The Effects of a Passive Bi-Polar Grid (BPG) on Ion Back Flow (IBF) & Resolution

Vladislav Zakharov

Department of Physics and Astronomy,
SUNY, Stony Brook, NY 11794-3800, USA

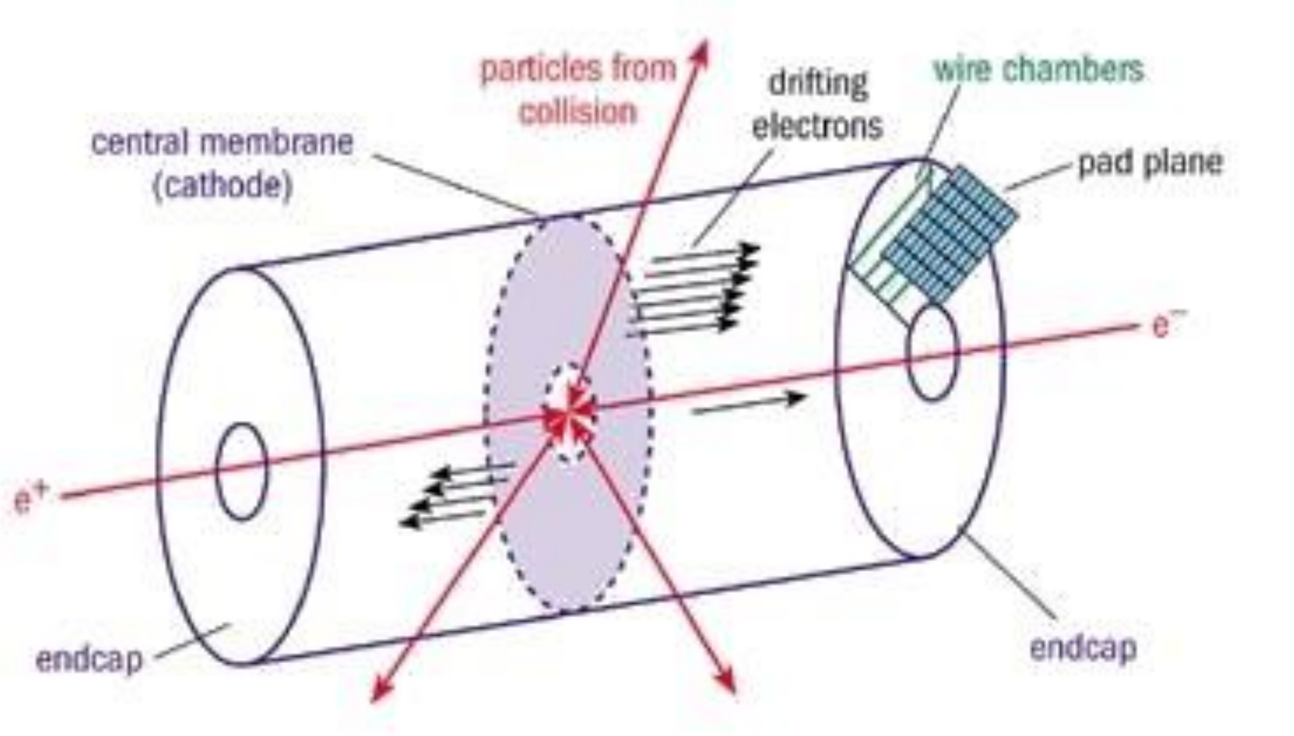
MPGD December 16, 2022

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Stony Brook University

Time Projection Chamber (TPC)[1]

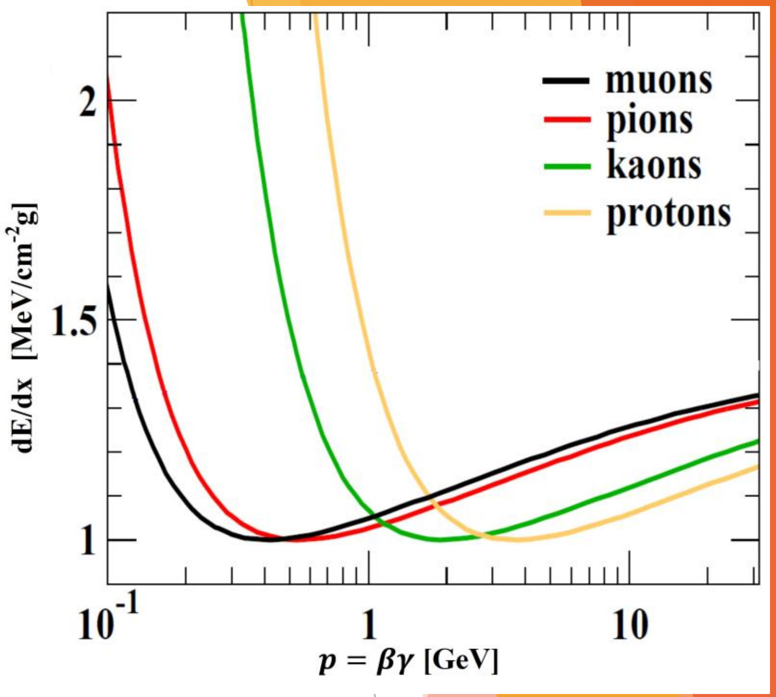
- Measures 3D space points of charged particles
- Gives Particle Identification (PID), dE/dx, & position resolution
- External $\vec{B}$-field lowers diffusion and is used for PID
- Minimally Ionizing Particle (MIP) creates electron-ion pairs
- Cathode & Anode collect charge and maintain uniform $\vec{E}$-field
- Intrinsically high-rate



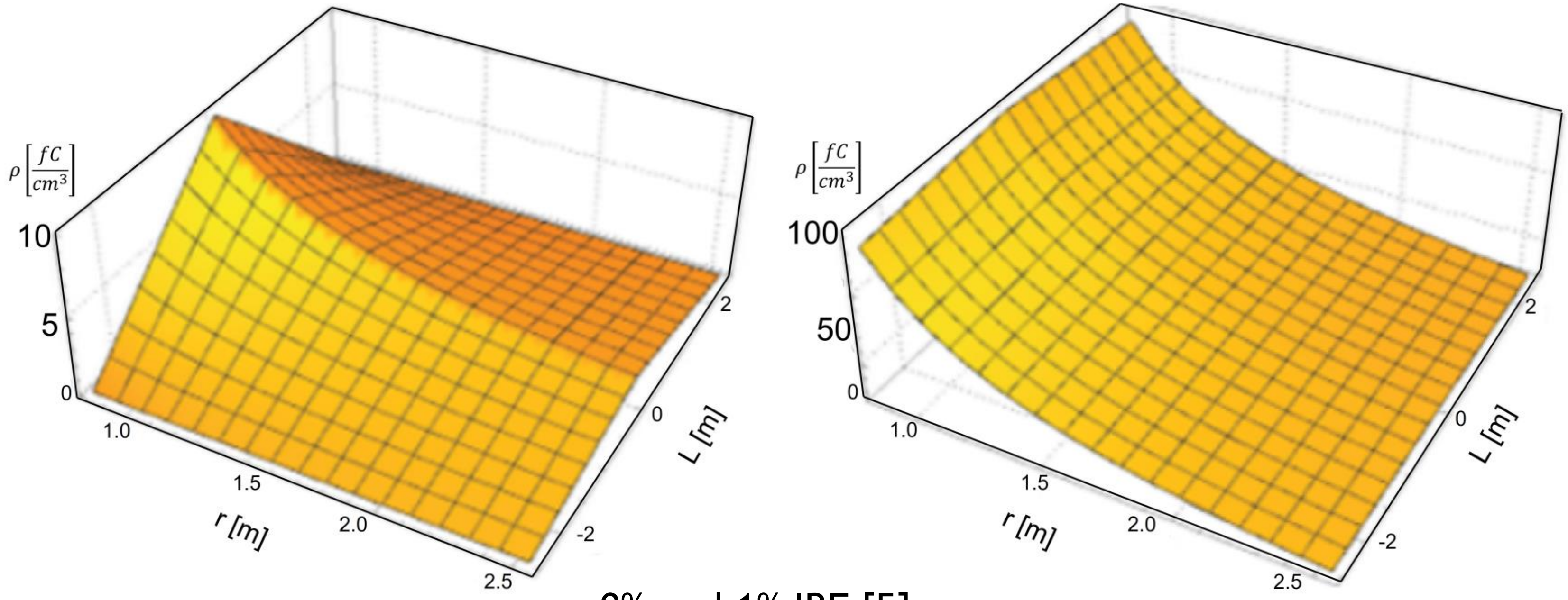
Typical Collider TPC [2]

Gain IBF & Space Charge (SC)

- Most tracks come from MIPs
- Release 1-3 electrons per atom [3]
- MWPC, GEM, & μM create ~1,000 gain to overcome noise
- $\vec{E}$-field distortion SC: $\rho(r,z) \propto \left(1 - \frac{L}{L_{total}}\right) + i$
- At 1% IBF 1 primary ion makes 10 gain ions: IBF is 90% of SC
- IBF limits the TPC's high rate



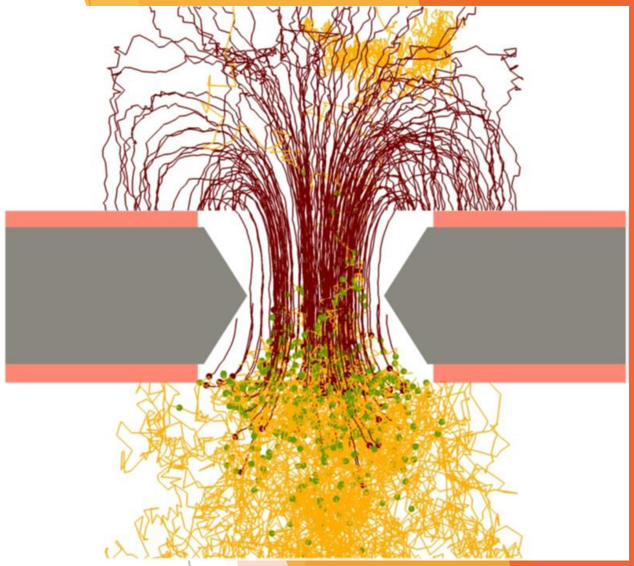
Bethe-Bloch region [4]



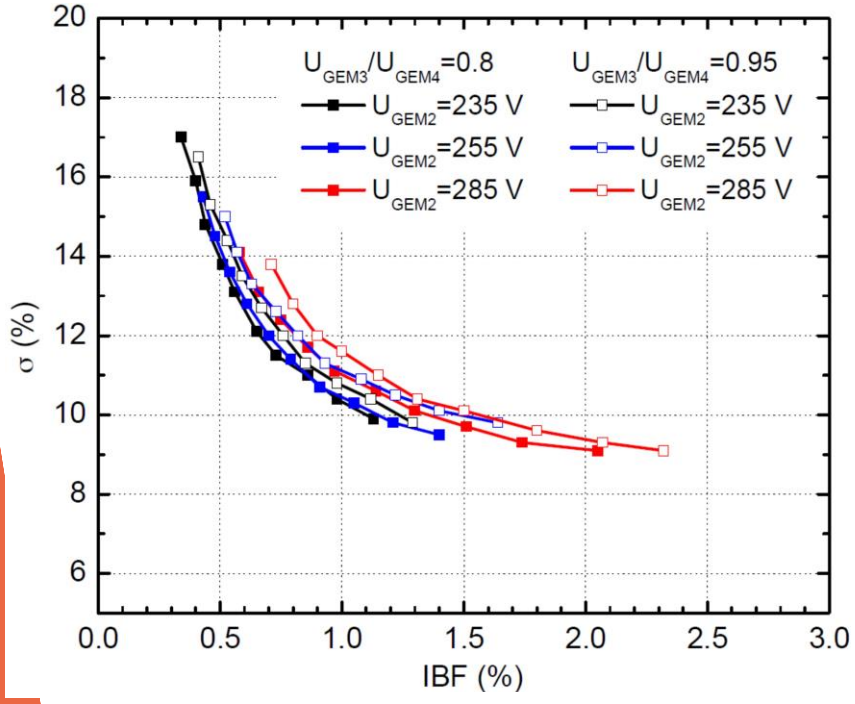
0% and 1% IBF [5]

$\vec{E}$-Field Ratios, Gain & Resolution

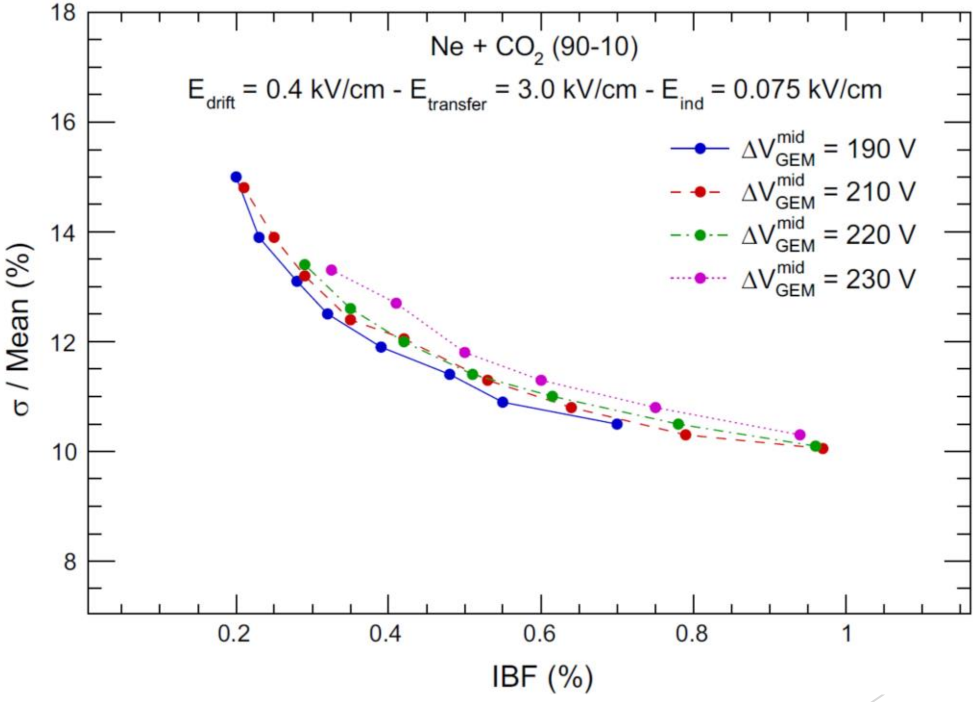
- Field lines can't cross & must start and end on charges
- $E_{below\ (transfer)} > E_{above\ (drift)}$ allows drift electrons to pass through while trapping most gain ions
- Gain biased away from the element that's strongly coupled to drift region causes fluctuations and hurts resolution



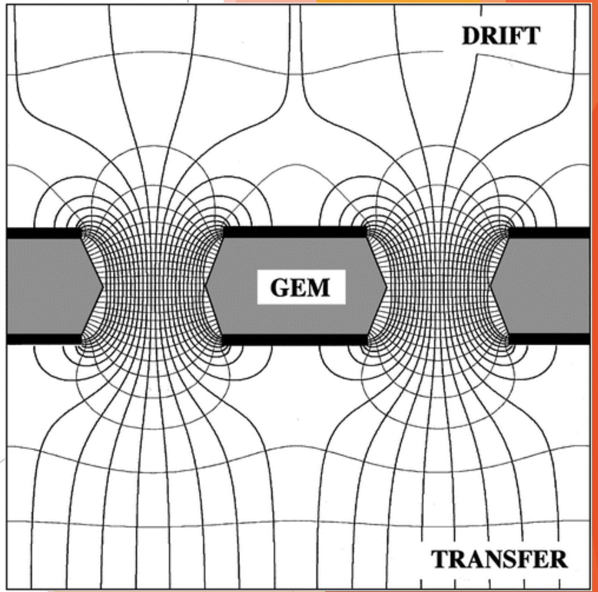
Red: ions
Yellow: electrons [6]



ALICE quad-GEM [6]



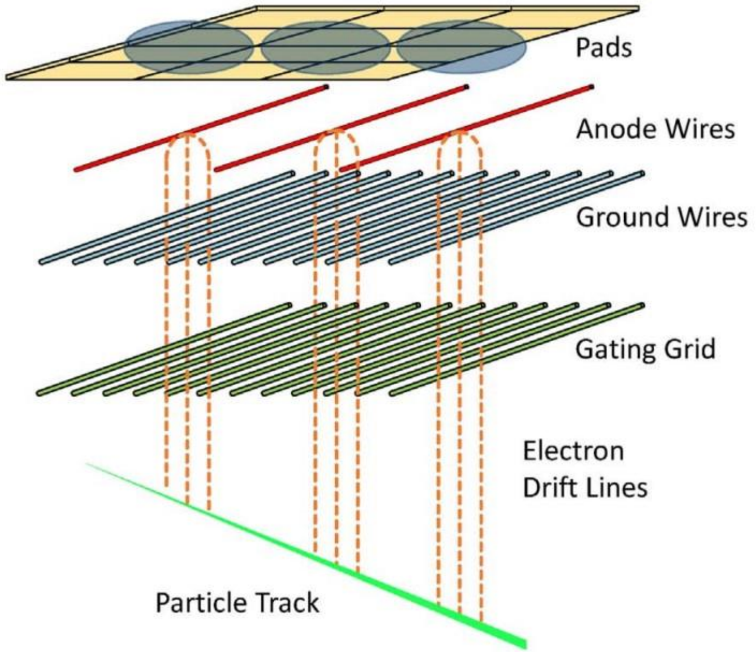
dual-GEM with μM [8]



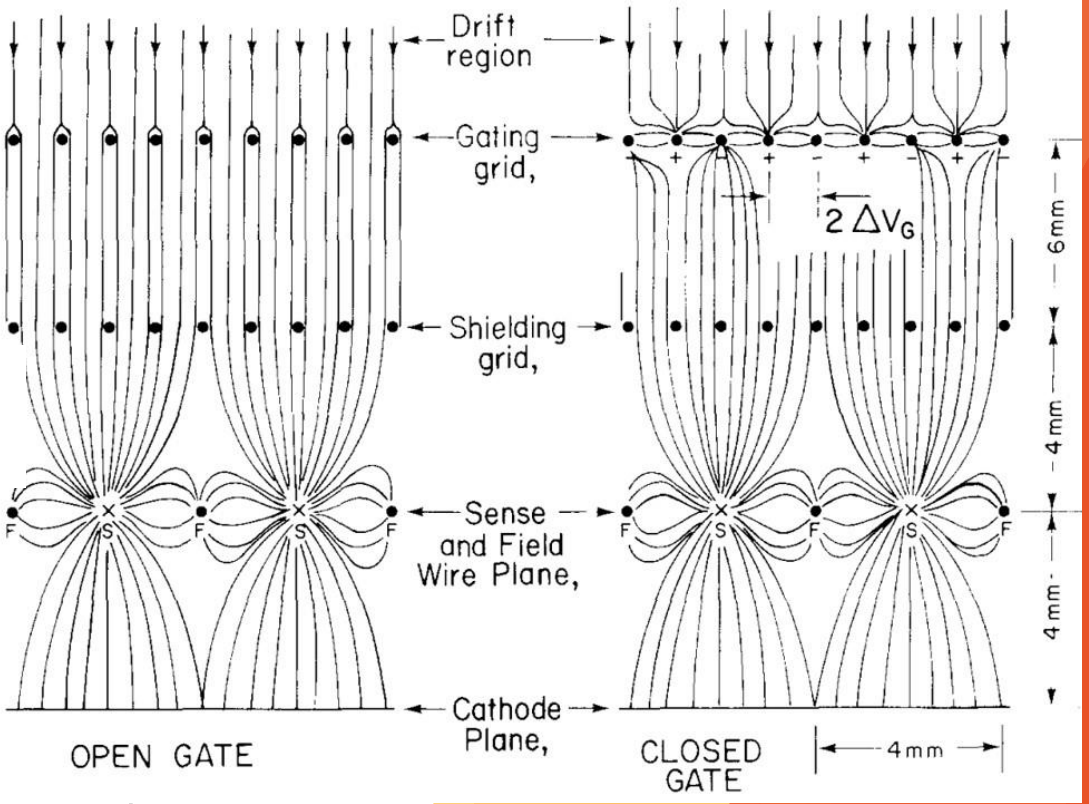
$\vec{E}$-field Ratios [7]

Gating Grid

- Array of wires.
- Can provide $\vec{E}$-field ratios.
- Bi-Polar $V_g \pm \Delta g$ alternating wires. Negative wires collect IBF ions (positive stop signal electrons).
  - Stays in the "on, closed position" of $\Delta g > 0$ until triggered. Then opens to allow electron collection. Closes and collects IBF ions while waiting for next trigger.
  - Example: successfully used by STAR at RHIC [9].
  - Low rate from dead time because of slow ion drift velocity.

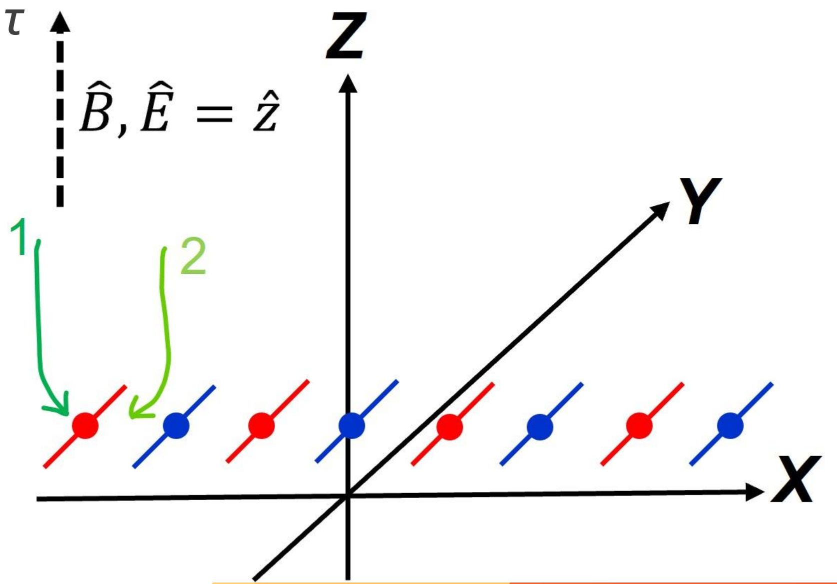


Active Gating Grid Examples [10,11]

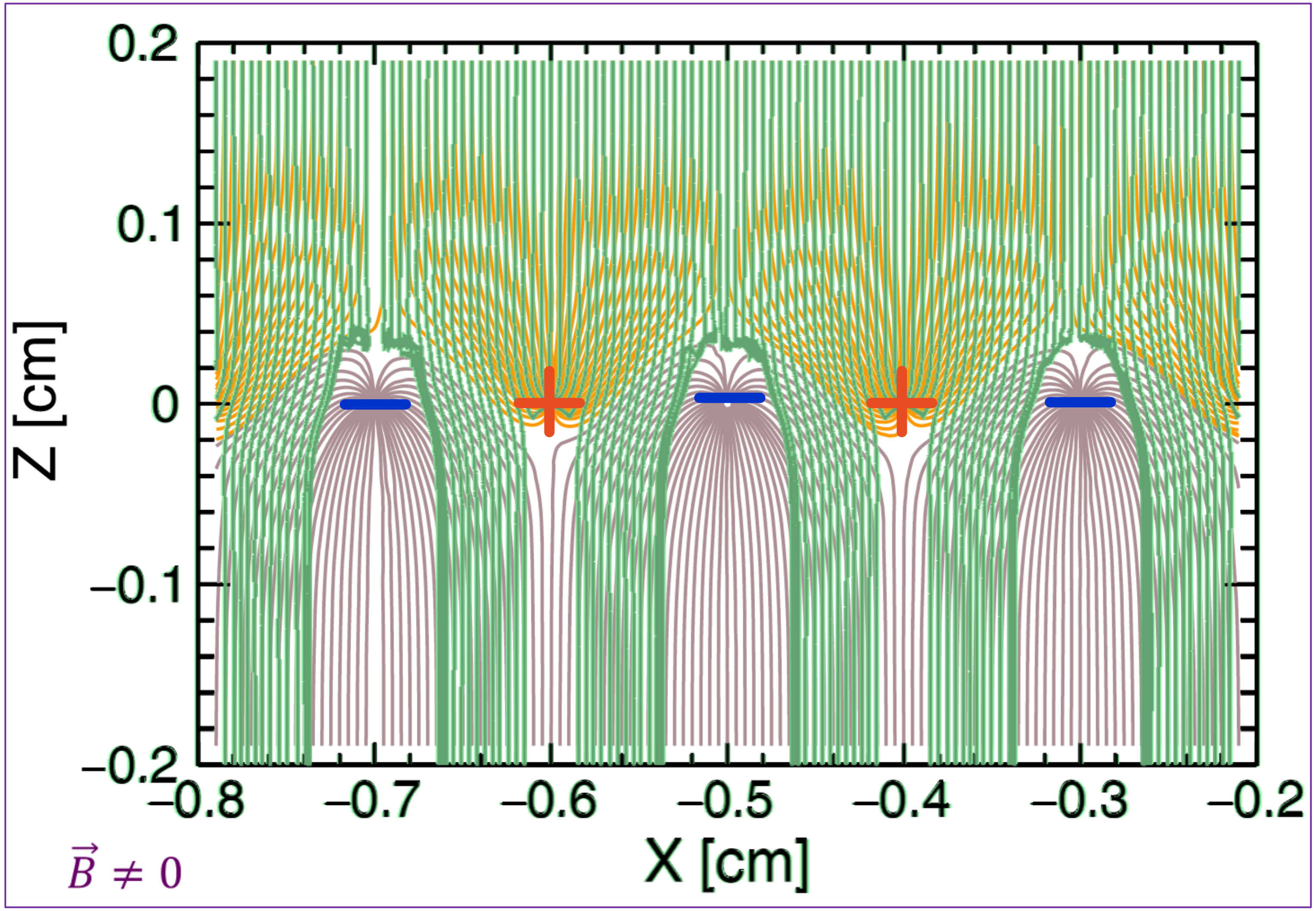


Passive Gate

- Still maintains $\vec{E}$-field ratios. *(This is a useful universal principle)*
- Langevin Eq: $m\frac{d\vec{v}}{dt} = q\vec{E} + \boldsymbol{q(\vec{v} \times \vec{B})} - \kappa\vec{v}$
  - Utilize external $\vec{B}$-field to "push" electrons past the Bi-Polar wires. IBF ions too heavy and slow, so they'll follow $\vec{E}$-field lines.
  - 1st stronger kick along wire, 2nd push past the wire
- Using $E_y = 0$ and angle α between $\vec{E}$ and *x-axis* gives [12]:
  - $v_x = \frac{\mu E \cos\alpha}{1+\omega^2\tau^2}$, $v_z = \mu E \sin\alpha$
    charge mobility $\mu = e\tau/m$, cyclotron frequency $\omega = eB/m$, collision time τ
  - For $\omega\tau \gg 1$ charges follow $\vec{B}$-field lines and ignore $\vec{E}$-field of the closed Bi-Polar Grid (BPG).
  - If $E_y \neq 0$, $v_x = c(\omega\tau E_y + E_x)$, $v_z = c(\omega^2\tau^2 E_y + E_z)$ where $c = \frac{\mu}{1+\omega^2\tau^2}$, still has a strong $\omega\tau$ dependence to transmit fast electrons and block slow ions



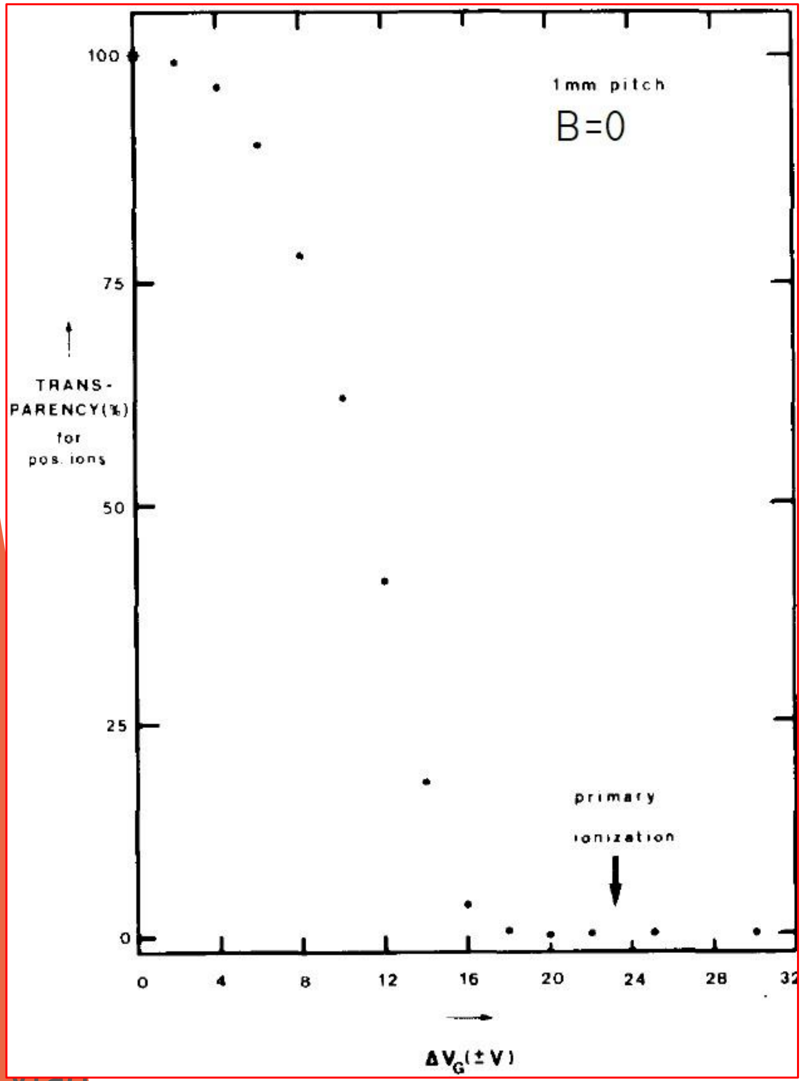
Introduction of Magnetic Field:

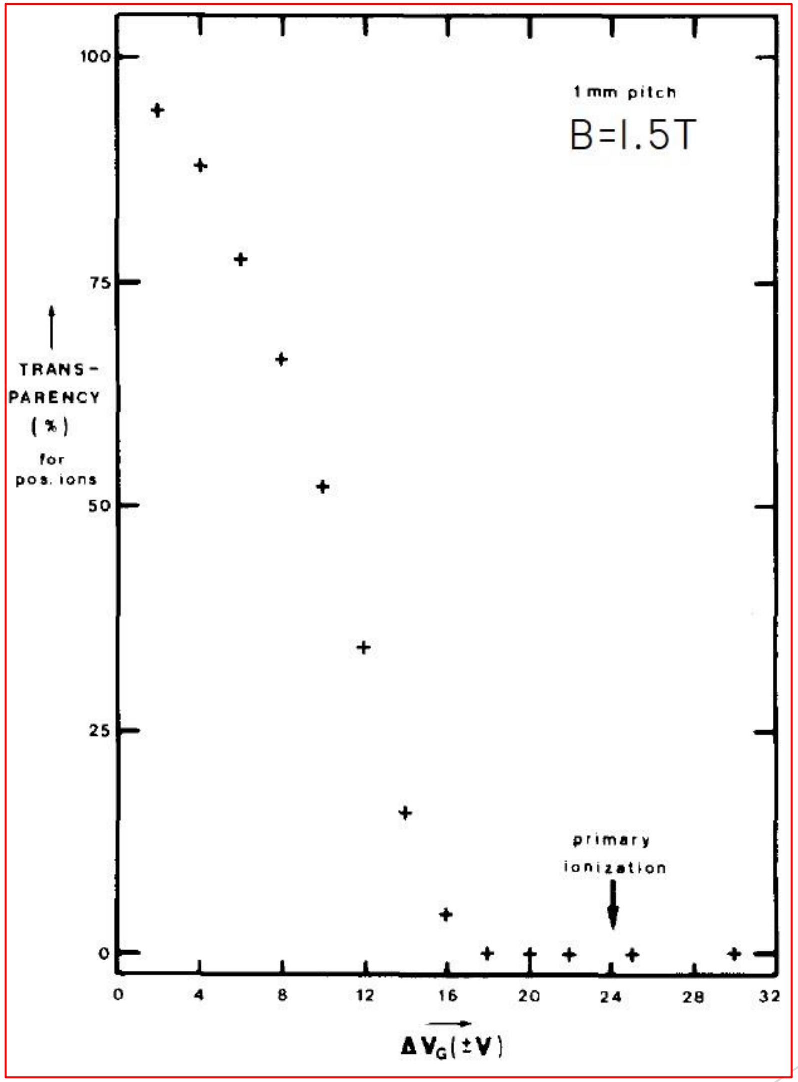


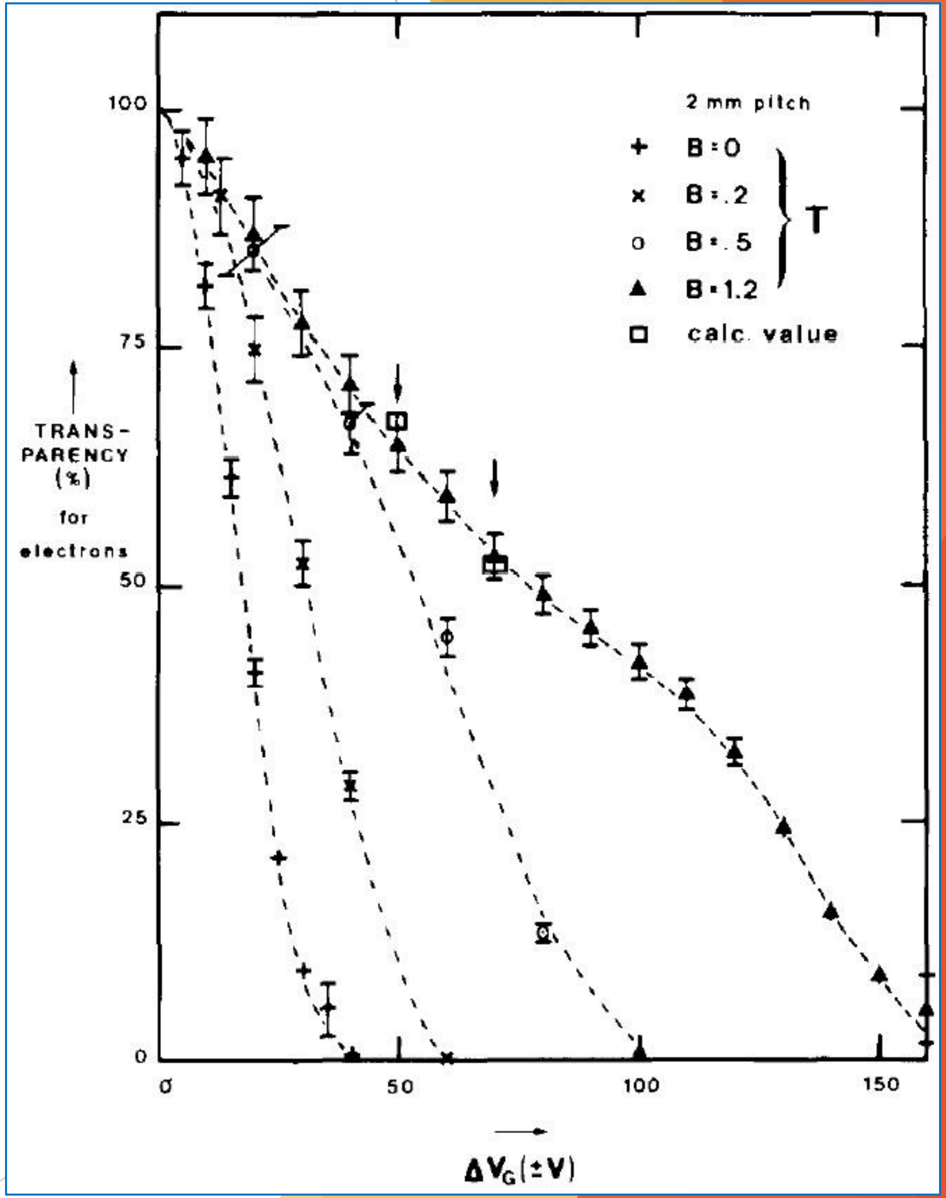
- Magnetic Field brings electrons through.
- Ions remain blocked.

1985 S. R. Amendolia et. al. results [12]

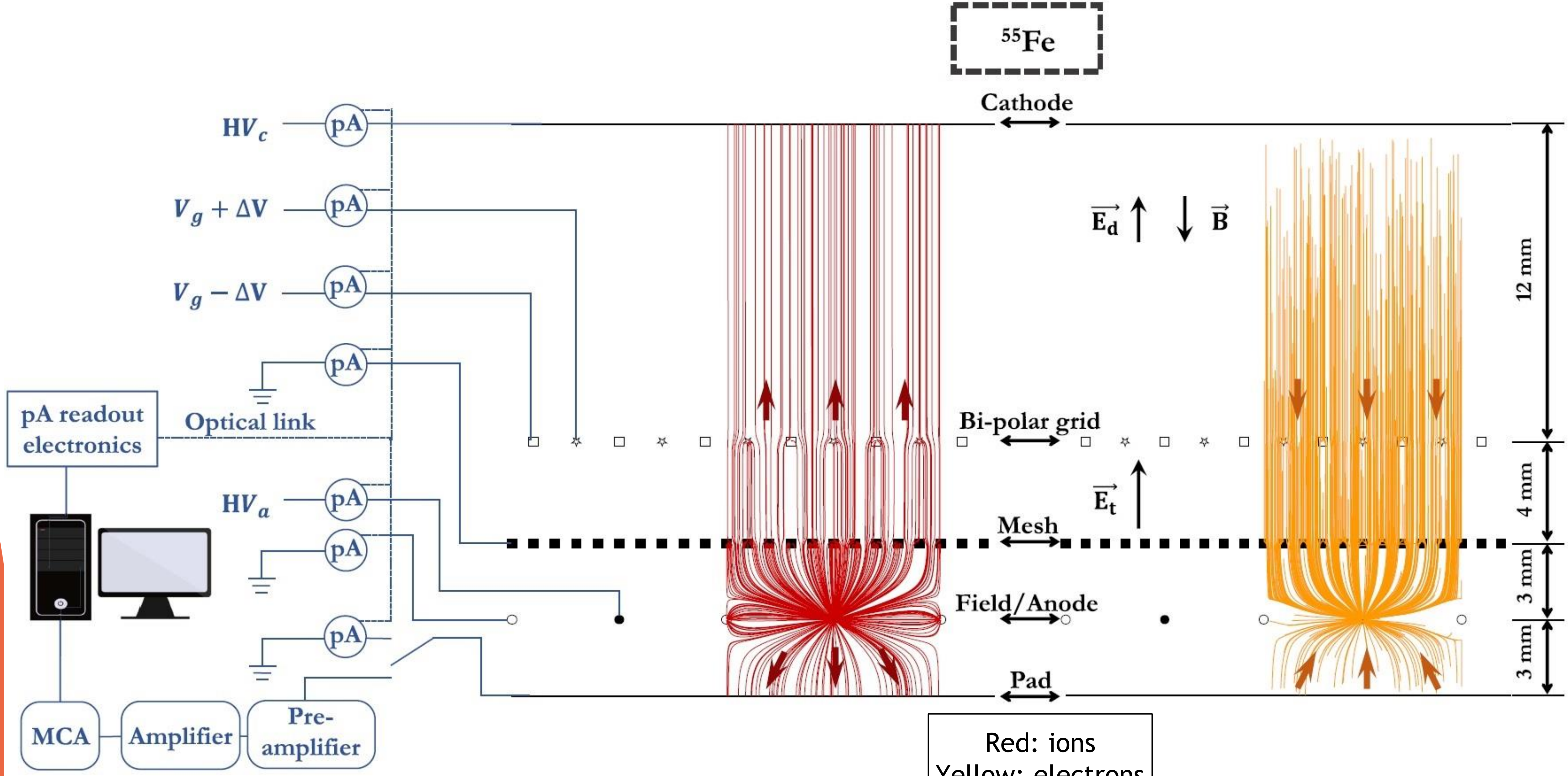
- Grid closed to ions at ΔV=20







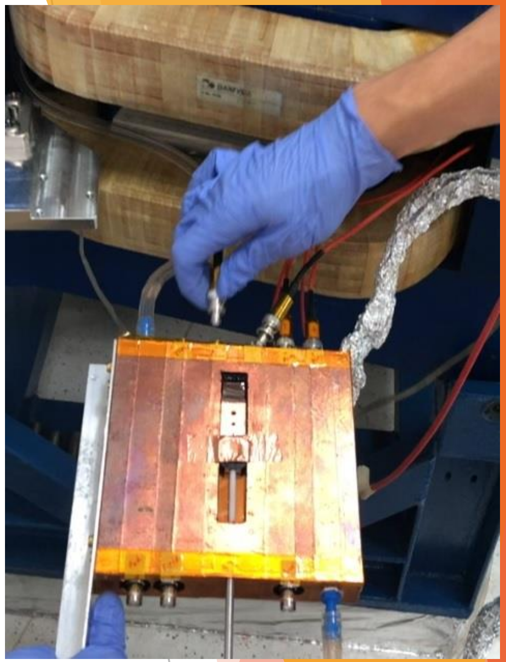
WIS Detector Schematic

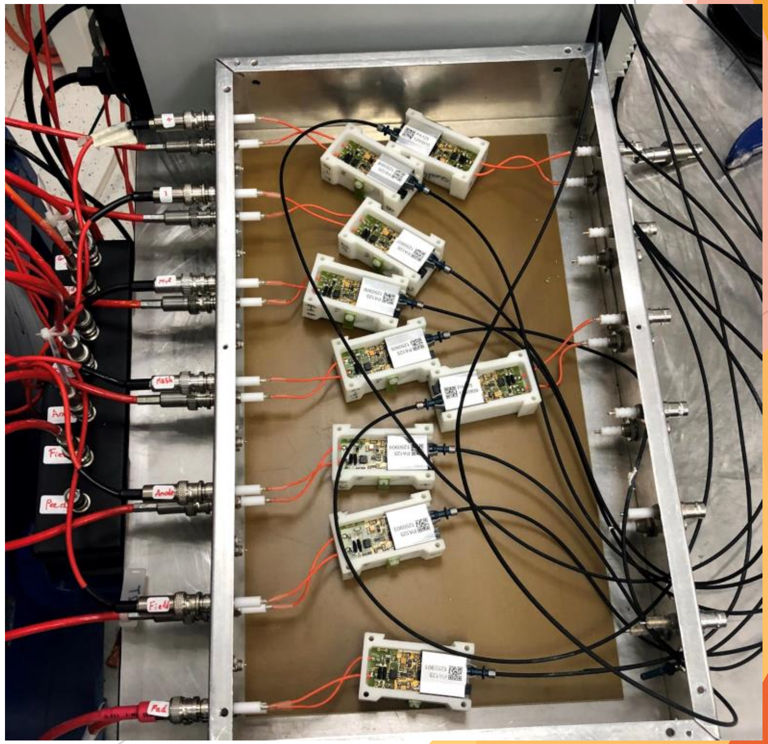


Red: ions
Yellow: electrons

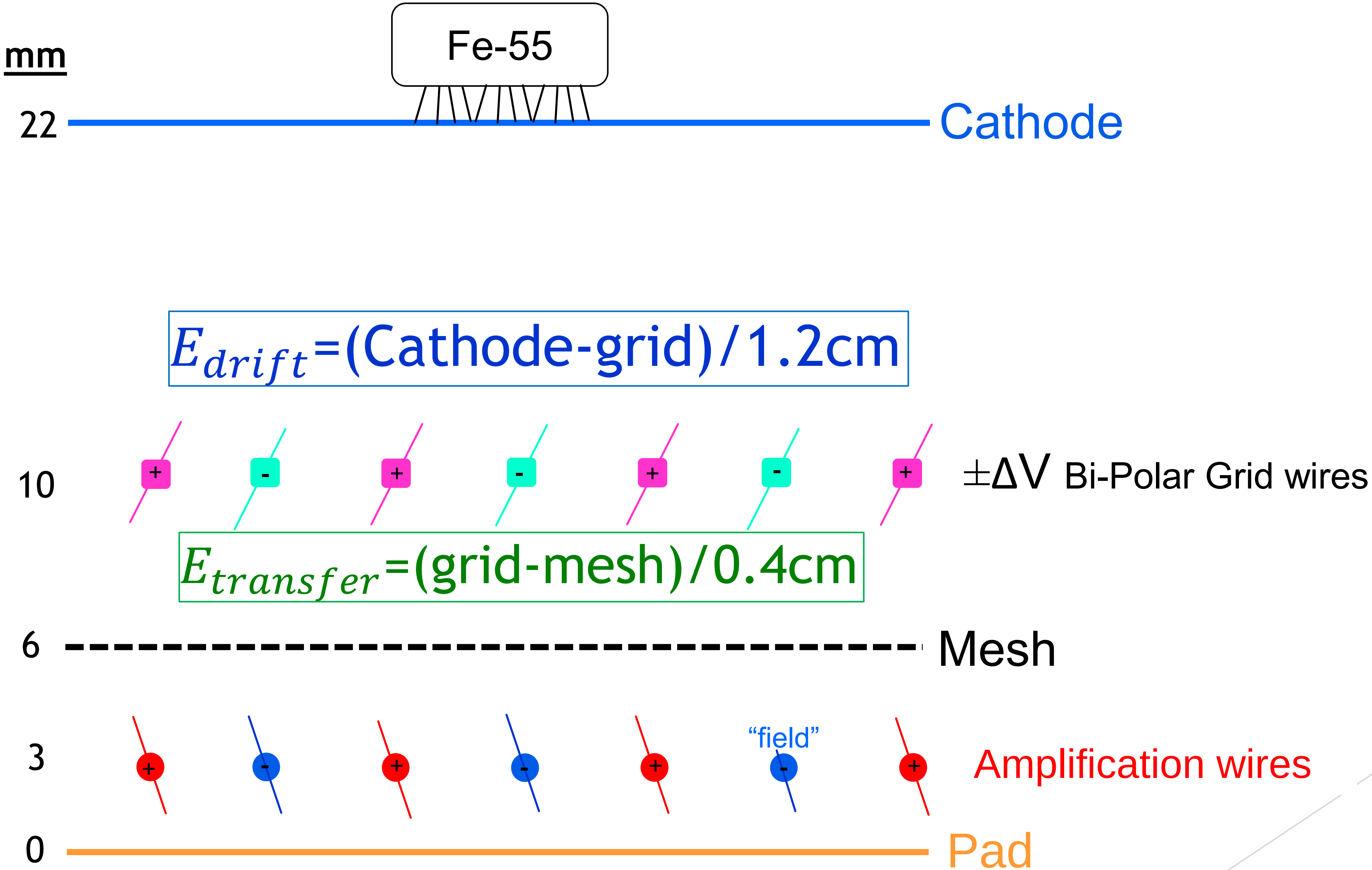
WIS Experiment setup

- ***Paper: DOI: 10.1109/TNS.2020.3042311 IEEE***
- MWPC, hot Fe-55 sourse, pAmmeters [a], MCA calibration, 1.2 T magnet



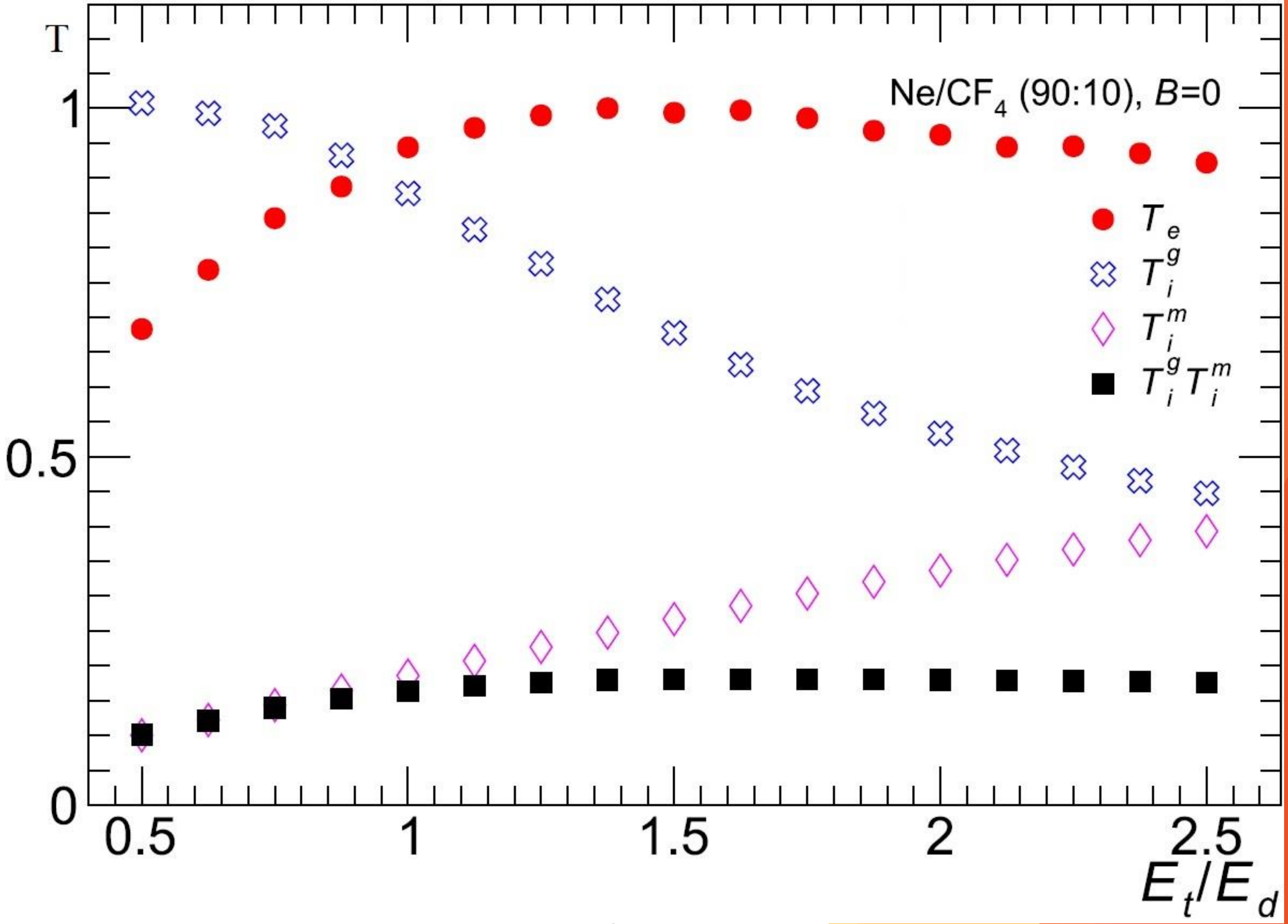


WIS Detector Schematic (simplified)



$\vec{E}$-field ratios

- T_e is amount of electrons that pass through the grid & field shaping mesh
- T_i^g shows that less ions pass through the grid as only the ratios are increased
- T_i^m increases since the ratio above and below (from gain wires) the mesh now decreases. Similar effects should be considered for full scale TPCs.
- We used a ratio of 1.5

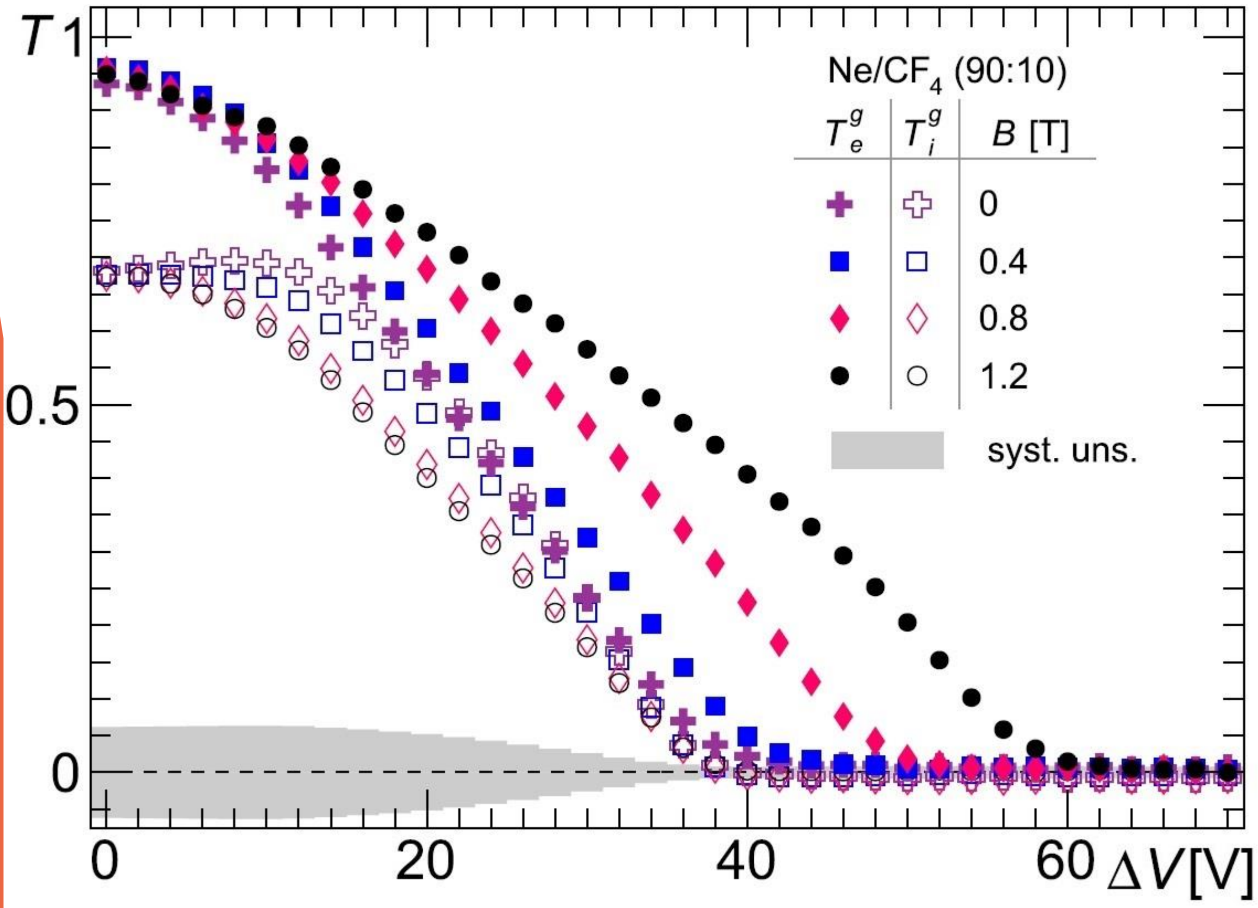


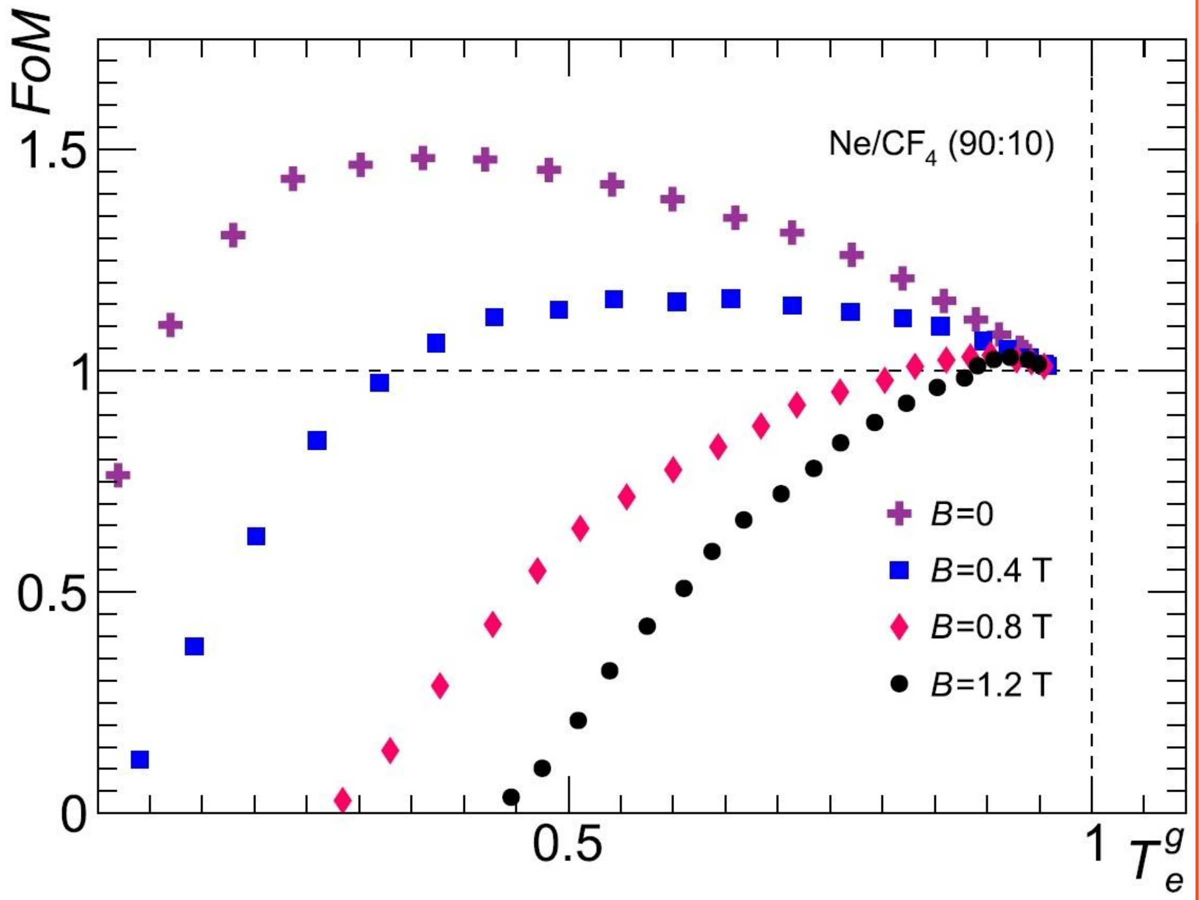
Some results

$$FoM(\omega, \Delta V) = \frac{T_i^m(\omega,0)}{T_i^m(1,0)} \cdot \frac{T_i^g(\omega,\Delta V)}{T_e^g(\omega,\Delta V)} \text{ with } \omega = \frac{E_t}{E_d}$$

- Ions at ΔV=0 are only at ~67% from field ratios

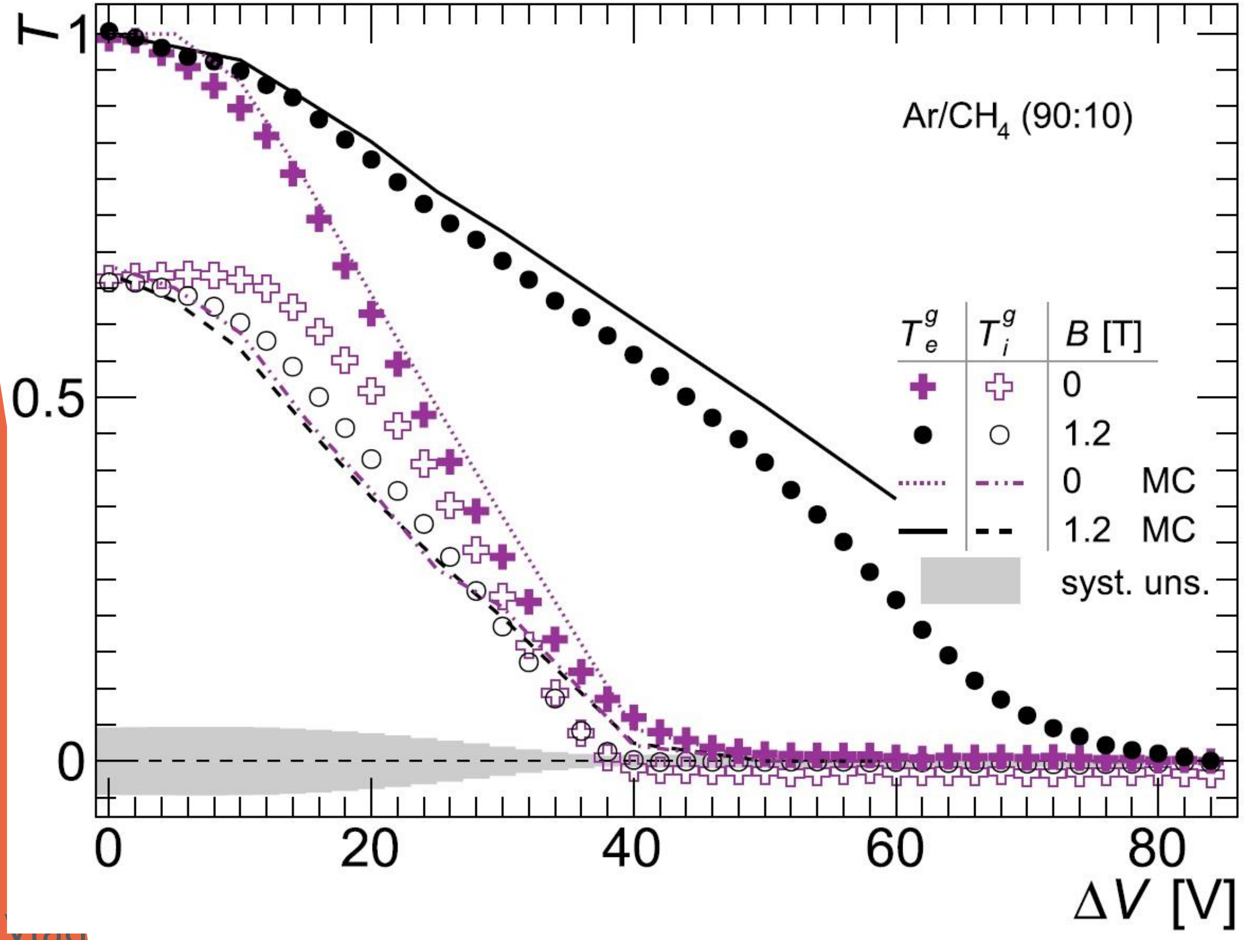
- 1st term is just field ratios, and shows how higher ratios can extract more ions from the gain region
- 2nd term has loss of primary electrons, which would be compensated with more gain and make more ions
- Point (1,1) on Figure of Merit graph is absence of BPG. FoM<1 values are desired

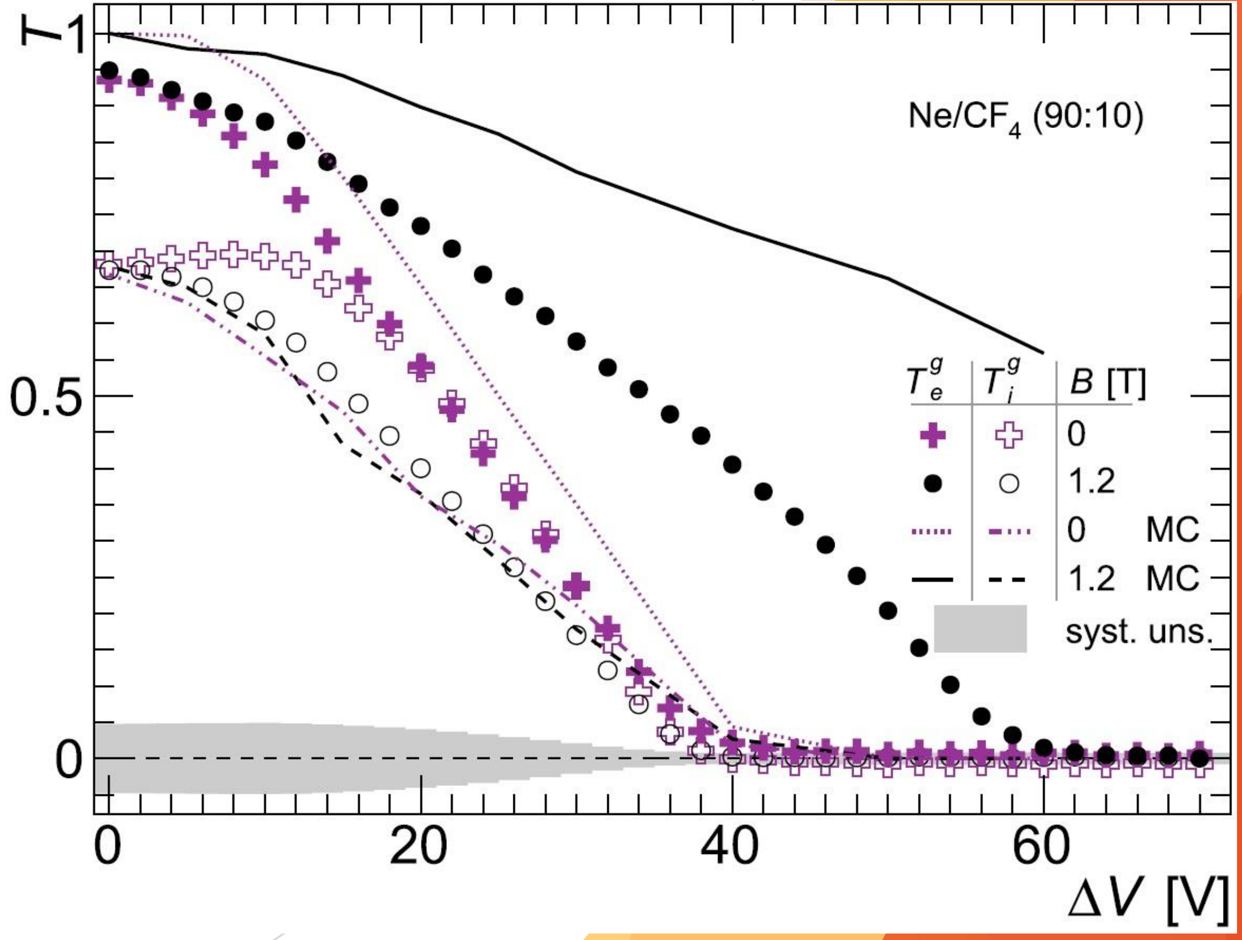




Simulations

- Show general trend, but deviate significantly from data for some parameters
- Long-range and average assumptions break down for small distances and small components
- Ar & CH4 mixtures more well known and better simulated

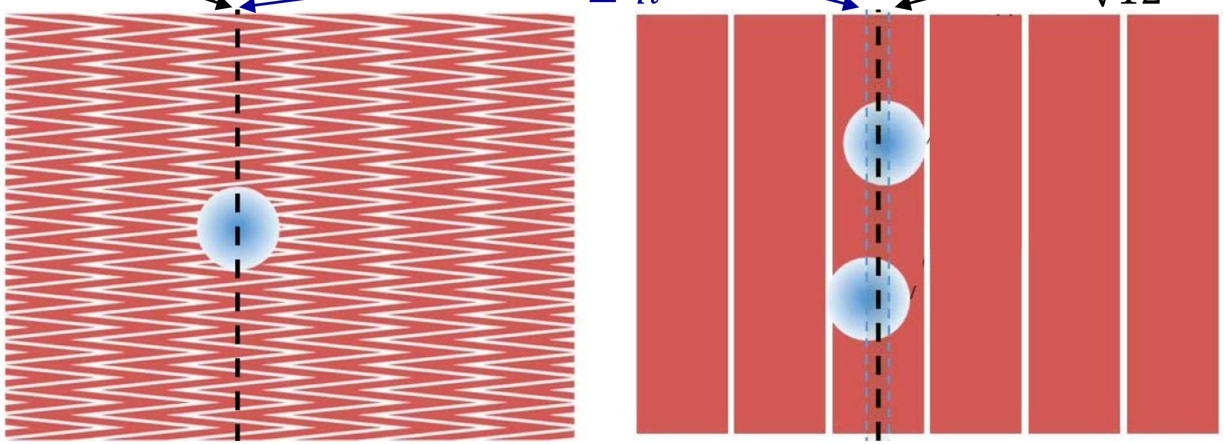




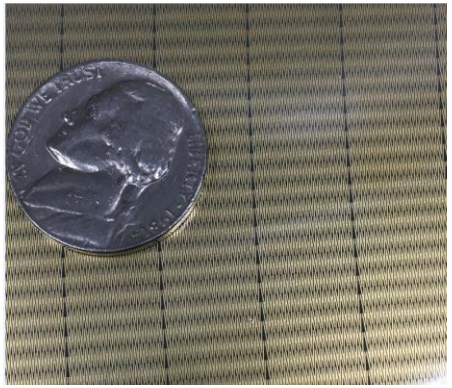
BPG Bias

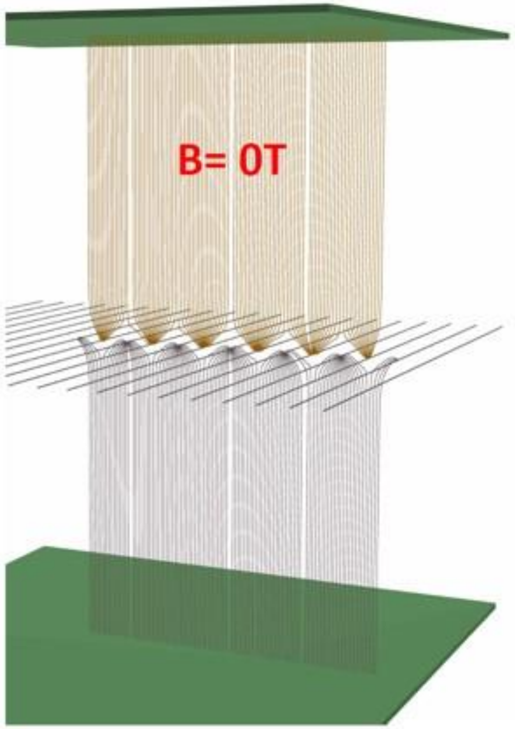
- Strong "push" along wire and weaker "push" around it creates two, potentially significant, distortions.
- Depends on detection pads. We'll use Zig-Zags [13]

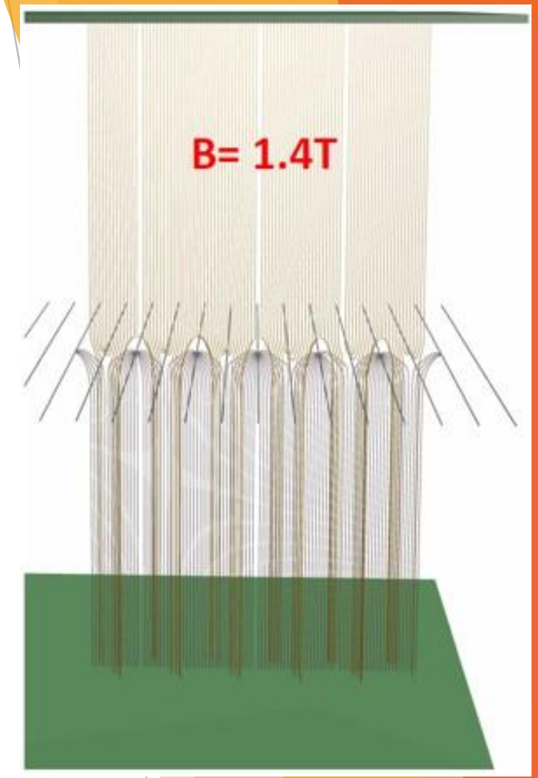
$\delta_x \approx \frac{Signal}{Noise}$ $X \sim \frac{\sum q_i x_i}{\sum q_i}$ $\delta_x \approx \frac{Width}{\sqrt{12}}$

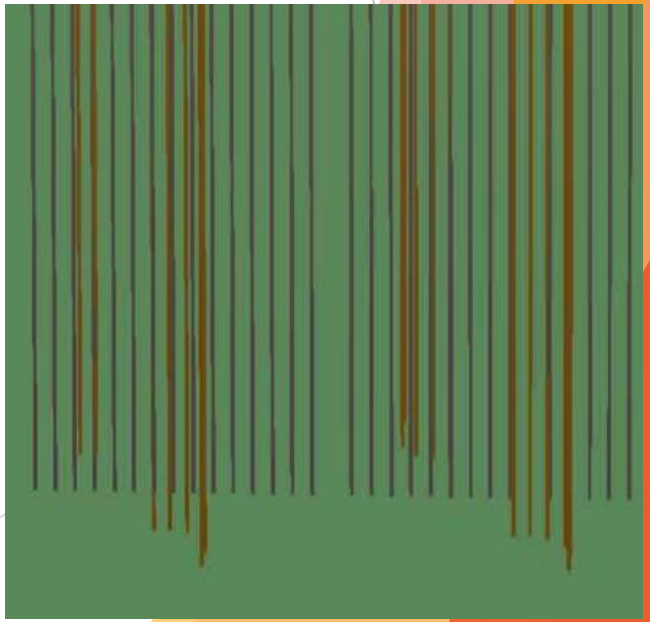


Charge clouds collected on multiple vs. a on single pad



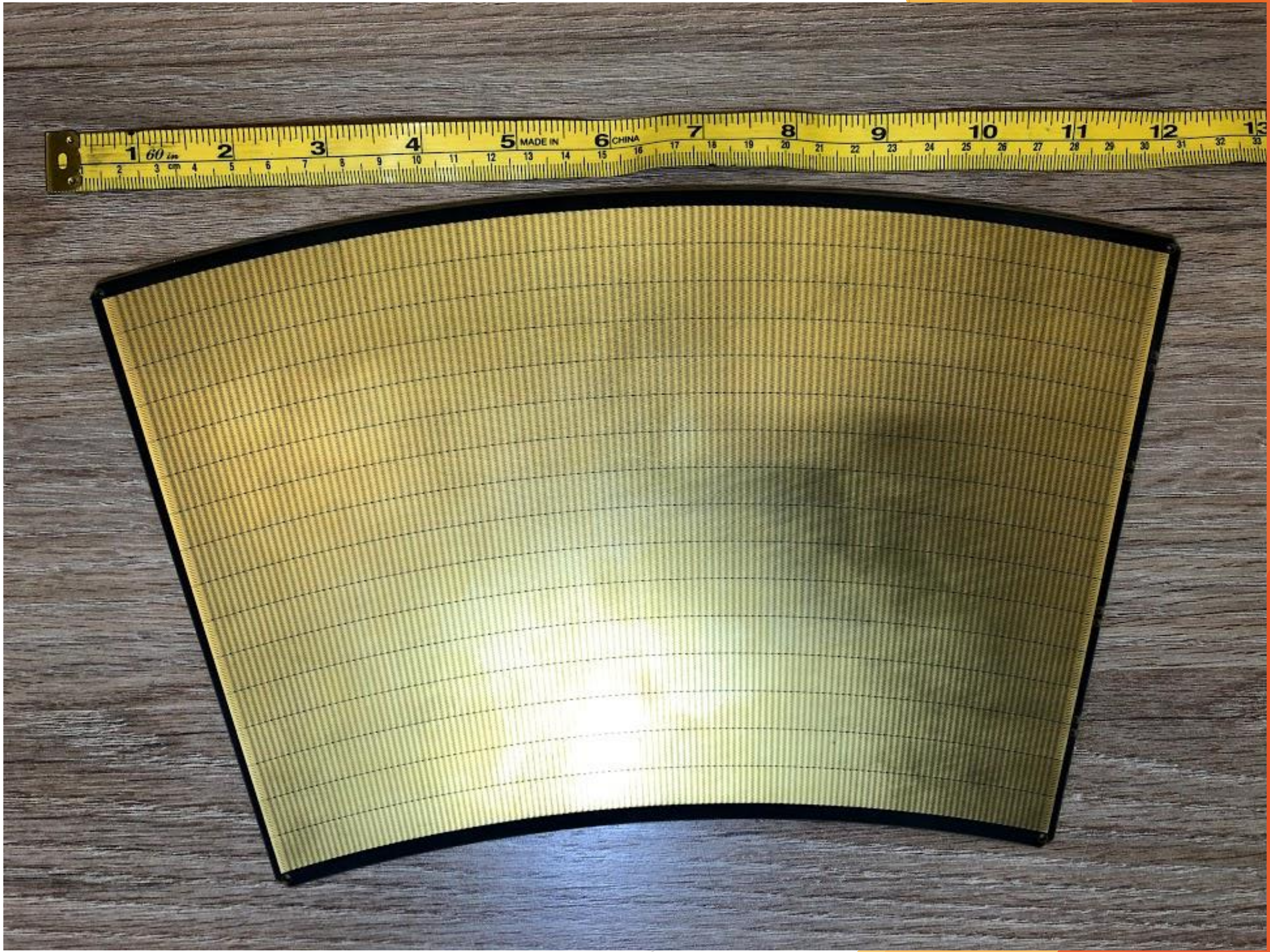




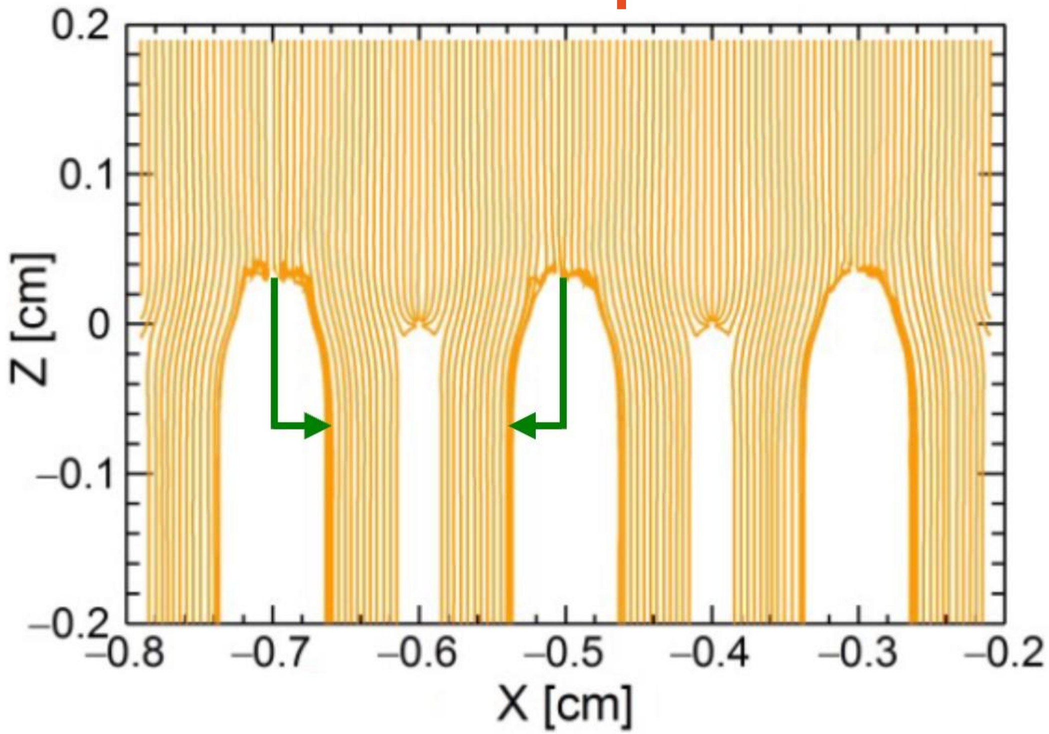


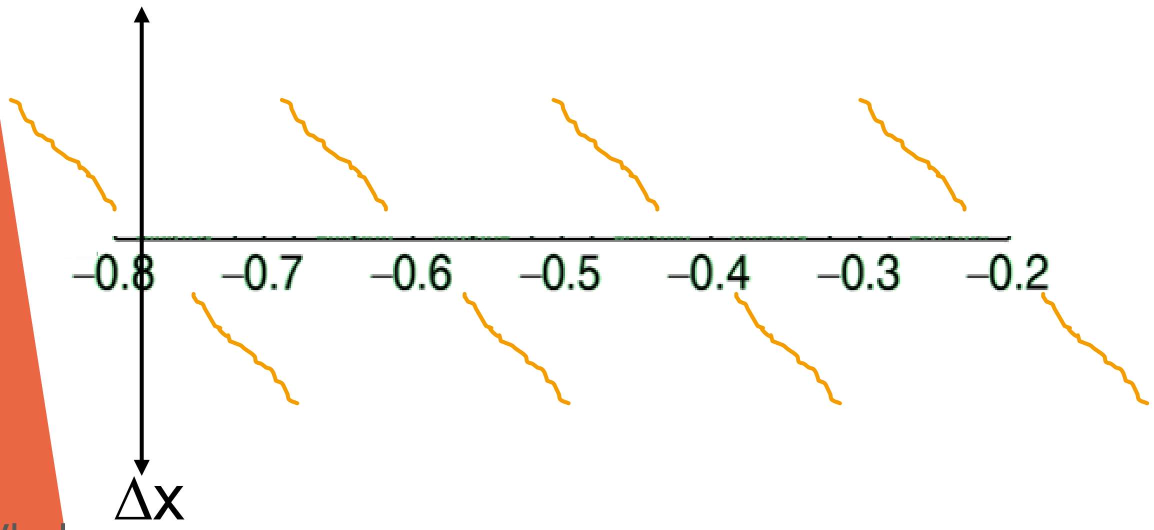
Full
Pad Plane

- Used in sPHENIX TPC [5]
- Each pad ~10mm height & 2mm width



Focus on 2nd "push" distortions



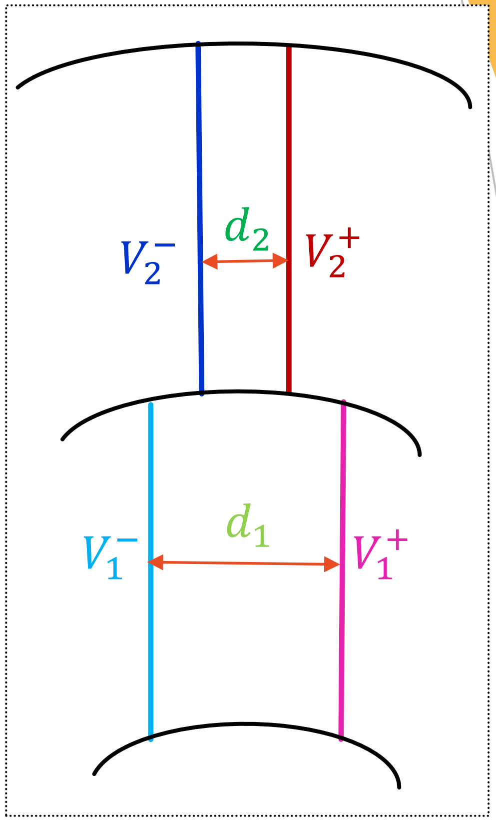


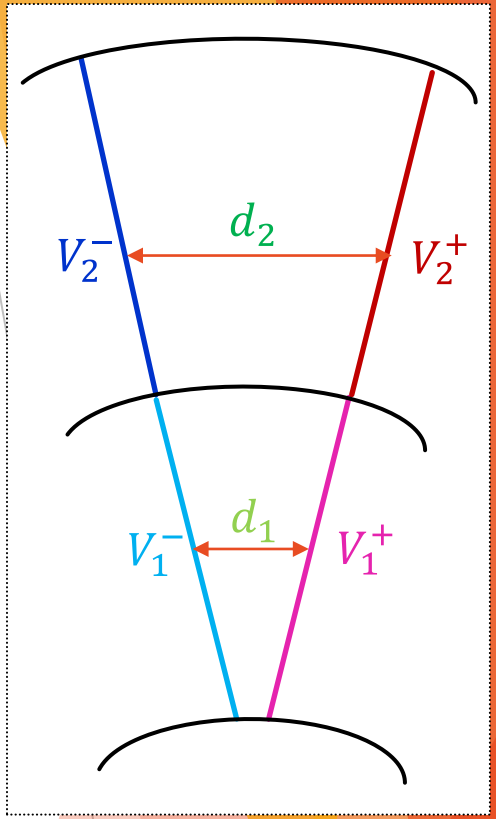
- The electron displacements from their original trajectories are cyclical
- The cycle repeats with the same period as the wires
- Cyclical shifts from ideal positions are known as ***Differential Non-Linearity*** (DNL)
- DNL is a well-known phenomena in our field
- Zig-zags have their own intrinsic DNL

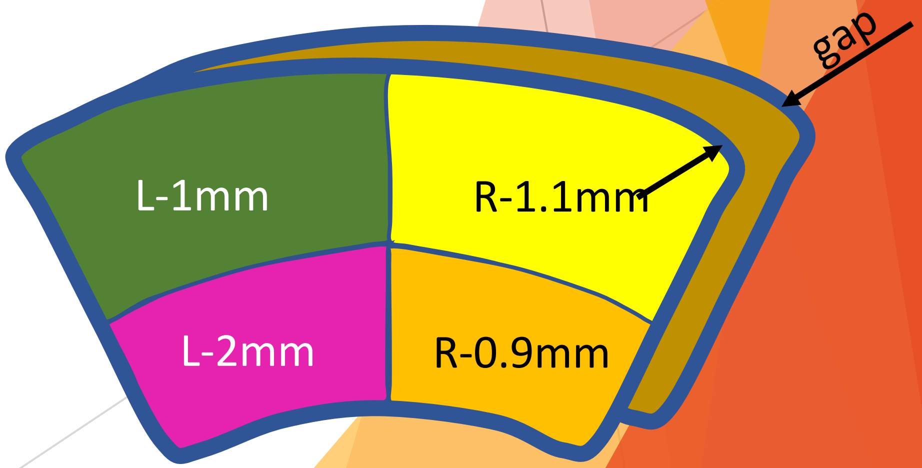
Average Out Vs. Periodicity

- BPG has a symmetric shift around the wires
- Will shifts simply average and cancel out over a particles track regardless of wire-to-pad placement?
- Would wires aligned to pads combine their individual DNL for better resolution?
- Will IBF be strongly affected for radial wires?

- BPG is some distance above our quad-GEM gain stage. Voltage will be controlled to maintain as much uniformity as possible.
- A central radial bar separates radial voltages. Its existence also used to test the linear portion.

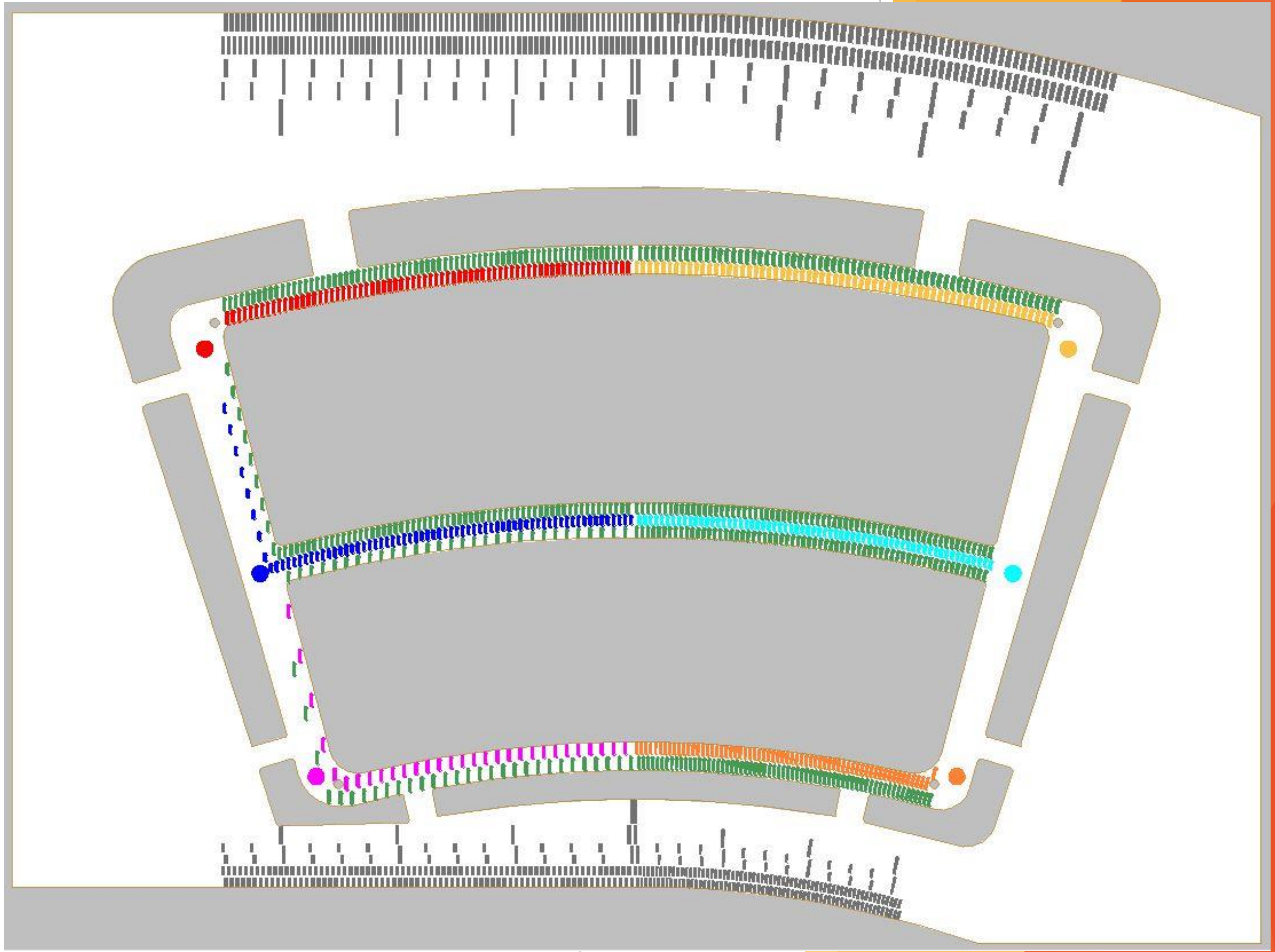






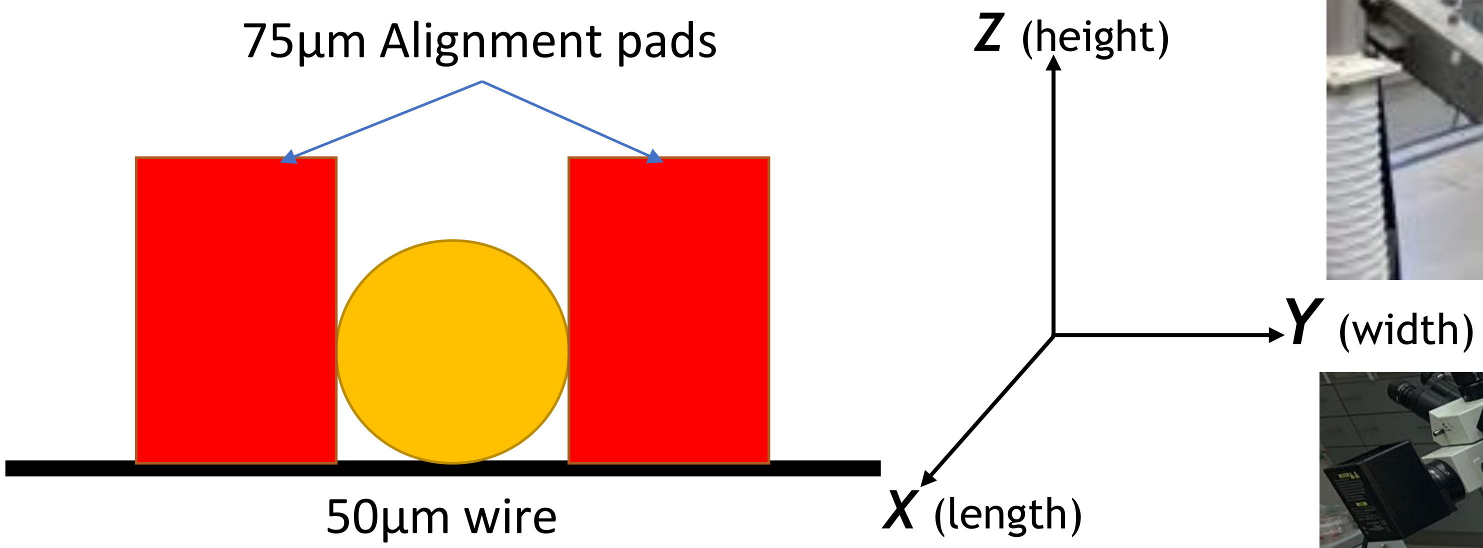
Second frame iteration

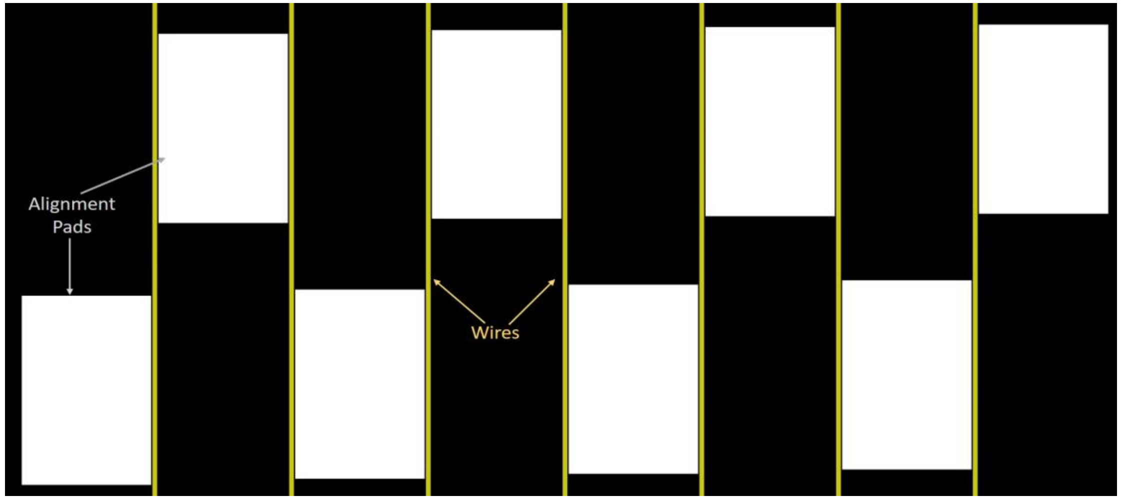
- Placed above gain stage
- Will have wires attached
- Designed as a Printed Circuit Board (PCB)
  - Use external pads for alignment and internal ones to solder
  - Once wires fully soldered and epoxied, remove external frame
- 6 colored rounded pads for power supplies
- Green pads for mechanical strength solder (instead of epoxy)

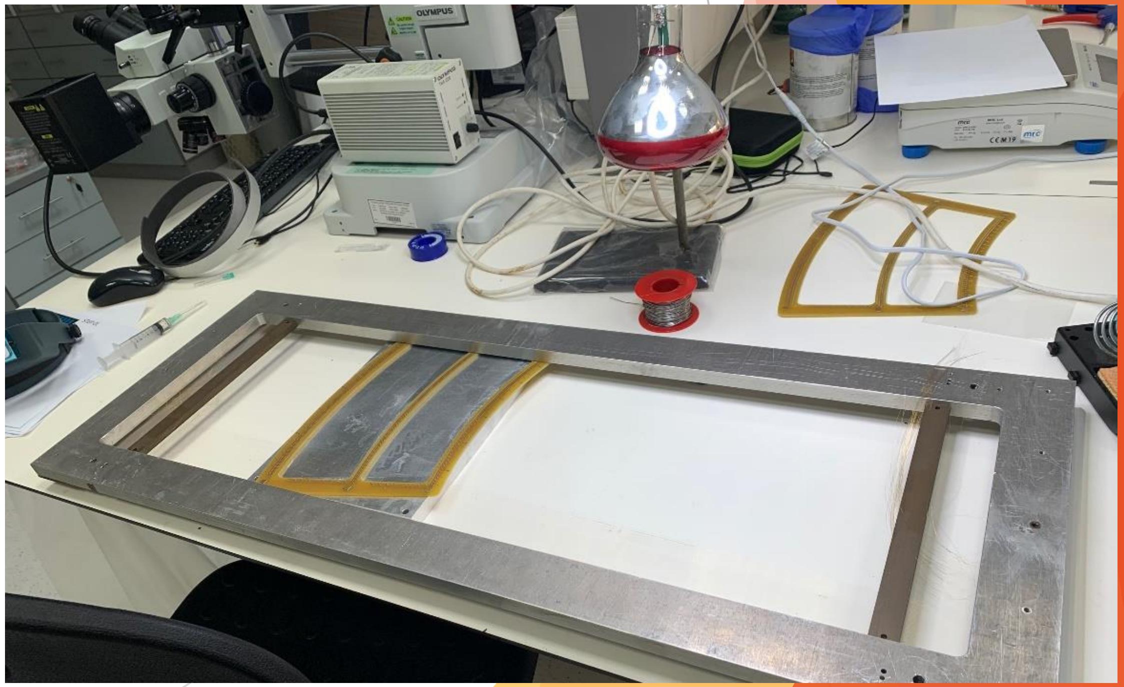


3oz Copper Alignment Pads

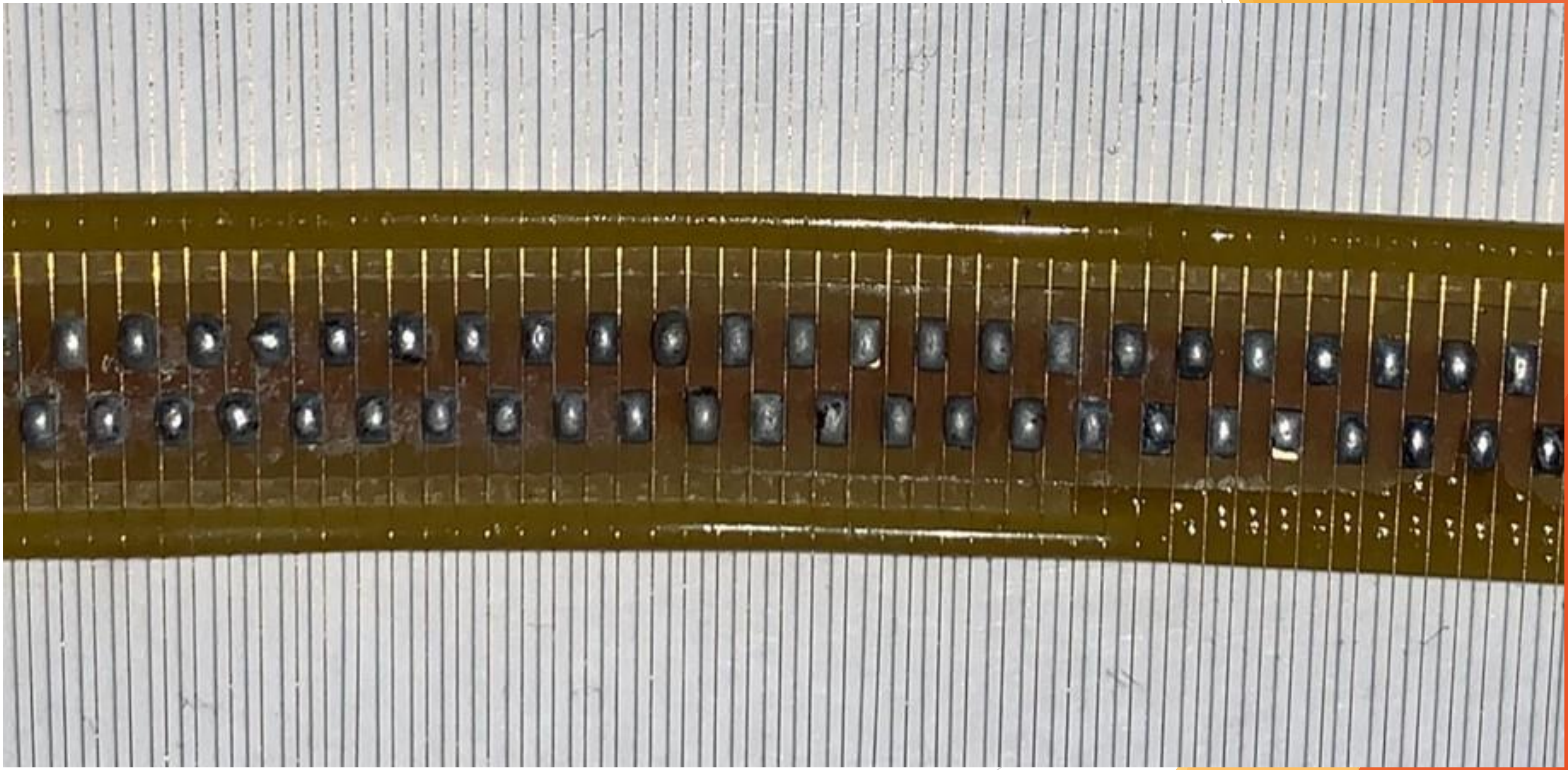
- Used WIS wire winding machine & transfer frame
- Tall pads maintain alignment. Epoxy wires, then cut alternate wires and solder to pads







Aligned and soldered nicely

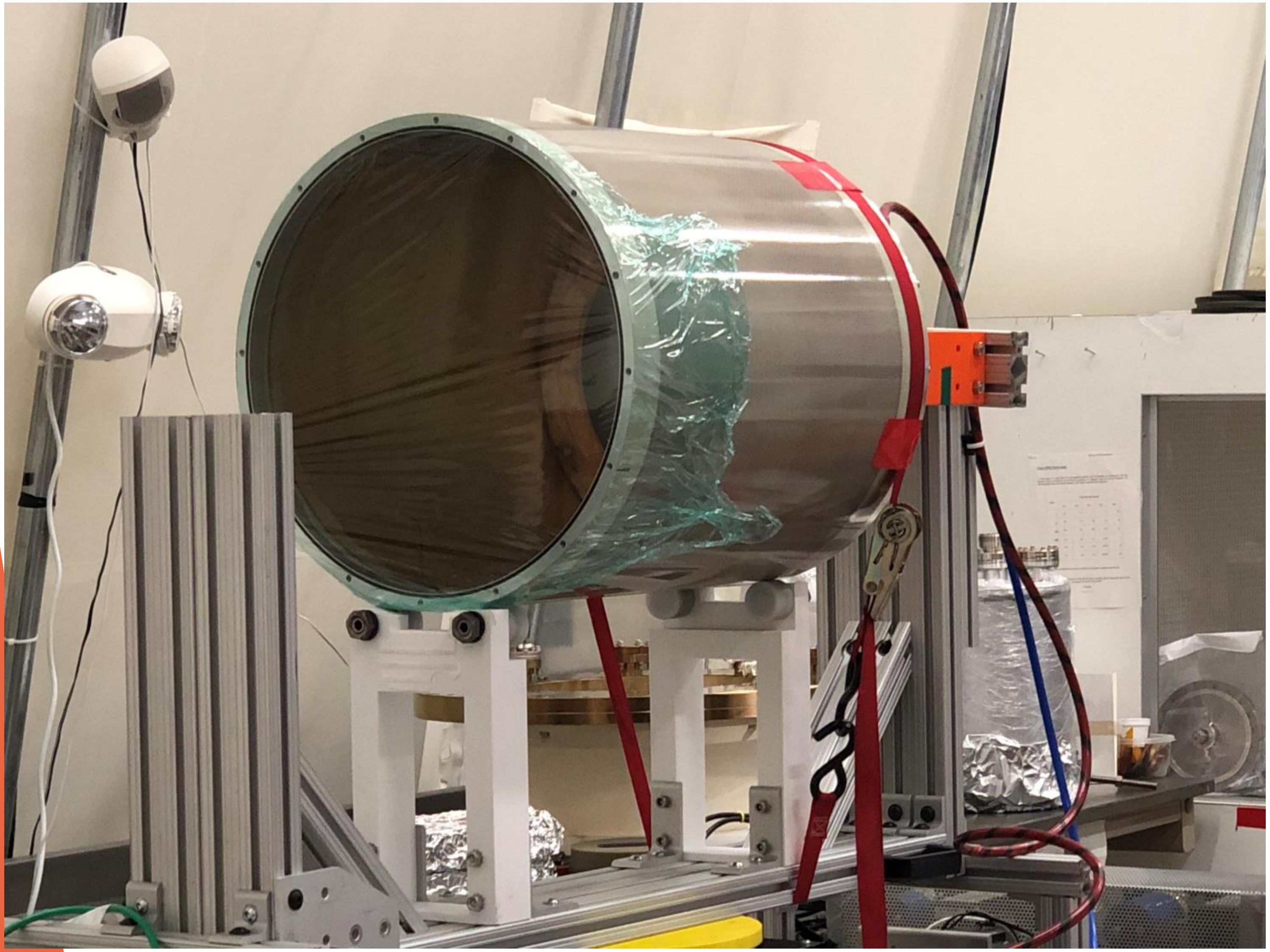


Large tension, extra stiffener

- The wire winder was configured for long ATLAS wires at 200-300g tension each
- Caused our 3mm mask to slightly deform
- An FR-4 additional stiffener was designed
- Darker green shows stretchers to bring mask to correct shape

Prototype & Argonne National lab

- We'll use cosmic rays



Summary & Future plans

- TPC’s high rate limited by SC from IBF
- $\vec{E}$-field ratios suppress IBF
- $\vec{B}$-field allows for *passive* grid
- Bi-Polar Grid test shows almost full Ion Back Flow suppression
  - sufficient electron transparency
- BPG’s effect on resolution will be studied this January

- Test IBF from radial wires
- Design pre-biased zig-zags

Thank you

References

1) David R. Nygren. Proposal to investigate the feasibility of a novel concept in particle detection. 1974
2) Spencer Klein. The Time Projection Chamber Turns 25. CERN Courier, 1 2004.
3) Walter Blum, Werner Riegler, and Luigi Rolandi. Particle detection with drift chambers. Springer Science & Business Media, 2008.
4) Abramowicz, H. et. al., Measurement of beauty production in DIS at HERA using decays into electrons, European Physical Journal C. 71. 1-15. 10.1140/epjc/s10052-011-1573-x, 2011-Jan.
5) sPHENIX Technical Design Report PD-2/3 Release. 5 2019.
6) Christian Lippmann and et. al. Upgrade of the ALICE Time Projection Chamber. 3 2014.
7) Fabio Sauli and Archana Sharma. Micro-pattern gaseous detectors. Annual Review of Nuclear and Particle Science, 49(1):341–388, 1999.
8) S. Aiola, R.J. Ehlers, S. Gu, J.W. Harris, R. Majka, J.D. Mulligan, M. Oliver, J. Schambach, and N. Smirnov. Combination of two gas electron multipliers and a micromegas as gain elements for a tpc. NIM-A: Accelerators, Spectrometers, Detectors and Associated Equipment, 834:149–157, 2016.
9) M. Anderson et. al. The STAR tpc: a unique tool for studying high multiplicity events at RHIC. NIM-A: Accelerators, Spectrometers, Detectors and Associated Equipment, 499(2-3):659–678, Mar 2003.
10) S. Tangwancharoen, W.G. Lynch, J. Barney, J. Estee, R. Shane, M.B. Tsang, Y. Zhang, T. Isobe, M. Kurata-Nishimura, T. Murakami, Z.G. Xiao, and Y.F. Zhang. A gating grid driver for time projection chambers. NIM-A: Accelerators, Spectrometers, Detectors and Associated Equipment, 853:44–52, 2017.
11) Peter N´emethy, Piermaria J. Oddone, Nobukazu Toge, and Akira Ishibashi. Gated time projection chamber. NIM in Physics Research, 212(1):273–280, 1983.
12) S. R. Amendolia et al. Influence of a Magnetic Field on the gating of a Time Projection Chamber. Nucl. Instrum. Meth. A, 234:47–53, 1985.
13) B. Azmoun *et al.*, "Design Studies for a TPC Readout Plane Using Zigzag Patterns With Multistage GEM Detectors," in *IEEE Transactions on Nuclear Science*, vol. 65, no. 7, pp. 1416-1423, July 2018, doi: 10.1109/TNS.2018.2846403.
14) Vladislav Zakharov, Prakhar Garg, Thomas Hemmick, and Klaus Dehmelt. Study of a Passive Gating Grid for Ion Back Flow Suppression. J. Phys. Conf. Ser., 1498(1):012026, 2020.

a) Utrobicic, A. and Kovacic, M. and Erhardt, F. and Poljak, N. and Planinic, M.,"A floating multi-channel picoammeter for micropattern gaseous detector current monitoring", 10.1016/j.nima.2015.08.021, NIM-A, 2015

Backup

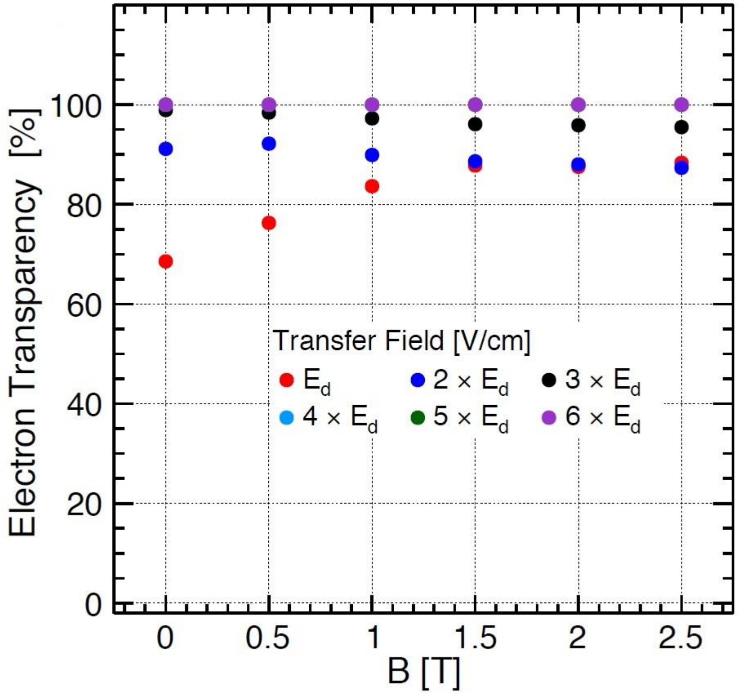
↓

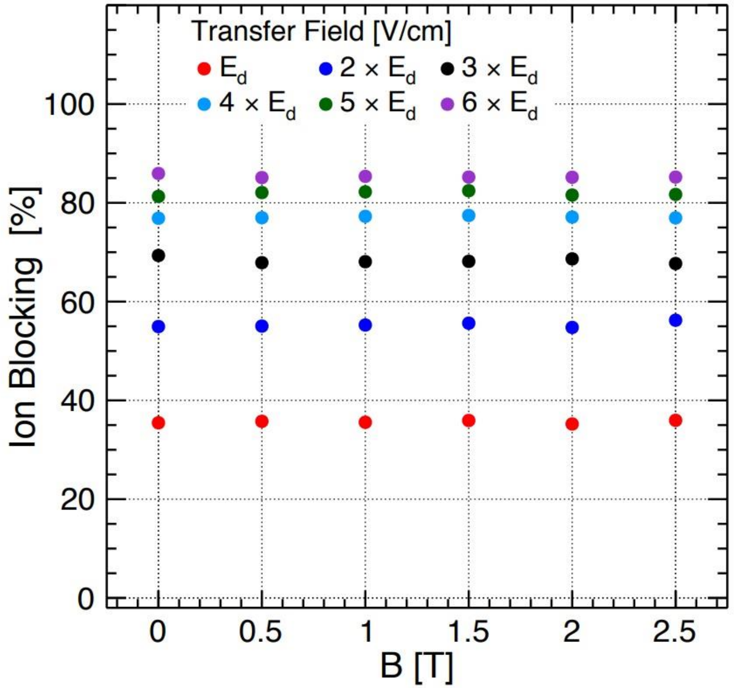
2019 MPGD talk

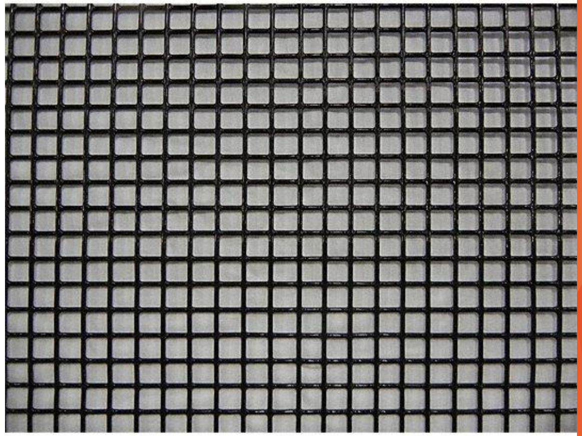
- https://indico.cern.ch/event/757322/contributions/3387100/
- https://arxiv.org/abs/1912.05005 proceedings

Passive structure

- No gain means no fluctuations, but $\vec{E}$-field ratios can still decrease IBF
- Example: a mesh of ~0.5mm spacing at a fixed voltage before the gain stage. Most electrons pass through while ions are blocked.
- Up to 85% blocking for $E_T = 6E_D$. But attachment must be considered at high fields, and IBF will still account for most of SC.







Woven wire mesh simulation for
E_D=400 V/cm in a $Ne+CF_4+iC_4H_{10}$ (95:3:2) gas mixture [14]

dE/dx Figure of Merit

- Loss of primary electrons deteriorates dE/dx
- For BPG, estimate it as loss of statistics. Assuming $\frac{dE}{dx} \propto 1/\sqrt{T_e^g}$, at B=1.2T we see that fully suppressing IBF ($T_e^g \sim 40\%$) is at a cost of 55% in resolution.
- Combined with an existing 10% dE/dx resolution TPC would give 15.5% while suppressing all ions.
- [https://arxiv.org/abs/2007.13616] for more