Simulation Study of Ionization Rate Discrepancies in Pure Freon for Variable-Gap Resistive Plate Chambers

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Motivation and Problem Statement

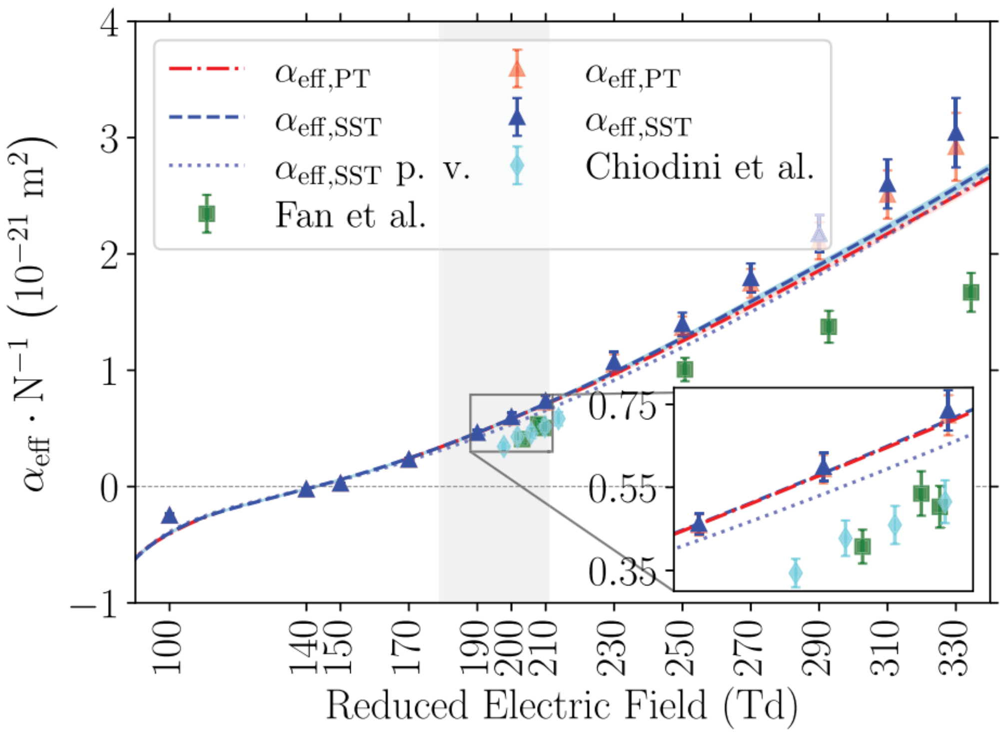


Figure: Ionization coefficient measured on the pulsed Townsend setup (blue) compared to literature values measured using RPCs (lightblue and green) [SMF24].

Pulsed Townsend (PT) and RPC data on ionization rates
- *contradict each other consistently* [LR04, Chi+09, Fan+22, SMF24]
- *contradiction pronounced at large fields (small gaps)*

PT data extrapolate to atmospheric pressures
- *slow transients (few dozen nanoseconds)*
- *reduced swarm parameters*
- *assuming no three-body effects (R-134a, not for HFO!)*

➢ **The reason PT and RPC data contradict remains unclear**
  - Space charge [Fan+22], three-body [Urq+09, SMF24], finite bandwidth, underestimated uncertainties, …?

Experimental Setup

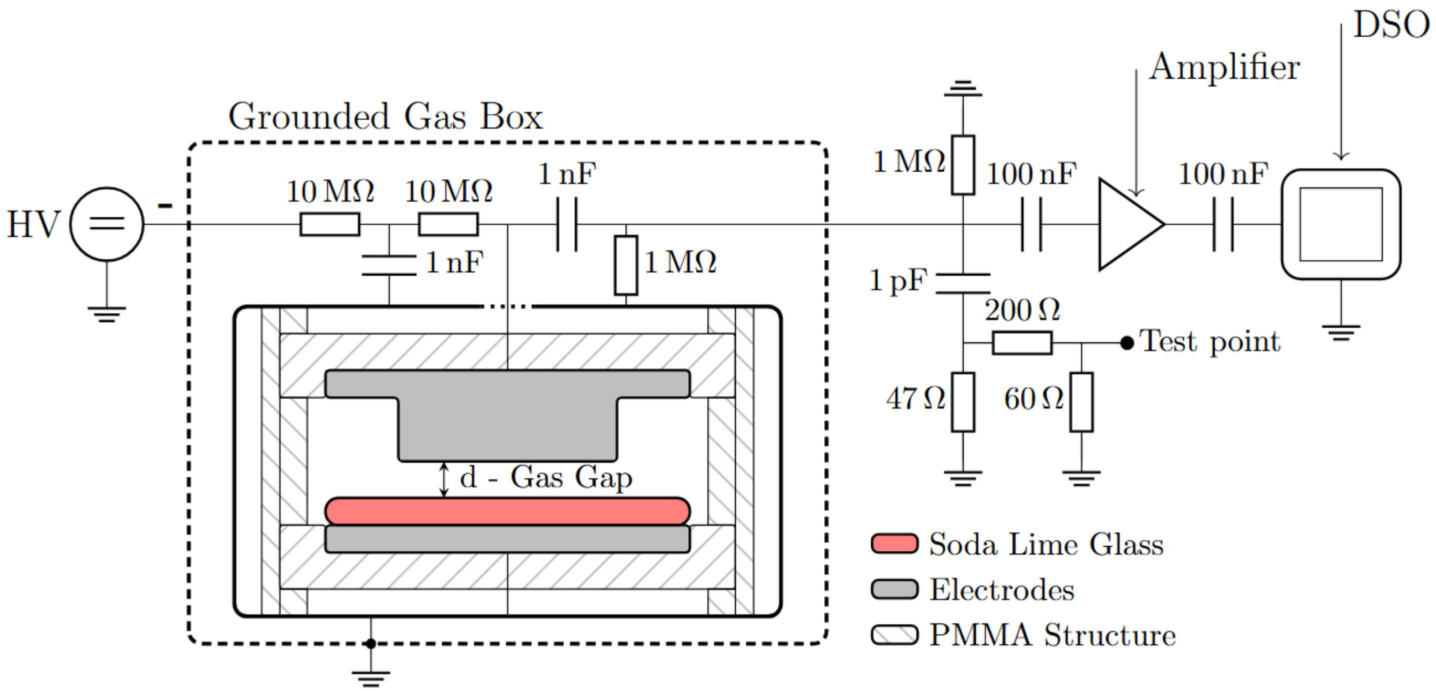


Figure: Illustration of the RPC setup by LIP Coimbra, including details on the electronics.

Data provided by Luis Lopes

– *LIP Coimbra (Portugal) [Lop+03]*
– *from 2010/2011 with cosmics*
– *pure R-134a (reducing systematics)*
– *Preamplifier INA 51063 [Bla+01]*

Single-*variable*-gap RPC

– *atmospheric pressure*
– *gap sizes 300 um to 1 mm*
– *field strengths 200 Td to 400 Td*

Ionization rate estimated by two-threshold method:

$$R = \frac{\log\left(\frac{V_2^*}{V_1^*}\right)}{(t_2 - t_1)}$$

Simulation Setup

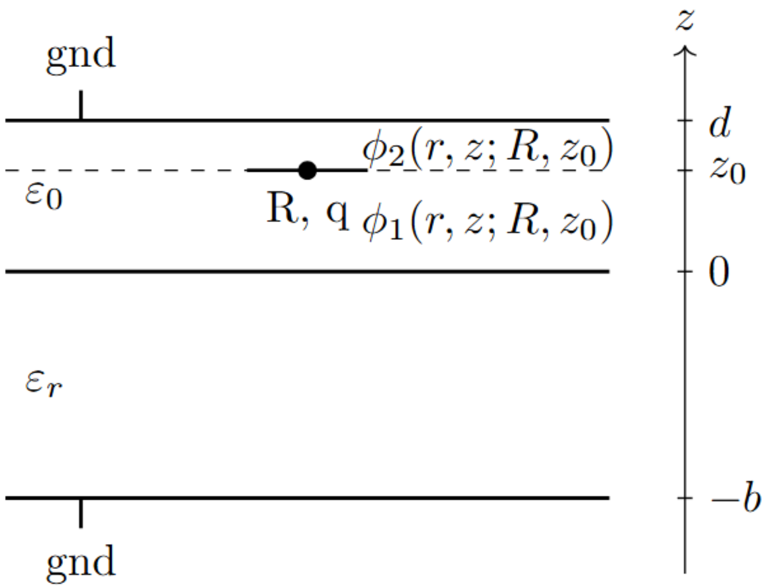


Figure: Configuration of the RPC used to integrate the seed electrons

1D Model for reference

- *Space charge modeled by saturation*
- *Energy and polar angle distribution for cosmics*

2D Model

- GARFIELD++ *with pad electrodes* [Gar++]
- *Detector capacitance with FEM solver*
- *Space charge modeled statically using charged rings*
  - *Mirror charges and charge accumulation on anode*
- *Only head-on events and fixed momentum (100 GeV)*

Signal Processing

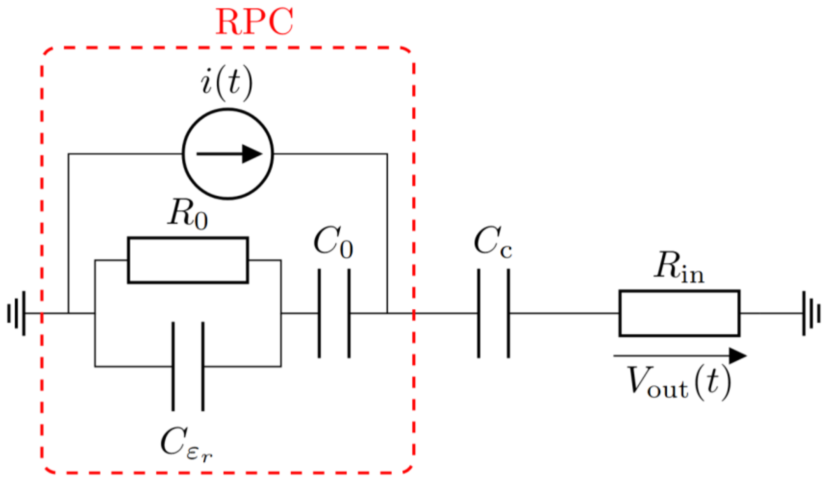


Figure: Lumped element circuit

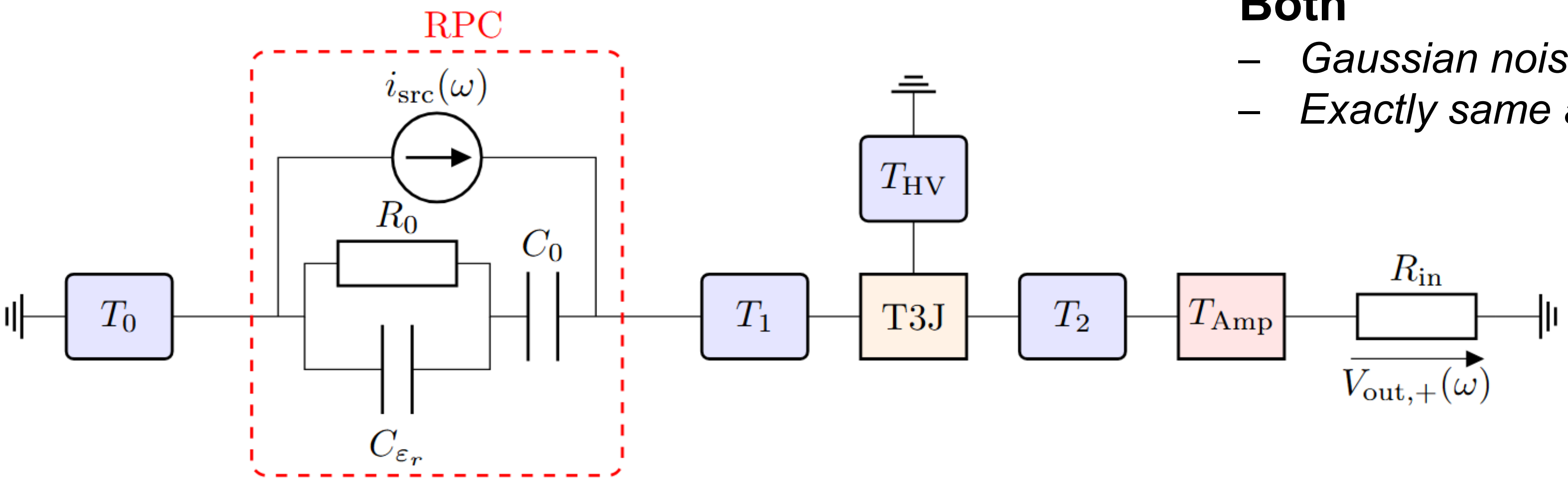


Figure: Transmission line representation including details (T_0, T_{HV}, …)

Lumped Element [R04]

- *Highly simplified topology*
- *Modeling AC-coupled signal to input impedance of DSO*
- *Apply gain and bandwidth of DSO on output voltage*

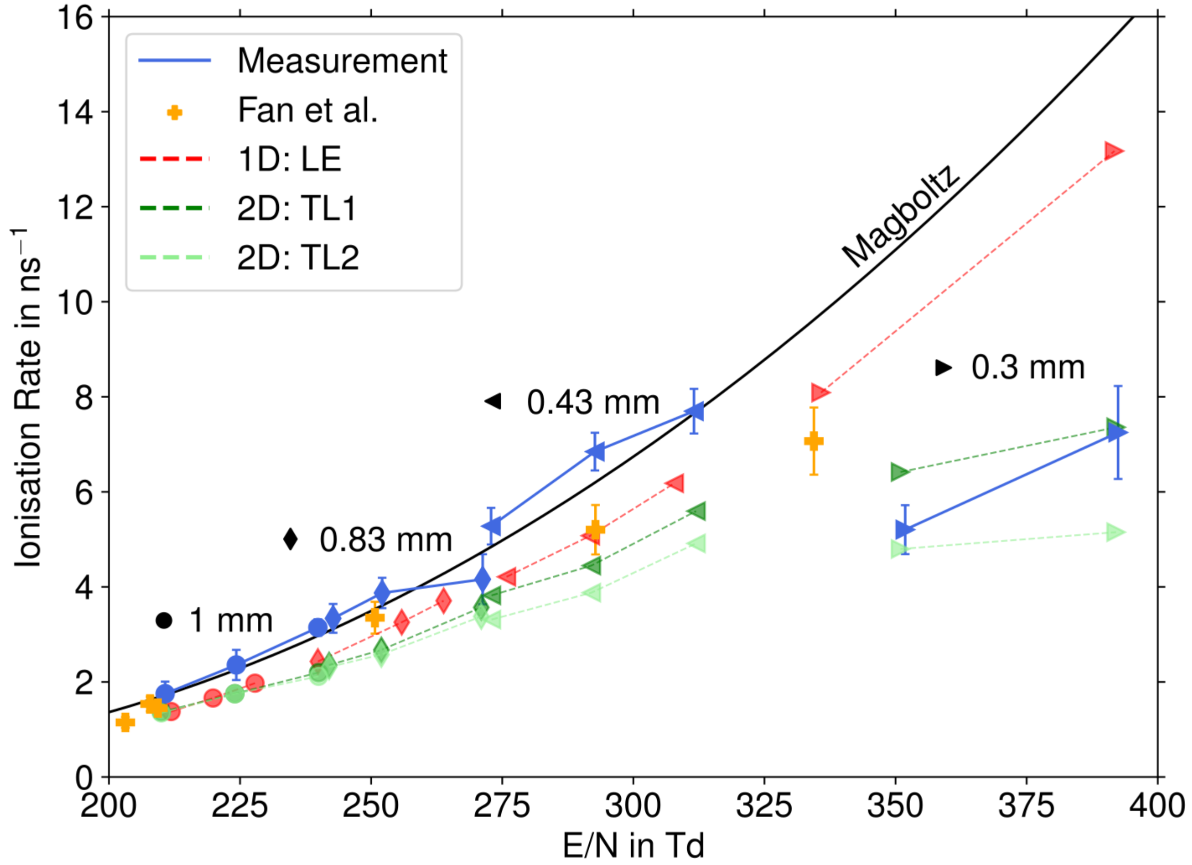
Transmission Line [RB02, GY12]

- *Consider transient behavior with T-blocks*
- *RPC modeled as an impedance junction*
- *Provides a lot of freedom*
  - *Parasitics, impedance mismatches, delays, …*
  - *Difficult to constrain given the circumstances*

Both

- *Gaussian noise + bandwidth + artificial sampling*
- *Exactly same analysis as with experimental data*

Ionization Rates



Lumped Element (LE)
Reference

Transmission Line 1 (TL1)
Simplified transmission line with no parasitics and not including electrically small T-blocks

Transmission Line 2 (TL2)
Advanced transmission line with realistic parasitics of the lumped elements and wires and T_0 != id

- Transmission line affects 0.3 mm most and can reproduce the observed discontinuity
- All models agree for 1 mm gaps: missing physics, uncertainty on Magboltz/PT measurements?

Figure: Ionization Rate measured (blue), reference measurement [Fan+22] (orange), and simulated (red, green, light green). Magboltz simulation values are given in black.

Corrected Time Resolution

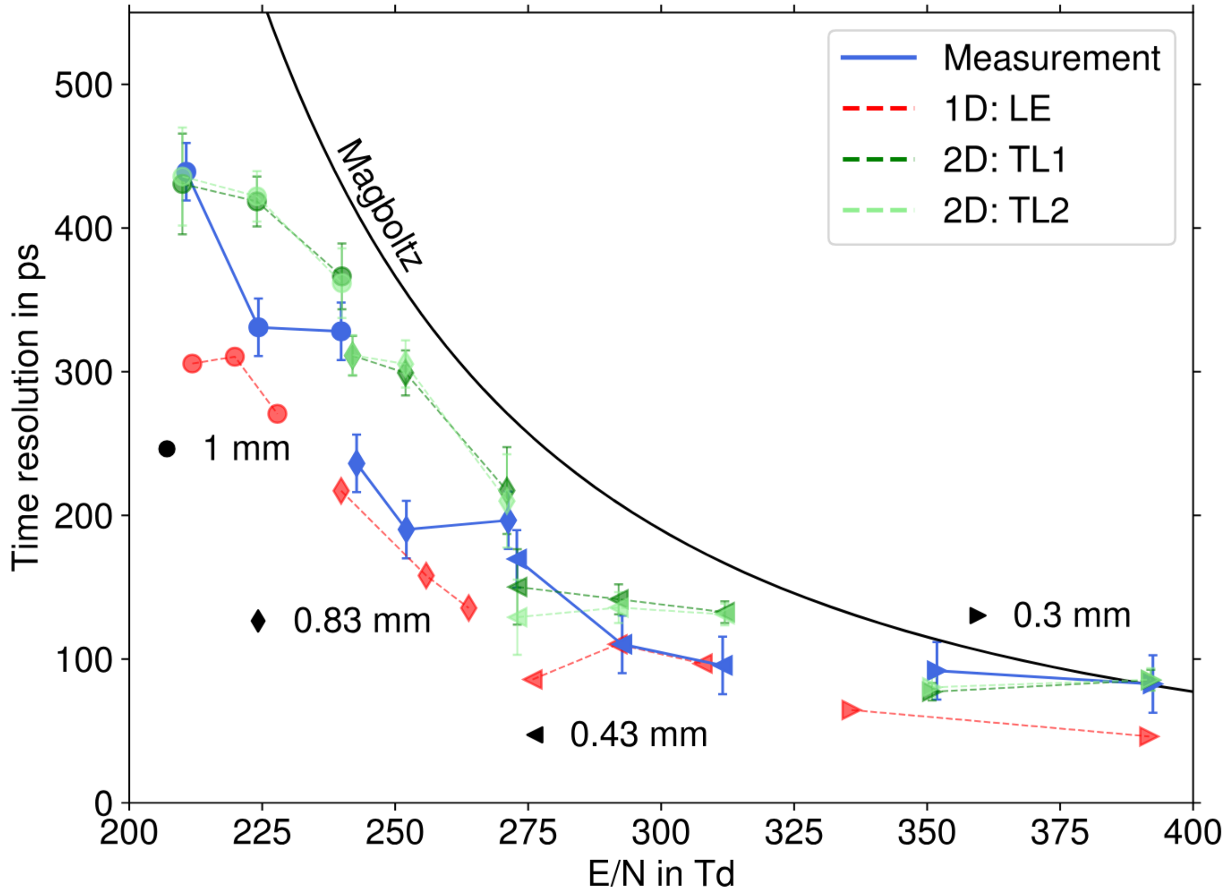
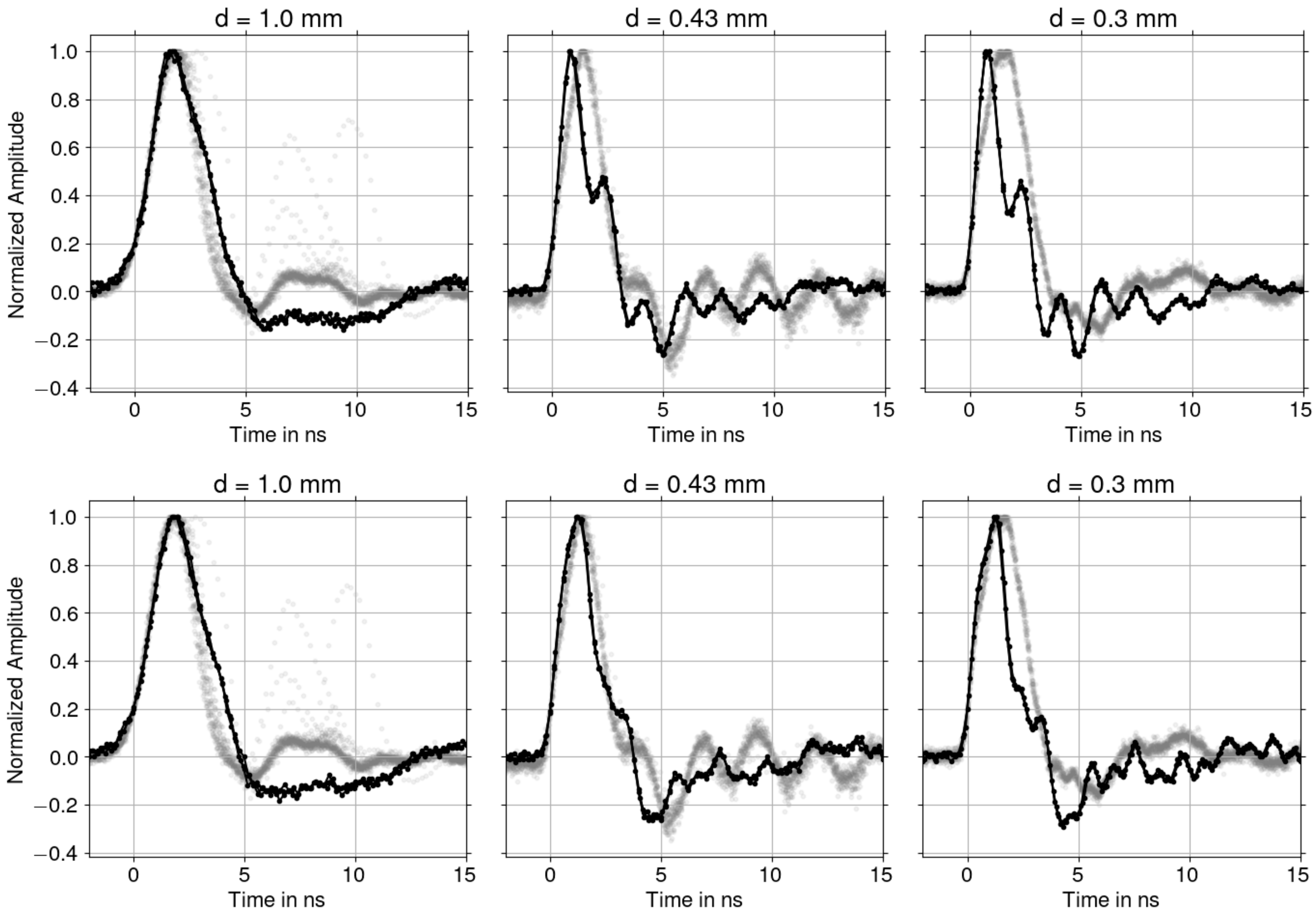


Figure: Corrected time resolution measured (blue) and simulated (red, green, light green). Magboltz prediction corresponds to $1.28/R_{\text{ion}}$ [RLV03].

1D + LE
Tends to underestimate time resolution

2D + TL
Tends to overestimate time resolution, but no difference between TL1 and TL2

Comparison of (typical) Waveforms – A Collection



Gray lines: overlay of 50 measured waveforms

Black lines: overlay of 3 simulated waveforms

Upper row
"Realistic" assumptions about line parameters and parasitics, called TL1; Multiple features cannot be reproduced

Lower row
Tuning of T_0-block shows that rising behavior at 0.43 and 0.3 mm can be reproduced; time over threshold and post-peak structure still differ

Figure: Normalized waveform overlap showing intrinsic, common structure. Black waveforms are simulated, and gray ones are measured.

Overview of Waveform Shape Parameters d = 1 mm

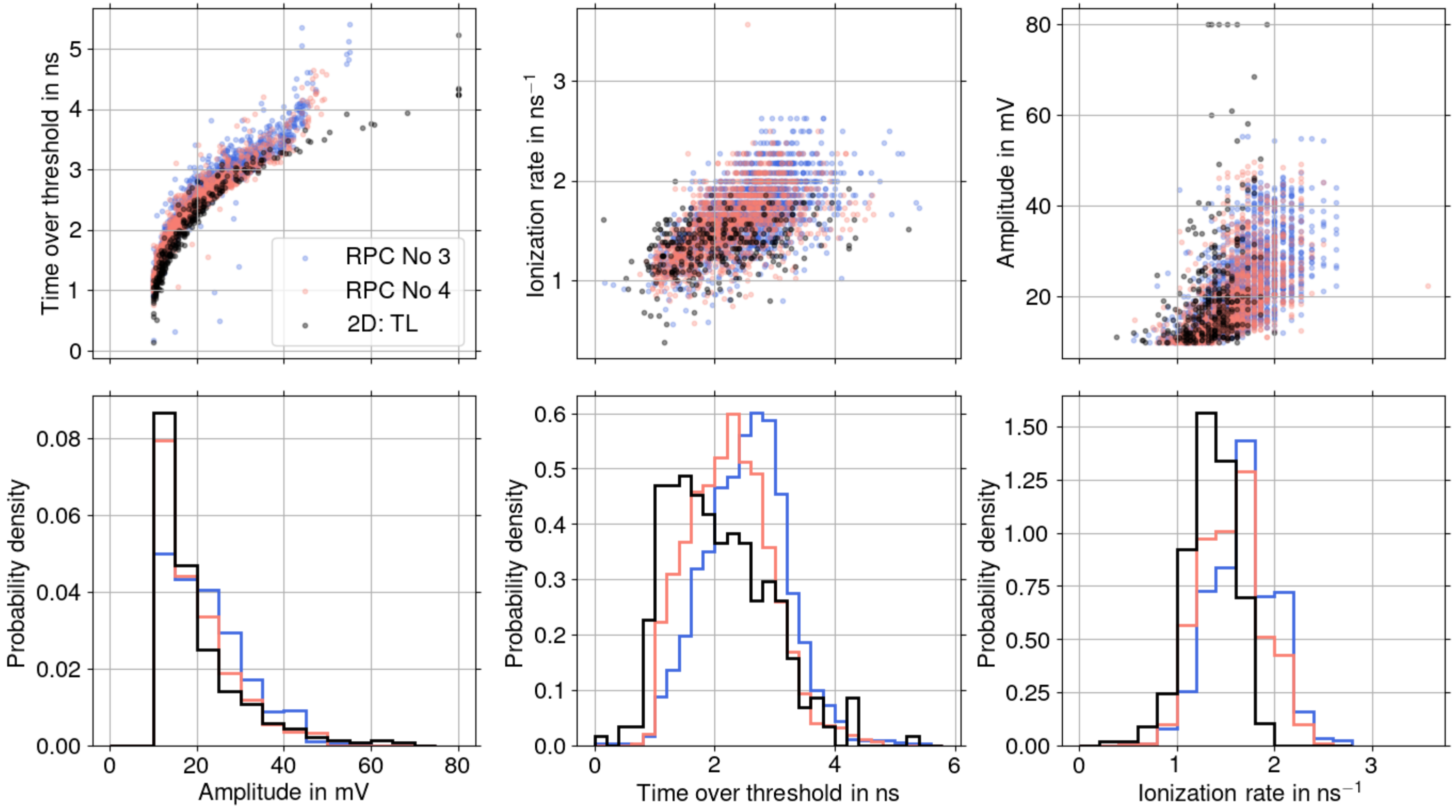


Figure: Overview of correlations and distributions of amplitude, time over threshold, and ionization rate for d = 1 mm.

2D + TL1

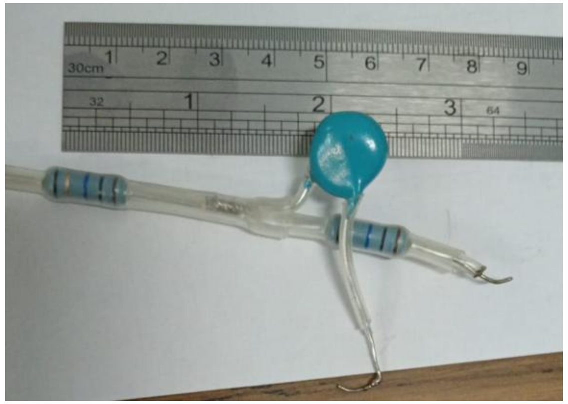
Distributions well reproduced with slightly reduced time over threshold and ionization rate

- **In the model, it is basically impossible to retrieve the *input* ionization rate:** electron clusters are distributed, space-charge effects, and diffusion

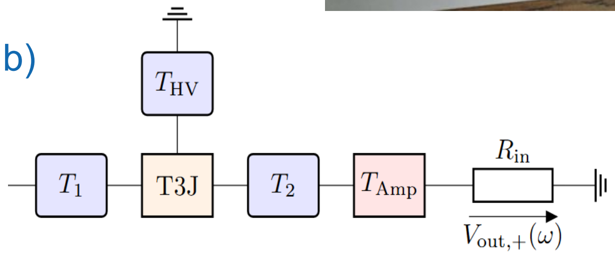
What we have tried (without success)

1. Non-linear effects from the wideband amplifier
   - *Instantaneous power-dependent S-matrix*
   - *Slew rate*
2. Including parasitics
   - *Bare wire comes with inductance*
   - *Capacitor comes with ESL and ESR*
   - *Resistor comes with parallel capacitance*
3. Transmission into the HV system
4. Optimization of transmission line parameters
5. Simulated space-charge with correction term
   - *including "all" mirror charges*

a)



b)



c)

$$\phi_2^{(2)}(r,z;R,z_0) = q\phi_0(r,z;z_0) - q\phi_0(r,z;2d-z_0) + q\frac{\epsilon_0-\epsilon_r}{\epsilon_0+\epsilon_r}\phi_0(r,z;-z_0) + \frac{q}{2\pi}\int_0^\infty \mathrm{d}k\; J_0(kr)J_0(kR)\cdot\left(f^{(2)}(z,z_0) - \mathrm{exp's}\right)$$

Summary and Conclusion:

- Ionization rate estimate from fast transients for various gap distances and fields
  - *State-of-the-art simulation tools combining detector physics and signal transmission*
- The transmission line description hints that the ionization rate can be drastically disturbed for small (0.3 mm) gaps, however, we cannot simultaneously obtain agreement at larger gaps (1 mm) so far
  - *Shape of measured waveform hints at non-understood transmission effects*
  - *For 0.3 and 0.43 mm gaps: Rate reduction depends mostly on finite bandwidth and transmission line design*
  - *For 0.8 and 1 mm gaps: Method-independent deviation from measurements, mostly depends on detector physics i.e. ionization rate uncertainty underestimation*
- Simulations show that achieving a good description of the time resolution is considerably simpler than describing the measured ionization rate, but both are vulnerable to finite bandwidth of the read-out system
- It is extremely important to have the transmission property of the read-out line under control to obtain qualitatively good results

Outlook:

- EM simulation of RPC
  - *As a series element for transmission behavior (OpenEMS, CST, …)*
  - *Induced current from moving charges*
- Redo experiment with a more carefully designed read-out line
  - *Impedance matching, proper connectors and PCB design, SMD components, grounding and shielding*
  - *Measure S-parameters of the read-out line and RPC (as a transmission block)*
  - *Decoupling T-line physics from plasma physics (avalanche, streamer formation)*

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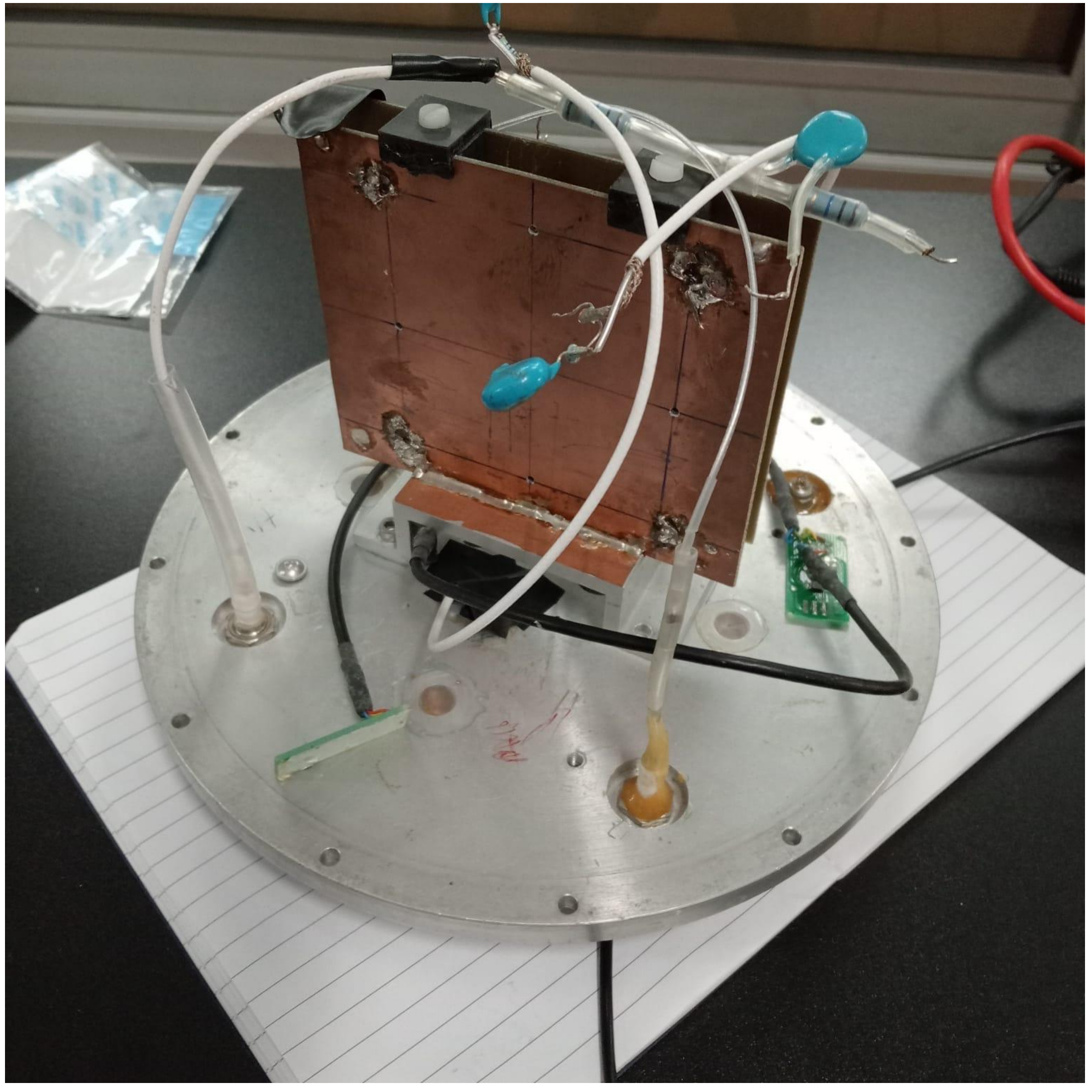
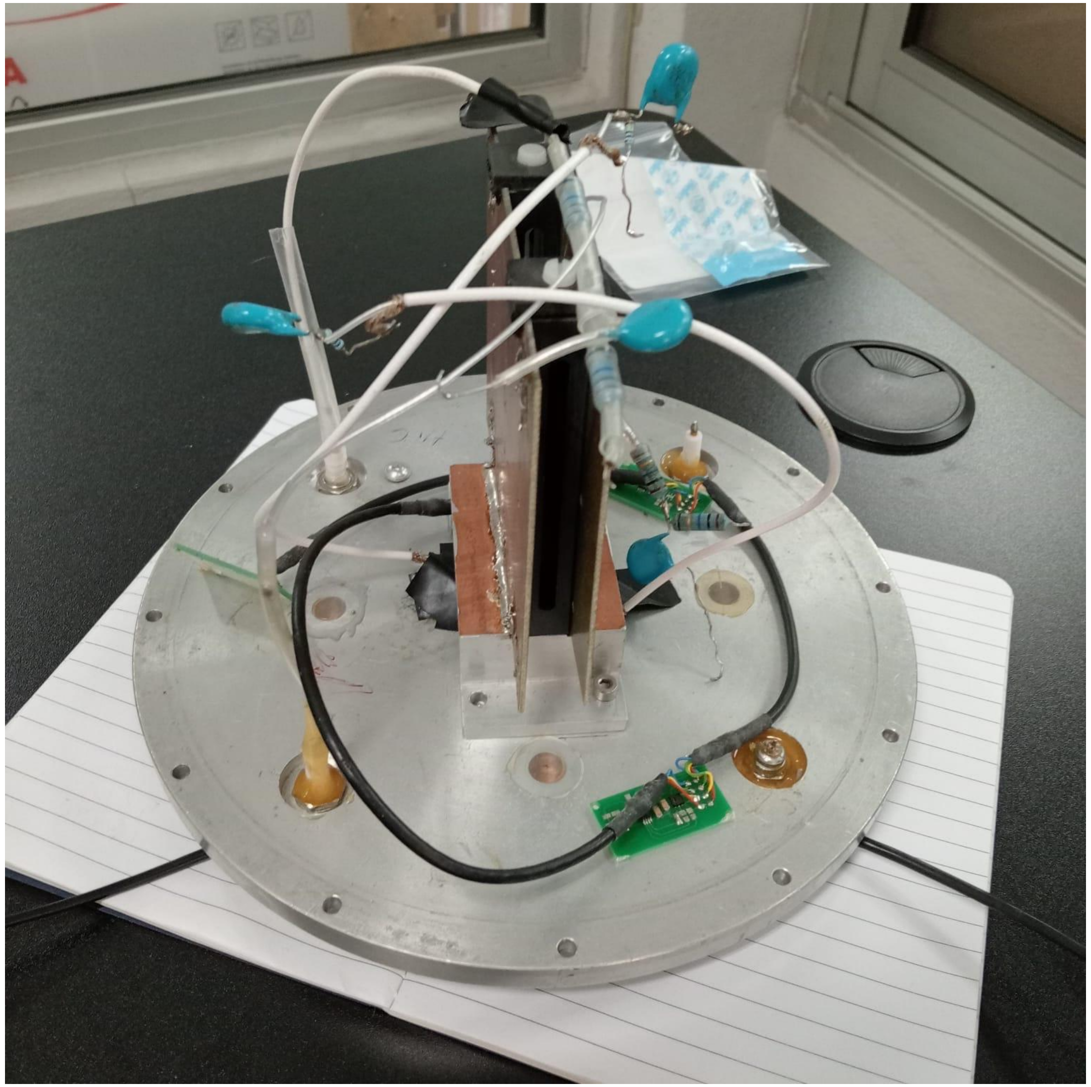
Backup

(Recent) Photos of Setup



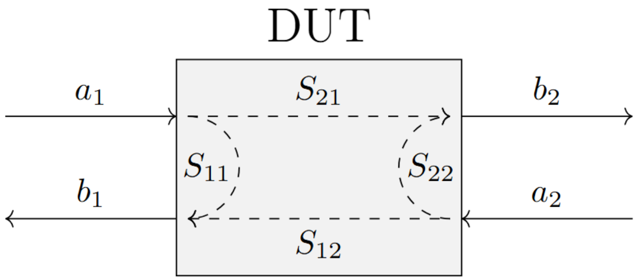


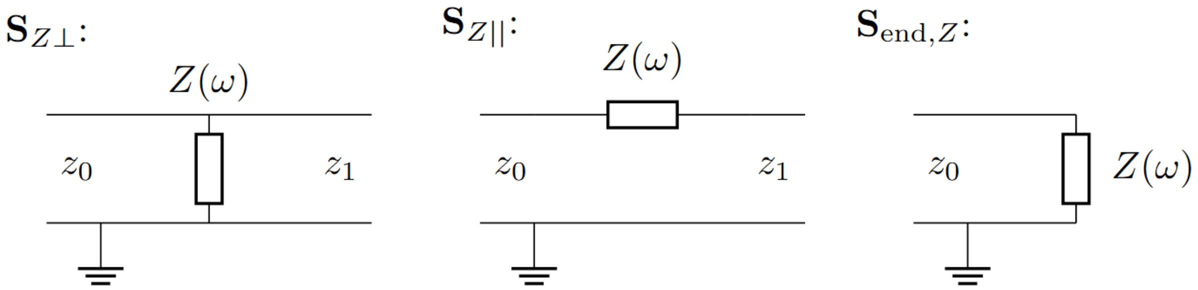
Space-Charge Correction Term

$$\phi_2^{(2)}(r, z; R, z_0) = q\phi_0(r, z; z_0) - q\phi_0(r, z; 2d - z_0) + q\frac{\epsilon_0 - \epsilon_r}{\epsilon_0 + \epsilon_r}\phi_0(r, z; -z_0) \tag{3.26}$$

$$+ \frac{q}{2\pi}\int_0^\infty \mathrm{d}k\ J_0(kr)J_0(kR)\cdot\left(f^{(2)}(z, z_0) - \text{exp's}\right).$$

S-Parameters and Solution to T-Line

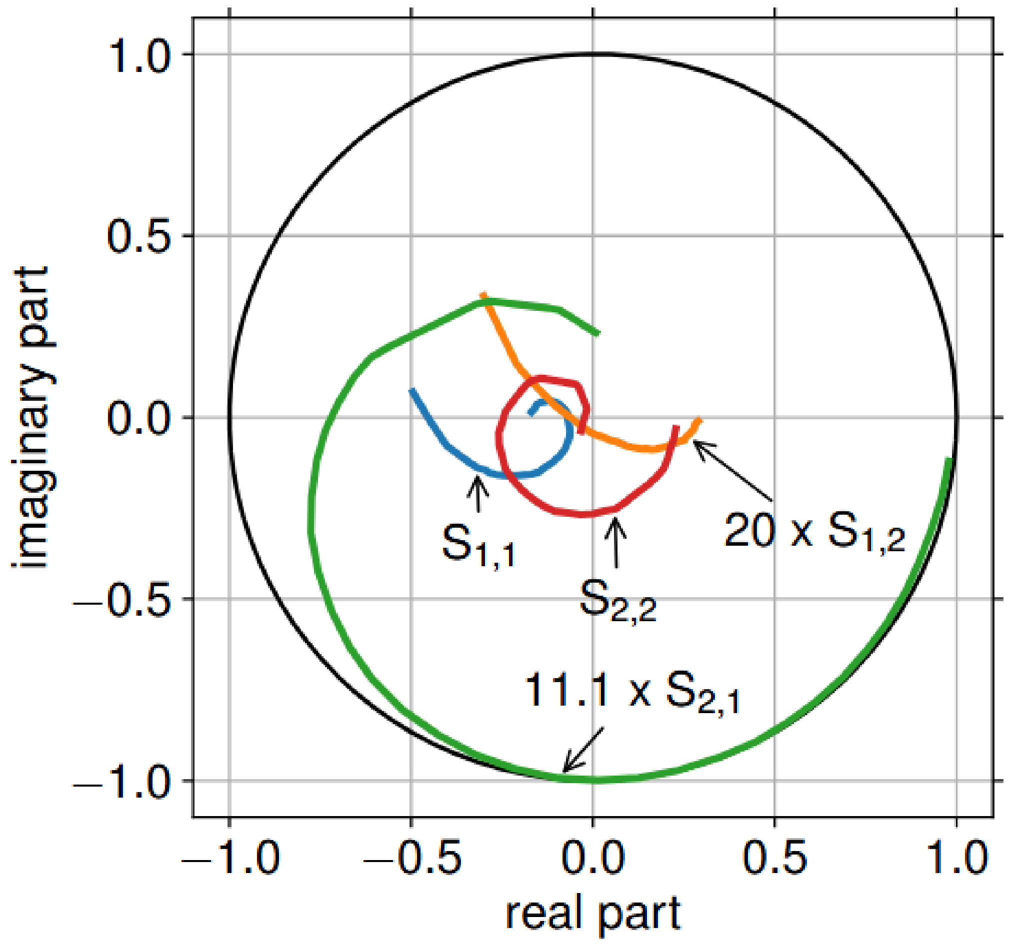




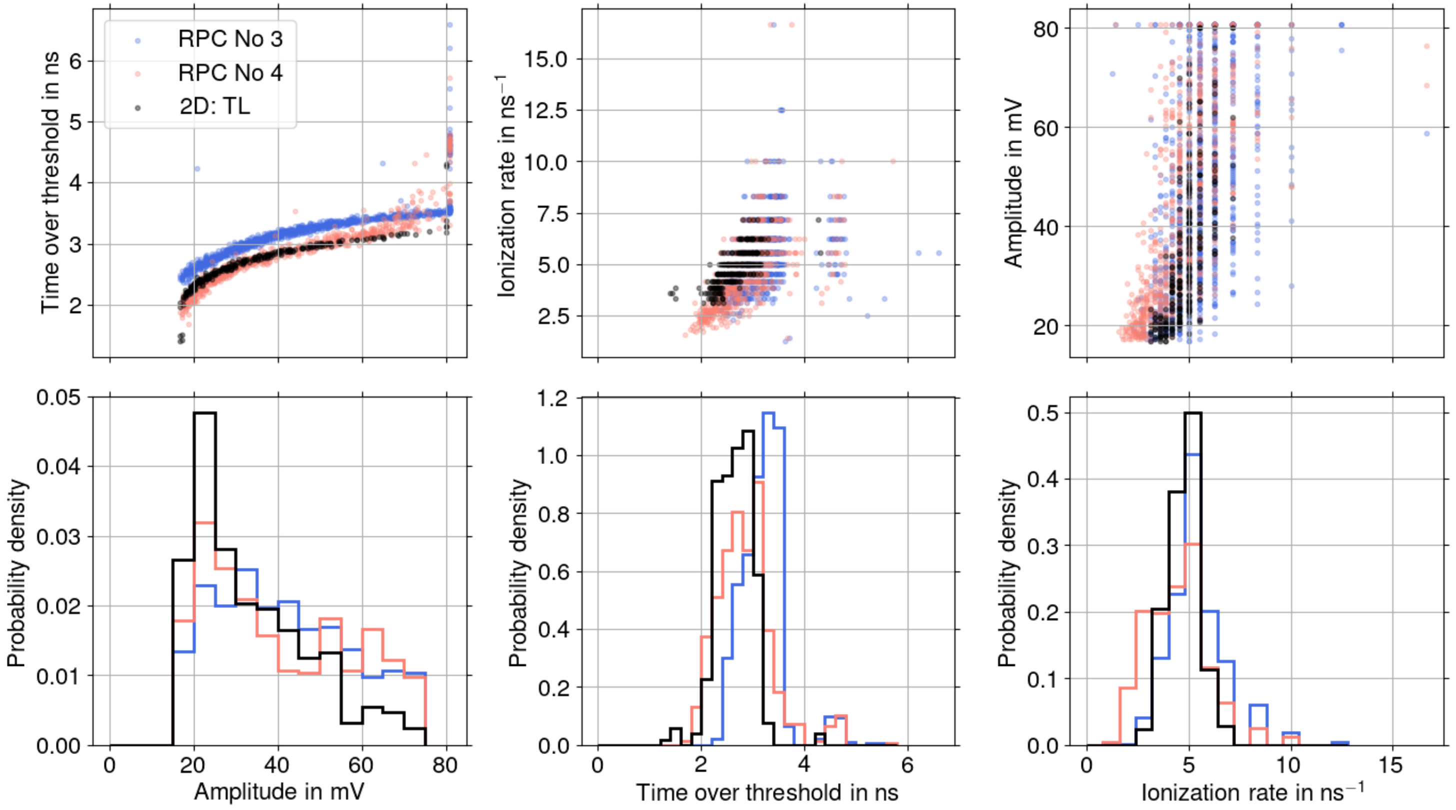
$$\mathbf{S}_{Z||}(z_0 \to z_1) = \frac{1}{Z + z_1 + z_0} \begin{pmatrix} Z + z_1 - z_0 & 2z_0 \\ 2z_1 & Z + z_0 - z_1 \end{pmatrix}$$

$$V_{\mathrm{out},+} = \left((Z^{-1} + z_0^{-1})\mathbf{T}_{2,2} + (Z^{-1} - z_0^{-1})\mathbf{T}_{1,2}\right)^{-1} i_{\mathrm{src}}(\omega)$$

Preamplifier S-Parameters



Overview of Waveform Shape Parameters d = 300 um



2D + TL1

Distributions well reproduced with slightly reduced time over threshold and too centered ionization rate

Figure: Overview of correlations and distributions of amplitude, time over threshold, and ionization rate for d = 300 um.