



University of Science and Technology of China

RPC2026

Study of Rate Effects in a Photo-RPC with Different Bulk-Resistivity Electrodes

Based on Stochastic Local Voltage-Drop Modeling

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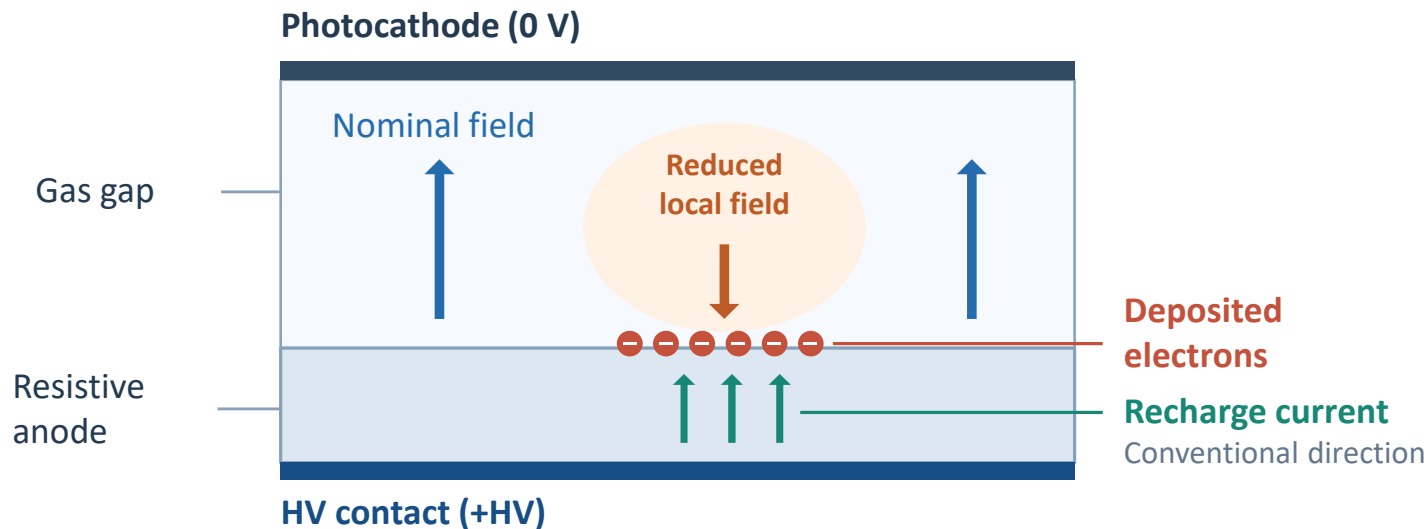
Outline



- 1 **Background and motivation**
- 2 **Photo-RPC setup and rate measurements**
- 3 **Stochastic local voltage-drop model**
- 4 **Model validation**
- 5 **Conclusions**

Resistive electrodes and rate capability

Local charging and field recovery



Simplified Photo-RPC cross-section, not to scale

Discharge protection

Resistive electrodes limit the discharge current. Local field reduction helps quench a discharge.

Field recovery

Deposited charge reduces the gap field locally. Charge leakage restores the field over time.

How does electrode resistivity affect gain and timing at high rates?

Rate effects from incomplete field recovery

Effective gap voltage

◦ Voltage before each event

Voltage seen by an event

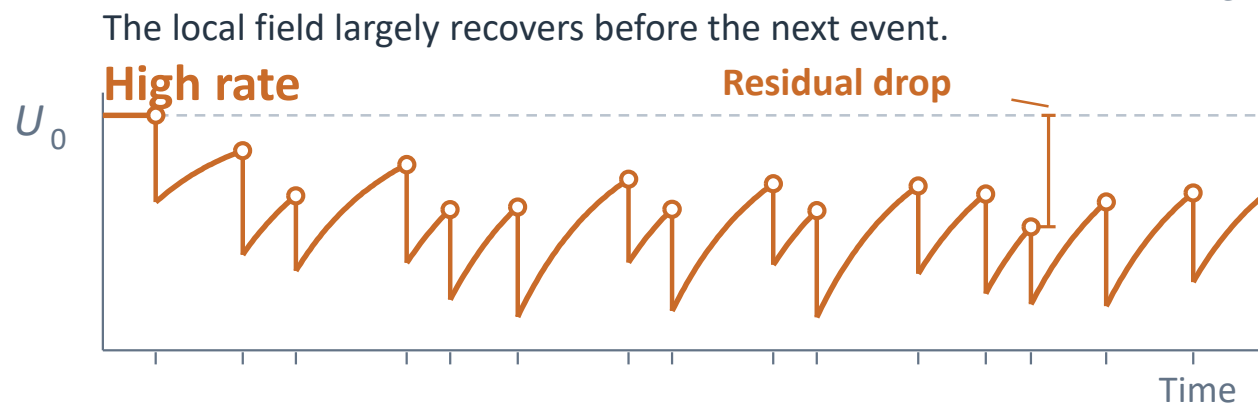
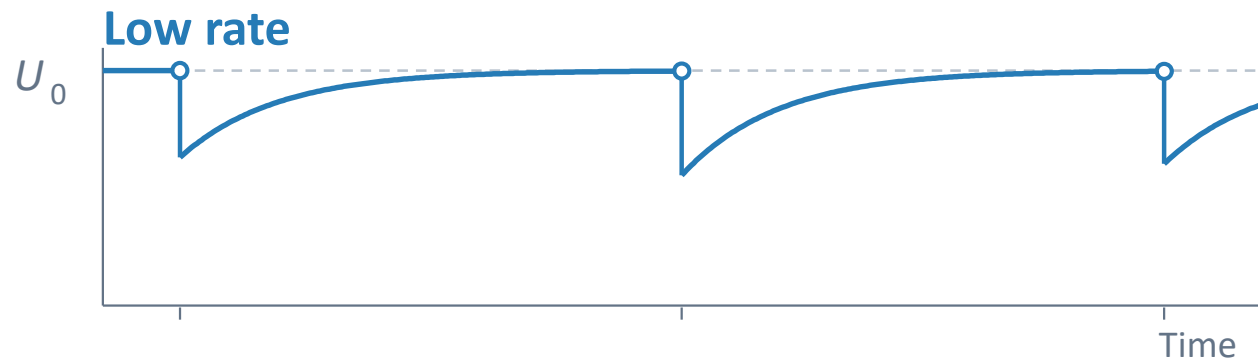
$$U_i = U_0 - \Delta U(t_i^-)$$

Gain

Lower effective voltage reduces the mean gain.

Timing

Reduced and fluctuating fields can broaden the time distribution.



Events arrive before full recovery.

Schematic: same local region, recovery time and axis scales.

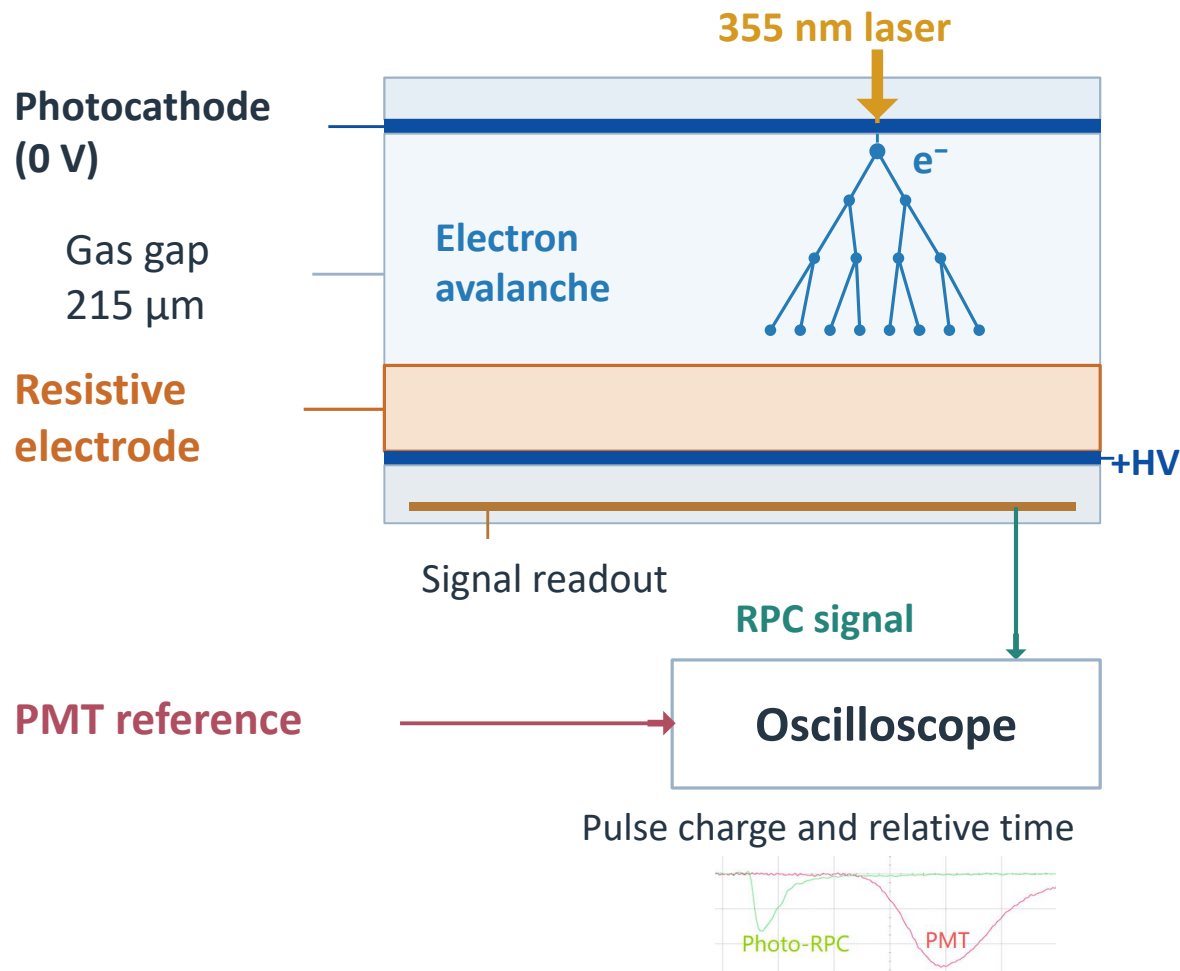
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Photo-RPC experimental setup

Photoelectron emission and avalanche



Single-photoelectron operation

R134a / SF₆ / i-C₄H₁₀ = 90 / 5 / 5

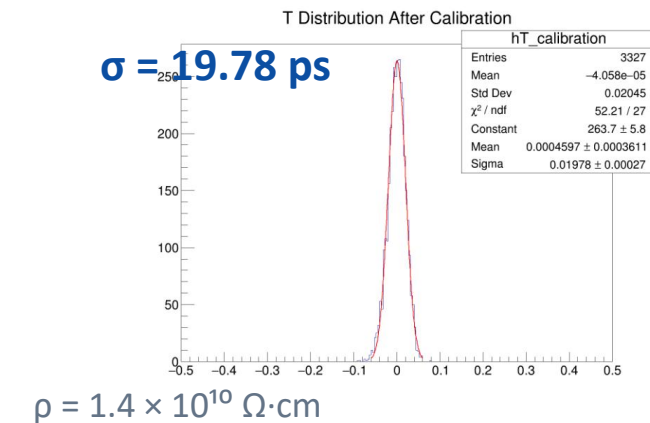
Gas gap: 215 μm

355 nm femtosecond laser

Adjustable repetition rate

Low-rate timing

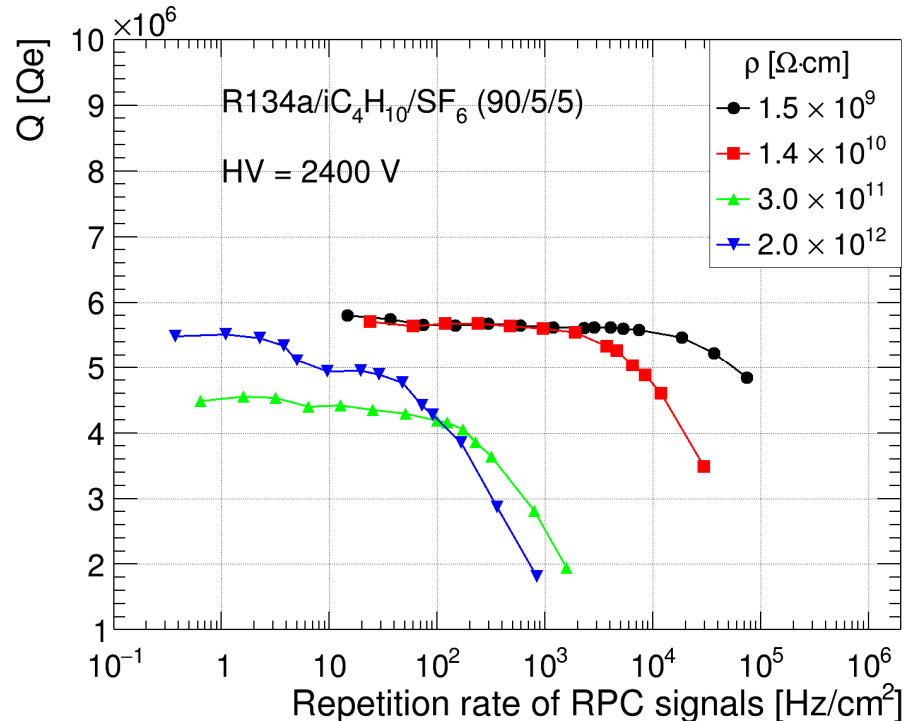
2500 V, after time-walk correction



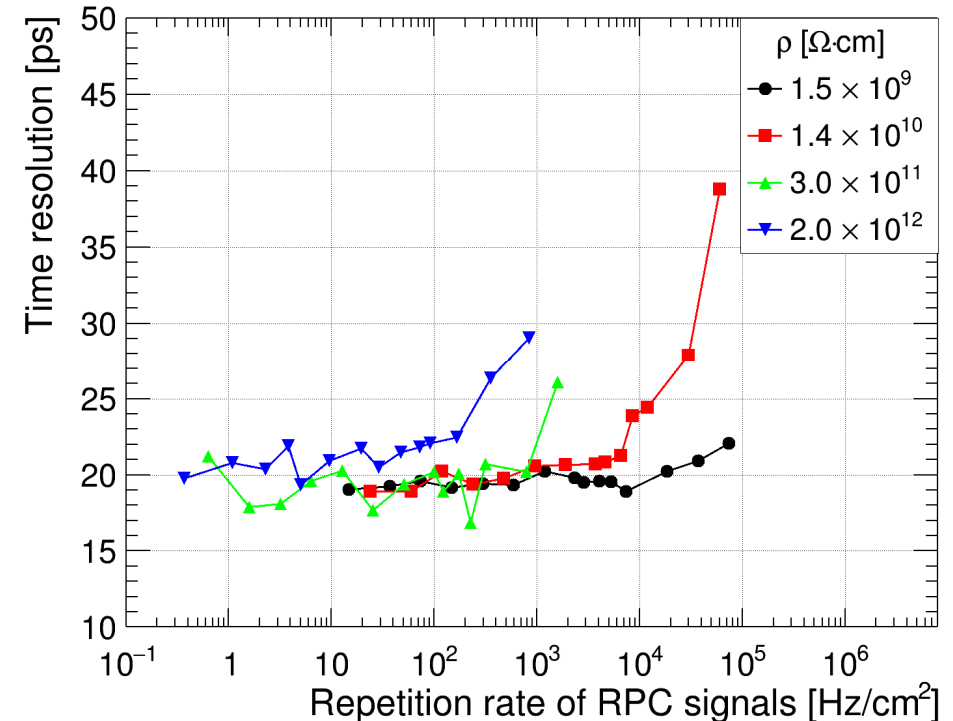
Lower resistivity extends the rate capability

Single-photoelectron measurements at 2400 V

Mean integrated charge

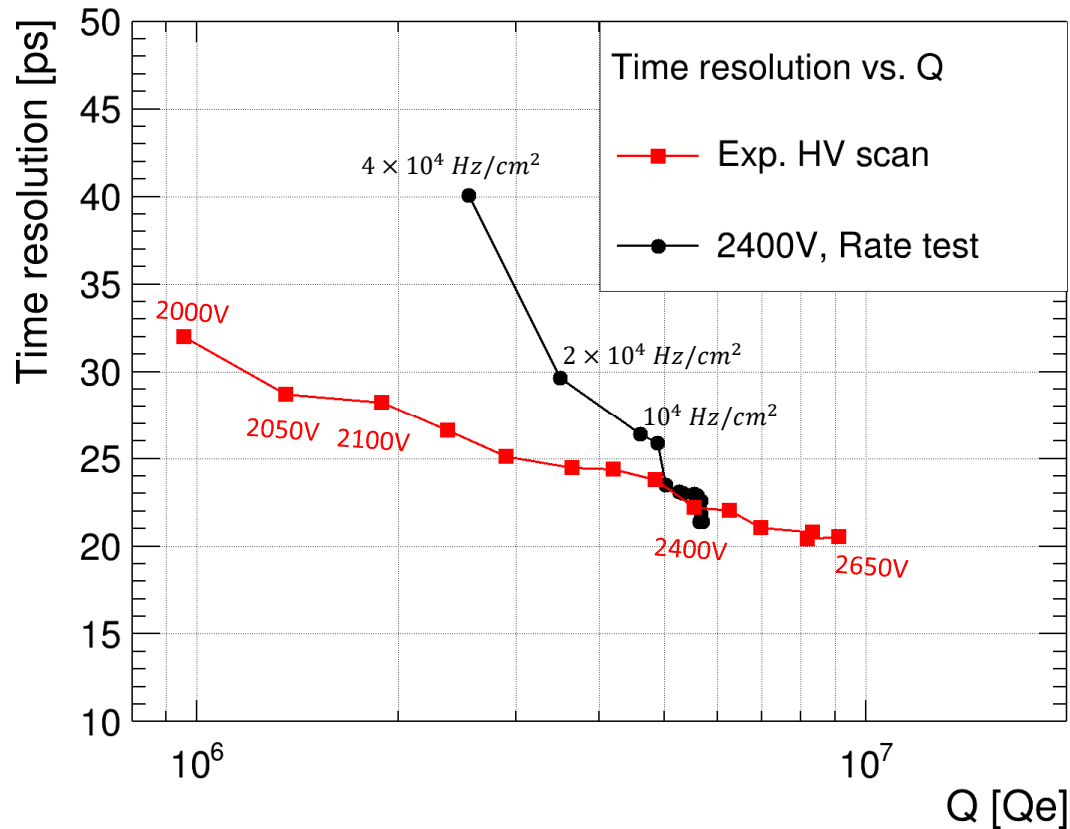


Time resolution



Lower resistivity shifts gain loss and timing degradation to higher rates.

Timing at the same mean gain



Measurement	Fixed	Scan
Rate scan	2400 V	Rate
HV scan	Low rate	Voltage

At the same mean gain, high-rate timing is worse than low-rate timing at reduced voltage.

Can local field fluctuations account for the additional timing spread?

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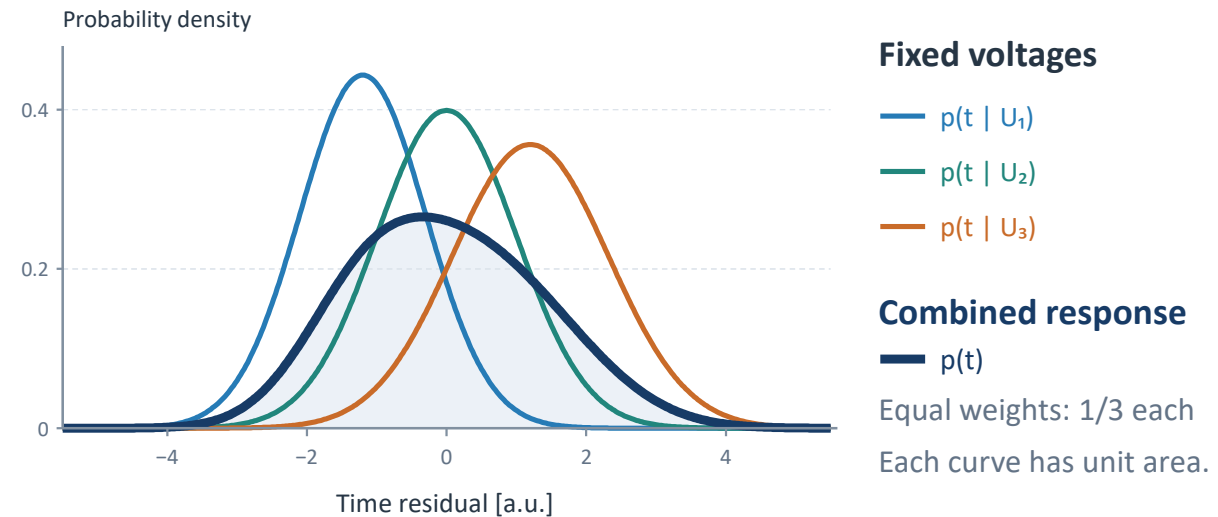
Local voltage fluctuations and timing response

Incomplete field recovery

The residual voltage depends on the charge and timing of previous avalanches.

$$U_i = U_0 - \Delta U(t_i^-)$$

The local voltage can change both the mean time and the intrinsic timing width.



Schematic, arbitrary units

$$\text{Var}(t) = \mathbb{E}[\text{Var}(t | U)] + \text{Var}(\mathbb{E}[t | U])$$

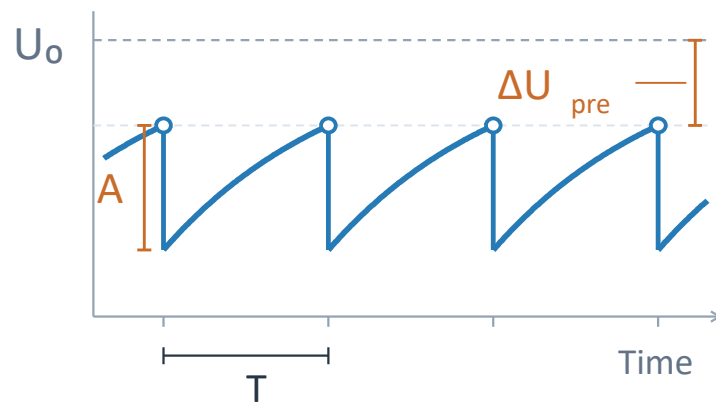
Spread at fixed voltage

Shift of the mean time

Periodic baseline for rate-dependent gain

Fixed event interval T , fixed deposited charge, exponential recovery

Periodic steady state



Same voltage before each event

$$U_{\text{eff}} = U_0 - \Delta U_{\text{pre}}$$

1 Single-event recovery

$$\delta U(t) = A e^{-t/\tau}, \quad A = \frac{q_{\text{dep}}}{C_{\text{eff}}}$$

2 Accumulation of previous events

$$\Delta U_{\text{pre}} = A(e^{-T/\tau} + e^{-2T/\tau} + \dots)$$

$$\Delta U_{\text{pre}} = \frac{A}{e^{T/\tau} - 1}$$

3 Gain response at low rate

$$\frac{g(U)}{G_0} \simeq e^{k(U-U_0)}$$

k from the low-rate HV scan
Mean charge $\propto$ mean gain

Normalized mean charge for the rate fit

$$Q_{\text{norm}}(R) = \frac{\bar{Q}(R)}{\bar{Q}_0} \simeq \exp \left[-\frac{c_2}{\exp[1/(\tau R \Delta S)] - 1} \right]$$

Fit parameter

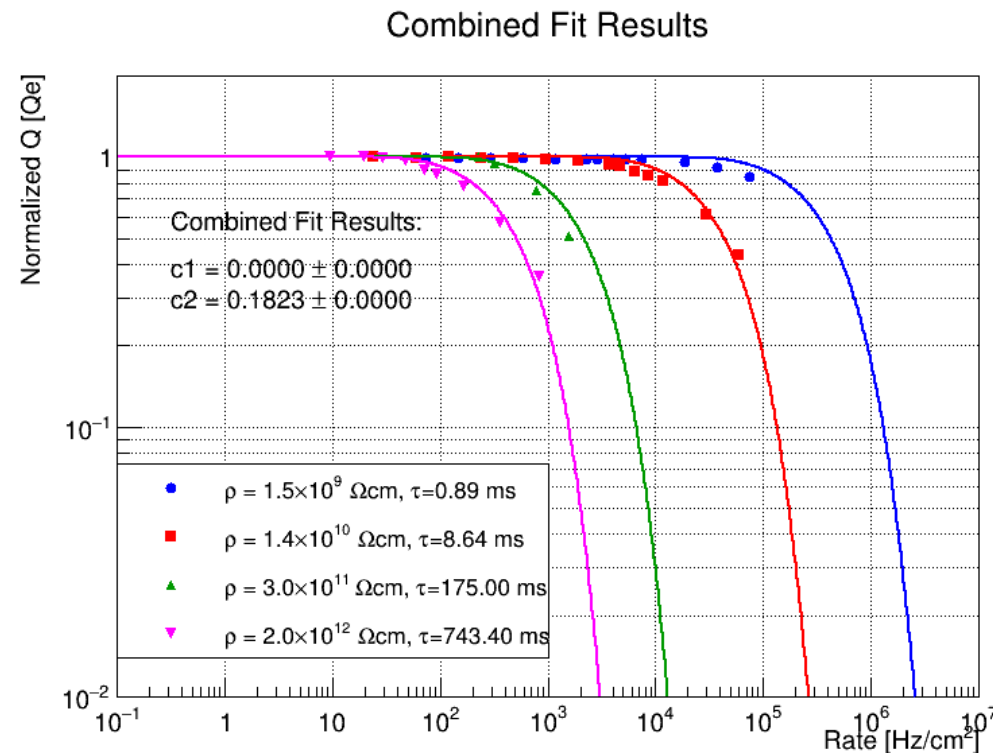
$$c_2 = kA$$

$$T = \frac{1}{R \Delta S}$$

R : rate density ΔS : effective local area τ : effective recovery time

Fits to the rate-dependent mean charge

Four electrode materials at 2400 V



$$Q_{\text{norm}}(R) \simeq \exp \left[-\frac{c_2}{\exp[1/(\tau R \Delta S)] - 1} \right]$$

Material parameters

$\rho [\Omega\cdot\text{cm}]$	ϵ_r	$\tau [\text{ms}]$
1.5×10^9	6.682	0.887
1.4×10^{10}	6.973	8.64
3×10^{11}	6.589	175
$2 \times 10^{12}^*$	4.2	743.4

* Fused quartz

$$\tau \simeq \epsilon_0 \epsilon_r \rho$$

Bulk relaxation-time estimate

$$c_2 = kA = 0.1823$$

$$\Delta S = \pi(0.06 \text{ cm})^2$$

Random event intervals and voltage-drop sampling

Poisson arrival approximation

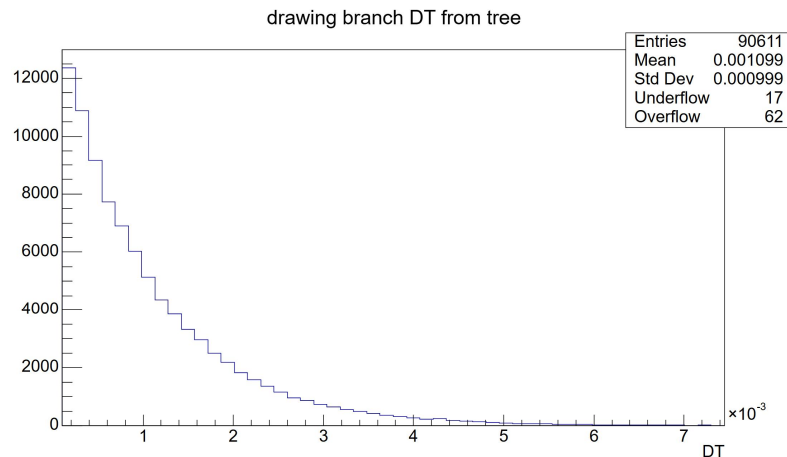
$$p(\Delta t) = f e^{-f\Delta t}, \quad f = R\Delta S$$

Example: $f = 1000$ Hz, $A = 28.155$ V, $\tau = 8.64$ ms

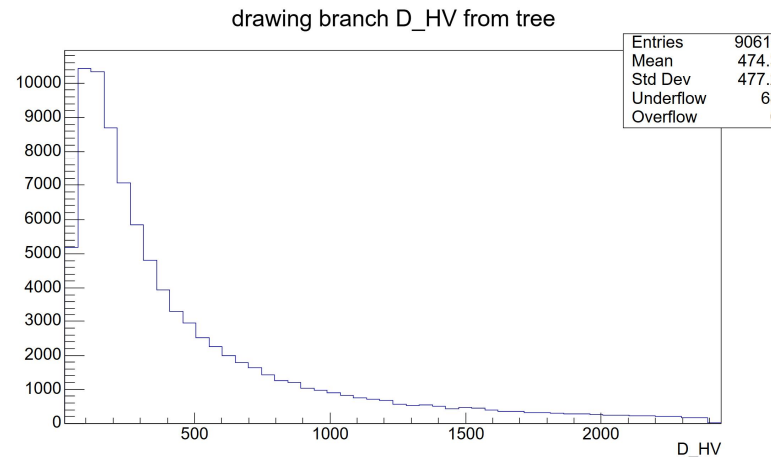
Sampling prescription used here

$$\Delta U_i = \frac{A}{\exp(\Delta t_i/\tau) - 1}$$

Inter-event interval



Sampled voltage drop



f [Hz]	⟨ΔU⟩ [V]
1	1
50	48
100	87
500	299
1000	474
2000	708

The current sampler evaluates the periodic expression at each sampled interval.

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Model validation

$$U_0 = 2400 \text{ V}$$

$$\rho \approx 1.4 \times 10^{10} \Omega \cdot \text{cm}$$

$$\Delta U_i = \frac{A}{\exp(\Delta t_i / \tau) - 1}$$

Stochastic local voltage model

$$U_i = U_0 - \Delta U_i$$

Waveform resampling

Select measured waveforms
at the effective voltage.

Garfield++ simulation

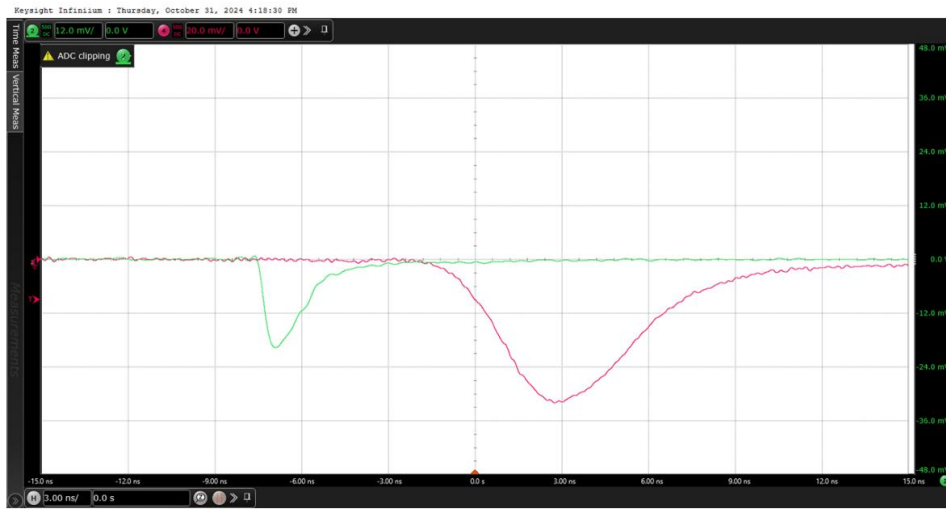
Simulate avalanches
at the effective voltage.

Compare mean charge and time resolution with high-rate data

Low-rate waveform library

2000–2650 V in 50 V steps

4,000 recorded waveforms per voltage

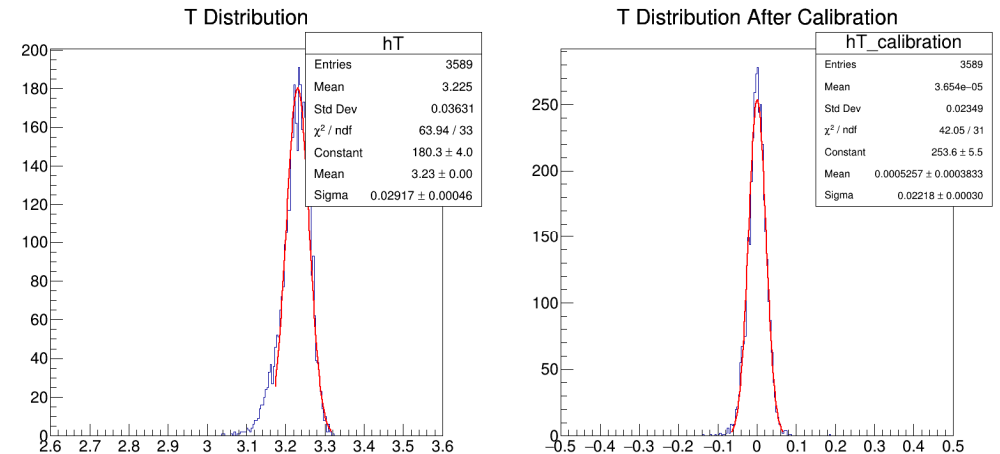


RPC signal: green PMT reference: red

$$\Delta t = t_{\text{PMT}} - t_{\text{RPC}}$$

CFD fraction: 20%

Time-walk correction and Gaussian fit



Before: 29.17 ps

After: 22.18 ps

$$\begin{aligned} \sigma_t &= \sqrt{\sigma_{\text{total}}^2 - \sigma_{\text{system}}^2} \\ &= \sqrt{22.18^2 - 10^2} \text{ ps} \simeq 19.8 \text{ ps} \end{aligned}$$

Waveform resampling method

Input: mean local signal rate f

1 Sample an event interval

↓ Exponential waiting time with mean $1/f$

2 Calculate the effective voltage

↓ Apply the current voltage-drop prescription

3 Select a measured waveform

↓ Randomly sample at the nearest measured voltage

4 Extract charge and time

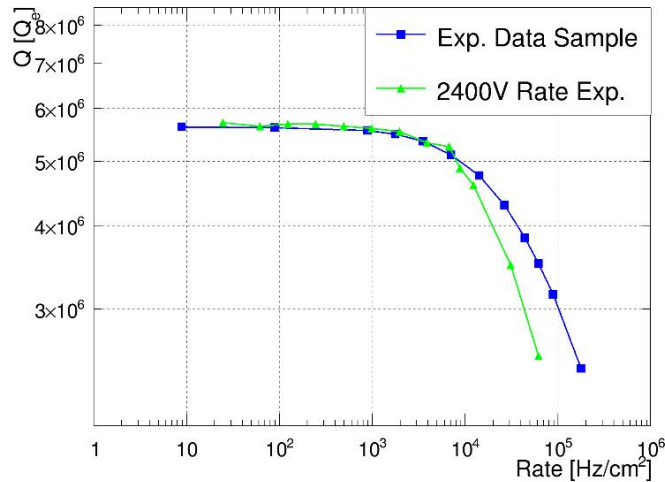
Use the same event analysis as for the data

**Repeat
8,000 times
per rate**

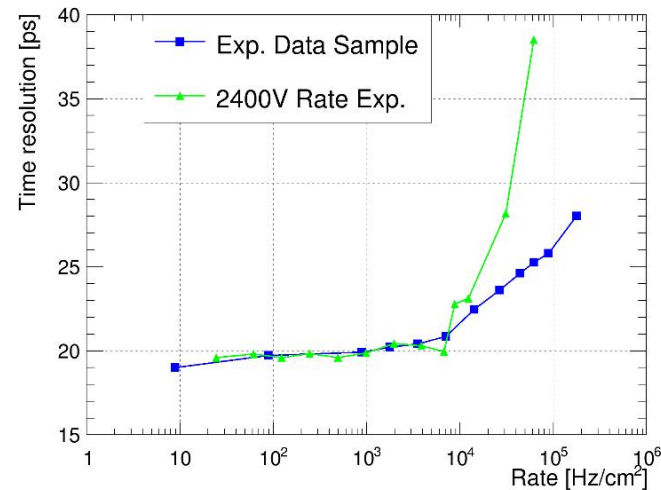
Time-walk correction and Gaussian fit of the resampled ensemble

Waveform resampling results

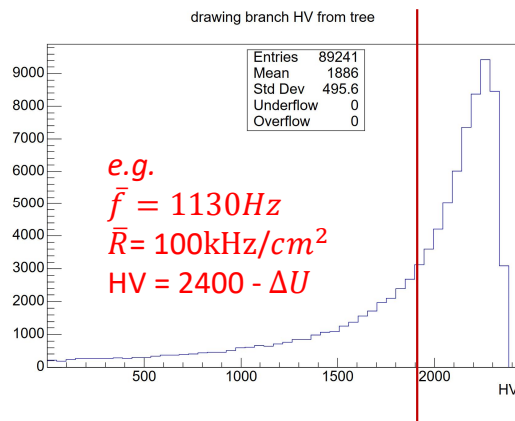
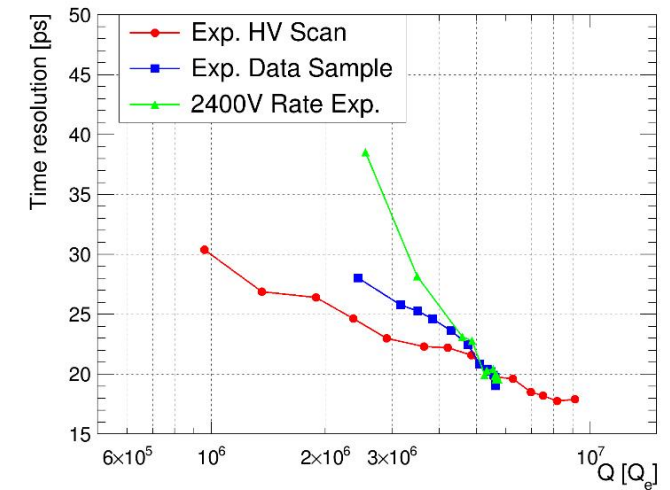
Mean charge



Time resolution



Timing at the same gain



Effective-voltage coverage

Resampling describes the overall measured trends.
Limited voltage coverage can bias the predicted charge and timing distributions.

Garfield++ response model

Uniform electric field within each simulated event

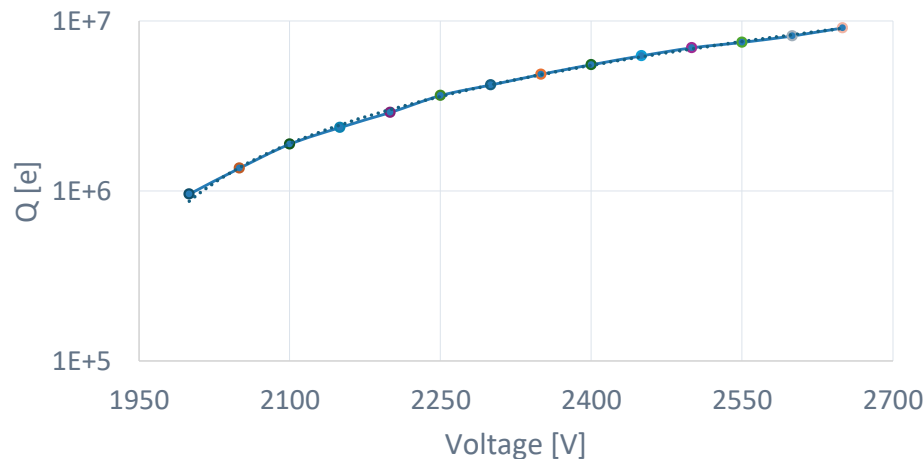
Calibrate the effective Townsend coefficient from the measured mean charge.

$$Q(U) = \exp[\alpha_{\text{eff}}(U)d]$$

```
avalgrid.SetElectronAttachment(0);
avalgrid.SetElectronTownsend(alpha);
```

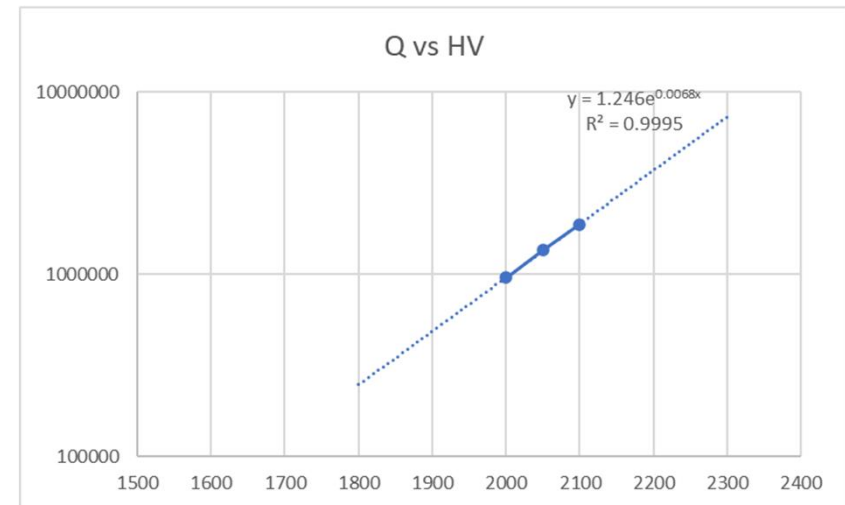
Other transport parameters: gas file

Fit to the measured response



Polynomial fit above 2100 V

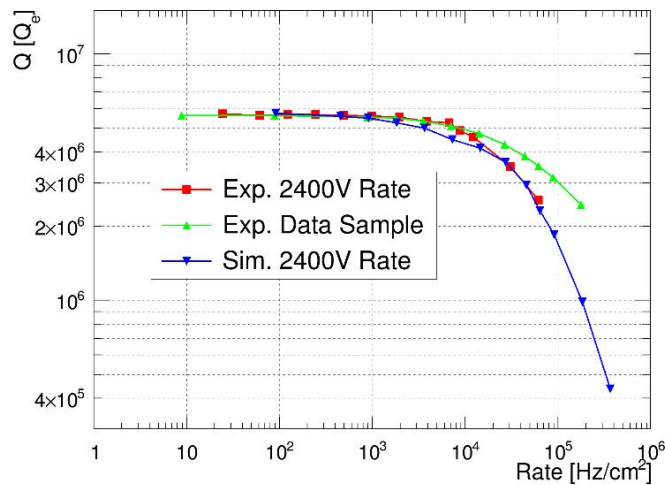
Exponential continuation



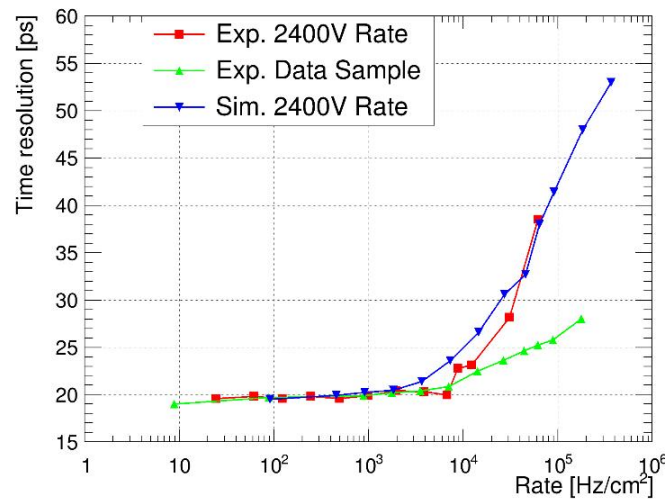
Exponential extrapolation below 2100 V

Comparison with high-rate measurements

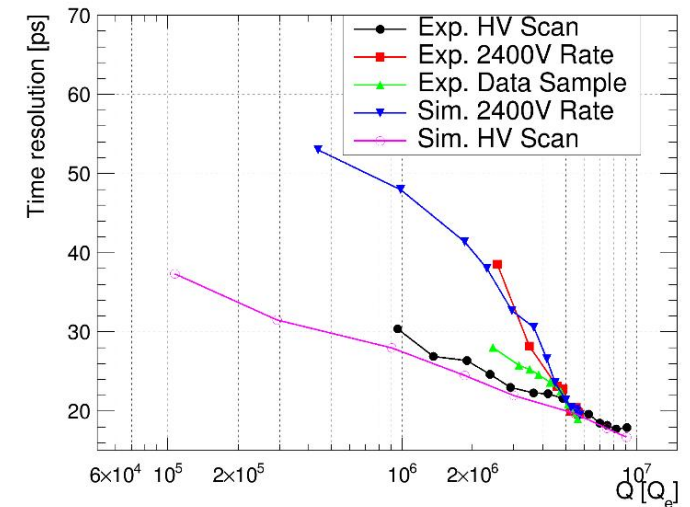
Mean charge



Time resolution



Timing at the same gain



Both approaches describe the main trends.

At comparable mean gain, the high-rate distributions show worse timing.

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Conclusions

Electrode resistivity

Lower bulk resistivity shifts gain loss to higher rates.

Timing at matched mean gain

High-rate timing is worse much than low-rate timing at reduced HV.

Local voltage fluctuations

The model comparisons support a contribution to the extra timing spread.

Validation

Experimental-data resampling and Garfield++ reproduce the measured gain loss and timing degradation.

Backup material

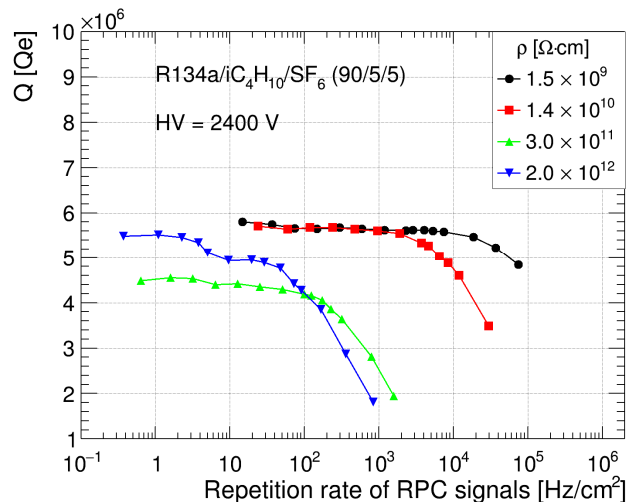
Rate scans and detector details

Rate scans across electrode materials

Single-photoelectron measurements at 2400 V

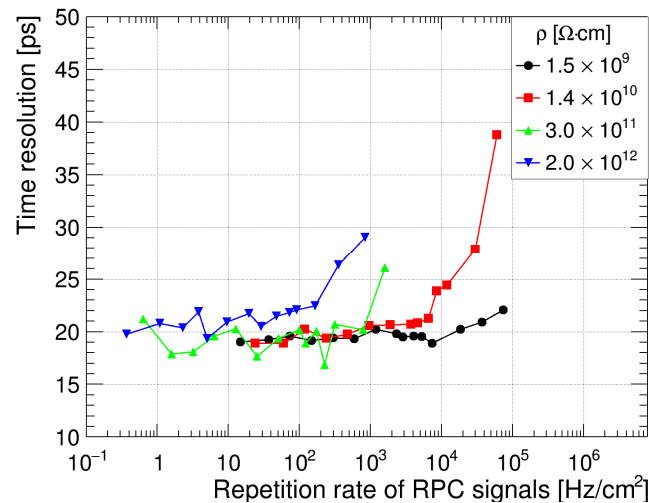
$\rho = 1.5 \times 10^9, 1.4 \times 10^{10}, 3 \times 10^{11}$ and $2 \times 10^{12} \Omega \cdot \text{cm}$

Mean charge

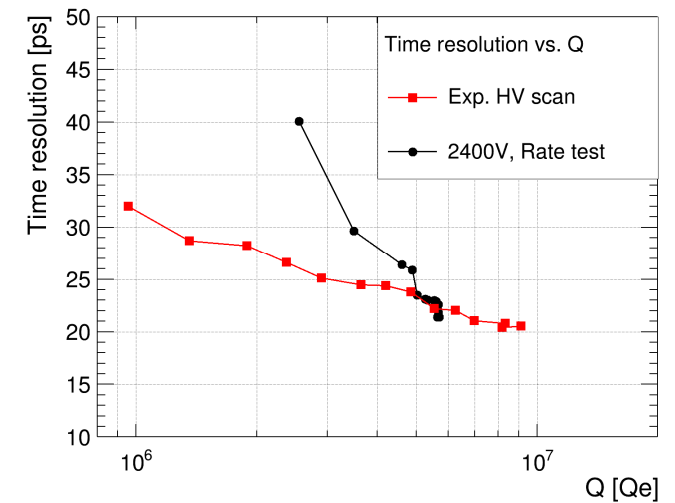


[DOI: 10.1088/1748-0221/20/10/C10001](https://doi.org/10.1088/1748-0221/20/10/C10001)

Time resolution



Timing at the same gain

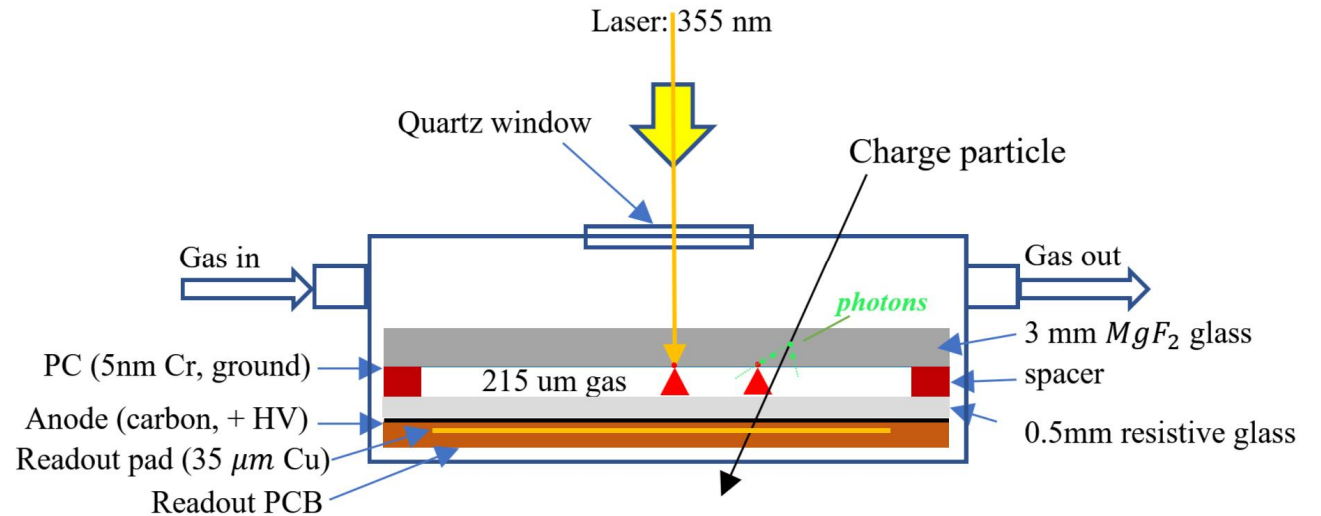
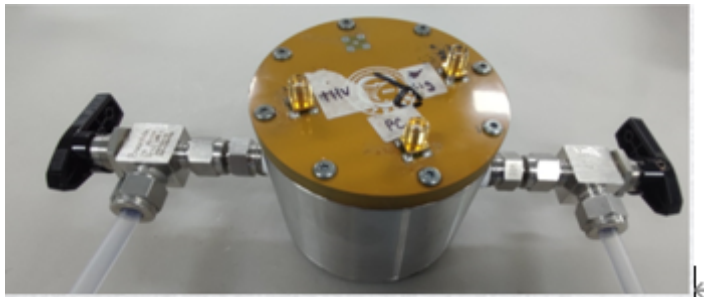


The highest-resistivity sample is quartz.

Photo-RPC detector and timing

Photoelectrons originate at the photocathode plane.

215 μm gap, R134a / SF₆ / i-C₄H₁₀ = 90 / 5 / 5



2500 V

$\sigma = 19.78 \text{ ps}$

After time-walk correction

$$\sigma_t \propto \frac{1}{\alpha v_d} \propto \frac{1}{E^2}$$

Qualitative scaling estimate

[DOI: 10.1016/j.nima.2025.170593](https://doi.org/10.1016/j.nima.2025.170593)

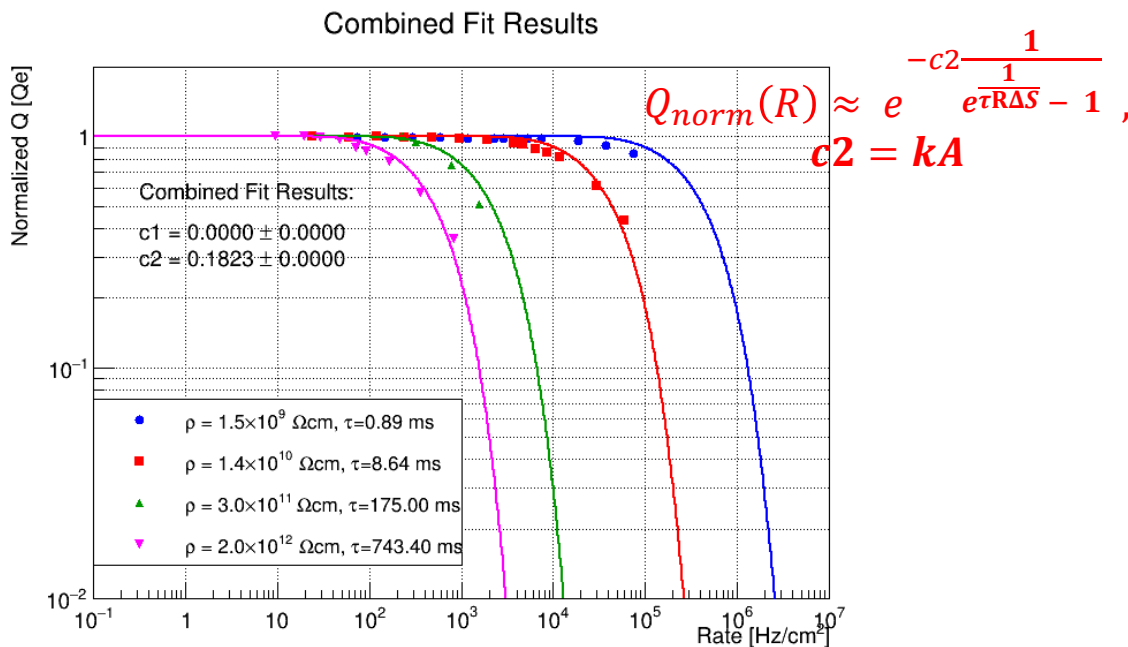


Fits to the rate-dependent mean charge

Four electrode resistivities at an applied voltage of 2400 V.

The mean charge is normalized;

$\Delta S = \pi(0.06\text{cm})^2$ is the laser-spot area and $\tau = \epsilon_0 \epsilon_r \rho$ is the relaxation time.



Recovery time: estimated from material properties

Fit parameter: $c2 = kA$

$\rho [\Omega \cdot \text{cm}]$	ϵ_r	$\tau = \epsilon \cdot \rho [\text{s}]$
1.5e9	6.682	0.000887
1.4e10	6.973	0.00864
3e11	6.589	0.175
2e12 (quartz)	4.2	0.7434

$$\bar{Q} = e^{k \cdot (U_0 - A \frac{1}{e\tau R\Delta S - 1})}, \text{ at low rate, } \bar{Q} = e^{k \cdot U_0}$$

For $U_0 = 2400\text{V}$, $\rho = 1.4e10 \Omega\text{cm}$

$$e^{kU_0} = 5.5e6, \Rightarrow kU_0 = 15.5397;$$

$$c2 = kA = 0.1823, \Rightarrow A = 28.155$$

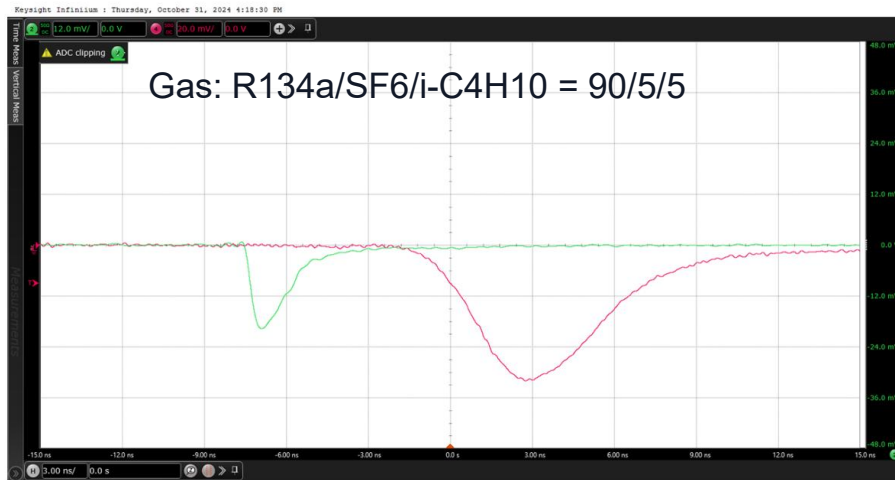
$$\overline{\Delta U} = \frac{A}{\frac{1}{e\tau R\Delta S} - 1} = \frac{28.155}{\frac{1}{e0.00864 \cdot R \cdot \Delta S} - 1}$$



Data analysis

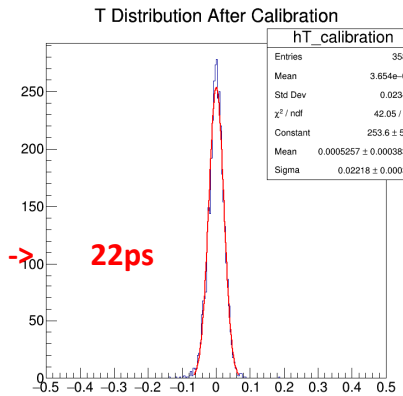
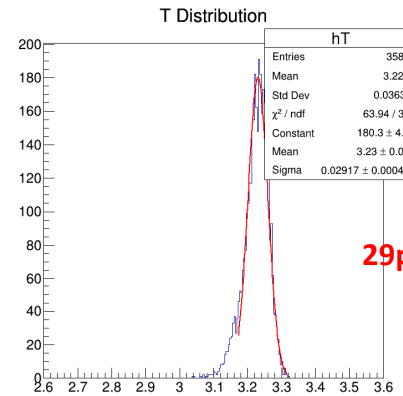
HV scan: 1900–2650 V in 50 V steps
Recorded waveforms: 4000 per voltage

CFD timing with a fraction of 20%, followed by time-walk correction.



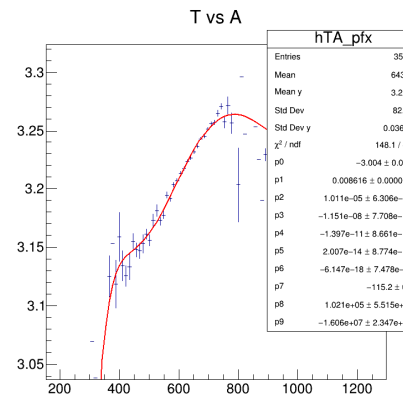
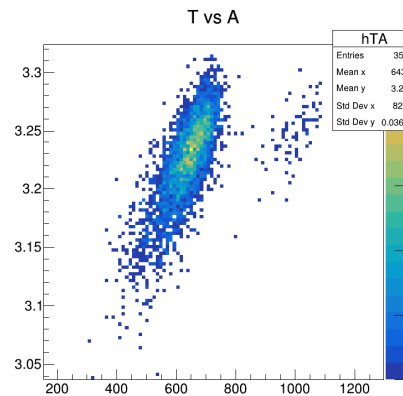
Oscilloscope traces: RPC signal in green;
PMT reference in red.

$$\Delta t = t_{PMT} - t_{RPC}$$



Before time-walk
correction: $\sigma \approx 29\text{ps}$

After time-walk
correction: $\sigma \approx 22\text{ps}$



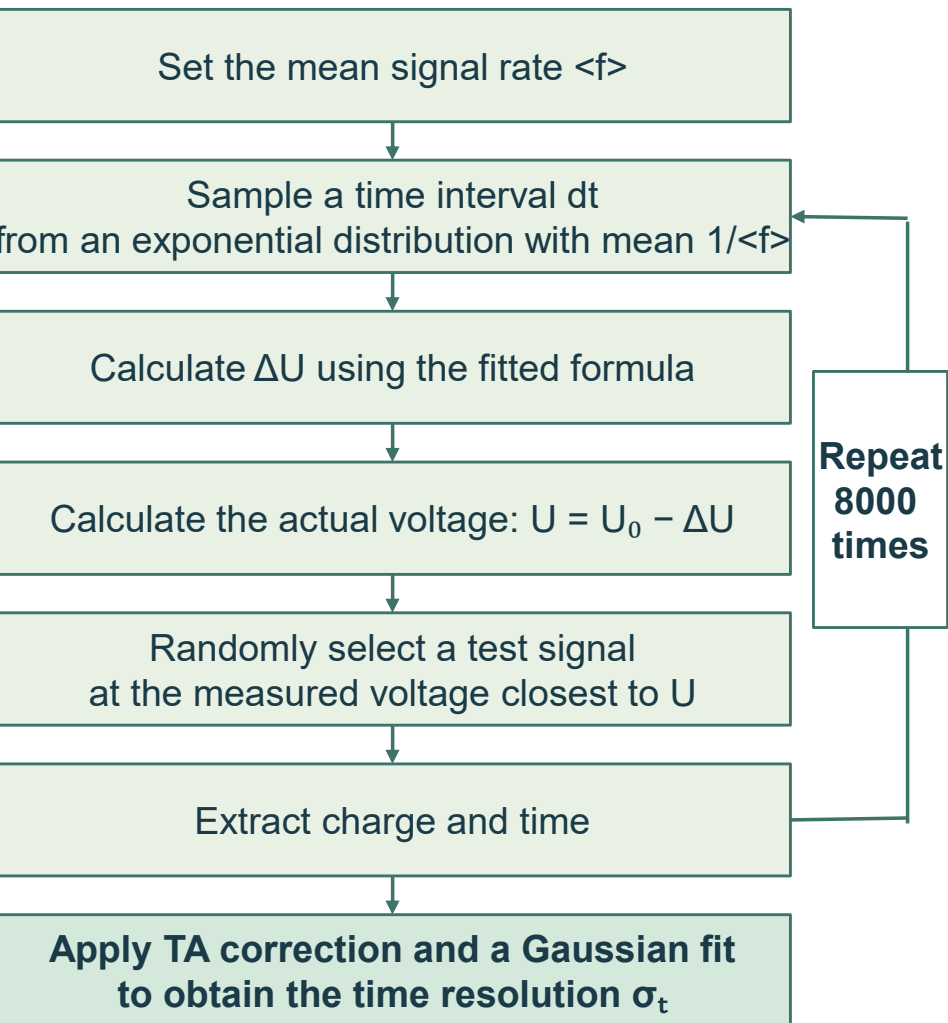
Intrinsic timing

$$\sigma_t = \sqrt{\sigma_{\text{total}} - \sigma_{\text{system}}}$$
$$= \sqrt{22^2 - 10^2} = 19.8\text{ps}$$



Waveform resampling with the voltage mode

Signal sampling and time-resolution analysis



The voltage model selects the operating point for each sampled event.