Space-charge distortions
in the ALICE TPC with continuous readout

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for the ALICE-TPC upgrade collaboration

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Santiago de Compostela

Outline

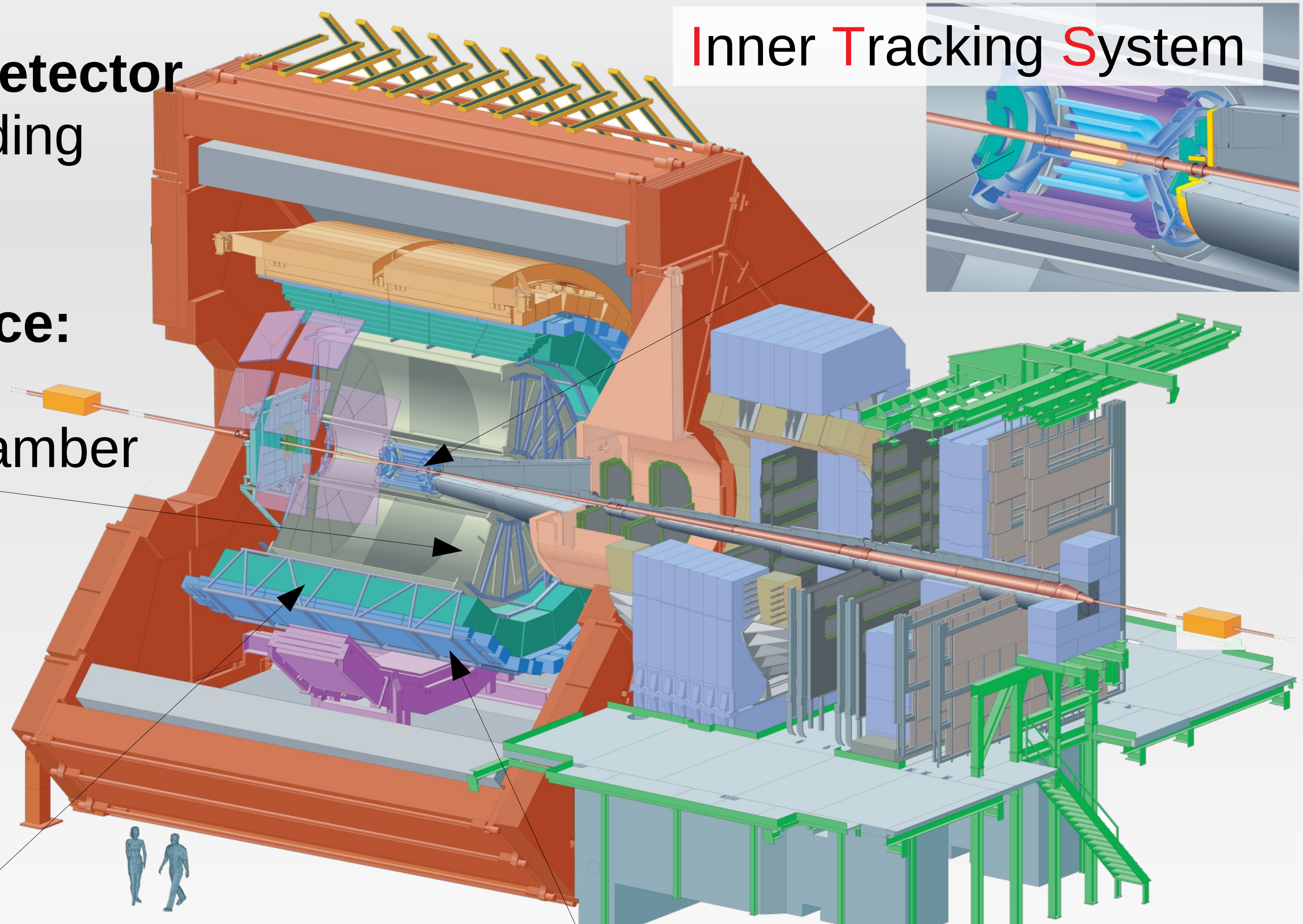
- The ALICE upgrade program
- R&D with GEM and GEM + MicroMegas systems for the TPC upgrade
- Impact of space charge on distortions
- Calibration strategy
- Summary

The ALICE detector

Overview

General purpose detector
Optimised for recording
Pb-Pb collisions

Main tracking device:
Large volume
Time Projection Chamber



Transition Radiation Detector

Time Of Flight

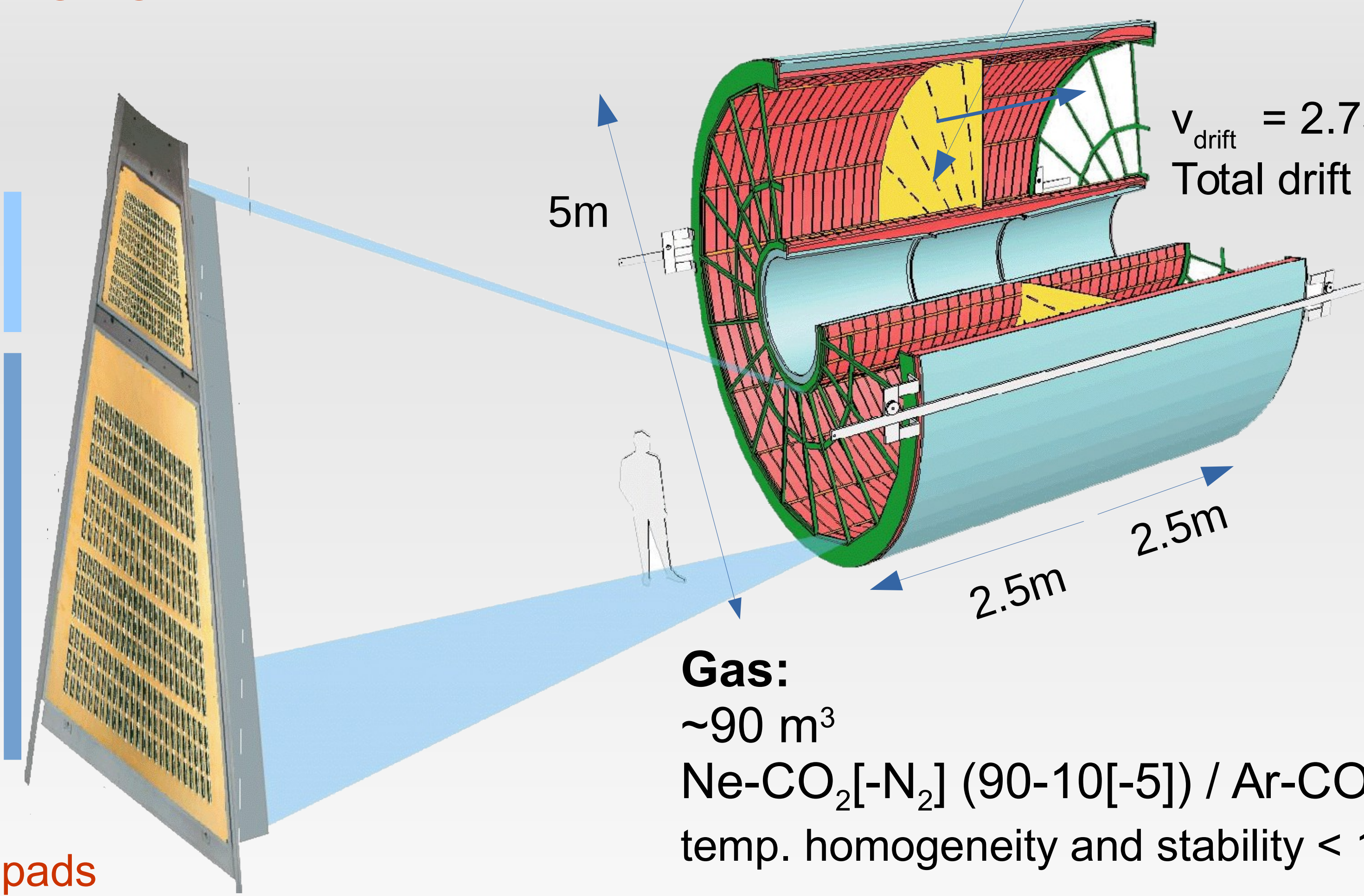
The ALICE Time Projection Chamber

In numbers

Most challenging TPC ever built

2x18 Inner Readout Chambers
4x7.5mm² pads

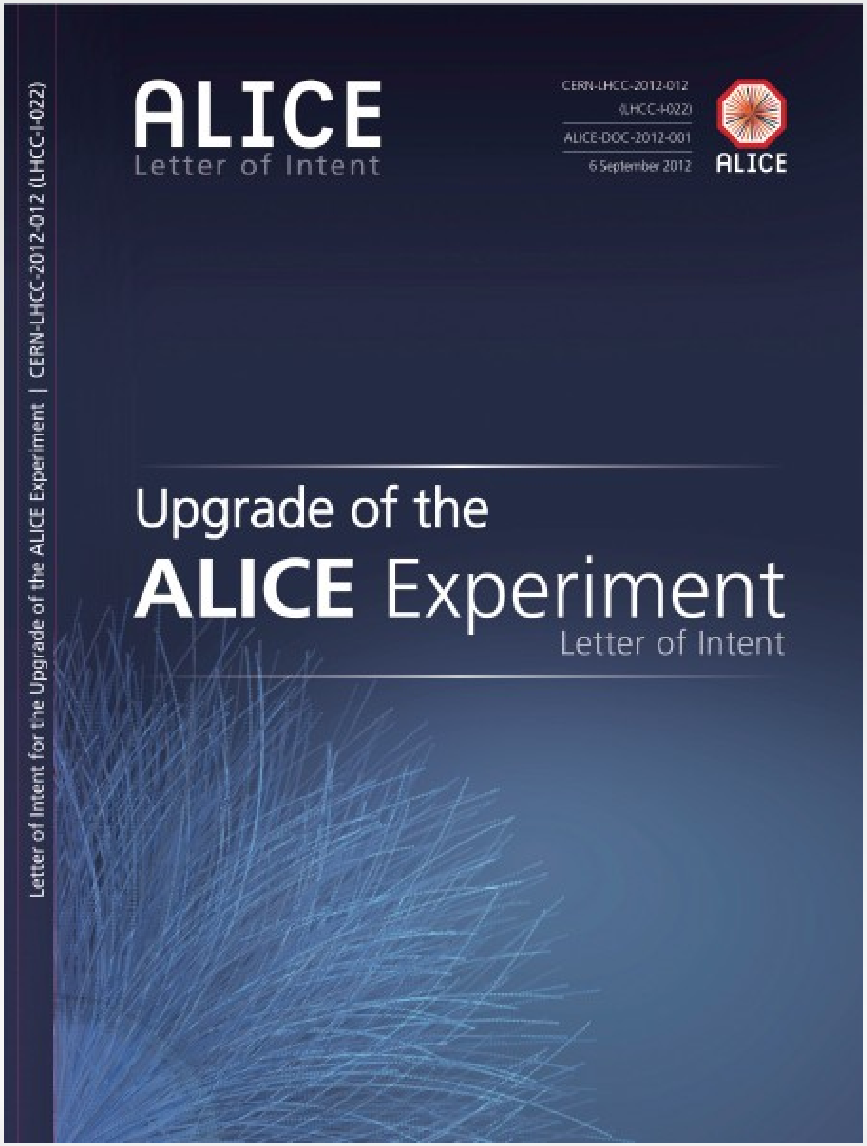
2x18 Outer Readout Chambers
6x10mm² and
6x15mm² pads



Gas:
~90 m^3
$Ne\text{-}CO_2[\text{-}N_2]$ (90-10[-5]) / $Ar\text{-}CO_2$ (88-12)
temp. homogeneity and stability < 100mK

557568 readout pads
1000 samples in time direction
Designed for charged-particle tracking and dE/dx measurement
in Pb-Pb collisions with dNch/dη=8000, σ(dE/dx)/(dE/dx)<10%

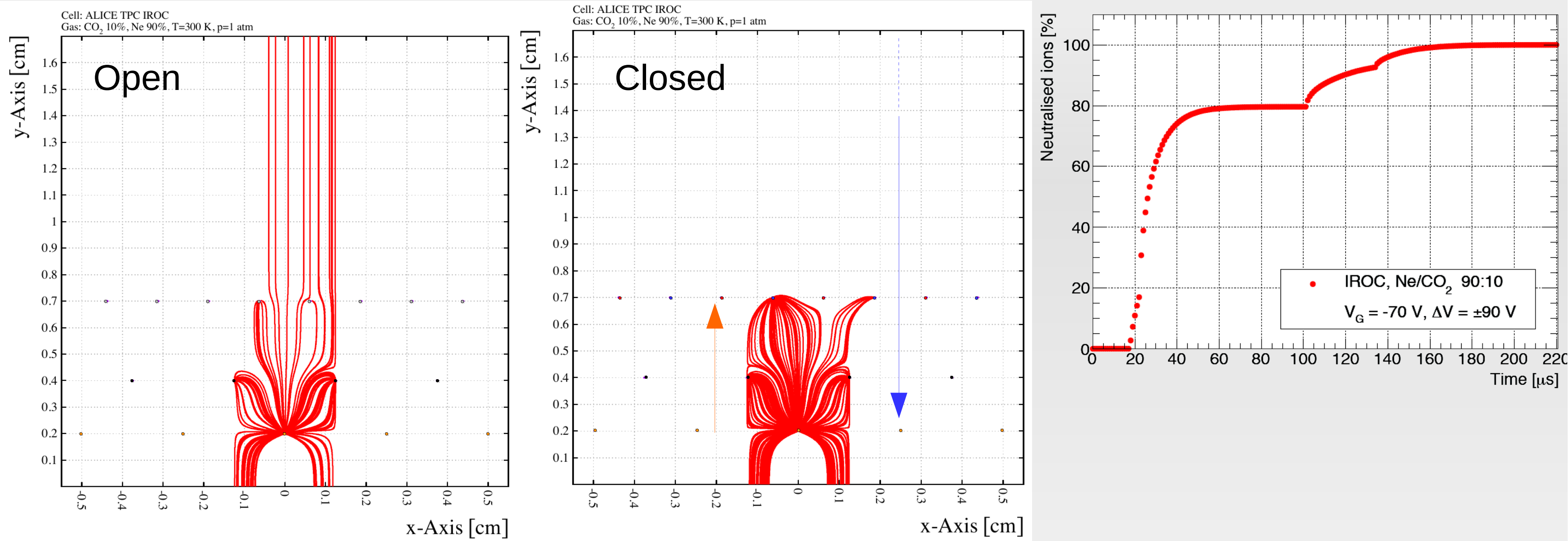
ALICE upgrade



- Rich physics program (Run3 - 2020)
  - Heavy flavour
  - Quarkonia
  - Low-mass dileptons
  - Jets
  - Anti- and hypernuclei
- Implies TPC readout at full minimum bias interaction rate
  → 50kHz in Pb-Pb
- Significant TPC upgrade (LS2 - 2018)
  - Readout chambers (2015-2017)
  - Frontend electronics (2015-2017)
  - Online calibration and reconstruction

The ALICE TPC

Limitations of the present system

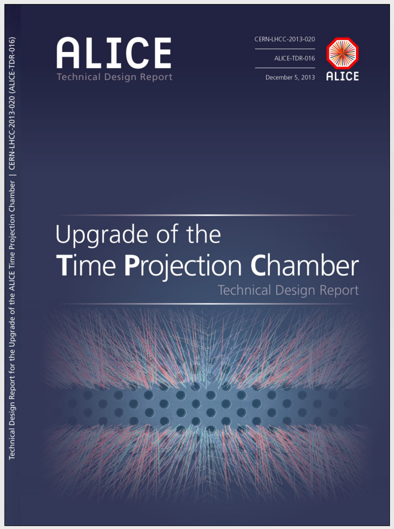


- Very good ion suppression (ion back flow – *IB* ~10^{-4} - 10^{-5})
- Limited rate capability
  - Readout cycle: $t_{readout} = t^{e-}_{drift,max} + t^{ion}_{drift}$
  - 100μs + 200μs → ~3.5kHz
- Change of readout system required to make full use of 50kHz interactions

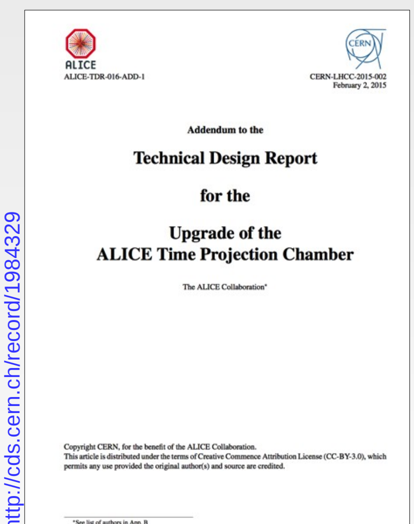
The ALICE TPC

Upgrade program

TDR
http://cds.cern.ch/record/1622286



TDR Addendum
http://cds.cern.ch/record/1984329


ALICE
ALICE-TDR-016-ADD-1

CERN-LHCC-2015-002
February 2, 2015

Addendum to the

Technical Design Report

for the

Upgrade of the
ALICE Time Projection Chamber

The ALICE Collaboration*

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*See list of authors in App. B

Intense R'n'D program

- Mainly GEM systems (3- and 4-stack)
- Also 2GEM + MM tested

Base line solution

- No gating and continuous readout with 4-GEM system

Implication

- Event pile-up in TPC: ~5 overlapping events

Requirements for readout

- Operate at gain 2000 in Ne-CO_2-N_2 → Signal to noise
- Ion back flow (*IB*) < 1% → Impact on distortions
- σ_E/E < 12% for ^{55}Fe → Impact on d*E*/dx resolution
- Stable operation under LHC conditions
- \+ novel calibration and online reconstruction schemes

Impact of the gas

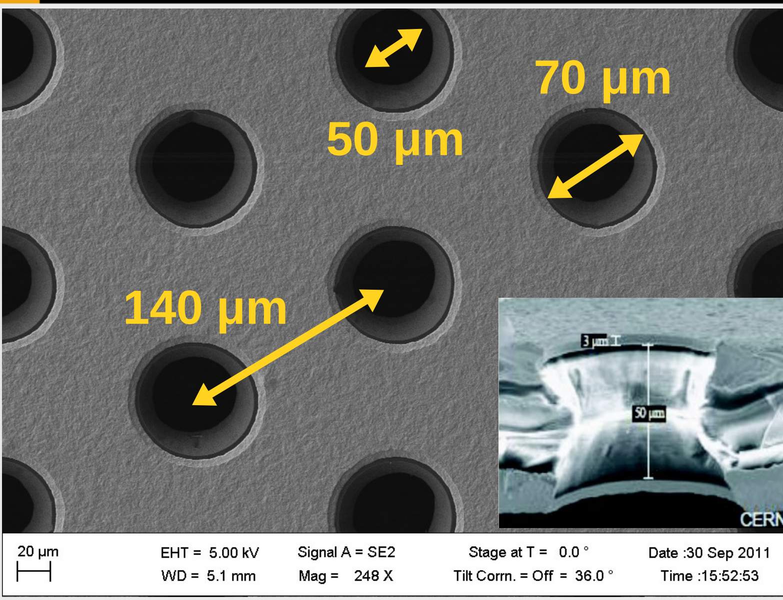
Argon vs. Neon

- Similar drift velocity, diffusion and *IB*
- Primary ionisation 2x larger in Argon
- Ion mobility about 1.8x lower in Argon Deisting et al.
  - → ~3.6x larger SC in Argon from primary ionisation
  - → ~1.8x larger SC in Argon for *IB* component
- Add additional quencher N_2 for increased stability

Gas	Drift velocity v_d (cm/μs)	Diffusion coeff. D_L ($\sqrt{cm}$)	Diffusion coeff. D_T ($\sqrt{cm}$)	$\omega\tau$	Eff. ionization energy W_i (eV)	Number of electrons per MIP N_p (primary) (e/cm)	Number of electrons per MIP N_t (total) (e/cm)
Ne-CO_2-N_2 (90-10-5)	2.58	0.0221	0.0209	0.32	37.3	14.0	36.1
Ne-CO_2 (90-10)	2.73	0.0231	0.0208	0.34	38.1	13.3	36.8
Ar-CO_2 (90-10)	3.31	0.0262	0.0221	0.43	28.8	26.4	74.8
Ne-CF_4 (80-20)	8.41	0.0131	0.0111	1.84	37.3	20.5	54.1

GEM technology

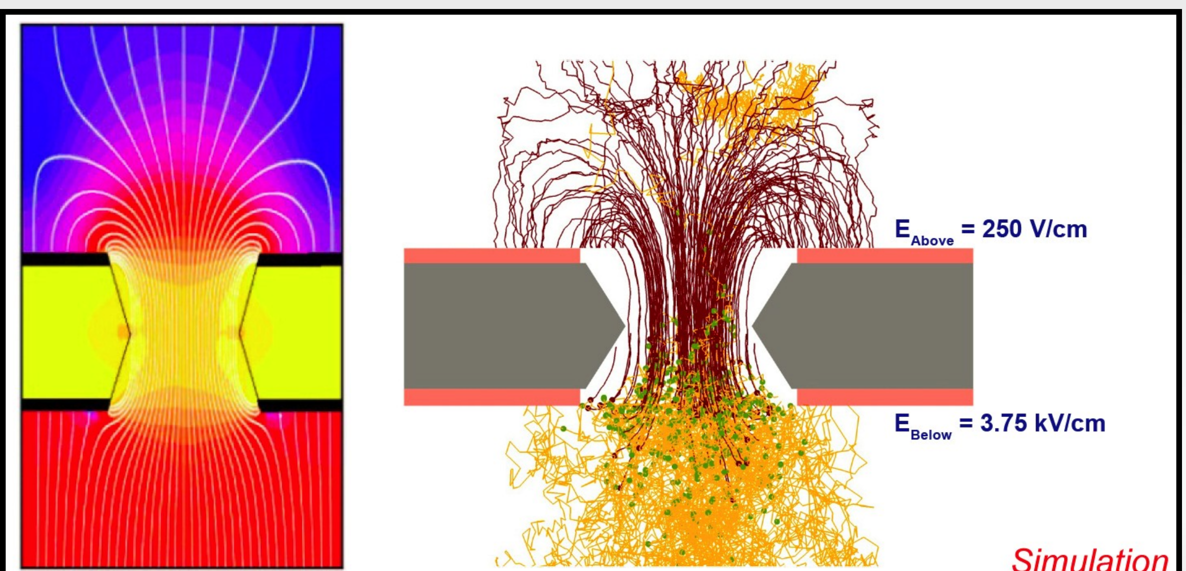
Introduction



- Thin polyimide foil ~*50* µm
- Cu-clad on both sides ~*5* µm
- Photolithography: ~10^4 holes/cm^2

<u>Typical GEM geometry:</u>

- Inner/Outer hole diameter: 50/70 µm
- **Pitch**: 140 µm
- Other geometries with different pitch sizes:
  - 90µm (SP), 200µm (MP), 280µm (LP)



- E_{Hole} up to 100 kV/cm with

  ΔV_{GEM} = 500 V
- $E_{Hole} >> E_{Above}$

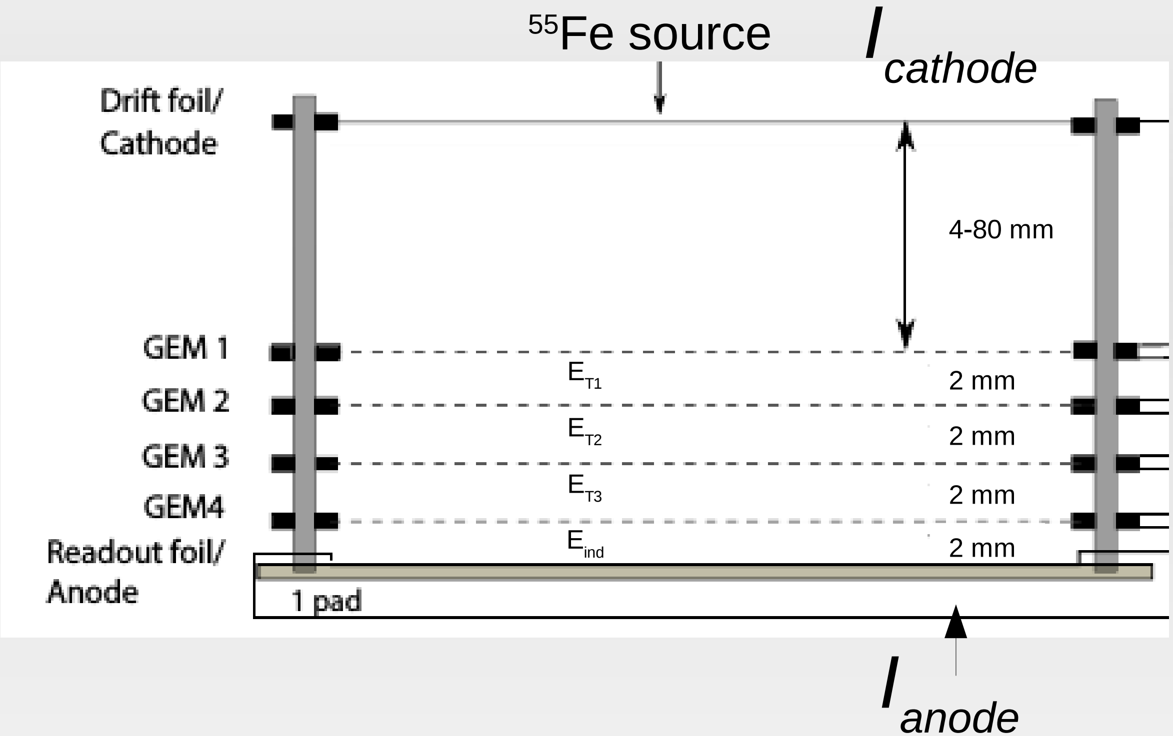
  most of the ions are collected on the top side of GEM
- $E_{Below} > E_{Above}$

  9

  electron extraction is improved

IB measurements

Introduction – nomenclature



$$IB = I_{cathode}/I_{anode}$$

$$\varepsilon = IB * G_{eff} - 1$$

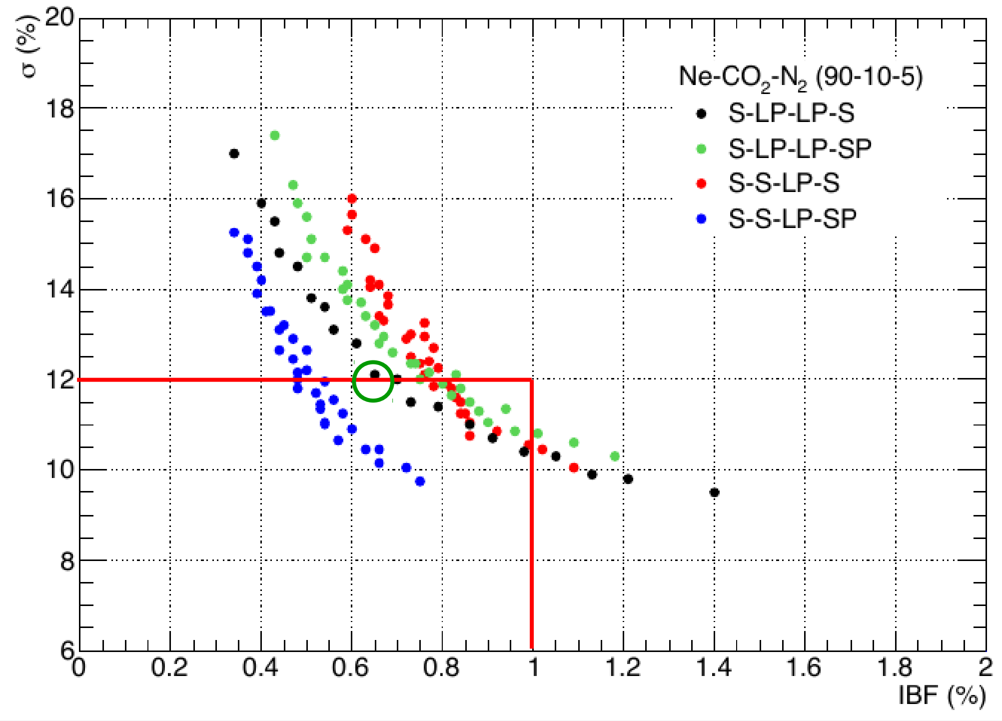
$$n_{tot} = n_{prim} * IB * G_{eff}$$

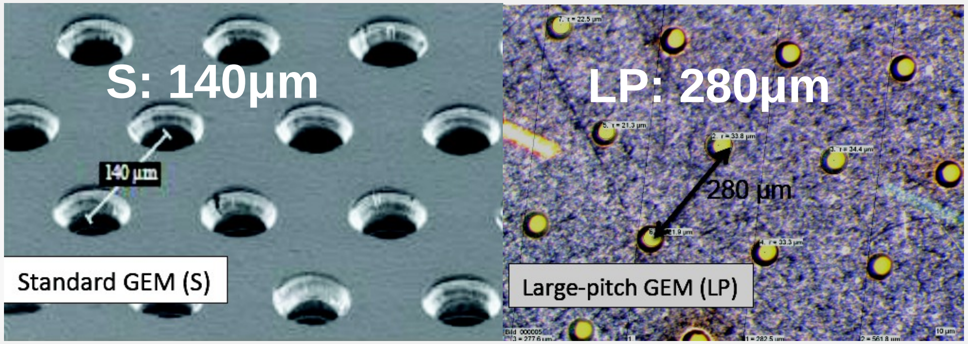
- Ion blocking (~10^{-2}) not as efficient as with gating grid (10^{-4} – 10^{-5})
- Total ions in drift volume (n_{tot}) strongly depending on *IB*
- Huge parameter space → N_{foils}, hole geometry, ΔV_{GEM1} - ΔV_{GEM4}, E_{T1}-E_{ind}
- Use lower GEMs (3, 4) to adjust the gain (usually $\Delta V_{GEM3}/\Delta V_{GEM4}$ = const.)

4-GEM measurements

Summary of results

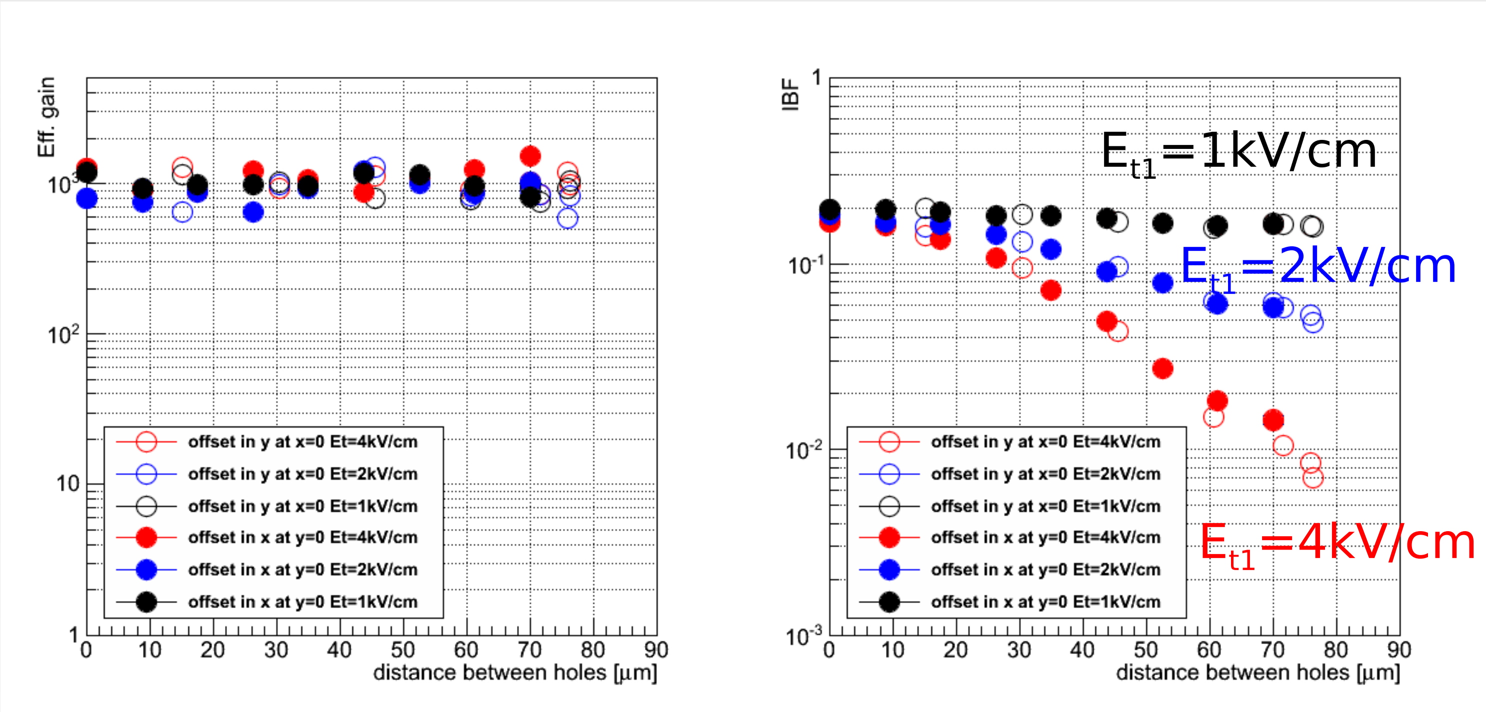
- Many GEM configurations scanned
- With 3-GEM (S-S-S) system *IB* > 2.5%
- With 4-GEM (S-S-S-S) system *IB* > 2.0%
- Base line solution 4-GEM (S-LP-LP-S)
  - Working point: IB ~0.65%, σ~12%
  - ΔV_{GEM} = 275, 235, 284, 345 (V)
  - $E_{T/Ind}$ = 4, 2, 0.1, 4 (kV/cm)
  - Small discharge probability (~5 per GEM stack per heavy-ion run)

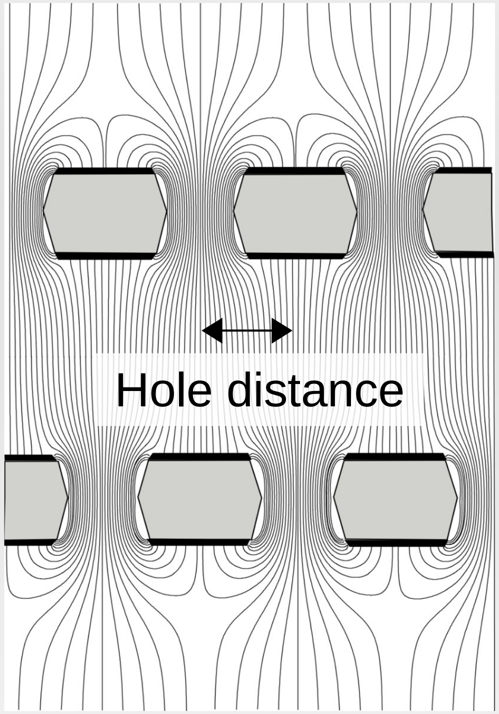




IBF simulations

Dependence on GEM hole distance





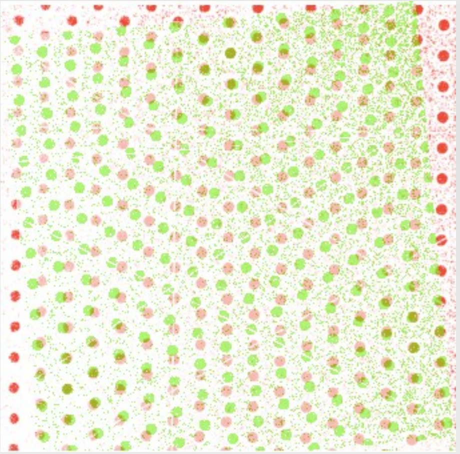
- Ne/CO_2 simulation studies
- In case of high ET1, alignment is an issue.
  - Gain and IBF vs. distance between holes in GEM1 and GEM2
- x10 difference in IBF w.r.t hole alignment

IBF simulations

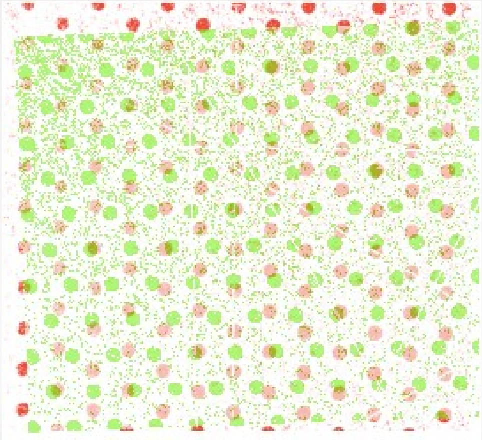
Dependence on GEM hole distance – optical transparency

- Alignment cannot be controlled on µm level
- 'Optical' transparency very different over the GEM surface
  - Resulting from hexagonal GEM pattern
  - Would result in very inhomogeneous IBF → unfavourable
- Rotate adjacent foils by 90°
  - More homogeneous pattern

GEM Foils aligned

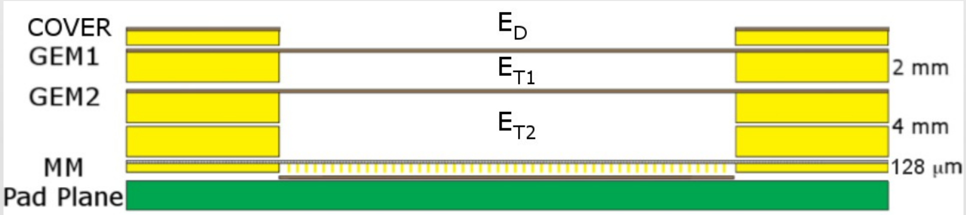


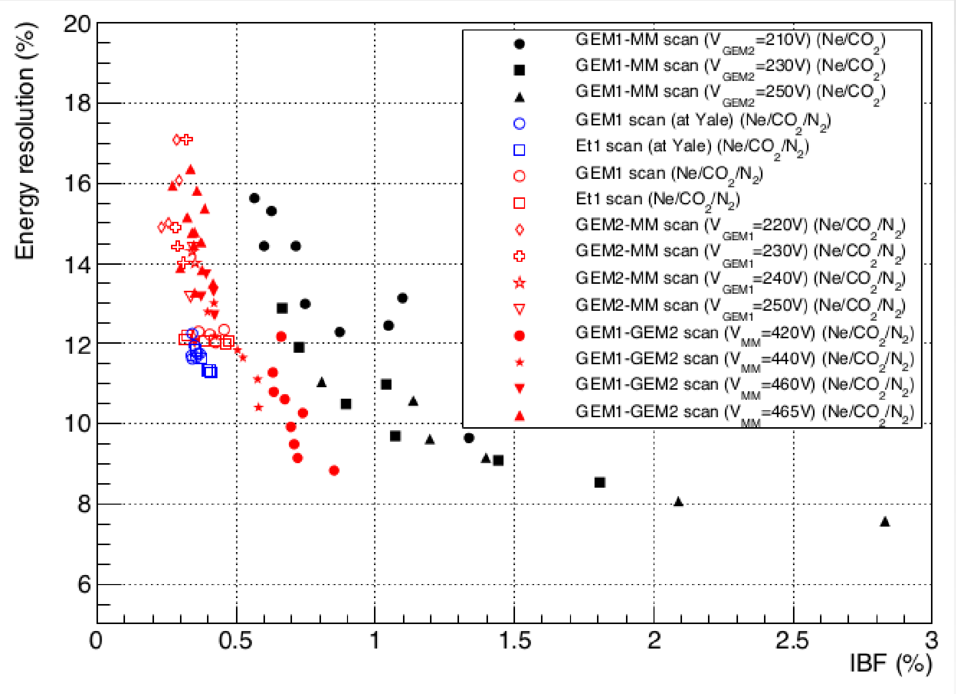
GEM Foils rotated by 90°



2GEM + MM measurements

- At same energy resolution *IB* only marginally smaller then in 4-GEM
- Discharge rate 2-3 orders of magnitude larger
  - Not further investigated

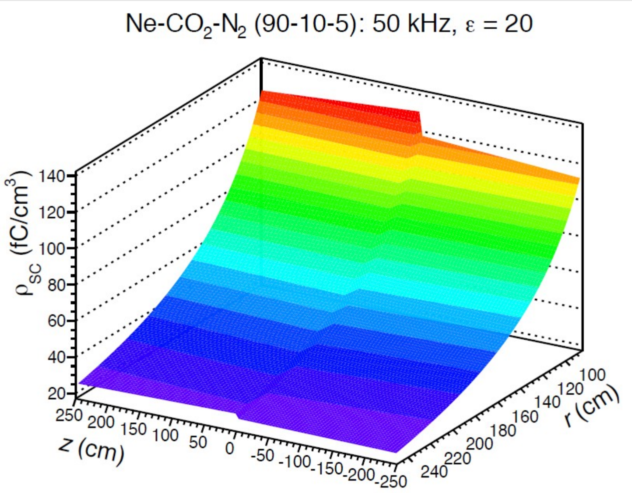




Space-charge distortions

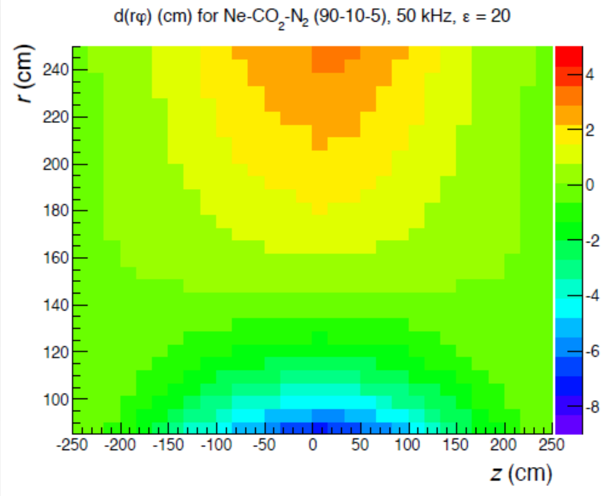
Calculation of the distortions

$$\rho_{\mathrm{sc}}(r,z) = \frac{a - bz + c\,\varepsilon}{r^d}$$



Space-charge density

ρ(x,y,z)



Space-point distortions

Δ**r**(x,y,z)

Laplace equation

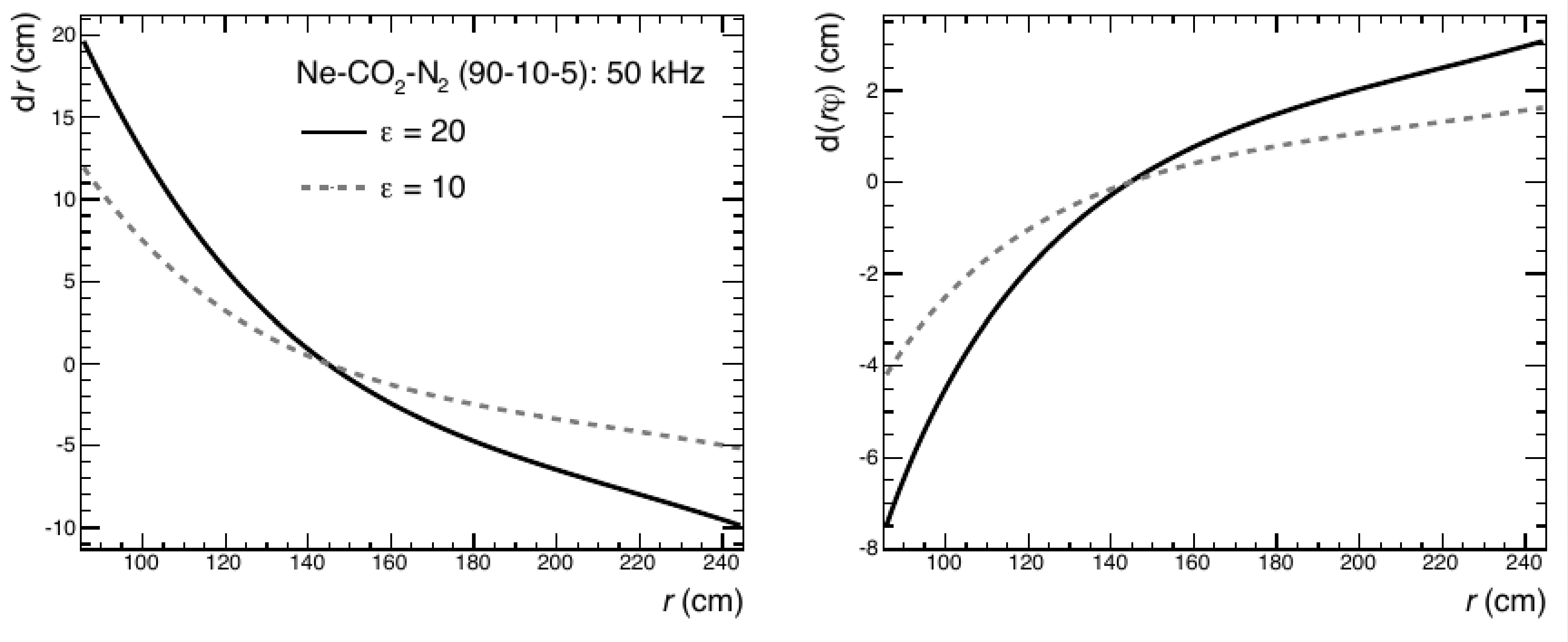
Electron transport
Langevin equation

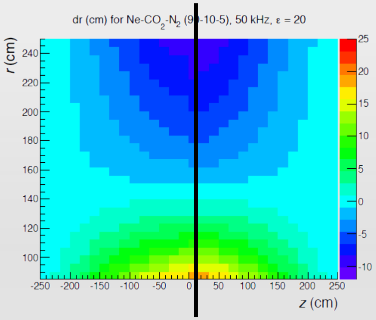
ΔE(x,y,z)

Electric field distortions

Space-charge distortions

Impact of the Ion Back Flow

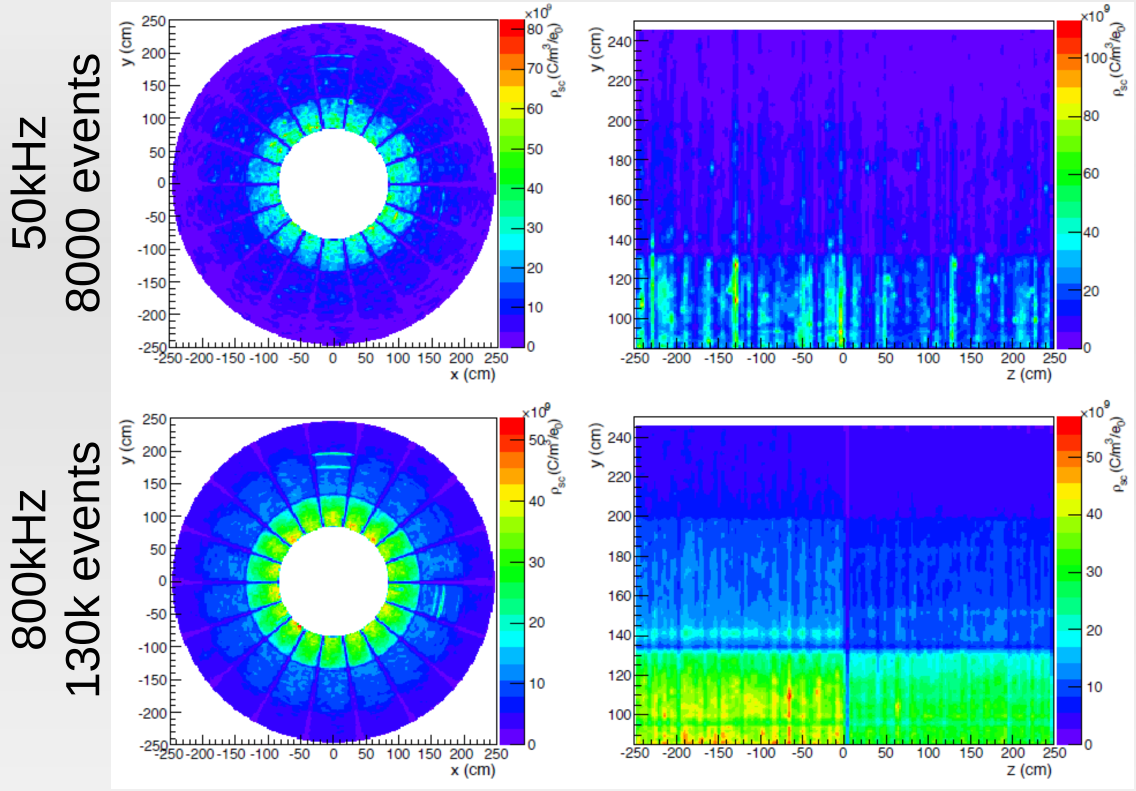




- 50kHz Pb-Pb, gain = 2000, IB=1% (ε=20)
  - $t_{d,ion}$ = 160ms → ion pileup from 8000 events
- Distortions up to dr ≈ 20cm drφ ≈ 8cm (small *r* and *z*)
  - Final calibration to ~10^{-3} required

Space-charge distortions

Distortion fluctuations

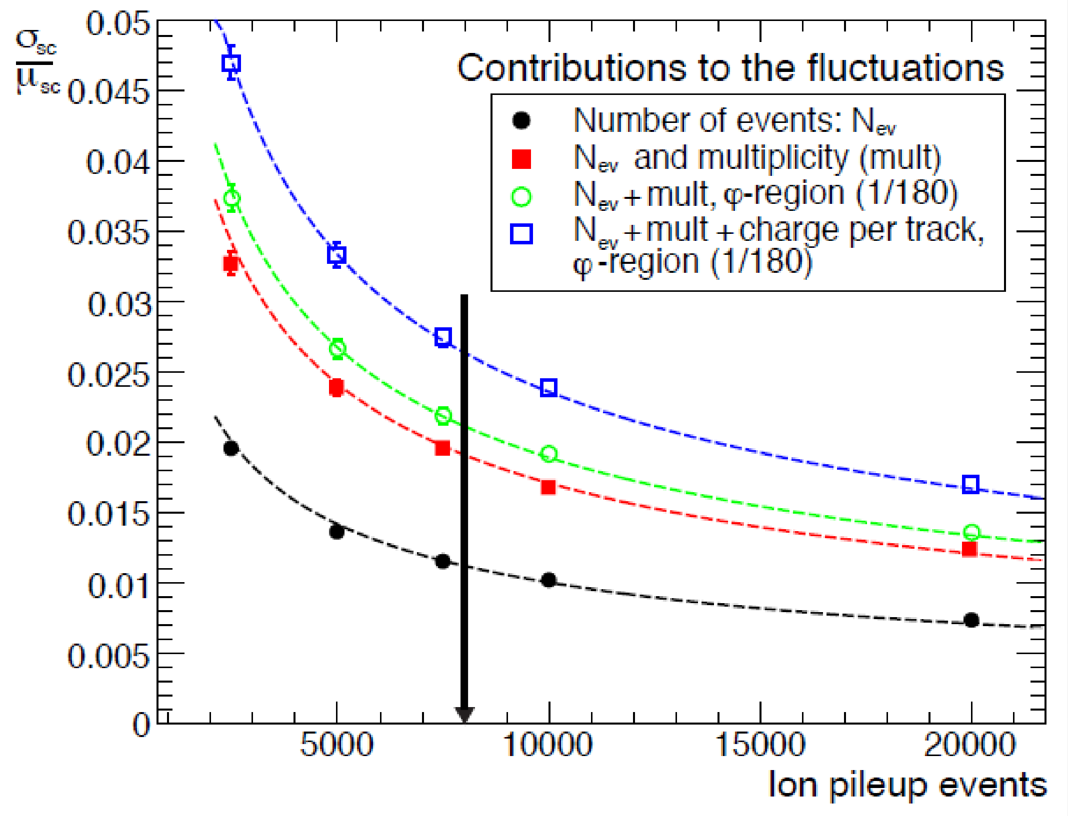


- Space charge estimated from min. bias raw data
- → subject to fluctuations
  - Number of ions piled up in drift volume
  - Event multiplicity fluctuations
  - Track charge fluctuations

$$\frac{\sigma_{\mathrm{sc}}}{\mu_{\mathrm{sc}}} = \frac{1}{\sqrt{N^{\mathrm{ion}}_{\mathrm{pileup}}}} \sqrt{1 + \left(\frac{\sigma_{N_{mult}}}{\mu_{N_{mult}}}\right)^2 + \frac{1}{F\,\mu_{N_{mult}}}\left(1 + \left(\frac{\sigma_{Qtrack}}{\mu_{Qtrack}}\right)^2\right)}$$

Space-charge distortions

Magnitude of distortion fluctuations

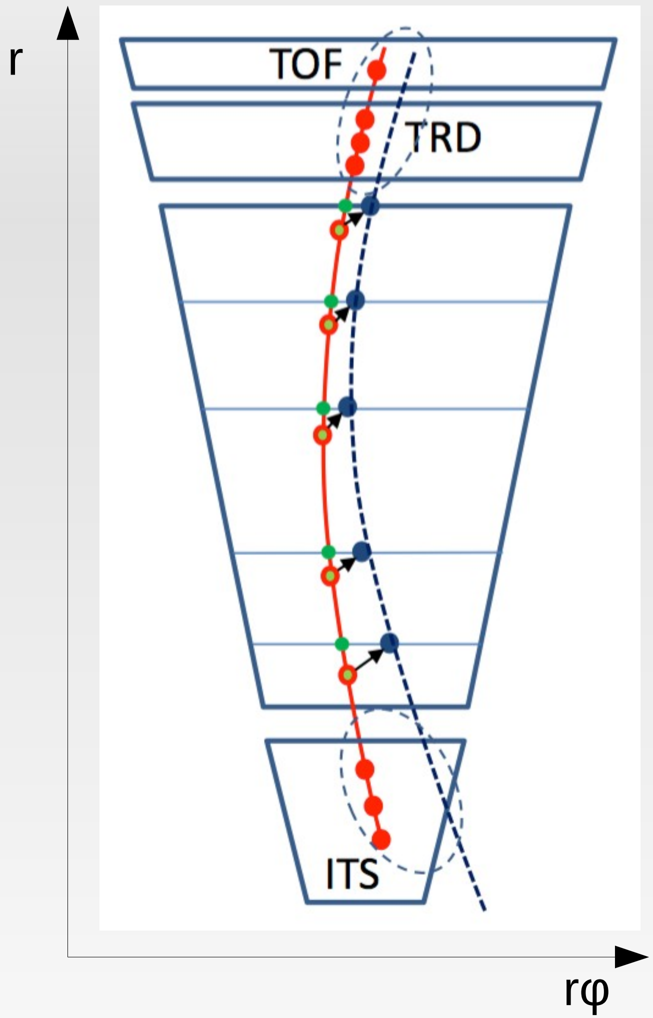


- Space-charge fluctuations at the level of 3%
- With knowledge of the average space-charge density this leads to
  - Max ± 6mm residual distortion in *r*
  - Max ± 2.5mm residual distortion in *rφ*

- Space-charge fluctuations are dominated by event and multiplicity fluctuations
- Must be taken into account for distortion corrections
  - Sets constraints on the update interval → every 5-10ms

Distortion calibration

Average distortion map



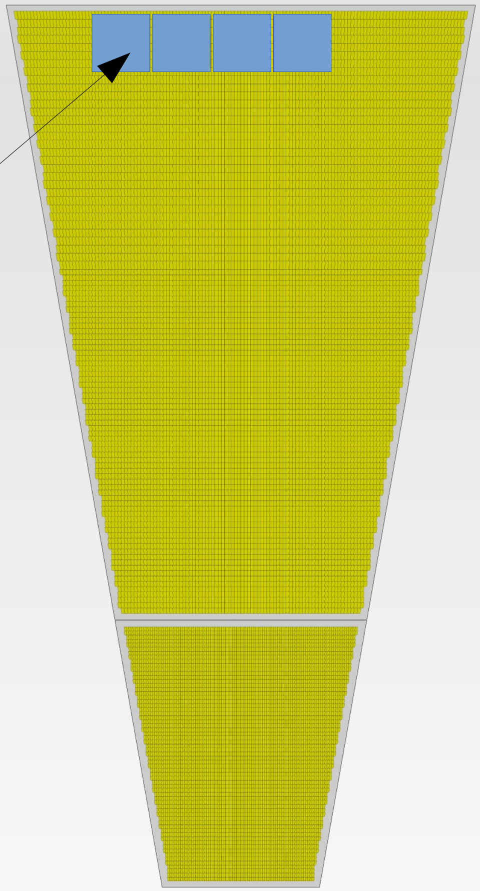
- Refit of ITS, TRD and TOF track segments as reference
- Difference of distorted TPC clusters and reference to extract 3D distortion maps
- Used to calculate “long term” (O(min)) average distortion map

Distortion calibration

Short term fluctuations

- Digital current related to space charge: $n_{tot} = n_{prim} * G * \mathrm{IB}$
  - Assume constant gain and IB over short time scales (O(min))
- Build local average of digital currents in 1ms intervals
- Estimate *SC* density variations and correct for distortion fluctuations

$$\vec{\Delta} = \vec{\Delta}_{\mathrm{ref}} + \sum_i \frac{\partial \vec{\Delta}_{\mathrm{ref}}}{\partial \rho^i_{\mathrm{sc}}} \delta \rho^i_{\mathrm{sc}}$$



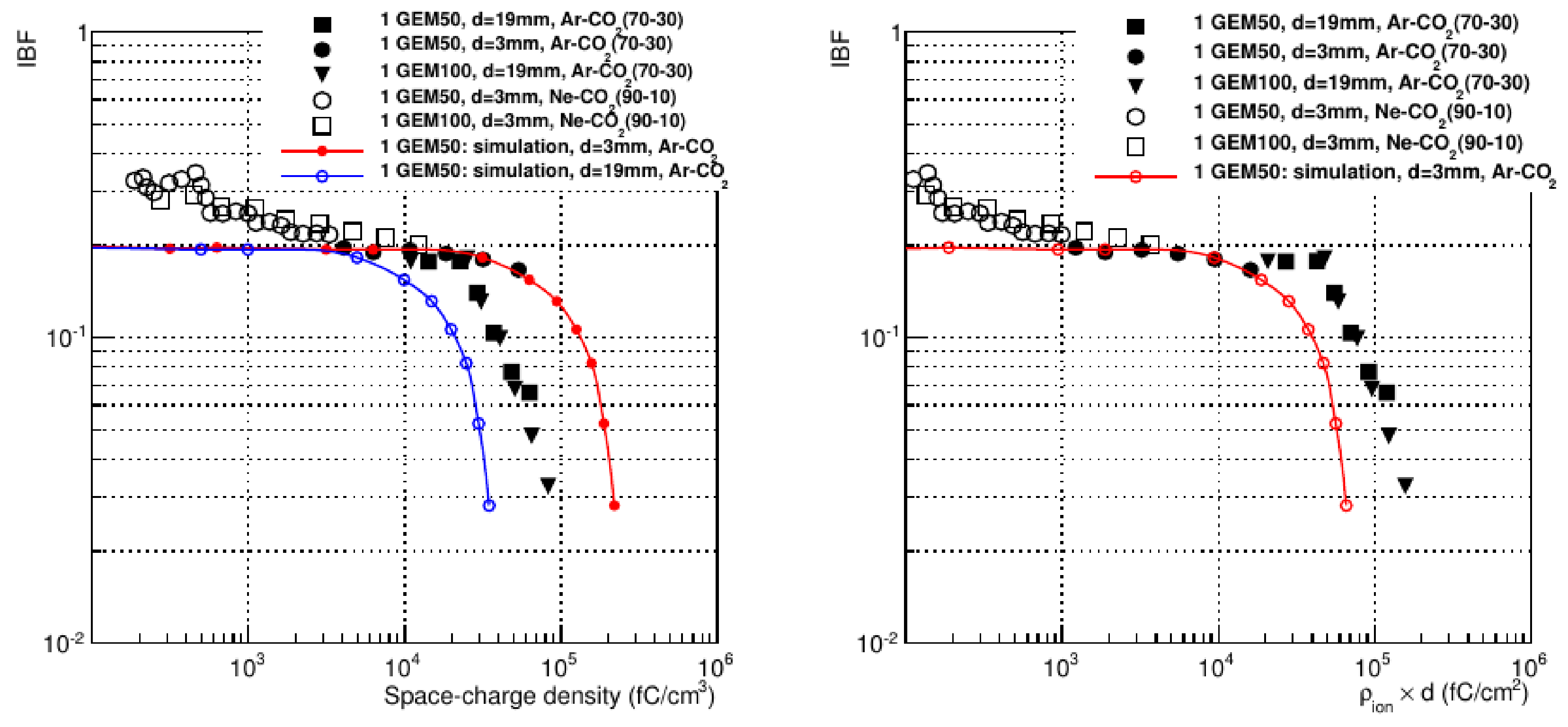
Summary

- The ALICE TPC will be upgraded for continuous readout
- Base line solution: 4-GEM stack (S-LP-LP-S)
  - $\sigma_E/E < 12\%$ for ^{55}Fe
  - $IB < 1\%$ @ gain 2000
  - Low discharge rate (5 trips per GEM stack per Pb–Pb running year)
- Large distortions (up to O(10cm)) expected
  - Calibration scheme developed to correct down to the intrinsic resolution (O(100μm))

Backup

IBF simulations

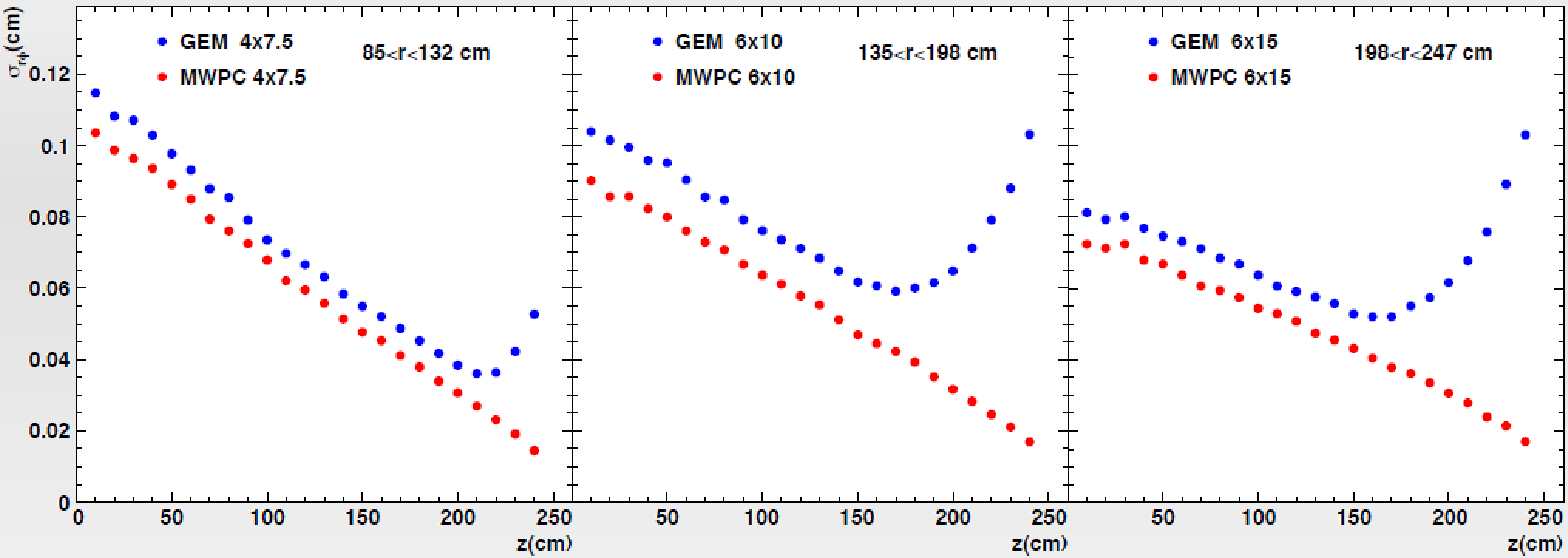
Ionisation dependence

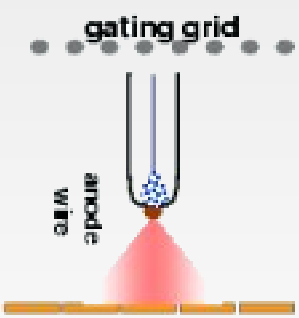


- Dependence of IBF on space-charge density (SCD) observed in measurements
- Trends reproduced well in simulations
  - SCD estimates in measurements coarse estimates
  - SCD in simulations assumed homogeneous
- At high SCD the effective drift field at GEM1 top is decreased
  - More filed lines end on GEM1 top → lower IBF

Intrinsic performance

Space point resolution

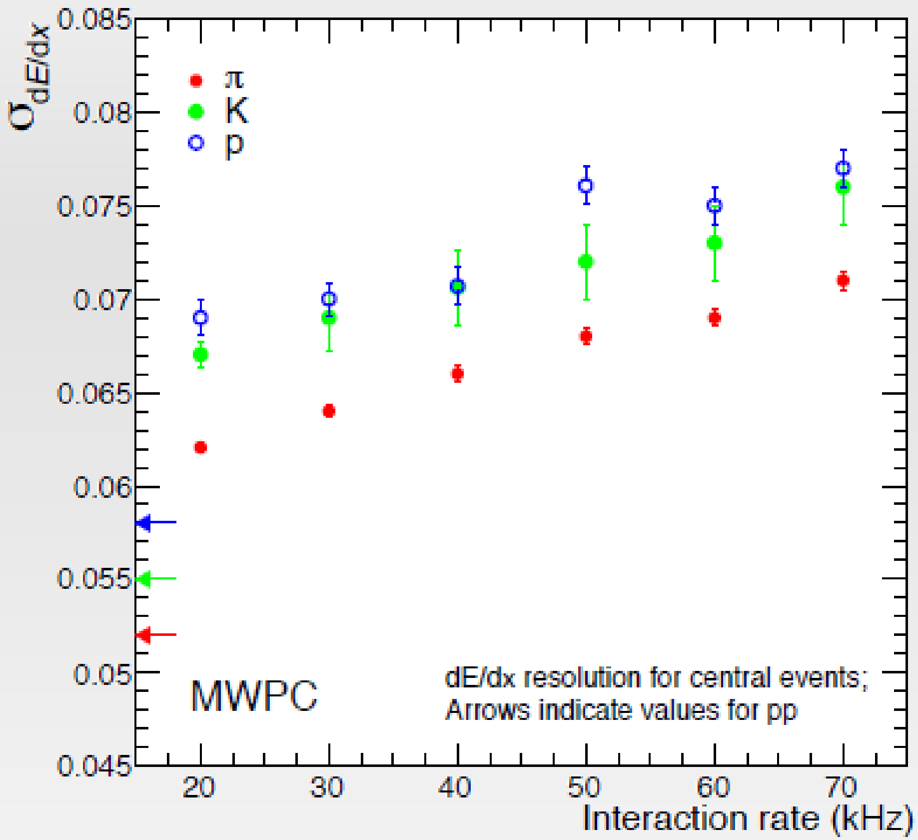


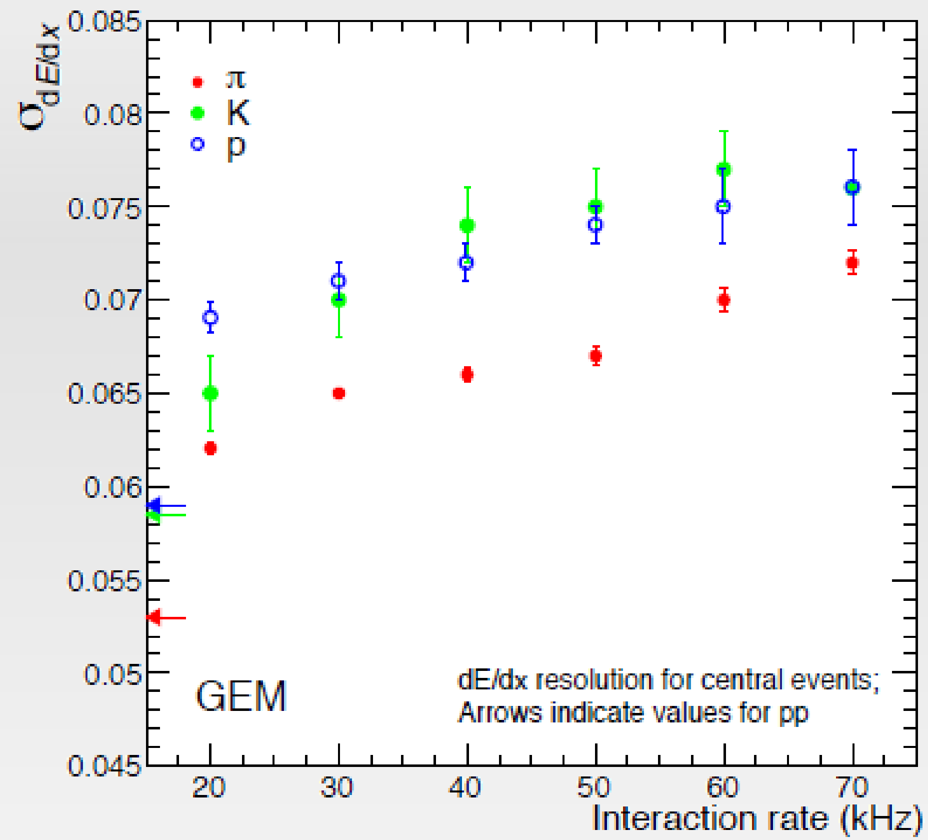


- Optmised Pad Response Function for MWPCs
- PRF of GEMs very narrow → diffusion helps to spread signal over several pads
- Slightly worse overall resolution with GEMs

Performance with pileup

dE/dx resolution

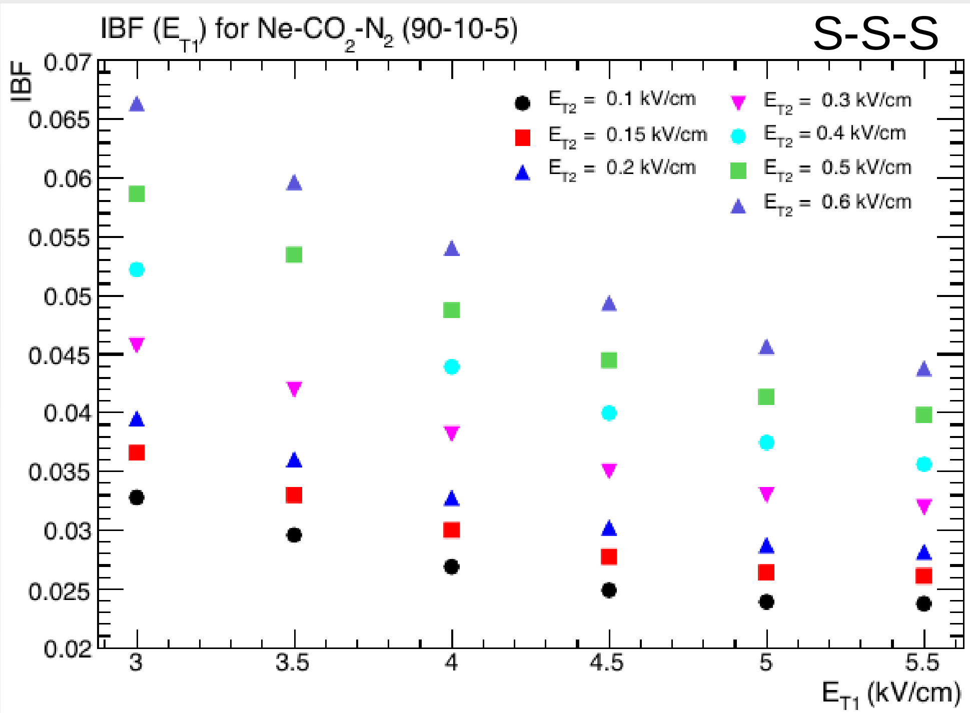


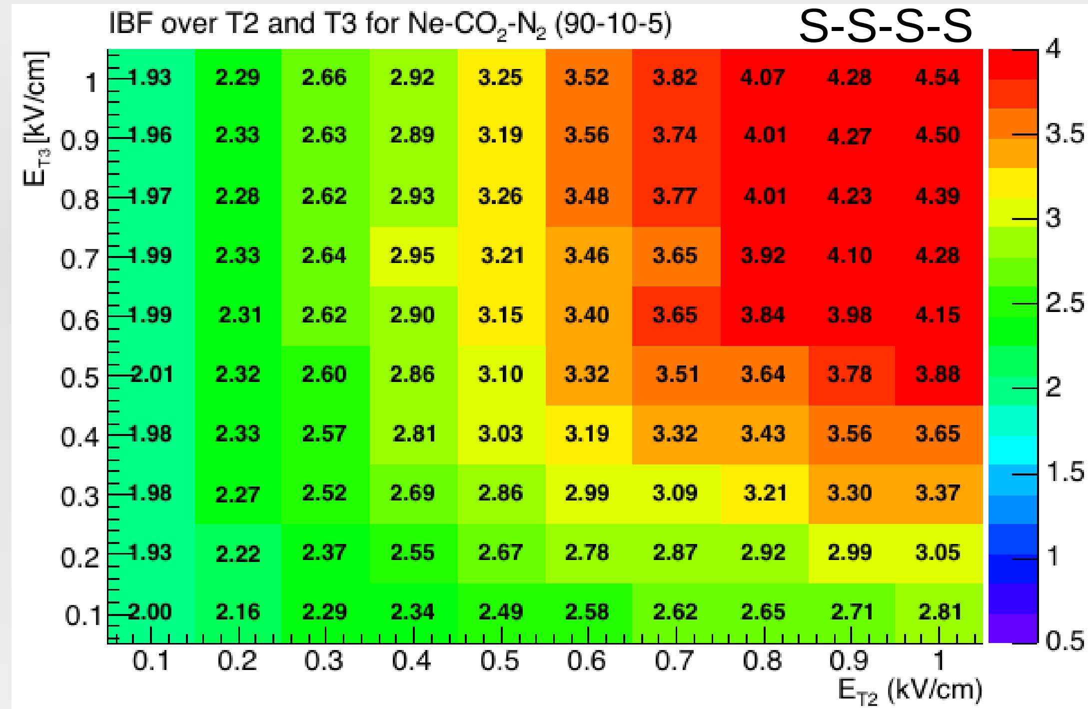


- Moderate worsening with increasing pileup (cluster merging)
- No difference between MWPC and GEM system

IBF measurements

Systematic scans – IBF minimisation

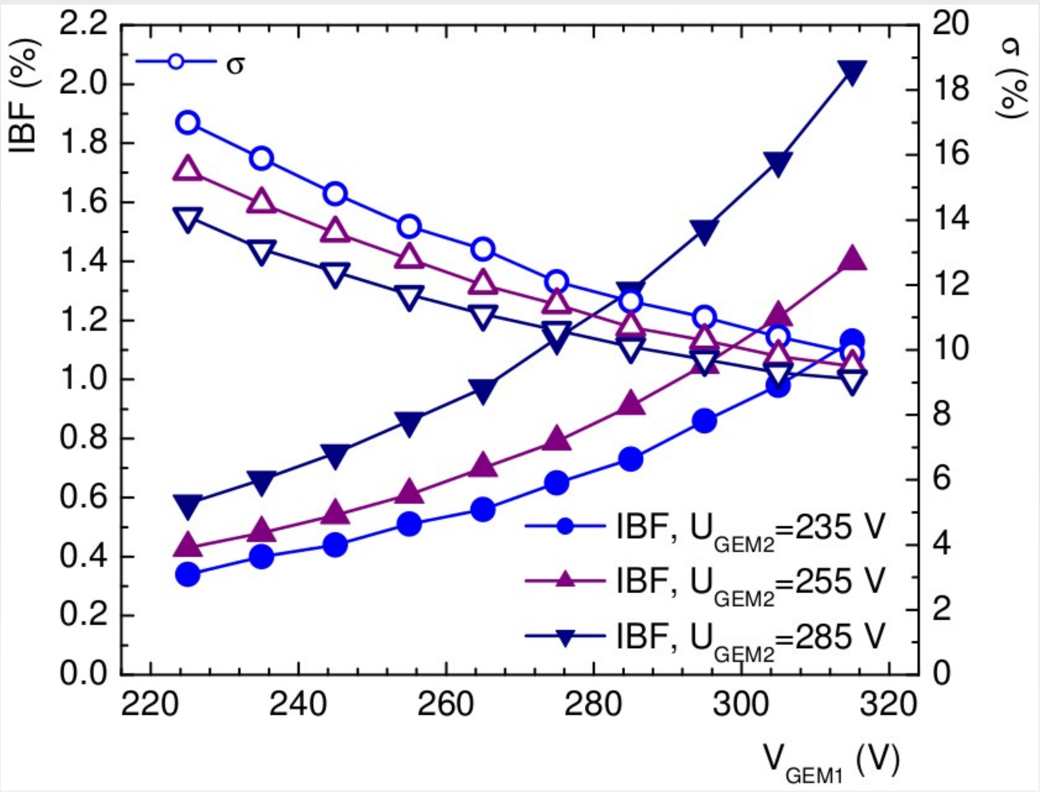




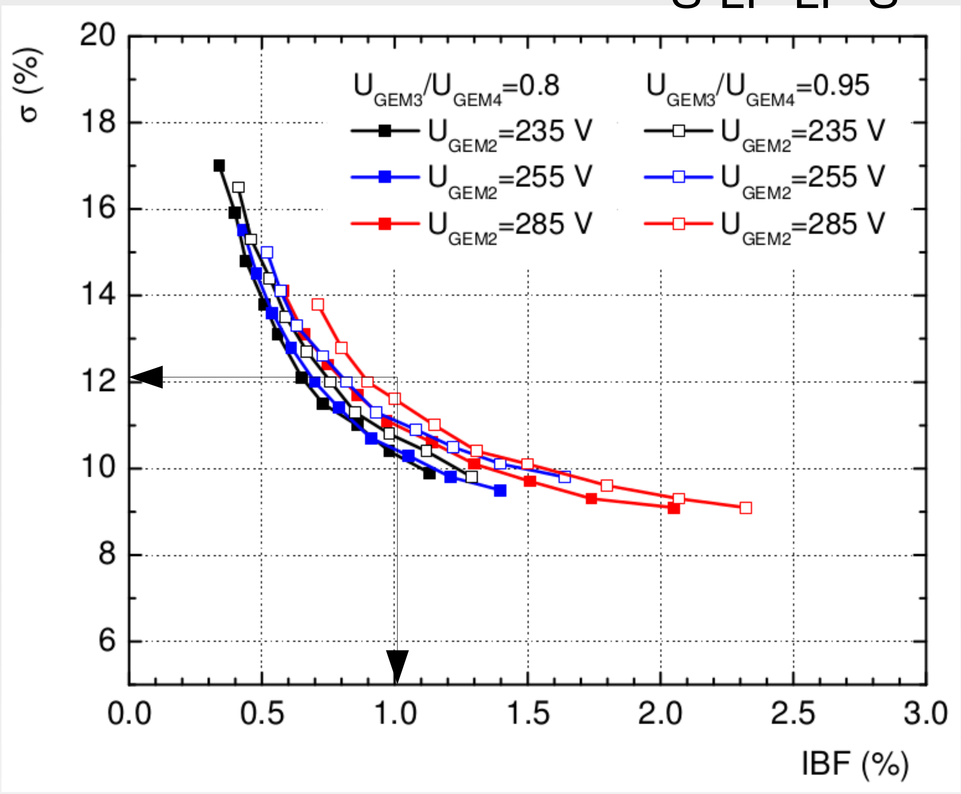
- Large parameter space scanned for triple GEM
  - IBF not lower than ~2.5%
- Move to quadruple GEM stack
  - IBF not lower than ~2% (S-S-S-S configuration)
  - → Test other GEM foil configurations

IBF measurements

Optimisation of IBF and local energy resolution



S-LP-LP-S

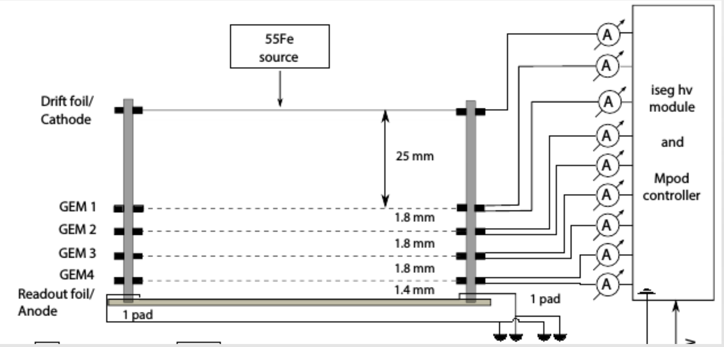


- ^{55}Fe resolution and IBF are competing
  - → always both parameters need to be monitored
- Mainly driven by ΔV_{GEM1}, ΔV_{GEM2}
- Plot variables against each other → show working point region

IBF measurements

Differential picture

	$\varepsilon_{\text{coll}}$	$n_{\text{e,in}}$	M	$n_{\text{e}-\text{ion}}$	$\varepsilon_{\text{extr}}$	$n_{\text{e,out}}$	G	$n_{\text{ion,back}}$	fraction of total IBF (sim.)	fraction of total IBF (meas.)
GEM1 (S)	1	1	14	13	0.65	9.1	9.1	3.6 (28%)	40%	31%
GEM2 (LP)	0.2	1.8	8	12.7	0.55	8	0.88	3.3 (26%)	37%	34%
GEM3 (LP)	0.25	2	53	104	0.12	12.7	1.6	1.3 (1.3%)	14%	11%
GEM4 (S)	1	12.7	240	3053	0.6	1830	144	0.84 (0.03%)	9%	24%
Total				3183		1830	1830	9 (0.28%)		



- Measure currents on all electrode
- Get differential picture of charge transport
- Main contribution to IBF from first two layers
- Main amplification from last layer
- Collection efficiency on first GEM drives the energy resolution