GEM simulations:
Impact of space and surface charge

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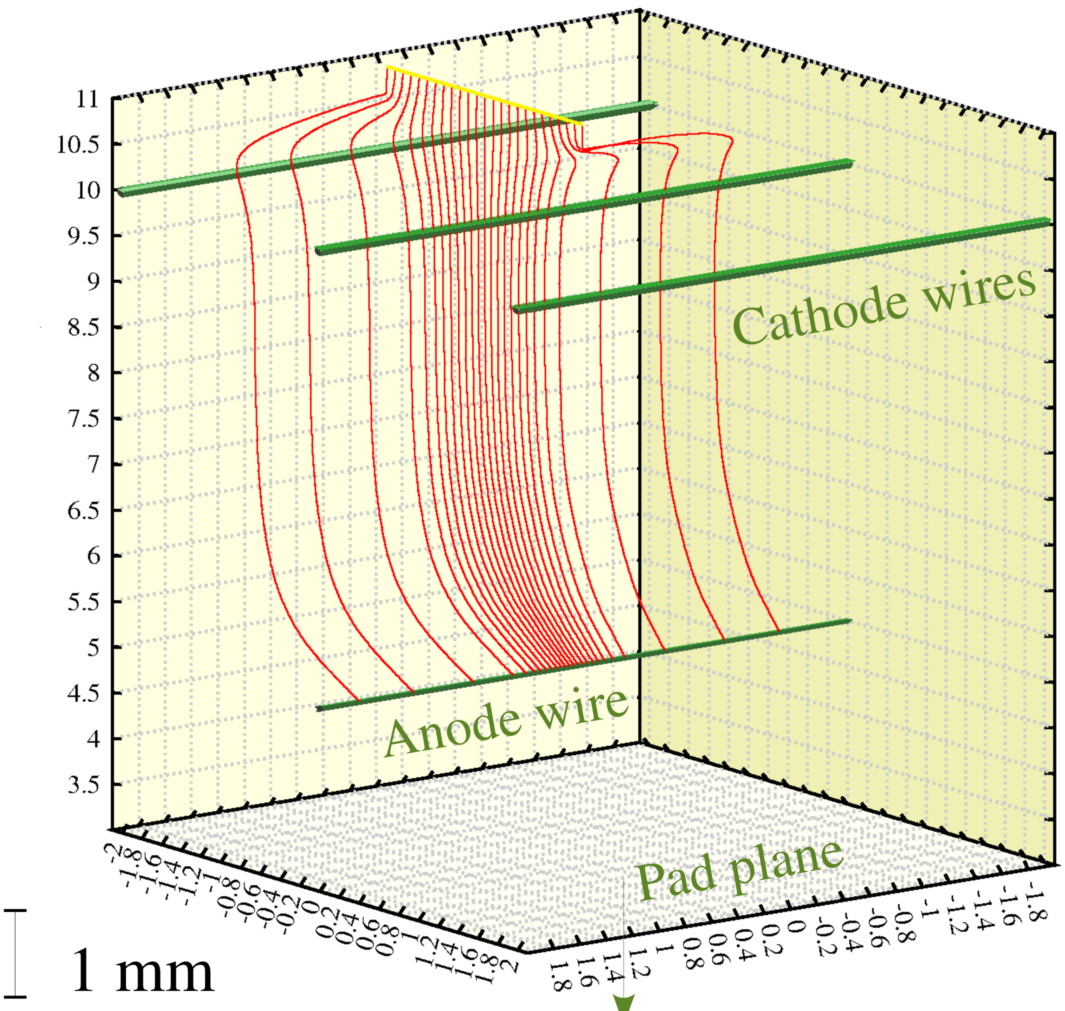
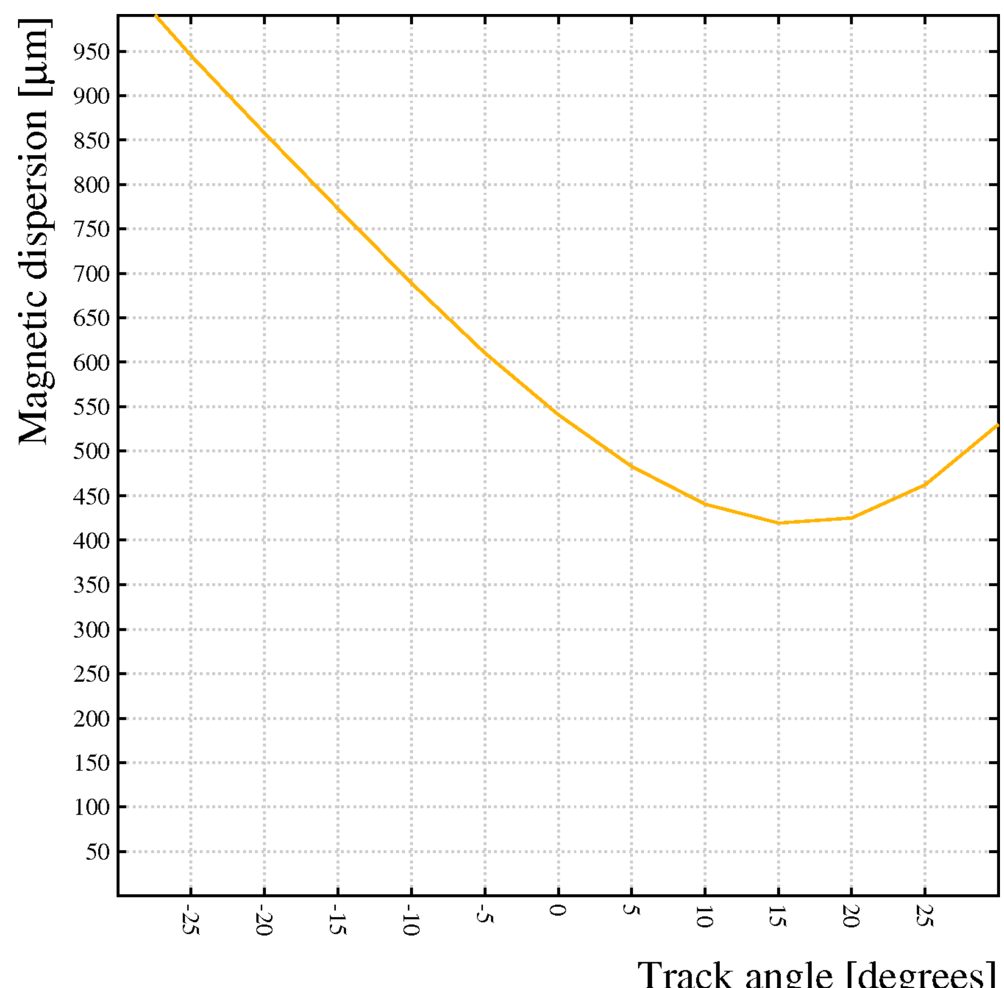
Runge-Kutta-Fehlberg integration

- Example (Harp): E×B effect in an enlarged ℵ read-out cell.

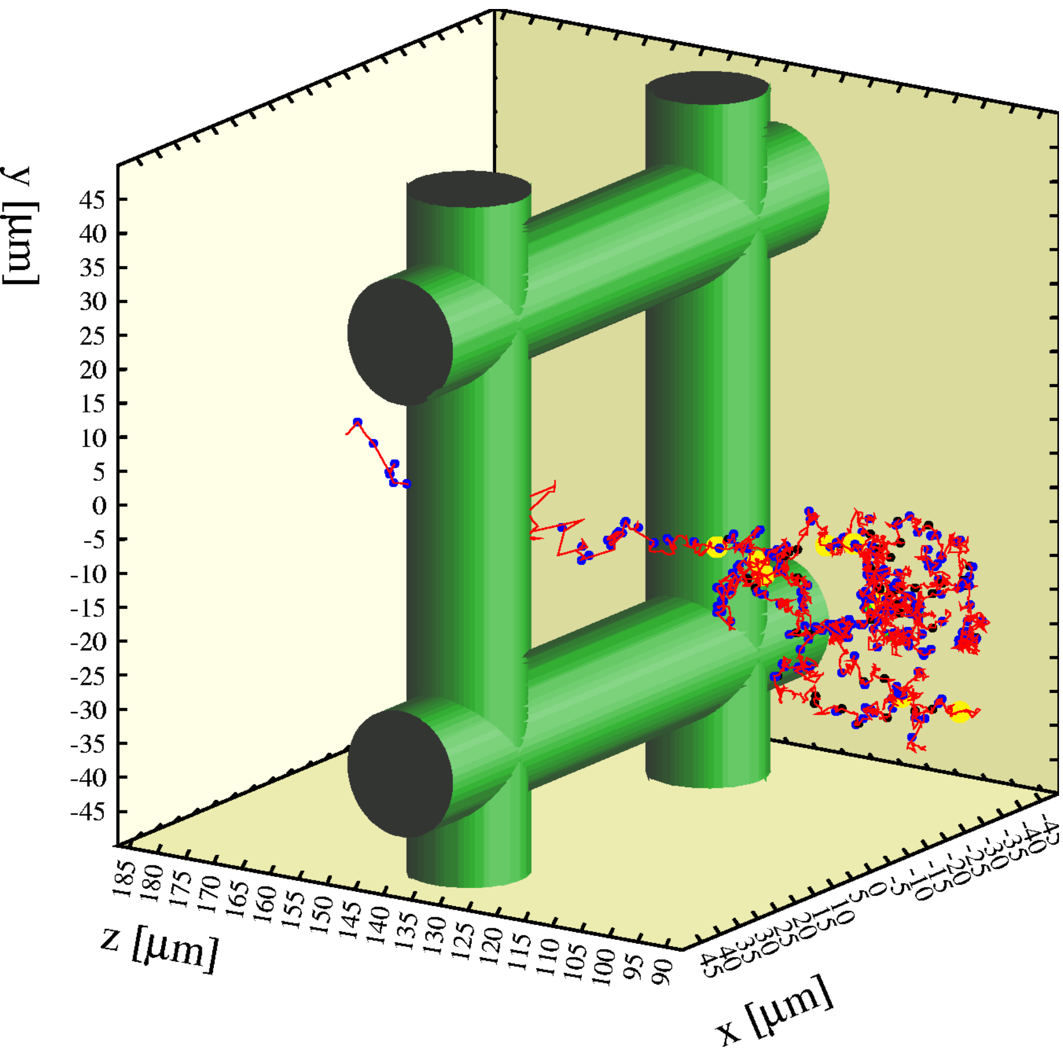


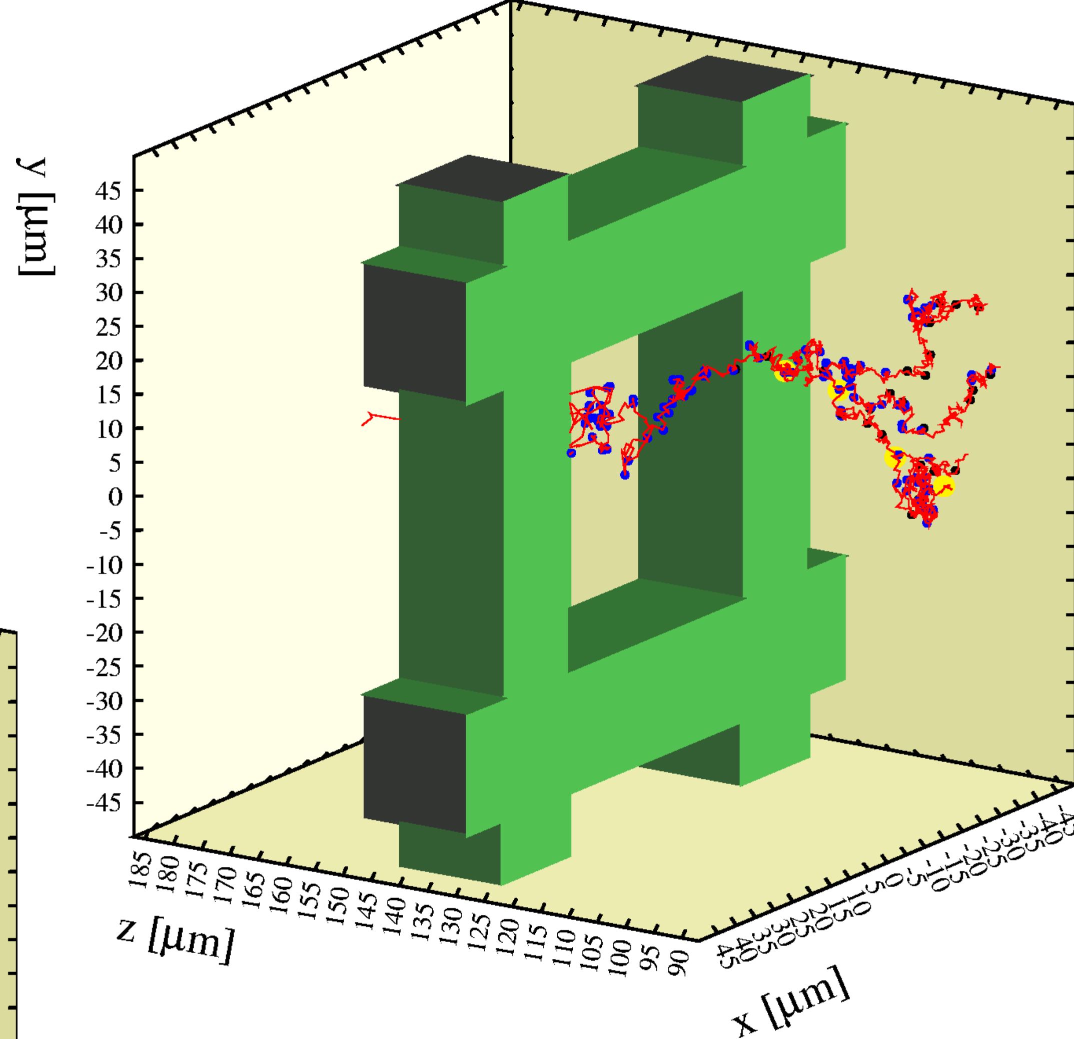


Why molecular level simulation

- Recall:
  - Mean free path of electrons in Ar: 2-5 μm,
  - diffusion: ~80 μm for 1 mm.
- Compare with:
  - Micromegas mesh pitch: 63.5 μm
  - GEM polyimide thickness: 50 μm
  - Micromegas wire thickness: 18 μm
  - GEM conductor thickmess: 5 μm
- Hence:
  - mean free path approaches small structural elements;
  - diffusion is not likely to be Gaussian;
  - such devices should be treated at a molecular level.

Microscopic Micromegas



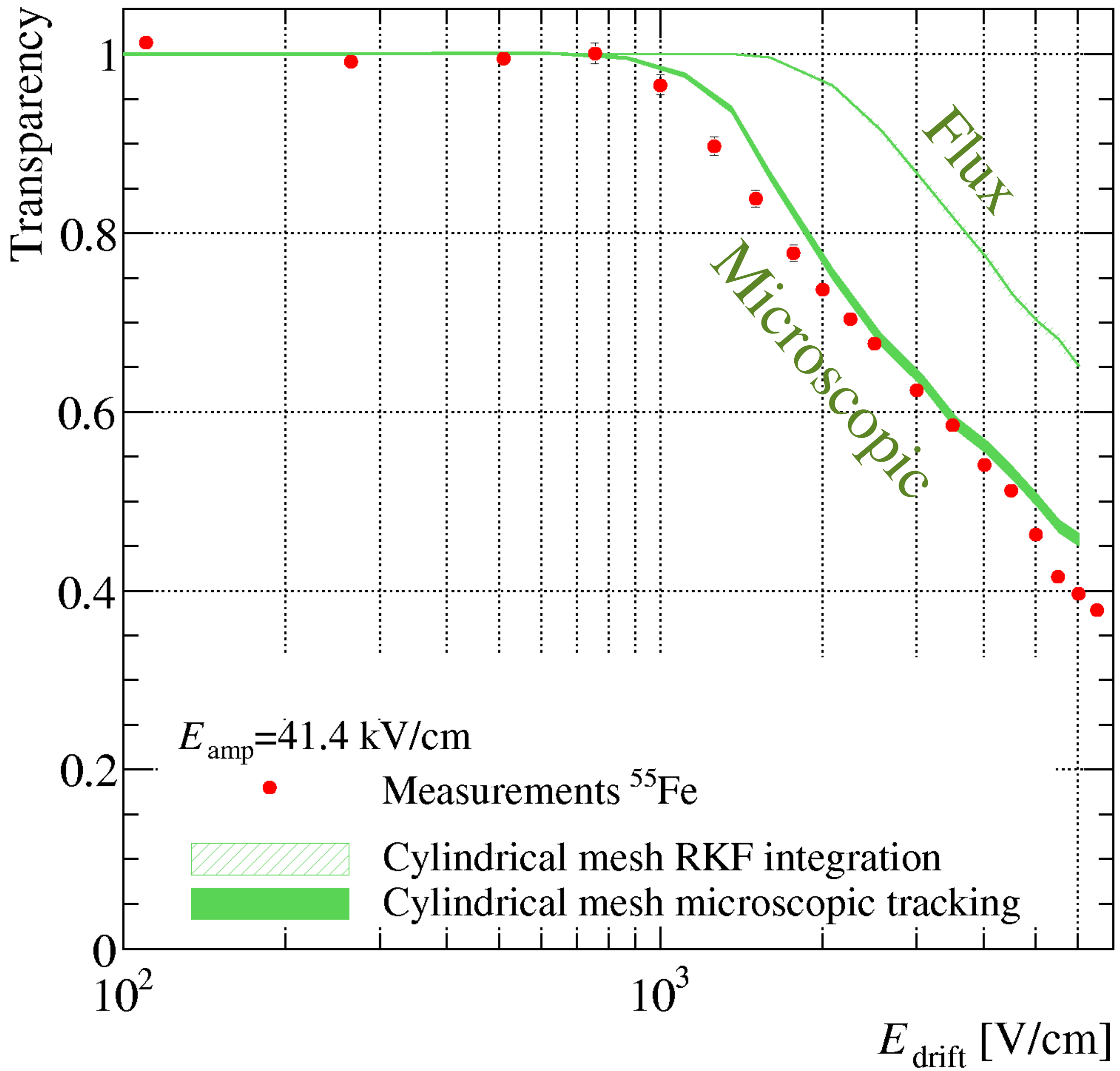


- Legend:
  - – electron
  - o inelastic
  - o excitation
  - o ionisation

Flux vs microscopic ?

- A diffusion-free flux argument does not reproduce the data ...
- but the microscopic approach works.

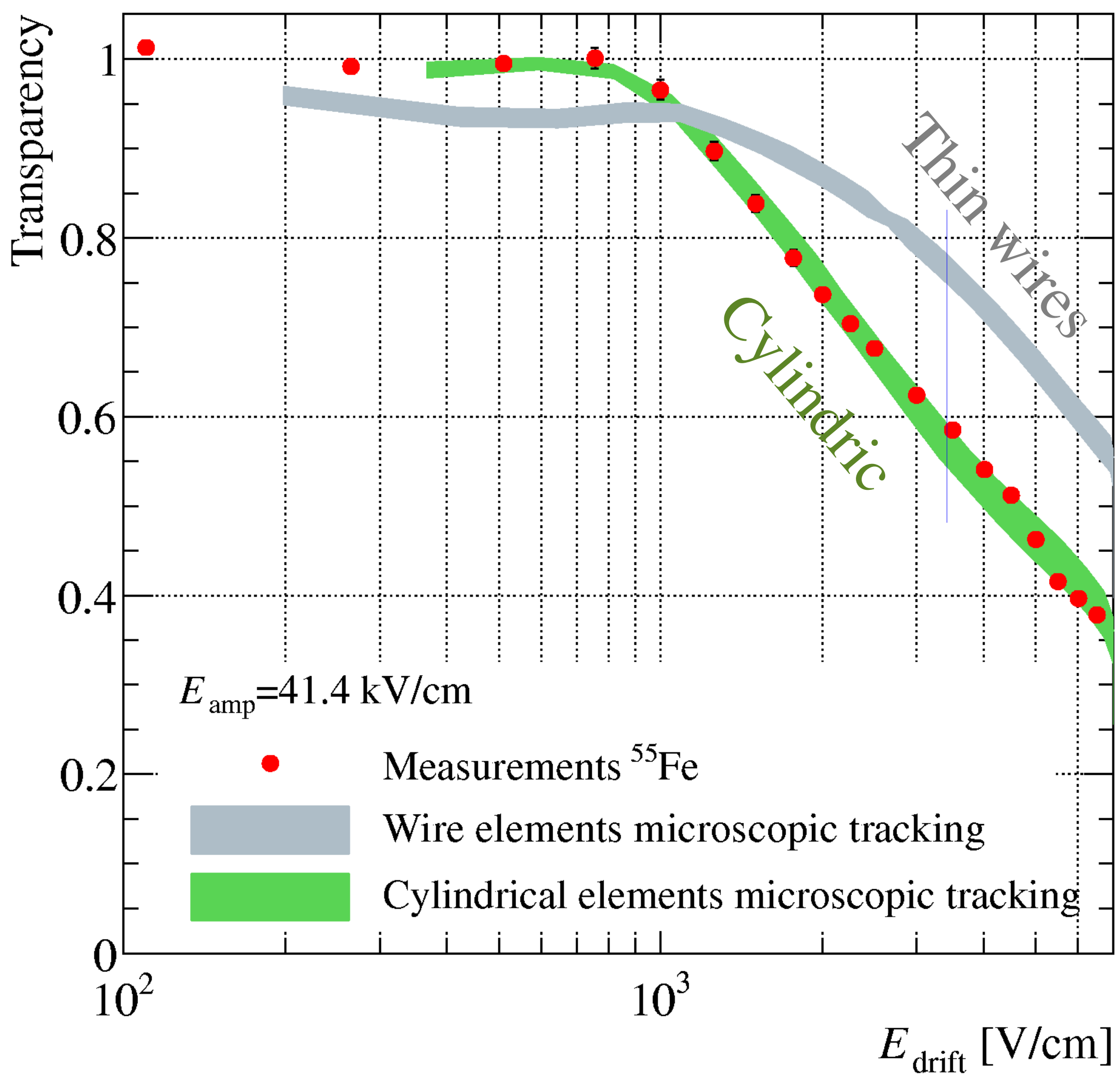
Field calculations: finite elements.



Thin-wire approximation ?

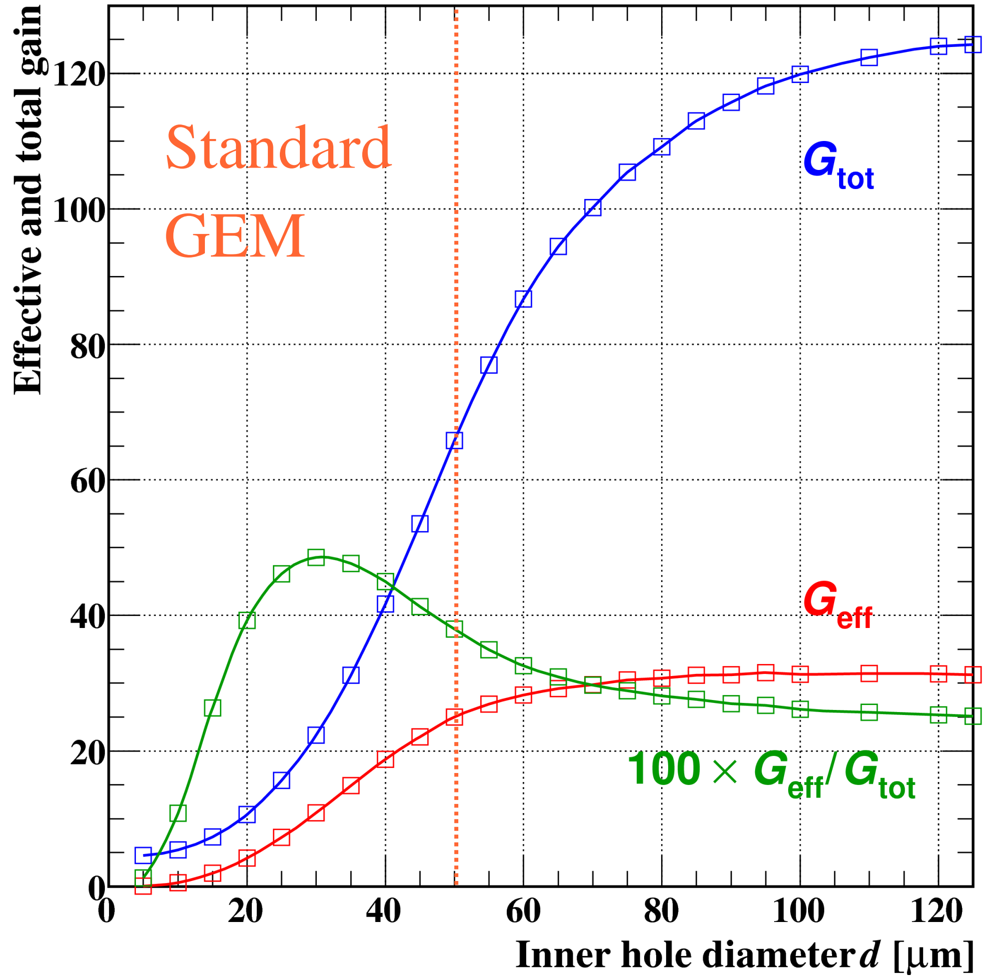
- The thin-wire approximation is usual in wire chambers – but is not adequate here.

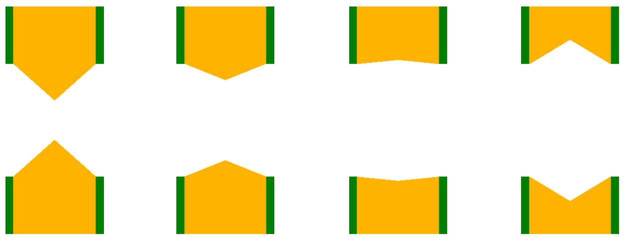
Field calculations: neBEM.



Gain calculations in a pristine GEM

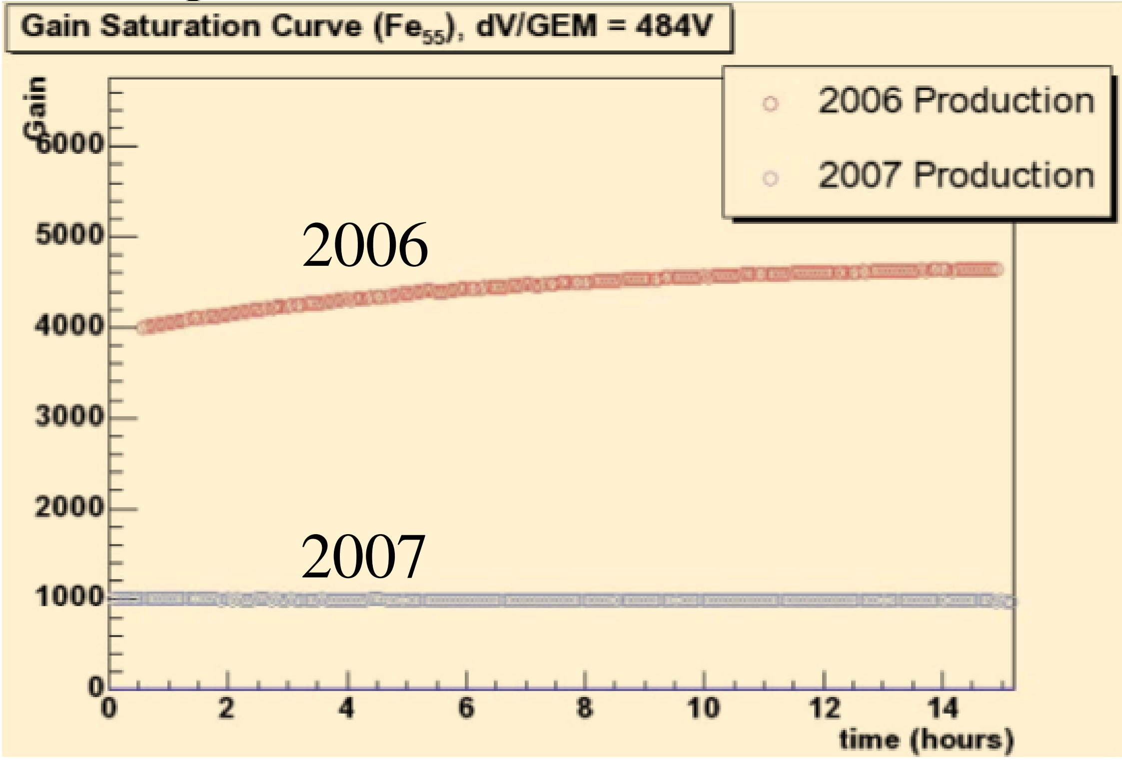
- Calculations predict that G_{tot} and G_{eff} rise with increasing inner hole diameter.
- G_{eff} rises mainly because the losses of incoming electrons diminish;
- G_{tot} rises because the exit electrode becomes more accessible.

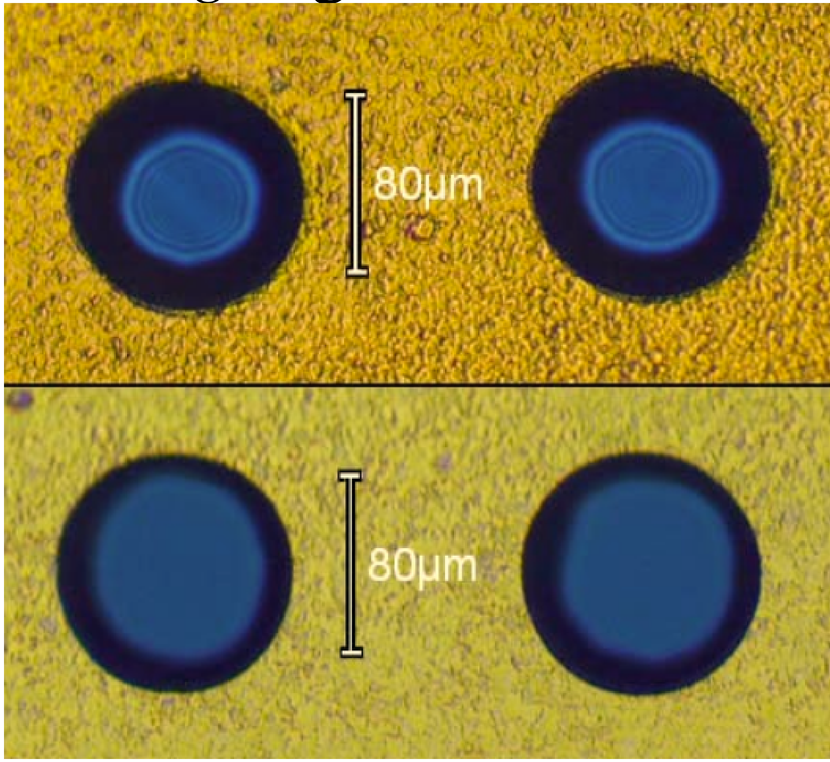




HBD data

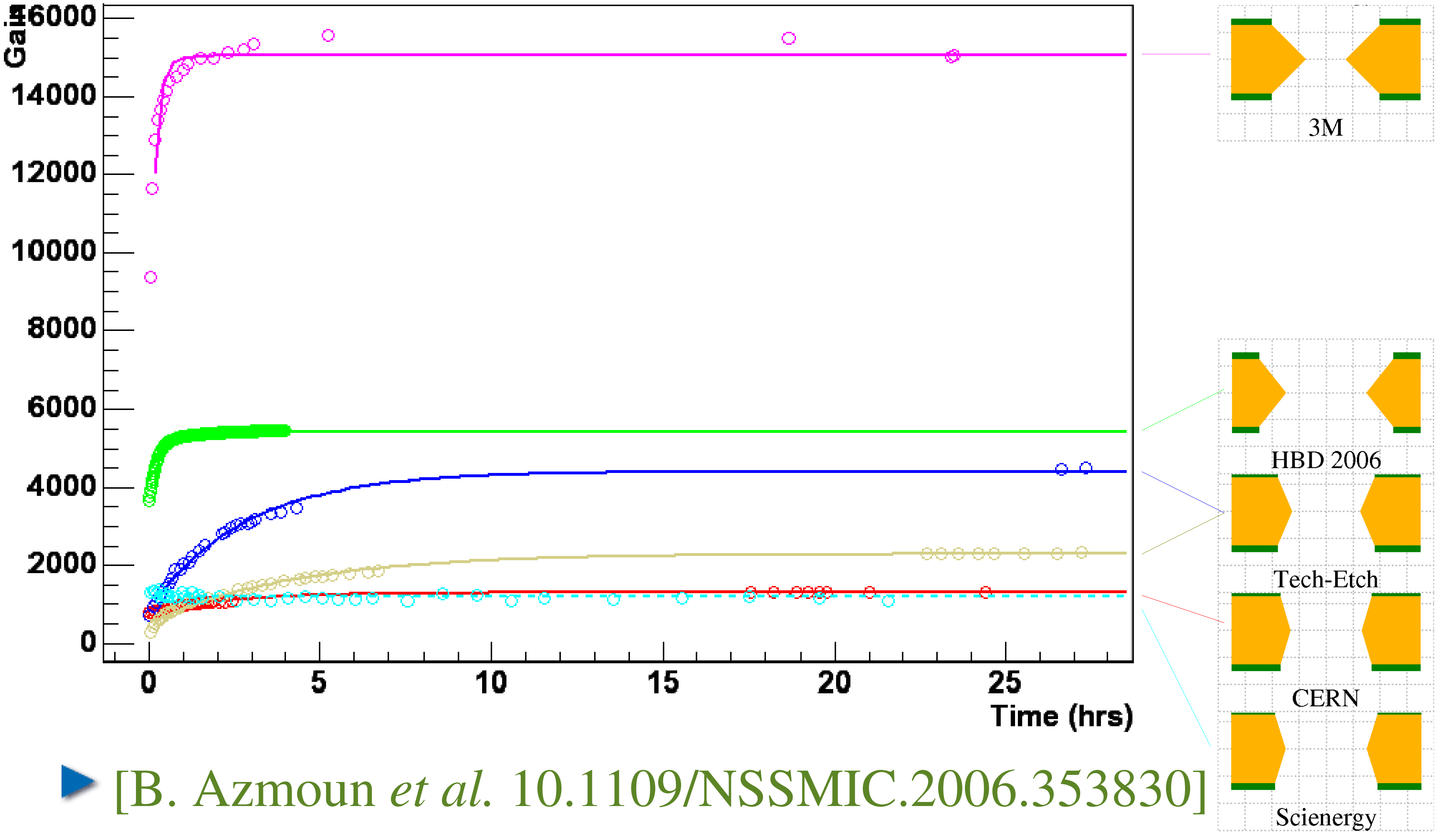
- Measurements for 2 triple GEMs with different hole shape shows that smaller holes lead to *larger* gain !





- [W. Anderson *et al.* 10.1109/NSSMIC.2007.4437147]

GEMs of various manufacturers



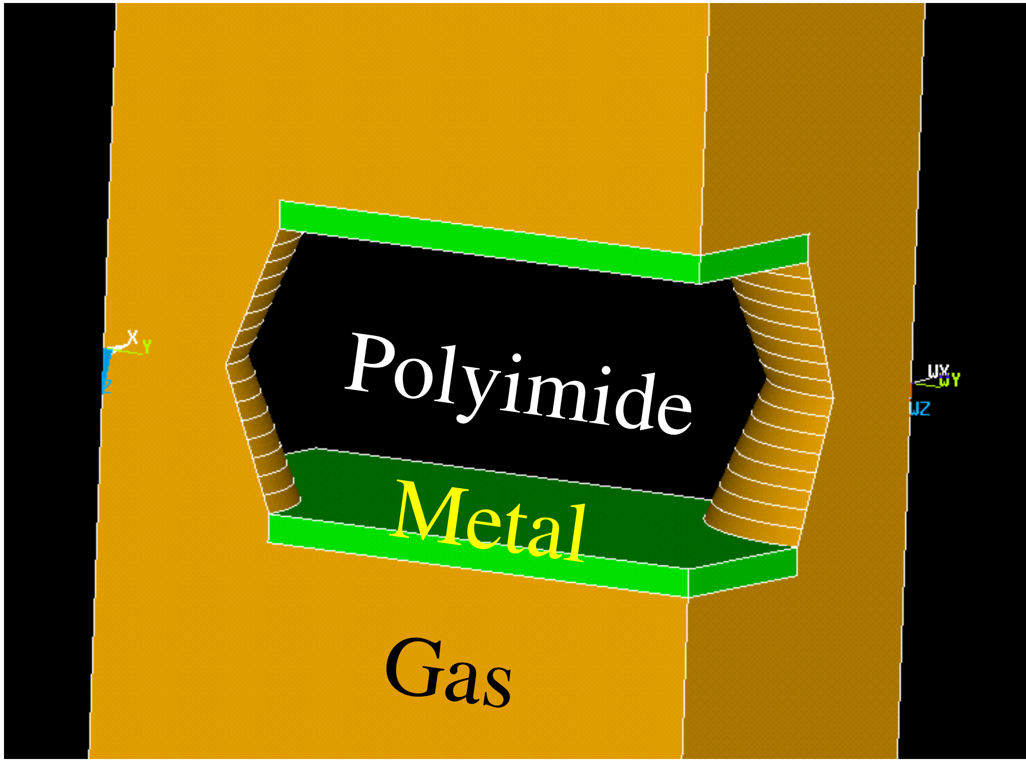
- [B. Azmoun *et al.* 10.1109/NSSMIC.2006.353830]

Surface charge

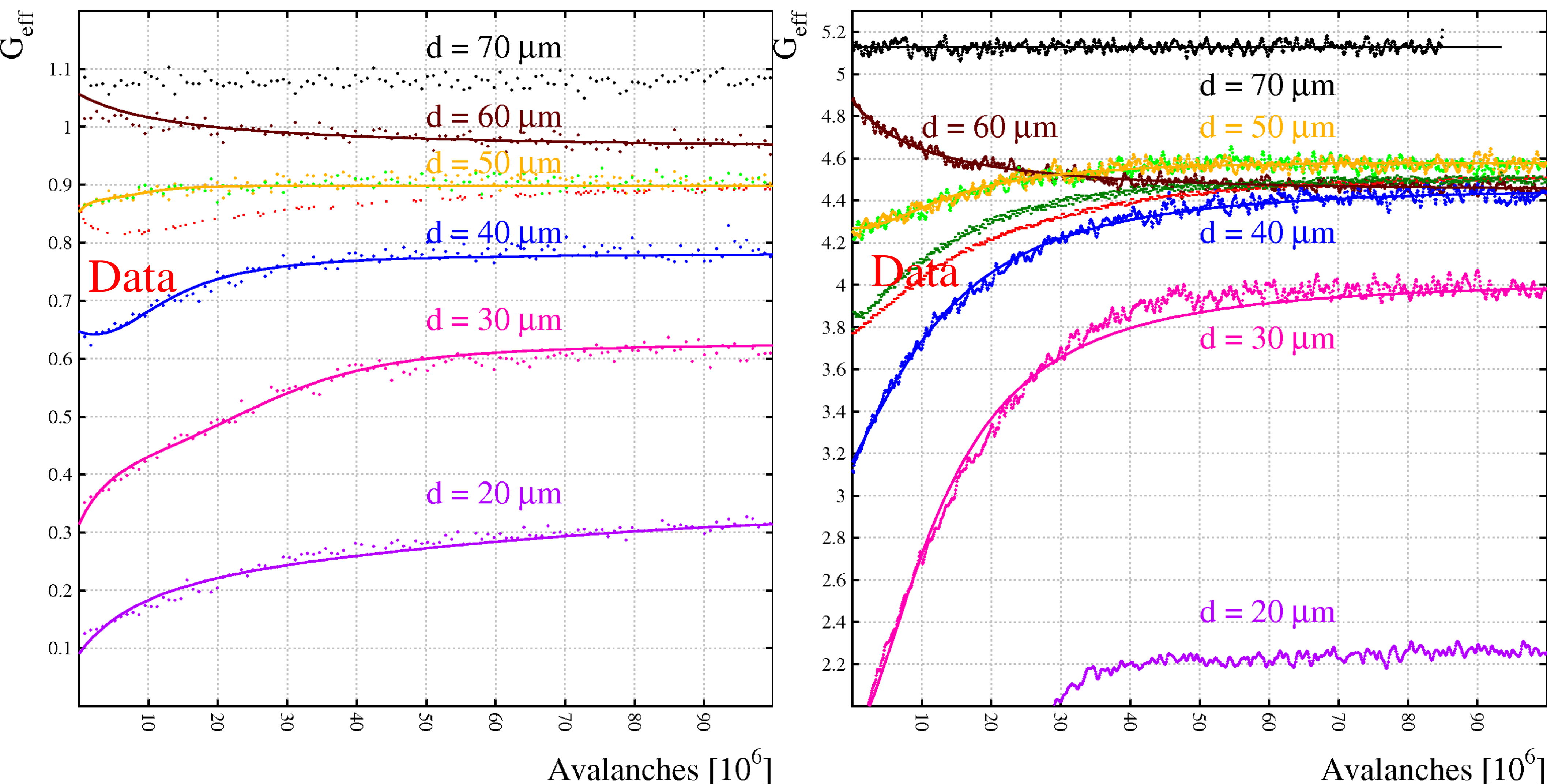
- GEMs violate the 1st law of gas-based detectors: active gas must not be in contact with an insulator.
- Electrons and ions will therefore land on the insulating material.
- Polyimide as used in GEMs is an extraordinarily good insulator: once on the surface, charge stays there.

GEMs with surface charge

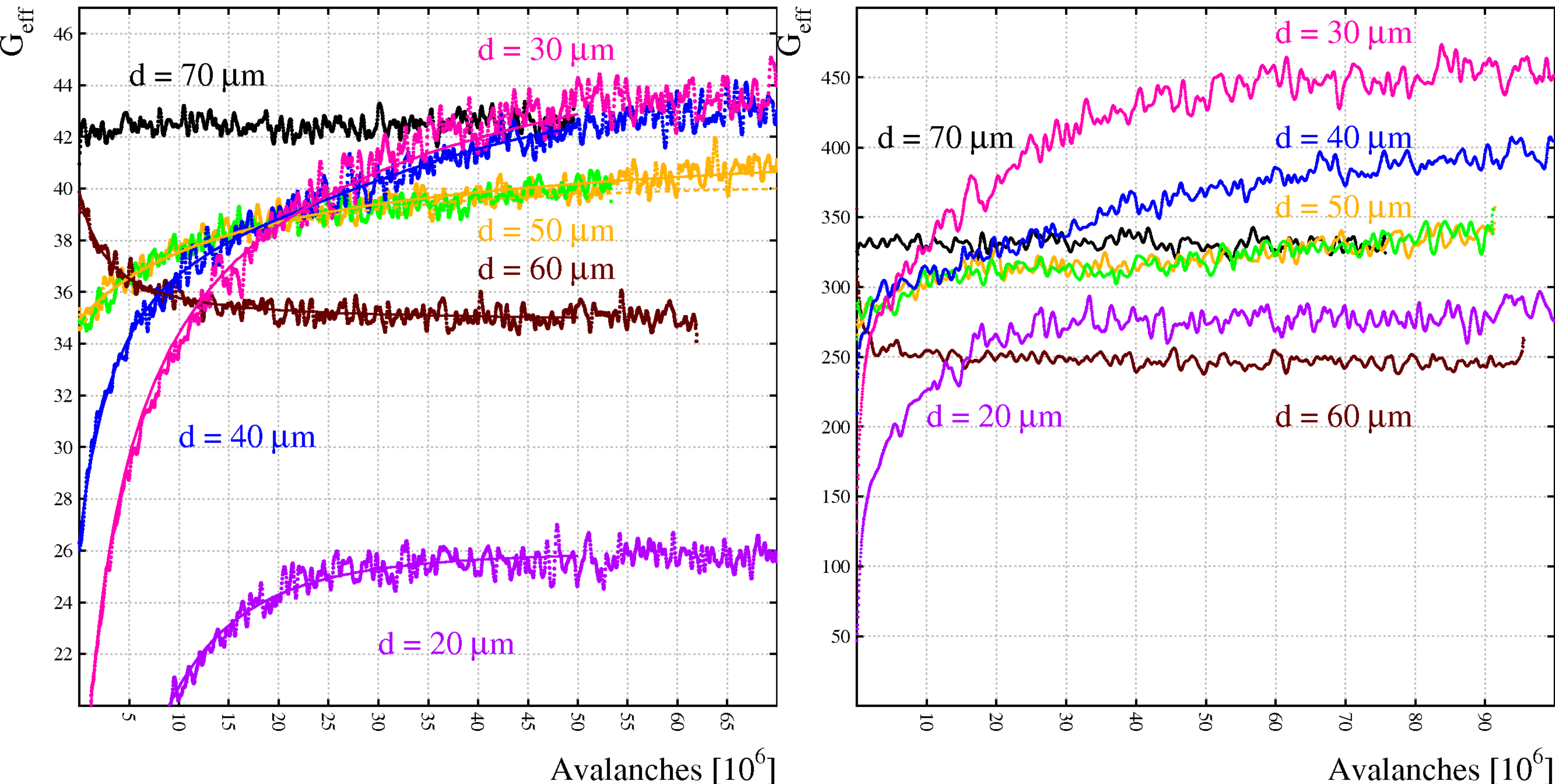
- The polyimide surface area inside the holes is sliced.
- Start: uncharged GEM;
- iterate:
  - simulate avalanches;
  - histogram electron and ion deposition patterns;
  - add surface charges and recalculate the field;
- convergence when electron and ion deposits balance.



V_{GEM} = 220 V and V_{GEM} = 300 V



V_{GEM} = 400 V and V_{GEM} = 500 V



GEM surface charge – summary

- Gain (effective and total) is modified by charging-up.
- Hole shape:
  - charge-induced increase is strongest in tapered holes;
  - gain is virtually stable in cylindric holes;
  - dependence on hole shape is non-linear.
- Voltage:
  - effect increases with voltage.
- Although the absolute gain is not yet understood, simulations do reproduce charging-up effects.

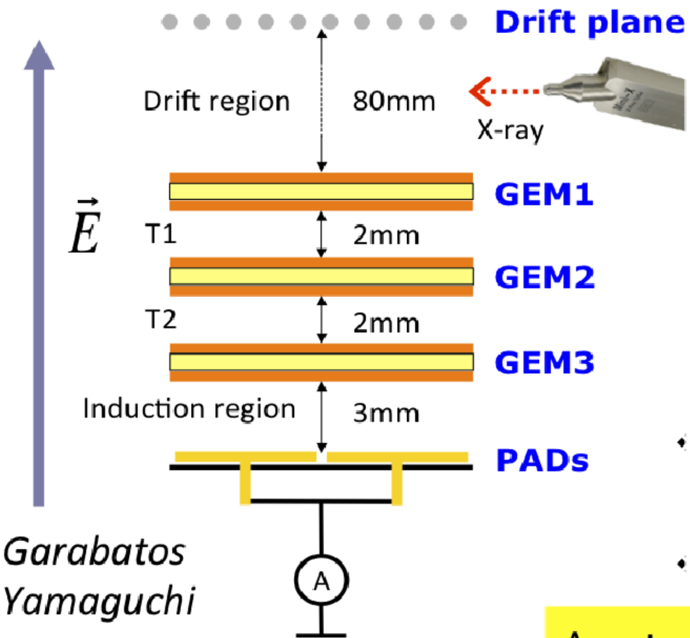
Ion back flow and space charge

- Alice plans using a triple GEM for TPC read-out with:
  - ion back flow   < 0.5 %   (< 0.25 % in some sources)
  - effective gain   2000

- https://cdsweb.cern.ch/record/1475243/files/LHCC-I-022.pdf

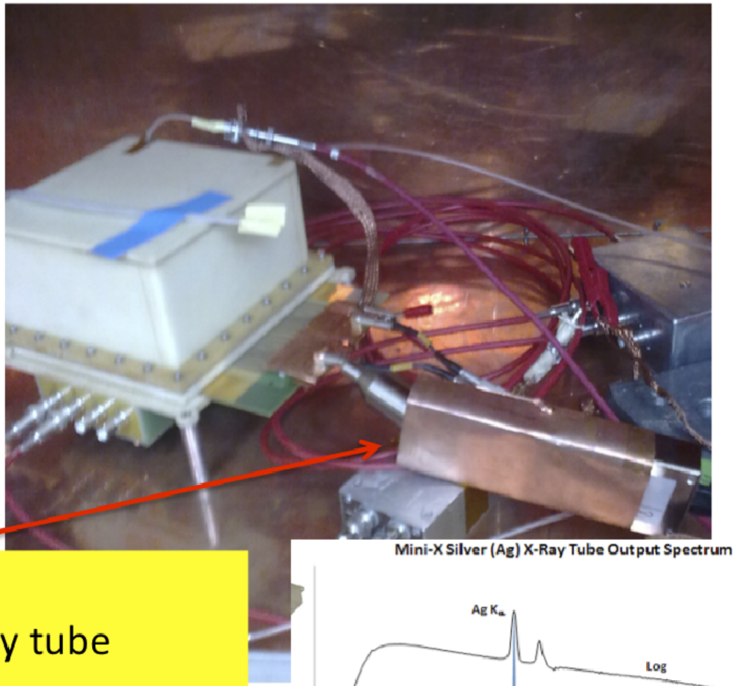
IBF Measurements at CERN

- Systematic measurements at RD51 lab. in CERN.
  - Field dependence (ΔV_{GEM}, T1, T2, Induction)
  - Rate, x-ray position dependence (charge current density)



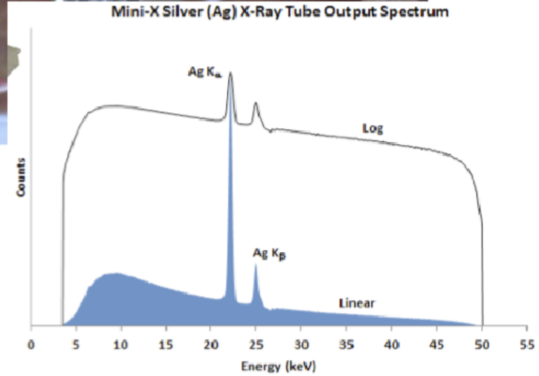
C. Garabatos
Y. Yamaguchi

- ❖ Currents at readout pads & drift plane are measured.
- ❖ The current of primary ions is measured with only HV ON for drift plane.
  - ✓ Gain = $I_{pad}/I_{prim.ion}$
- ❖ Always E_{drift} = 400V/cm



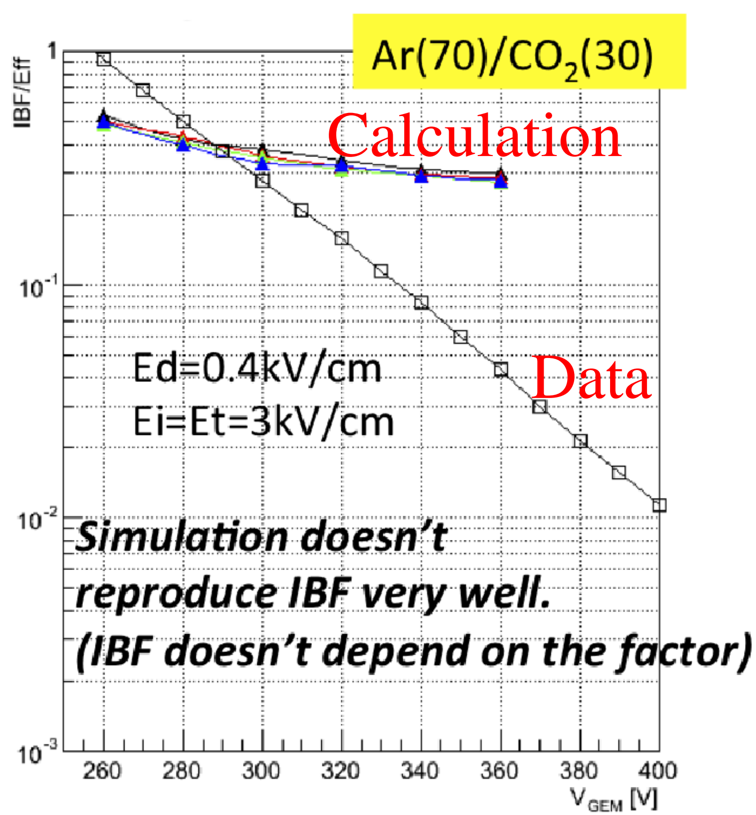
Ampteck
Mini X-ray tube

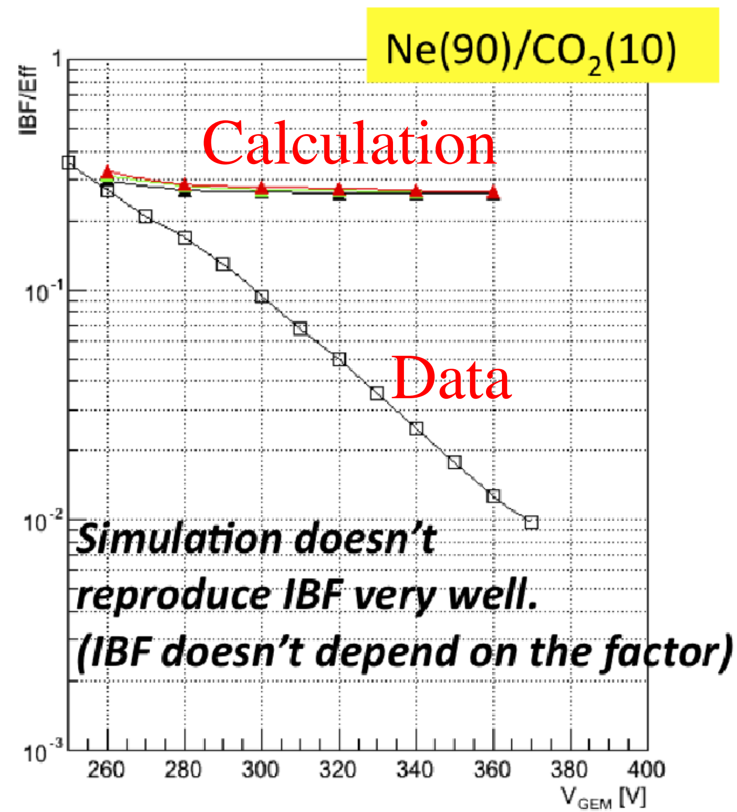
Ag target: Kα=22KeV
Rate (Ar(70)/CO2(30)) = 5e7 estimated by I_d



First comparison of IBF between real and simulations

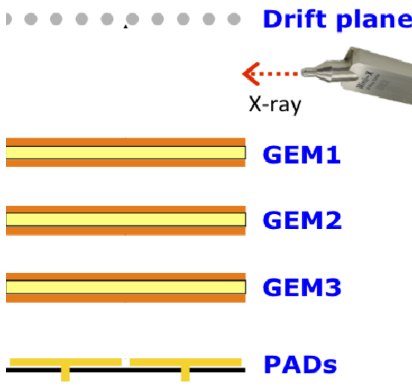
- Simulation (Penning factor) is tuned to reproduce the gain.
- However, IBF in simulation doesn't agree with the measurements.
- Strong dependence on V_{GEM} in the measurements

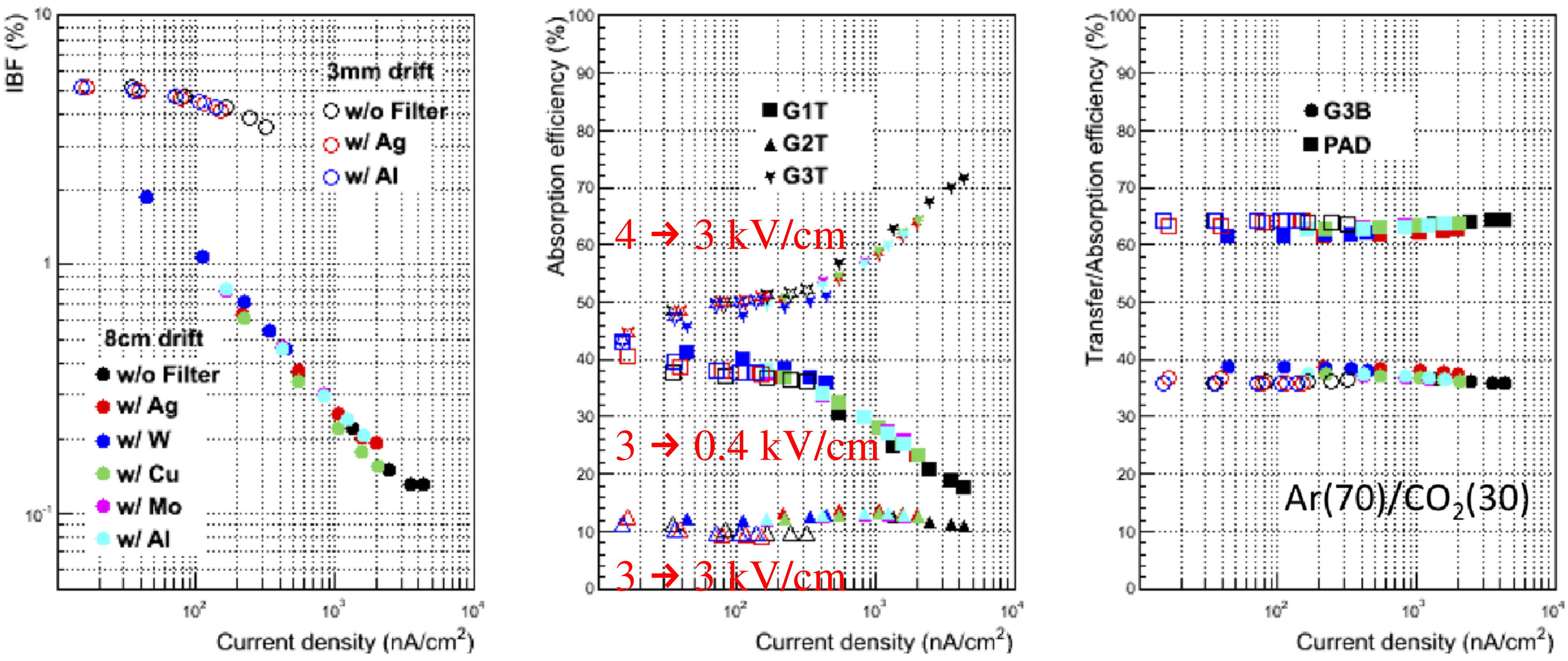




More results from the measurements

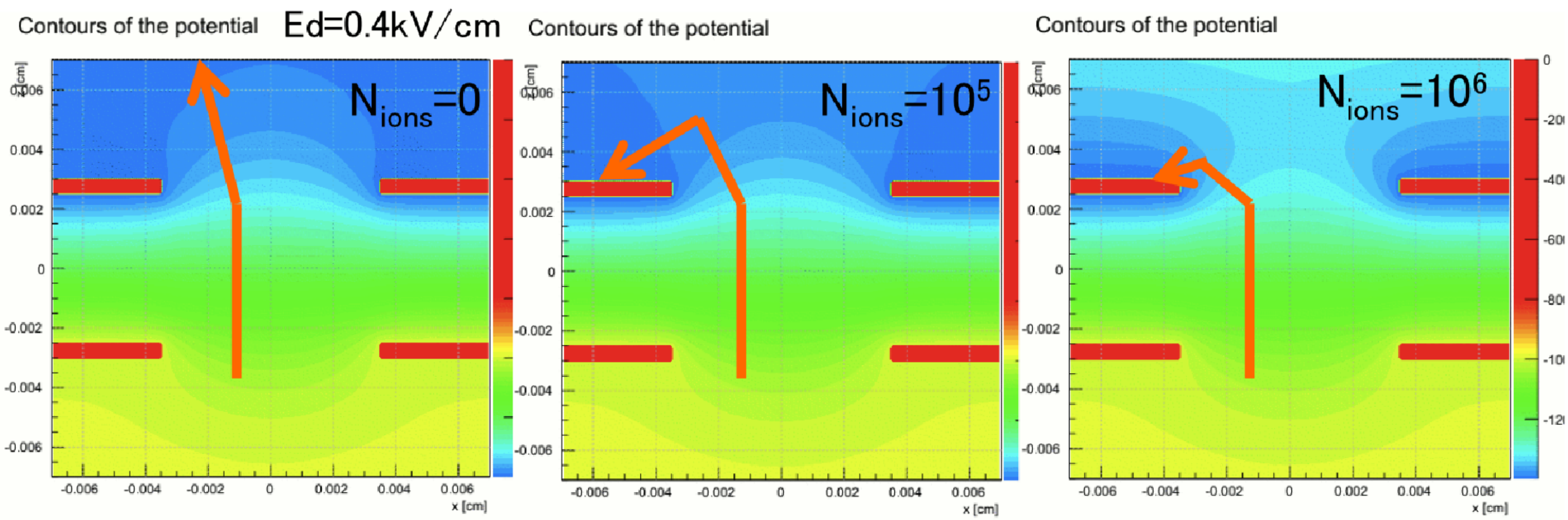
- Rate, Energy (target), drift-space (3 mm or 80 mm) dependence
- Clear rate and drift-space dependence of IBF.
- Indicating space-charge effect ($\propto$ rate$\times$gain$\times$seed) to IBF...



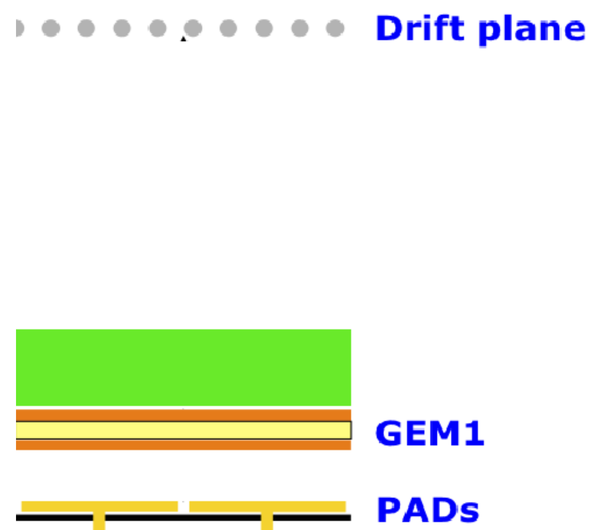


Space-charge simulations: Method

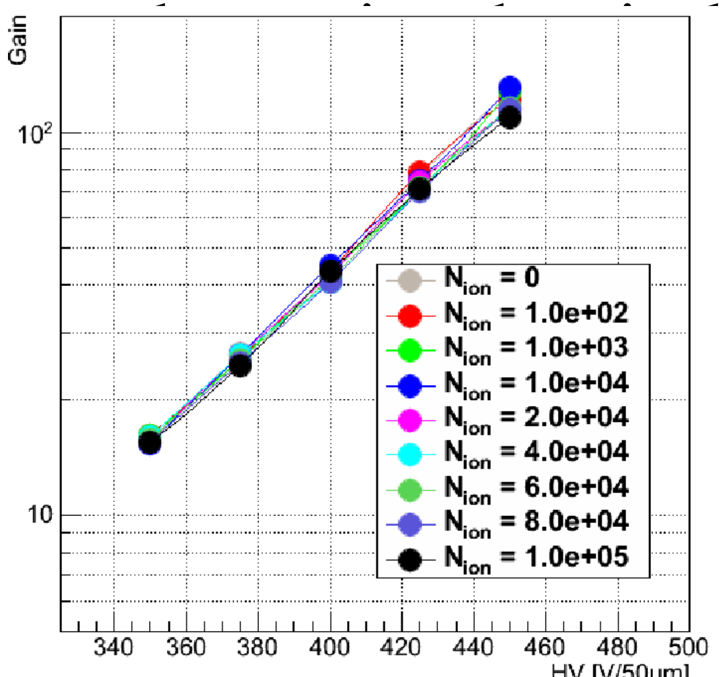
- Slice the space in drift direction by 100 μm
- Uniformly distribute ions in space $z \in [Z, Z+100\mu\mathrm{m}]$
- Calculate the field by ANSYS and evaluate gain/IBF by Garfield++
- Example of the field around GEM1 with N_{ions}=0, 10^5, 10^6 with E_{drift}=0.4kV/cm. less IBF with huge N_{ions}?

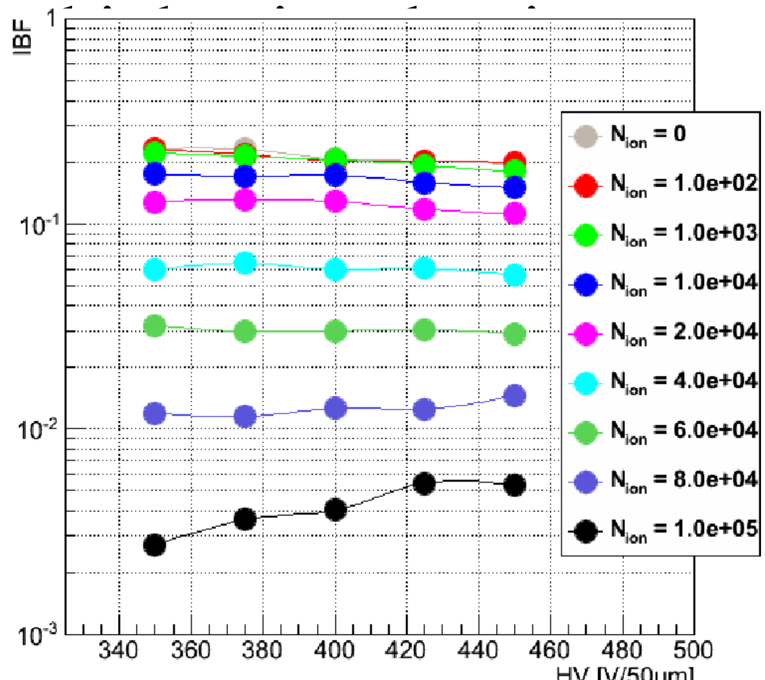


Space-charge above a single GEM



- Ions at $z \in [0,\ 100\ \mu\mathrm{m}]$ above the GEM; $E_{dr} = 400$ V/cm; Ar/CO_2 70/30;
- Gain: Does not depend on the ion density;
- IBF: Onset of decrease at ~10^4 ions/hole,

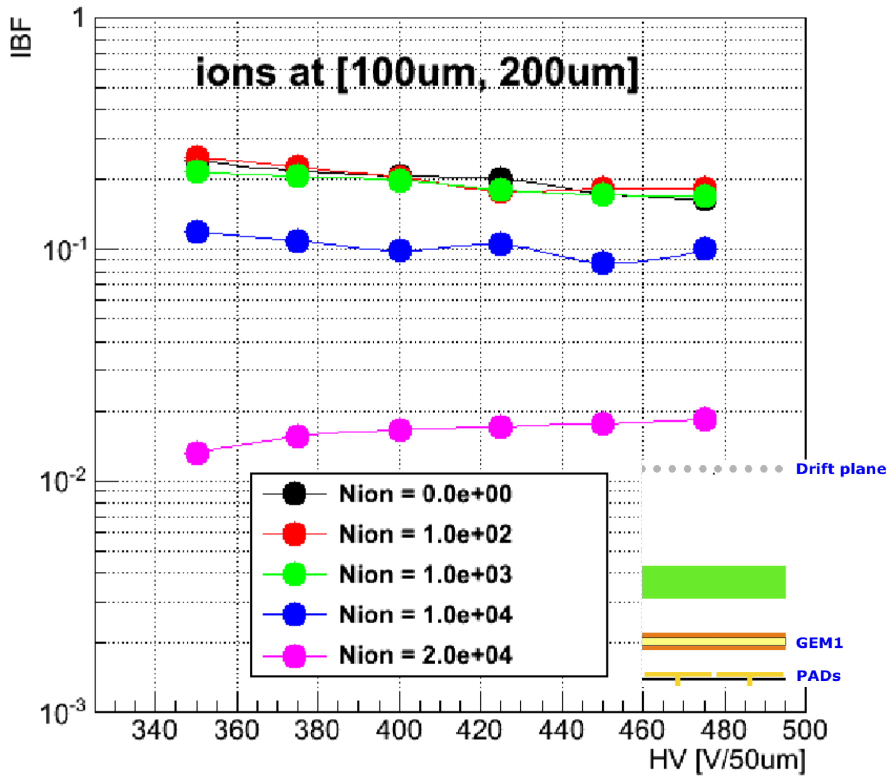


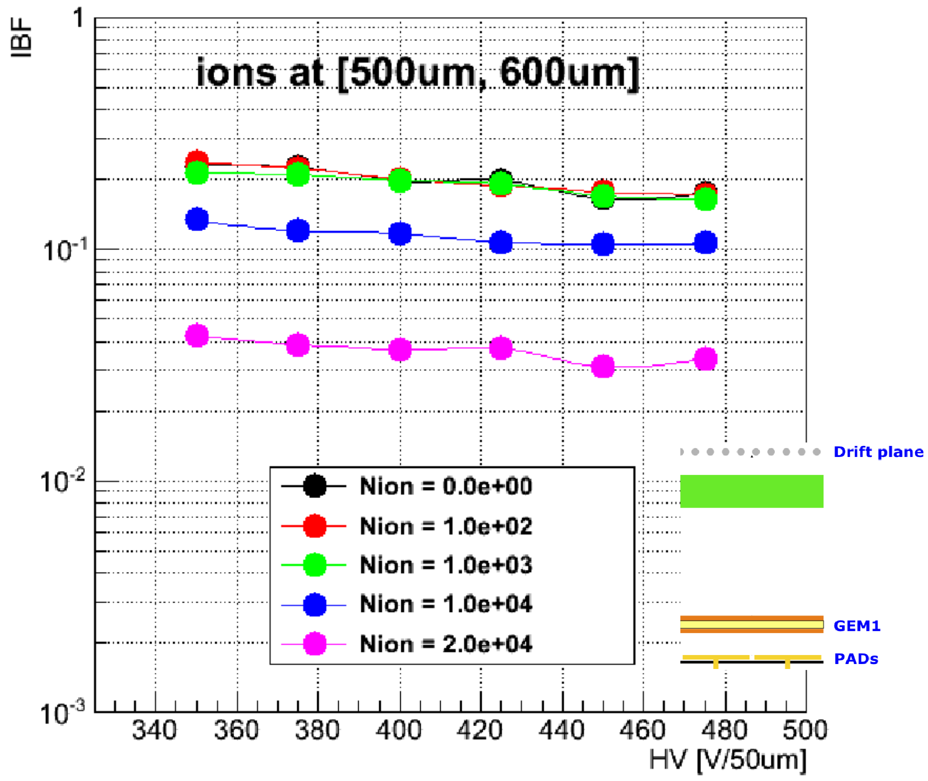


Note: N_{ions} is expressed in ions / ½ hole

Space-charge above GEM

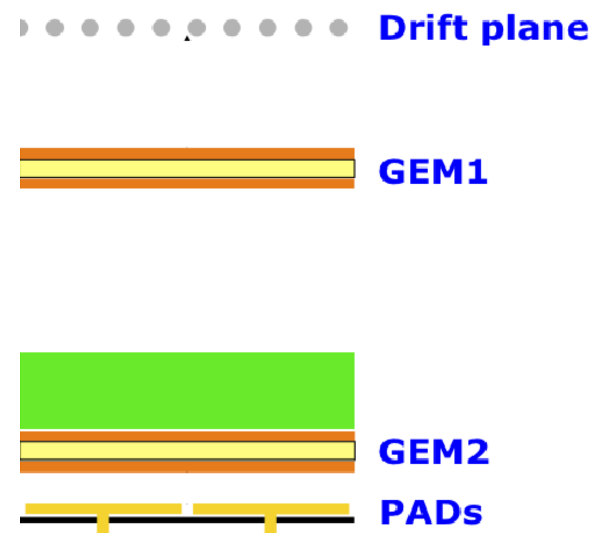
- Ions at $z \in [100, 200\ \mu\mathrm{m}]$ (left) and $z \in [500, 600\ \mu\mathrm{m}]$ (right) above GEM1. N_{ions}: from 0 to 2×10^4
- For $N_{ions} \geq 10^4$, IBF gets smaller ($\times10$) with more N_{ions}.
- N_{ions} cannot be 4×10^4. In this case, the field is reverted (no electrons going into GEM).

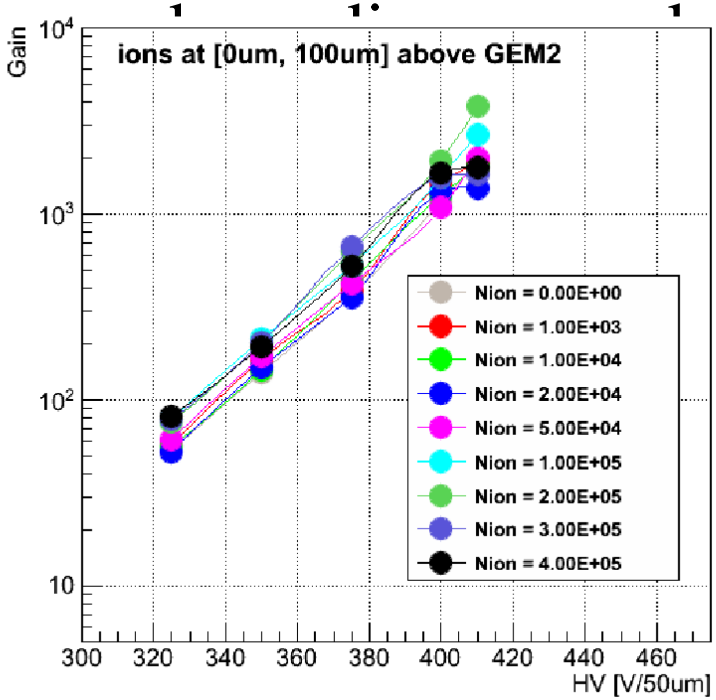


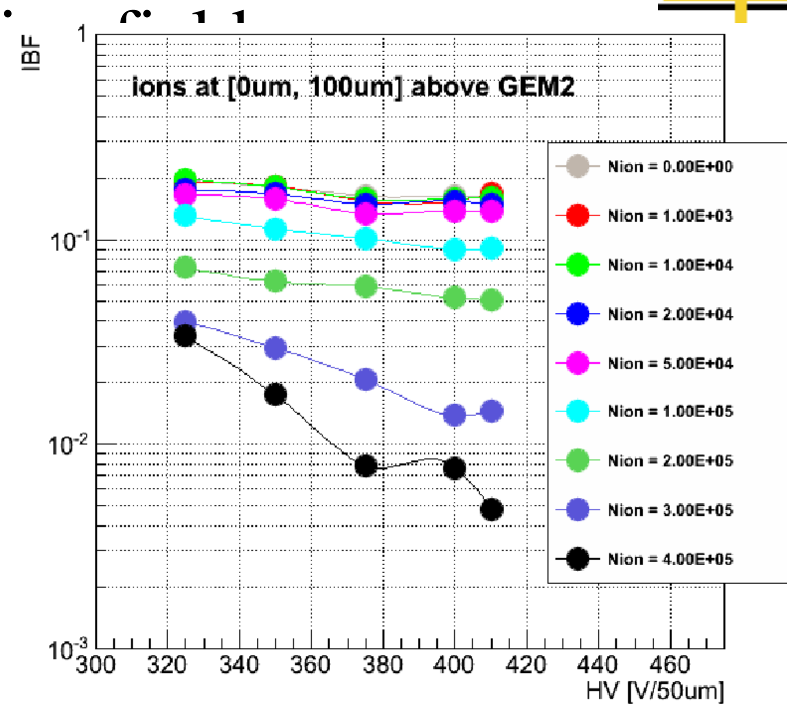


Space-charge above a double GEM

- Ions at $z \in [0, 100\ \mu m]$ above GEM2;
- Gain changes by a factor 2: smaller electron collection losses at GEM1 ?
- IBF decreases from ~5 10^4 ions/½ hole,



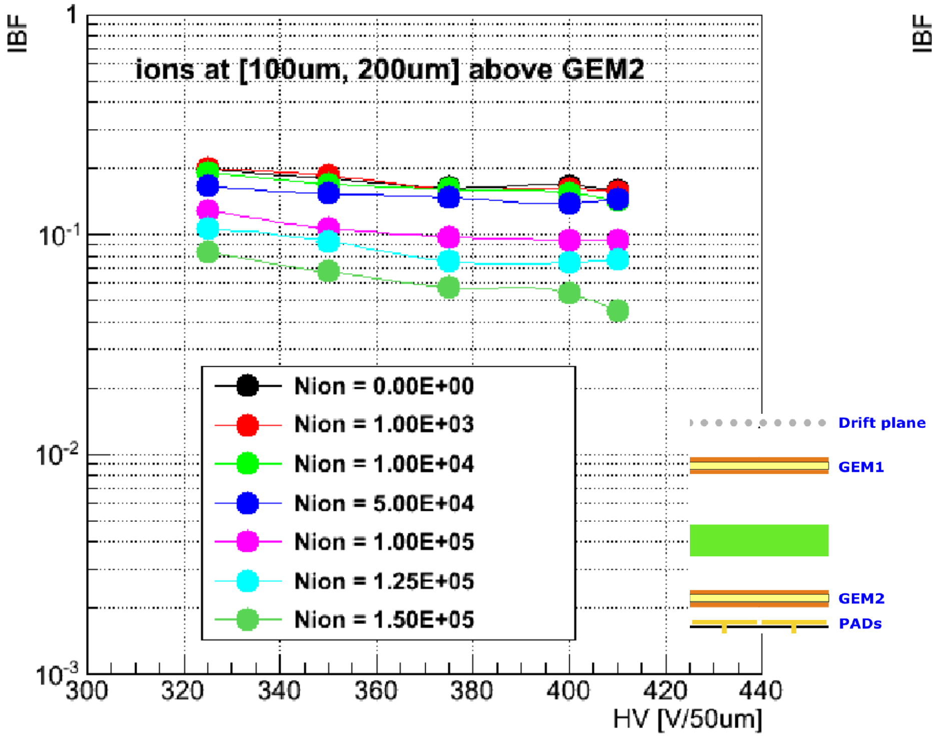


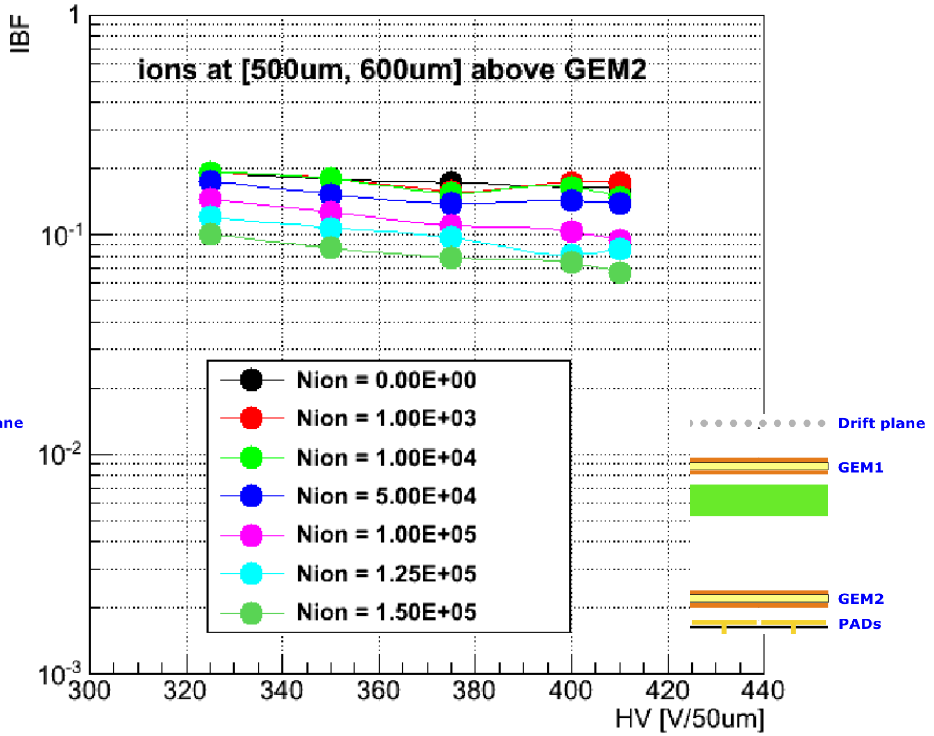


Note: N_{ions} is expressed in ions / ½ hole

Space-charge above GEM2

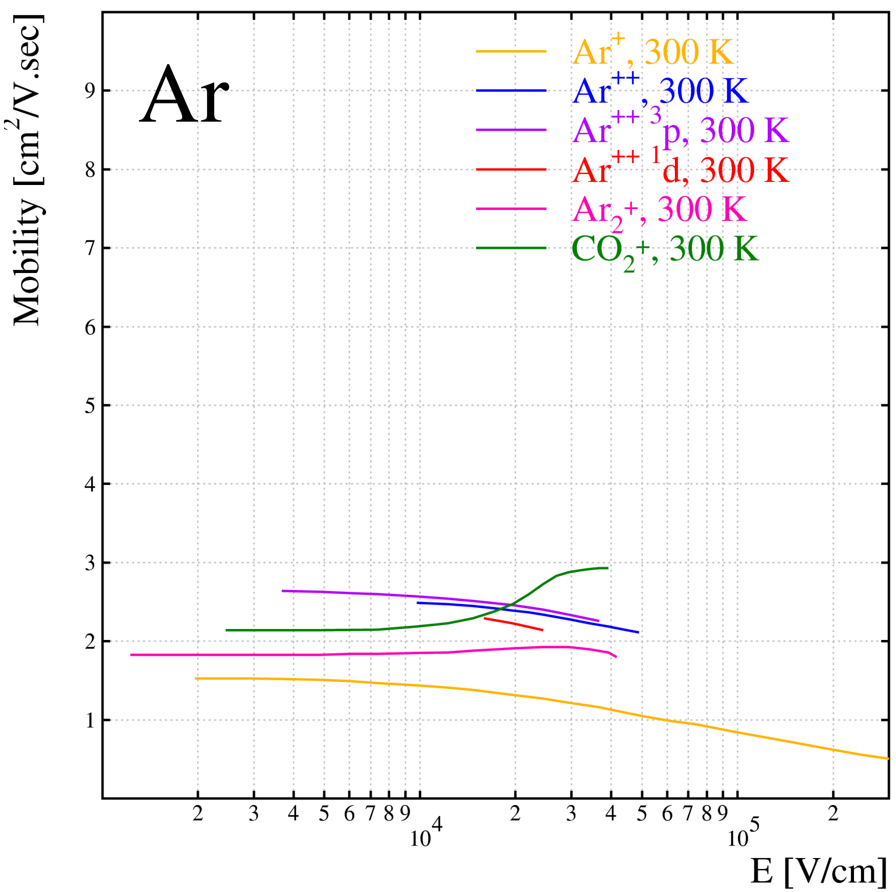
- Ions at $z \in [100, 200\ \mu\text{m}]$ and $z \in [500, 600\ \mu\text{m}]$ above GEM2. N_{ions}: from 0 to $1.5{\times}10^5$
- IBF changes for $N_{ions} \geq 5{\times}10^4$. Onset depends on underlying field.
- N_{ions} cannot be $4{\times}10^5$. The field is reverted (no electrons going into GEM).

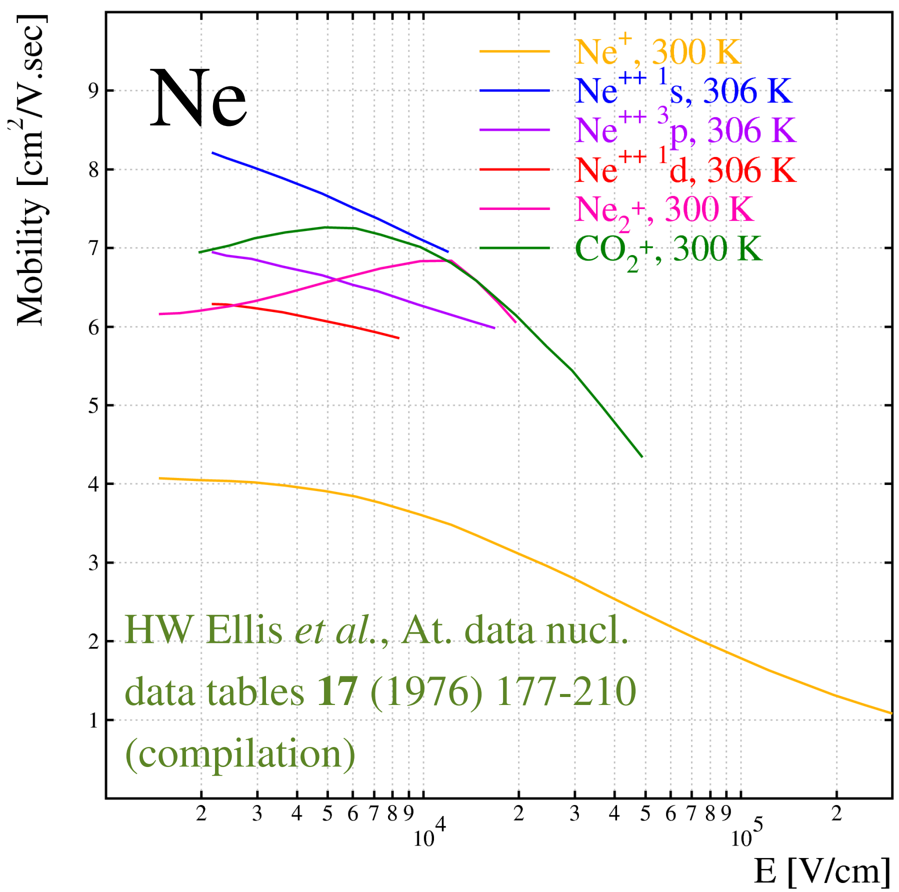




GEM – time scale

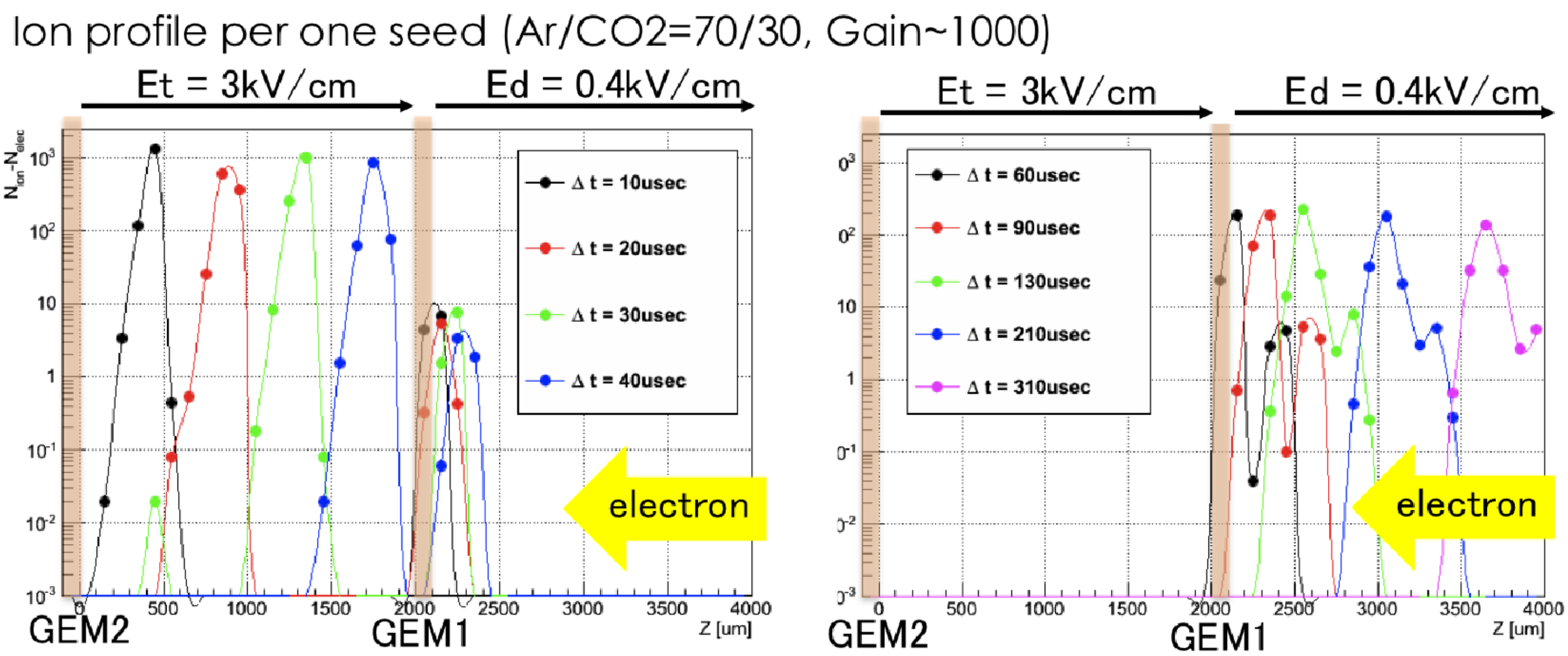
- Avalanches take a few ns: http://cern.ch/garfieldpp/examples/gemgain
- Ion velocity at 3 kV/cm: Ar: ~20 µs/mm, Ne: ~8 µs/mm





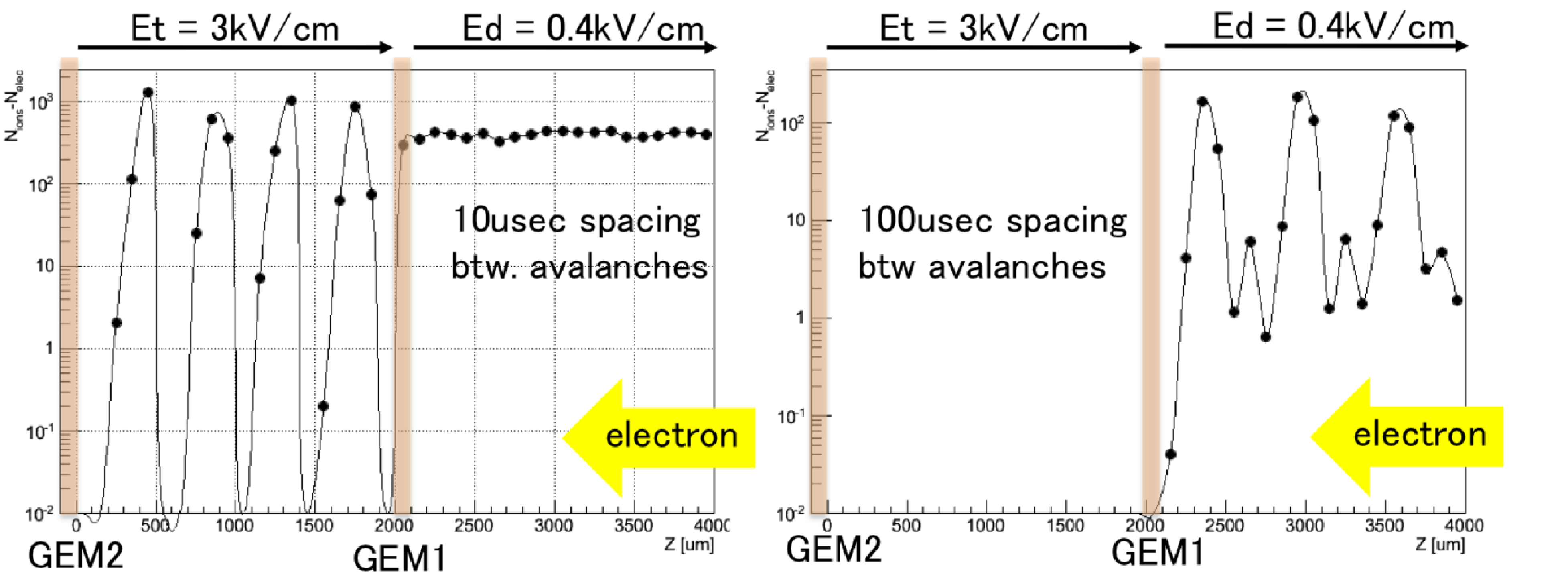
A little more dynamical simulations

- Look at the spacial ion profile along drift direction for each 10μsec after avalanche.
  - Ion profile from 10μsec to 40 μsec (left) and from 60μsec to 300μsec (right) after the avalanche (at the gain of 10000)
  - Ions are swept sway from T1 quickly (3kV/cm) and stays above GEM1 due to low field (0.4kV/cm)
- No transverse profile is taken into account.



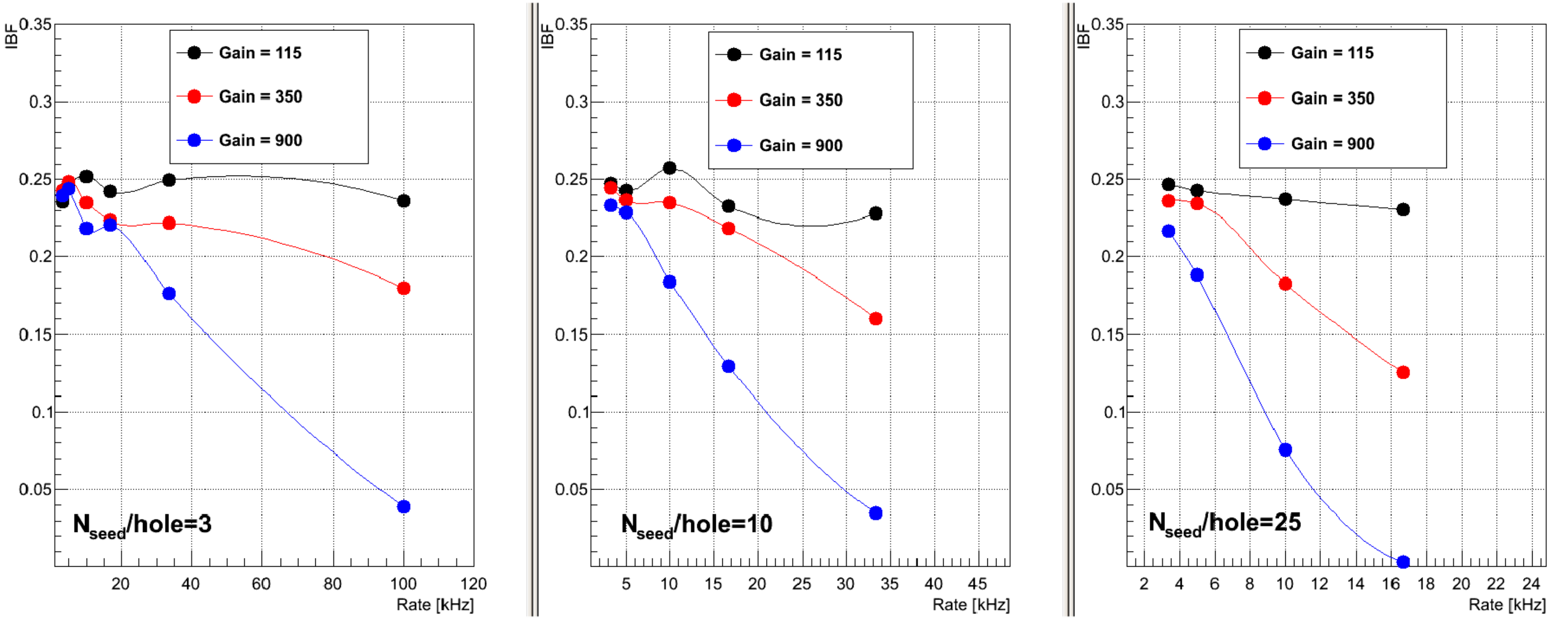
Ion Profile

- Summed up the ion profile at each time step and make ion profile corresponding for various rate.
  - If rate/hole = 100kHz, ion profiles for each 10μsec are summed up.
  - Ion profile under 100kHz (left) and 10kHz (right) avalanches at the gain =1000 and the number of seeds/hole (N_{seed})=1
- Scale this profile according to gain and N_{seed}



Ion Back Flow vs. Rate/Seed

- IBF vs. Rate and $N_{seed} = (3, 10, 25)$ at Gain = 115, 350, 900
- Clear rate dependence and dependence is much larger for higher gain
- IBF gets smaller with higher rate and high gain
  - Rate at CERN ∼ 25kHz. N_{seed} = 20-40. Gain ∼ 2000
  - Large effect of space-charge to IBF
- More dynamical and iterative simulations will be done!!

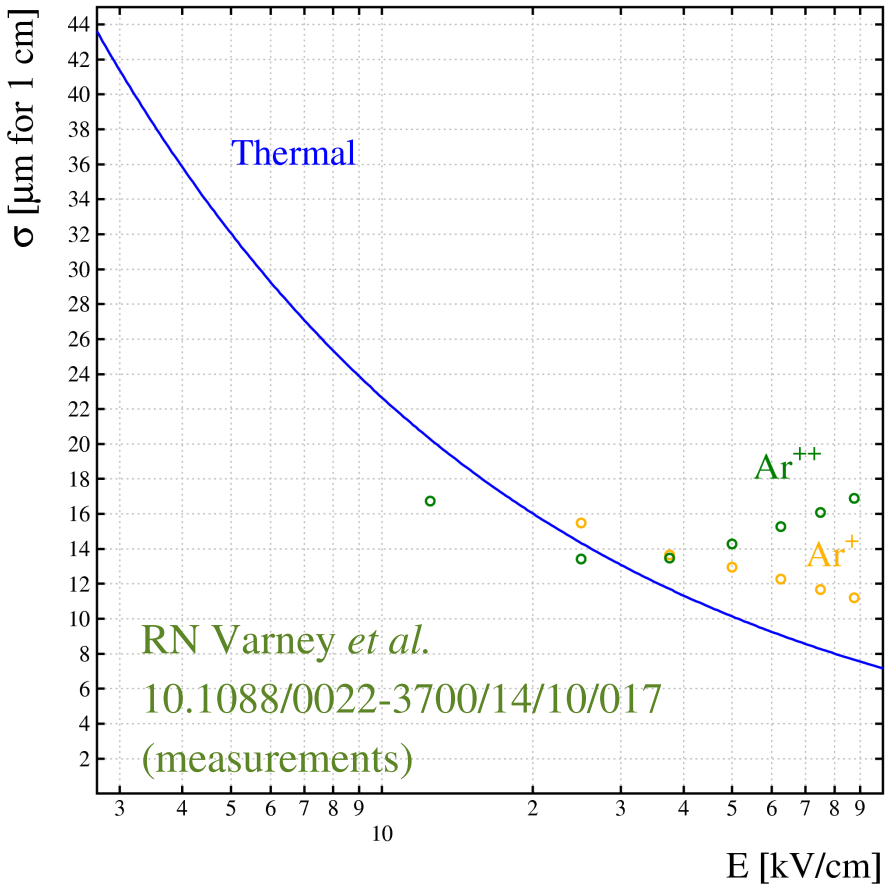


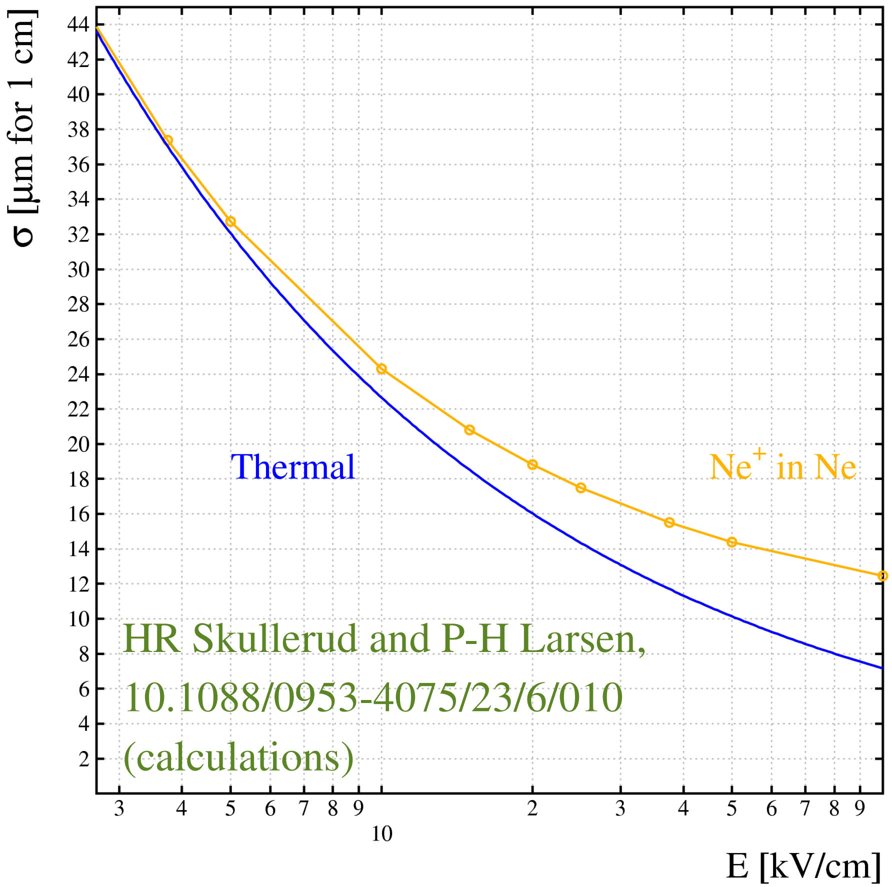
IBF studies with various configurations

- Motivation
  - To search for the optimal solutions for the suppression of IBF
  - For example, 0.25% of IBF at gain=2000 (ALICE GEM-TPC upgrade)
- What have been studied so far.
  - 3 GEM configurations under Ar/CO_2 and Ne/CO_2(/N_2)
  - 4 GEM configurations under Ne/CO_2(/N_2)
  - Hole Alignment Dependence
  - Conical GEMs
  - Extoic GEMs (Flower-GEM, COBRA-GEM)

Diffusion of Ar^+ in Ar and Ne^+ in Ne

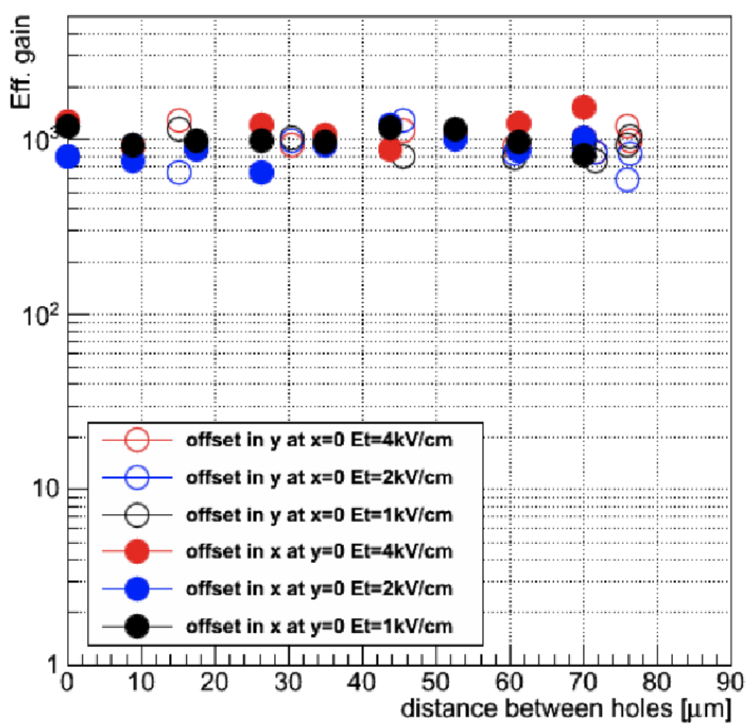
- Little experimental data, in particular at low fields.
  extrapolated from higher fields: ~10 μm for 1 mm

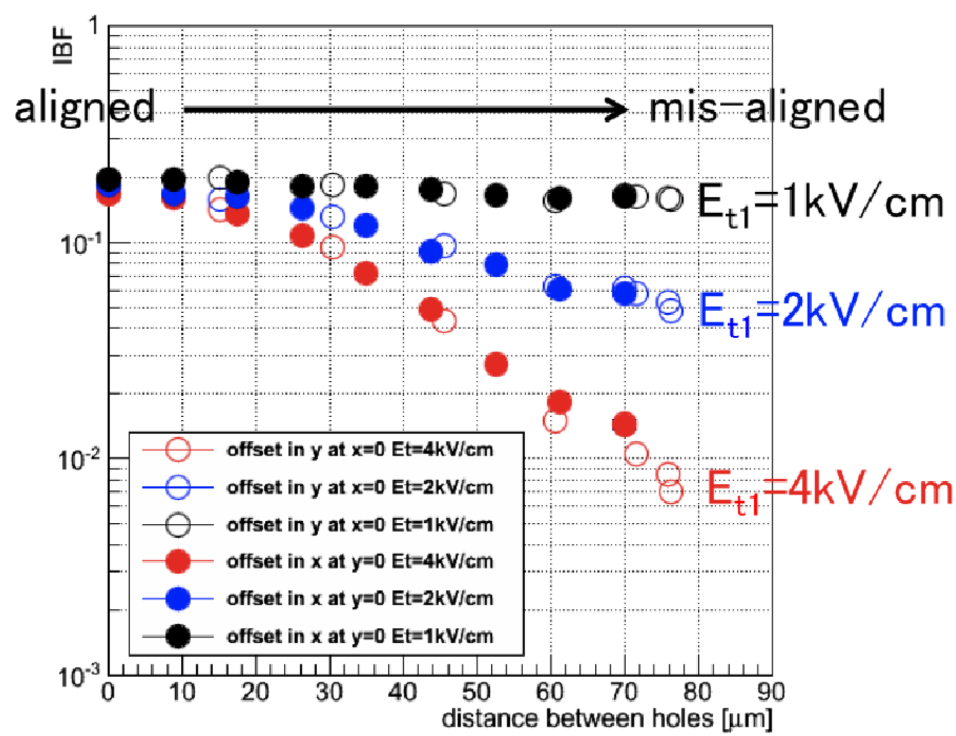




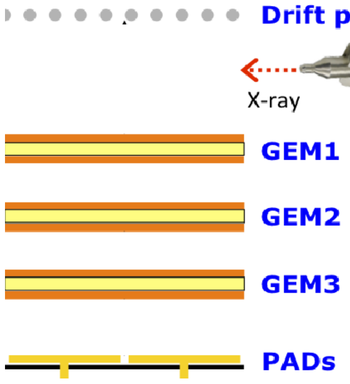
Hole Alignment

- IBF with 3 GEMs. Ne/CO_2=(90/10).
- IBF vs. hole distance between GEM1 and GEM2.
- Strong alignment dependence ($\times 10$) for $E_{T1} \geq$2-4 kV/cm.
- No alignment dependence for $E_{T1} \sim$1 kV/cm. But IBF is worse.

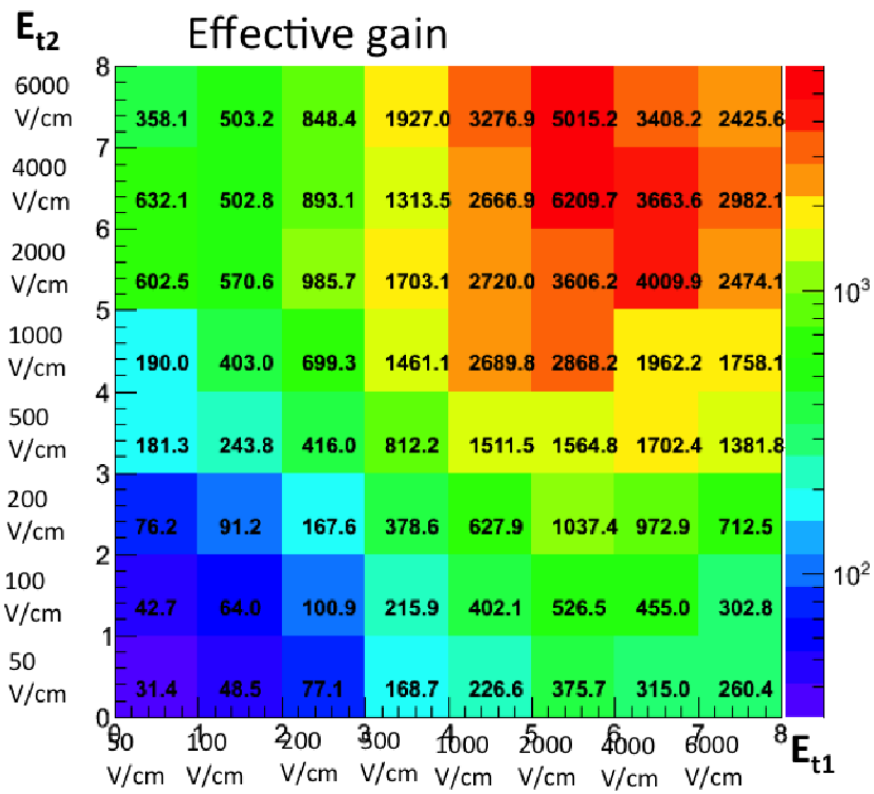


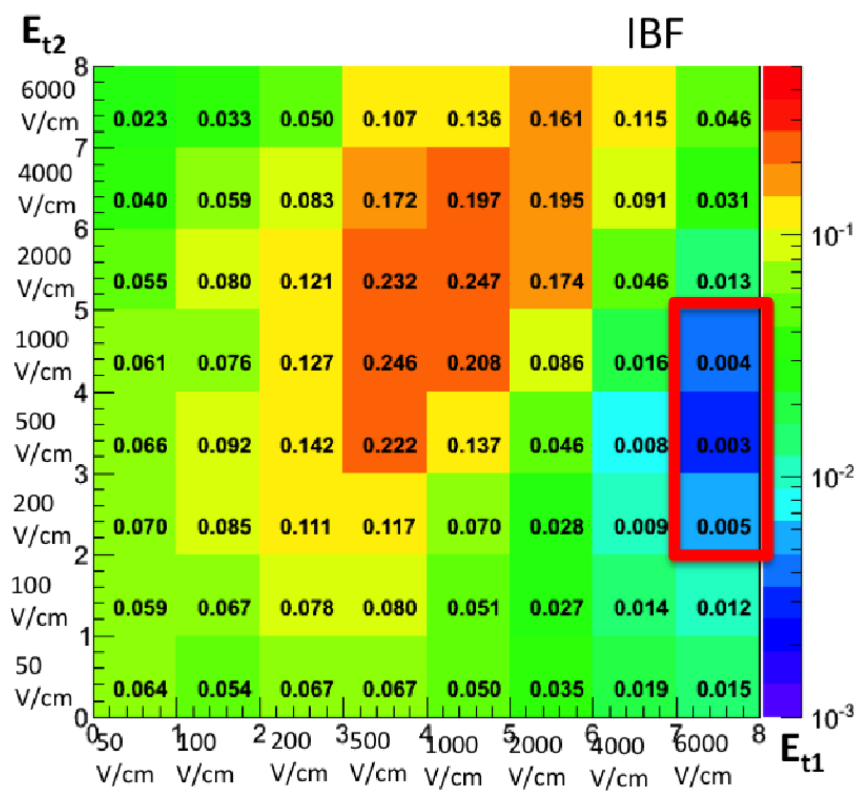


3 GEM configurations



- 3 GEM configurations. $Ar/CO_2=(70/30)$
- GEM2 is mis-aligned with respect to GEM1 and GEM3.
- $V_{GEM1} = 260,\ V_{GEM2} = 360,\ V_{GEM3} = 460$
- 0.3-0.5% of IBF with high $E_{T1\ (GEM1-GEM2)} \sim 6$kV/cm and low $E_{T2\ (GEM2-GEM3)} \sim 0.5$kV/cm.

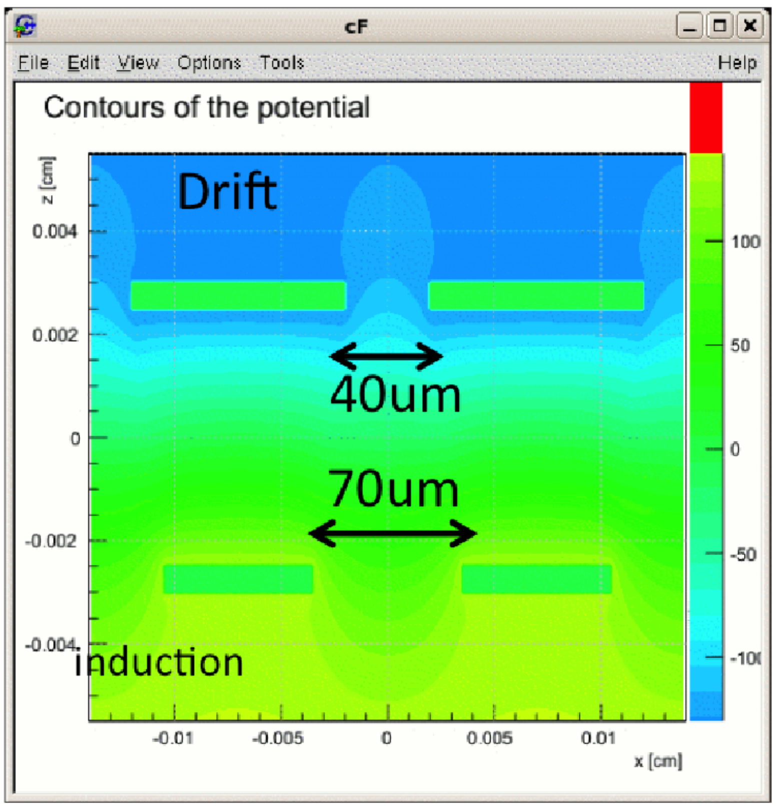


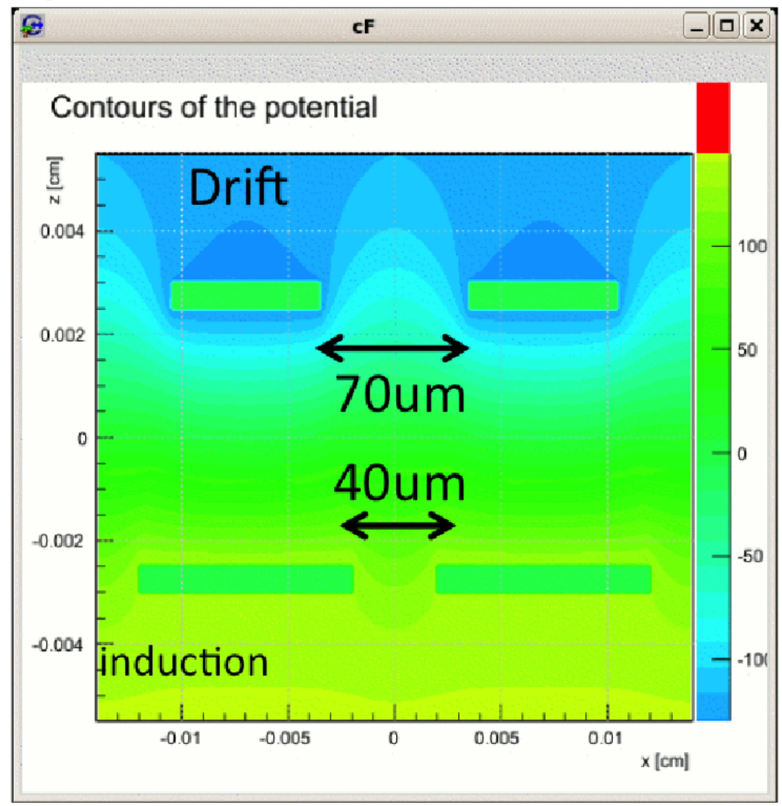


The mediæval solution ... arrow slits !

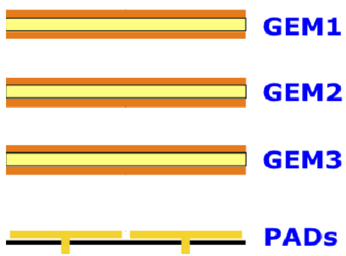
Conical GEMs

- Conical GEMs (different hole size on upper and bottom electrode)
- Left: Field of GEM1 in case Narrow(N)$\rightarrow$Wide(W)
- Right: Field of GEM1 in case Wide(W)$\rightarrow$Narrow(N)
- N$\rightarrow$W is promissing. Better extraction of electrons and IBF.

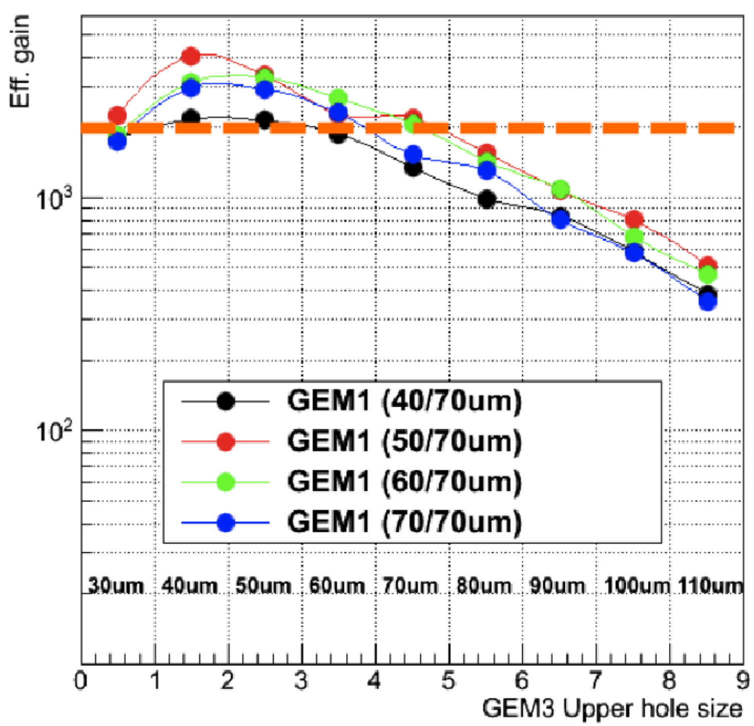


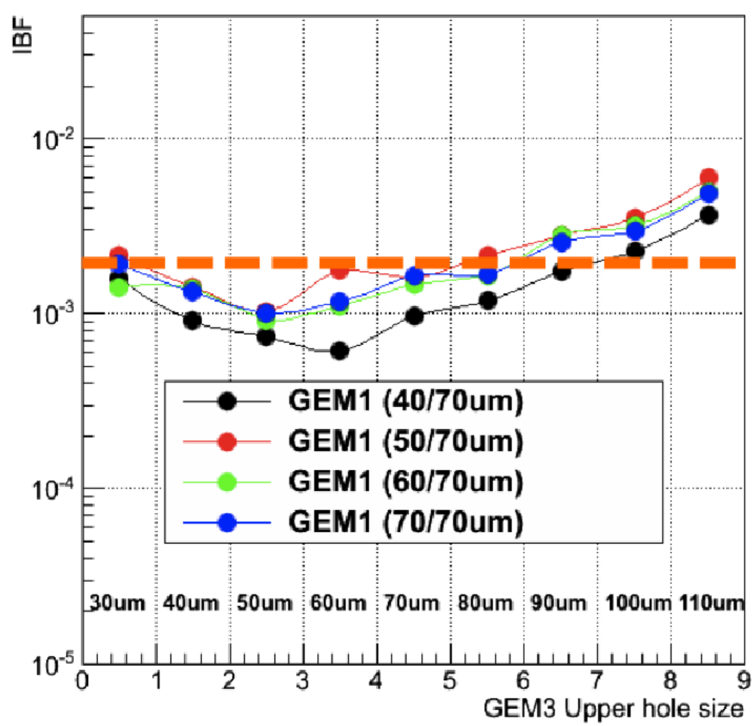


IBF with Conical GEMs



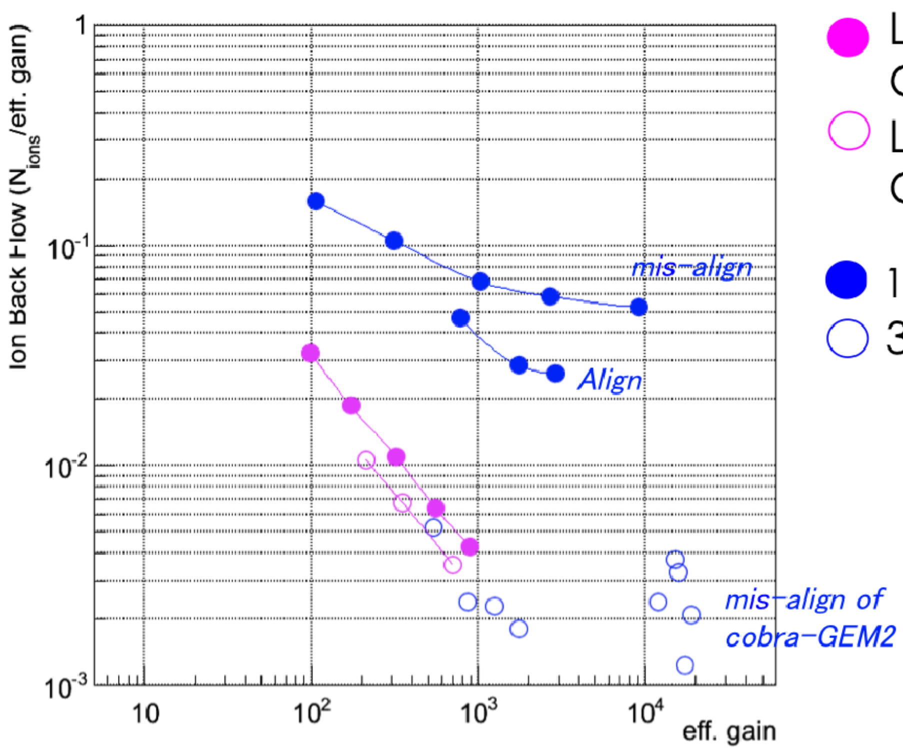
- IBF with conical GEMs with different hole size
  - $E_{T1} = 6$kV/cm, $E_{T2} = 0.5$kV/cm. Ar/CO_2=(70/30). GEM2 is mis-aligned.
  - GEM1 upper hole size: 40-70μm. bottom hole size: 70μm
  - GEM3 upper hole size: 30-100μm. bottom hole size: 70μm
- $\times$2-3 improvement of IBF with 40μm/70μm GEM1 and 40-70μm/70μm GEM3.





Exotic GEMs

- IBF simulations with Flower-GEM and COBRA-GEM
- 0.2% of IBF is achievable with Flower-GEM and 3 COBRA-GEMs
  - Need to control geometry for the Flower GEM
  - Less sensitive to the COBRA-GEM for the alignment.

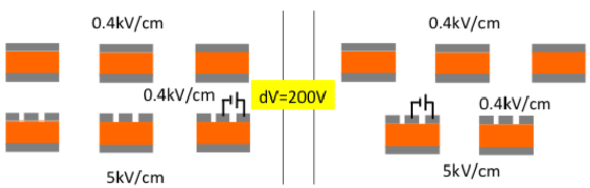


● Large pitch GEM1 + standard GEM2 (Flower GEM structure)

○ Large pitch GEM1 + standard GEM2 & GEM3

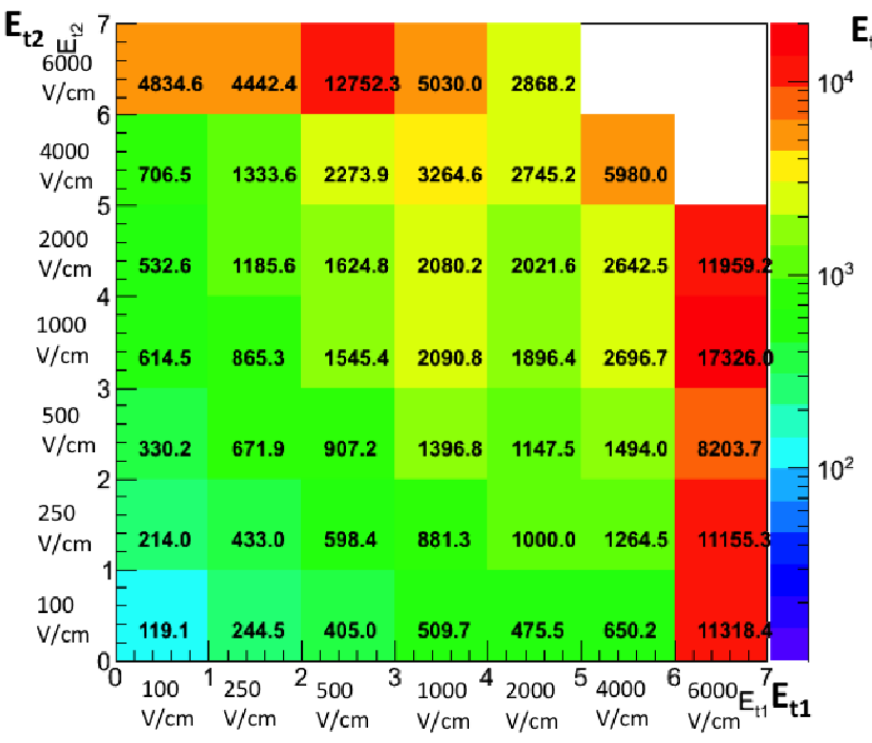
● 1 STD GEM + 1 cobra GEM

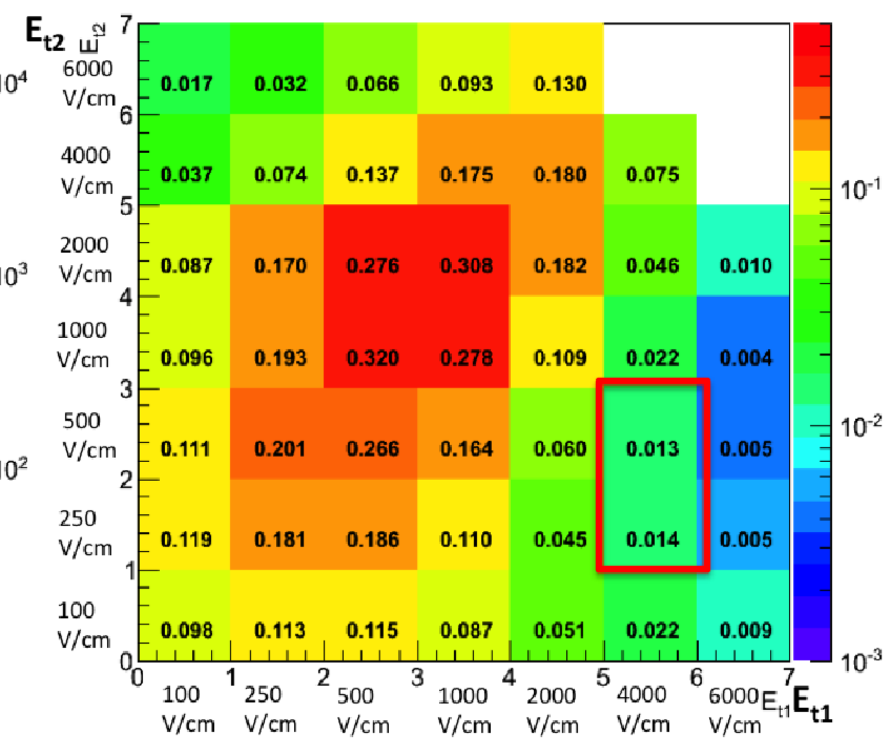
○ 3 layers of cobra GEMs



3 GEM configurations in Ne/CO_2

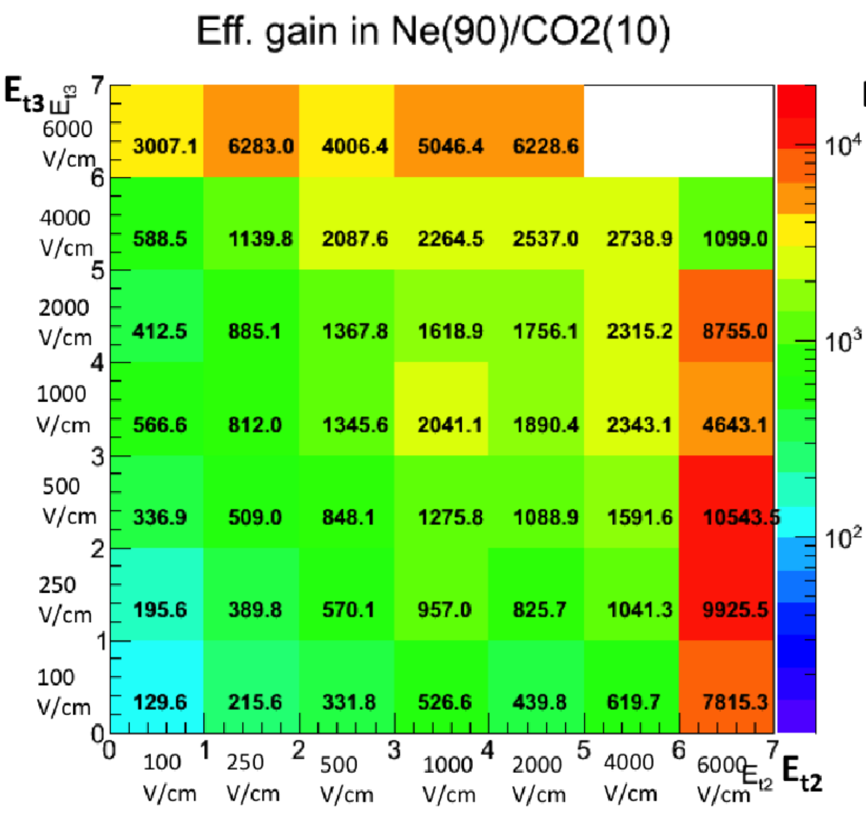
- 3 GEMs under Ne/CO_2=(90/10). GEM2 is mis-aligned.
- E_{T1} cannot go higher than 4kV/cm.
  - Townsend: $\sim$ 14/cm at 6kV/cm. $\times$7 gain in 2mm.
  - Adding N_2? 14/cm$\rightarrow$4/cm at 6kV/cm with 5% N_2
- 1-2% of IBF with $E_{T1} \sim$ 4kV/cm and $E_{T2} \sim$ 0.5kV/cm.

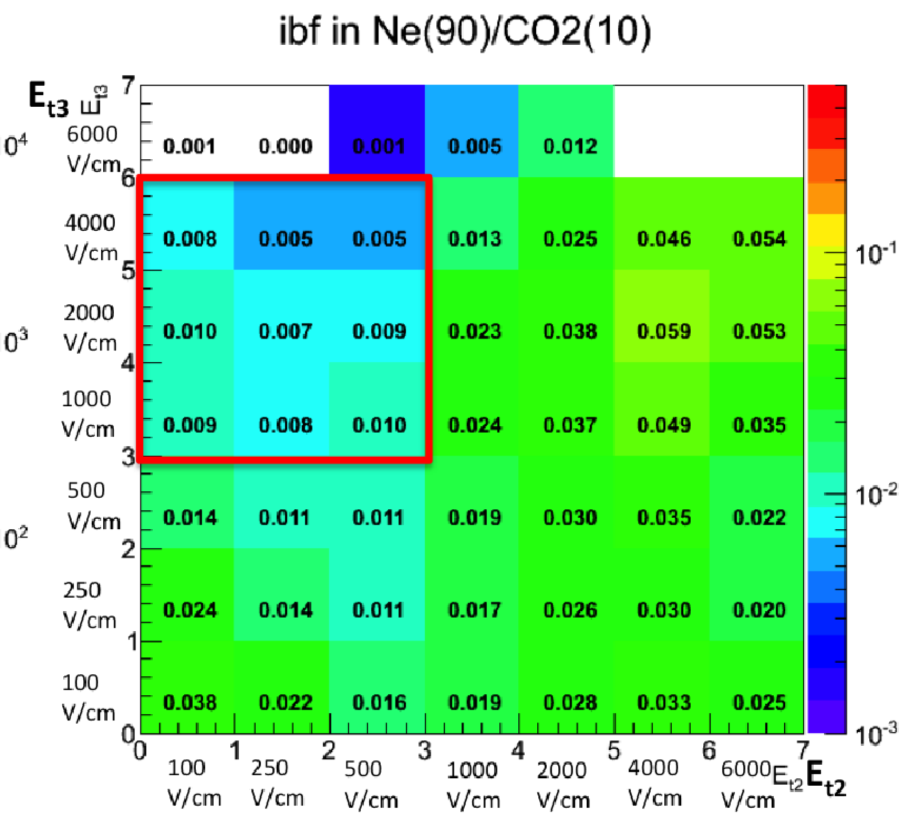




4 GEM configurations in Ne/CO_2

- 4 GEM configuration under Ne/CO_2. E_{T1}=4kV/cm
- GEM2 and GEM4 are mis-aligned.
- E_{T2} and E_{T3} scan.
- ×2-3 improvement with 4 GEM configurations. 0.5% of IBF can be achievable with low E_{T2} and high E_{T3}.





Next Steps

- More dynamical simulations for space-charge effects.
- Search for the optimal solutions for IBF
  - Combination of GEMs with different pitch, hole size, and hole shape (conical)
    - For example, opaque and conical GEM for GEM1 (high E_{T1}).
    - We have to rely on the ramdom alignment.
    - Need to check uniformity of gain and IBF.

GEM space charge – summary

- Space charge between GEMs pushes ions towards the cathode ("upper") GEM electrode. This reduces the ion back-flow.
- The trend of the measured rate dependence of ion back-flow is reproduced by simulations.
- By a stroke of luck, higher rates lead to improved ion back-flow reduction.
- Conical GEMs and misalignment can reduce ion back-flow.

Conclusions

- Microscopic simulations, although time consuming, are capable of reproducing e.g. the transparency of Micromegas meshes.

- GEMs have insulating material in contact with active gas. As a result, the insulator collects charge and the surface charges modify the detector behaviour.

- Evacuation of ions from multiple GEMs is sufficiently slow for space charge effects to become noticeable at high rates. This modifies the ion back-flow rate.