Markov Modeling of Performance Deterioration in irradiated RPCs

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6th DRD1 Collaboration Meeting

Irradiated Resistive Plate Chambers

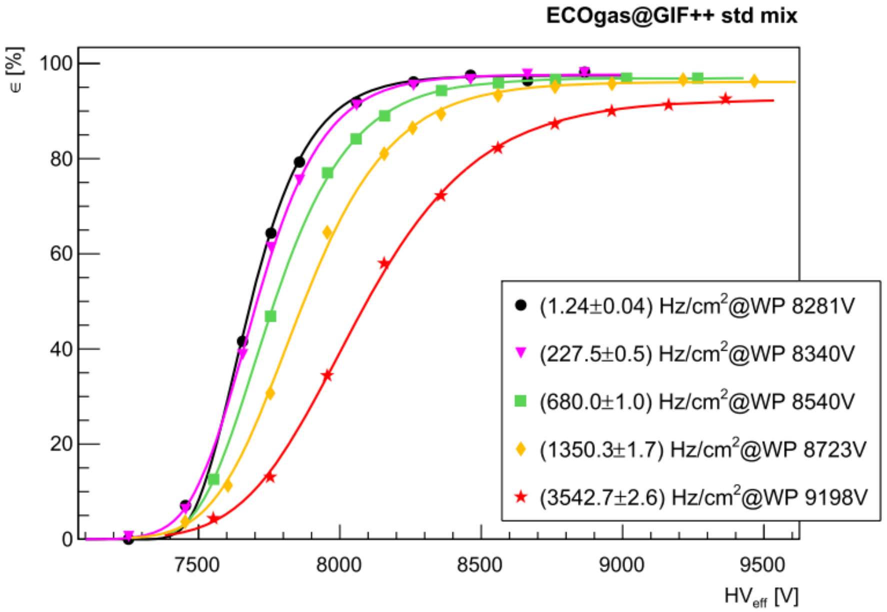


Figure: Efficiency curve deterioration [A]

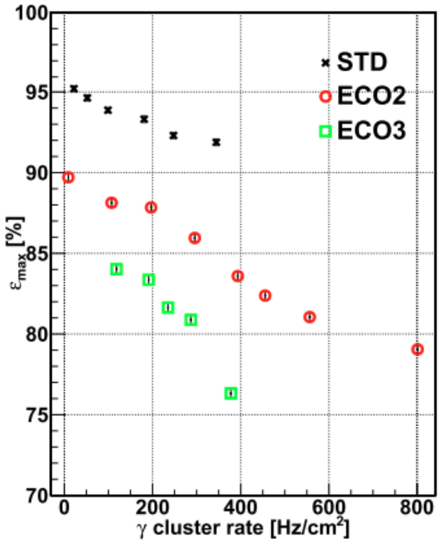


Figure: Plateau reduction for different eco-mixtures [B]

- RPC impinged with background irradiation, e.g.,
  - GIF++ with gamma's
- Rate-induced performance reduction, e.g.,
  - Efficiency plateau
- Estimating *rate capability* of eco-mixtures
  - $\frac{\Delta\varepsilon_{max}}{\Delta\Phi}$ gets worse for eco-mixtures

[A] RPC ECOGas@GIF++ Collaboration: M. Abbrescia, *et al.* 2024 *Eur. Phys. J. C* **84** 605.
[B] RPC ECOGas@GIF++ Collaboration: L. Quaglia *et al.* 2025 *Eur. Phys. J. Plus* **140** 40.

Charge Transport in RPCs

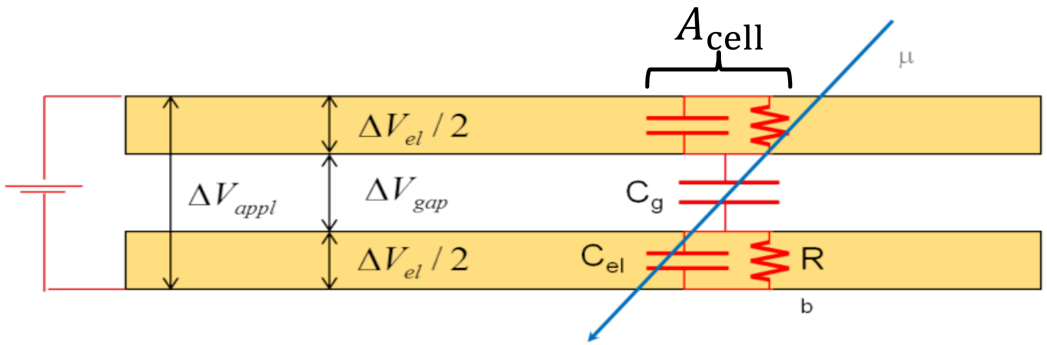


Figure: RPC divided into cells represented by its equivalent circuit [A]

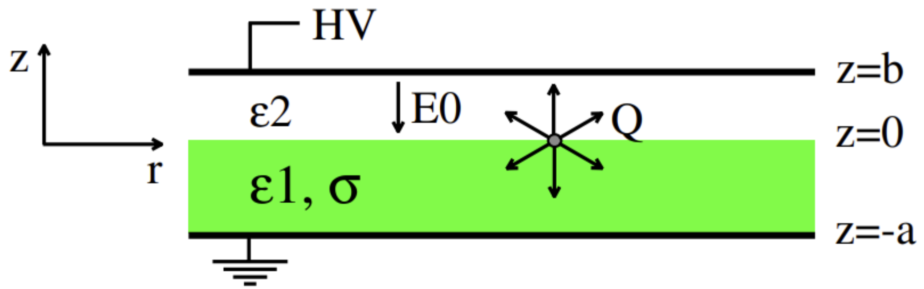


Figure: Charge transport through resistive layer due to point charge [B]

- Charges are removed through resistive elements
- RC equivalent circuit by [A]
  - Artificial cell size dependency
- More realistic setup by [B] with point charge
- Charge deposit is typically modelled linearly

$$\langle Q_{\text{dep}} \rangle = \alpha(V - V_{\text{th}})\theta(V - V_{\text{th}})$$

[A] Marcello Abbrescia 2016 *JINST* **11** C10001
[B] C. Lippmann, W. Riegler, A. Kalweit *Nucl. Physics B* 2006 **158** 127-130

Deterioration of Performance Parameters

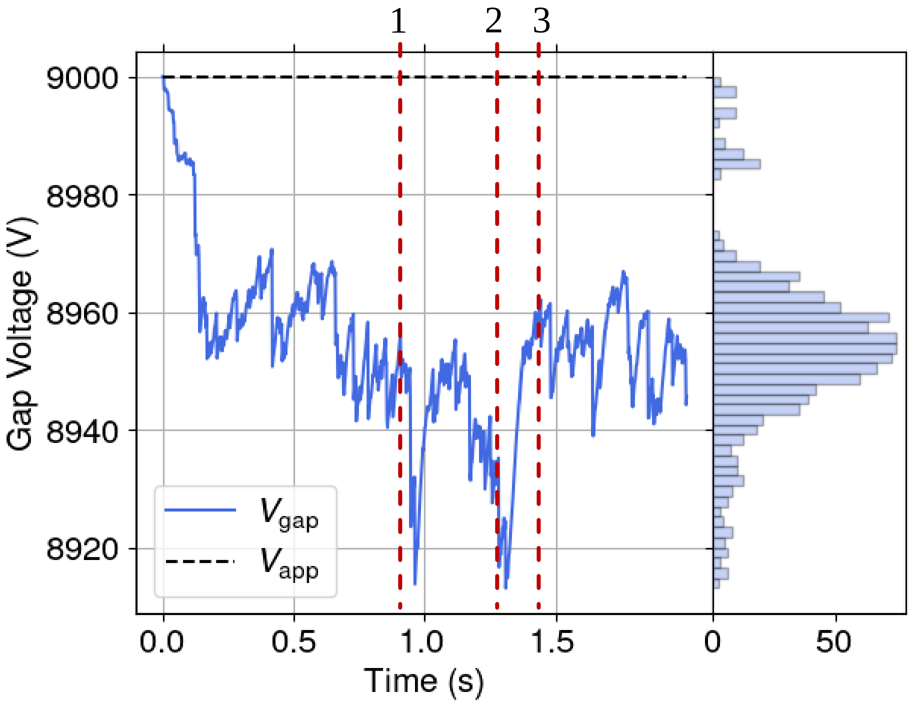


Figure: Example gap voltage time series and spectrum within two seconds. The red lines illustrate events.

- Events *feel* a voltage V_i with probability p_i given by the voltage spectrum
- Detection probability is given by the efficiency at $\varepsilon(V_i, \Phi = 0)$ multiplied by the voltage spectrum:

$$\varepsilon(V_{app}, \Phi) = \sum_i p_i \varepsilon(V_i, \Phi = 0) \underset{\substack{\uparrow \\ \text{continuous}}}{=} \int dV \underbrace{\rho_{V_{gap}}(V; V_{app}, \Phi)}_{\textit{This expression is needed}} \varepsilon(V, \Phi = 0)$$

- Similar for the time resolution etc.

Campbell Theorem

[A]

$$\mathrm{rms}^2_{V_{gap}} = \frac{\rho^2 d^2}{2\tau_g}\frac{\phi}{A}\bar{q}^2\left(1+\frac{\mathrm{rms}_q^2}{\bar{q}^2}\right)$$

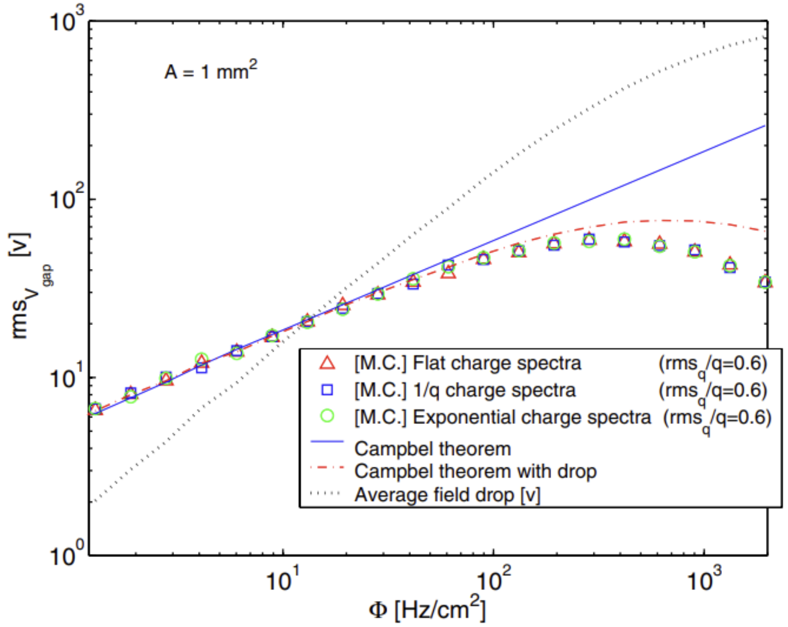


Figure: Rate-dependent field fluctuation comparing MC and equation.

[B]

$$\frac{\Delta E(z)}{\overline{E}} = \frac{1}{\sqrt{2\Phi\tau_2 A(z)}}\sqrt{1+\frac{(\Delta Q)^2}{\overline{Q}^2}}$$

Φ [Hz/cm^2]	100	200	300	400	500
r.m.s. [%]	0.52	0.58	0.66	0.67	0.70
$\frac{\Delta E(z)}{\overline{E}}$ [%]	0.64	0.78	0.85	0.88	0.90

Table: Rate-dependent field fluctuation MC and equation.

- Sum of events → *too much averaging*
- Strong correlation between events (shot-to-shot)

➢ **High-action problem**

[A] D. Gonzalez-Diaz *et al.* 2006 *Nucl. Physics B* **158** 111-117
[B] C. Lippmann, W. Riegler, A. Kalweit *Nucl. Physics B* 2006 **158** 127-130

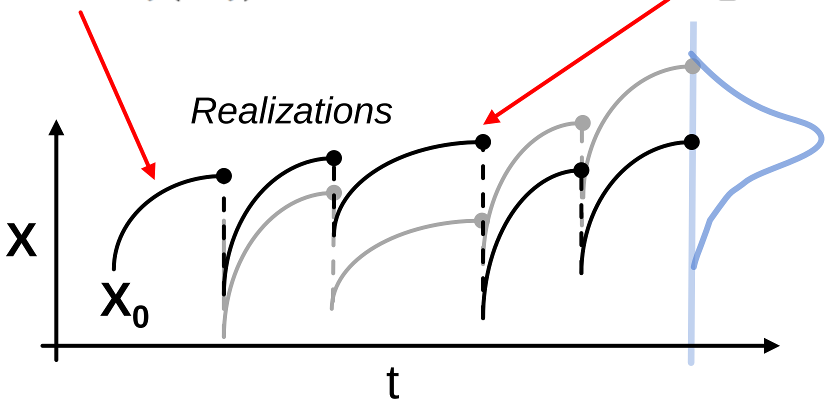
Voltage Spectrum including *Shot-to-Shot* correlation

Piecewise deterministic:

$$\frac{\mathrm{d}\mathbf{X}_t^{(i)}}{\mathrm{d}t} = \Phi_i(\mathbf{X}_t)$$

Markov Process:

$$\mathbf{X}_{t^*} \sim q(\cdot|\mathbf{X}_{t^*_-})$$



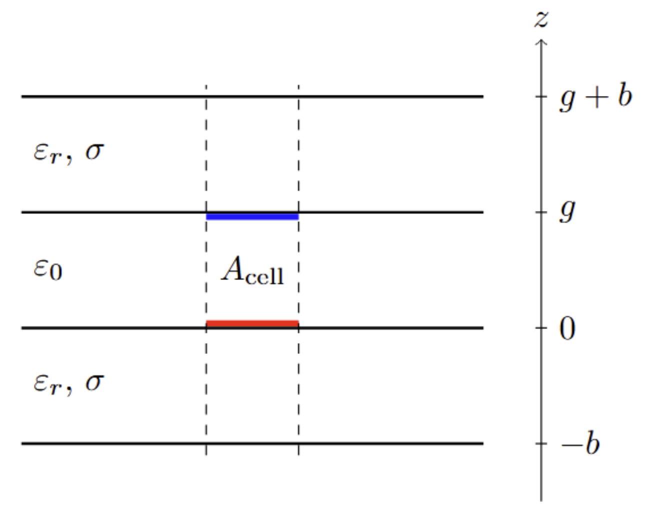
e.g.: $\mathbf{X} = V_{\text{gap}}(\boldsymbol{x})$, $\Phi_i \propto \frac{1}{RC}$, and $q \propto \rho(Q|V_{\text{gap},t^*_-})$

- Piecewise deterministic Markov process (PDMP)
  - Uniform hit-rate ΦA
- **Voltage evolution** with **dependent jumps**
- Shot-to-shot correlation respected
  - Limited by the charge transport model!

➢ DDE for stationary gap voltage spectrum (light blue)

Dario Stocco *et al.* 2025 *EPJ C* submitted for publication

Three-layer single-gap RPC – Field Fluctuations



$$\oplus\ \langle Q_{\mathrm{dep}}\rangle = \alpha(V - V_{\mathrm{th}})\theta(V - V_{\mathrm{th}})$$

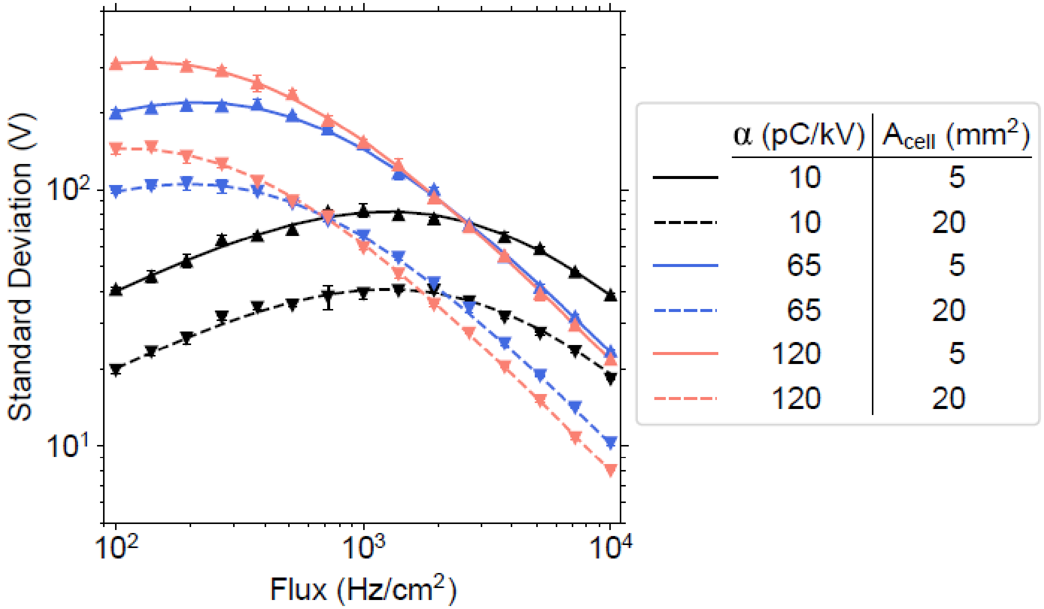
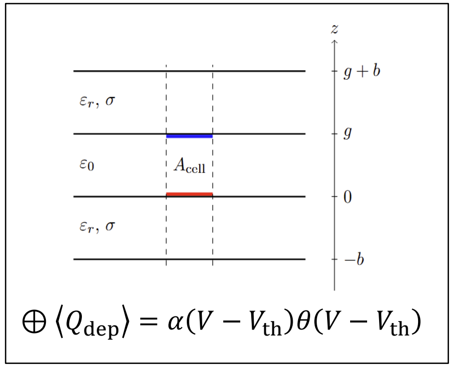


Figure: Gap voltage field fluctuations for different charge slopes and cell sizes.

- Simple for linear model
  - No general closed form expression for arbitrary charge spectrum shapes

- Same values (analytic) as MC (within uncertainty)
  - ➢ Solves high-action problem

Gap Voltage Spectrum



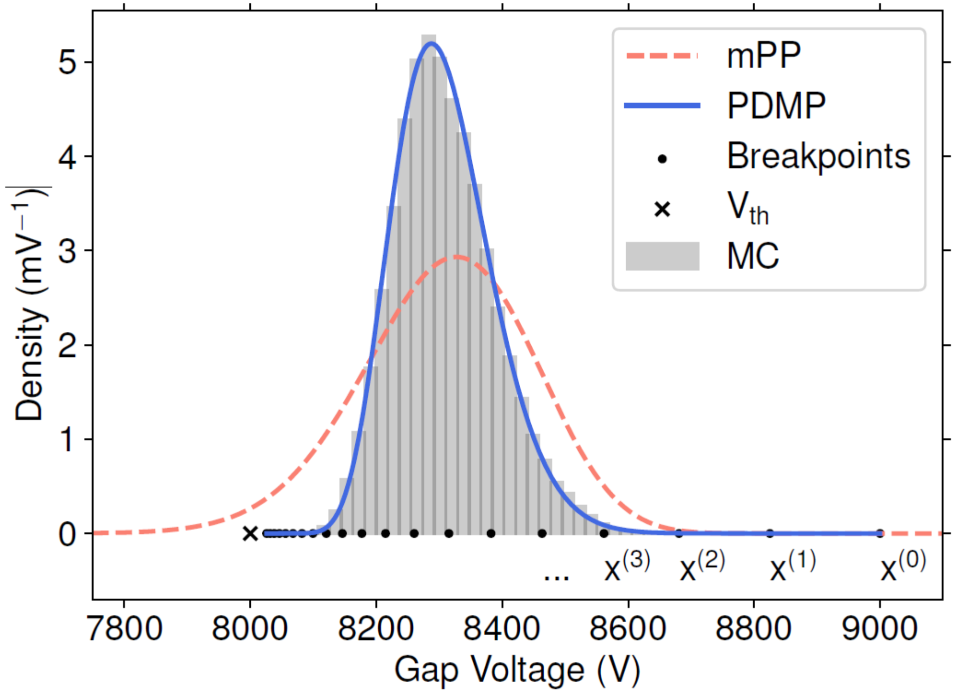
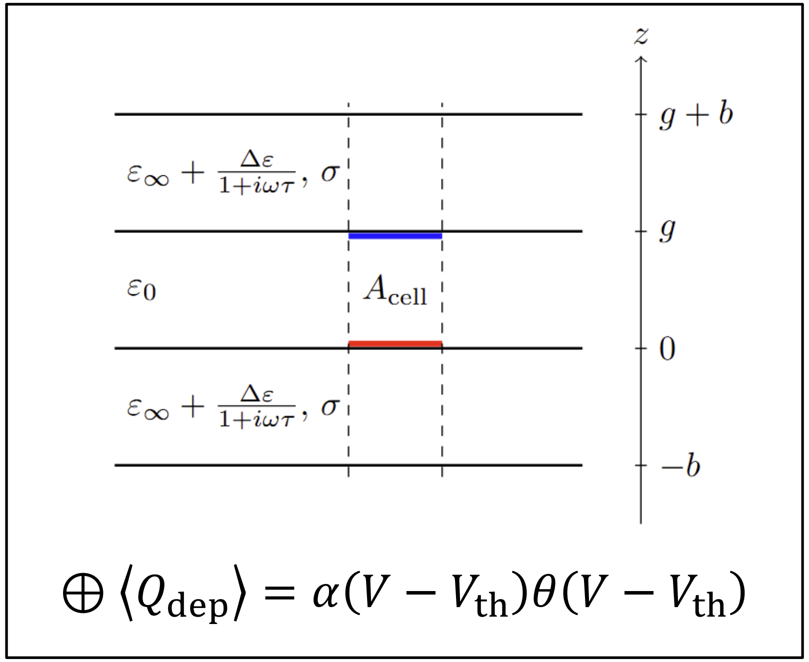


Figure: Voltage spectrum comparison mPP, PDMP, and MC.

- PDMP agrees well with MC
- Campbell theorem (mPP) fails at high rates
- Can be extended to arbitrary charge spectra
- Very fast (up to 100 times)!

Three-layer single-gap RPC – Debye-like Material



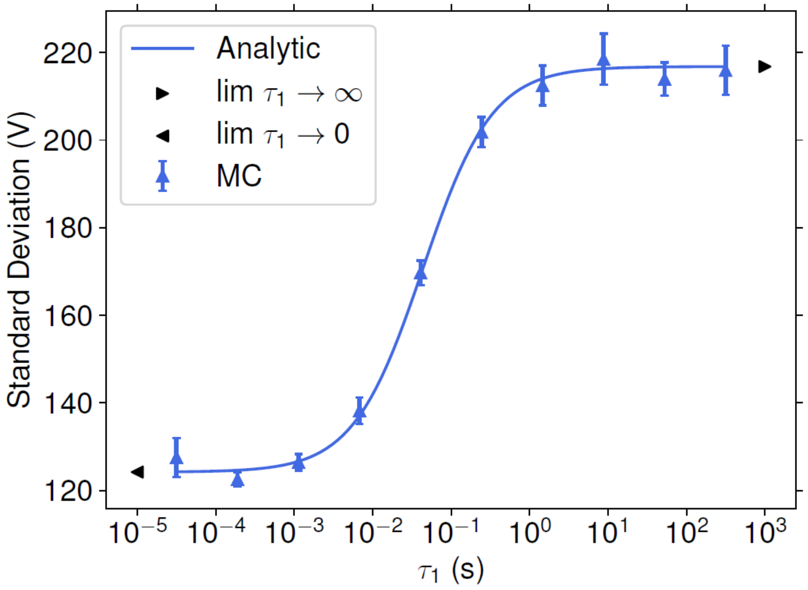
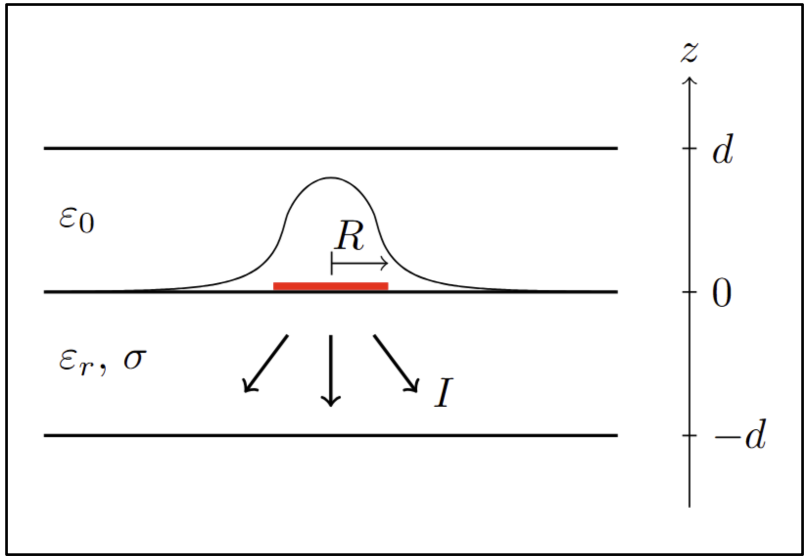


Figure: Gap voltage field fluctuations depending on the relaxation time.

- PDMP could be extended beyond
- Same values (analytic) as MC (within uncertainty)

Two-layer single-gap RPC – 2D Models



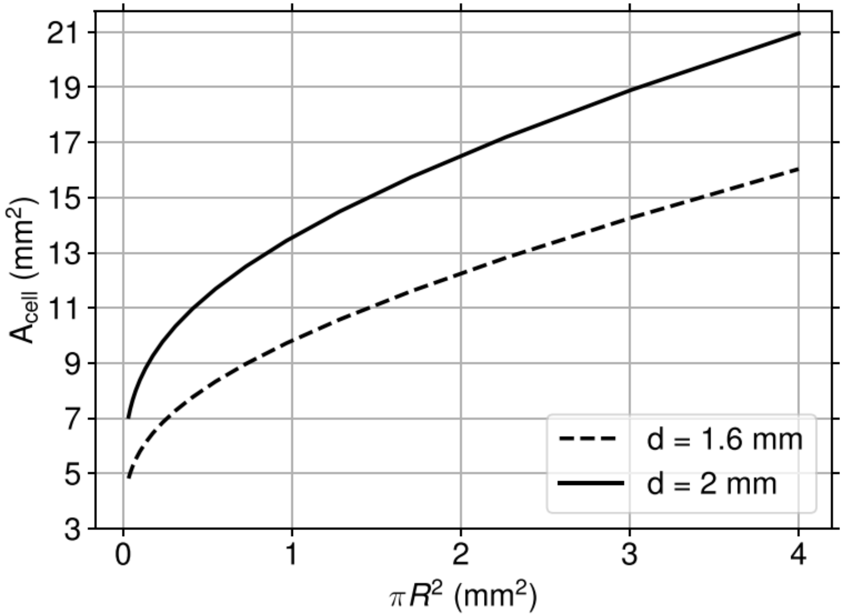
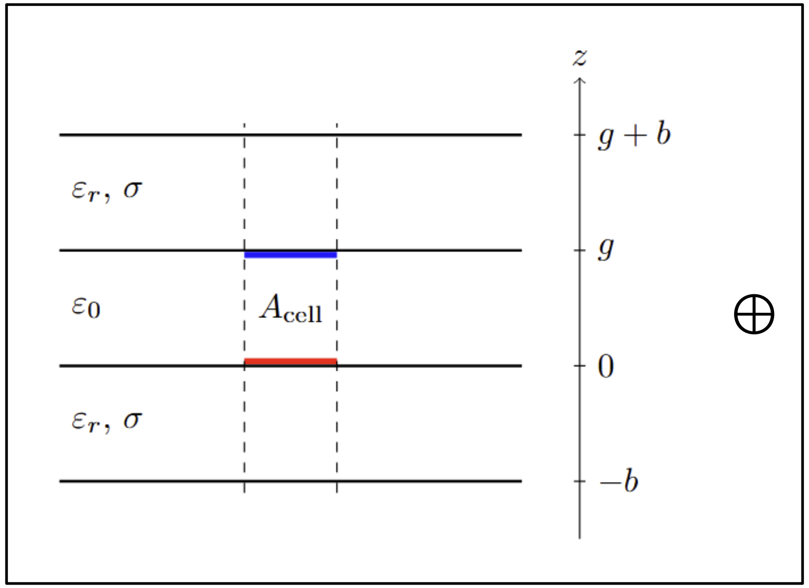


Figure: Relation between cell size and size of charged disk.

- “2D models” - current can flow radially
  - Not entirely clear to define the voltage drop depending on radial coordinate
- Relation to “1D models” via cell size
  - Matching the field fluctuations (1st central moment)

Arbitrary Charge Spectrum – Cesium-137 Source (GIF++)



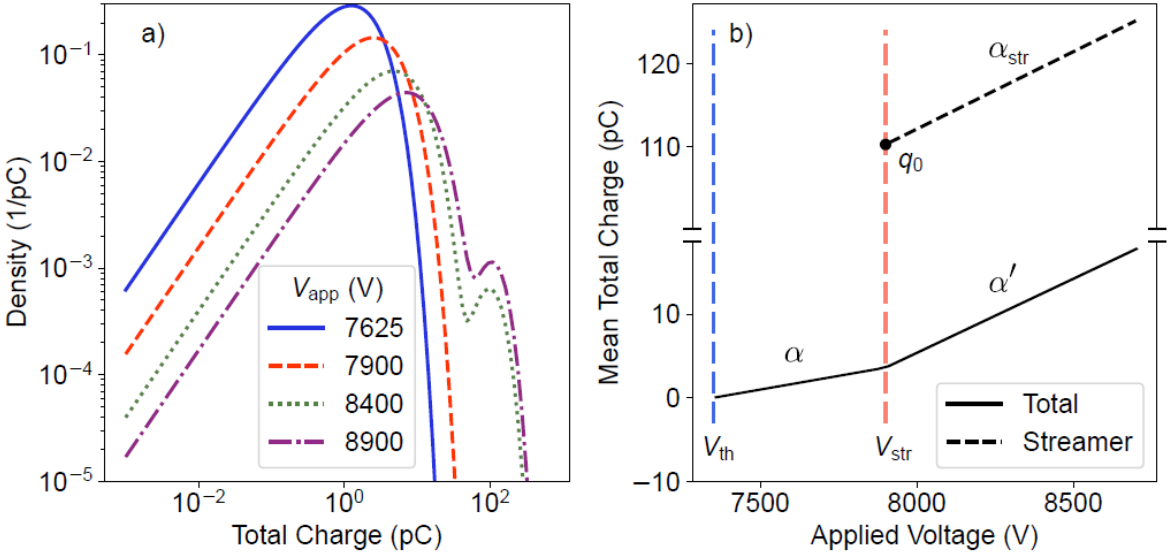
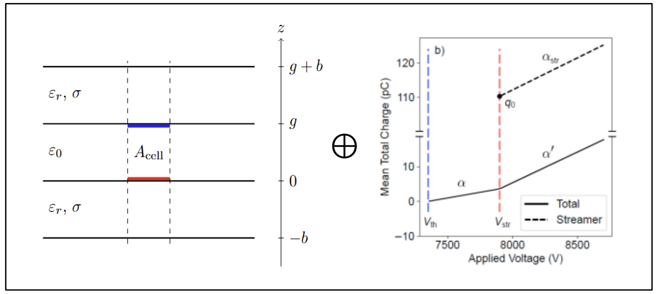


Figure: a) Charge spectrum including large charge events and b) the associated mean charge at no irradiation condition

- Γ – *shape* inspired by Blanco, A. *et al.* (2009) and Fonte, P. *et al.* (2023)
- Mean charge shape inspired by Aielli, G. *et al.* (2000)

Fitting thin-RPC Efficiency – Standard Mixture



ρ	A_{cell}	α	α'	$\Phi_{ABS=22,\ d=3\,m}$	$\Phi_{ABS=22,\ d=6\,m}$
$8.62 \times 10^{10}\,\Omega\,cm$	$37.2\,mm^2$	$5.4\,pC\,kV^{-1}$	$30.0\,pC\,kV^{-1}$	$373\,Hz\,cm^{-2}$	$105\,Hz\,cm^{-2}$

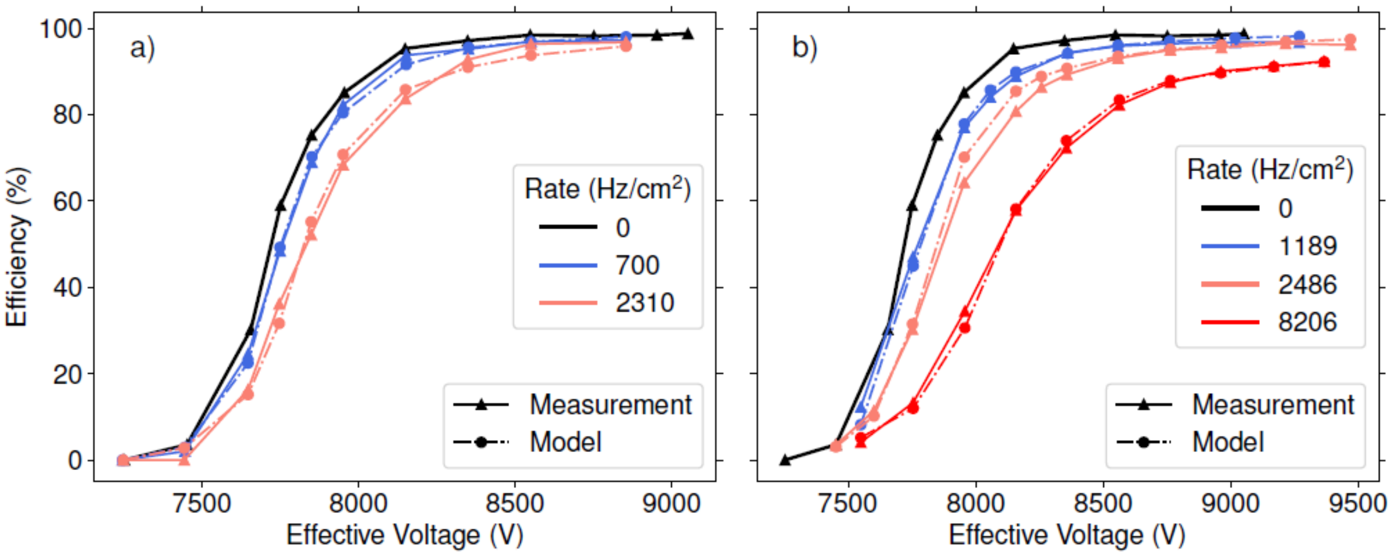


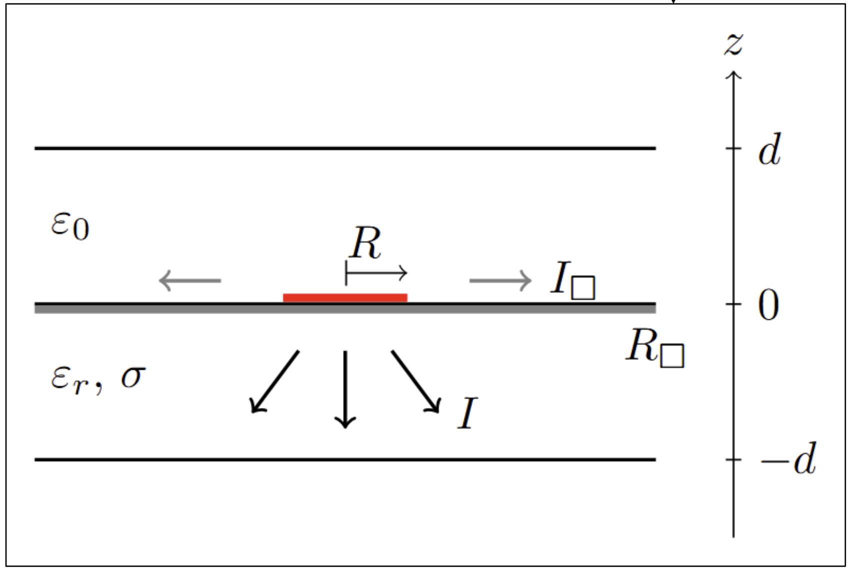
Figure: Efficiency curves at different distances to the gamma source a) 6m, b) 3m. Modeled data (circles), measured data (triangles). Hit rate (converted gammas) in the simulation given in legend.

- Global fit on all data points
- Large cell size: DC Model is valid
  - Deviation expected for small cell sizes (skewed spectra)
- ➢ Streamers are the mechanism reducing the plateau
  - Shape of mean charge deposition is highly relevant
  - Large charges keep gap voltage low and thus the efficiency plateau

Conclusion

Conclusion:

- PDMP incorporates the strong *shot-to-shot* correlation
- Applying PDMP works for various models (1D, 2D) and materials, but is limited (surface resistivities)
- Under the assumption of the gamma charge spectrum, the model fits measurements well
- Streamer contamination reduces the efficiency plateau ⇒ large A-S separation, small streamer charges



Outlook:

- Applying the model to eco-gas measurements subject to aging
- *Do you have any ideas?*

Contact Information

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Bibliography

From slide No 12:

Blanco, A. et al. Efficiency of RPC detectors for whole-body human TOF PET. *Nucl. Instrum. Meth. A,* **602,** 780-783 (2009).

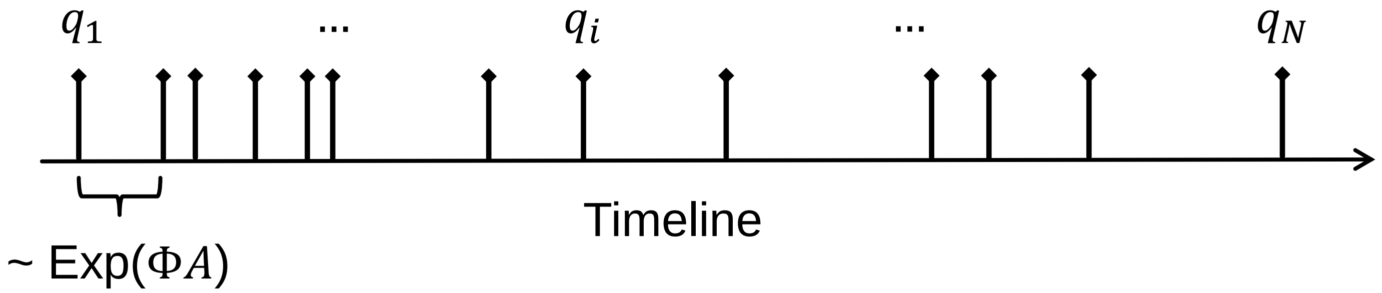
Fonte, P. et al. An RPC-PET brain scanner demonstrator: First results. *Nucl. Instrum. Meth. A,* **1051,** 168236 (2023).

Aielli, G. et al. An RPC γ irradiation test. *Nucl. Instrum. Meth. A,* **456,** 82-86 (2000).

Backup

RPC Multi-Event Modelling in 1D and 2D

Marked Poisson Process:



Campbell's Theorem:

$$\langle e^{k\xi} \rangle = \exp\left(\int_S \mathrm{d}\mathbf{x} \lambda(\mathbf{x}) \left(e^{kf(\mathbf{x})} - 1 \right) \right)$$

$\Rightarrow$

Sum of effects (stochastic):

$$\xi = \sum_i f(\mathbf{x}_i)$$

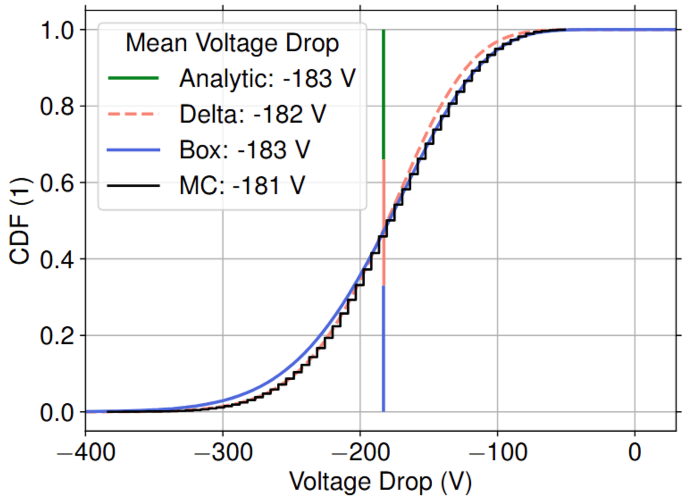


Figure: TODO

Stocco, and Franck, A Semi-Analytical Approach to Modeling Performance Deterioration in Irradiated Resistive Plate Chambers. *J. Phys. D,* under review (2025).

RPC Multi-Event Modelling in 1D and 2D

High-Action problem

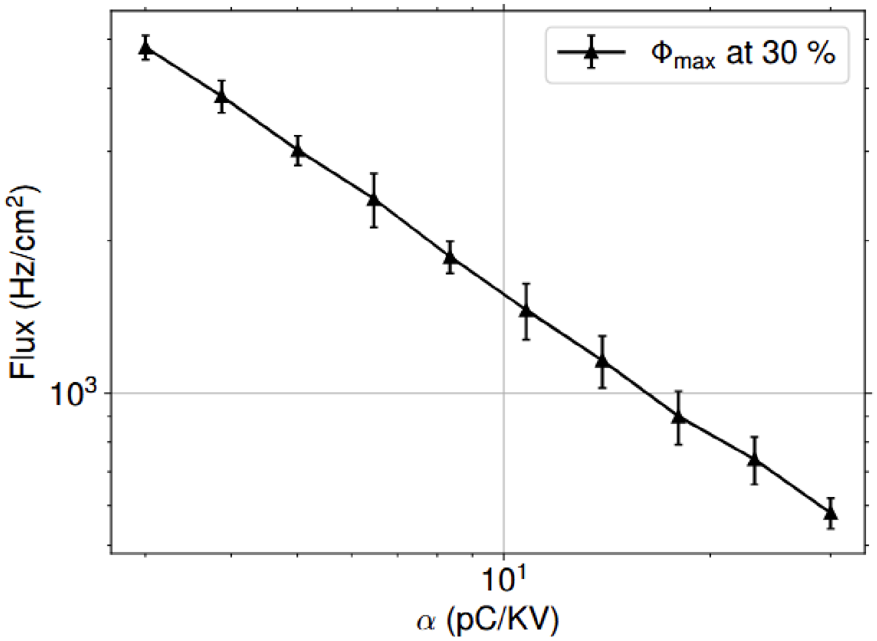


Figure: Flux limit given the charge deposition magnitude.

– At high *action*, the correlation between events is large, e.g., only a **small charge event** can **follow** a **large charge event**

➢ Improvement of the theoretical description

Two-layer single-gap RPC – 2D Model with resistive layer

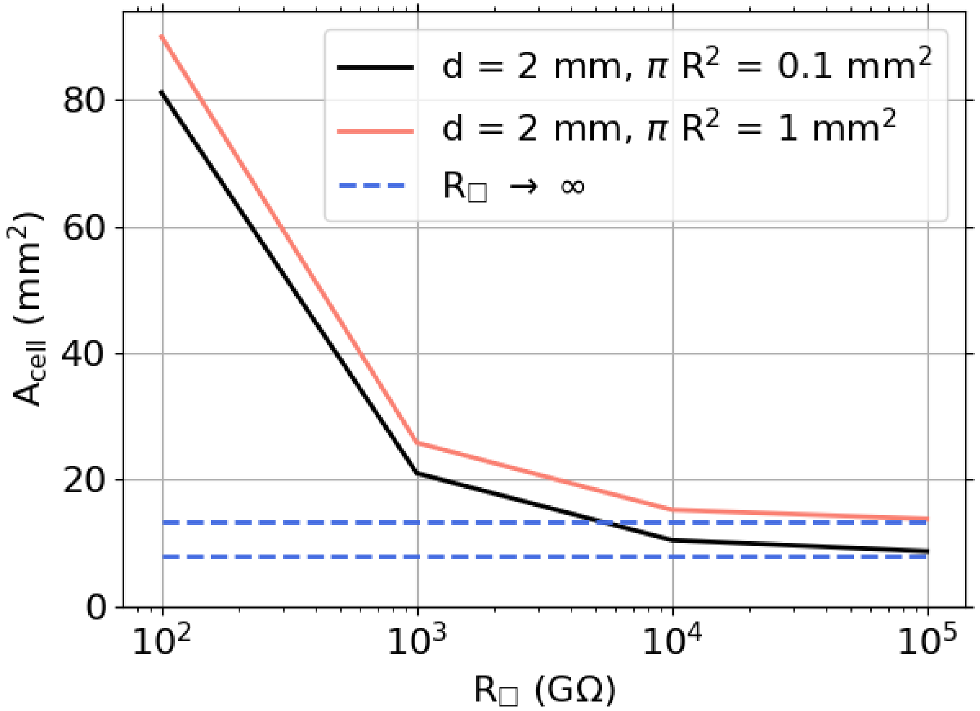
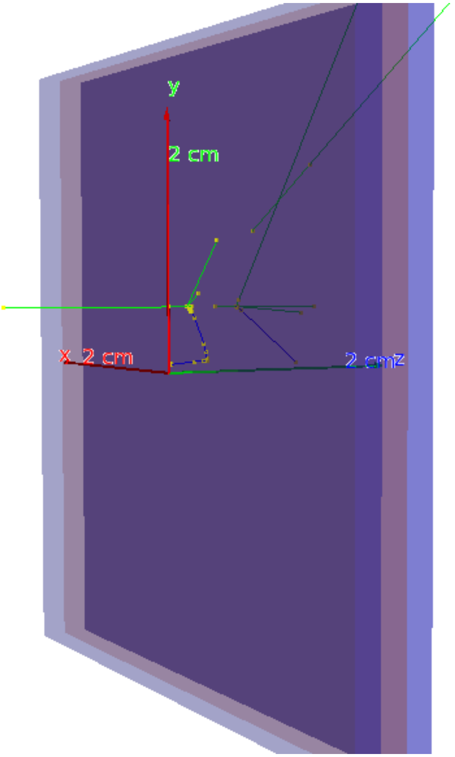


Figure: Cell size representation depending on discharge size and surface resistivity

– Matching the field fluctuations with the single-cell model

➢ The higher the surface conducts, the bigger the cell size
  – Charges remove along surface
  – Mean gap voltage drop remains unchanged
  – Spark quenching gets worse with higher conductivities

Gamma-Ray Interaction with RPC



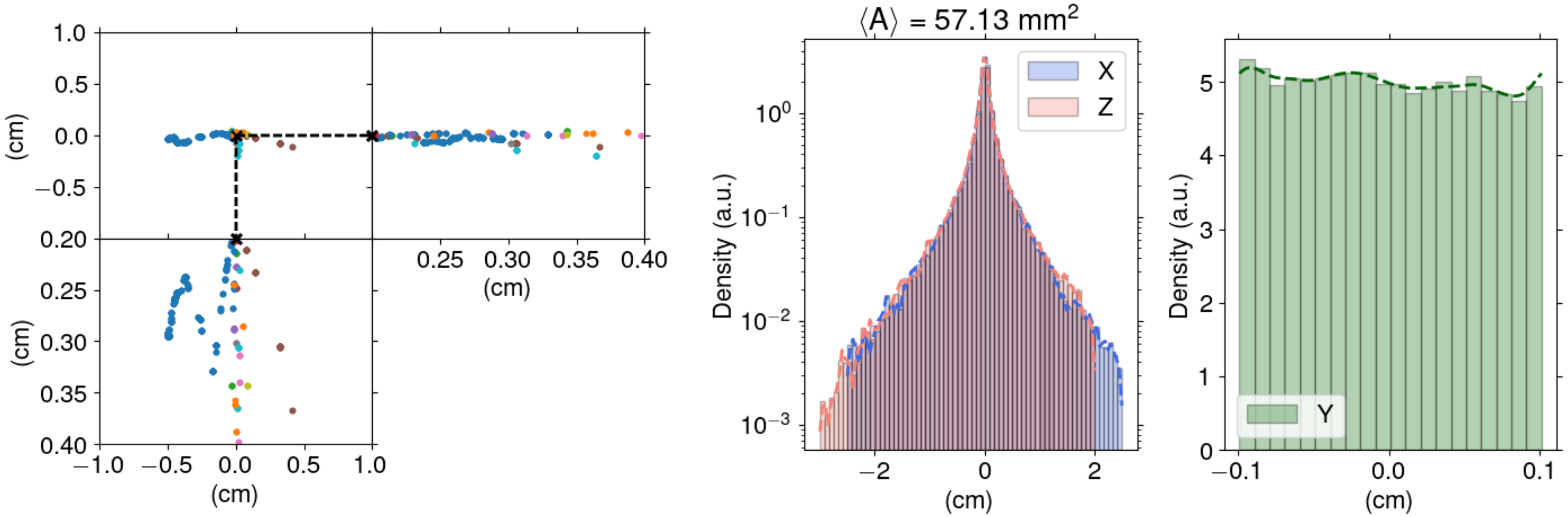


Figure: left: Spread of electrons, right: lateral spread of electron distribution & mean covered area (on top)

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- Spread of thermalized electrons can be relatively large

Fitting without Streamer Contribution