Ion space-charge effects in multi-GEM detectors: challenges and possible solutions for future applications

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- The ion back-flow into the conversion volume results in field distortions
- Can the ion back-flow be further reduced?
- What are the intrinsic limits of GEM detectors?
- How severe are the distortions if detectors are operated close to these limits?

Part 1 – Ion back-flow elimination with graphene?

- What is graphene?
- Why and how do we want to use it?
- What has been done
- What still needs to be done

Part 2 – Effects of high charge-densities in triple-GEM detectors

- Space-charge effects in the transfer stages
- Space-charge effects in the amplification stages
- How can the effects be reduced?

Part 1
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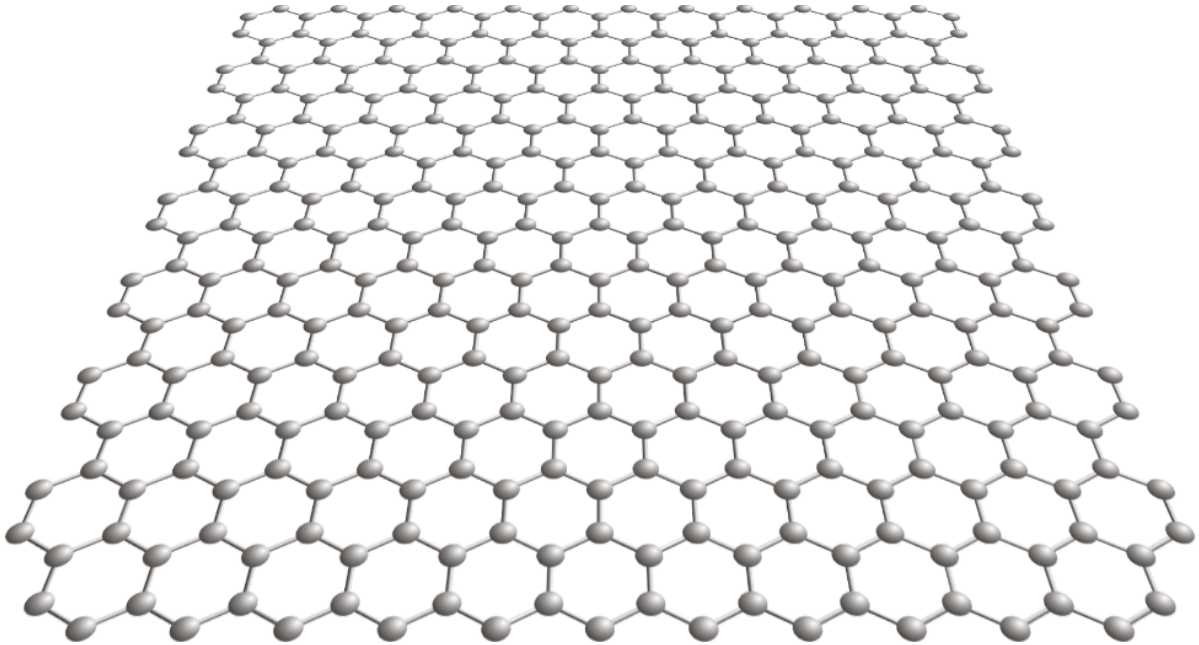
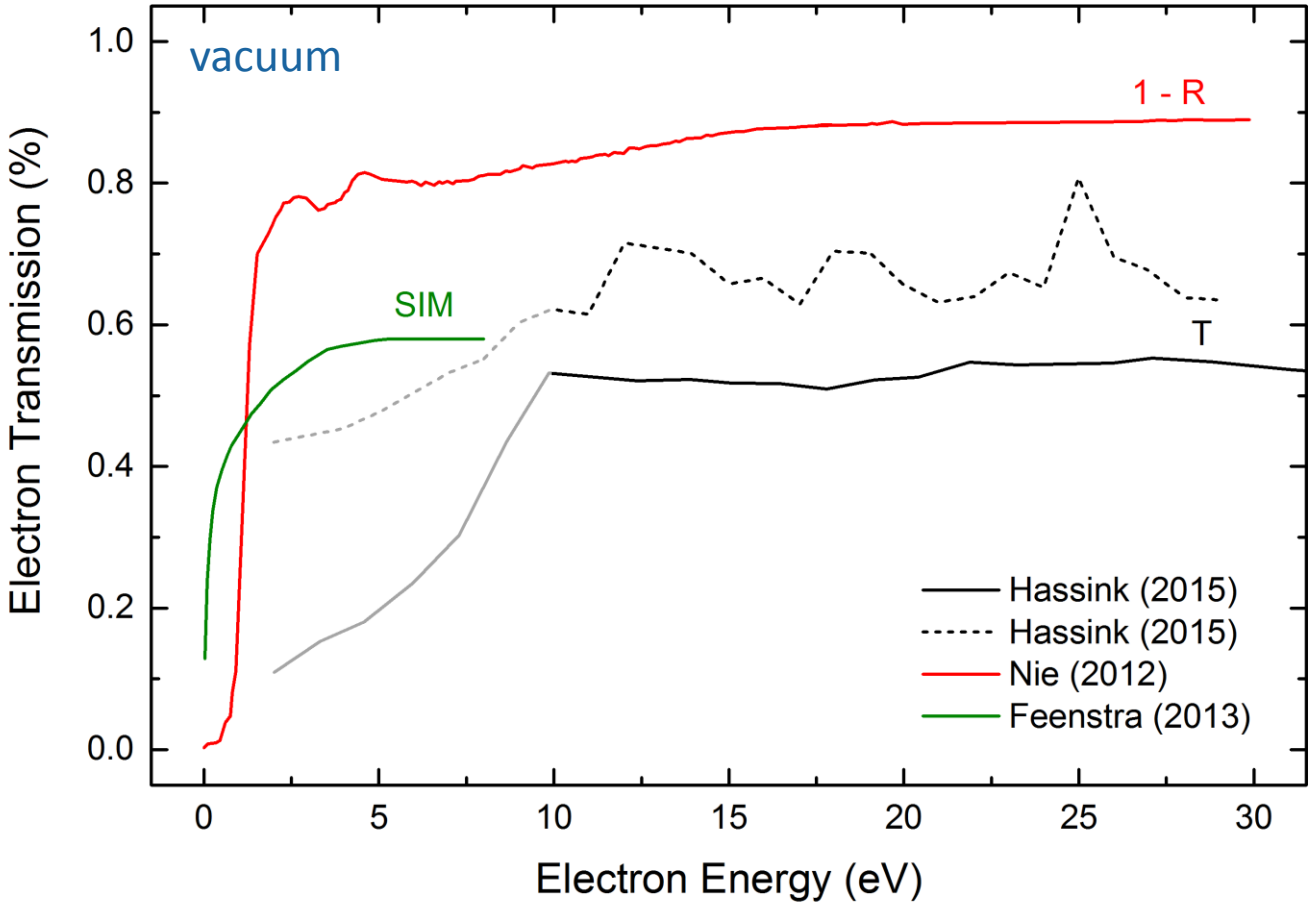
Can the ion back-flow be eliminated completely?

What is Graphene?

- Graphene is a single layer of carbon atoms arranged in hexagonal lattice
- Regarded as the thinnest possible conductive mesh with pore size ~ 0.6 Å



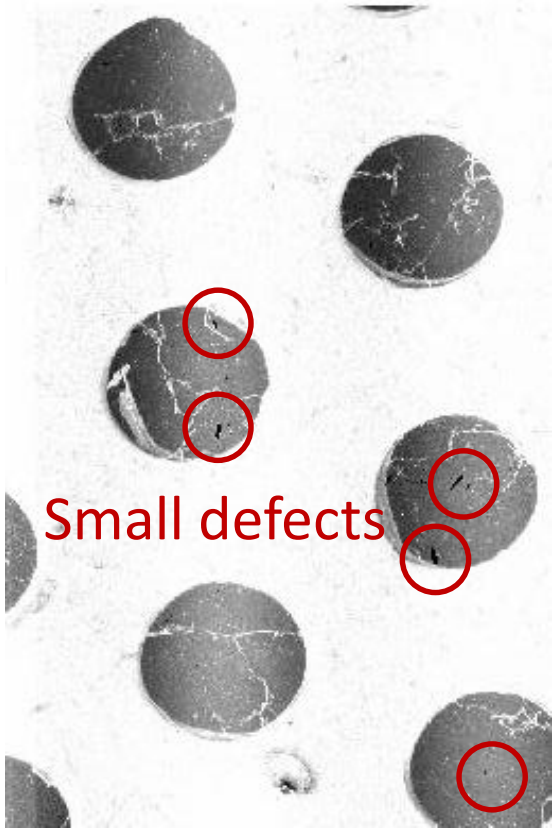
- Reported strong assymetry in electron and ion transmission through graphene



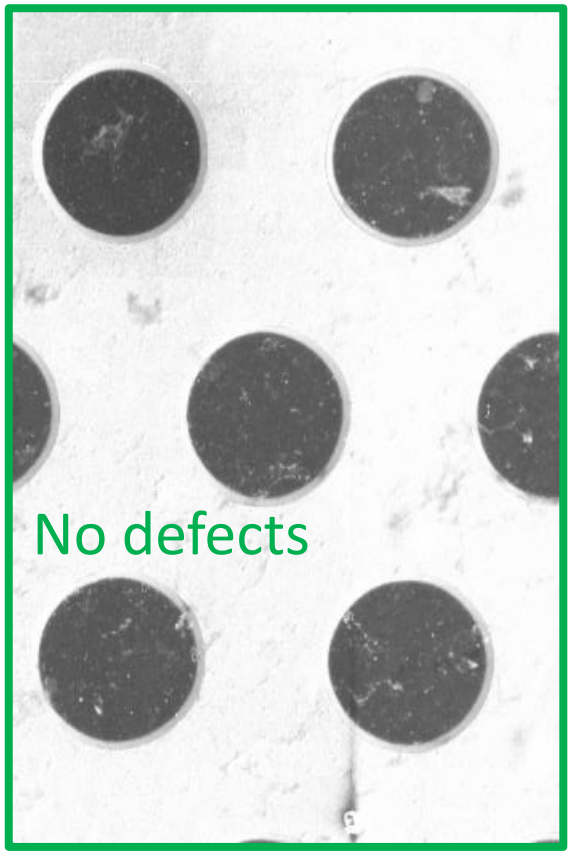
Why is it interesting?

- Mechanically robust in respect to its thickness: it can be freely suspended over tens of µm
- Idea: create a membrane fully transparent to electrons and fully opaque to ions eliminating ion back-flow in gaseous detectors
- Goal: Measure electron and ion transparencies of graphene layers $O(\mathrm{cm}^2)$ suspended on metal meshes in gas as function of electric field and gas mixture

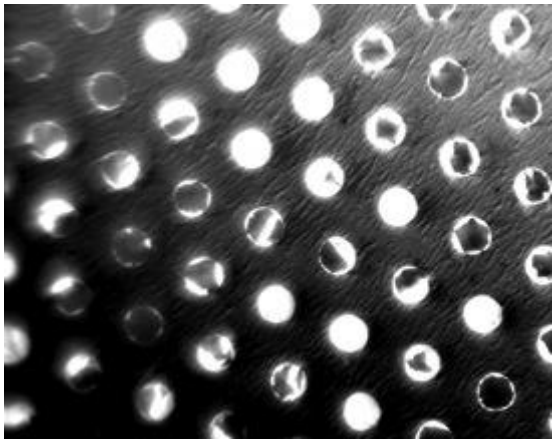
Transfer of graphene samples onto supporting copper meshes

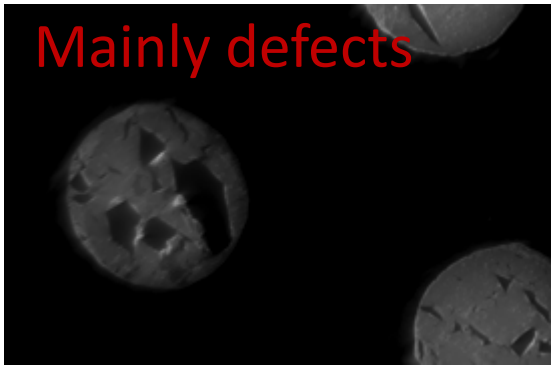


Transfer of single layer graphene



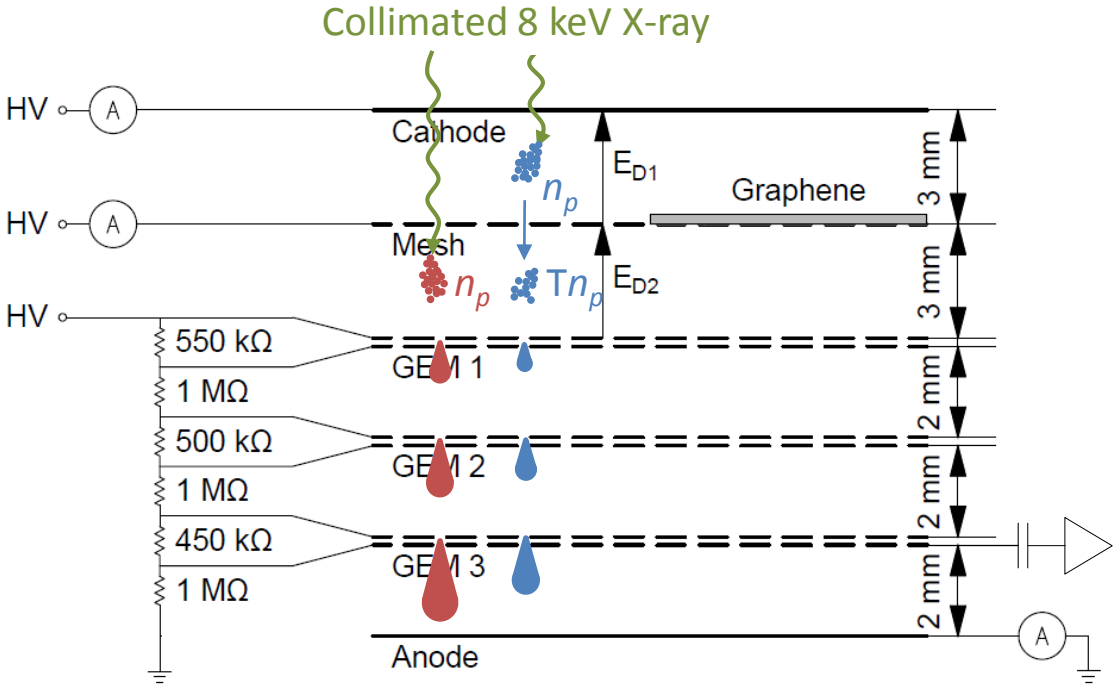
Transfer of triple layer graphene

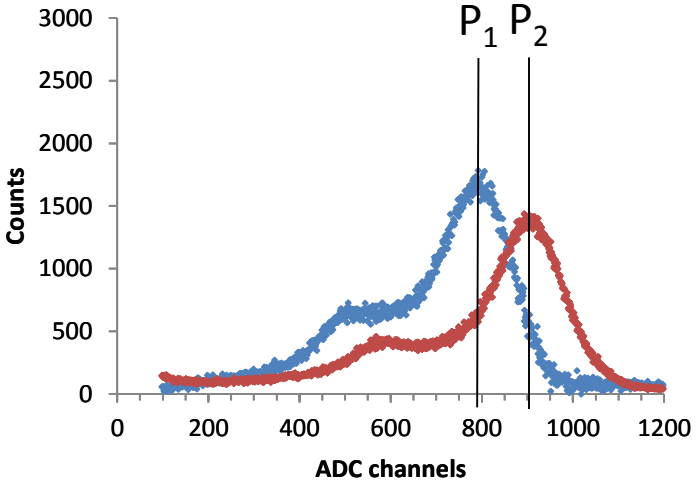




Direct etching of support structure

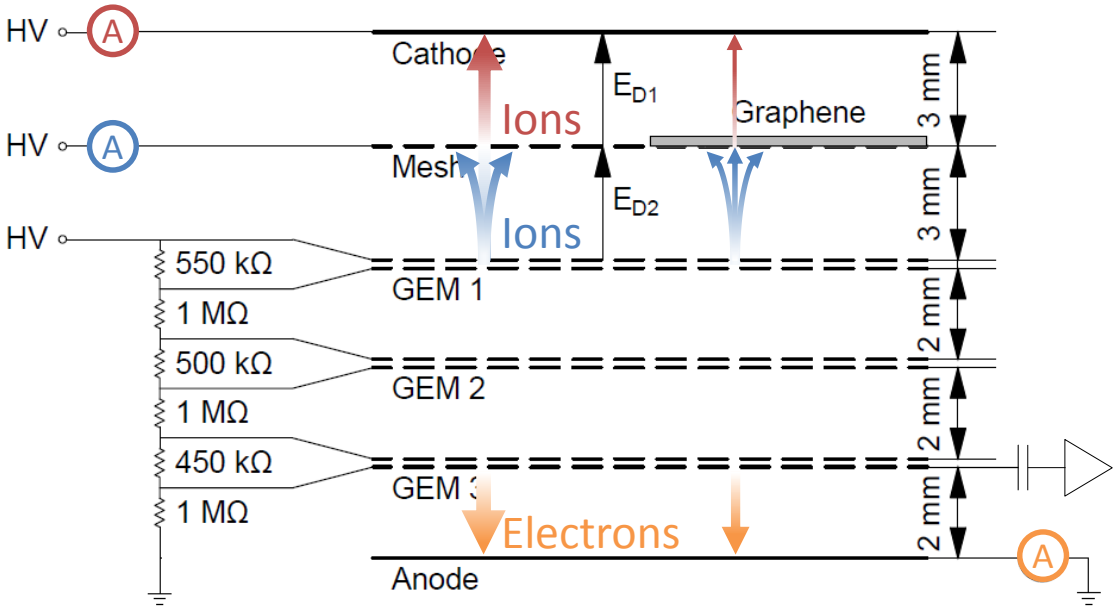
Measurements





$$T_{electron} = P_1/P_2$$

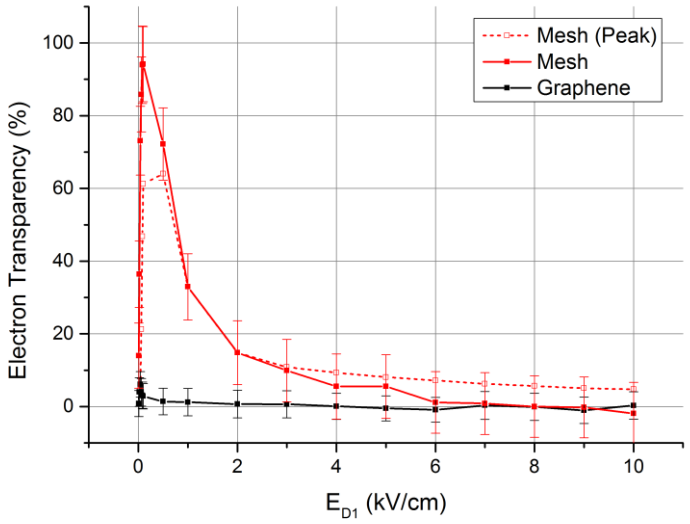
Measurements

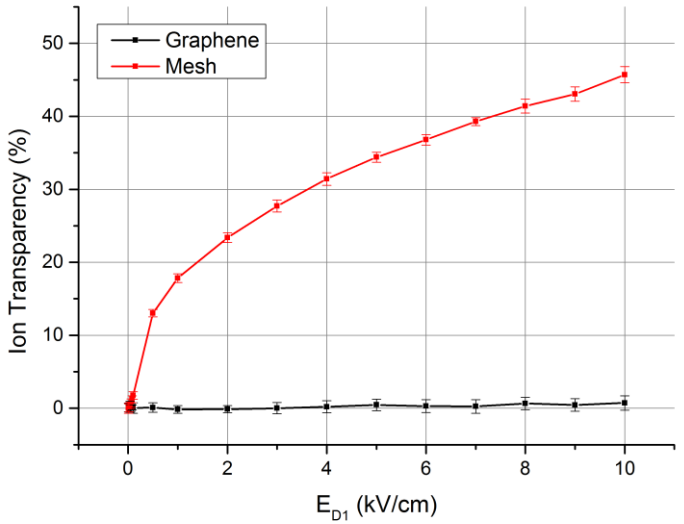


$$T_{ion} = I_C/(I_C+I_M)$$

Ar/CO_2 70/30 mixture, Ø 30 µm and pitch 60 µm mesh

Ø 0.5 mm collimated beam of 8keV Cu X-rays



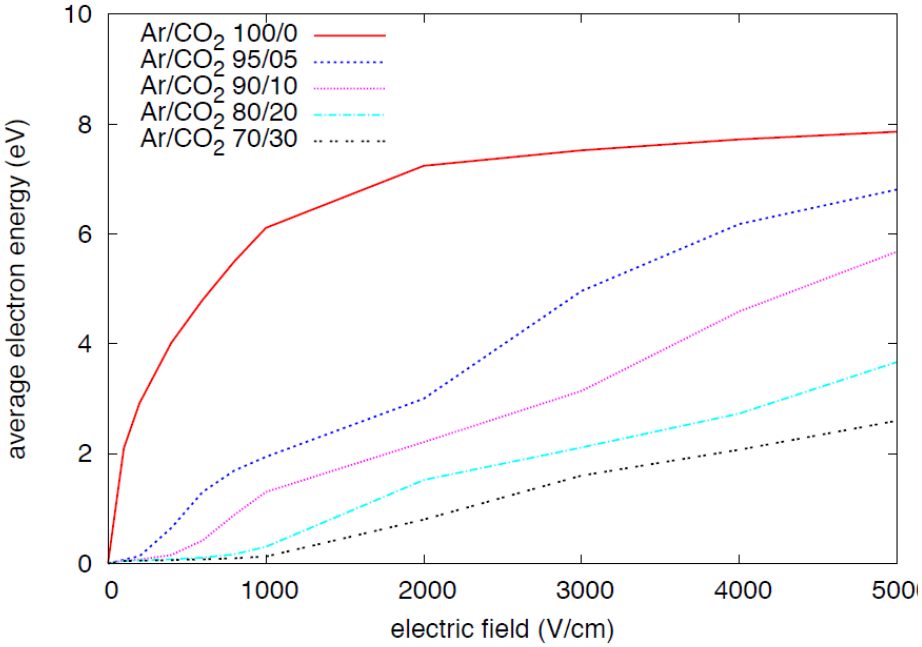


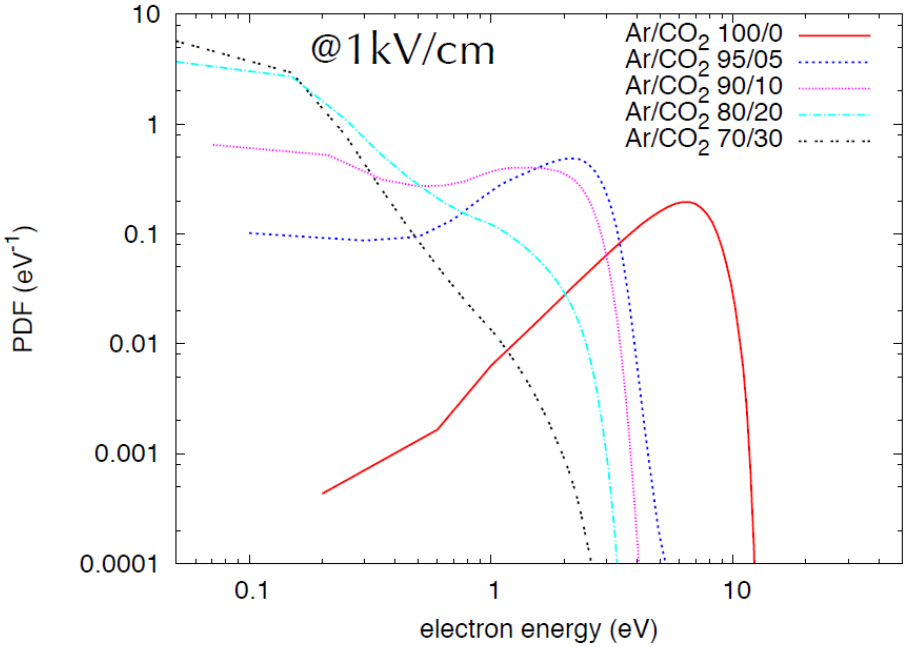
Ion transparency reduced to the measurement sensitivity level but electrons do not tunnel easily

Space or contaminants between the layers? Still defects?

Close to measure intrinsic properties of graphene

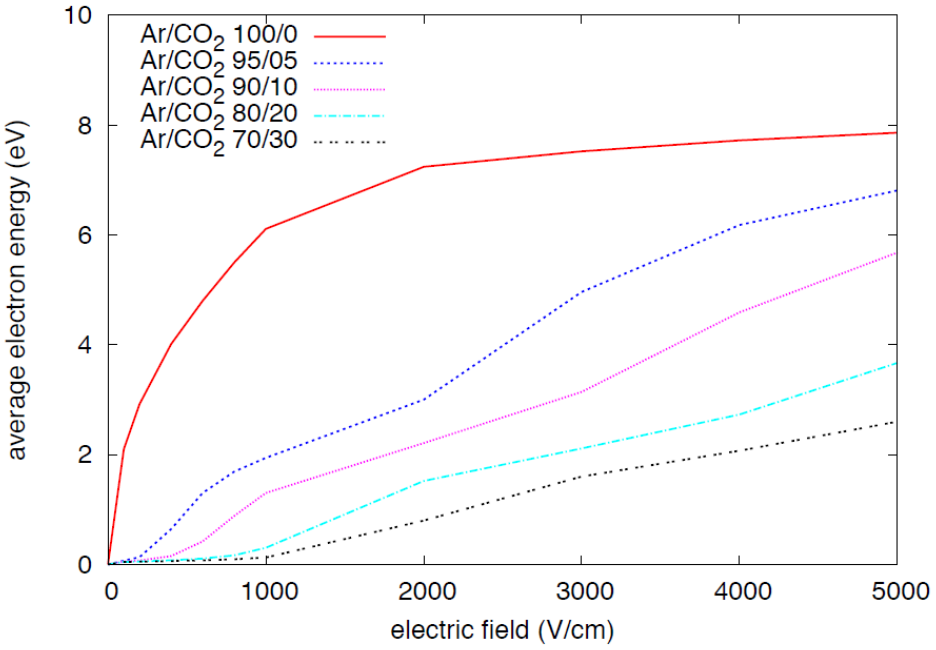
- Changing the electron energy by:
  - increasing the electric field
  - changing the gas mixture (more argon, neon)



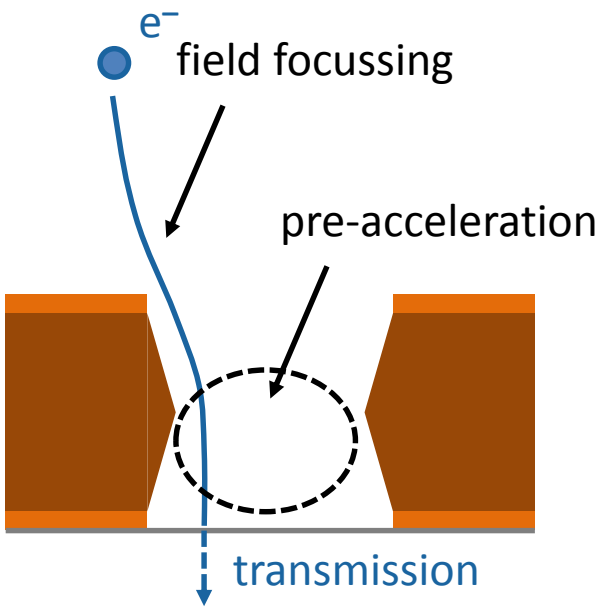


- Why not transfer a graphene layer on a GEM?

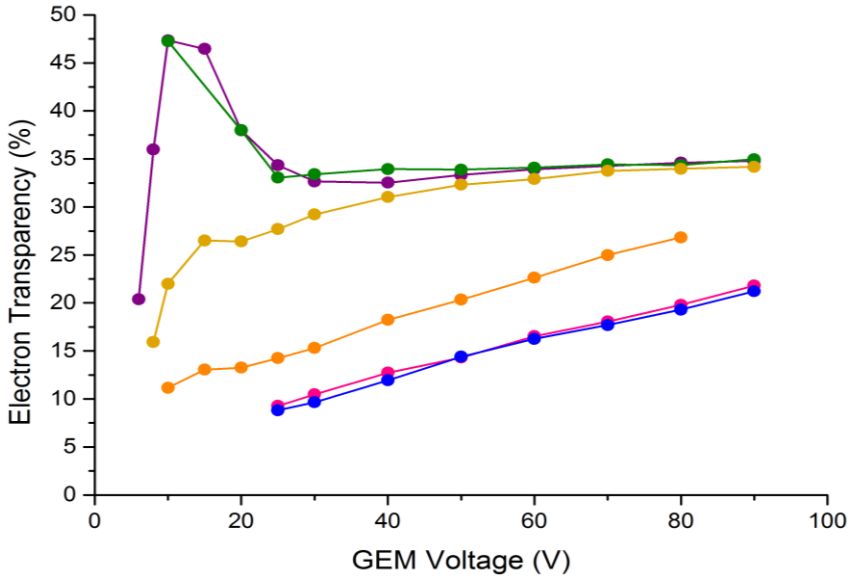
- Changing the electron energy by:
  - increasing the electric field

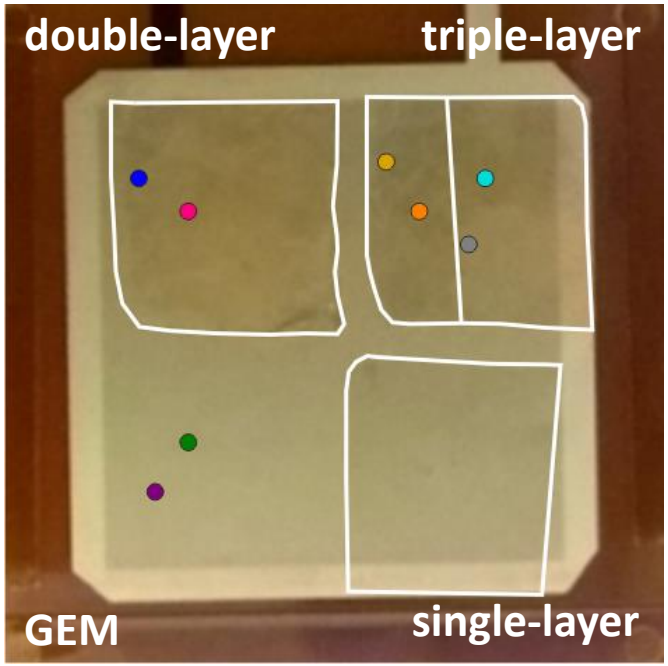


Graphene layer on the bottom electrode of a GEM



Graphene on a GEM





Graphene on top of a GEM

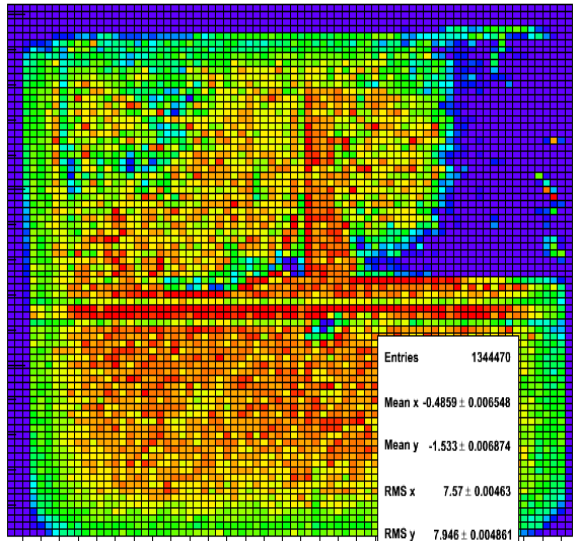
Ar/CO_2 70/30 gas mixture

E_{D1} = 50V/cm, E_{D2} = 1kV/cm

X-ray beam (collimated and not)

Triple-layer not transparent to electrons

Graphene shorted the GEM electrodes



Summary of part 1

- Graphene was successfully transferred onto copper meshes and GEM electrodes
- A transfer-less method to produce graphene-covered meshes is under development
- A method was developed to measure the electron and ion transparency in gaseous detectors
- With the field settings and gas mixtures currently used graphene is not transparent to electrons and ions
- Real multi-layer graphene grown by CVD will improve transmission of electrons
- Changing the GEM layout will overcome challenges with defective graphene layers in the GEM holes

Part 2

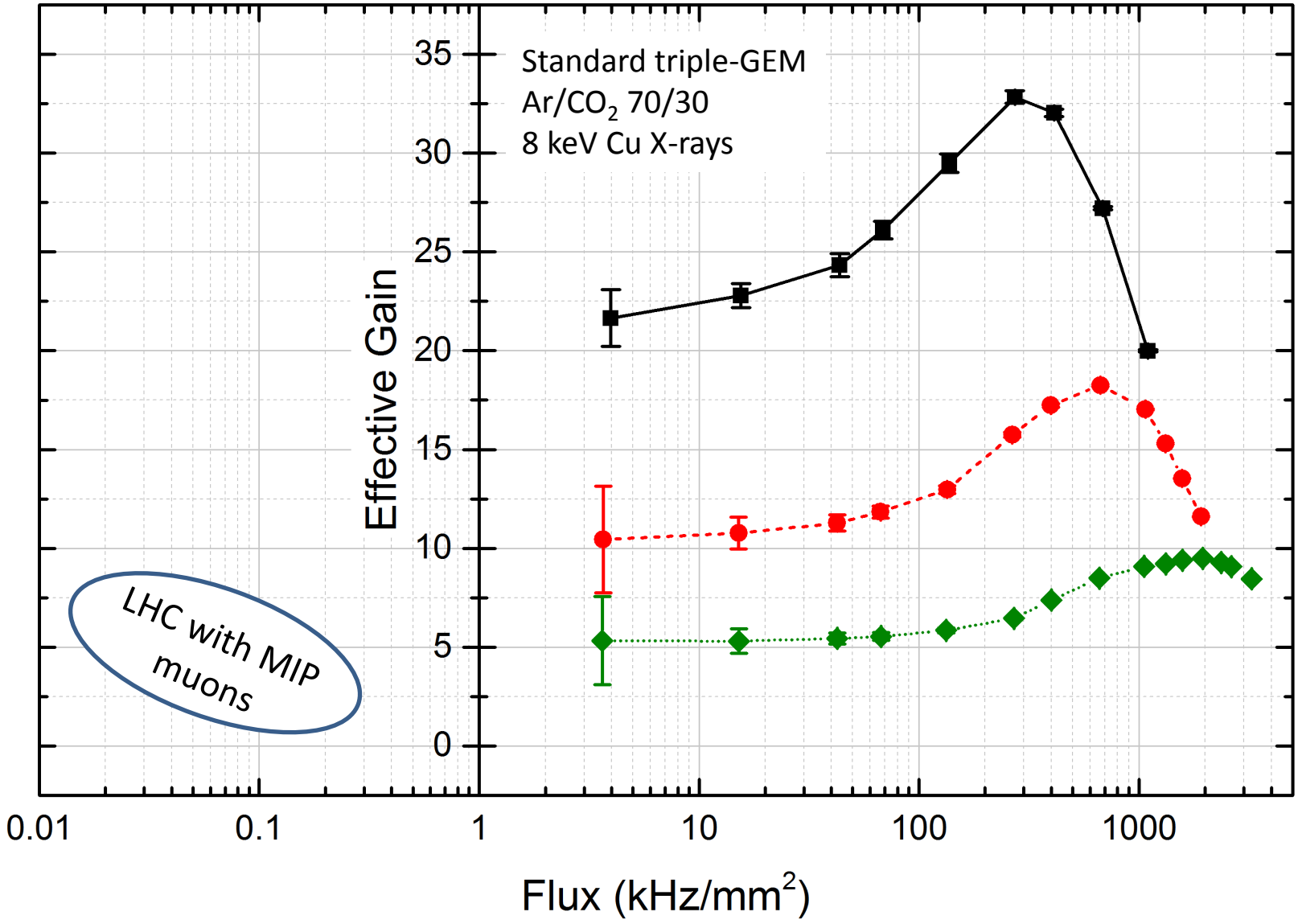
-

Why the need for an elimination of the ion back-flow?

Motivation

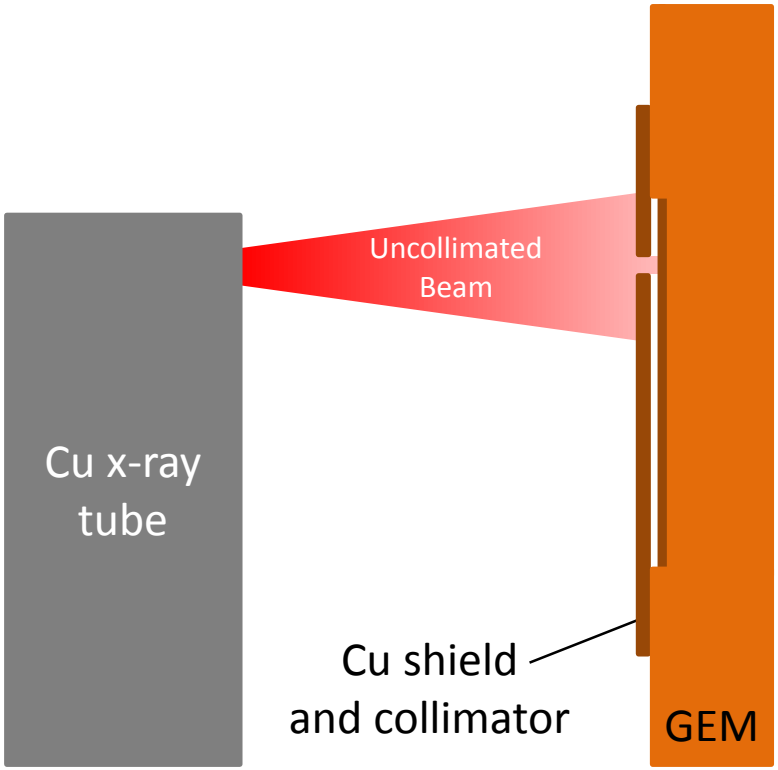
- Behaviour of triple GEM gain (Everaerts, 2006)
  - Increasing the flux first increases and for even higher flux decreases the effective gain
- Decrease of ion back-flow in GEMs (ALICE, 2013)
  - Increasing the flux reduces the ion back-flow
- Increase of mesh transparency (GDD lab, 2014)
  - Increasing the flux increases the electron transparency of a GEM-like mesh

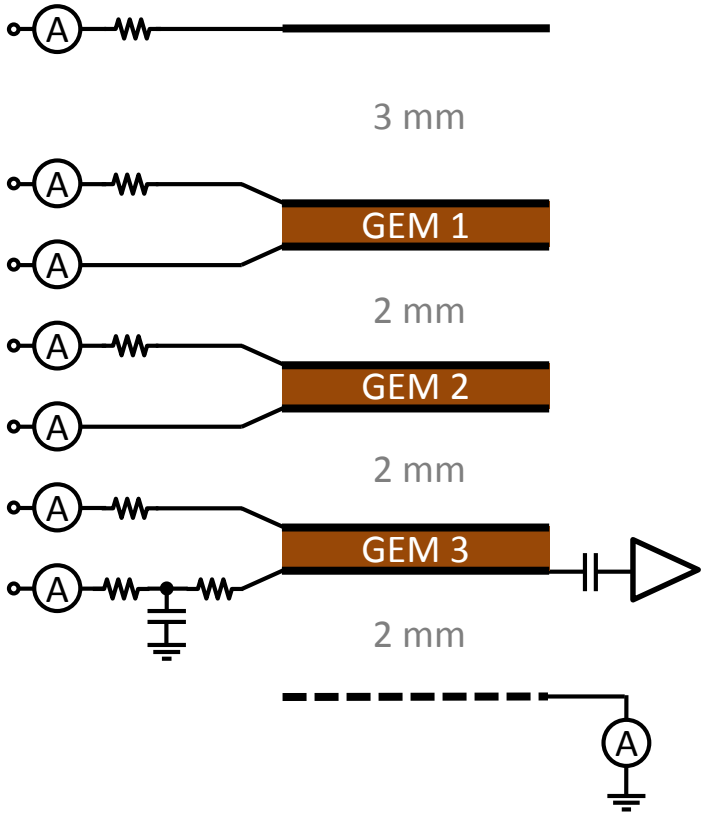
Effective gain



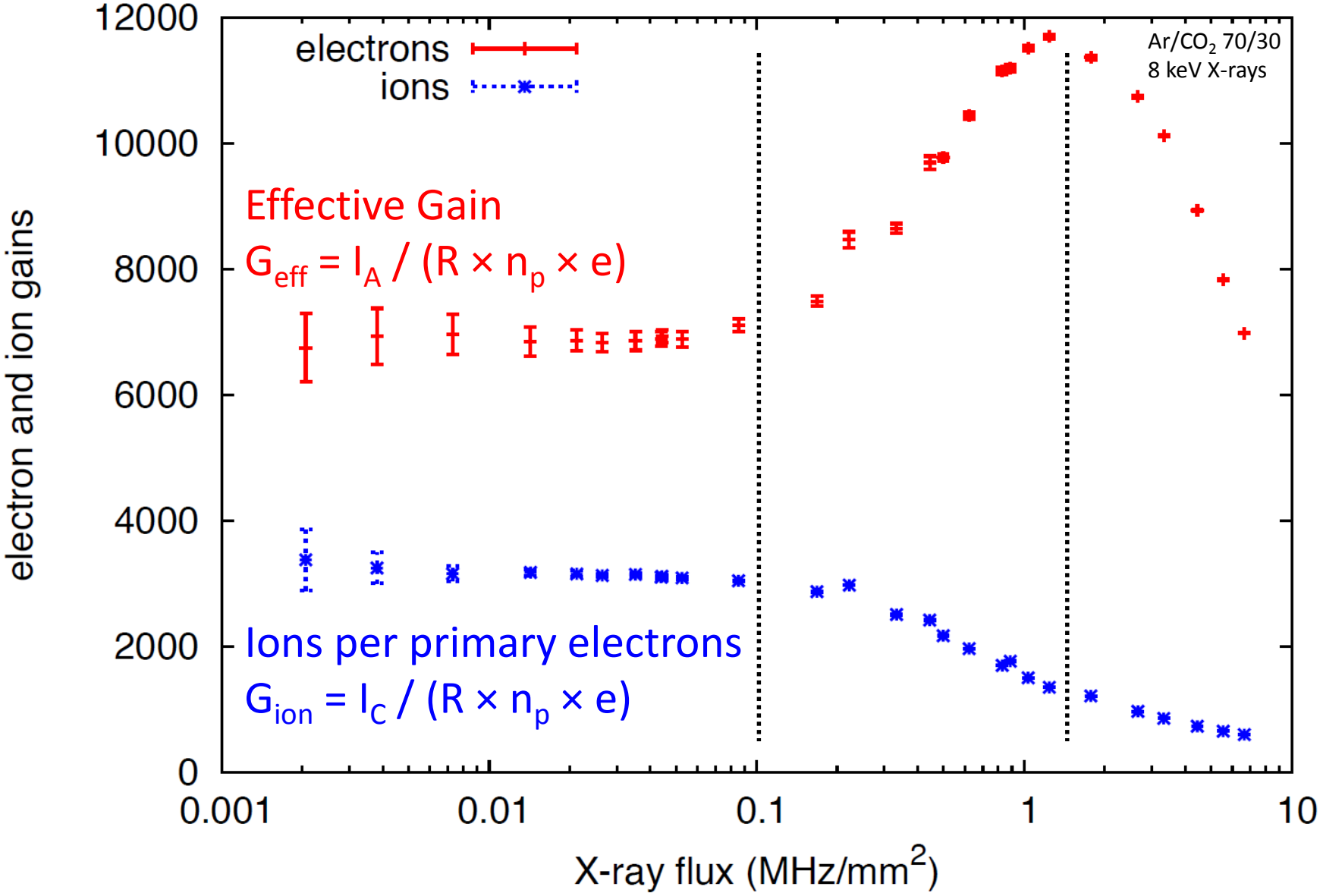
Ar/CO_2 70/30
Cu x-ray, $E_{x\text{-}ray}$ = 8 keV
d_{beam} = 1 mm

$n_p \approx 300$

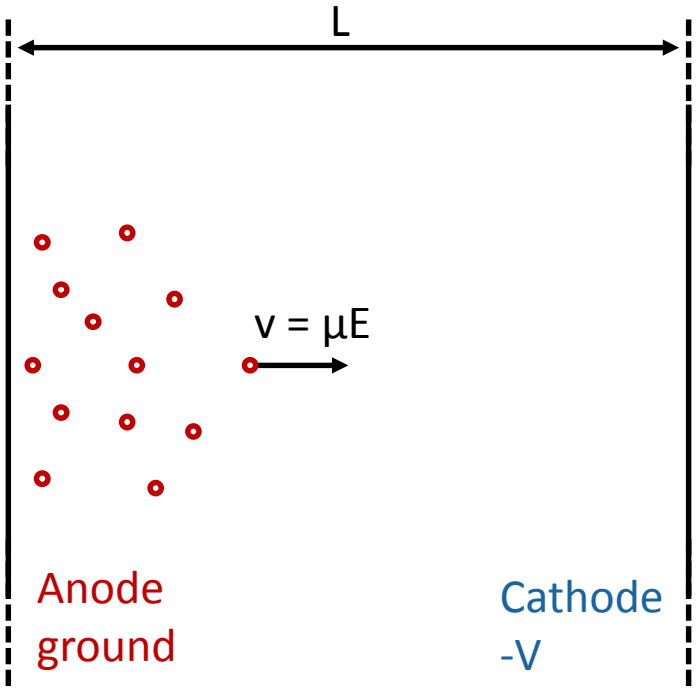


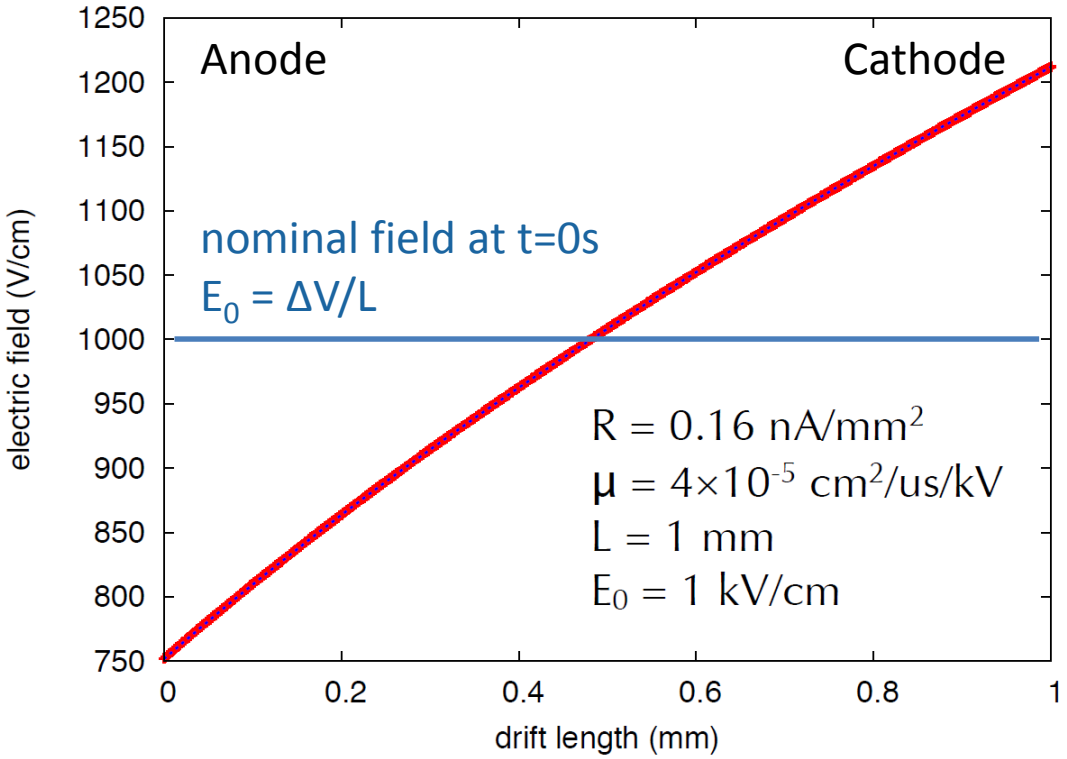


Observations pt. 1



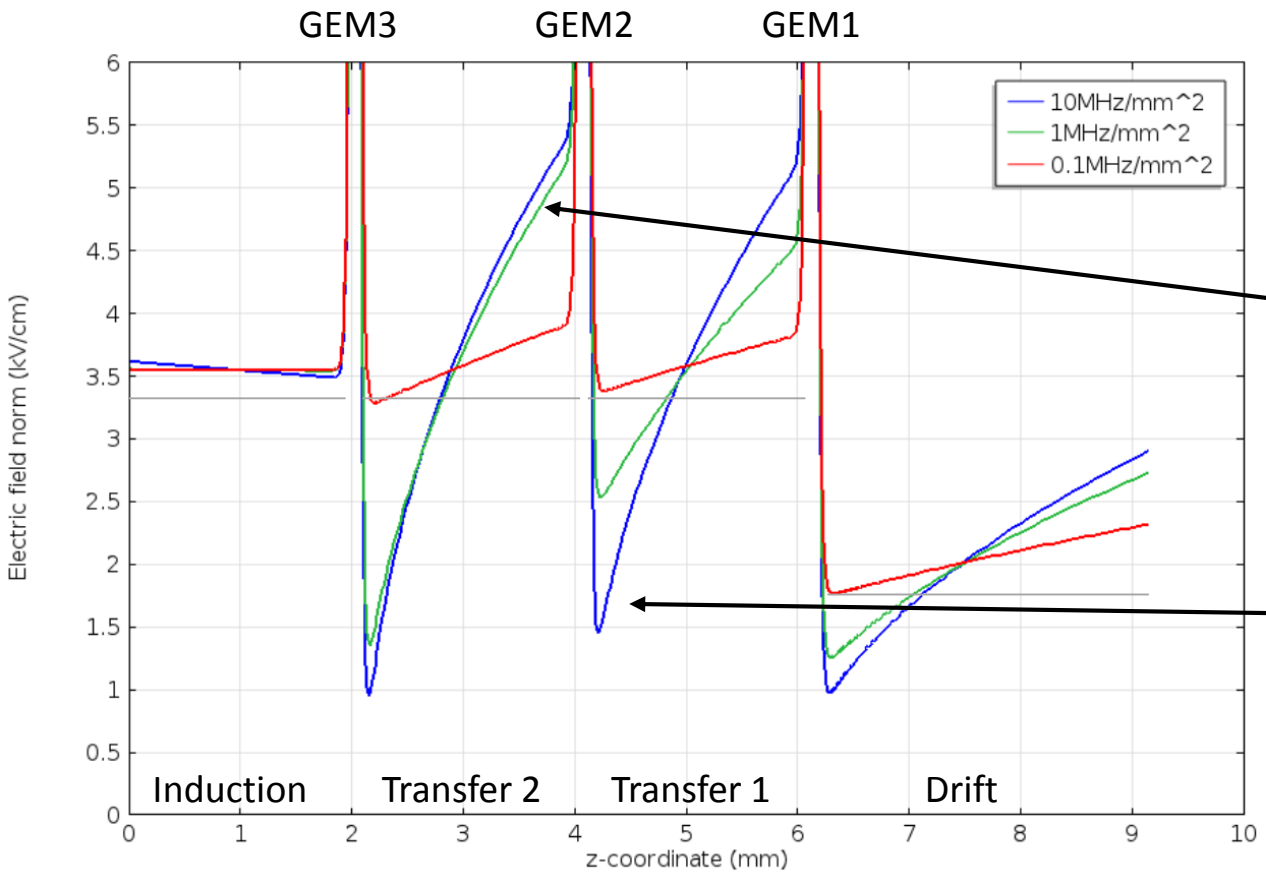
Space-charge effects in the transfer region





- Electric field decreases at anode and increases at cathode
- Average electric field over whole length equals nominal field
- Larger number of ions lead to a stronger effect
- Transfer fields and drift field behave similiarly

Space-charge effects in the transfer region

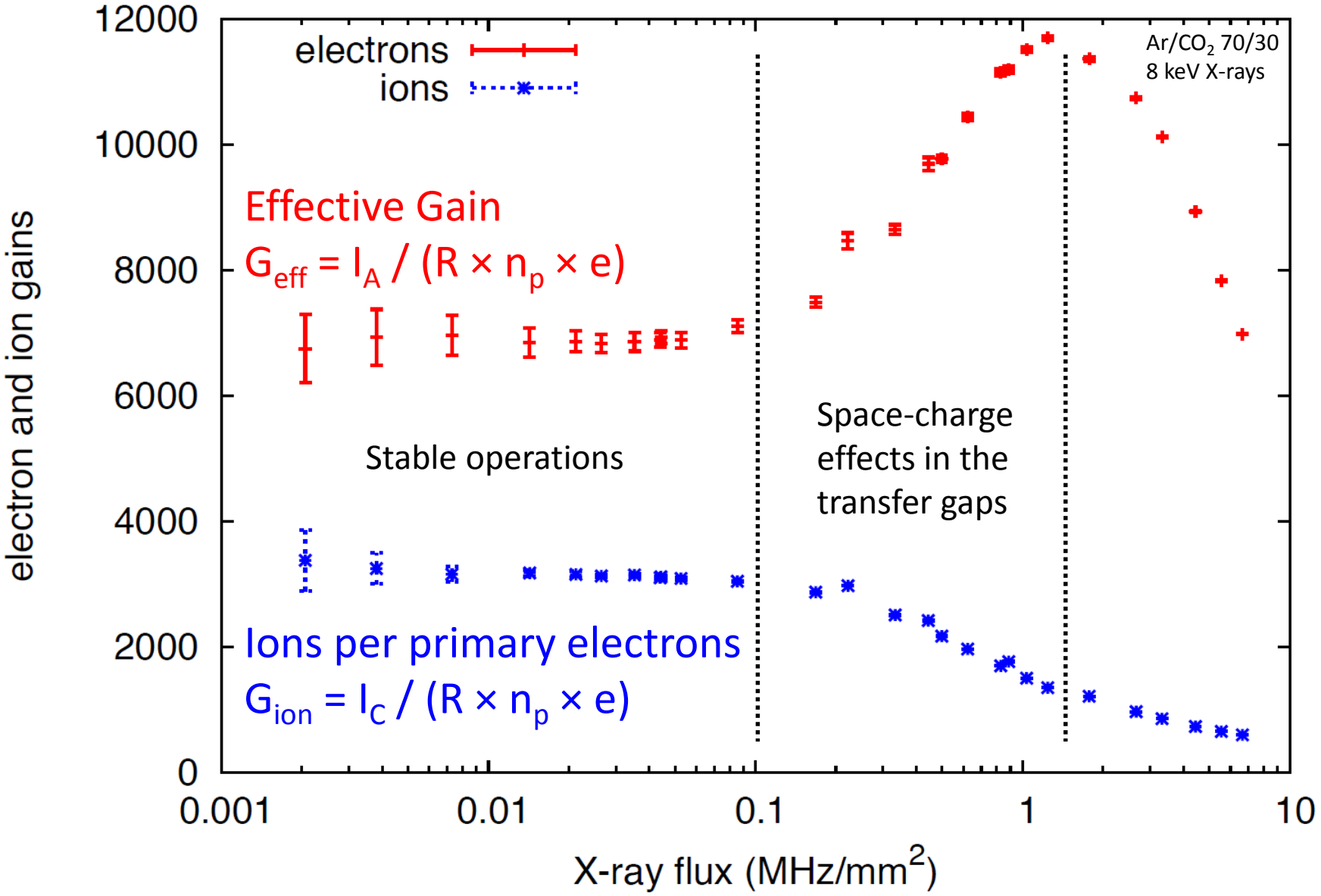


Electric field increases close to GEM bottom electrodes

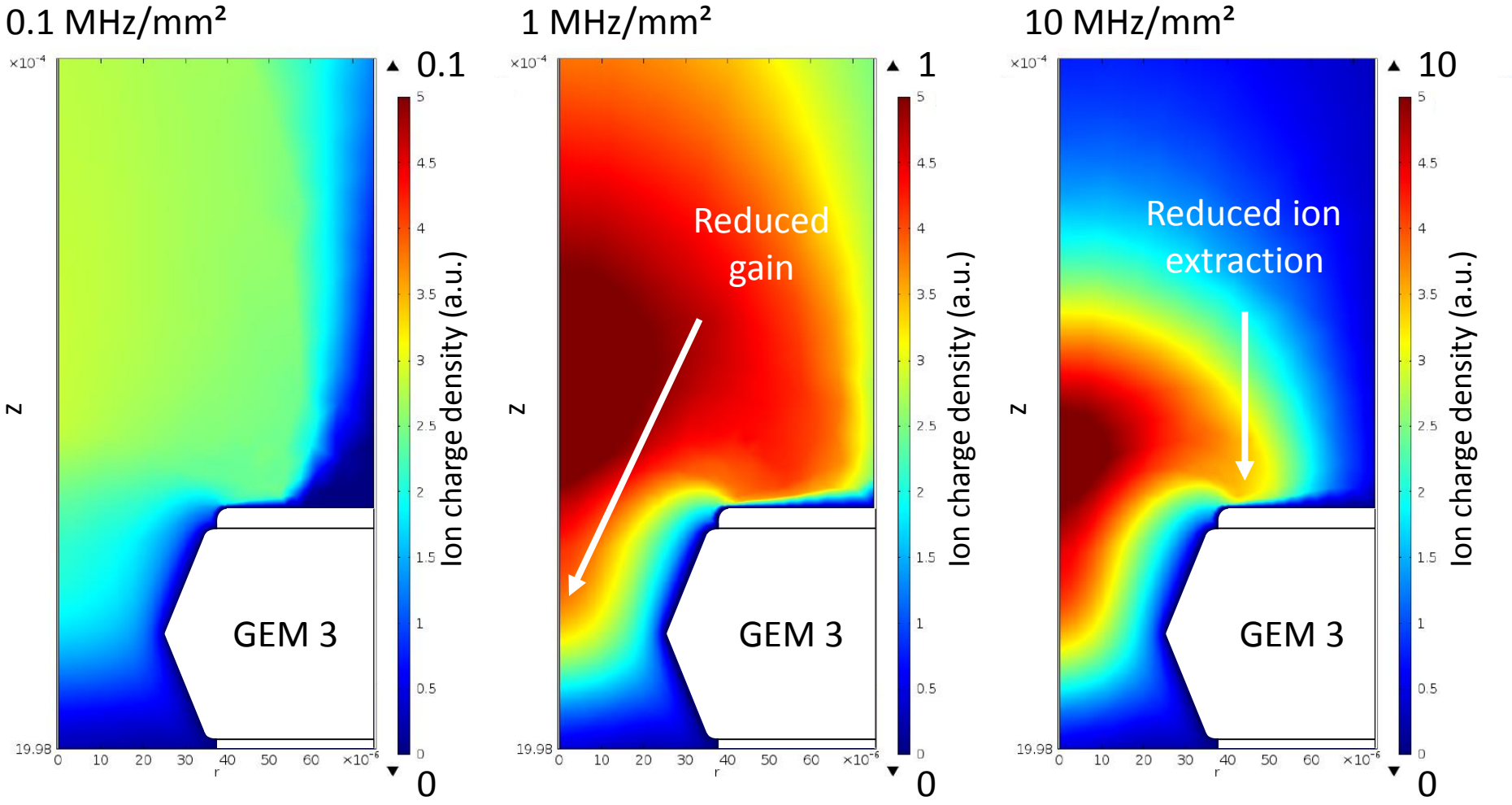
Electric field decreases close to GEM top electrodes

- Electron (ion) collection efficiency increasing (decreasing) with flux
- Electron (ion) extraction efficiency increasing (decreasing) with flux
- Effect more pronounced with every stage of the triple GEM
- Effect more pronounced for larger particle flux

Observations pt. 1



Space-charge effects in the amplification region



COMSOL simulation: single GEM hole, axial symmetric, stationary solution

Summary of part 2

- Space-charge effects for high fluxes of 8 keV X-rays in an Ar/CO_2 70/30 gas mixture were observed
- Ion space-charge modifies first the transfer fields and then the amplification fields
- The effects are modelled for standard triple GEMs and are quantitatively understood
- The effect is reduced by
  - Faster evacuation of ions
  - Increased GEM transparency

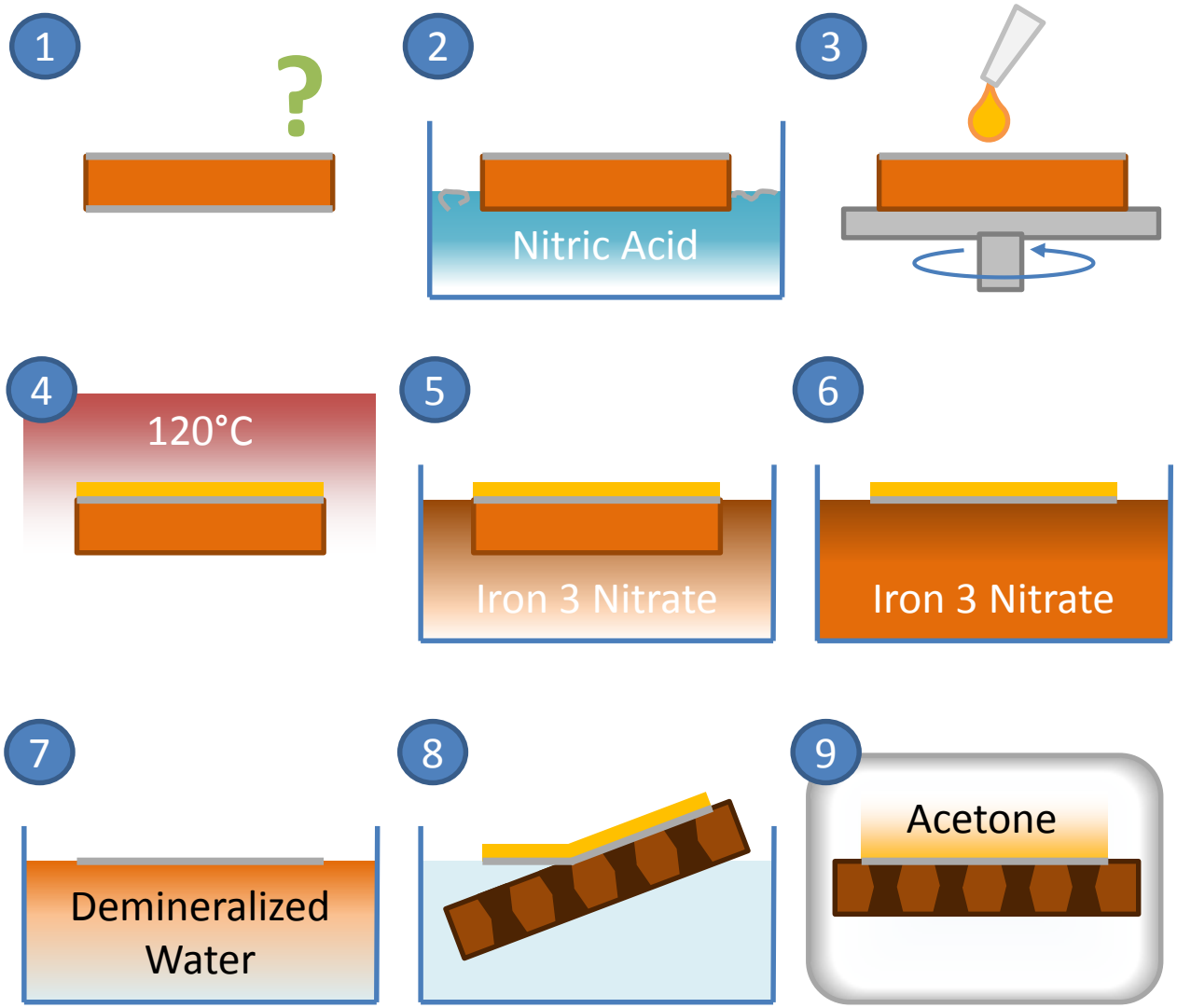
Future detectors need to be optimized for new requirements (e.g. ion back-flow, effective gain)

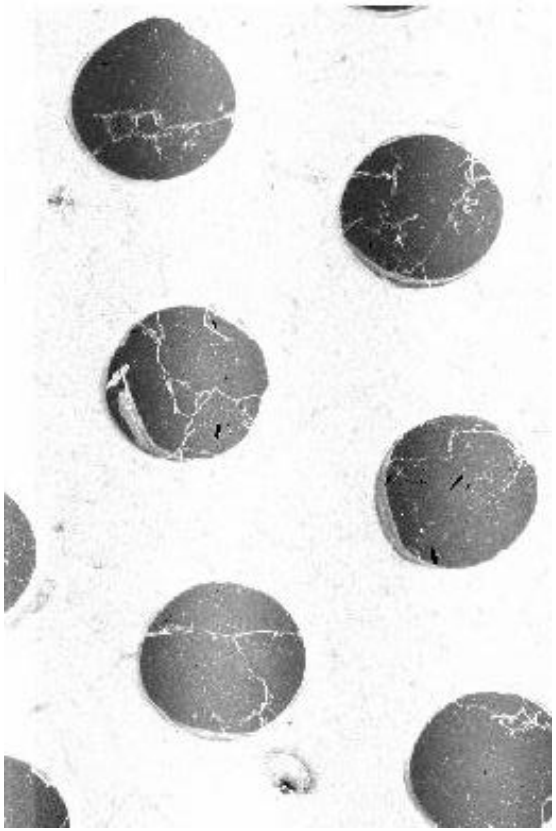
- Optimization of geometry and gas mixture to eliminate effects observed at particle fluxes of $O(10^5)$ Hz/mm^2 and above

- Graphene as a membrane only transparent to electrons may eliminate the ion back-flow

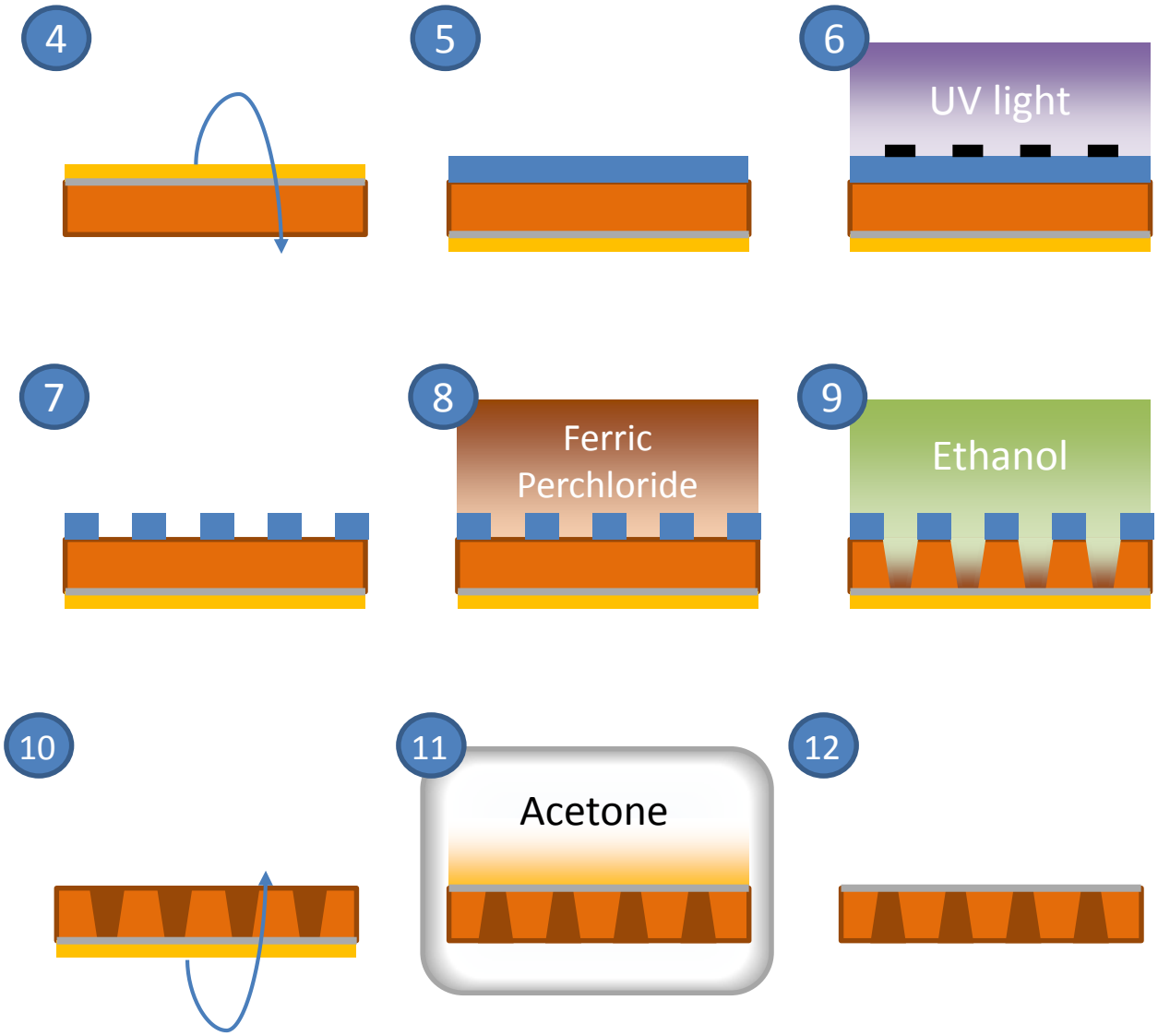
Backup

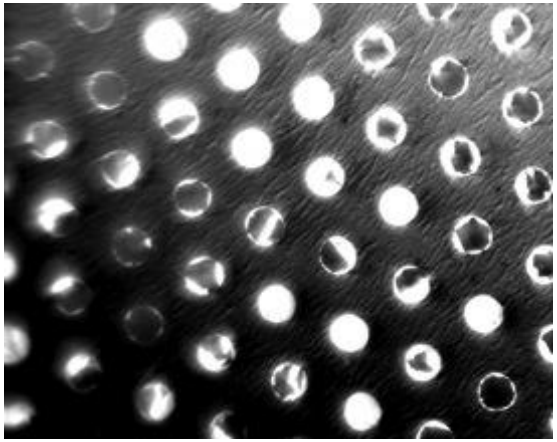
CVD graphene transfer onto support

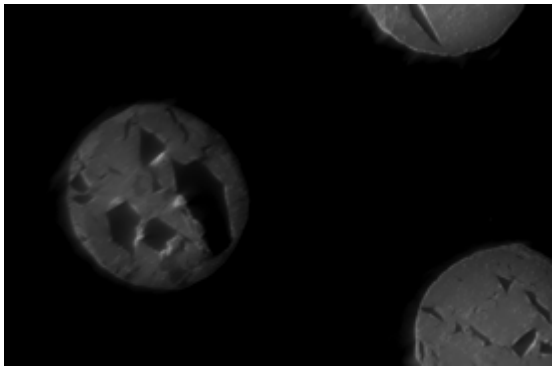




Direct etching of CVD graphene copper foil

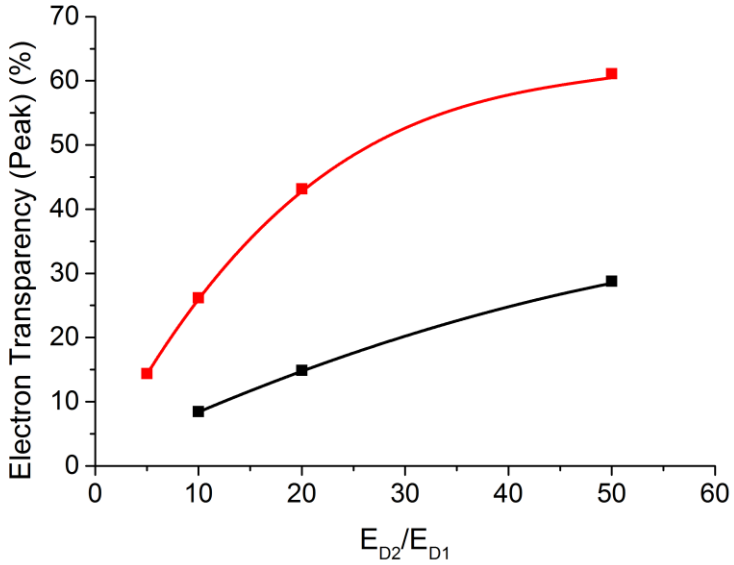


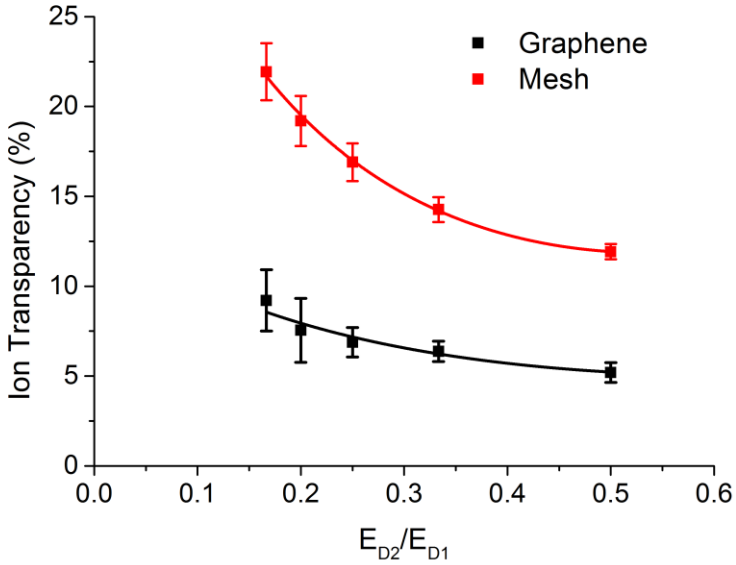




Ar/CO_2 90/10 mixture, 30 µm Ø and 120 µm pitch mesh

1 mm Ø collimated beam of 8keV Cu X-rays





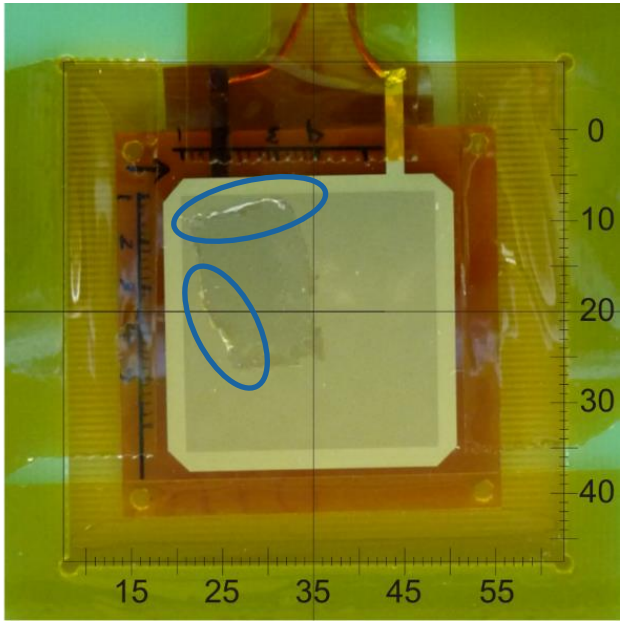
Reduced electron and ion transparencies

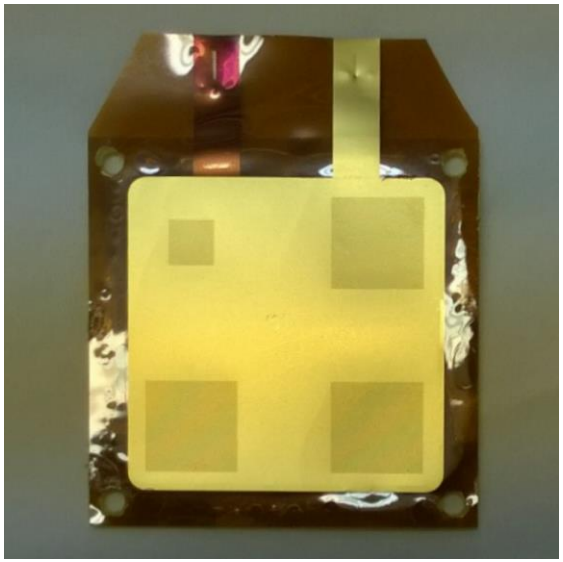
Same behaviour as very small optical transparency mesh

Measurement dominated by defects in graphene layer

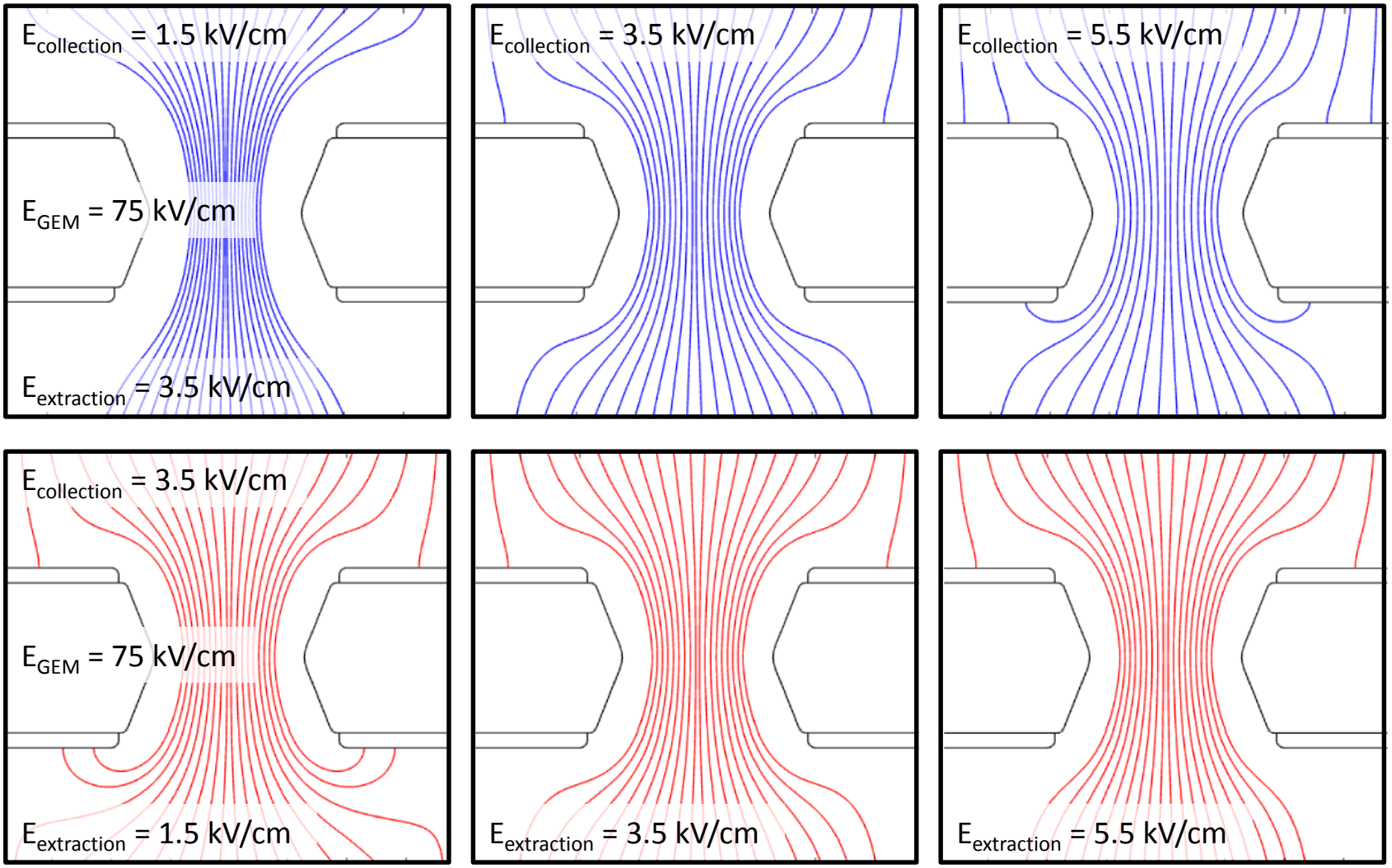
Defects on borders of graphene short the GEMs and contaminate the triple-GEM detector

Change of GEM layout to move borders out of active area



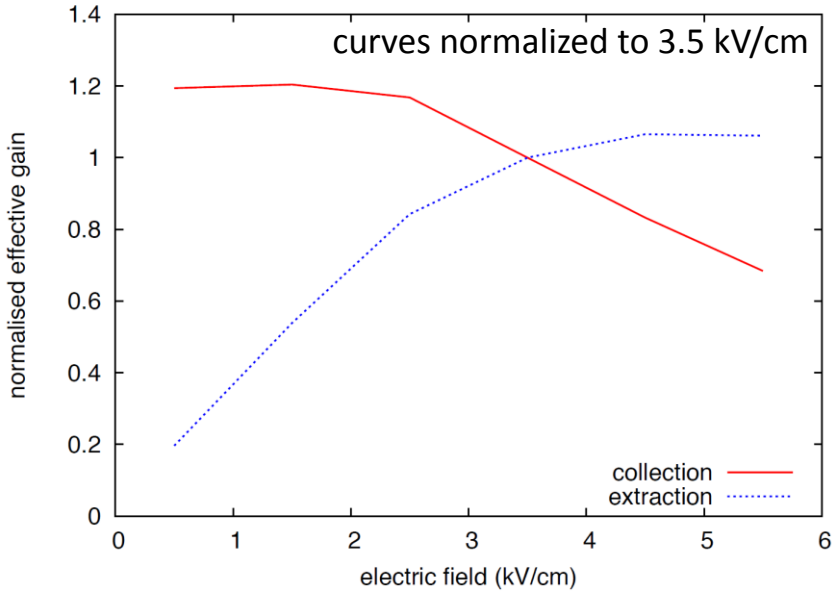


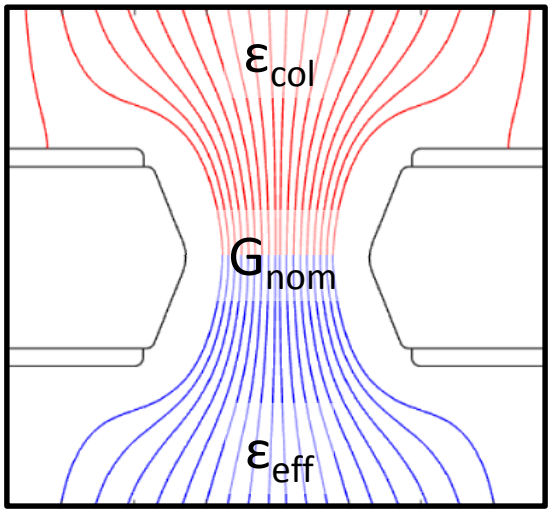
Collection and extraction efficiency



Collection and extraction efficiency

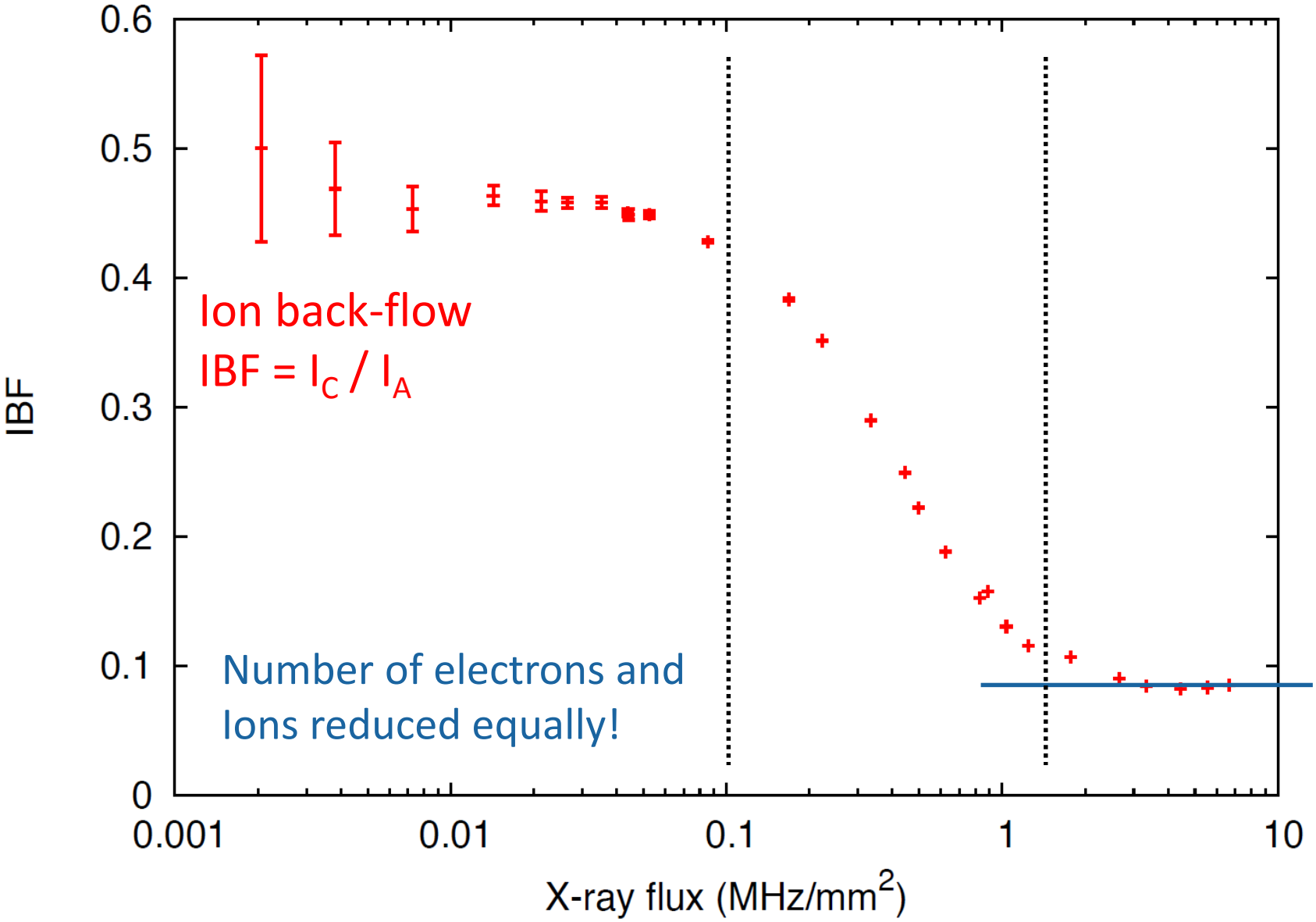
- Effective gain is the gain of the GEM, taking into account the collection and extraction efficiencies



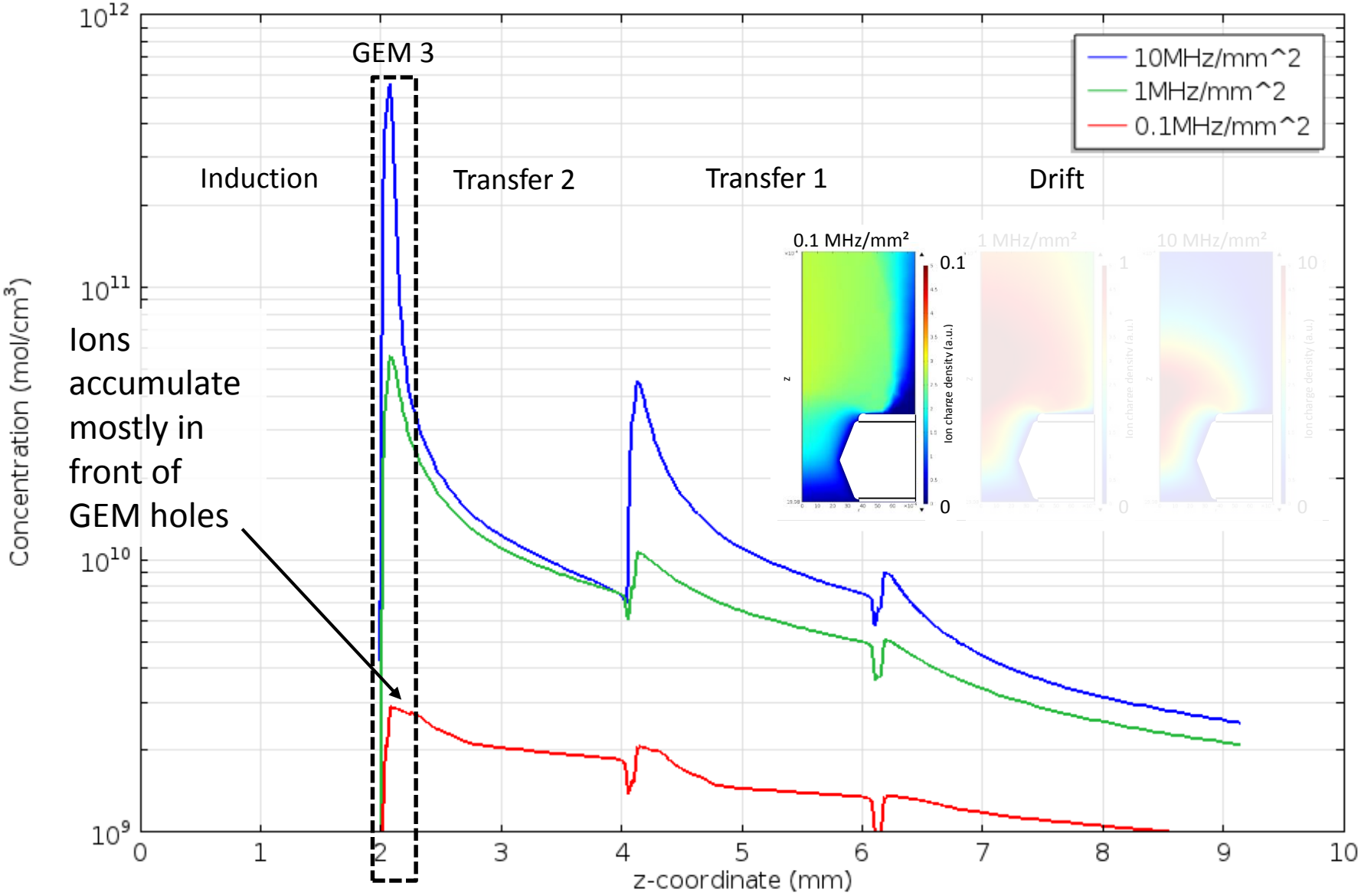


$$G_{eff} = \varepsilon_{col} \times \varepsilon_{extr} \times G_{nom}$$

Observations pt. 2



Space-charge effects in the amplification region



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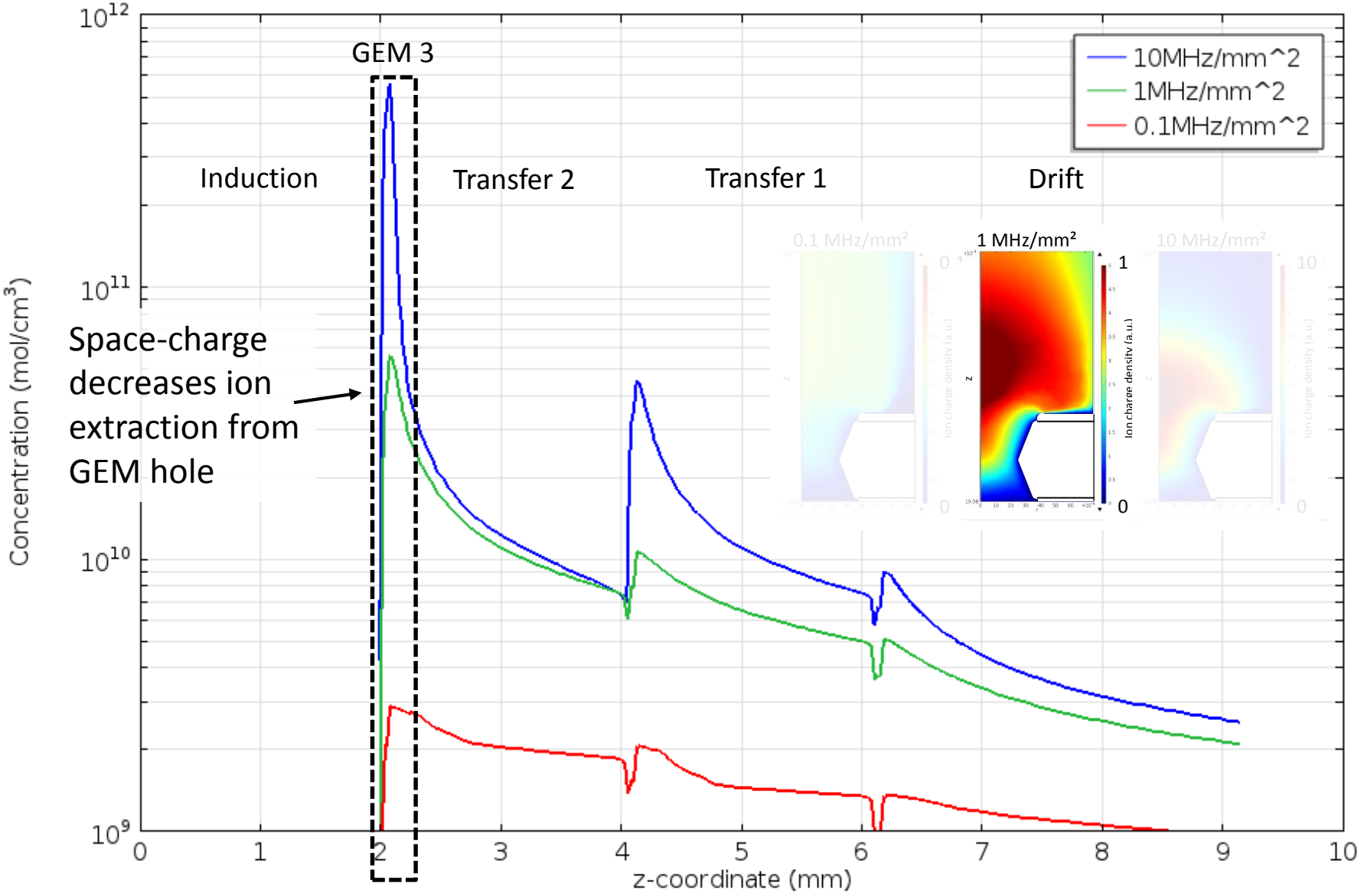
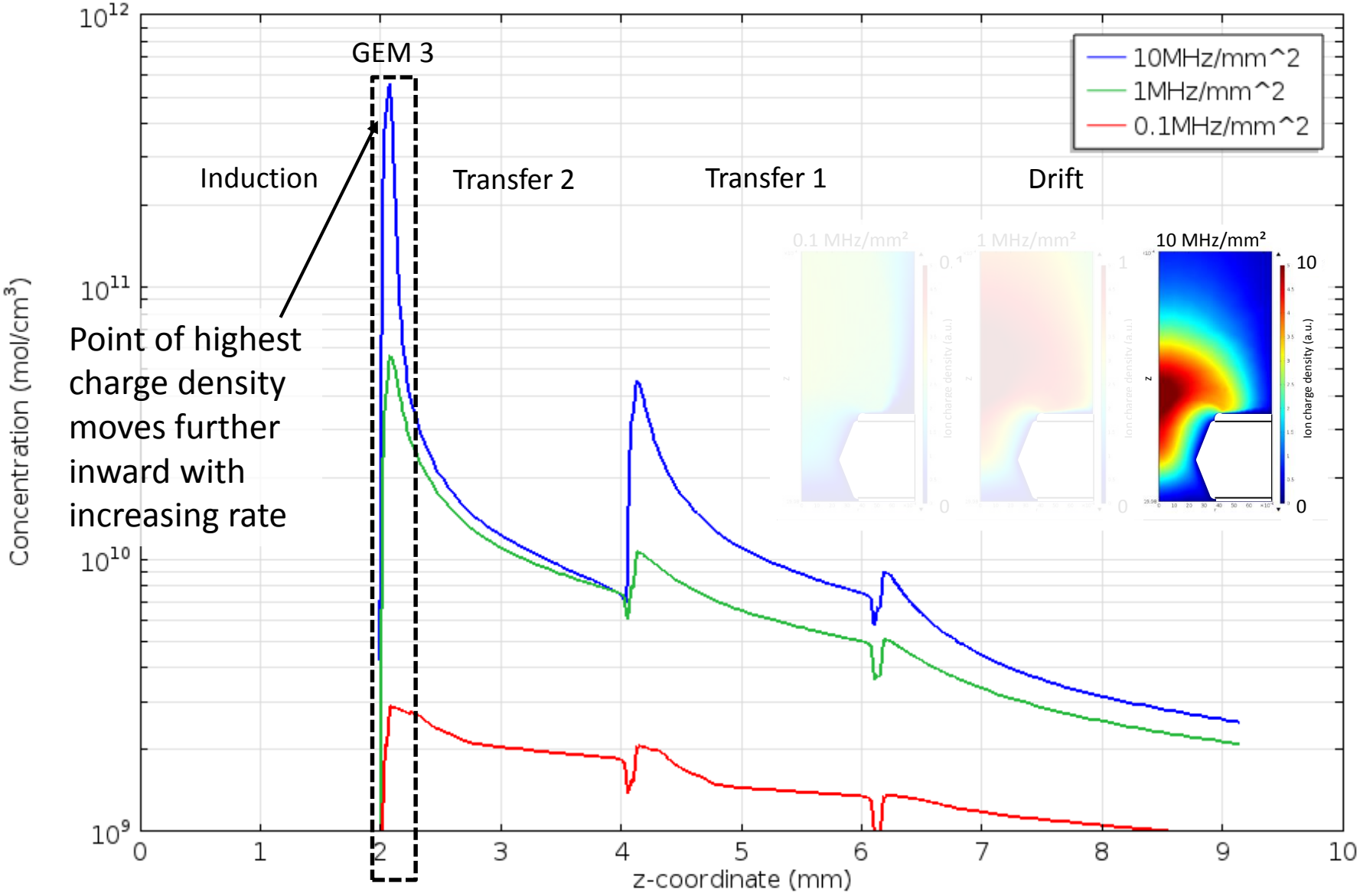
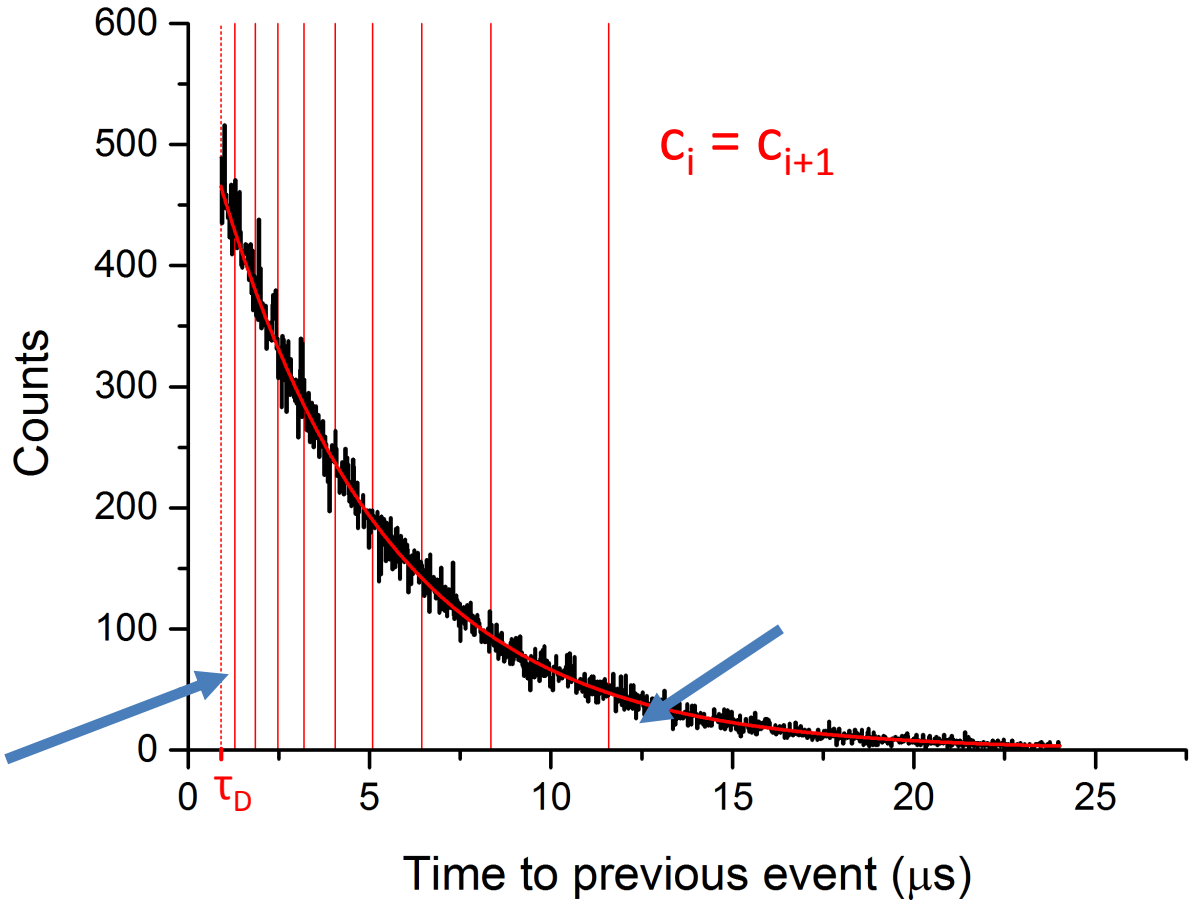


Space-charge effects in the amplification region

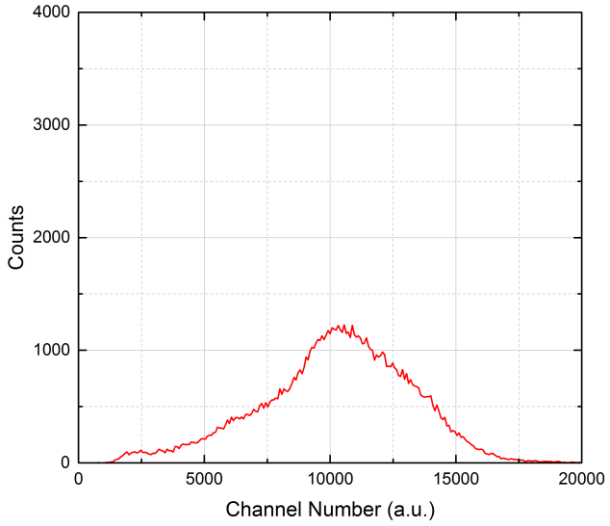


- Histogram of time to previous trigger
- Exponential fit
- Split into time intervalls with equal number of counts

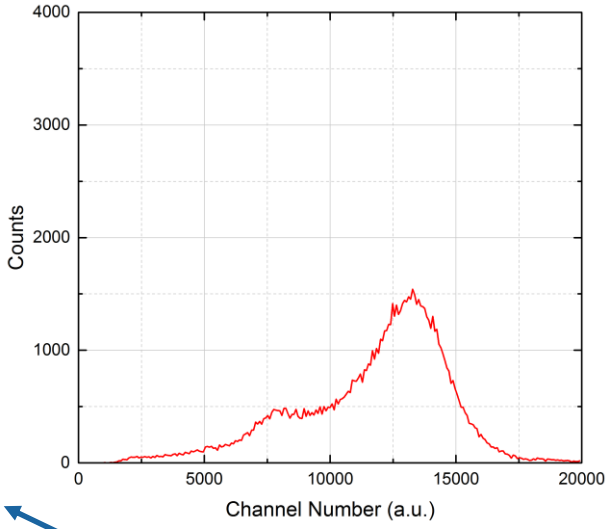


Energy resolution

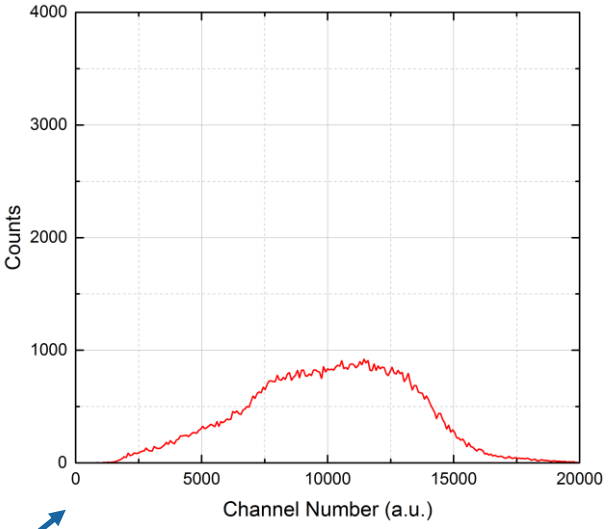
140 kHz/mm²



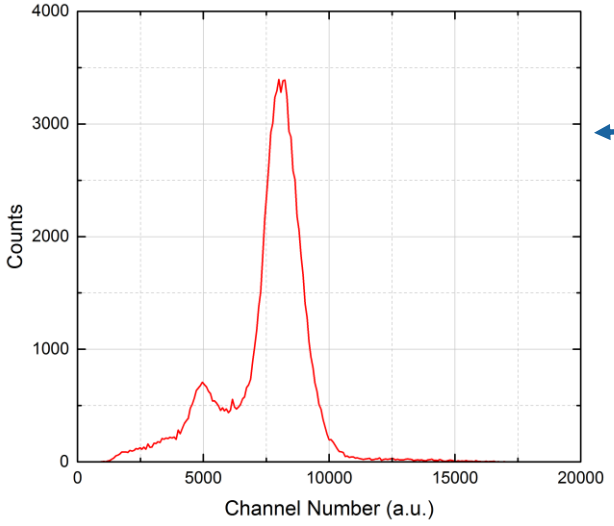
270 kHz/mm²

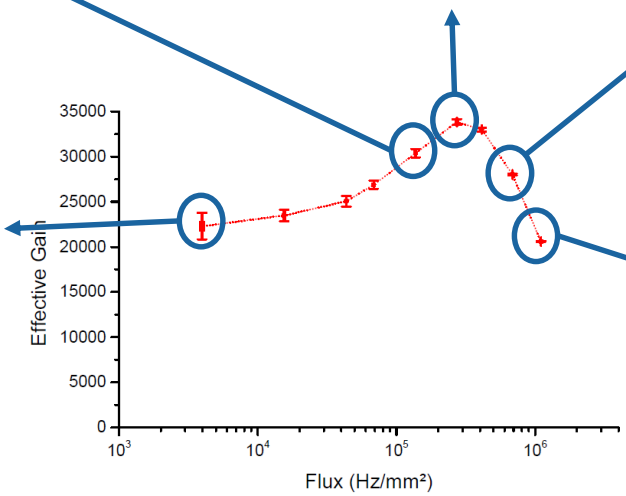


690 kHz/mm²

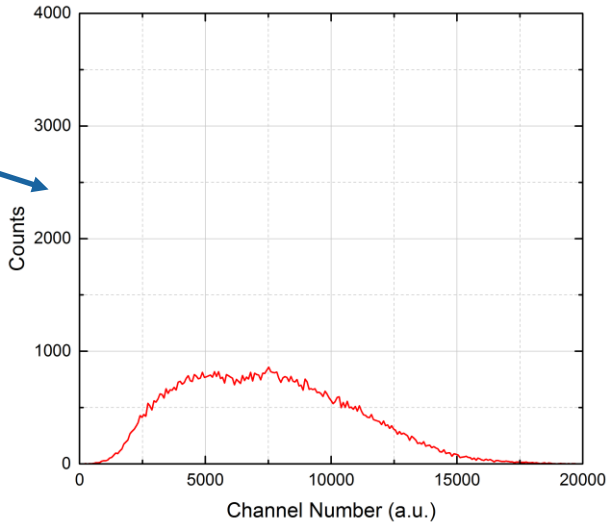


4 kHz/mm²

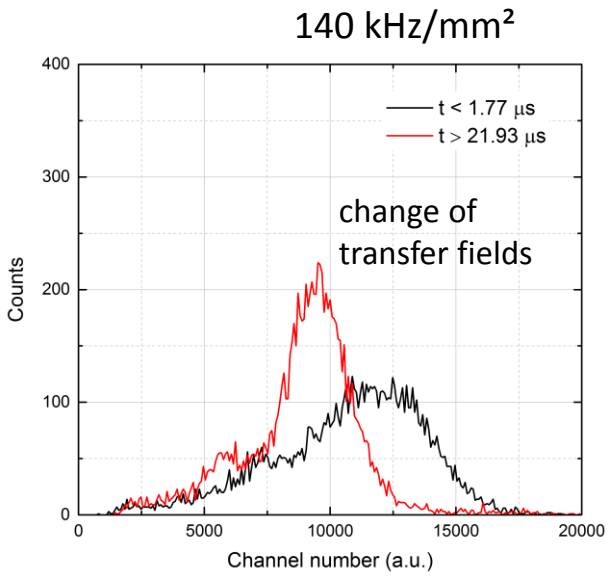


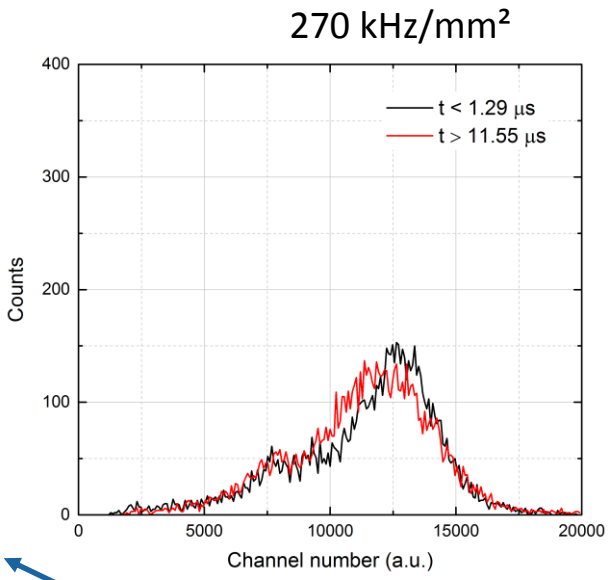


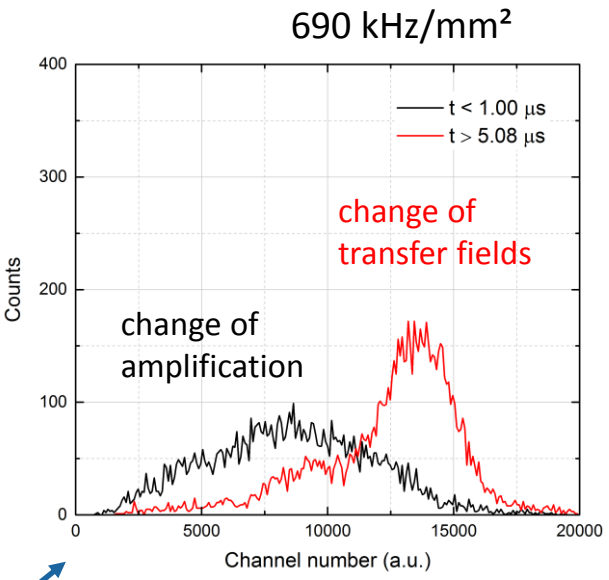
1 MHz/mm²

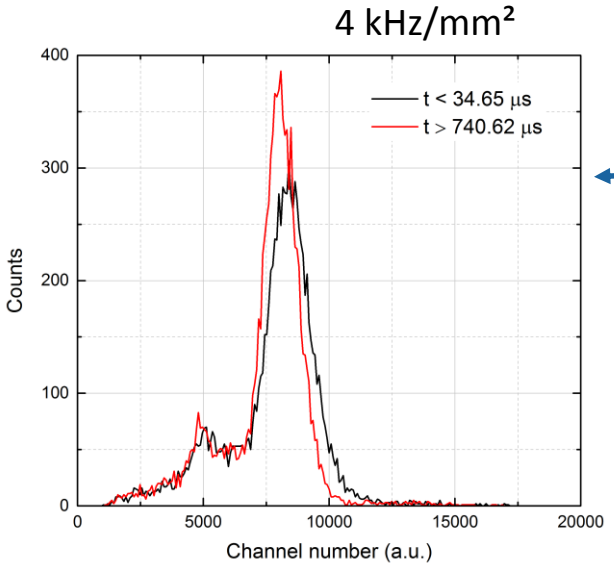


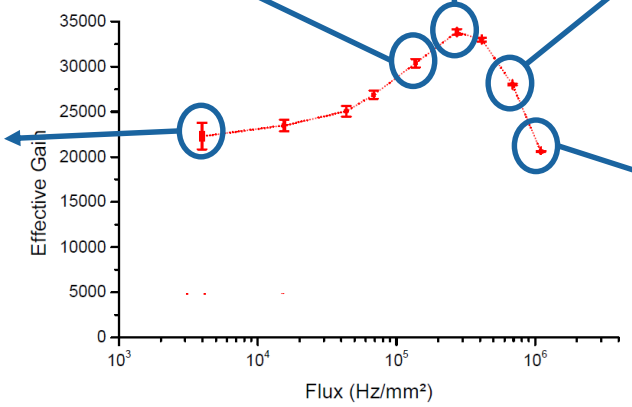
Energy resolution

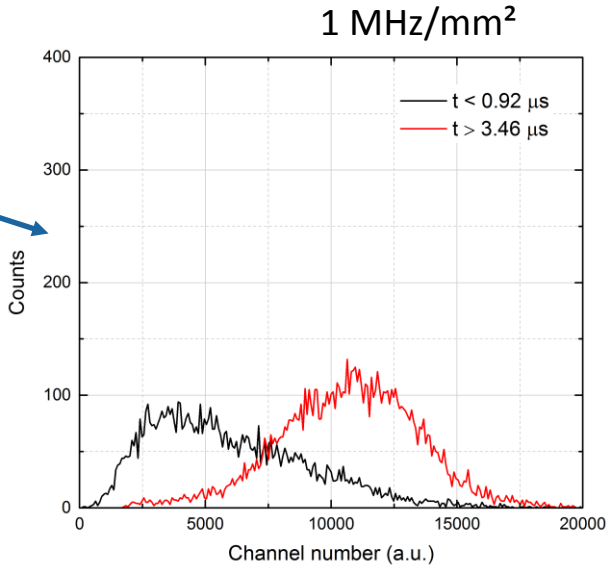












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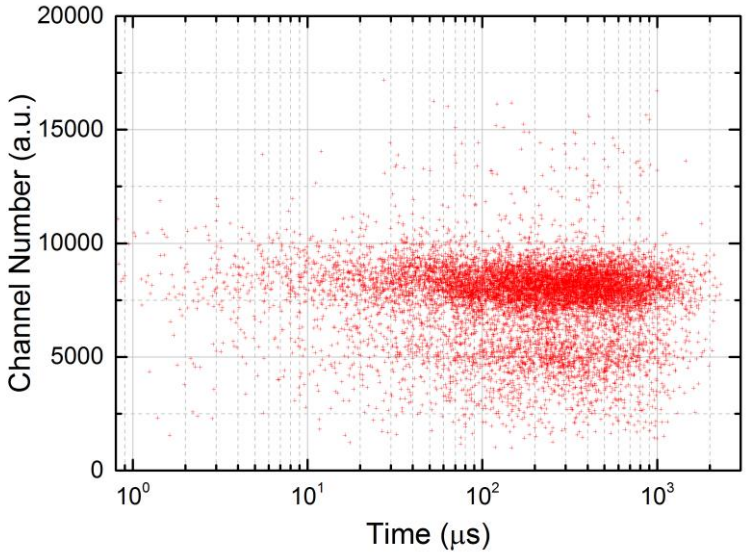

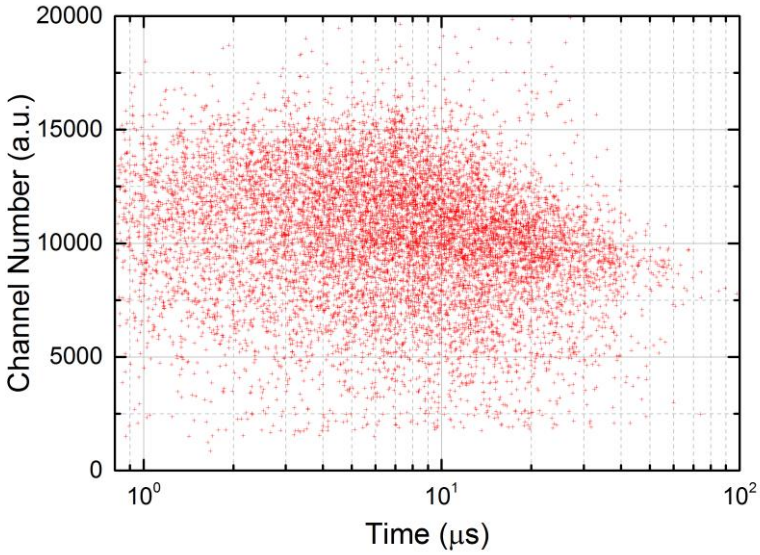

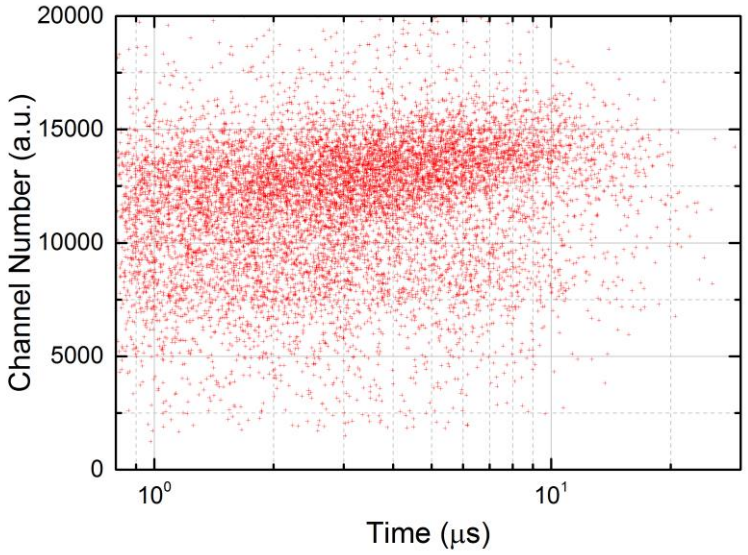

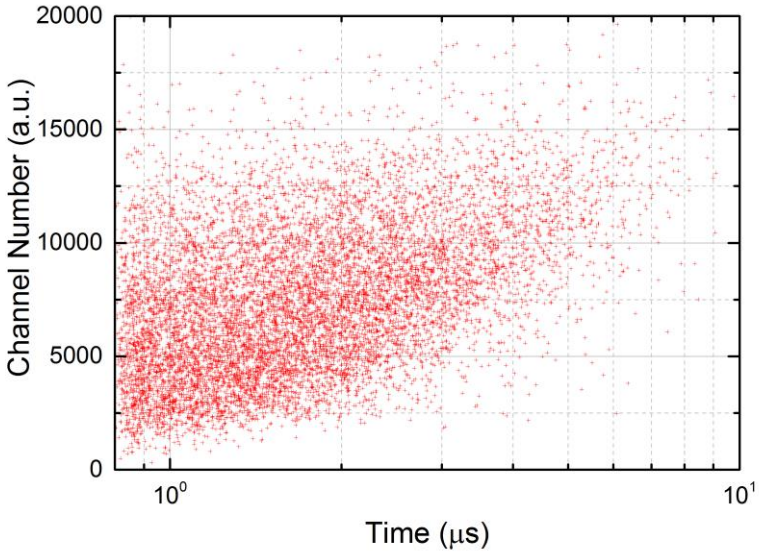

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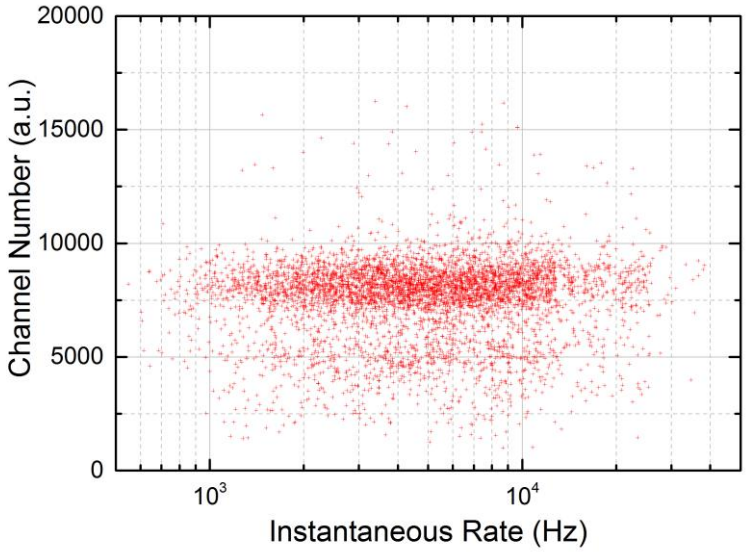

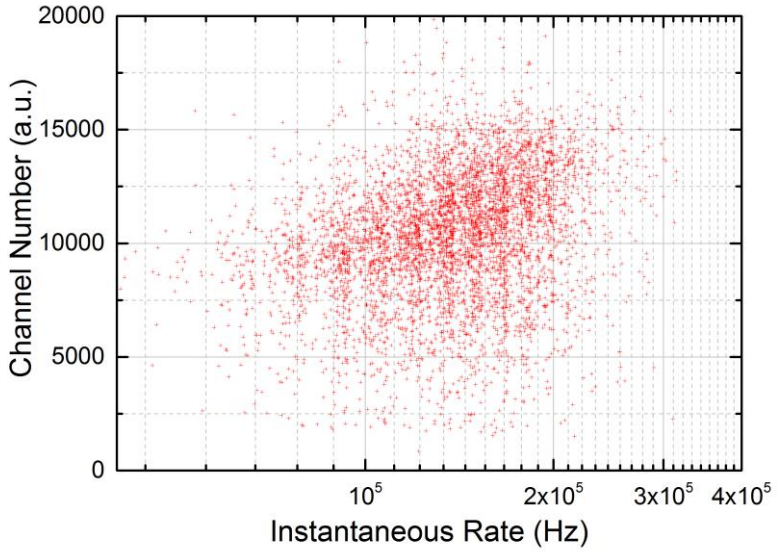

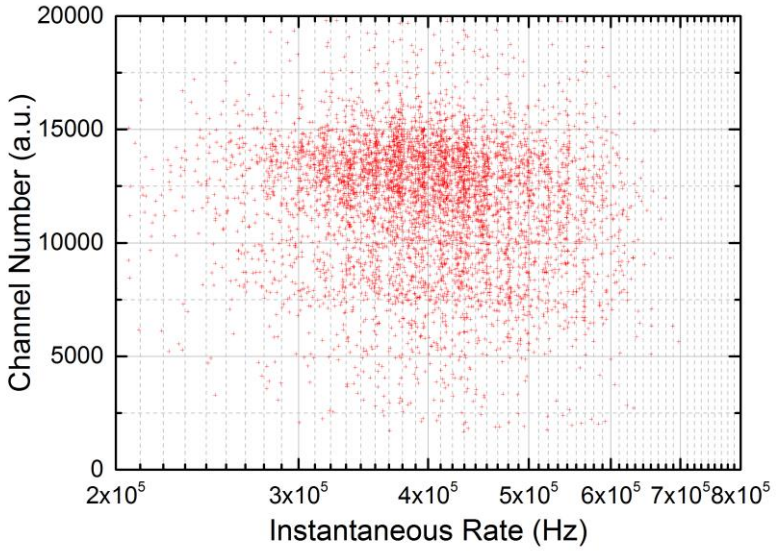

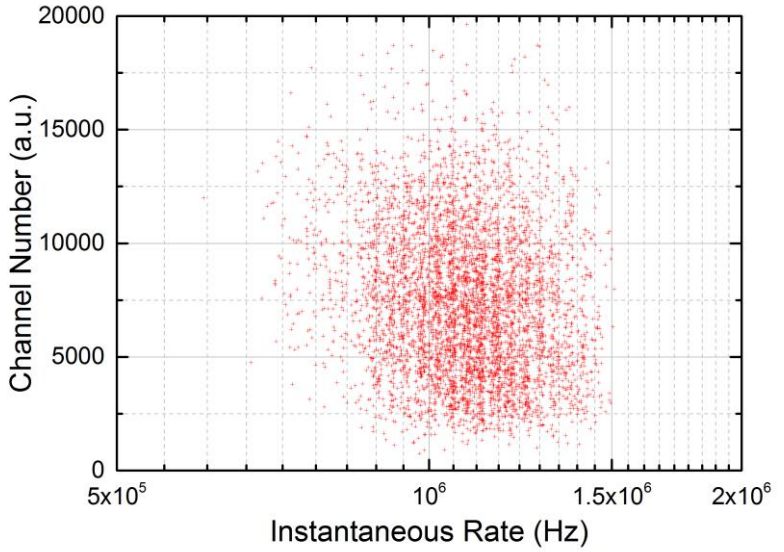

Energy resolution