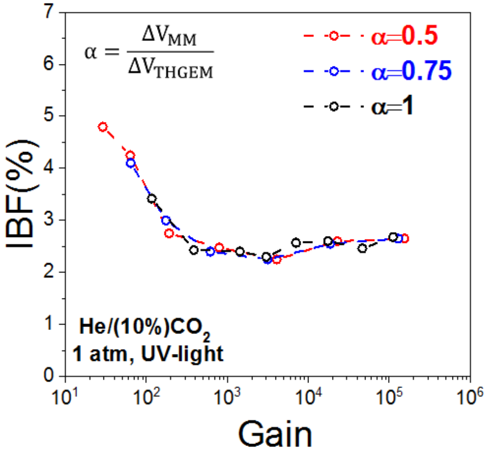




C. Shalem et al. NIM A558 (2006) 475-489







-) 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

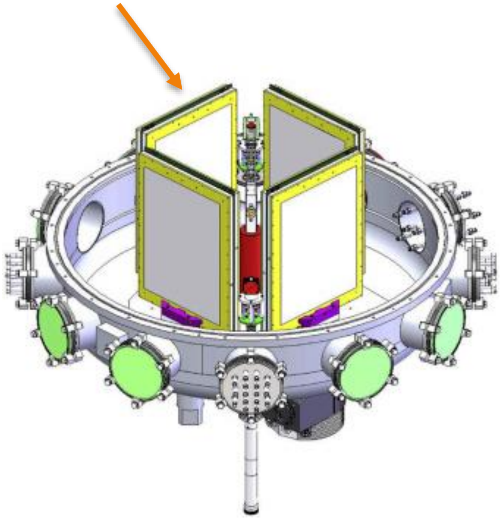
MM-THGEM for Fission Fragment Study

- 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

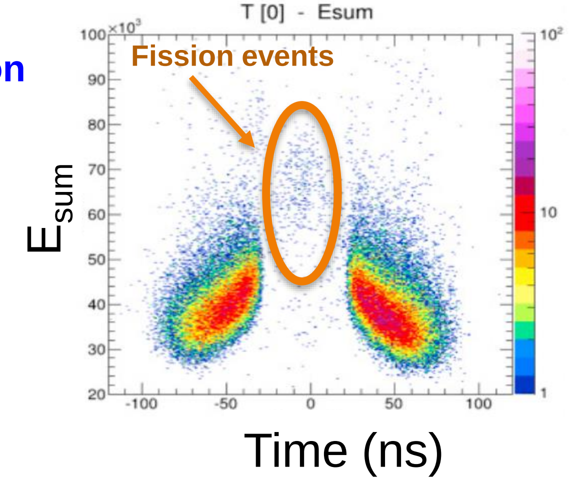
-) Large area → Fragile, difficult to maintain

-) Poor spatial resolution ~ 4 mm (FWHM)

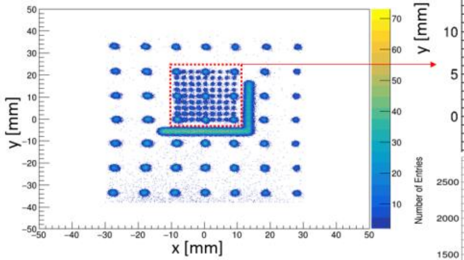
-) Modest rates (up to a few kHz)

➔ Test new technology to improve resolution

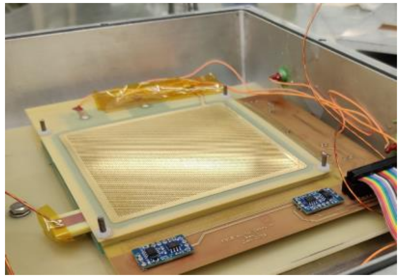
PPAC-based tracking system

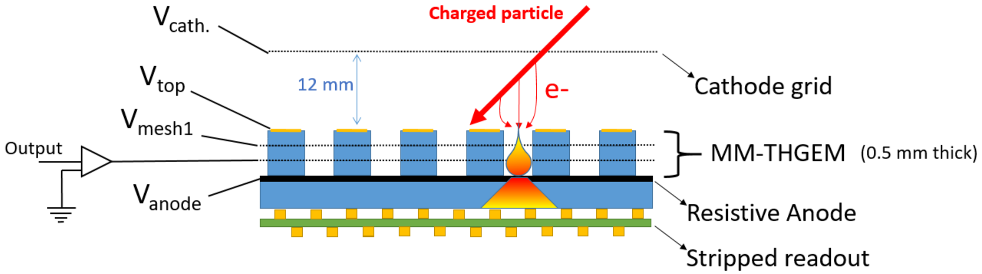


10x10 cm^2

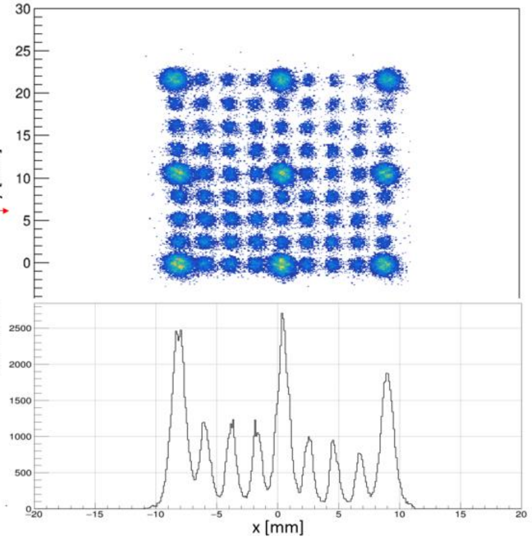


MM-THGEM imaging detector prototype (10x10 cm^2)





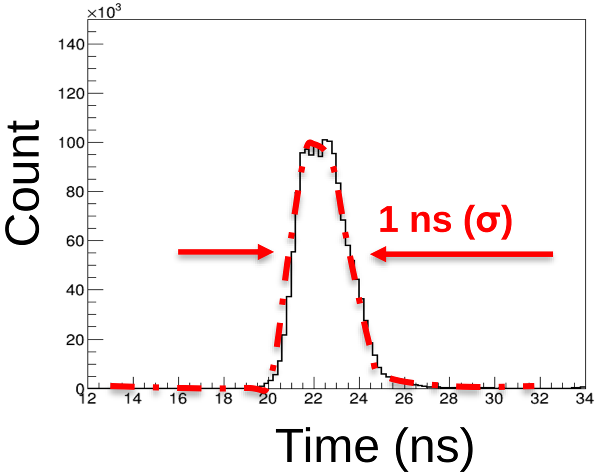
Isobutane (7 Torr)



Performance:

-) Spatial Resolution < 0.5 mm (σ)

-) Time resolution ~ 1 ns (σ)



New trend: Optical Readout for TPC

Advantages:

-) Improved event information by a lower limit of detection
(down to single photoelectrons)

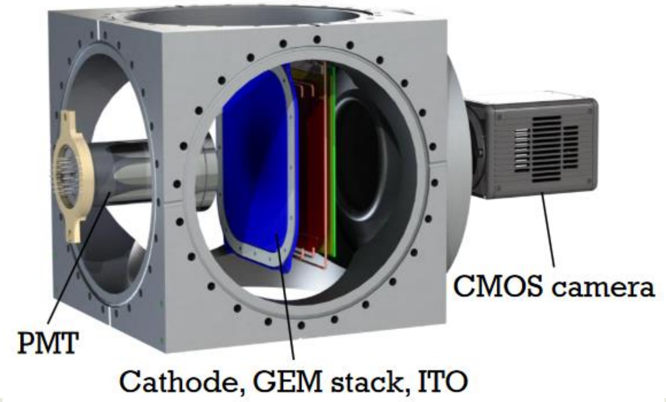
-) High granularity with very low noise. High SNR:
Excellent momentum resolution, two-track separation and tracking efficiency

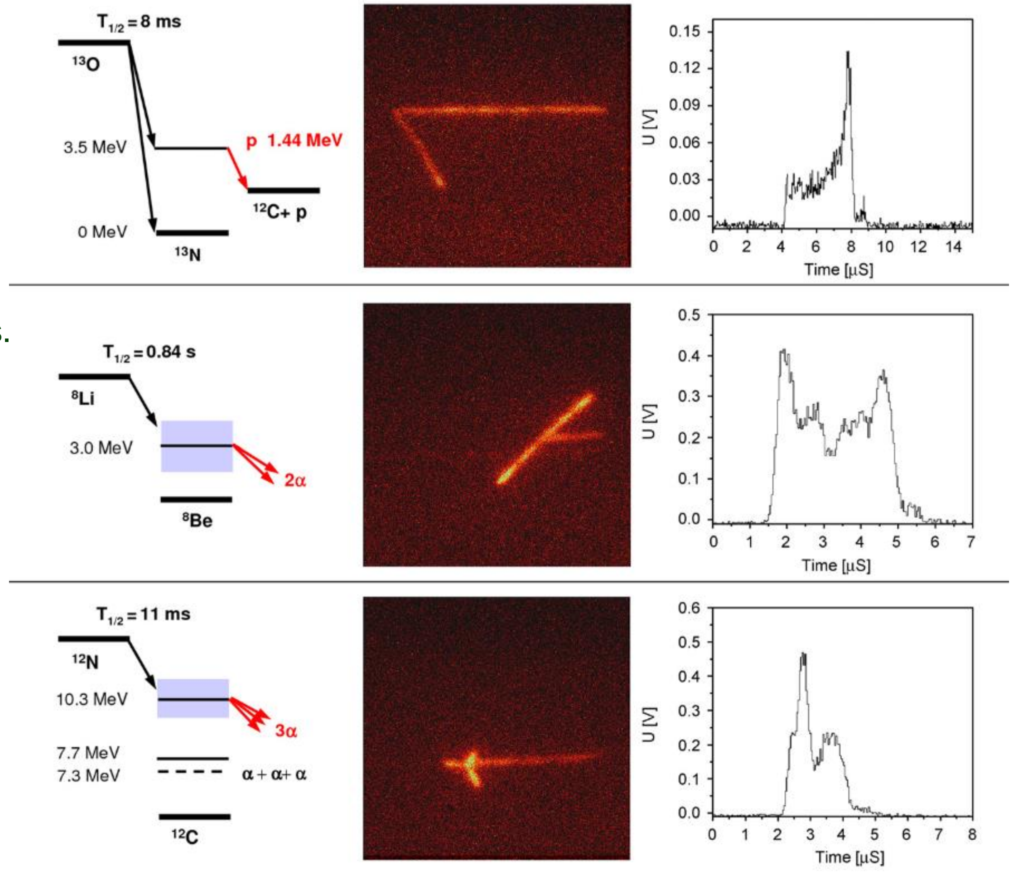
-) Can be placed outside the detector.
Readout decouple from effective volume

-) With suitable lens, large areas coverage using small sensors.

-) Combining the CMOS 2D readout with a time measurement, using a fast light detector like a PMT or a SiPM,
3D reconstruction of the tracks can be achieved.

T. Marley, the Migdal Experiment (MPGD2022)





T. Tanimori et al., Phys. Letters B 578 (2004) 241–246

TPC with Optical readout with M-THGEM

Goal: develop M-THGEM optical readout for TPC operated at low pressure

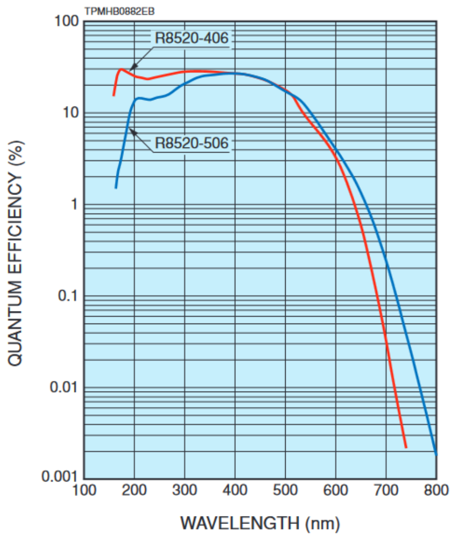
→ Applications: nuclear reaction study (FRIB), direct DM search (Others)

Two-layer M-THGEM:

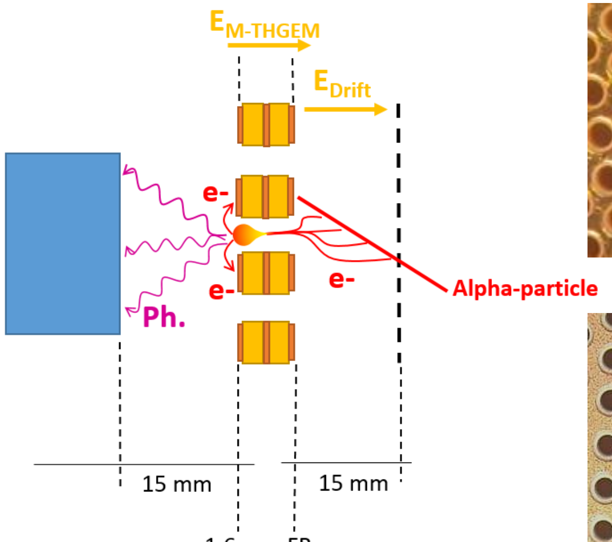
-) Robust structure, long avalanche volume – ideal for low-pressure application

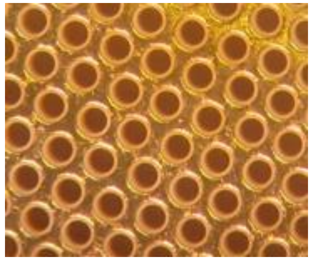
→ High gas gain, high scintillation yield

-) Work in pure elemental (Noble) gases (excellent scintillation yield)

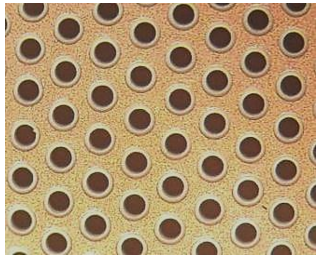


Hamamatsu PMT
Model R8520





FR4 – 1.6 mm thick
0.8 mm pitch
0.4 mm hole diam.
0.1 mm rim

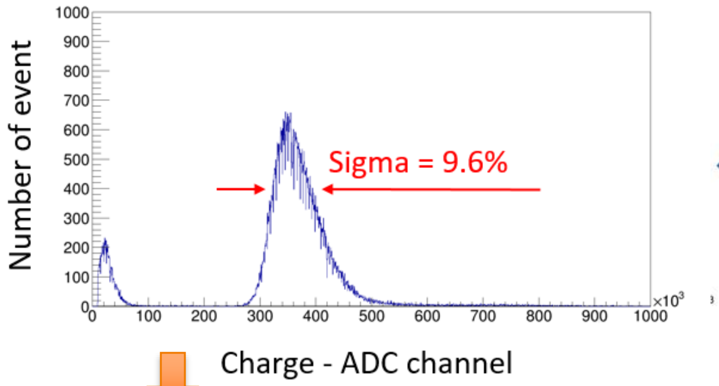


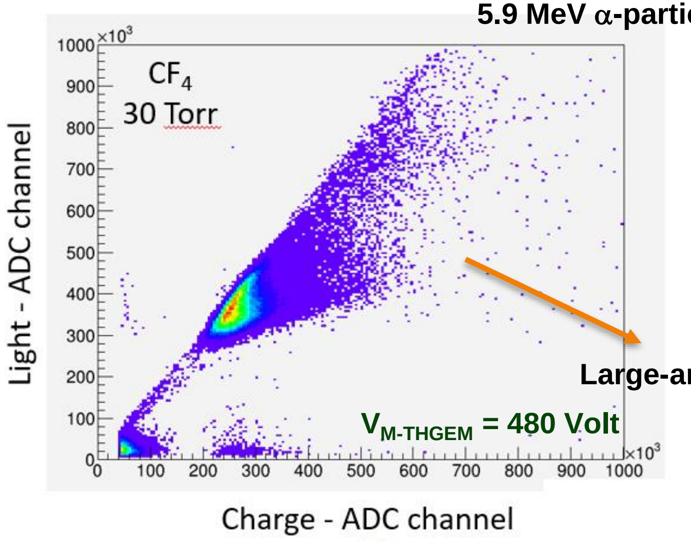
Ceramic – 1.1 mm thick
0.8 mm pitch
0.25 mm hole diam.
0.1 mm rim

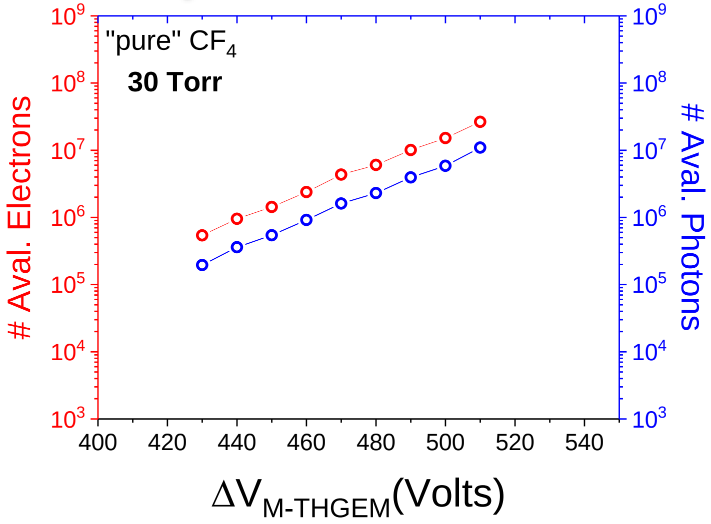
Gas Filling: CF_4 (20-100 Torr) and Ar/5%Xe (20-50 Torr)

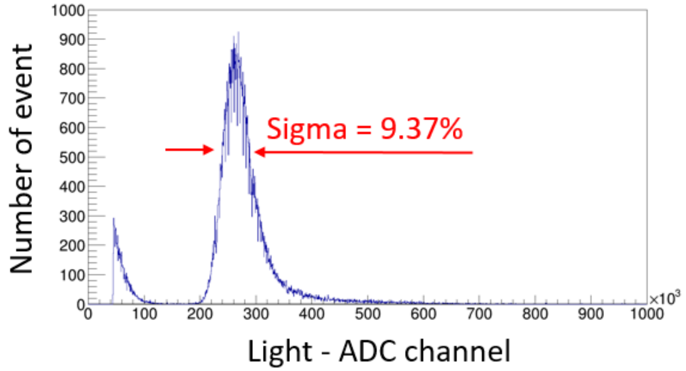
RD51 common project: Cortesi Marco (FRIB), Pawel Majewski (RAL), Ioannis Katsioulas (ESS)

Charge/Light correlation study



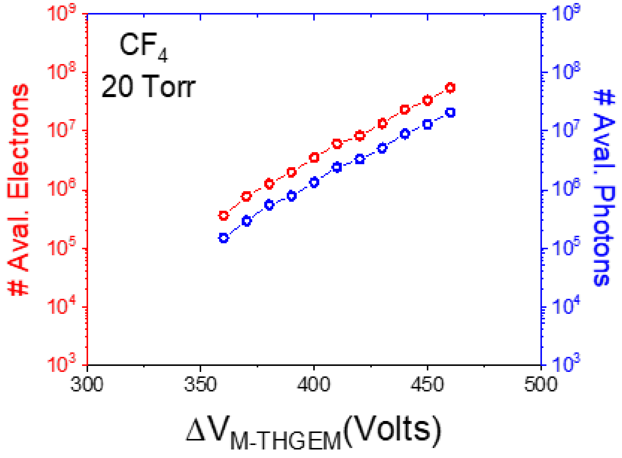


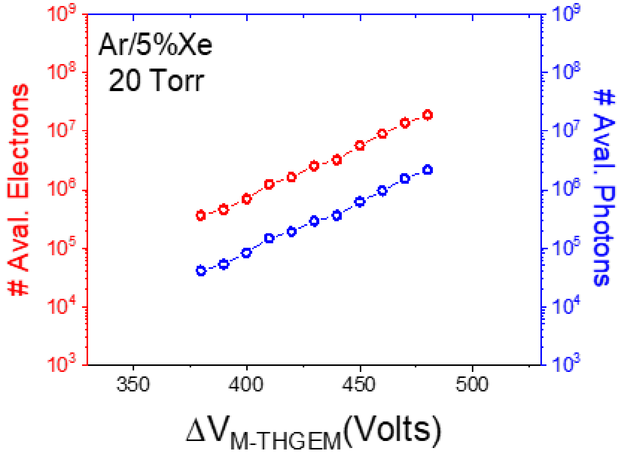




-) Signal process by charge–sensitive pre-amplifiers + ADC-Faster Digitizer

Secondary Scintillation Yield

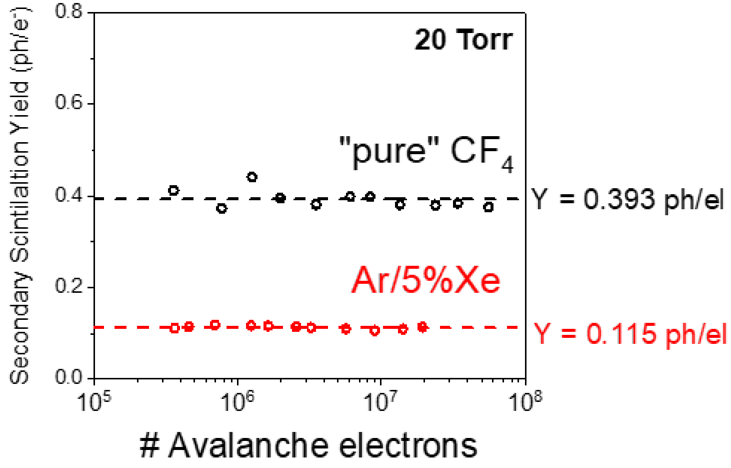




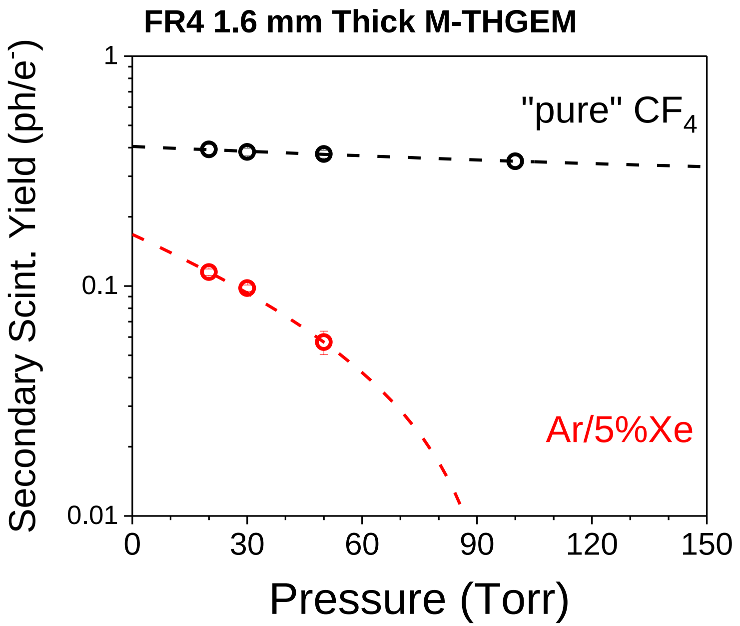
$$Y = \frac{\text{Avalanche Photons}}{\text{Avalanche Electrons}} = \frac{ADC_{light} \cdot Cal_{light}}{ADC_{charge} \cdot Cal_{charge}} \cdot \frac{4\pi}{\Omega} \cdot \frac{1}{GAIN_{PMT} \cdot PDE}$$

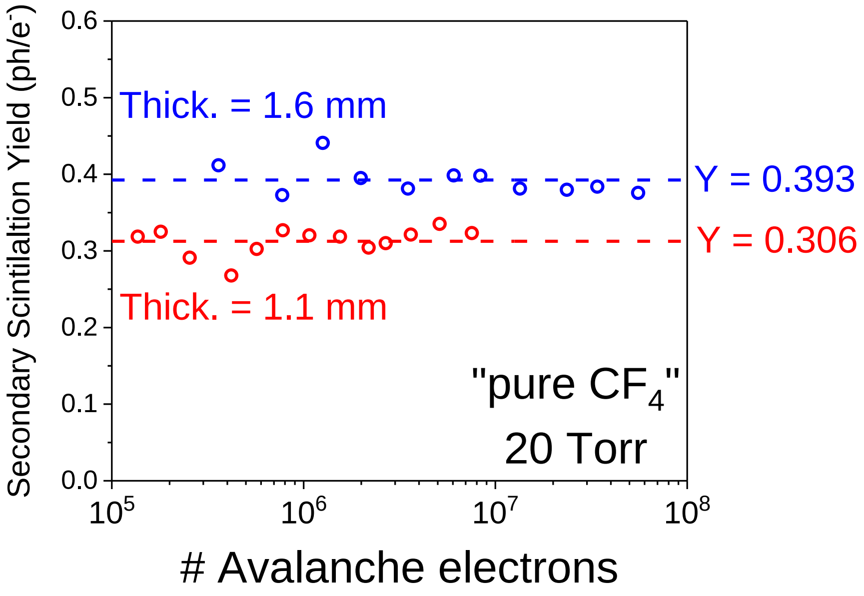
PDE (CF_4) = 14%
PDE (Ar/5%Xe) = 30%

FR4 1.6 mm Thick M-THGEM



Light Yield vs Pressure/Thickness





-) High e- and light gain over a large range of pressures
-) Excellent scintillation at low pressure – long tracks at low energies
-) Larger yield for longer avalanche volume (i.e., thick hole-type multipliers)

Path Forward: Optical readout with M-THGEM couple to a Timepix Optical camera (Y. Ayyad and Leslie Rogers)

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

AT-TPC approved experiments:

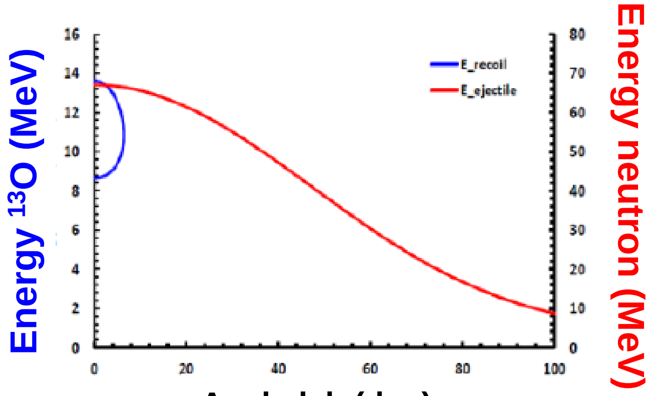
E15328-NSCL:
Measurement of ANC of $^{12}N(p,\gamma)^{13}O$ relevant for the r-process study
Spokesperson: J. Pereira (NSCL).

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***

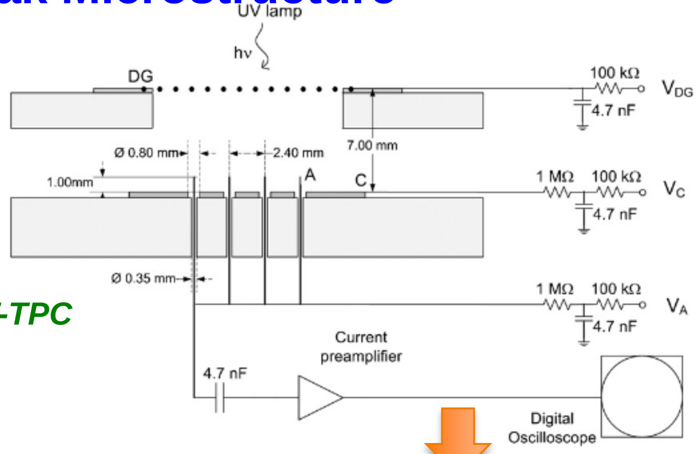
Example: study of $^{12}N(d,n)^{13}O$ reaction to constrain $^{12}N(p,\gamma)^{13}O$ via asymptotic normalization coefficient (ANC) method with 15 MeV/u ^{12}N beam on deuterium or deuterated target.

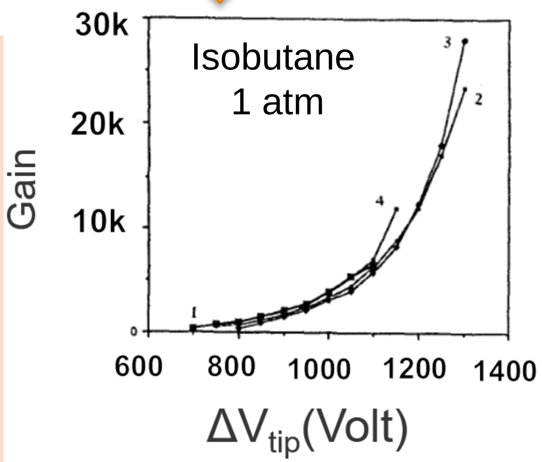


Cannot detect the neutron!
Kinematic variables and PID derived by tracking & stopping the recoiled ^{13}O
→
AT-TPC operated in iC_4D_{10} @ atmospheric pressure

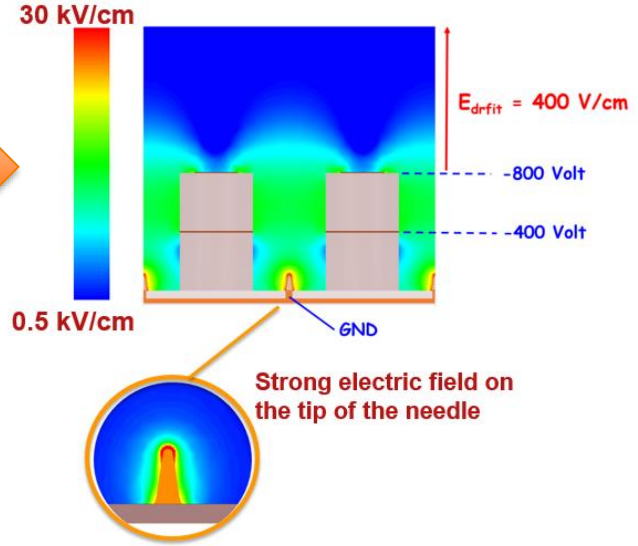
Lombardi et al. 1996 IEEE Conf. Rec., pg. 603-607

Leak Microstructure





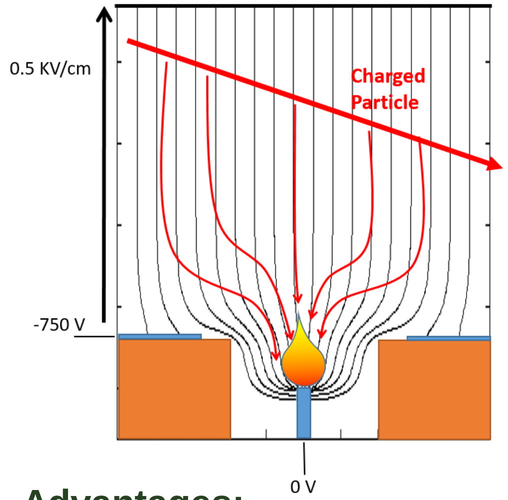
M-THGEM + Tip anode



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.

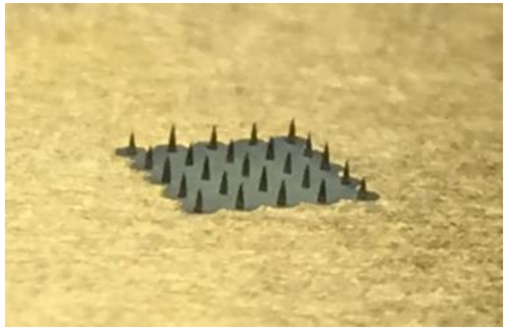
TIP-Hole prototype

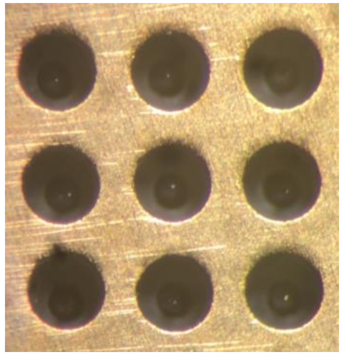
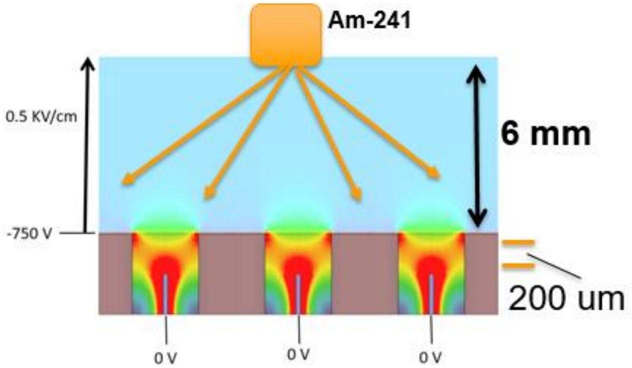
The first "homemade" prototype successfully operated at different pressures in P10



5x5 needles TIP-HOLE detector

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

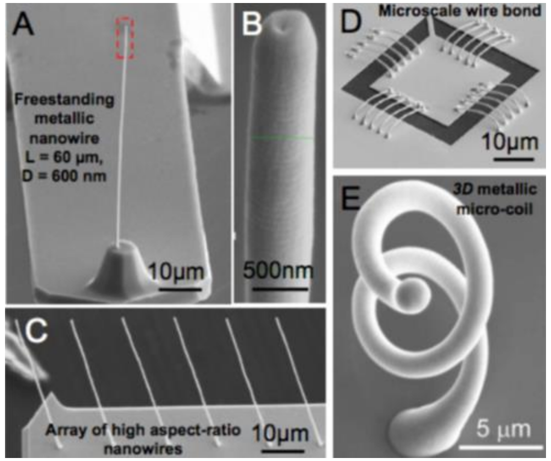


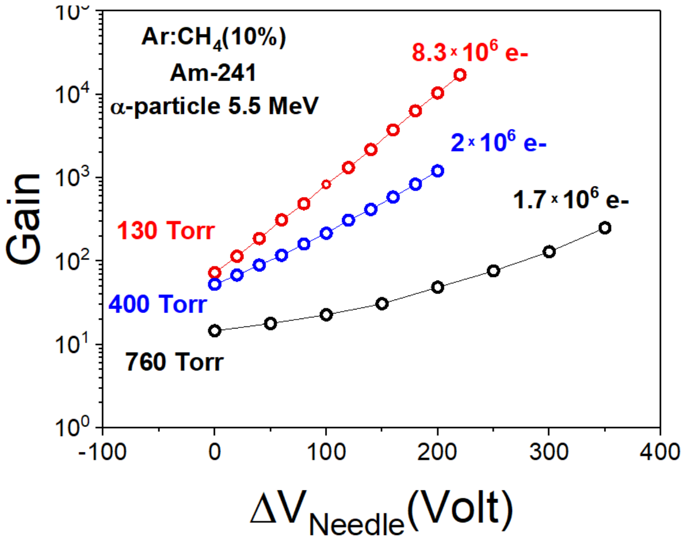



Tattoo Needle (Nickel): Size 00

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

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, Hole-TIP …

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