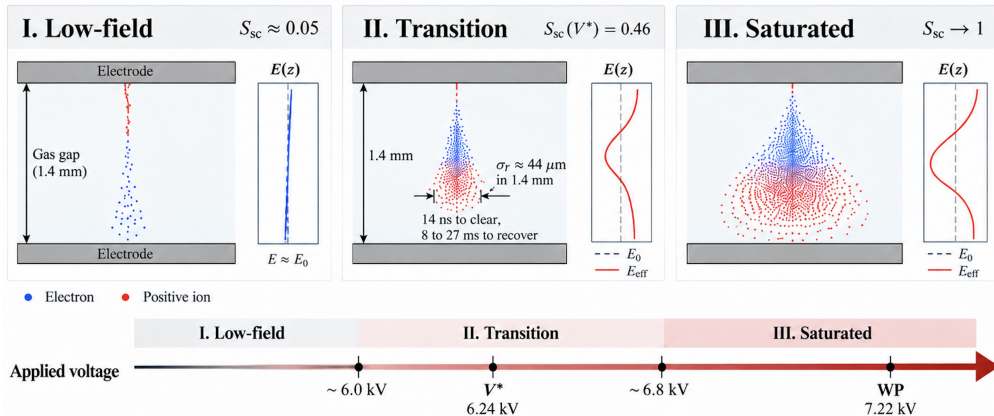

Dynamic Multiscale Simulation of Avalanche-Induced Field Perturbations in RPC Detectors

Victor Olenin Ramírez Beltrán
Universidad Iberoamericana

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- The standard chain splits at the gas: space-charge feedback never crosses from Geant4 into Garfield.¹
- The turn-on curve says nothing about feedback, so every new gas mixture needs its own beam campaign.



¹Resistive plate chambers: Santonico and Cardarelli 1981. Space-charge regimes: Lippmann and Riegler 2004. Working-point convention: Abbrescia, Peskov, and Fonte 2018, ch. 3. Measured chamber: Pinheiro 2025.

Simulation

- 81 voltage states, 5900 to 7500 V in 20 V steps.
- 20 000 events per state.
- Space-charge feedback resolved within each avalanche; no residual field is carried between events.
- Compared against a measured 1.4 mm double-gap RPC, standard mixture, 60 fC threshold.

Observables and test

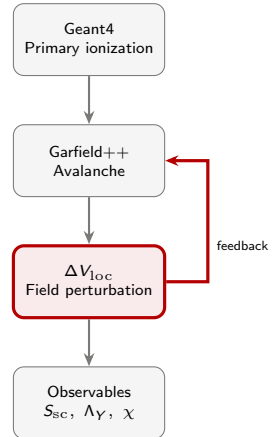
$\langle \Delta V_{\text{loc}} \rangle$	local field perturbation
S_{sc}	space-charge suppression
Λ_Y	field sensitivity of the yield
$\chi = dS_{\text{sc}}/dV$	feedback susceptibility

Locate $V^* = \arg \max_V |\chi|$, bootstrap its confidence region, and test it against the stencil width.

If feedback governs the transition, S_{sc} should saturate and χ should show a single, well-localized maximum that remains stable under the stencil. That voltage would characterize the avalanche dynamics and need not coincide with V_{50} .

Carrying the Perturbation Across the Chain

- Geant4 delivers the primary ionization event by event; Magboltz supplies α , η , and v_d for each of the 81 voltage states.
- Each avalanche is developed with its own space charge, and the resulting E_{sc} acts back on the field it grows in. This is the step the standard chain leaves out.
- Detection is frozen: $q_{rec} = eN_+ / (\alpha L_{eff})$ per gap; the chamber fires if either gap crosses 60 fC.
- Two productions on the same grid: muons and muons plus γ , with 1.62×10^6 events each.



$$HV_{eff} = V_{applied} / 0.98358 \text{ at } 969.7 \text{ mbar and } 293.15 \text{ K.}$$

Locating the Scale, and Bounding It

The estimator

S_{sc} is sampled on the 81-state grid, 20 V apart. Its derivative is taken with a symmetric stencil of half-width h , and quoted per 100 V:

$$\chi(V) = \frac{S_{sc}(V+h) - S_{sc}(V-h)}{2h}.$$

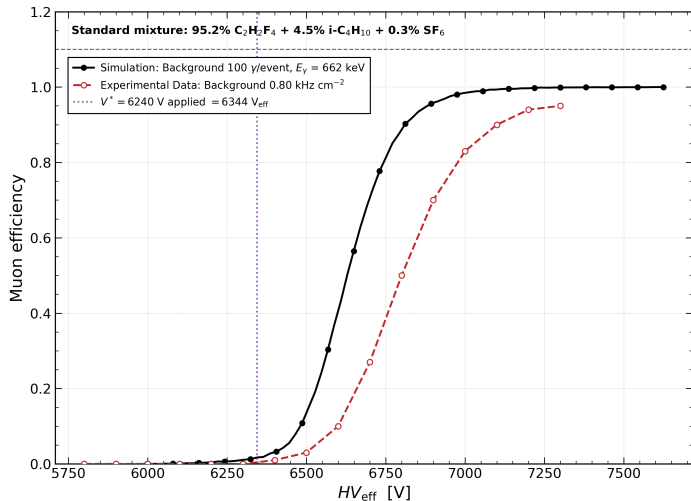
The scale is $V^* = \arg \max_V |\chi(V)|$. Two stencils are used, $h = 20$ V and $h = 40$ V: the wider one is smoother and more biased, the narrower one noisier and less biased.

The bound

- The resampling unit is the *event*, not the voltage point: avalanches inside one event share a primary and are correlated.
- Each replica yields its own $\chi(V)$ and its own $\arg \max$.
- The quoted region is the 95% quantile of that $\arg \max$ distribution. It is not a fit error bar, and it does not assume a peak shape.

A maximum that survives both stencils, and whose bootstrap region is narrower than the transition it sits in, is a property of the chamber. One that moves with h is an artifact of differentiating noise.

The feedback transition precedes detector turn-on



The chamber turns on after the feedback transition has already taken place.

$$V_{eff}^* = 6344\text{ V}$$

$$V_{50} \text{ (measured)} = 6.80\text{ kV}_{eff}$$

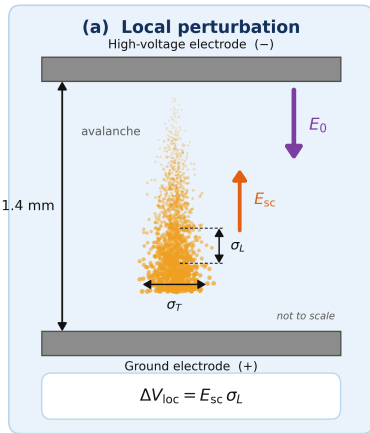
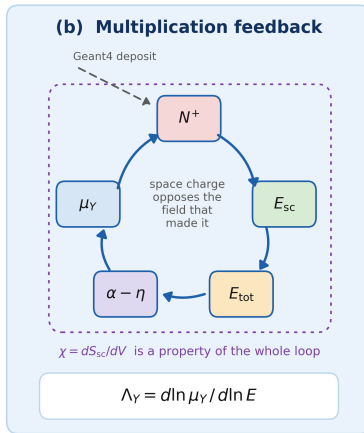
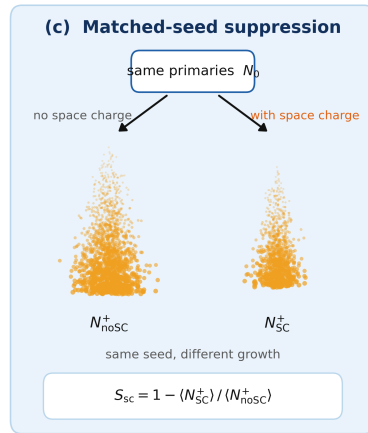
$$V_{WP} \text{ (measured)} = 7.22\text{ kV}_{eff}$$

$$V_{50} - V_{eff}^* = 456\text{ V}$$

$$V_{WP} - V_{eff}^* = 876\text{ V}$$

The simulated turn-on lies 171 V below the measured one. That offset does not enter the extraction of V^* , which is obtained independently from the shape of $S_{sc}(V)$. Measurements from Pinheiro 2025.

What we measure, and how



at $V^* = 6240$ V

$\sigma_T = 43.6 \mu\text{m}$

$\sigma_L = 34.9 \mu\text{m}$

$\langle \Delta V_{loc} \rangle = 22.3$ V

$\langle |E_{sc}|/E_0 \rangle = 14.1\%$

$\Lambda_\gamma = 70.65$

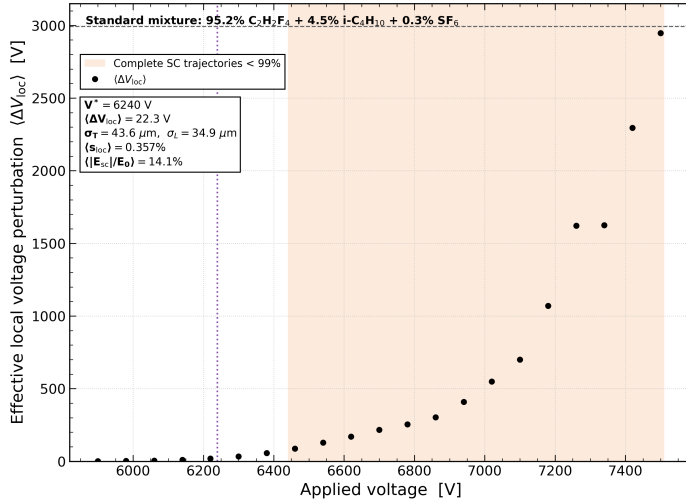
$\Lambda_{tr} = 66.07$

$S_{sc} = 0.464$

The perturbation becomes dynamically relevant

Results The Perturbation Becomes Dynamically Relevant

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At V^* the space-charge field is no longer a correction to the applied field. It is a fraction of it.

$$\langle \Delta V_{loc} \rangle = 22.3 \text{ V}$$

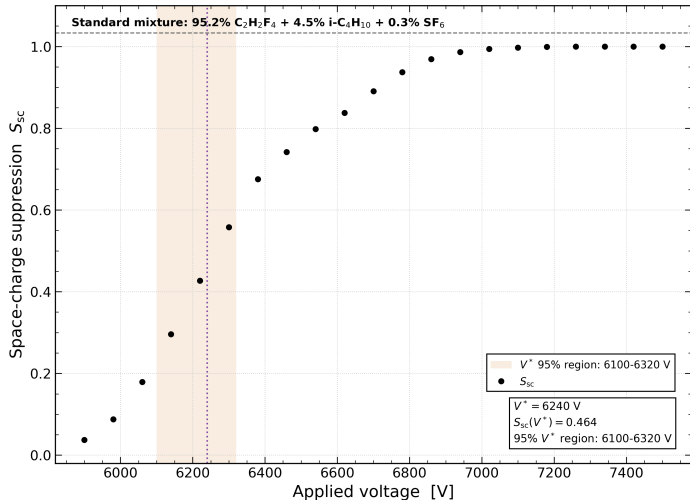
$$\langle |E_{sc}|/E_0 \rangle = 14.1\%$$

$$\sigma_T, \sigma_L = 43.6, 34.9 \text{ } \mu\text{m}$$

The perturbation stays localized on the diffusion scale, well below the gap. It is small in extent and large in effect.

The shaded region marks incomplete-avalanche coverage and is not interpreted.

Space-charge feedback saturates before operation



The suppression is not a threshold. It is a transition with a beginning, a middle and an end.

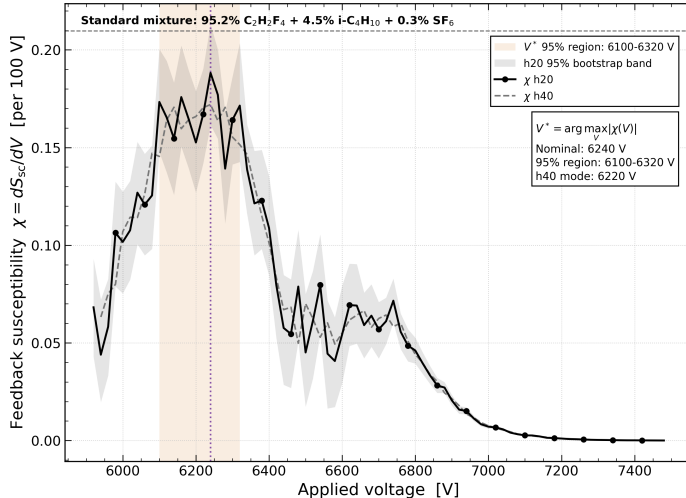
$$\begin{aligned} S_{sc} &\simeq 0 \\ &\downarrow \\ S_{sc}(V^*) &= 0.464 \\ &\downarrow \\ S_{sc} &\rightarrow 1 \end{aligned}$$

V^* falls near the midpoint of that transition, not in its saturated regime. The natural question is where the transition is steepest.

A single feedback scale emerges

Results A Single Feedback Scale

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The rate of change of the suppression has a maximum, and that maximum is a property of the chamber, not of the readout.

$$\chi = dS_{sc}/dV$$

$$V^* = \arg \max_V |\chi(V)|$$

$$V^* = 6240 \text{ V}_{\text{applied}} = 6344 \text{ V}_{\text{eff}}$$

95% region 6100 to 6320 V

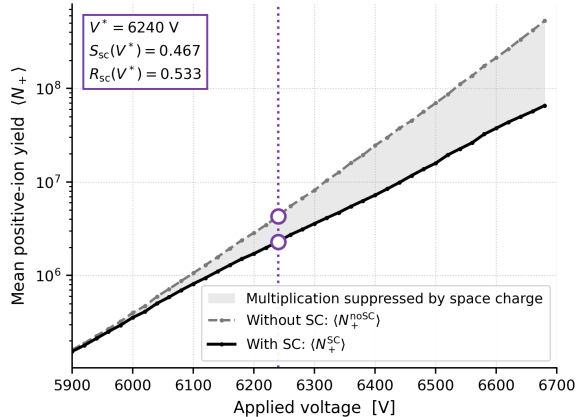
Above 6400 V individual avalanche records are truncated, so absolute yields there are lower bounds. Ratios are far less affected, since both branches carry the same truncation. V^* and its confidence region lie below this voltage.

The cost of omitting the feedback

Results A Single Feedback Scale

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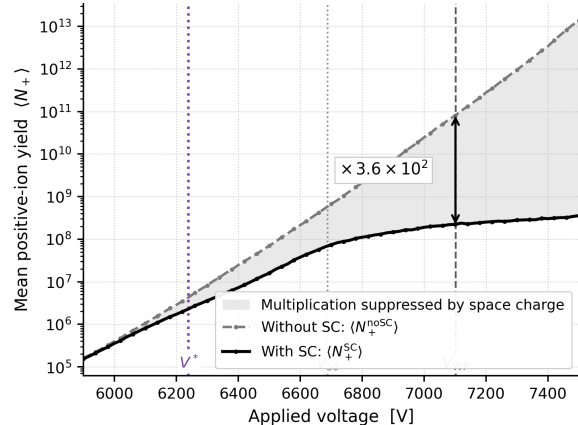
(a) Where the feedback scale is set



Same primaries, feedback active and suppressed. V^* sits where the two branches separate fastest, in the region of complete coverage.

Above 6400 V individual records are truncated and absolute yields are lower bounds. The suppressed branch is truncated less, so the separation shown is

(b) Where the chamber works



At the working point the two differ by about three orders of magnitude. Only the self-consistent branch saturates, near the Raether limit; the frozen-field branch does not.

The aim was not only to compute efficiency, gain and sensitivity, but to identify what is integrated away when these are reduced to threshold-defined observables.

- 1 Space charge does not simply reduce the final signal. It progressively modifies the avalanche growth itself, separating the self-consistent response from the frozen-field multiplication.
- 2 That separation has a voltage structure of its own. Its rate of change has a single interior maximum, which defines V^* : a pre-threshold scale of the avalanche dynamics, not a working point, and not set by the readout threshold.
- 3 Where the detector previously offered one voltage, there are now two. The working point requires a beam. V^* does not.
- 4 This opens a candidate metric for comparing gas mixtures before beam characterisation, and a quantified cost for any simulation chain that omits the feedback. Whether V^* transfers across mixtures and gap geometries is the parametric study that follows.

Efficiency and gain describe the detector after the microscopic dynamics have been reduced. The self-consistent simulation makes that dynamics accessible before the reduction.

-  Abbrescia, Marcello, Vladimir Peskov, and Paulo Fonte (2018). *Resistive Gaseous Detectors: Designs, Performance, and Perspectives*. Weinheim: Wiley-VCH. ISBN: 9783527340767. DOI: 10.1002/9783527698691.
-  Aielli, G. et al. (2016). "Improving the RPC rate capability". In: *JINST* 11.07, P07014. DOI: 10.1088/1748-0221/11/07/P07014.
-  Lippmann, Christian and Werner Riegler (2004). "Space charge effects in Resistive Plate Chambers". In: *Nuclear Instruments and Methods in Physics Research Section A* 517, pp. 54–76. DOI: 10.1016/j.nima.2003.08.174.
-  Pinheiro, João Pedro Gomes (2025). "Performance of eco-friendly alternative gas mixtures in CMS iRPC detector in the HL-LHC environment". In: *PoS ICHEP2024*, p. 957. DOI: 10.22323/1.476.0957.
-  Santonico, R. and R. Cardarelli (1981). "Development of resistive plate counters". In: *Nucl. Instrum. Meth.* 187, pp. 377–380.

Thank you

The RPC does not operate at the feedback transition.

It operates after the transition has saturated.

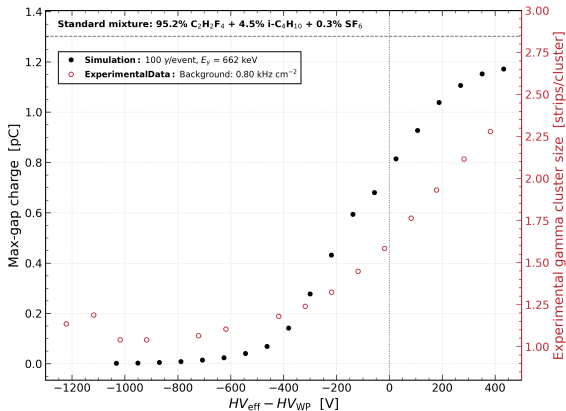
$$V^* = 6240 \text{ V}_{\text{applied}} = 6344 \text{ V}_{\text{eff}}, \text{ operating margin } 876 \text{ V}$$

Victor Olenin Ramírez Beltrán · Universidad Iberoamericana

vicolenin04@gmail.com

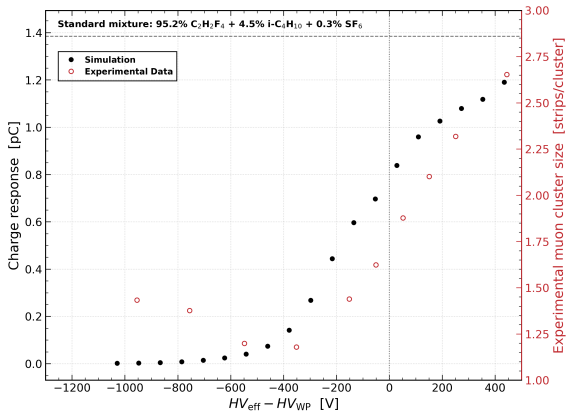
Backup slides follow.

Backup: the response remains muon-driven



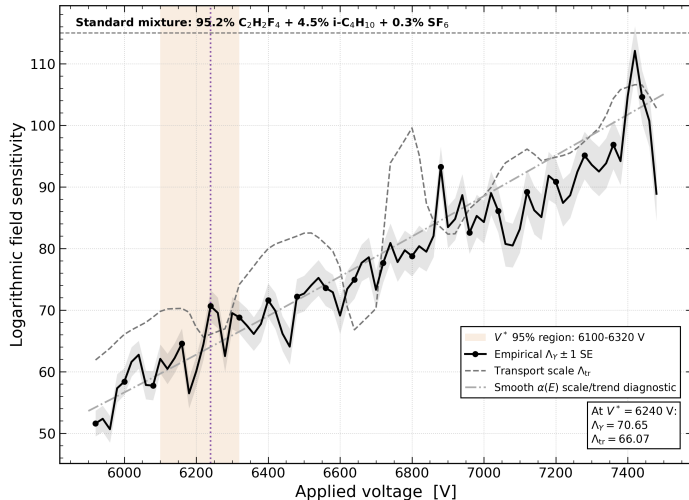
Adding 100 γ /event at 662 keV changes the number of avalanches between the two productions by +34, against a spread of $\sigma \simeq 540$. Consistent with zero.

Left and right axes carry different observables: simulated gas-level charge and published strip cluster size Pinheiro 2025. What is compared is the trend, not the value.



Without background the charge evolves smoothly into the operating region. The scale reported in the talk is therefore set by the muon avalanche, not by the photon flux.

Backup: multiplication sensitivity



Logarithmic field sensitivity of the multiplication. At V^* ,

$$\Lambda_Y = 70.65, \quad \Lambda_{tr} = 66.07.$$

The empirical estimator and the transport route agree to better than 7%, which is why a single Λ can be quoted.

For a resistive-plate detector under an incident flux Φ , the drop across the electrodes is ohmic and independent of chamber area:

$$\Delta HV = \rho t \langle Q \rangle \Phi,$$

with t the total electrode thickness and $\langle Q \rangle$ the *delivered* charge per count ($\rho = 0.9$ to $3.0 \times 10^{10} \Omega \text{ cm}$, $t = 0.4 \text{ cm}$).

Combining this with the operating margin,

$$\Phi_{\max} = \frac{V_{\text{WP}} - V^*}{\rho t \langle Q \rangle} \simeq 3.7 \text{ to } 12 \text{ kHz cm}^{-2},$$

the flux at which the operating point returns to the region where χ is still changing. This is an overlay of a steady-state result on the computed scale, not an output of the event-by-event loop.

The induced charge that sets the discrimination threshold is smaller than the delivered charge by $\alpha L_{\text{eff}} = \ln(\text{gain}) \approx 14$ to 18. Consistency: $\simeq 1.1 \text{ pC}$ induced at the working point gives $\simeq 18 \text{ pC}$ delivered, against 19.6 pC reported for a 2 mm gap Aielli et al. 2016. Nothing was tuned to make this agree.

Backup: separation of time scales

Process	Scale	Set by
Electron transit across the gap	14.4 ns	drift velocity
Electrode relaxation $\tau = \rho \epsilon_0 \epsilon_r$	8.0 to 26.6 ms	bulk resistivity

The two differ by roughly six orders of magnitude. The avalanche therefore sees a fixed electrode charge, and the electrode sees a time-averaged current. This is what allows the two stages to be solved separately and coupled through the field.

All voltages are reported as effective high voltage,

$$HV_{\text{eff}} = \frac{V_{\text{applied}}}{0.98358},$$

evaluated at 969.7 mbar and 293.15 K with $\alpha = 0.80$.

V^* applied	6240 V
V^* effective	6344 V

The correction is applied to the simulation so that it can be placed on the same axis as the published measurement, which is quoted in effective voltage.

In the transport stage the strip multiplicity is built from the set of geometric strip indices crossed by the primary, before the field solver is called. It carries no dependence on the high voltage by construction, and it is not the quantity a front-end measures.

What is reported instead is the gas-level charge, which is the observable the space-charge feedback actually acts on.

Converting to a strip cluster size would require the induced-signal and discrimination chain, which is outside the scope of this work. The comparison in the control slide is therefore between trends, on two deliberately separate axes.