Towards Directional Dark Matter Detectors using High Gain Negative Ion TPCs with Continuous Radon Reduction

Alasdair McLean[1], Callum Eldridge[1], Robert Renz Marcelo Gregorio[1], Neil Spooner[1], Kentaro Miuchi[2], Hiroshi Ogawa[3].

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1. University of Sheffield. 2. Kobe University. 3. CST Nihon University

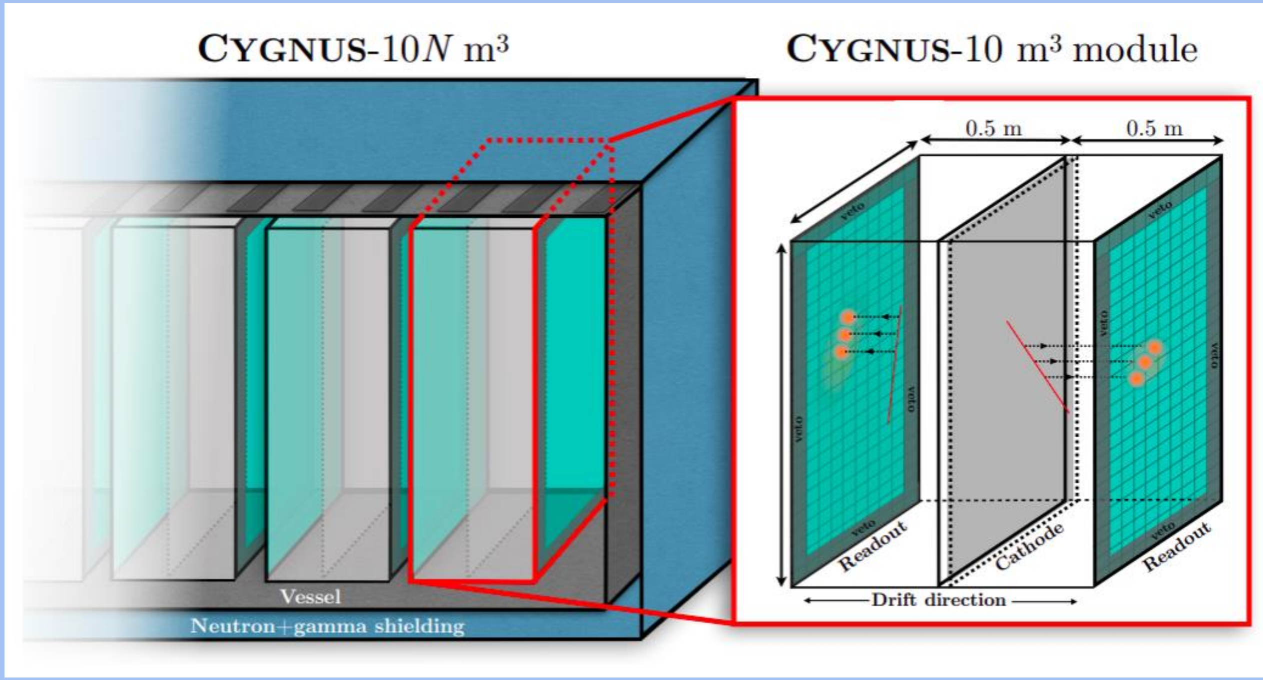
The CYGNUS Collaboration

- CYGNUS proposes a modular and multi site nuclear recoil observatory
- Time Projection Chambers (TPCs) filled with a low pressure negative ion gas like SF_6
- Capable of directional sensitivity to dark matter and neutrinos.

[S. E. Vahsen, C. A. J. O'Hare, W. A. Lynch, et al., Cygnus: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos, 2020.]

CYGNUS detector with a 755:5 He:SF_6 mixture at atmospheric pressure with a 6 year exposure predicts:

1. 10-40 solar neutrinos
2. unexplored sub-10 GeV/c^2



Proposed sites for network:

- Boulby, UK
- Gran Sasso, Italy
- Kamioka, Japan
- Stawell, Australia

Detector Development for NID Gasses

- Sufficient positional resolution is required to achieve directional sensitivity.
- Electrons experience longitudinal and latitudinal diffusion during the drift stage.

Solution: Negative Ion Drift (NID) gasses like SF_6 are much less sensitive to diffusion.

Side effect: Electronegativity makes it more difficult to achieve a sufficient gas gain.

To achieve a sufficient gas gain in a NID gas:

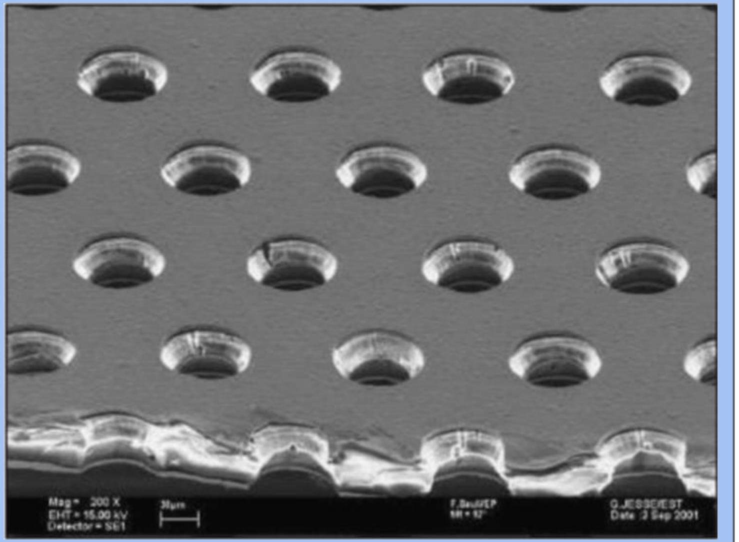
Gaseous Electron Multipliers (GEMs) used as amplification stages

Multiple GEMs/ThGEMs can be used for additional amplification

Arranged in double or triple GEM configurations

Charge can be lost between GEM stages

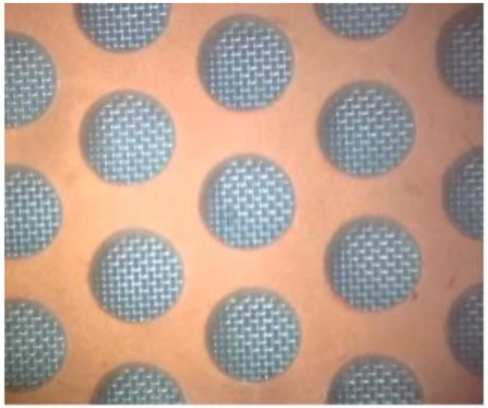
No suppression of Ion Back Flow (IBF)



[F. Sauli, "The gas electron multiplier (gem): Operating principles and applications"]

Multi-Mesh ThGEM (MMTHGEM) Device

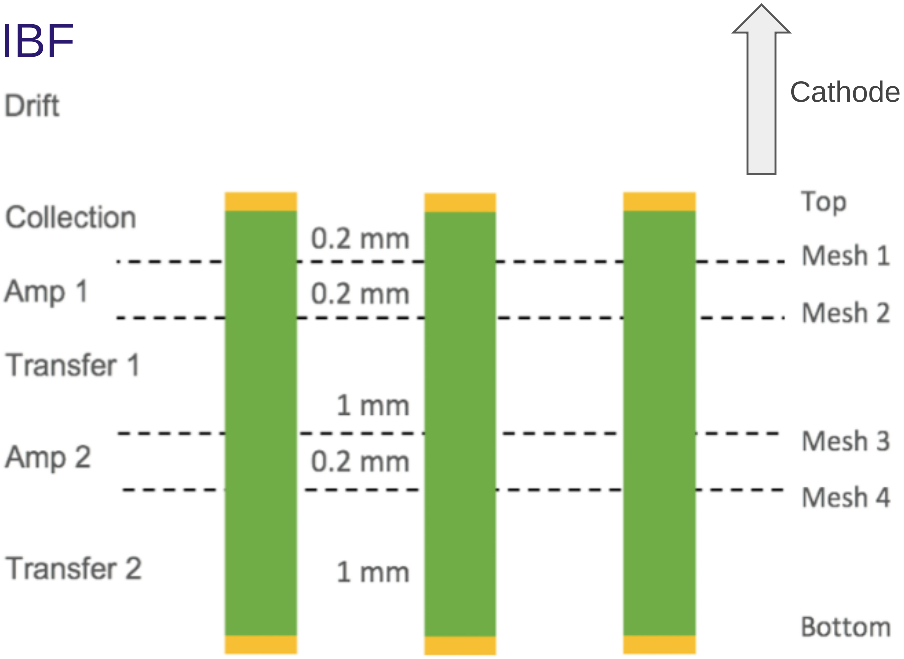
Similar to a ThGEM but it has additional mesh layers.



- Made by MPGD group (CERN)
- Mesh layers make the amplification fields uniform
- Potential to improve the avalanche characteristics
- Reduction in IBF

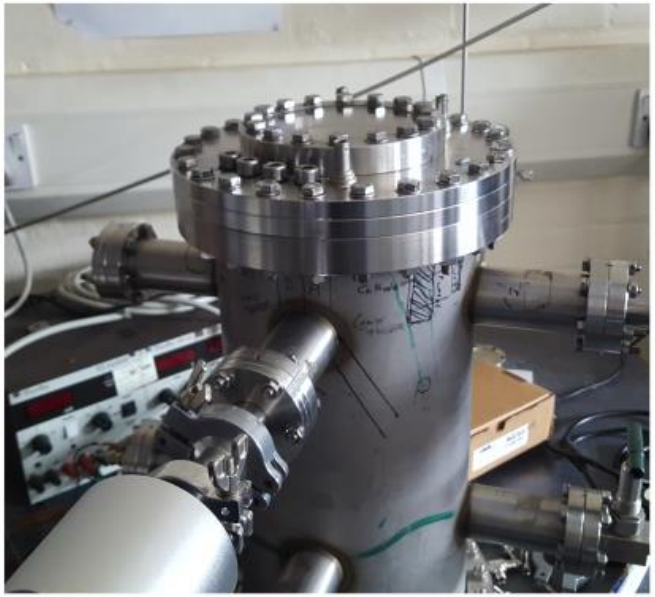
Detector can be divided into six regions:

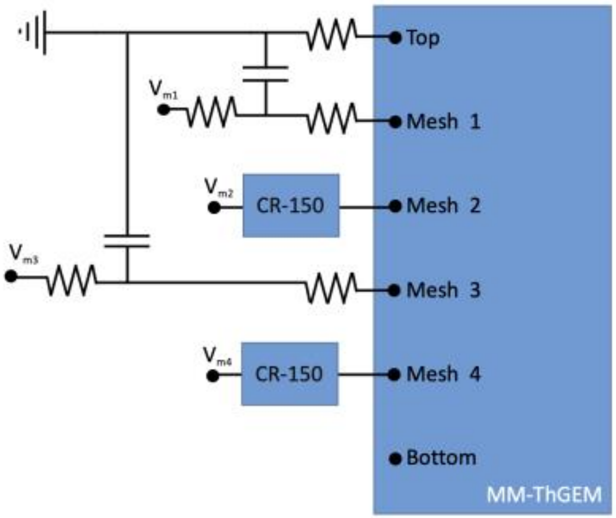
1. drift field
2. collection field
3. first amplification field
4. first transfer field
5. second amplification field
6. second transfer field



Experimental Setup

- MMThGEM device was placed inside a sealed vacuum vessel
- Meshes were biased individually with HV supplies
- M2 and M4 were instrumented with CREMAT preamps and shapers
- The vacuum vessel was evacuated and then filled with the target gas
- ^{55}Fe source inside the vessel with x-rays directed towards the drift volume
- An energy spectrum was collected using an ADC
- Gain and energy resolution calculated from the ^{55}Fe photopeak





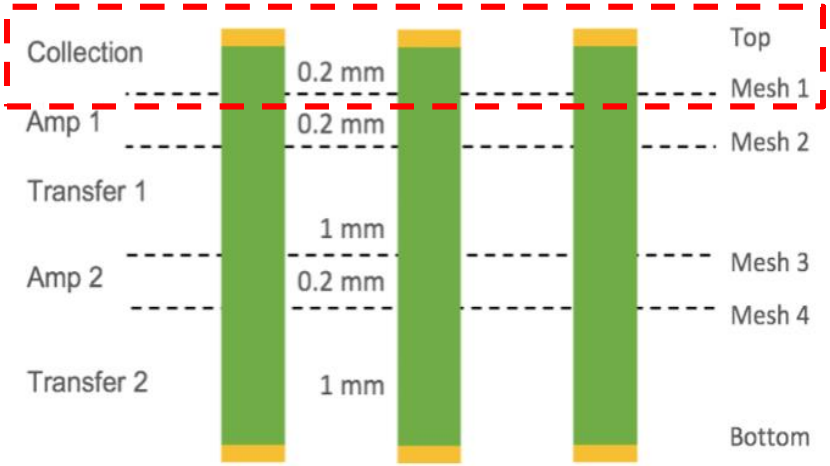
Investigation of Collection Field - CF_4

Motivation:

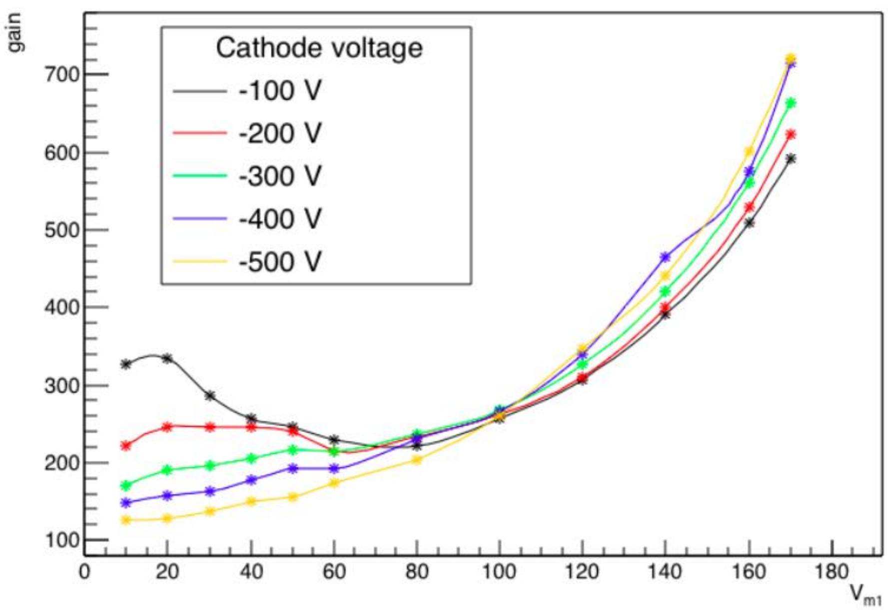
- Does the collection field affect the gain and energy resolution of the device?

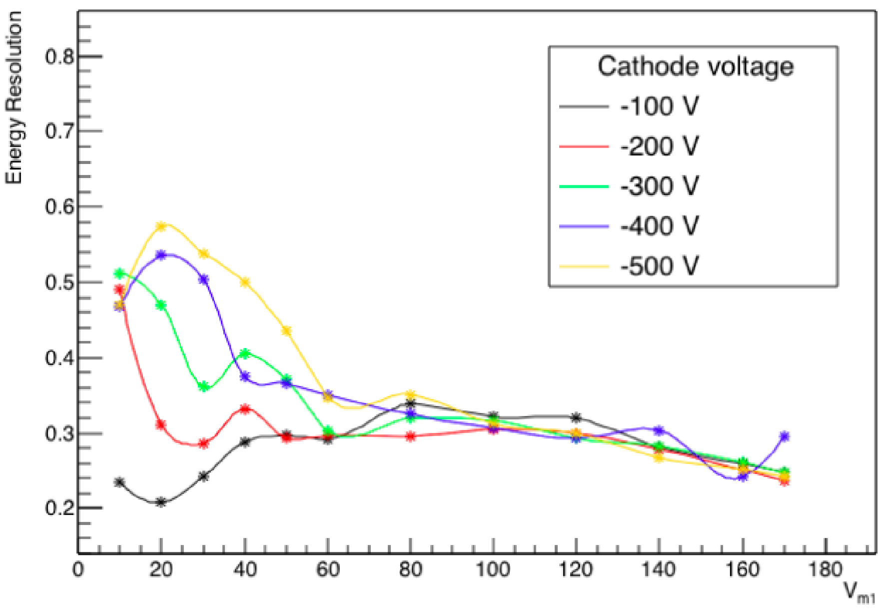
Procedure:

- The first amplification field was held constant at 26500 V/cm
- The cathode voltage was varied from -100 V to -500 V
- The M1 voltage was varied from 10 V to 170 V
- Charge was collected on mesh 2 and the output was passed to the ADC
- CF_4 at 40 Torr was used
- Gain in SF_6 was too small from 1 amplification stage



Investigation of Collection Field - Results





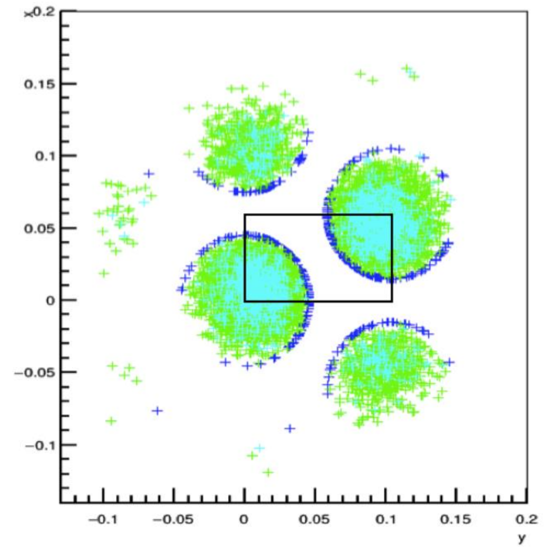
Gain:

- $V_{m1} \leq 60$ V - gain is inversely related to the cathode voltage
- $V_{m1} > 60$ V - gain exponentially increases with increasing V_{m1}

Energy resolution:

- $V_{m1} \leq 60$ V - ER decreases with increasing cathode voltage
- $V_{m1} > 60$ V - ER independent of cathode voltage

Simulation of Collection Field using Garfield++

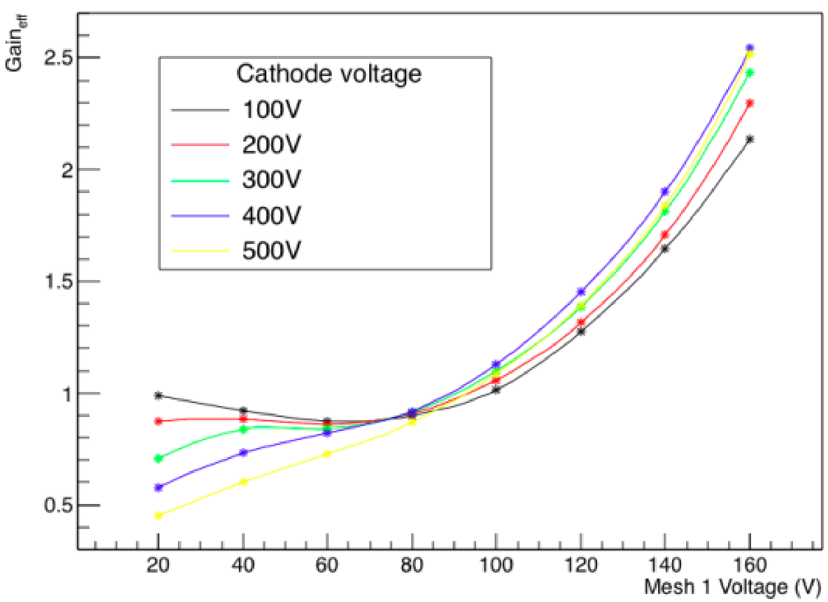


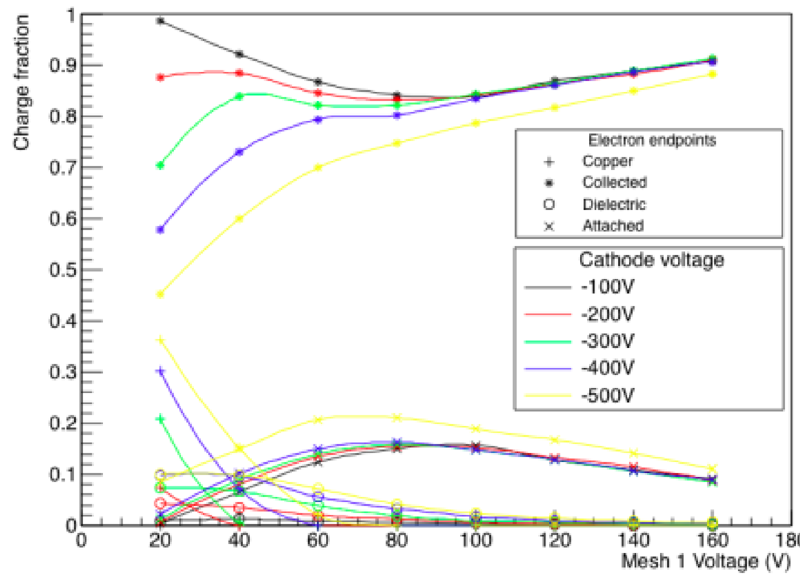
Details of simulation:

- The drift and collection field were simulated
- Electron drift was simulated from a starting point 8 mm above the holes
- The position was randomised but confined to a single cell (black rectangle)
- The electron endpoints were recorded

Results:

- Effective gain shows same trend as experimental gain
- Experimental energy resolution could be explained by the electron endpoints





Collection Field - Conclusions

- Collection field significantly affects the gain and energy resolution of the device
- Simulated effective gain is in agreement with experimental results
- Simulation suggests that energy resolution is likely limited by the charge collection

Operation in SF_6

- Single amplification stage is insufficient to observe the ^{55}Fe signal in SF_6
- Both amplification fields had to be utilised and signal was measured on mesh 4
- Contributions of the two amplification fields to the total gain difficult to disentangle

Two approaches were employed to investigate the amplification fields:

Equal Amplification Field Strengths

Gain should be equal in both stages

For all runs:

- V_{m1} was held at 30 V
- Cathode was held at -500 V
- Amp 1 = Amp 2

20 Torr:

- Transfer field was held at 500 V/cm

30 and 40 Torr:

- Transfer field was held at 600 V/cm

Constant Amplification Field 1

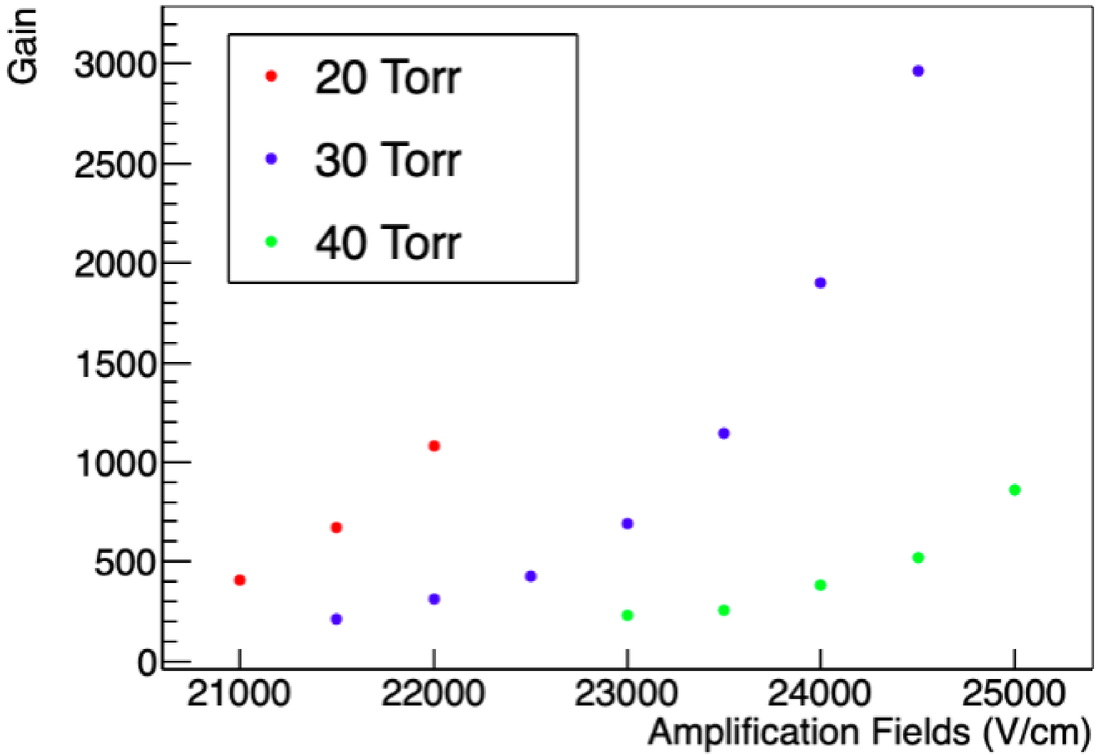
For all runs:

- Cathode was held at -500 V
- V_{m1} was held at 140 V
- Transfer field was held at 600 V/cm

Amplification Field 1 Strengths:

- 20 Torr = 22000 V/cm
- 30 Torr = 23500 V/cm
- 40 Torr = 26000 V/cm
- 50 Torr = 28500 V/cm

Equal Amplification Fields - Results



Townsend gas parameters:

$$\ln(Gain) = dPAe^{-\frac{BP}{E}}$$

Extended to 2 gain stages:

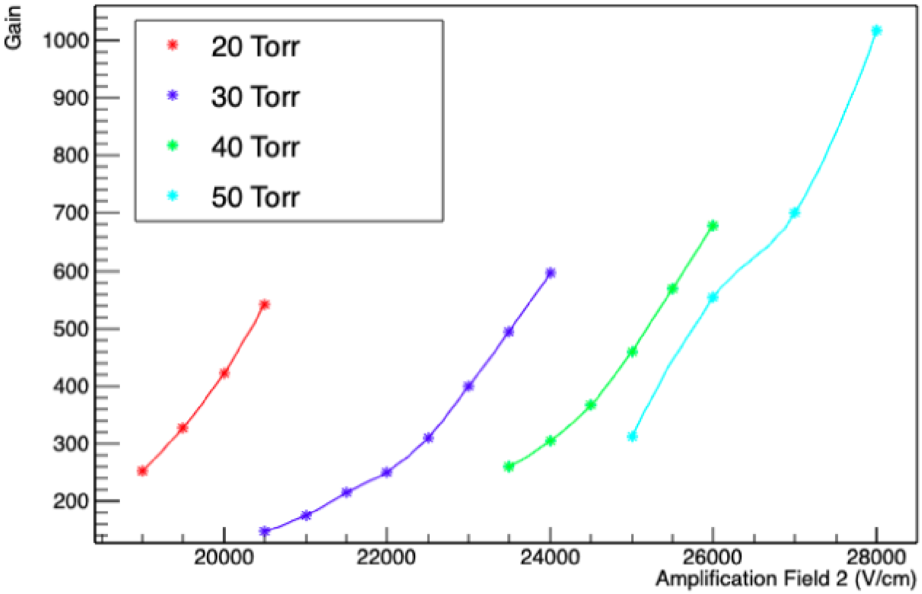
$$\ln(\ln(Gain)) = \ln(2dPA) - \frac{BP}{E}$$

ln(ln(Gain)) vs 1/Amplification field

Linear regression → A and B

Pressure (Torr)	A (cm^{-1} $Torr^{-1}$)	B (V cm^{-1} $Torr^{-1}$)	λ (μm)	I_e (eV)
20	201 ± 10	3500 ± 50	2.49 ± 0.12	17.4 ± 0.9
30	176.5 ± 15	2666 ± 66	1.89 ± 0.16	15.1 ± 1.3
40	89.0 ± 30	1909 ± 120	2.81 ± 0.95	21.4 ± 7.4

Constant Amplification Field 1 - Results

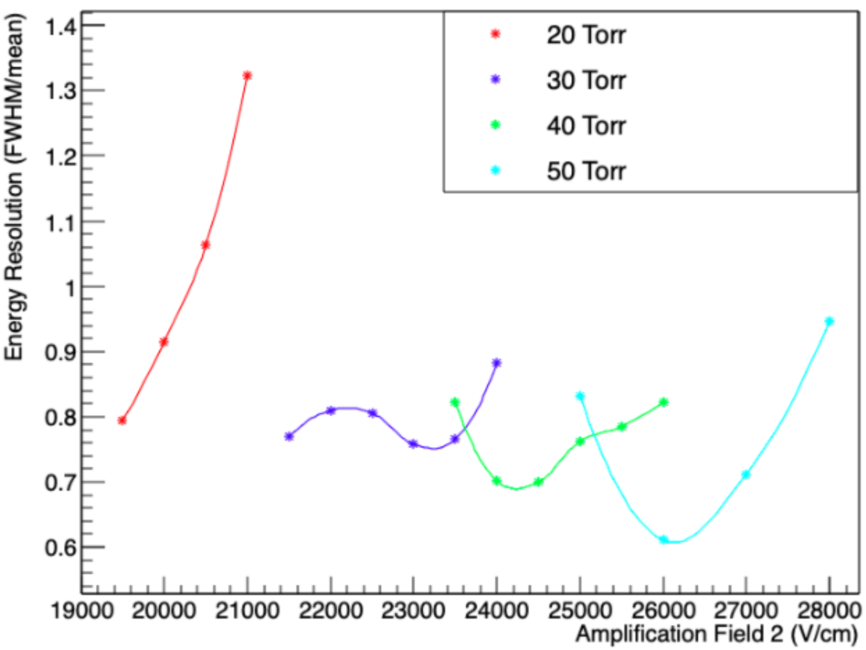


Gas Gain

- Gain does not appear to be strictly exponential
- Exponential exponential at lower pressure/field
- Linear at higher pressure/field
- Artifact of charge transport between regions

Energy Resolution

- Some minima in energy resolution observed
- Best energy resolution was obtained with 50 Torr at 60%
- Locations of minima used for optimisation of the device
- Minima occur when 2nd amplification field is lower than 1st



Could be a trade off between:

1. amount of charge reaching the detection element
2. degradation approaching the maximum operating voltage

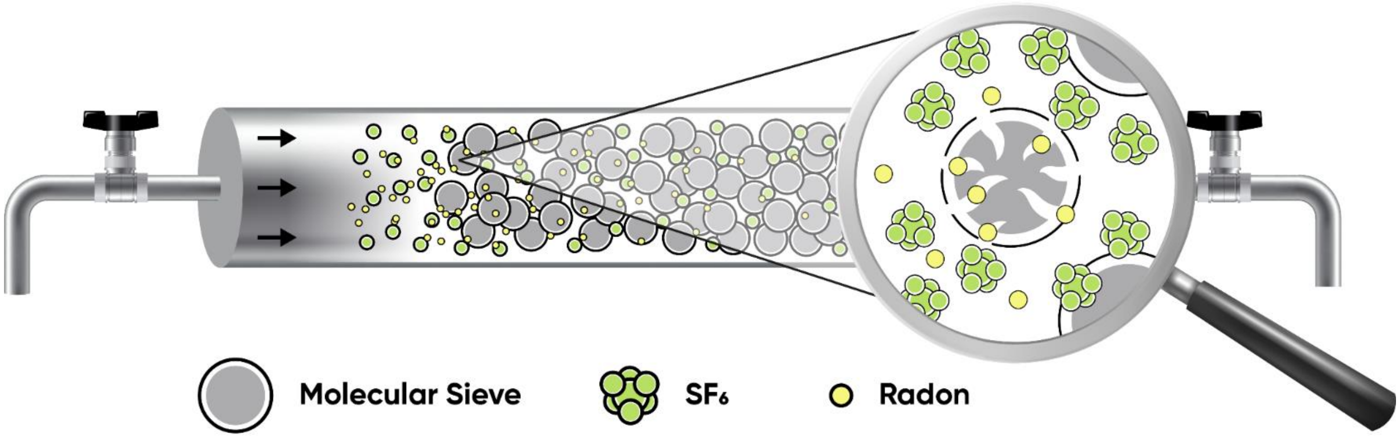
Operation in SF_6 - Conclusions

- Successful operation of the MMThGEM in low pressure SF_6
- Highest gain (3000) achieved in 30 Torr SF_6 with equal fields = 24500 V/cm
- Equal field strengths allowed the extraction of the Townsend parameters
- Optimisation of the device with distinct minima in the energy resolution
- Measurements did not account for charge transport between the regions

Future work:

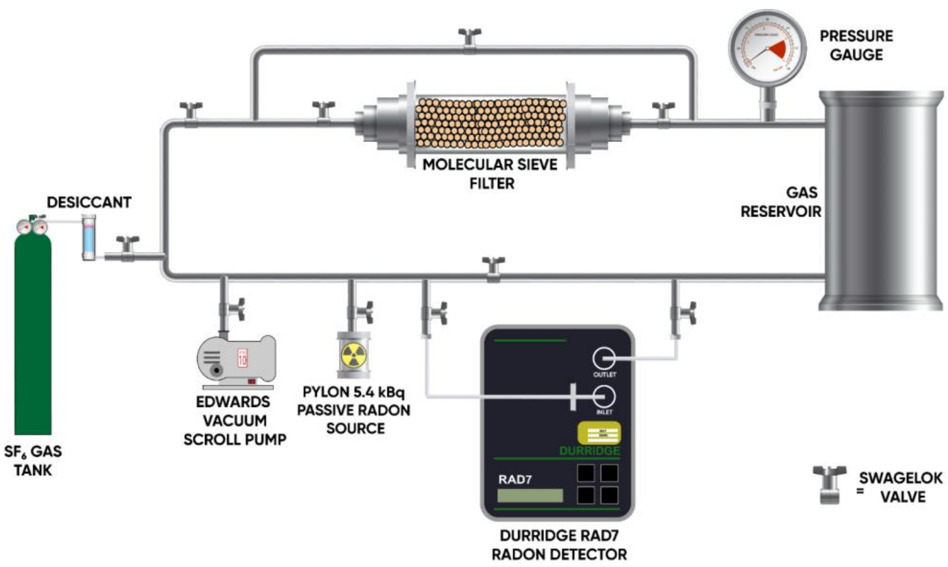
- Charge transport/mesh transparency
- Helium gas mixtures

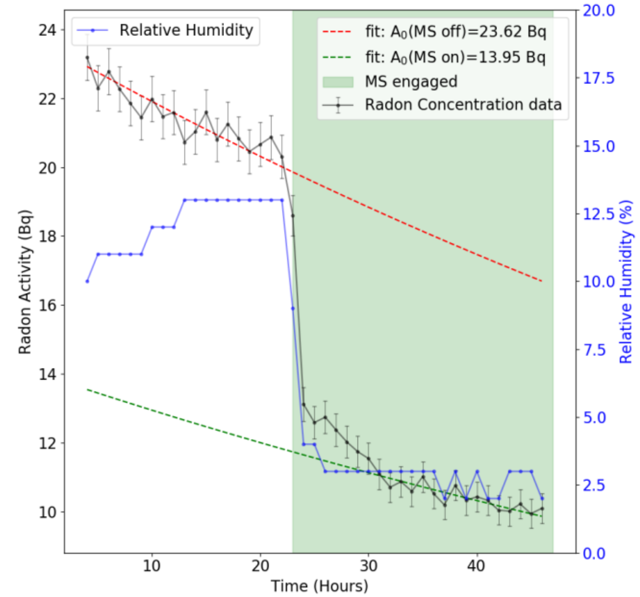
Molecular Sieves for Radon Reduction



- Molecular sieves (MS) are structures with specific pore sizes.
- Pores allow molecules with the critical diameter equal or below to be adsorbed on to the structure
- Molecules with diameters larger than the critical diameters pass between the bead gaps
- A good sieve should: absorb radon without absorbing target gas and not emanate radon itself

MS Radon Filtration

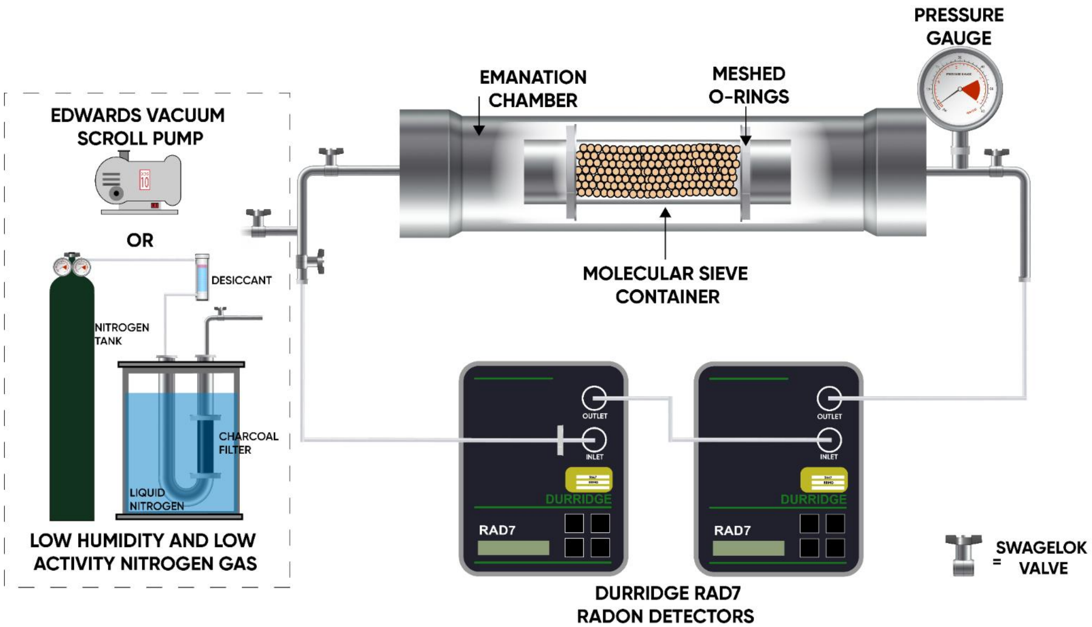


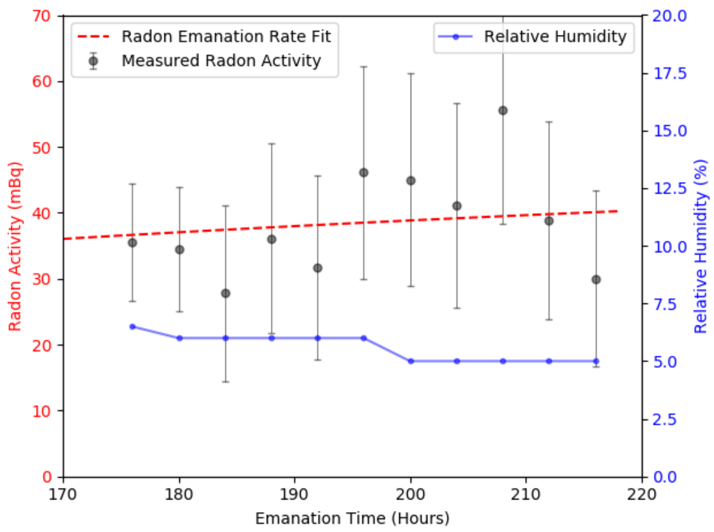


- Demonstration of radon removal from SF6
- Radon removed from SF6 by 97±1 Bq/Kg
- Can be further improved by cooling molecular sieve filter

[R.R. Marcelo Gregorio et al., Demonstration of radon removal from SF6 using molecular sieves]

MS Intrinsic Radon Emanation





- Commercial MS intrinsically emanate radon at levels unsuitable for ultra-sensitive rare-event physics experiments (525±37 mBq/kg)
- Goal is to maximise amount of MS allowed by radioactive budget of an experiment ~ 1 mBq
- **We need to identify a low radioactive MS**

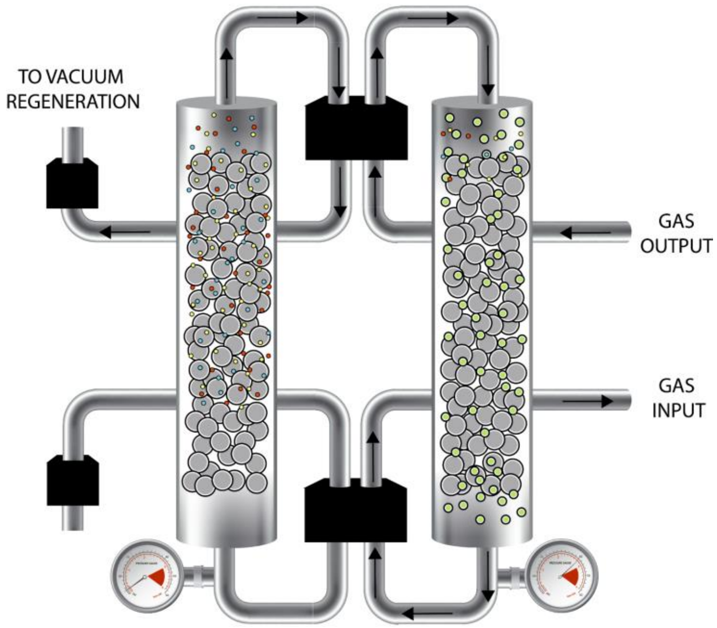
[R.R. Marcelo Gregorio et al., Test of low radioactive molecular sieves for radon filtration in SF6 gas-based rare-event physics experiments, 2021]

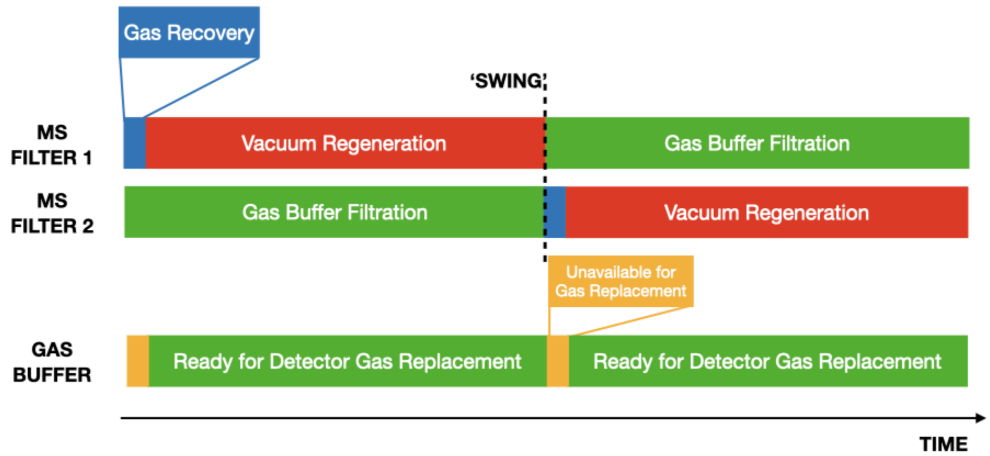
Low Radioactive MS

MS	Geometry	Rn emanated mBq/kg	Rn Captured Bq/kg	Emanated per captured x10^{-3}
Sigma Aldrich (Commercial)	8-12 mm uniform Beads	525±37	97±1	5.4±0.7
Nihon-Uni (V1)	1-2 cm Granules	99±23	35±2	2.8±0.4
	Fine Powder	680±30	330±3	2.1±0.1
Nihon-Uni (V2)	Powder	<32	254±3	**<0.12**

- **The NU-developed (V2) 5Å MS emanated radon at least 98% less per radon captured, compared to the commercial Sigma-Aldrich MS**

MS Gas Recycling System





- MS are regenerated using a vacuum to desorb the captured gas components
- Dual MS design utilises Vacuum Swing Adsorption (VSA) Technique, allowing the continued use of absorbent material by simultaneous regeneration and filtration

Final Conclusions

- MMThGEM has been investigated as a new technology for use in a NID gas TPC
- Gain and energy resolution were shown to be strongly dependant on the collection field
- Maximum gain achieved in SF6 was 3000 but could be higher with more comprehensive optimisation
- Device shows promise to be optimised based on energy resolution
- Molecular Sieves are a promising route for radon removal

Thank you for listening

Any questions?

References

[1] S. E. Vahsen, C. A. J. O'Hare, W. A. Lynch, et al., Cygnus: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos, 2020. arXiv:2008.12587

[2] F. Sauli, "The gas electron multiplier (gem): Operating principles and applications," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 805, pp. 2–24, 2016, Special Issue in memory of Glenn F. Knoll, issn: 0168-9002.

[3] R.R. Marcelo Gregorio et al., Demonstration of radon removal from SF6 using molecular sieves, 2017 JINST 12 P09025.

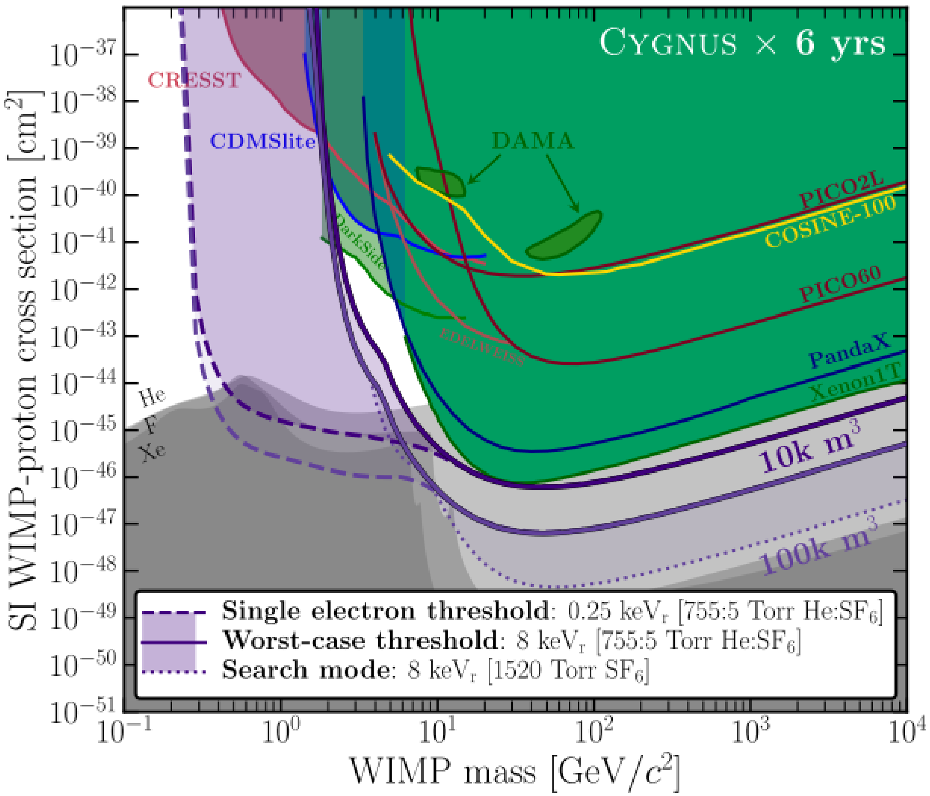
[4] R.R. Marcelo Gregorio et al., Test of low radioactive molecular sieves for radon filtration in SF6 gas-based rare-event physics experiments, 2021 JINST 16 P06024

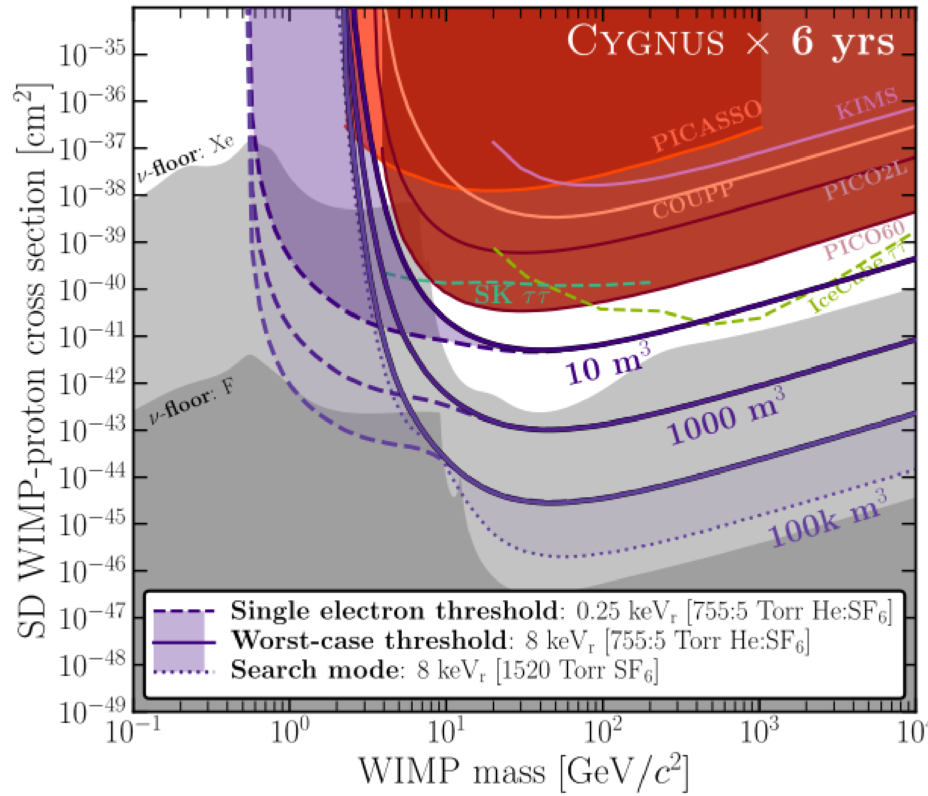
CYGNUS WIMP Limits

CYGNUS WIMP cross sections compared to other DM searches

Worst case threshold 8 keV_r above which ERs rejected by factors greater than 10^3–10^4

Best case threshold 0.25 keV_r, physical limit for the detection of 1 electron



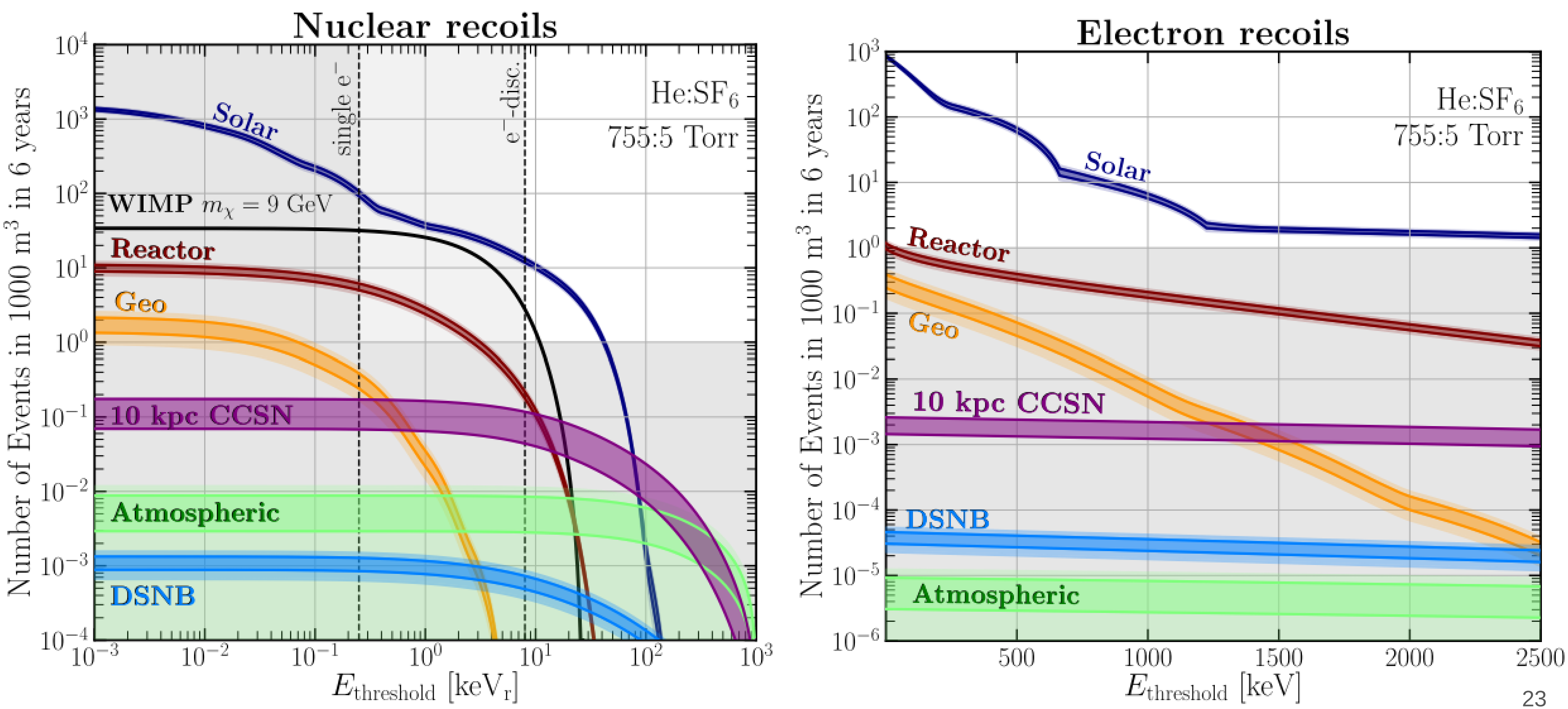


CYGNUS Neutrino Recoil Events

Most important neutrinos originating from originating from ^{8}B decay

Best (0.25 keV_r) and worst (8keV_r) case scenario for the energy threshold

10 - 40 nuclear recoils induced by solar neutrinos over a six year exposure



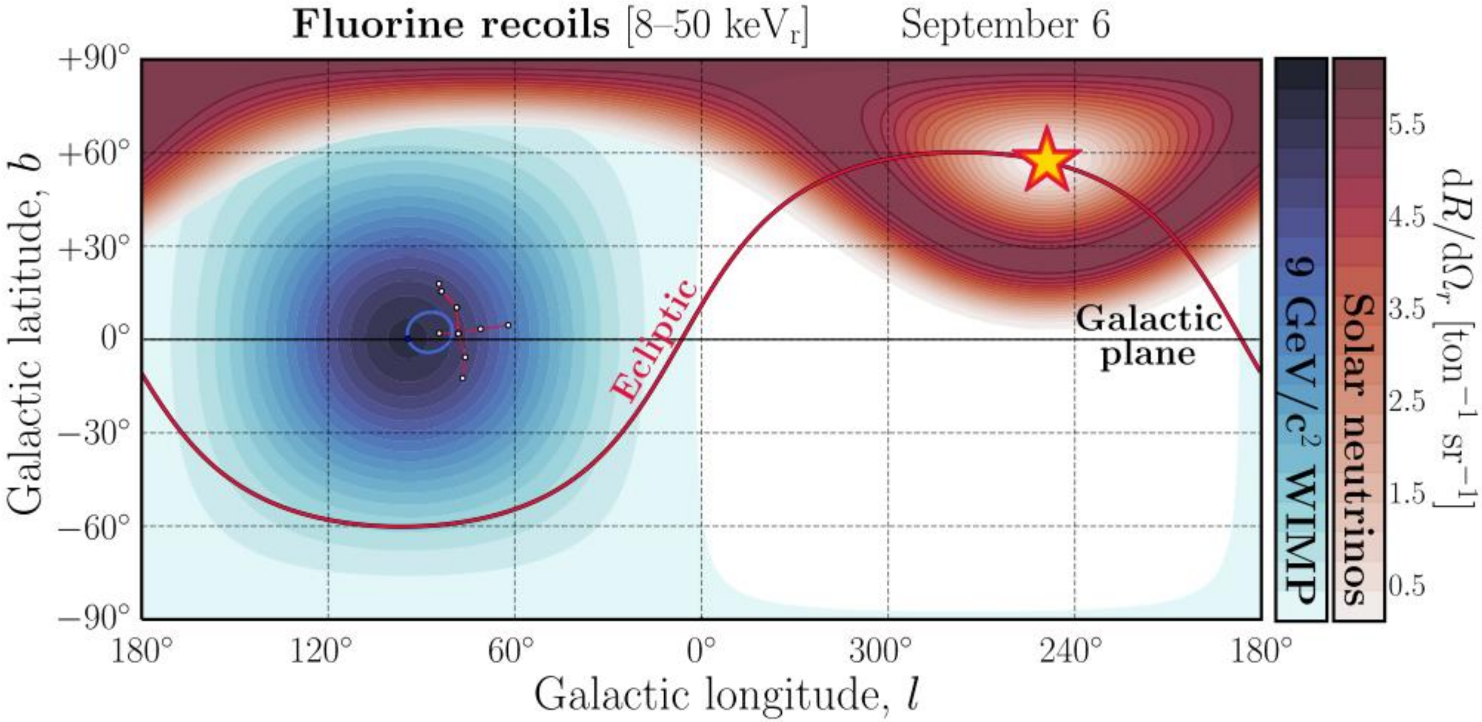
WIMP Detection Below Neutrino Floor

Directionality facilitates WIMP search below Neutrino floor

Unique angular signatures

DM appears to originate from CYGNUS constellation

Minimum separation of 60° in March, maximum of 120° September



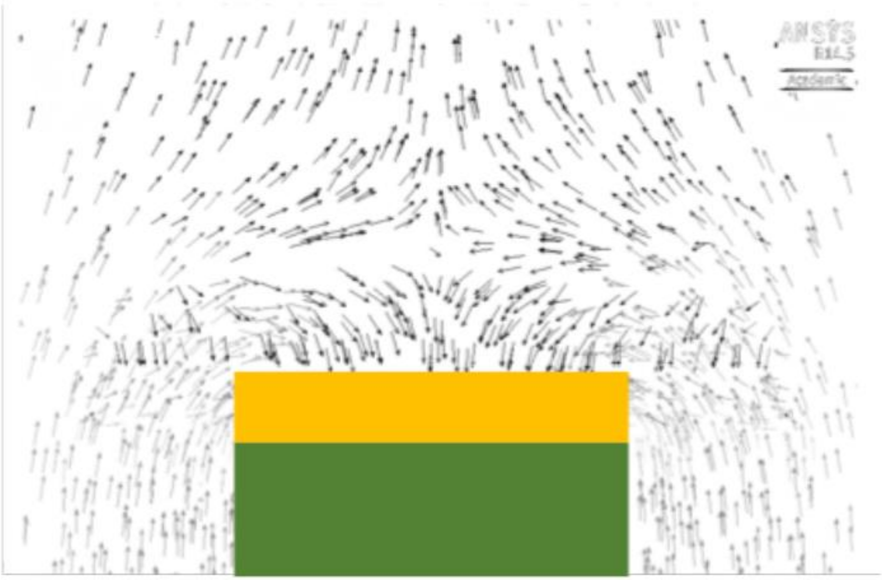
GARFIELD++ Field Shape

Arrows represent direction of electric field and the length indicates the strength

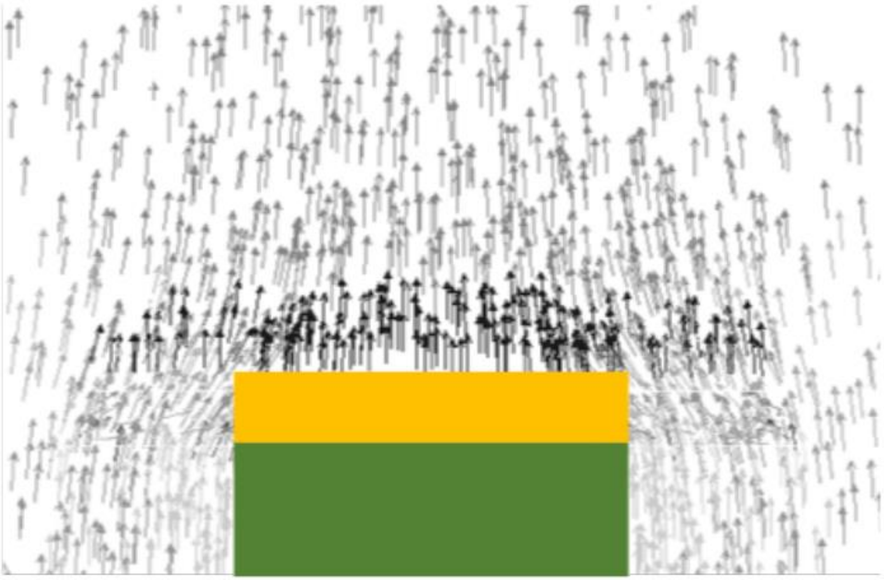
Lower strength drift field has dipole like shape

This shape is more likely to funnel electrons into the holes

Explains the improvement collection efficiency and ER at lower drift fields



(a) $V_{m1} = 20\,V,\ V_{cath} = 100\,V.$



(b) $V_{m1} = 20\,V,\ V_{cath} = 500\,V.$

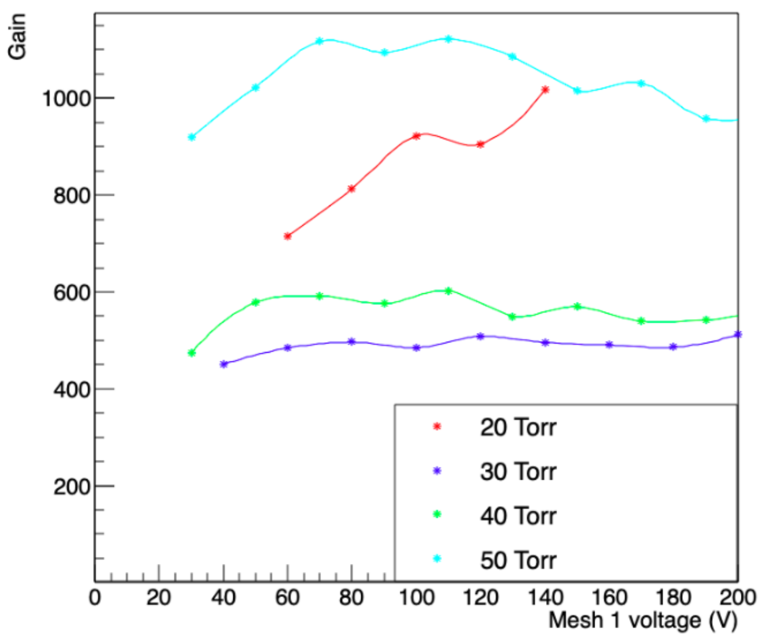
Collection Field in SF_6

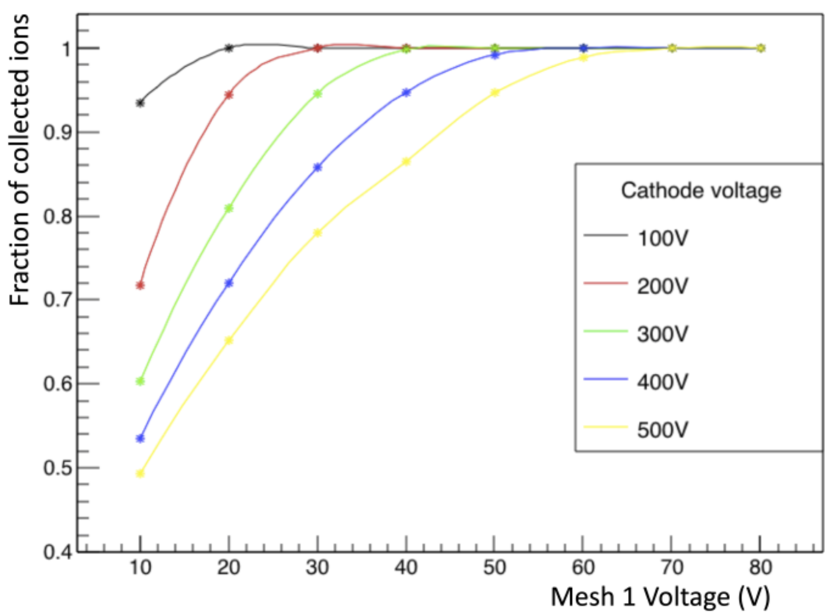
Keeping all the fields constant and varying the mesh 1 voltage

Does not significantly affect negative ion collection efficiency

Garfield “hack” using +ve ions and reversing fields

Suggest collection efficiency plateau above 70 V





Gain Calibration

Ortec pulser used to calibrate electronics via a capacitor on the evaluation board

Pulse with V_{max} can be used to determine how much charge reaches the preamp

Output of preamp can be used to calculate the electronic gain

V_{max} output for fast signal

Integrated output for slow signal

Gas gain determined from W-value

electrons = X-ray Energy / W-value