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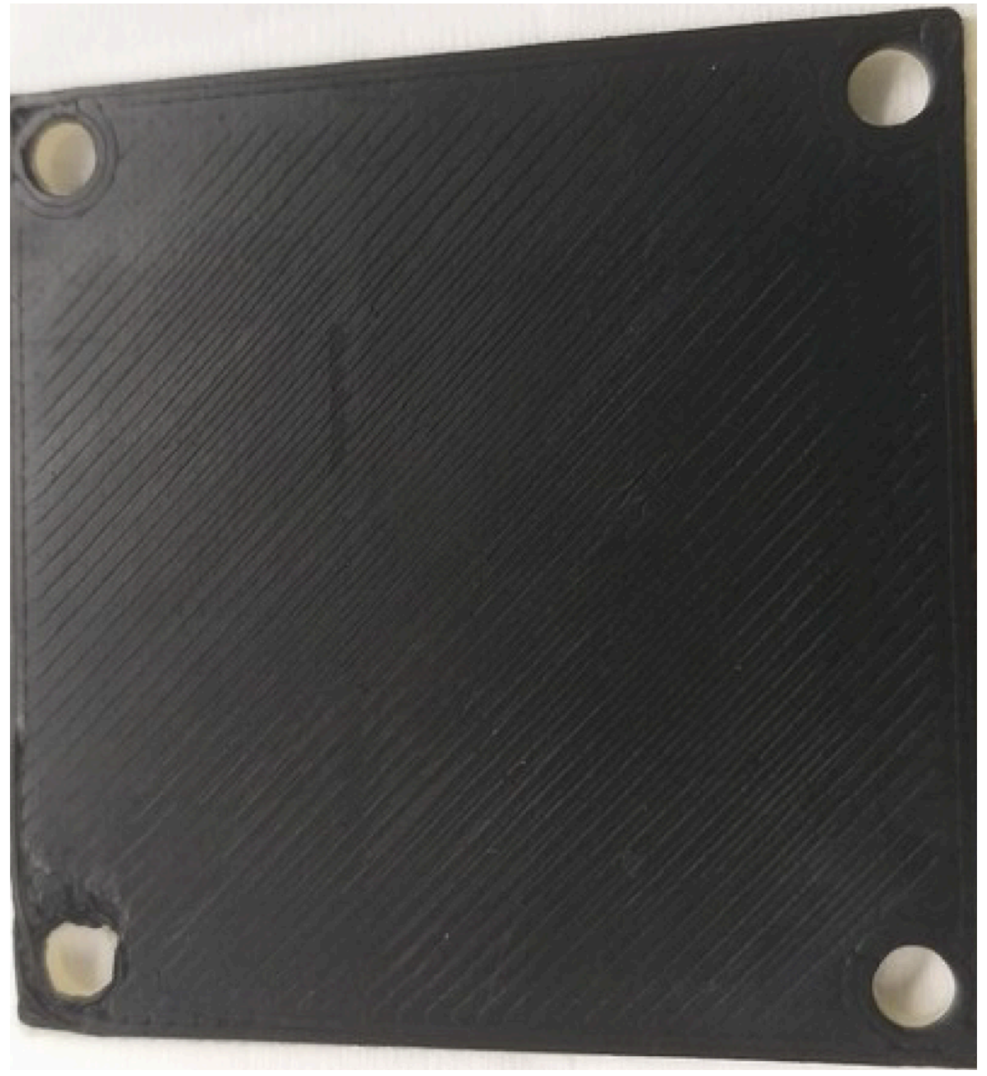
Discharge quenching mechanism and RPWELL performance with tunable 3D printed resistive plates

Luca Moleri - Abhik Jash - 3rd International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors
CERN, 8th November 2023

Discharge quenching and resistive materials
Motivation for the present study

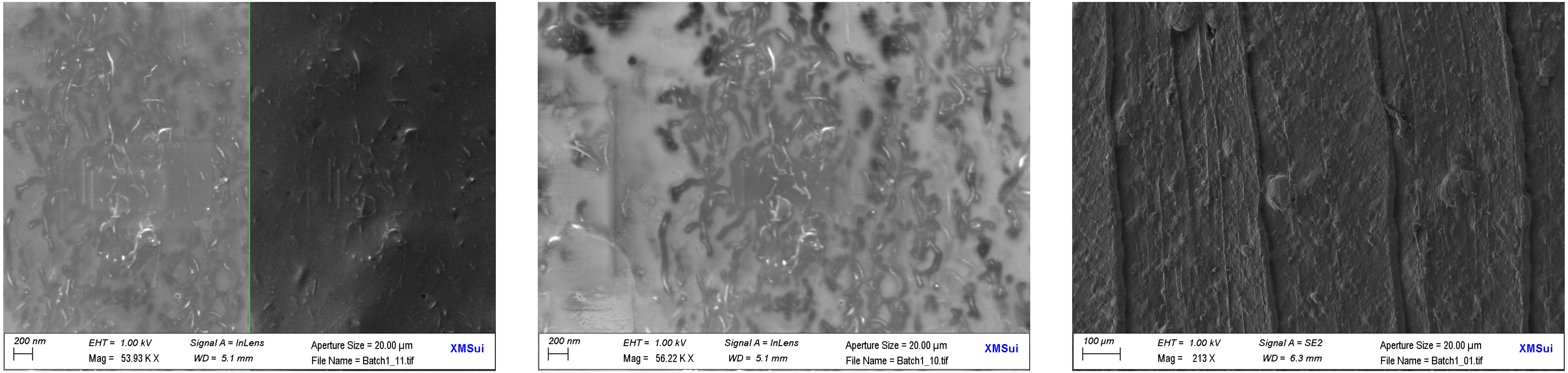
- At present the available selection of **resistive plate materials** is small (e.g. Semitron ESD 225, semiconductive glass*)
- Classic resistive materials have fixed resistivity (at fixed temperature)
  → no optimization wrt rate and quenching power
- The **physics of discharge quenching** and the effect of quenched discharges on detectors is still not well understood
- In this work we
  1. Produce and characterize 3D printed resistive plates with tunable resistivity
  2. Use classic and tunable resistive plates to investigate discharge quenching effects (quenching power, charge persistence, discharge probability, gain variations)

* Wang, Y., Wang, J., Yan, Q., Li, Y. and Cheng, J., 2008, October. Study on the performance of high rating MRPC. In *2008 IEEE Nuclear Science Symposium Conference Record* (pp. 913-916). IEEE.



3D printed resistive plates
with tunable resistivity

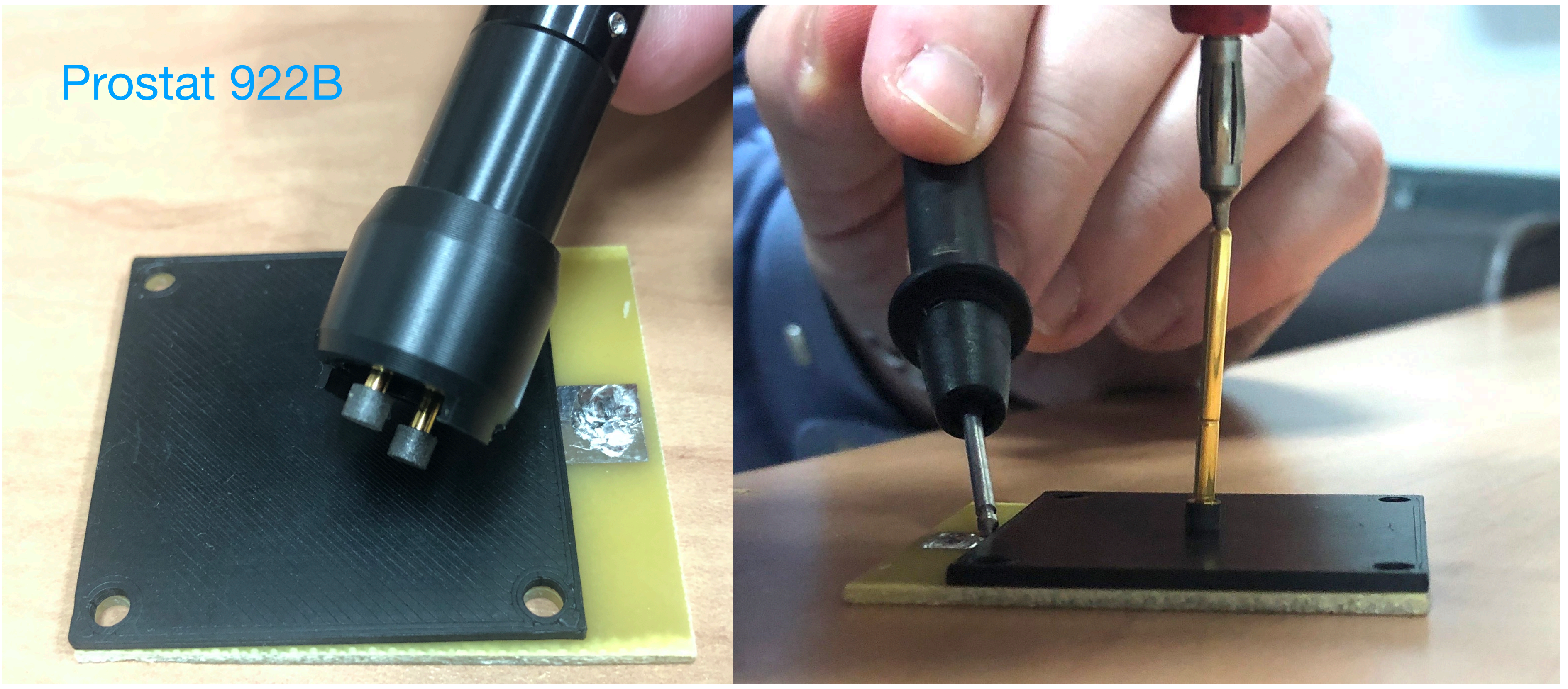
- 3DXSTAT^{TM} ESD ABS (Acrylonitrile Butadiene Styrene)
- Conductive additive: embedded multi-wall carbon nano-tubes (CNT)
- Printed with standard FDM 3D printer.
  Hot base and extruder nozzle temperature are inversely proportional to sample resistivity (min ~10^5 Ω cm)
- Samples of different thickness and resistivity were produced by 3D & functional printing center @HUJI



SEM images by Xiaomeng Sui @WIS. Directionality of filament deposition and of CNT distribution are clearly visible.

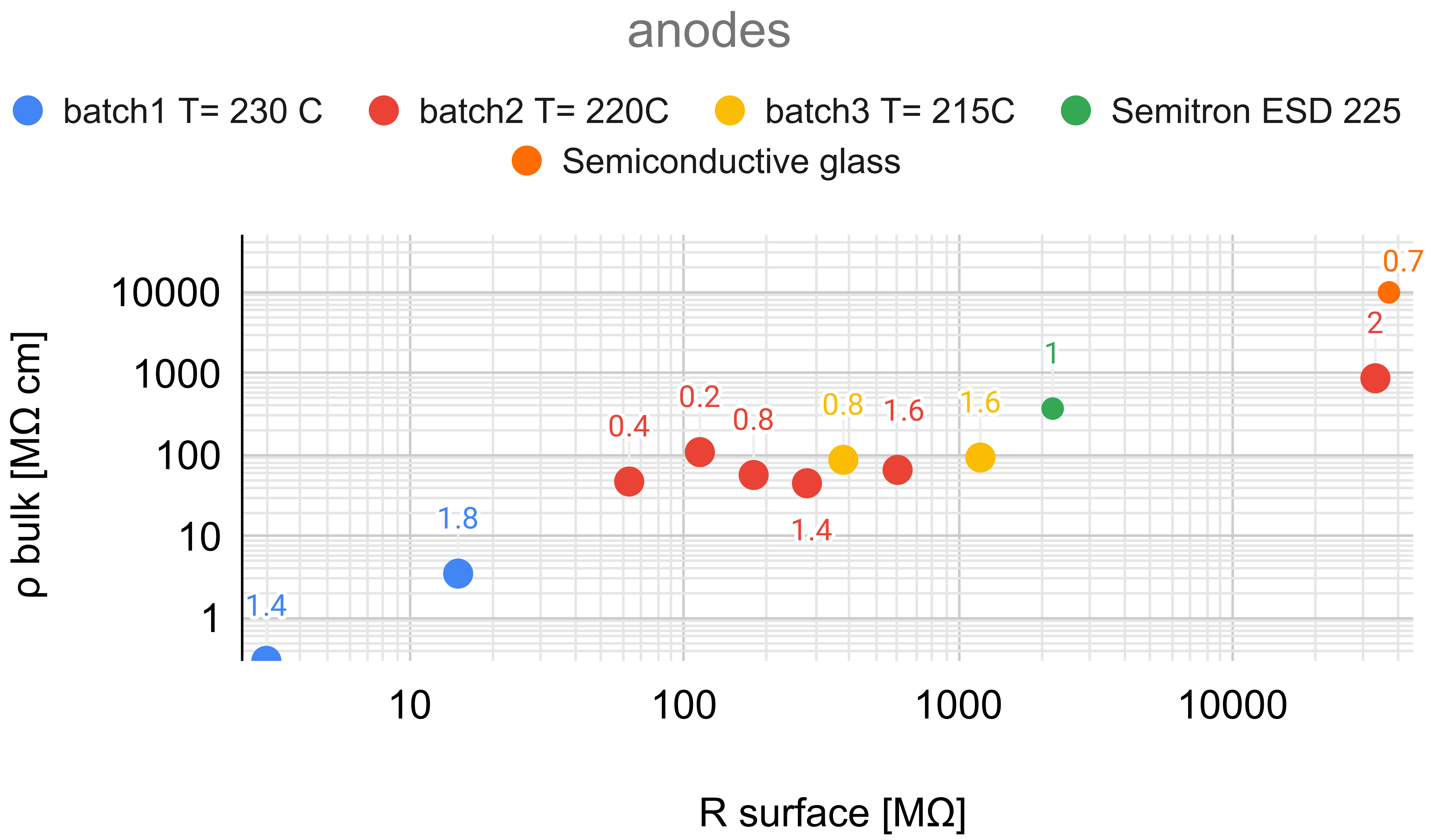
3D printed resistive plates

characterization: variable T and thickness



ANSI/ESD STM11.13 Bulk resistivity @50V-250V

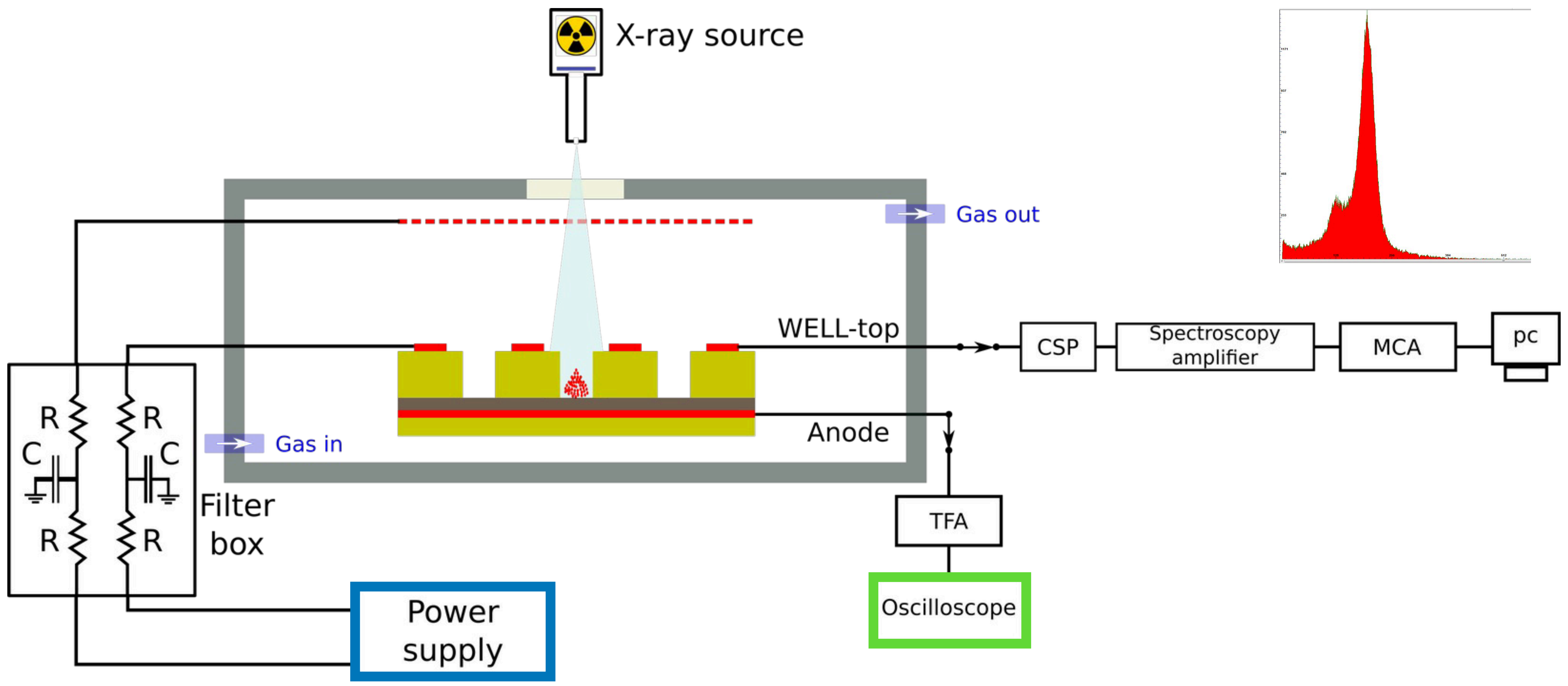
- RP characteristics are not predictable as a function of T only.
  Large variability from plate to plate
- Need a dedicated measurement of surface and bulk resistance for each anode
- **Surface resistance** of hot plate side increases quite consistently for thicker plates (labels) while **bulk resistivity** fluctuates. Batch 2 with t= 2 mm sample shows exceptionally high resistivity.
  (Semitron and semiconductive glass are referenced).
- Surfaces are important, bulk measurements are not enough to characterize samples



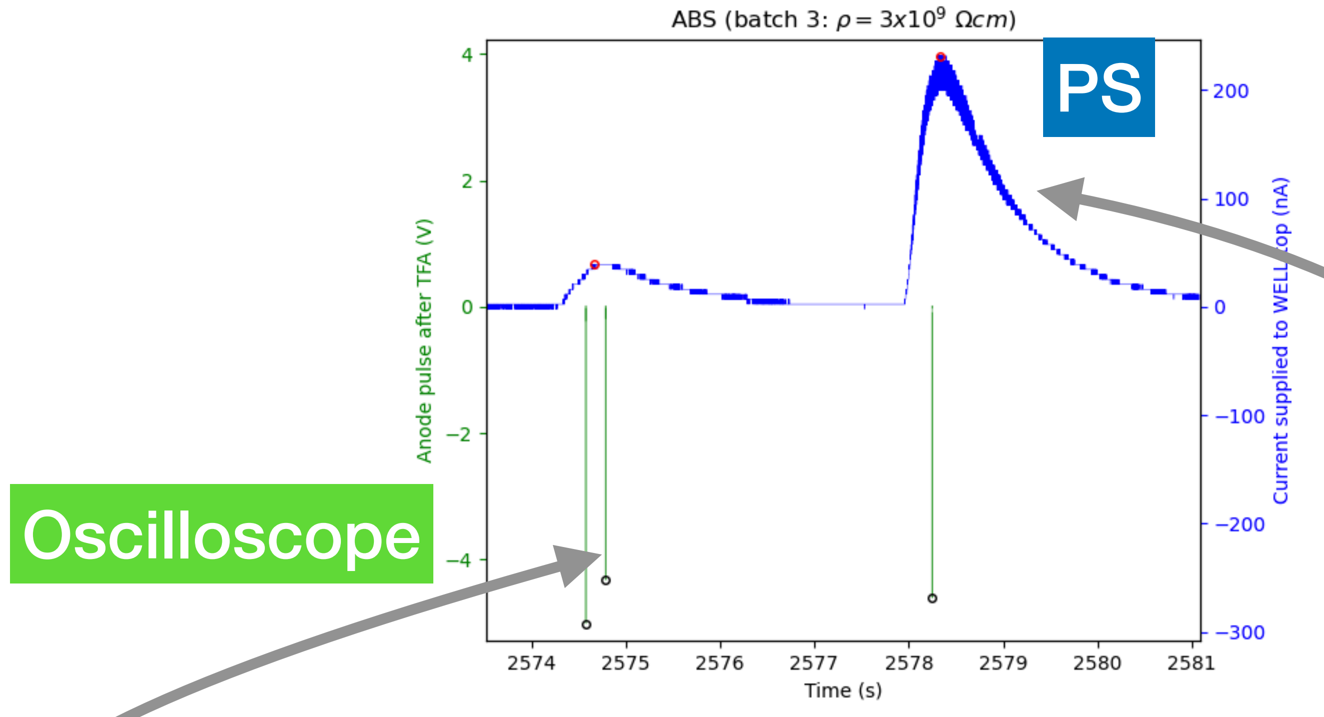
The RPWELL detector

characterization of gain and electrical breakdown

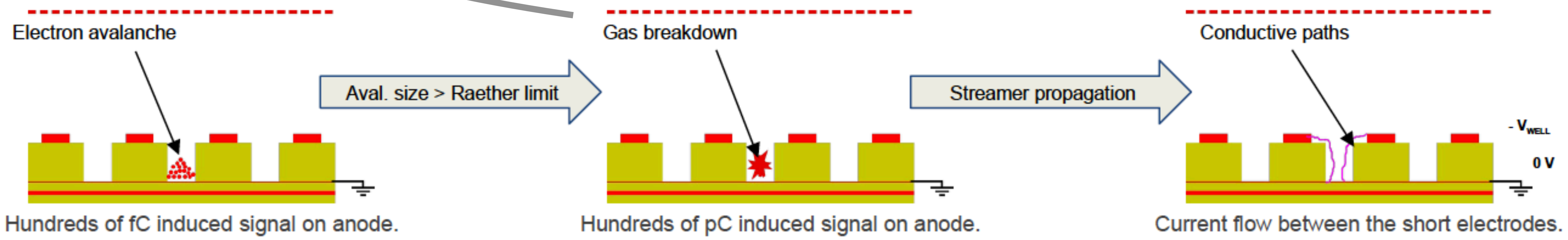
- RP+anode at ground potential.
  During a quenched discharge the hole region is charged up with ~10nC, resulting in a local potential change relative to the effective capacitance involved*
- When gas breakdown occurs:
  - Large current pulse is **induced** on Anode and WELL-top
  - **DC current** is produced by detector capacitance discharge between WELL and anode
- Amplitude of anode pulses is calibrated to measure **induced charge from gas breakdown**
- Power supply currents are recorded and integrated to measure **discharge intensity**
- RPWELL gain is monitored as a function of time and source rate



Setup for characterization of RPWELL gain and electrical breakdown



Model of electrical breakdown mechanism



*Jash, A., Moleri, L. and Bressler, S., 2022. Electrical breakdown in Thick-GEM based WELL detectors. *Journal of Instrumentation*, *17*(11), p.P11004.

The RPWELL detector

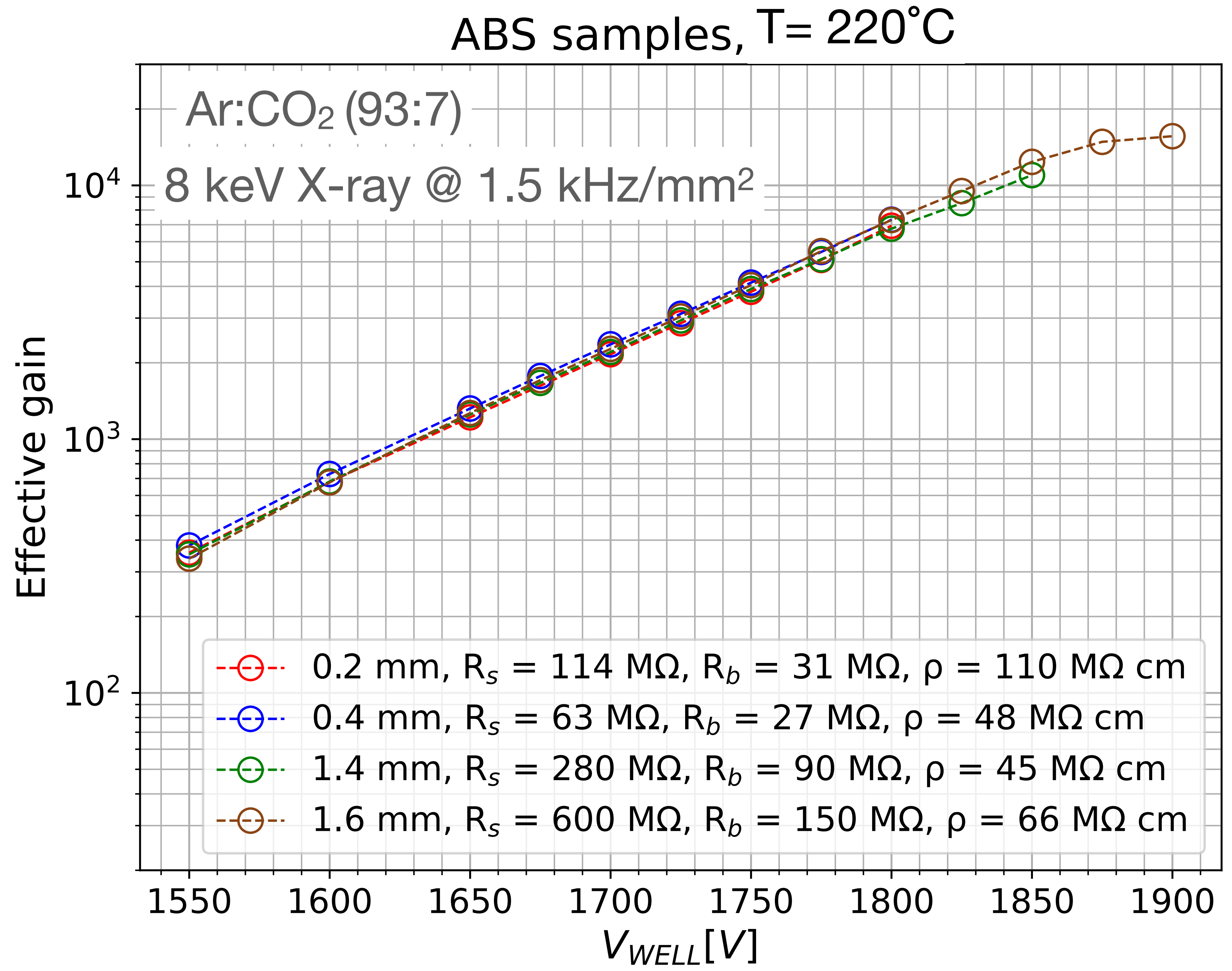
Gain vs RP thickness

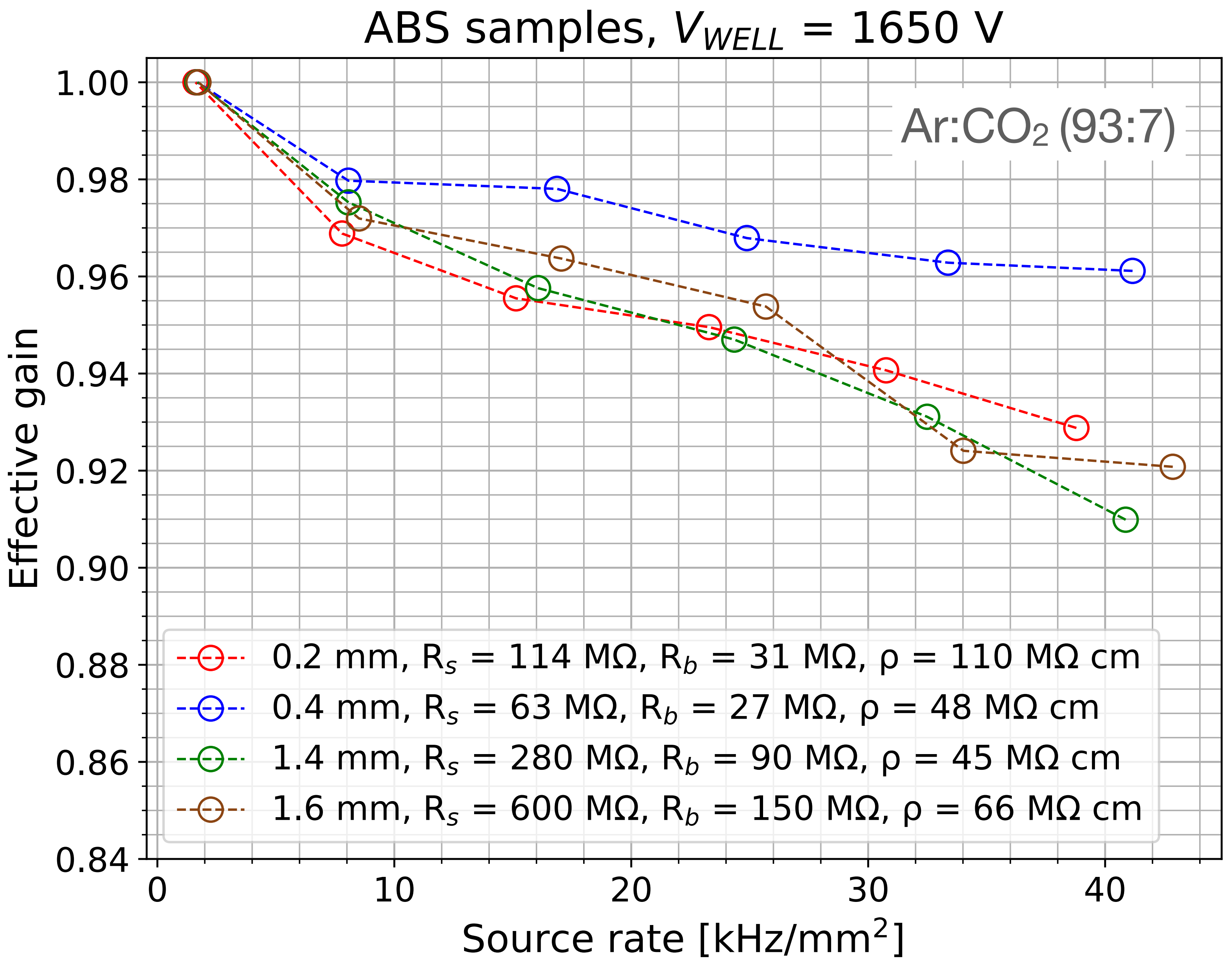
114 MΩ < R_s < 600 MΩ, 30 MΩ < R_b <150 MΩ

- maximum gain achieved ~ 1.5×10^4
  (translates to ~ 5×10^6 e-, Raether limit?)
- Stopping measurement when spectrum gets distorted because of discharges or quenched discharges
- Max gain is higher, reaching saturated regime at larger RP thickness, R_s and R_b (how to disentangle the effects?)

In this resistivity range:

- **Gain** does not depend on **RP thickness**: RP is transparent like an insulator allowing induced signal across it but it does not affect the weighting field (no field within RP, like a conductor)
- **Rate** dependance is mildly affected by **thickness**, and by **bulk and surface resistance**
  (caveat - might be different if current through entire electrode area)





The RPWELL detector

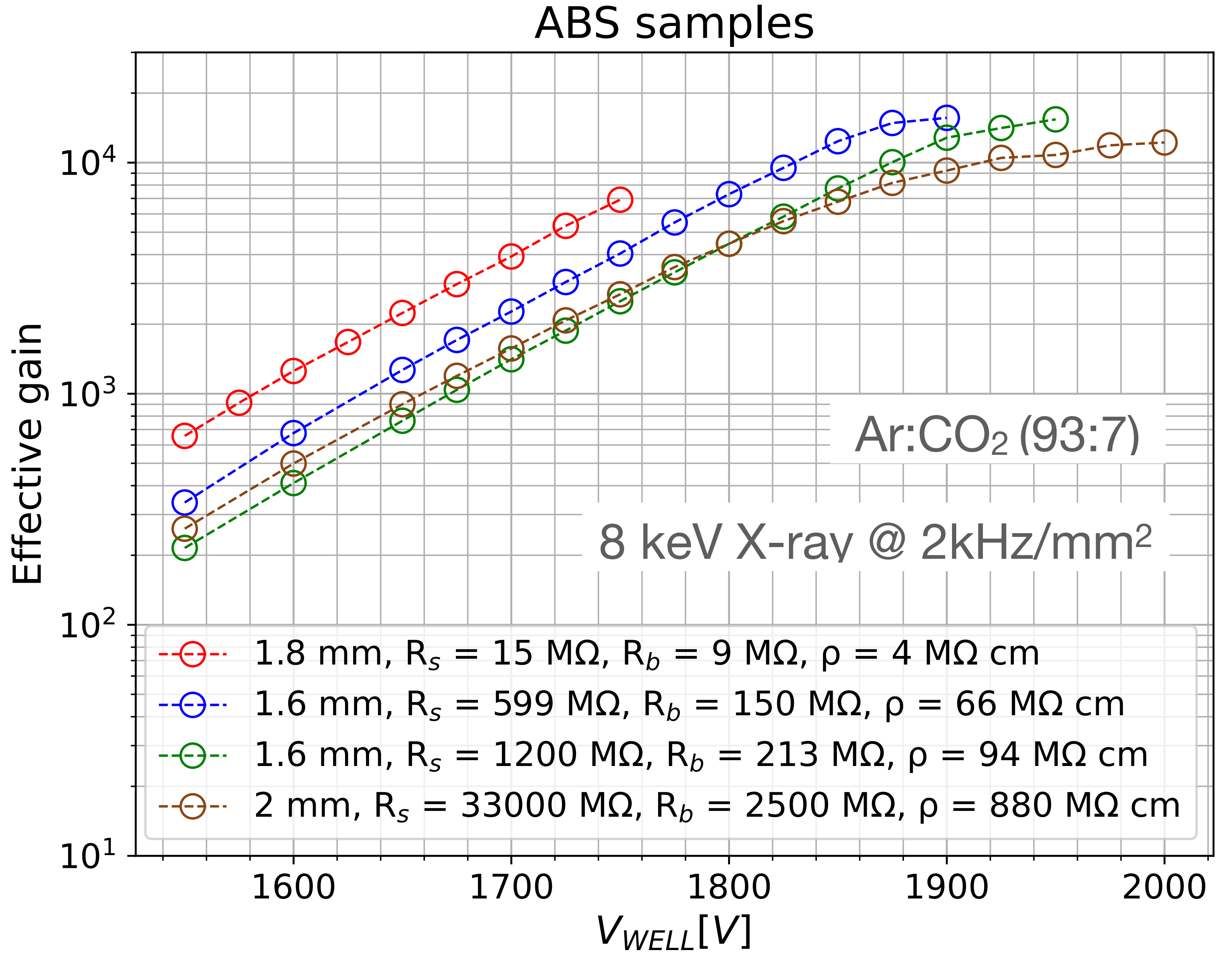
Gain vs resistivity

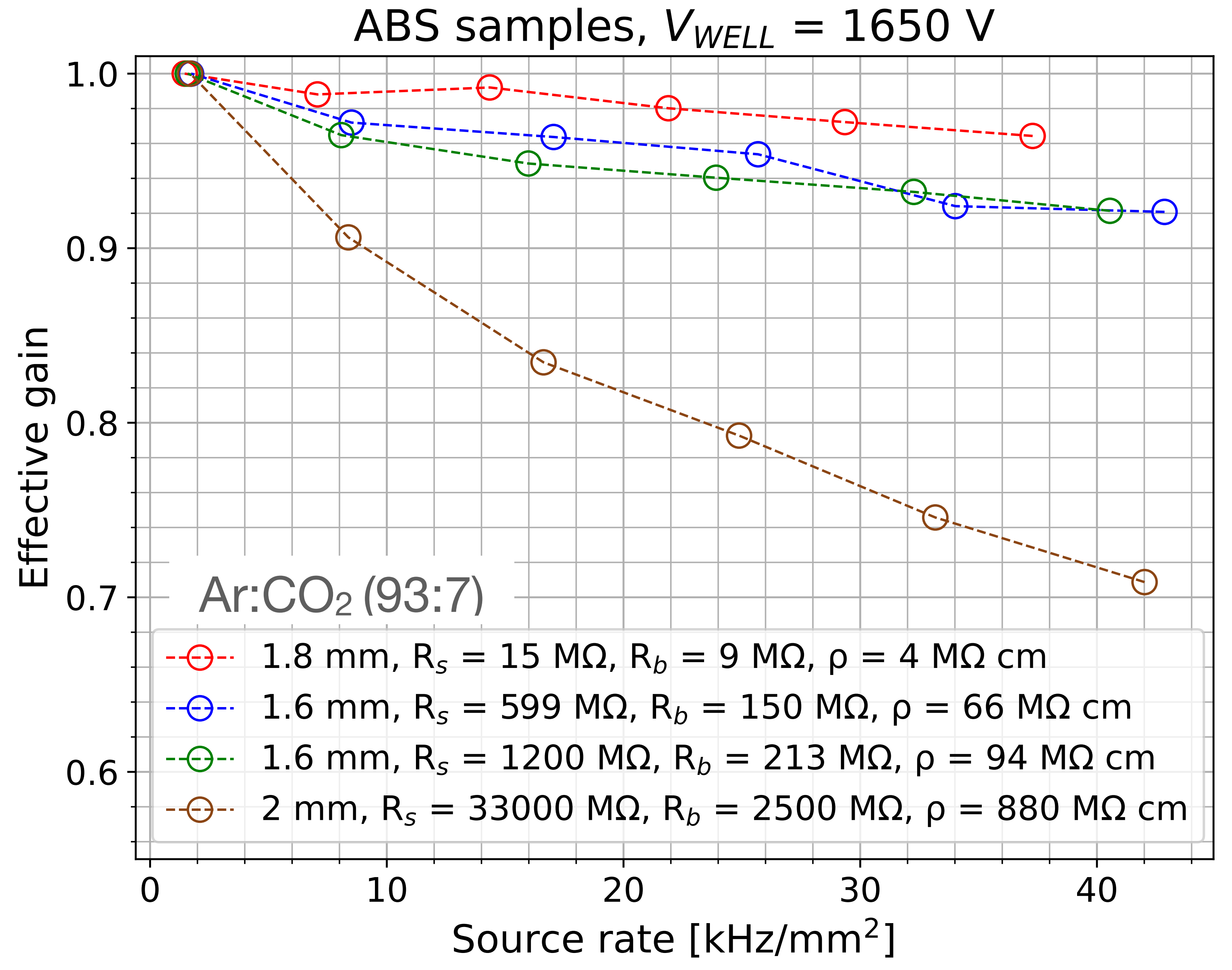
15 MΩ < R_s < 33 GΩ, 9 MΩ < R_b < 2.5 GΩ

- Lower gain at higher resistivity values could be due both to a rate effect and to weighting field.
  A measurement in current mode should allow distinguishing the two.

- Rate dependance is mild, except for the most resistive sample (R_s= 33 GΩ, R_b= 2.5 GΩ, ρ= 880 MΩ cm)

- Gain saturation regime starts:
  15 MΩ < R_s < 600 MΩ
  9 MΩ < R_b < 150 MΩ
  4 MΩ cm < ρ < 66 MΩ cm

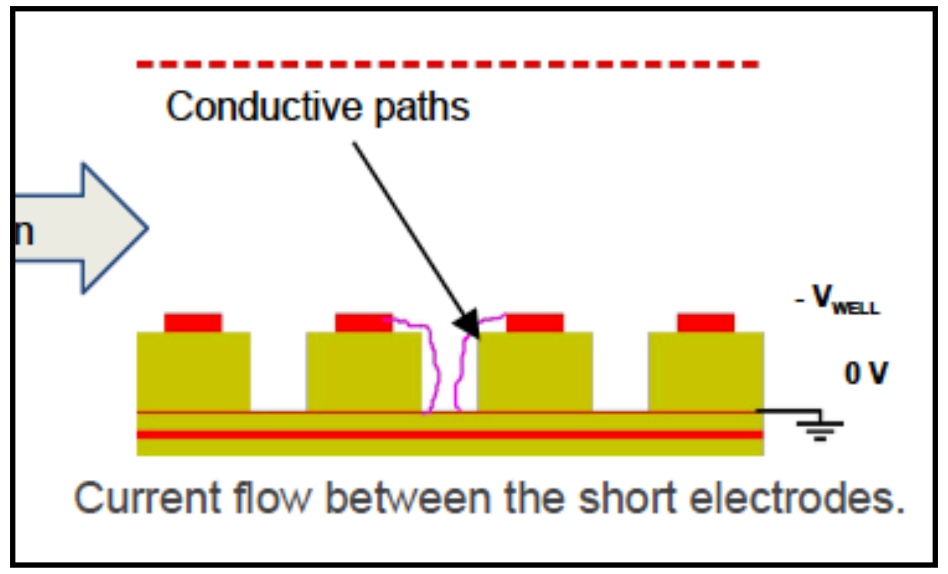




Discharge characterization

Power supply currents

Discharge



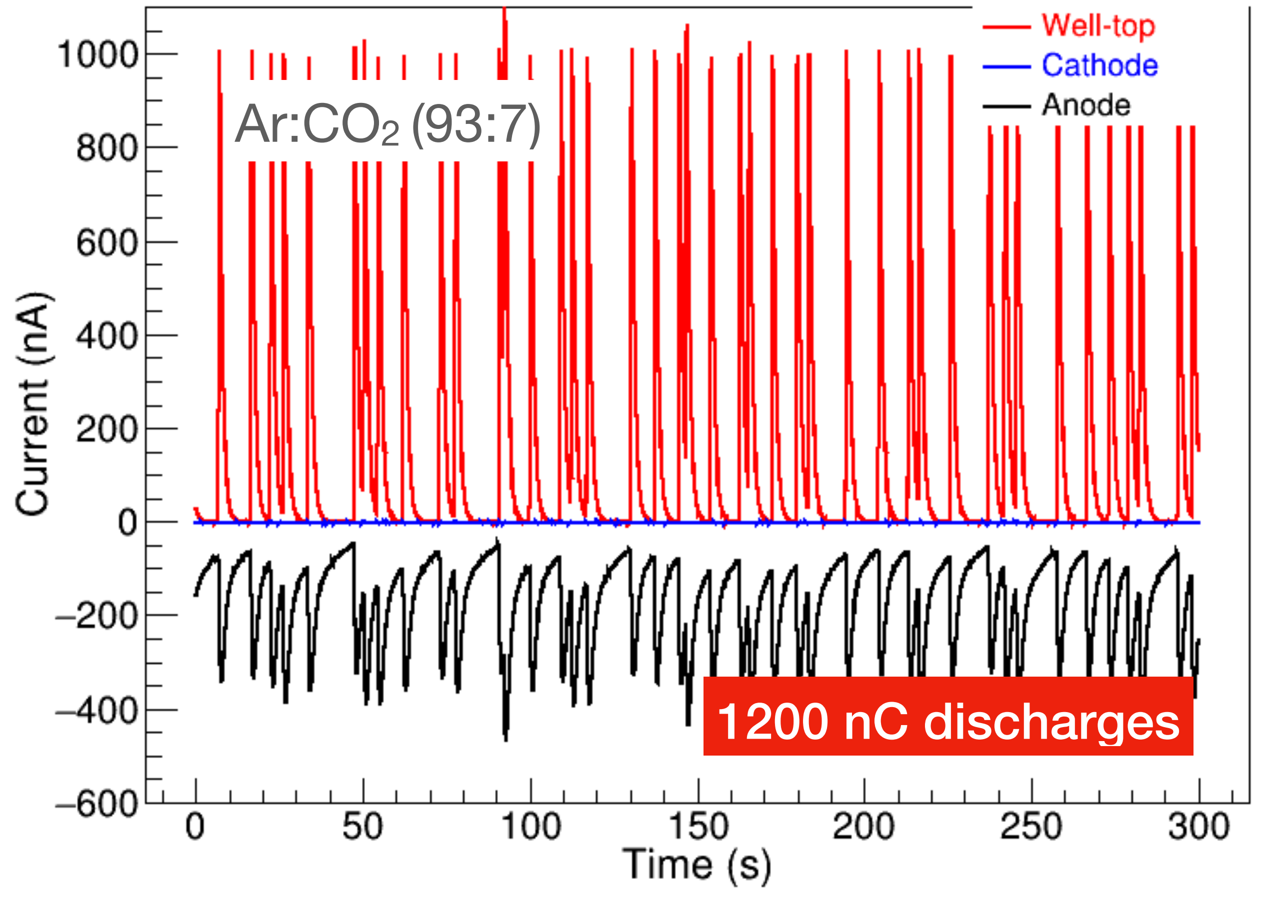
Three different discharge regimes identified

1) Non quenching region:

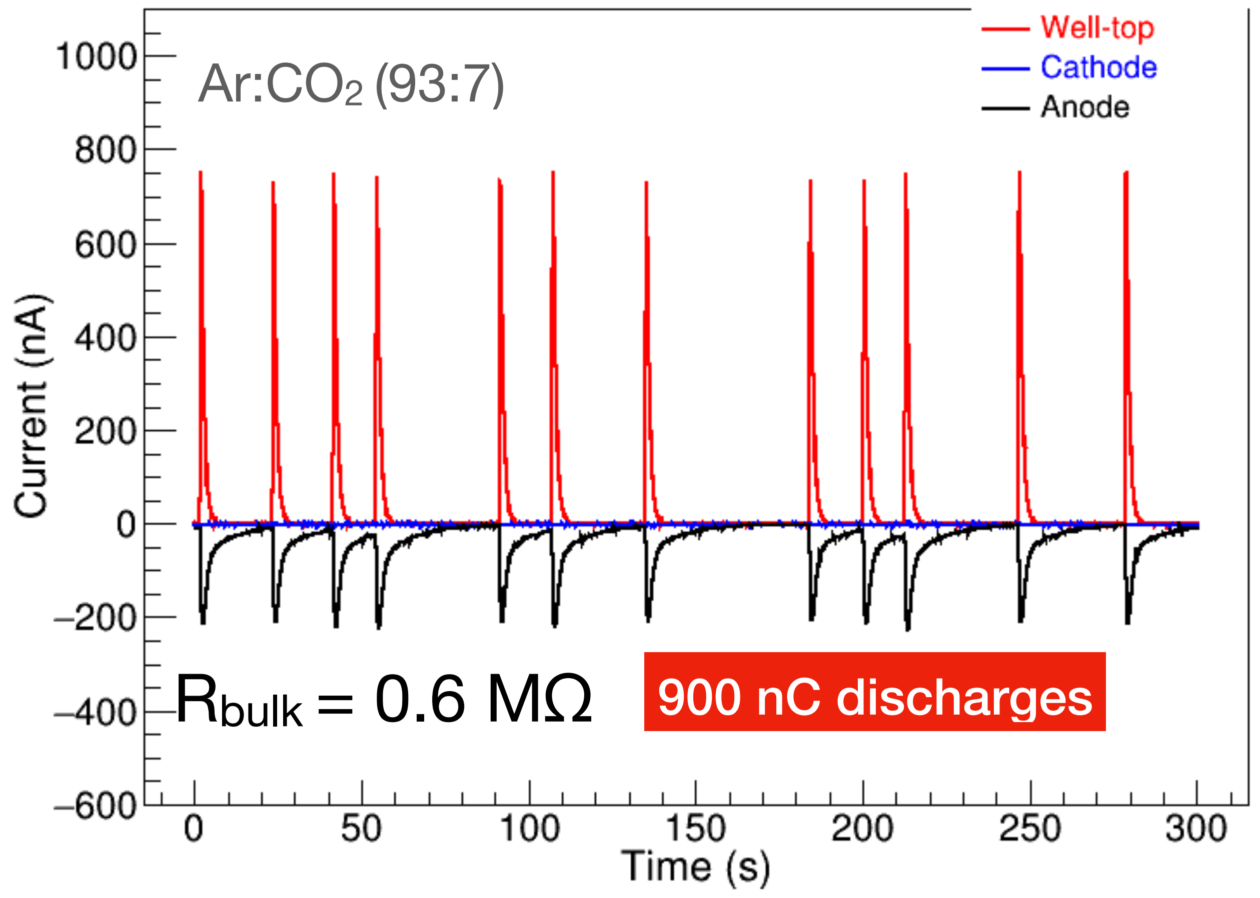
$R_{bulk} < 50\ M\Omega$

- For THWELL discharge $C_{well-RP}$~nF (including HV cable and PS)
- Any RP allows reaching higher voltages with respect to THWELL (lower discharge probability)
- Thick (1.8 mm) ρ= 4 MΩ cm and thin (0.4mm) ρ= 48 MΩ cm plates can only mildly reduce discharge intensity

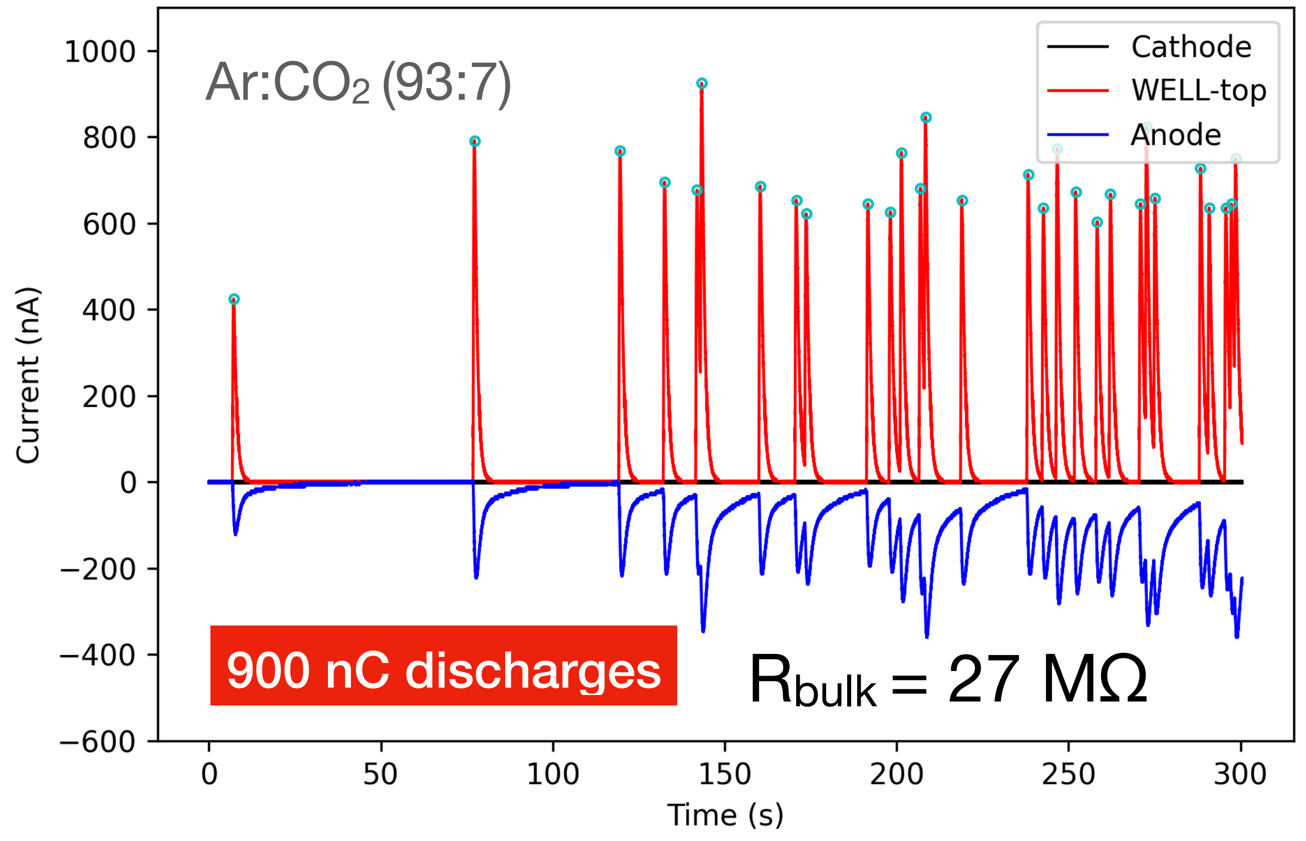
No RP (THWELL) - 1650 V



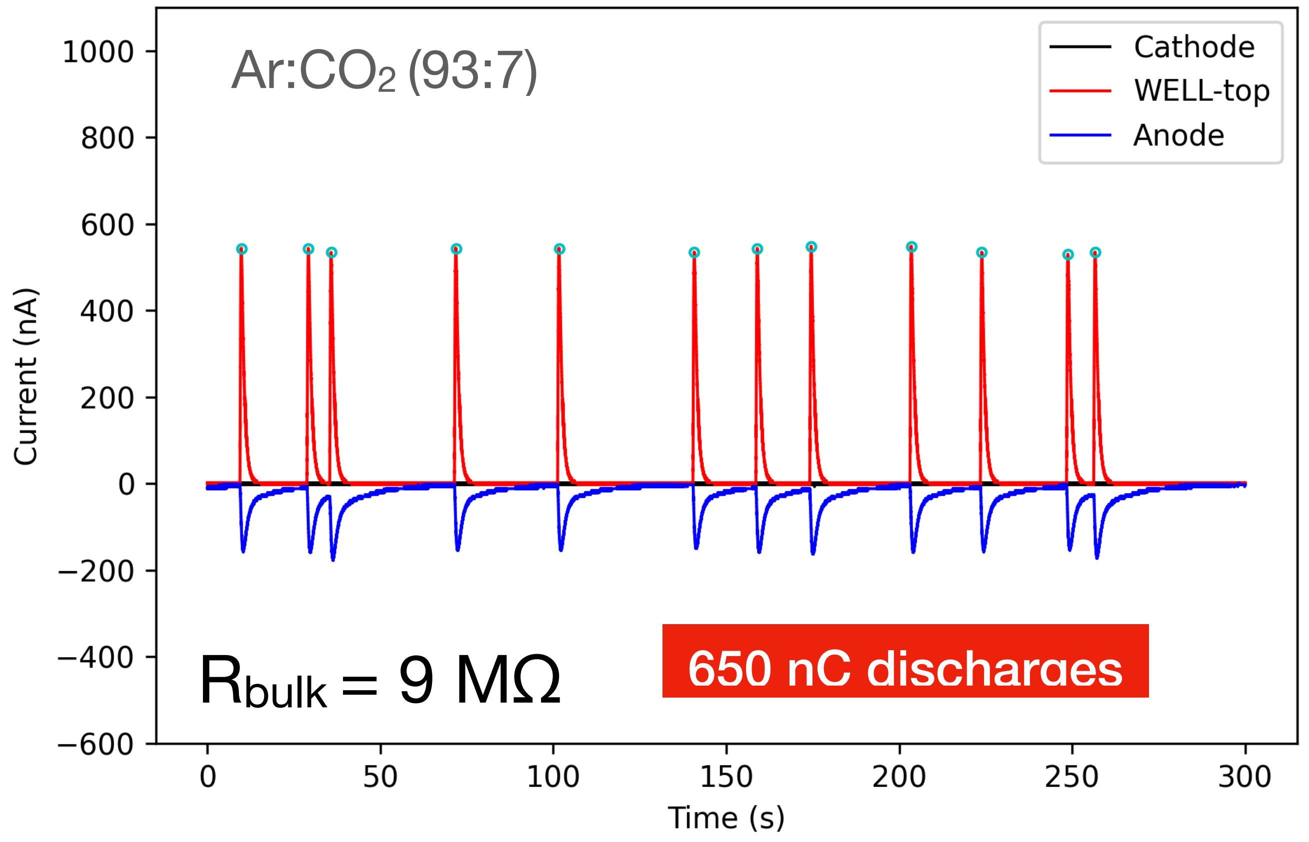
ρ= 0.3 MΩ cm ABS 1.4 mm - 1750 V



ρ= 48 MΩ cm ABS 0.4 mm - 1800 V



ρ= 4 MΩ cm ABS 1.8 mm - 1750 V



Discharge characterization

Power supply currents

Three different discharge regimes identified

2) Transition region:

50 MΩ < R_{bulk} < 250 MΩ

- Both quenched and non-quenched discharges
    - ~150-200 nC discharges (material defects?)
    - Quenched discharges ~10 nC (quite close to baseline noise)

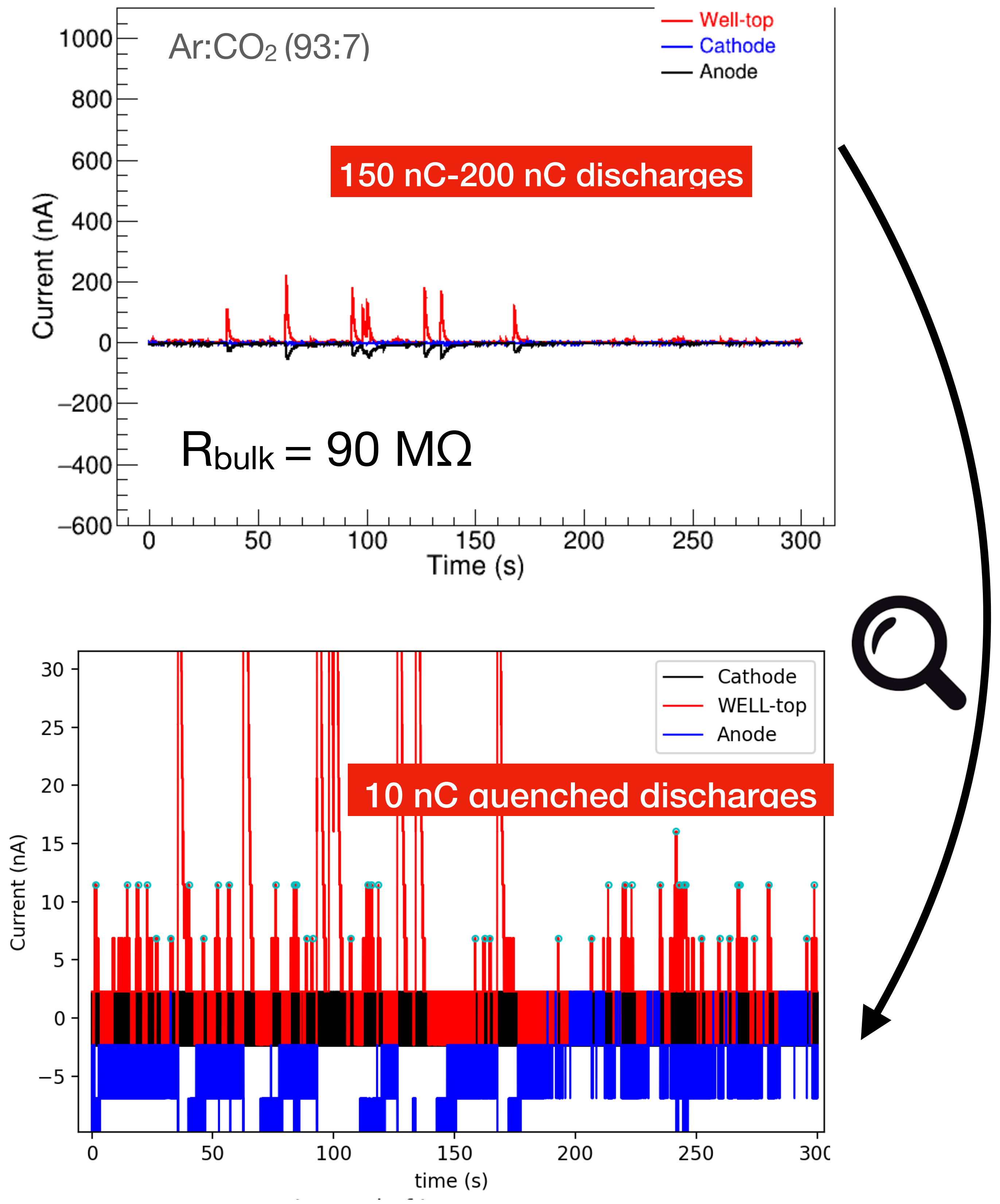
3) Quenching region:

$R_{bulk} \geq$ 250 MΩ

- Only quenched discharges

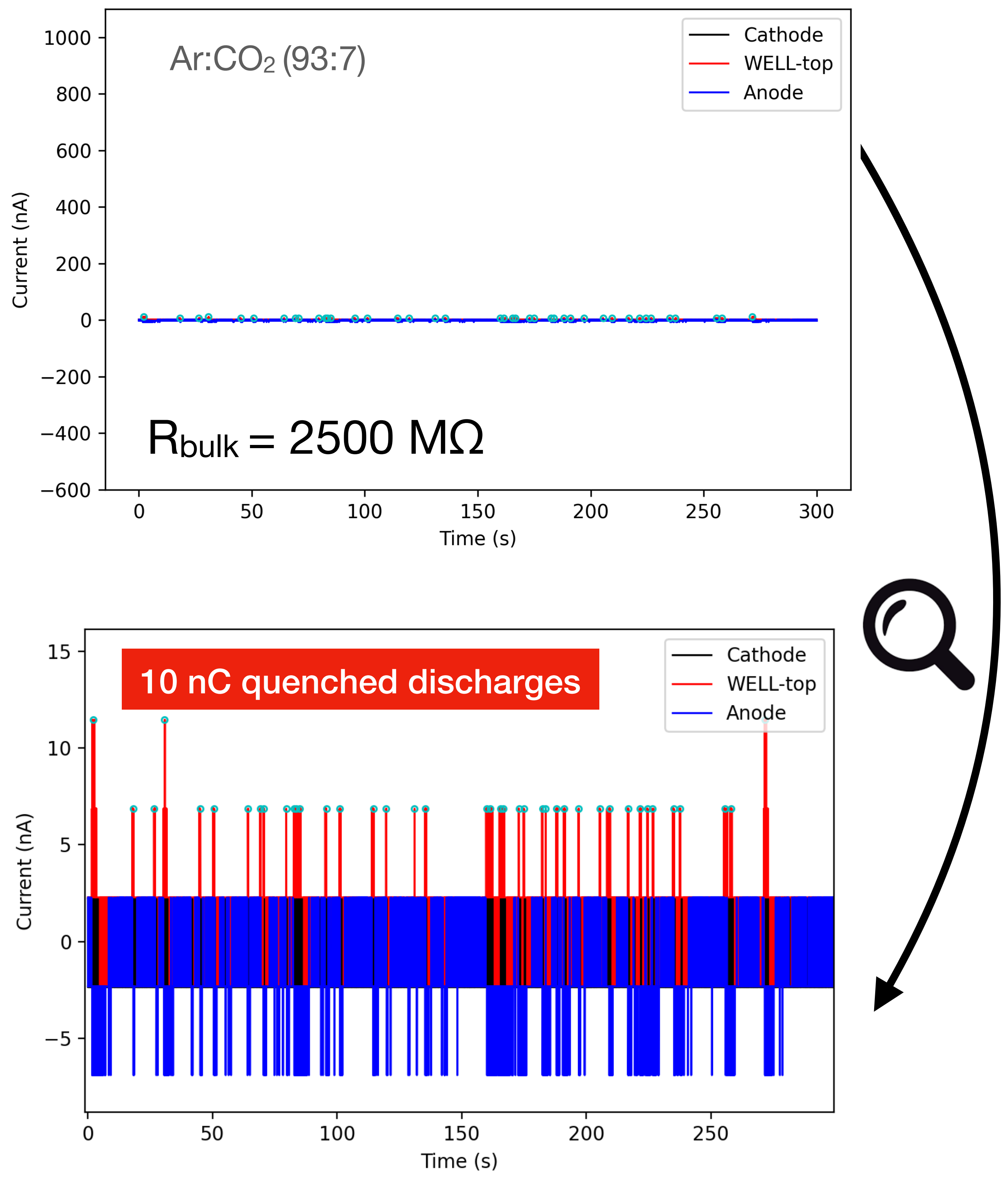
Transition region

45 MΩ cm ABS 1.4 mm - 1800V



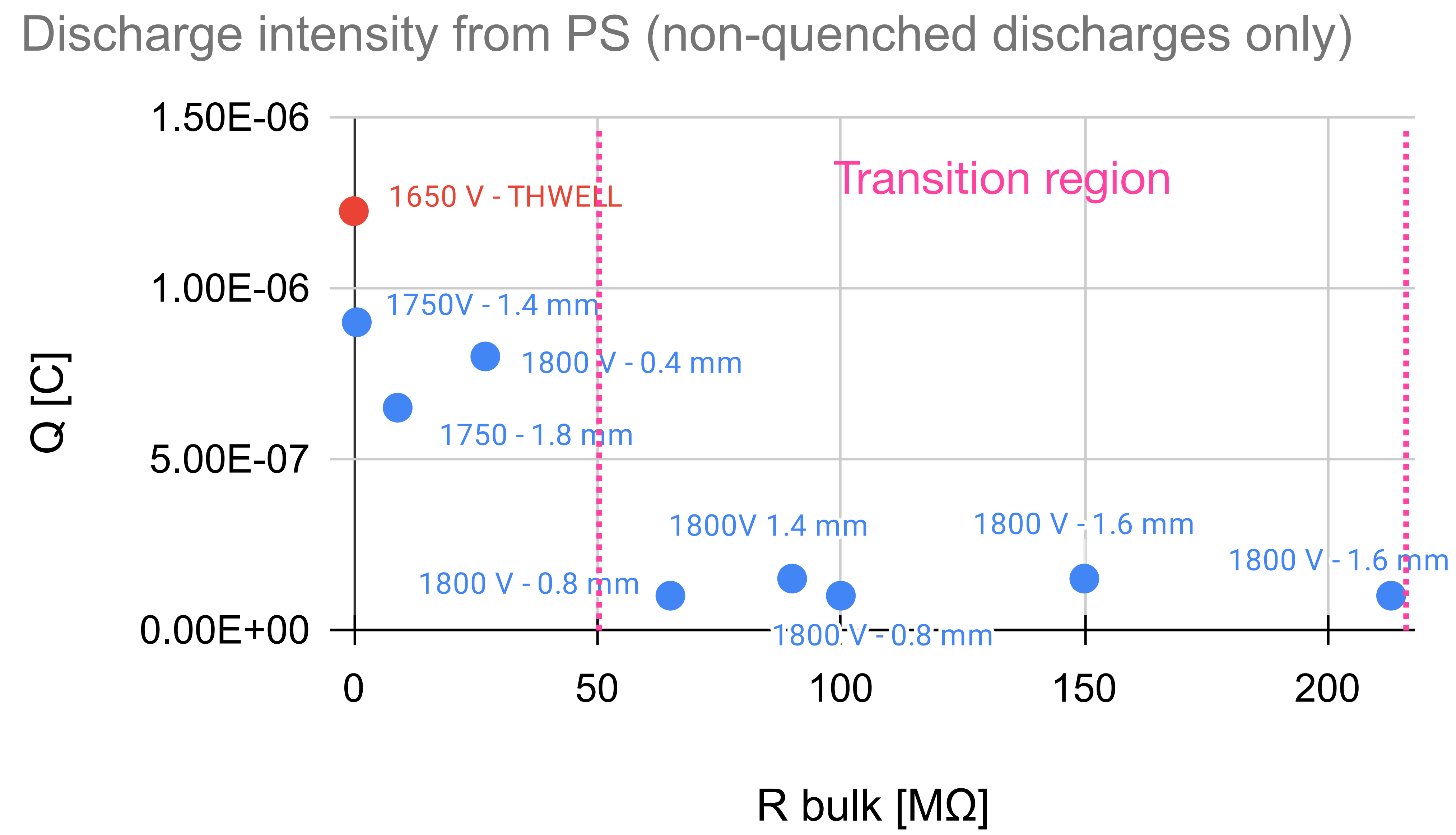
Quenching region

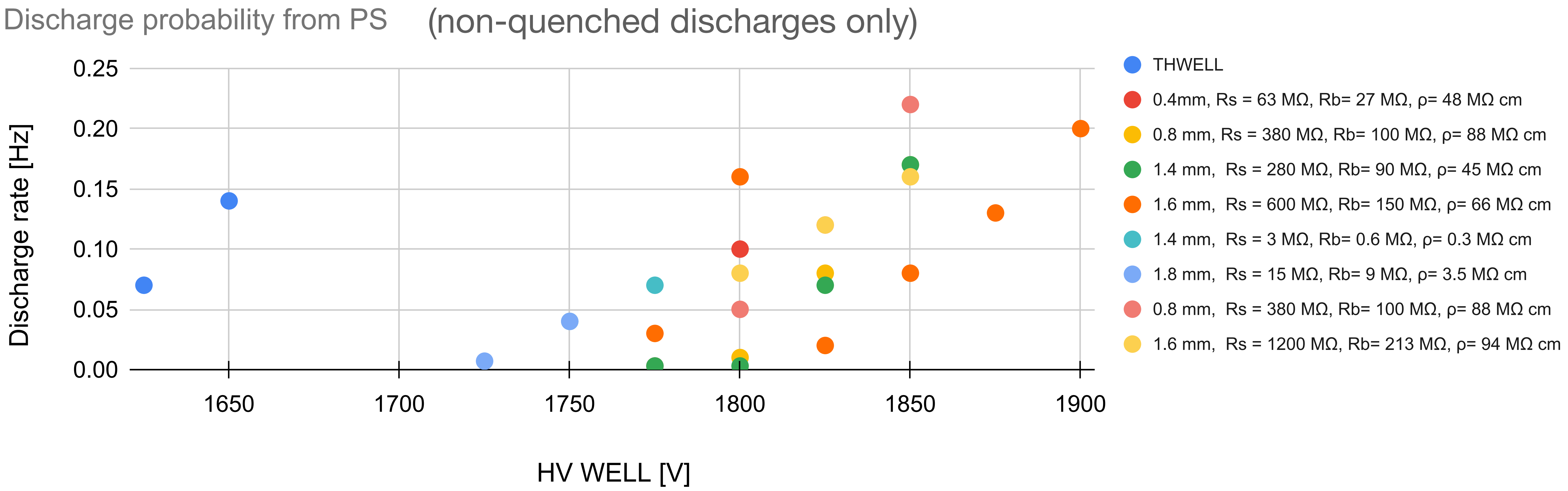
880 MΩ cm ABS 2 mm - 1800V



Discharge characterization
Power supply currents

- Similar discharge intensity for samples in transition region
- Discharge probability is similar for all tested resistive plates
- All resistive plates show discharge regime at higher voltage wrt THWELL



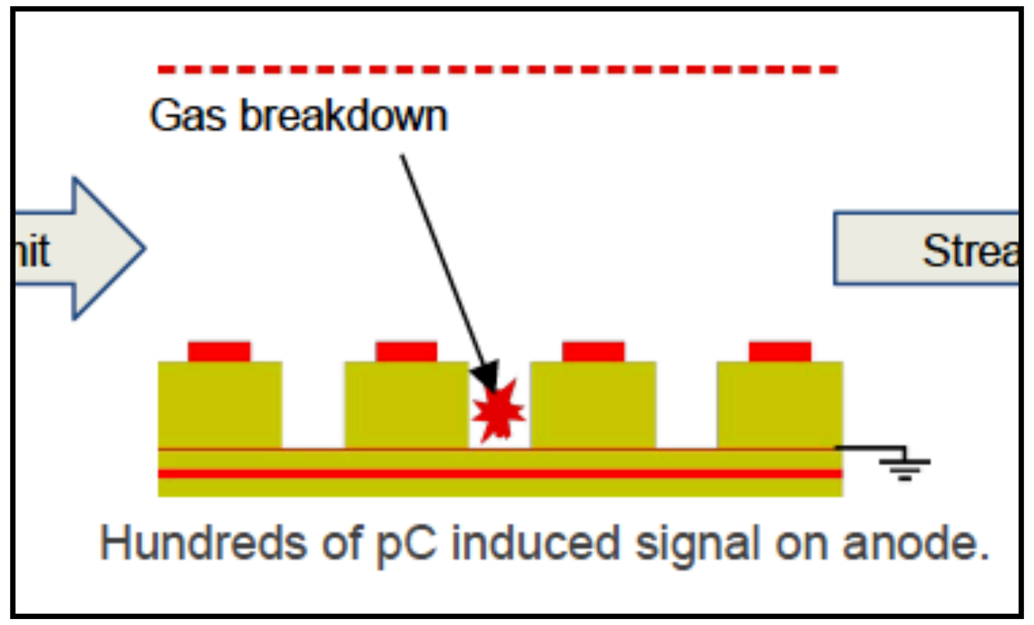


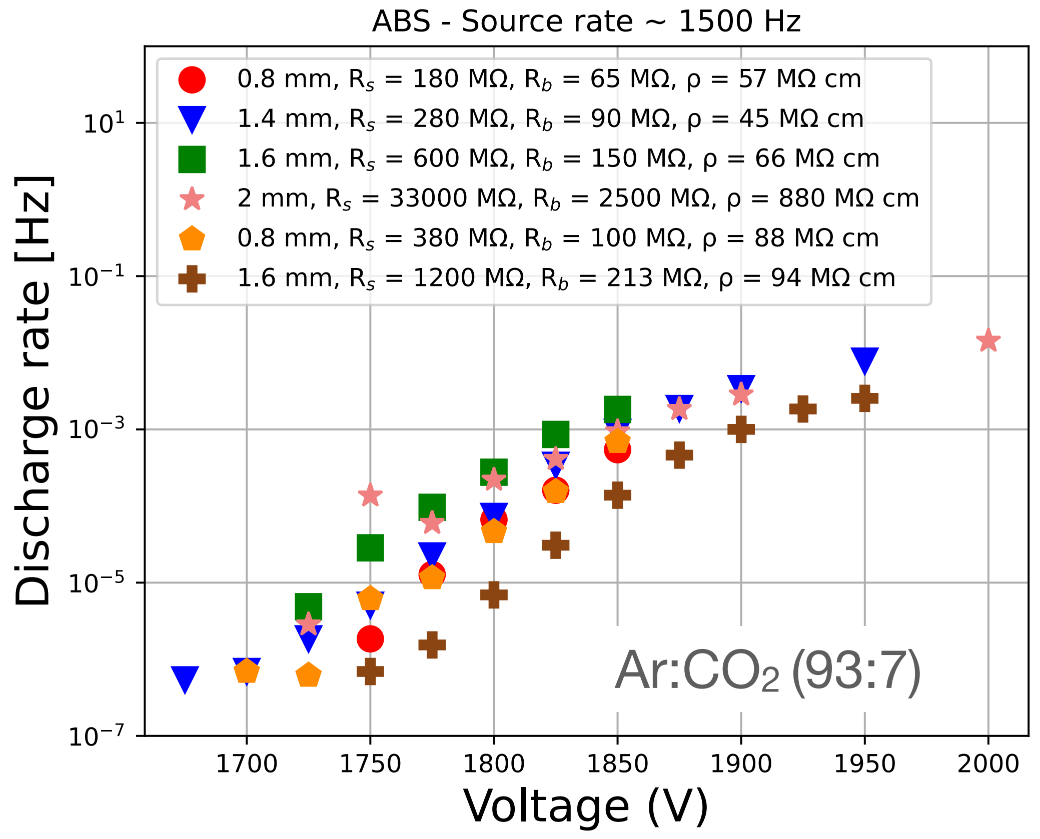
Discharge characterization

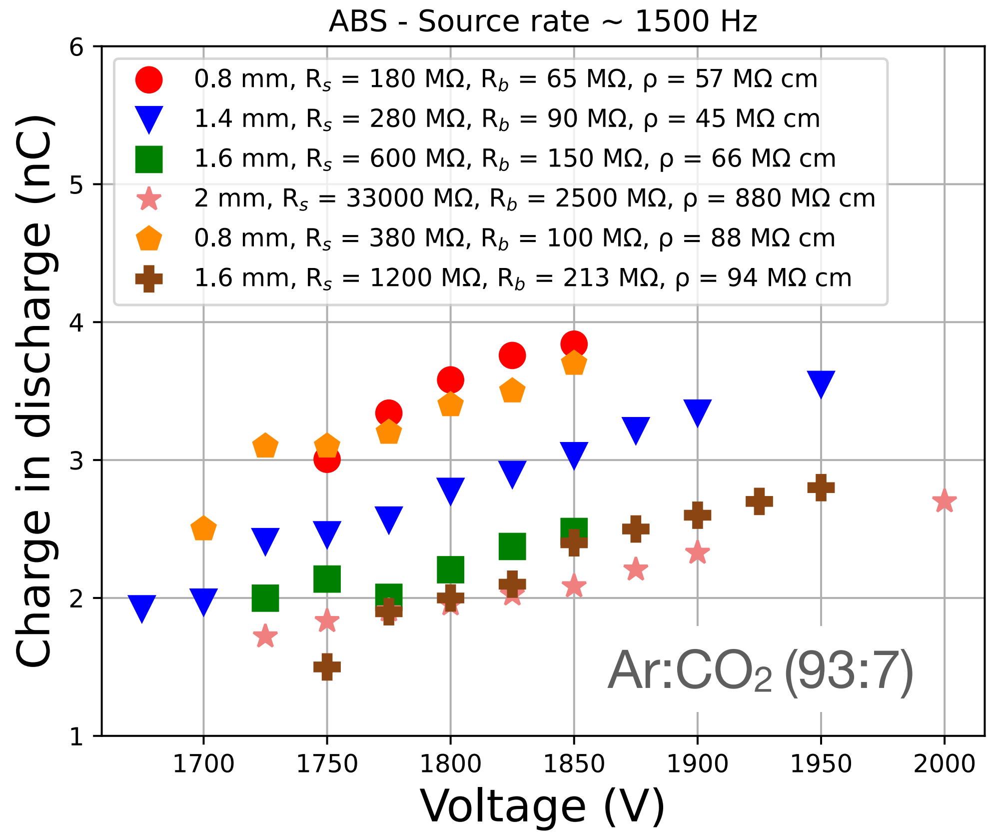
Induced pulses from gas breakdown

- Good indicator for quenched discharges
- Might affect electronics dead time and eventually burn sensitive readout

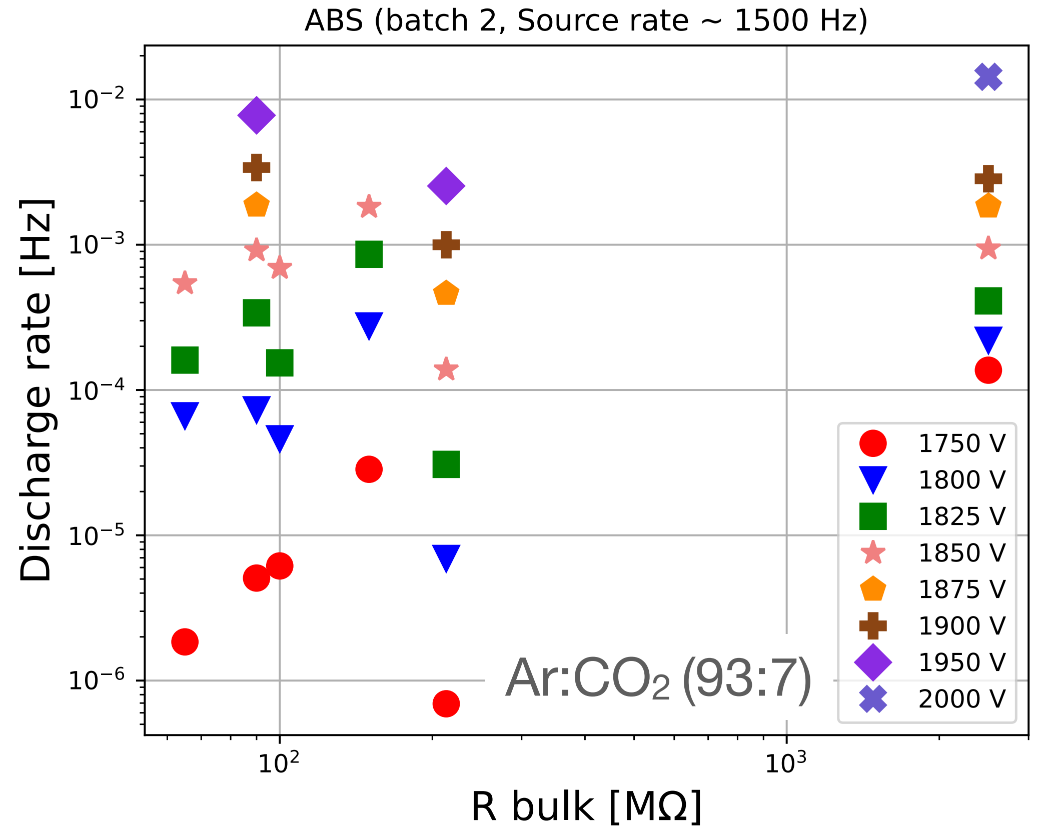
Gas breakdown

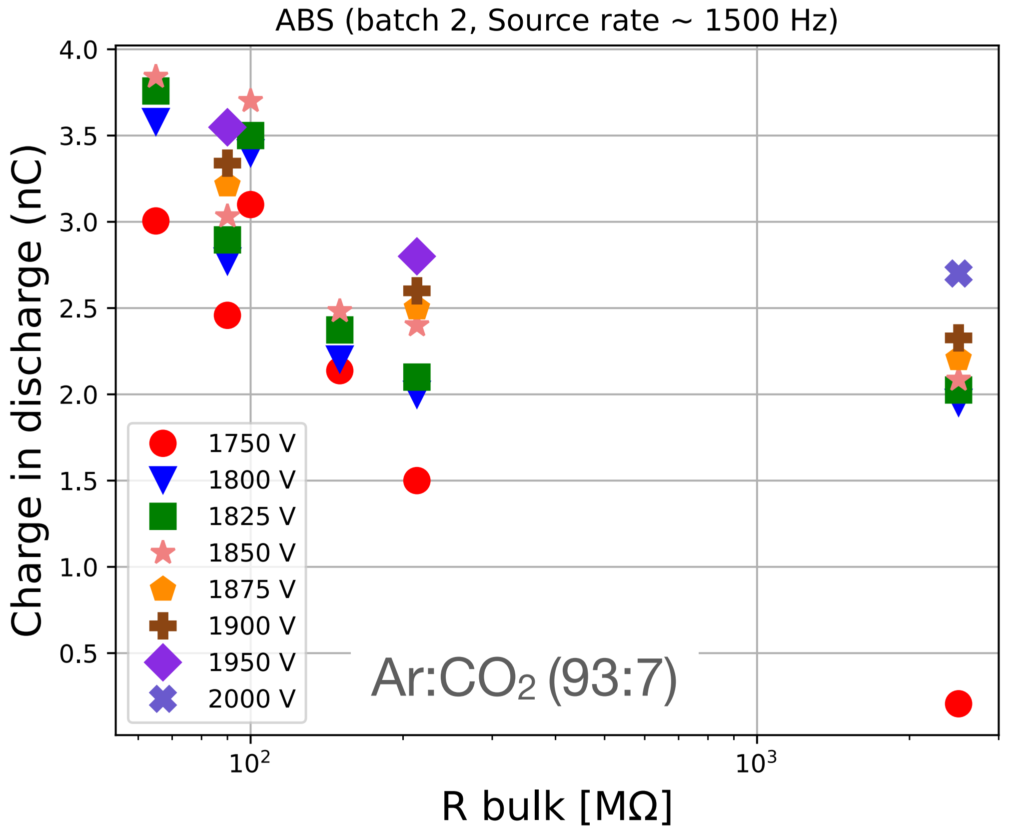






- Gas breakdown probability does not seem dependent on resistivity and thickness
- Induced signal intensity mild dependance on voltage attributed to pileup



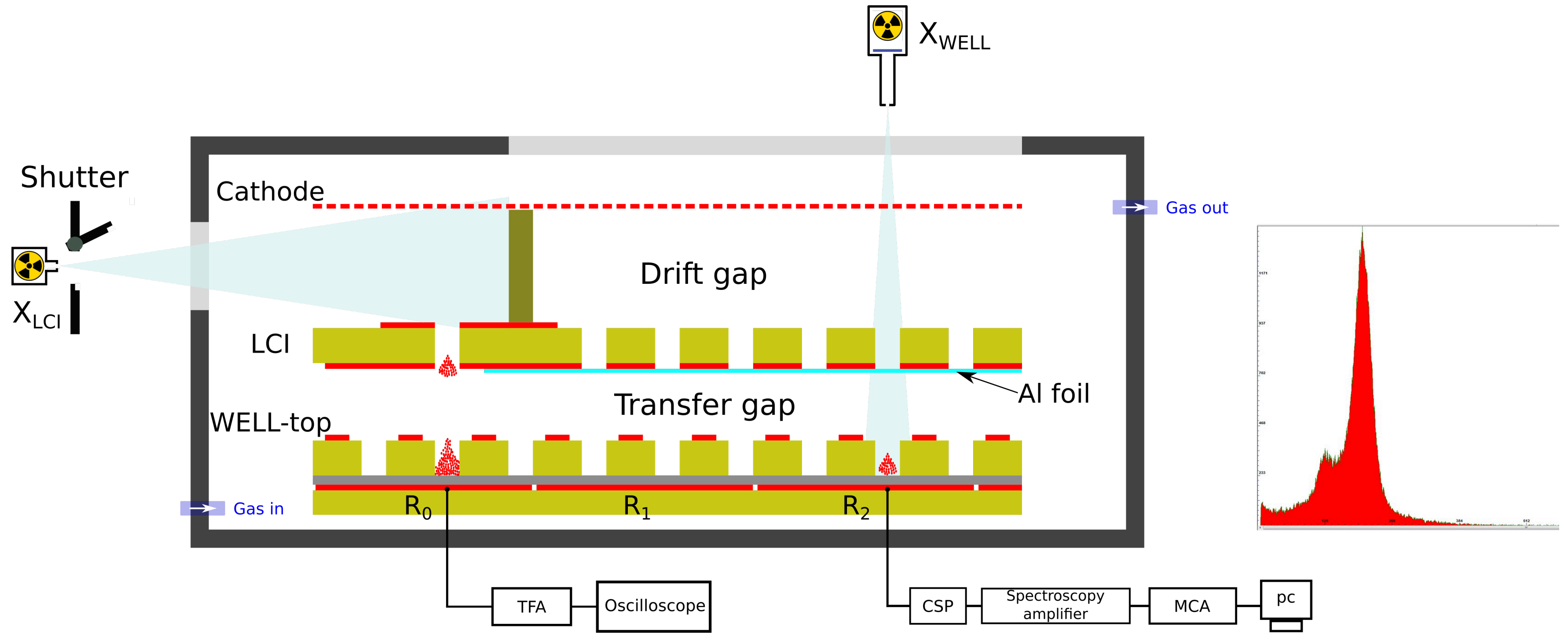


- Induced pulse intensity decreases with thickness and resistivity (in a similar way wrt R_{bulk} or $R_{surface}$)
  - Due to weighting field reduction?

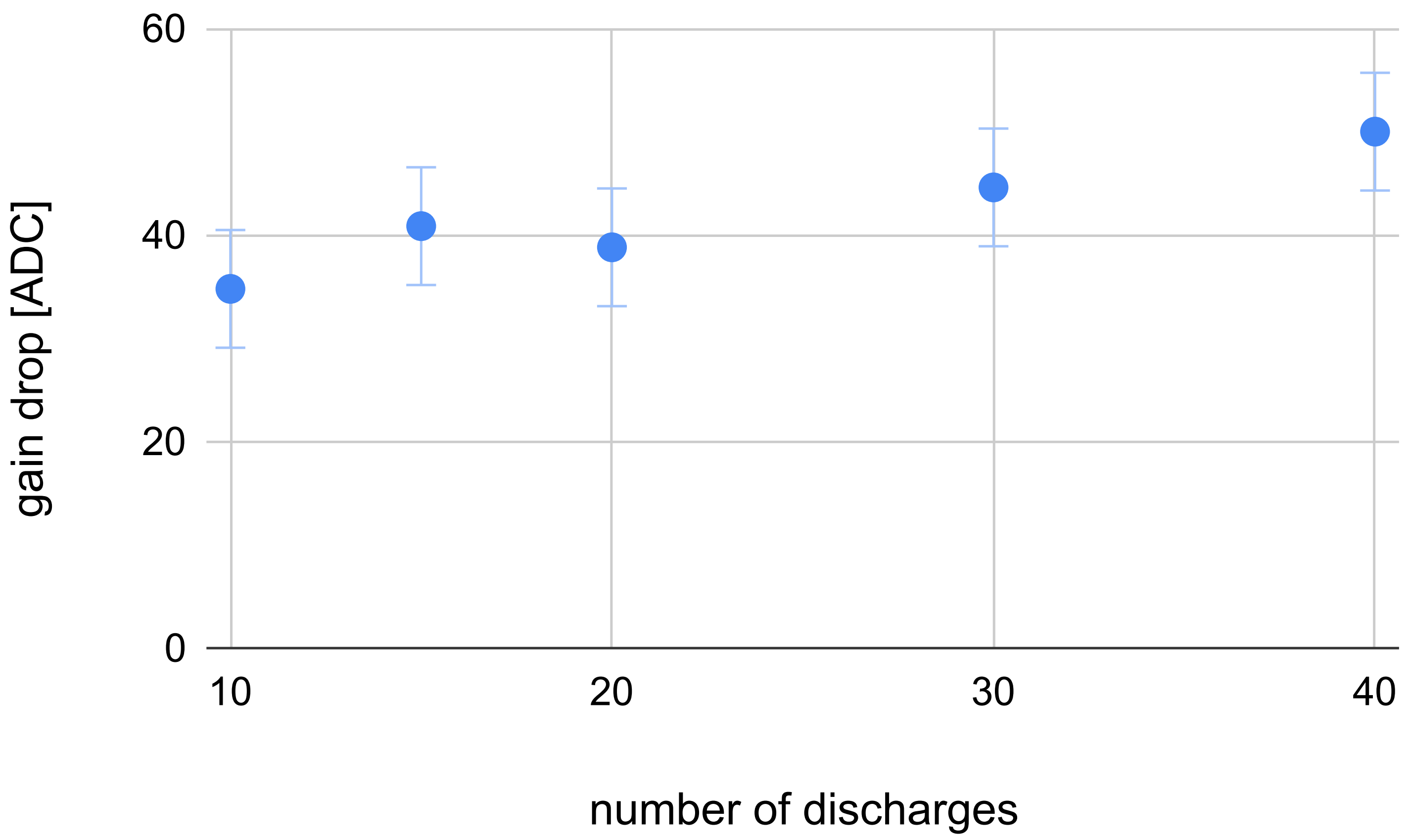
*Jash, A., Moleri, L. and Bressler, S., 2023. Electrical discharges and their effect in a Resistive Plate WELL detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1045*, p.167540.

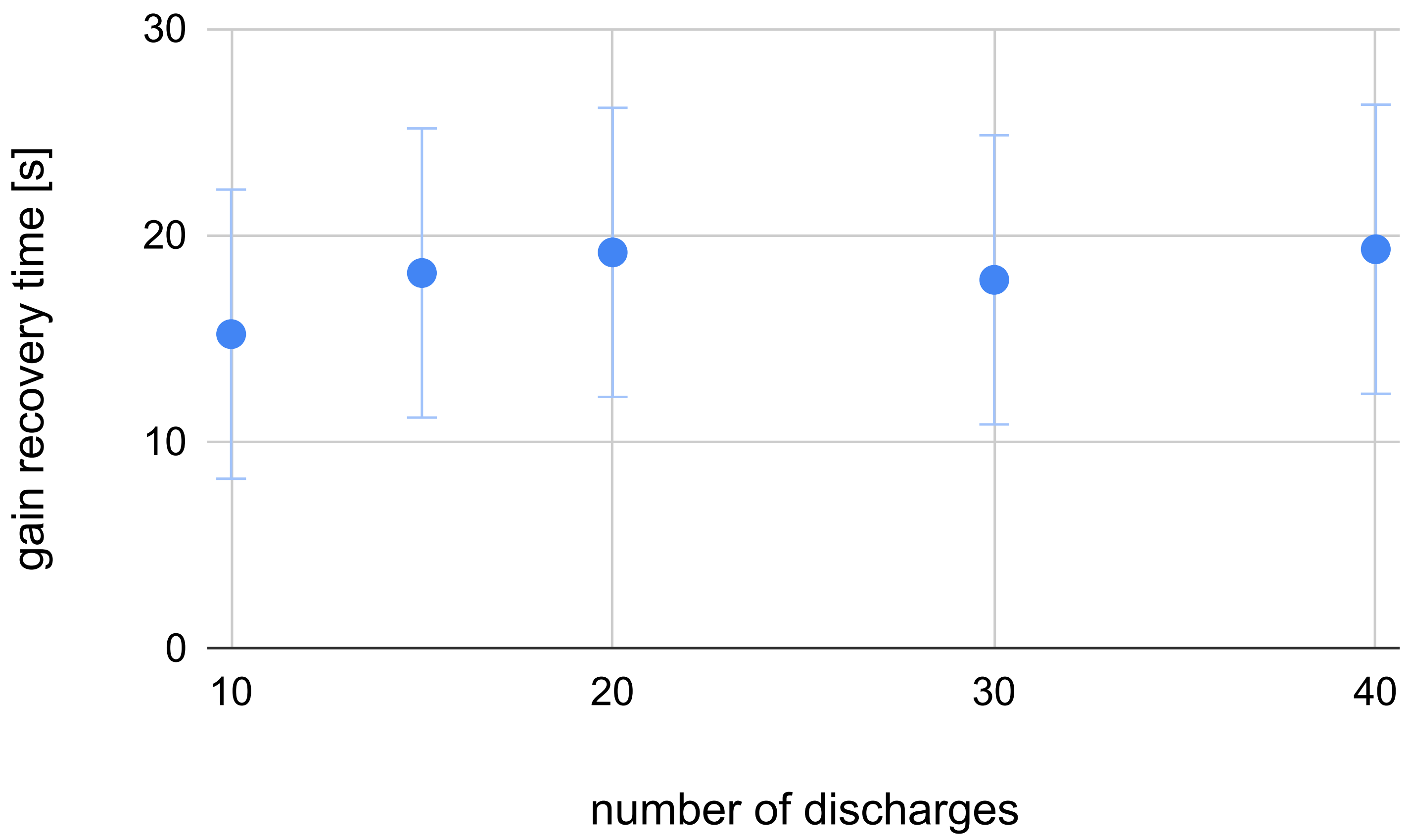
Charge evacuation in RP

Discharges' effect on gain



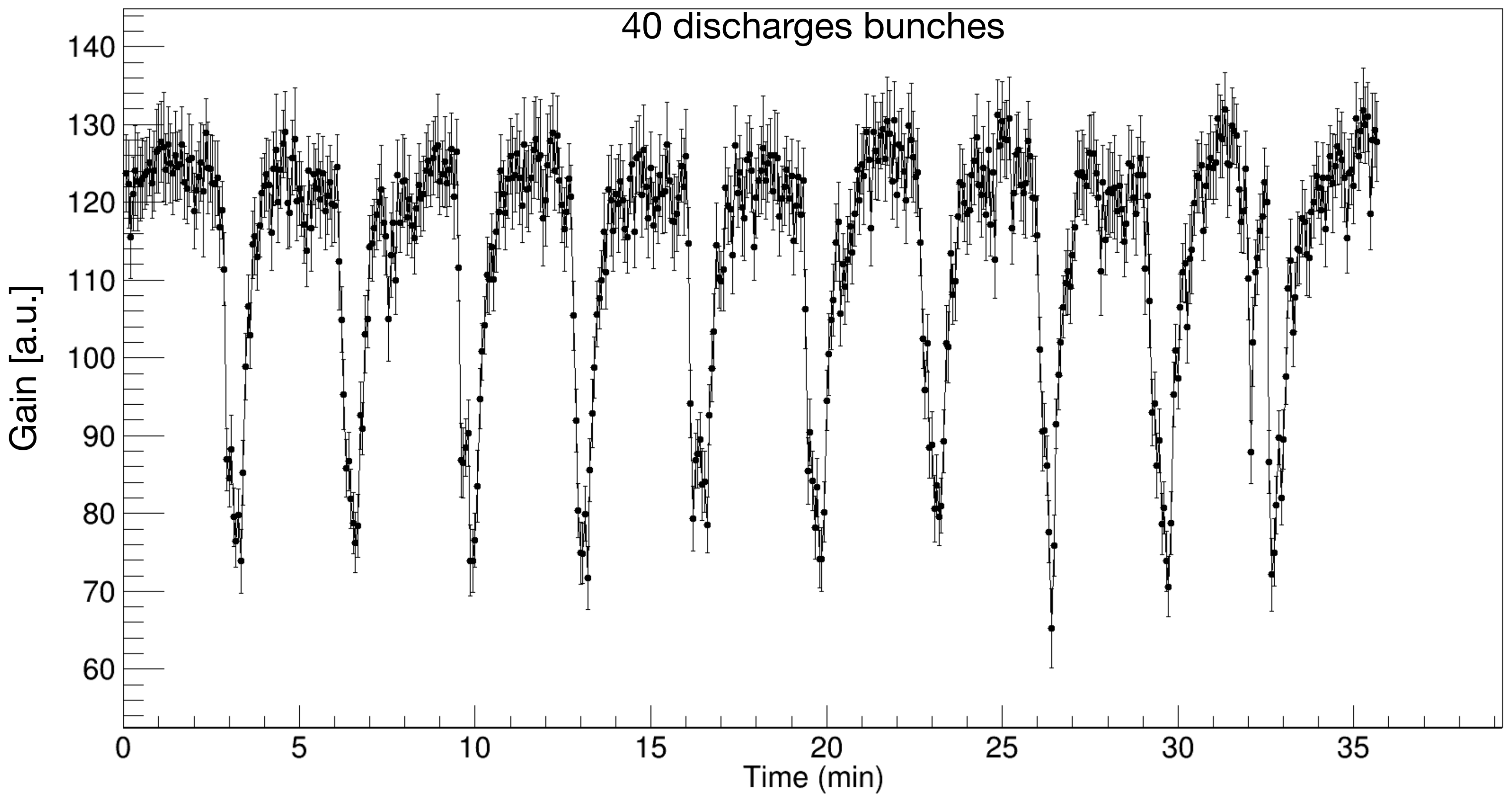
- 3 mm strips, 6 mm between discharge and gain measurement
- Discharge rate 0.5 Hz - 3 Hz
- Gain drop clearly visible for >10 discharges' bunches
- Fit gain recovery to y= B-exp((x-x_0)/τ)





40 discharges bunches

Evolution of peak position



- Gain recovery time independent on number of discharges
- Gain drop mildly dependent on number of discharges in this regime
- **Charge evacuation** ~20s (!) → ~~τ= ρε ~ ms*~~
- Requires a dedicated study of the underlying phenomena in the context of charge mobility in the RP material

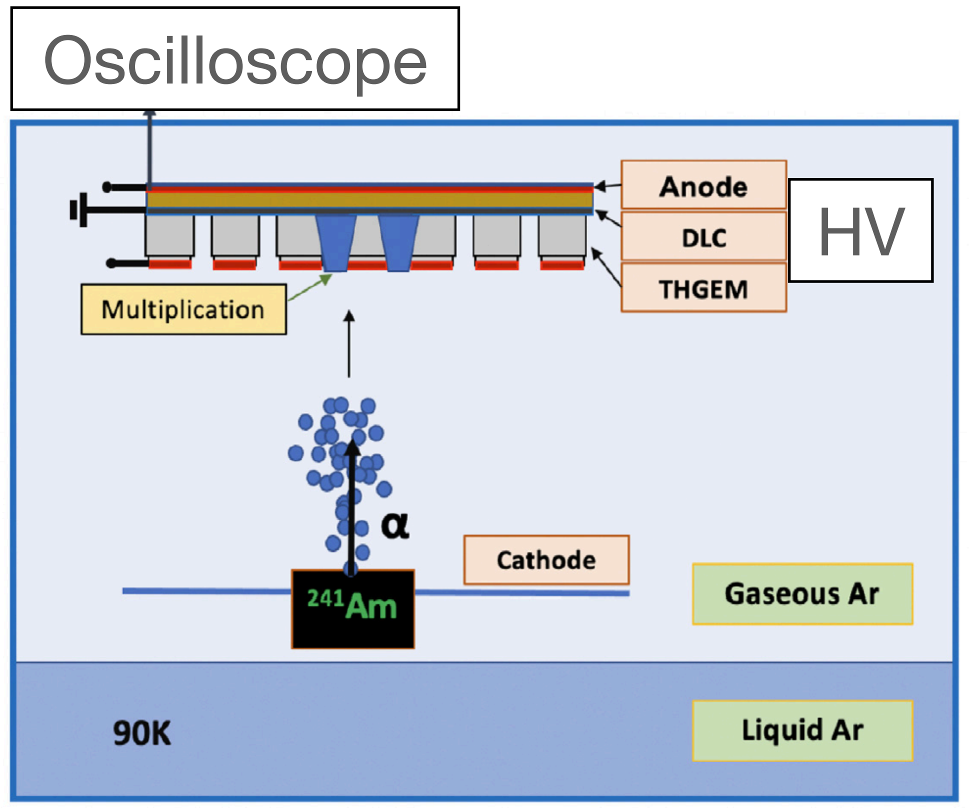
*Rubin, A., Arazi, L., Bressler, S., Moleri, L., Pitt, M. and Breskin, A., 2013. First studies with the Resistive-Plate WELL gaseous multiplier. Journal of Instrumentation, 8(11), p.P11004.

Bonus slide

*Leardini, S., Zhou, Y., Tesi, A., Morales, M., González-Díaz, D., Breskin, A., Bressler, S., Moleri, L. and Peskov, V., 2023. Diamond-like carbon coatings for cryogenic operation of particle detectors. NIMA

Resistive layer of variable resistivity

RWELL operation in cryogenic Ar vapor

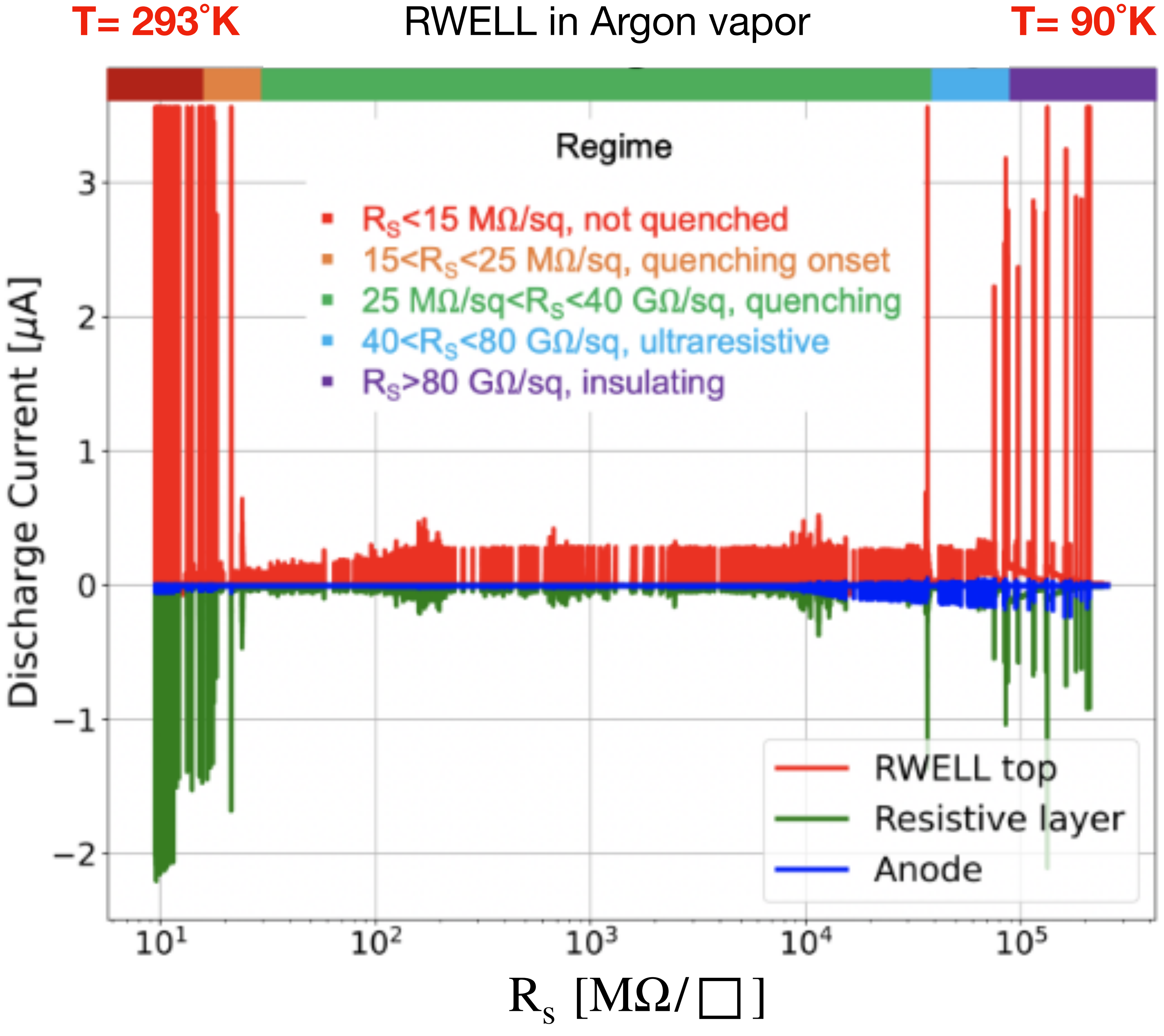


- RWELL detector with DLC coated Kapton resistive layer*
  - Surface resistivity smoothly increasing at low temperatures
- Attempt to observe transition between quenching regimes as the resistivity varies in a continuous way
- Technique was …
- Caveat - many variables changing together (resistivity, voltage, gain, vapor density)

Observations:

- 4 regions with different quenching properties
- Discharge quenching effective between conductive and insulating regimes (300 MΩ/□ - 10^5 MΩ/□)
- Confirmed by measurements of scintillation light

Power supply currents vs R_s



Presented by A. Tesi at MPGD22 conference: "Cryogenic RWELL: high gain with quenched discharges"

Main observations and next steps

Observations

- Resistive plates with tunable resistivity (surface and bulk) can be produced by 3D printing commercial plastic materials loaded with CNT
- Resistive plates with tunable resistivity provide a tool to investigate discharge quenching effects (quenching power, charge persistence, discharge probability, gain variations) and to understand the underlying physics
- Quenched and non- quenched discharges seem to be related to different processes: gas breakdown and capacitance discharge
- Quenched discharges can be studied by means of induced signals, which will also affect the detector operation (dead time, electronics damage)
- Any tested RP has an effect of reducing discharge probability with respect to THWELL. This should be explained.
- In the quenched regime, discharge probability and intensity seems not to depend on the RP resistance values.
- Charge evacuation time was measured by its effect on gain. The result is 3 orders of magnitude larger than what expected by a RC model. This deserves further investigation.

Next steps

- Implement methodologies from material science (e.g. Impedance spectroscopy) to investigate charge evacuation
- Explore other materials loaded with CNT

Thank you

Backup

Resistive plates used in RPWELL

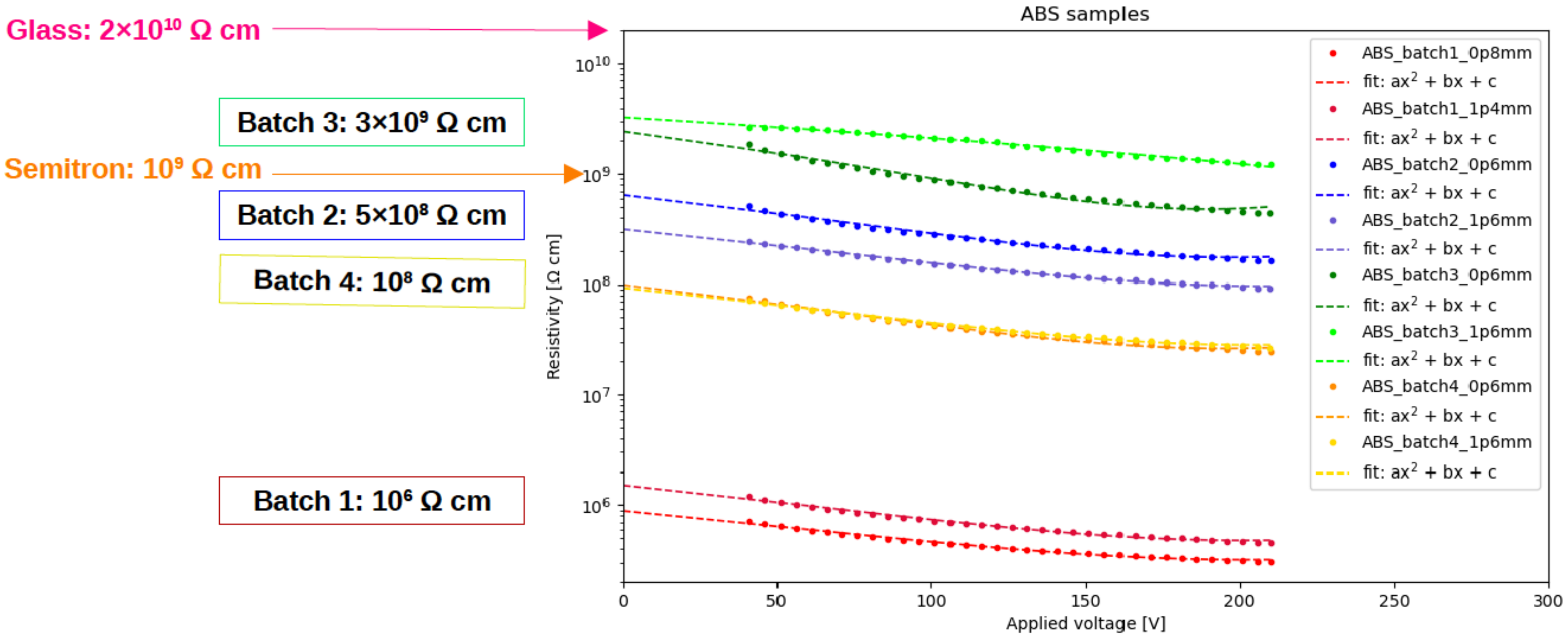
Production batches and measured values

3DXSTAT ESD ABS (Acrylonitrile Butadiene Styrene)

Batch	Thickness [mm]	Bulk resistance (V_{test}) [MΩ]	Bulk resistivity [MΩ cm]	Surface resistance (100 V) [MΩ]	T[°] hot plate/nozzle
1	0.2	55	194 (250 V)	560	105/230
	1.4	0.6	0.3 (50 V)	3	
	1.8	9	3.5 (50 V)	15	
2	0.2	31	110 (50 V)	114	105/220
	0.4	27	48 (50 V)	63	
	0.8	65	57 (100 V)	179	
	1.4	90	45 (100 V)	280	
	1.6	150	66 (250 V)	599	
	2	2500	883 (1000 V)	33000	
3	0.8	100	88 (500 V)	380	105/215
	1.6	213	94 (500 V)	1200	

3D printed resistive plates

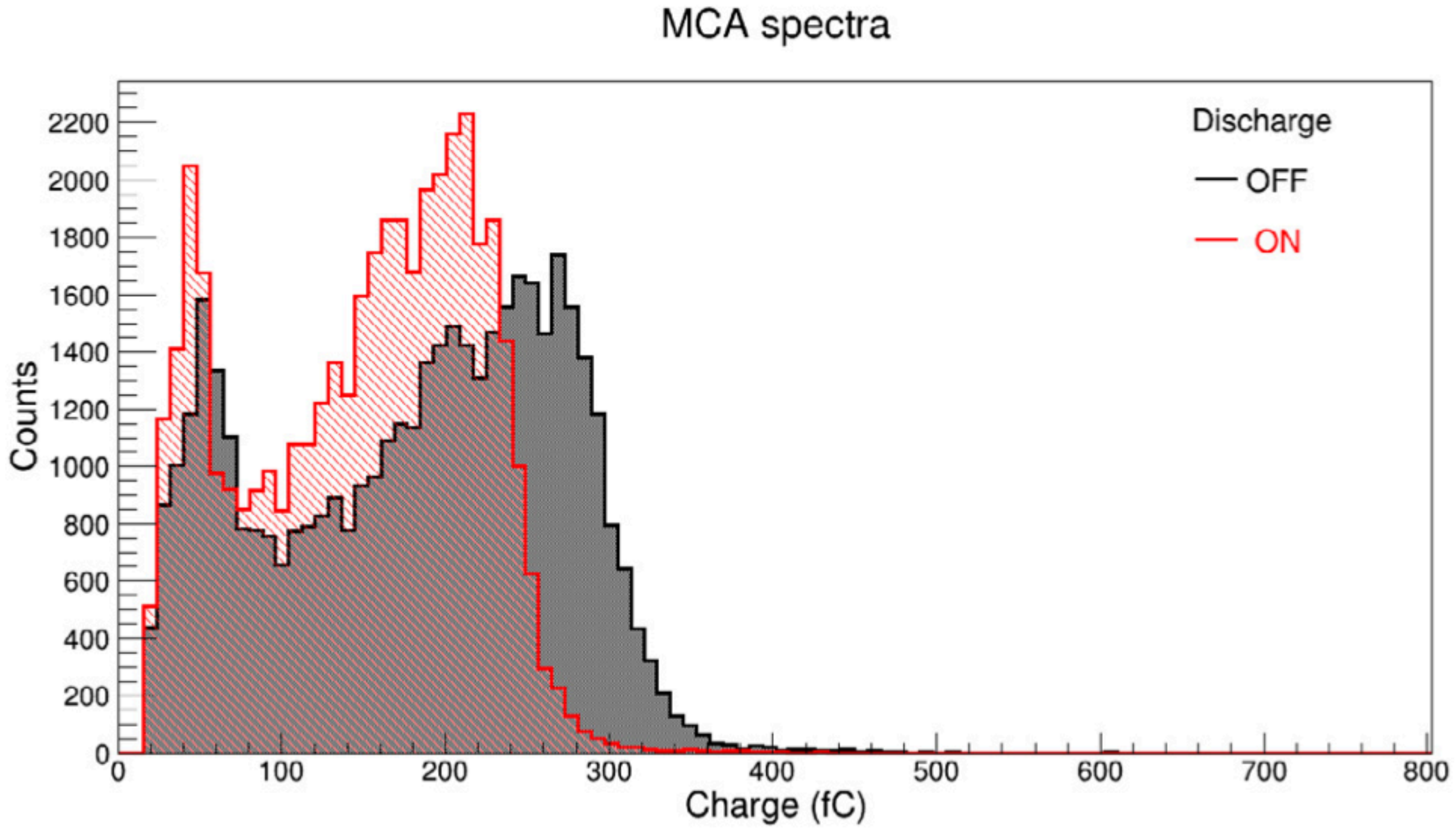
characterization: variable T and thickness

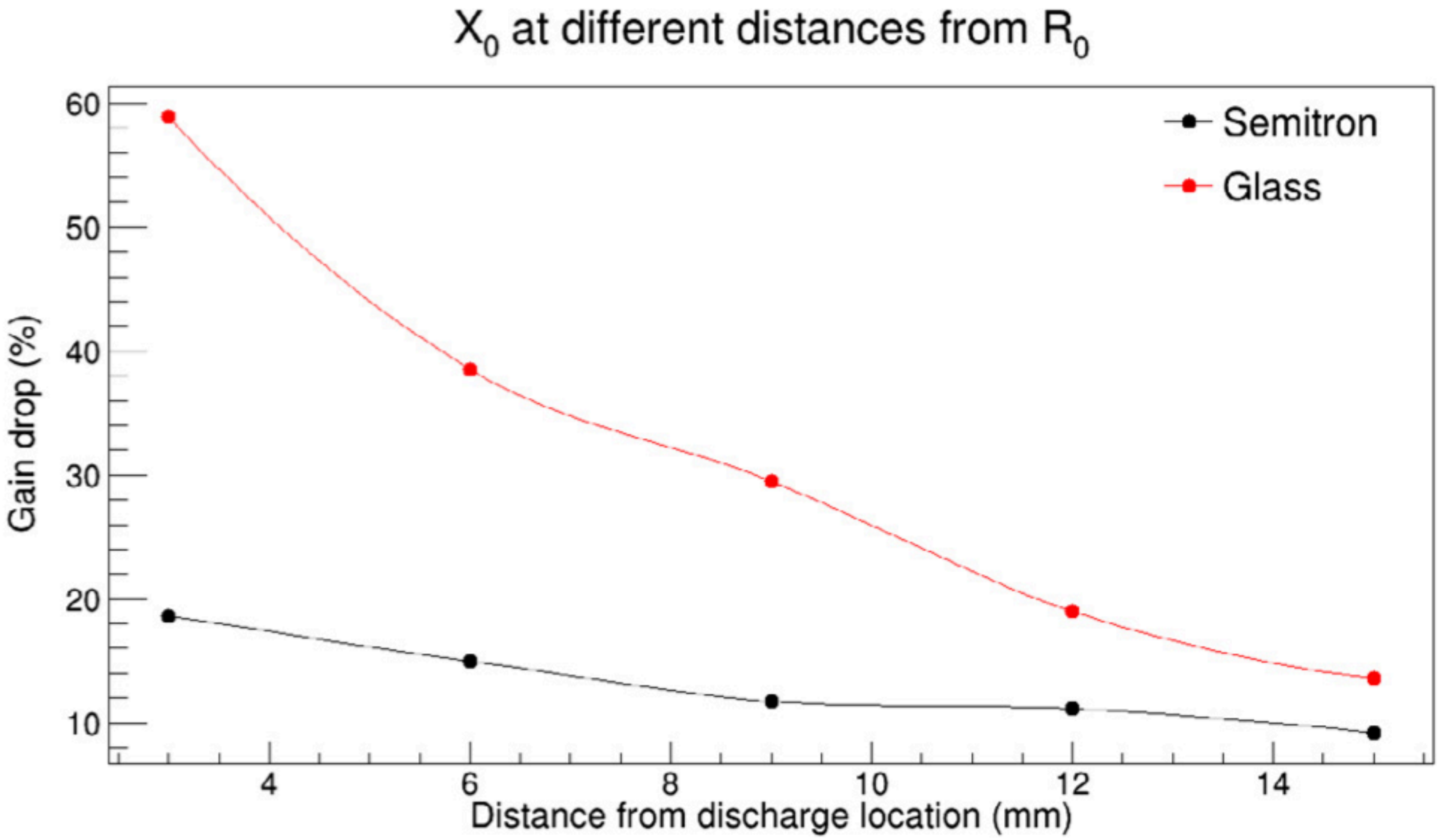


- What is the relevant voltage to test samples?
- During a discharge the local voltage in the area of a THGEM hole can be very high

Charge evacuation

Gain variation





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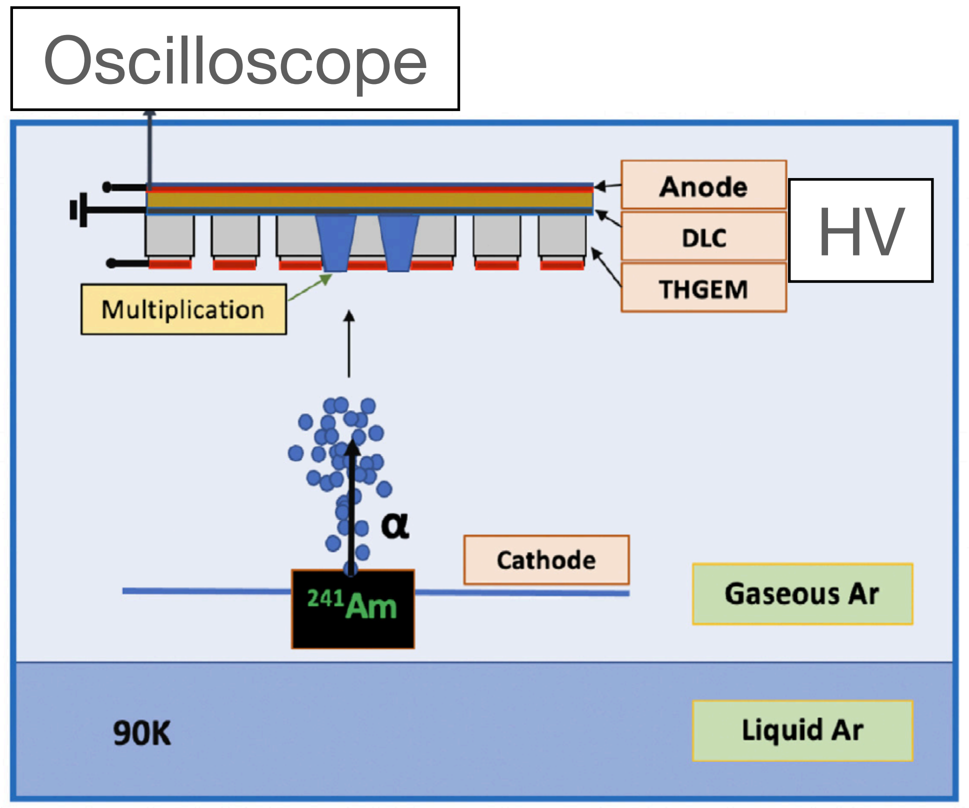
*Leardini, S., Zhou, Y., Tesi, A., Morales, M., González-Díaz, D., Breskin, A., Bressler, S., Moleri, L. and Peskov, V., 2023. Diamond-like carbon coatings for cryogenic operation of particle detectors. *NIMA*

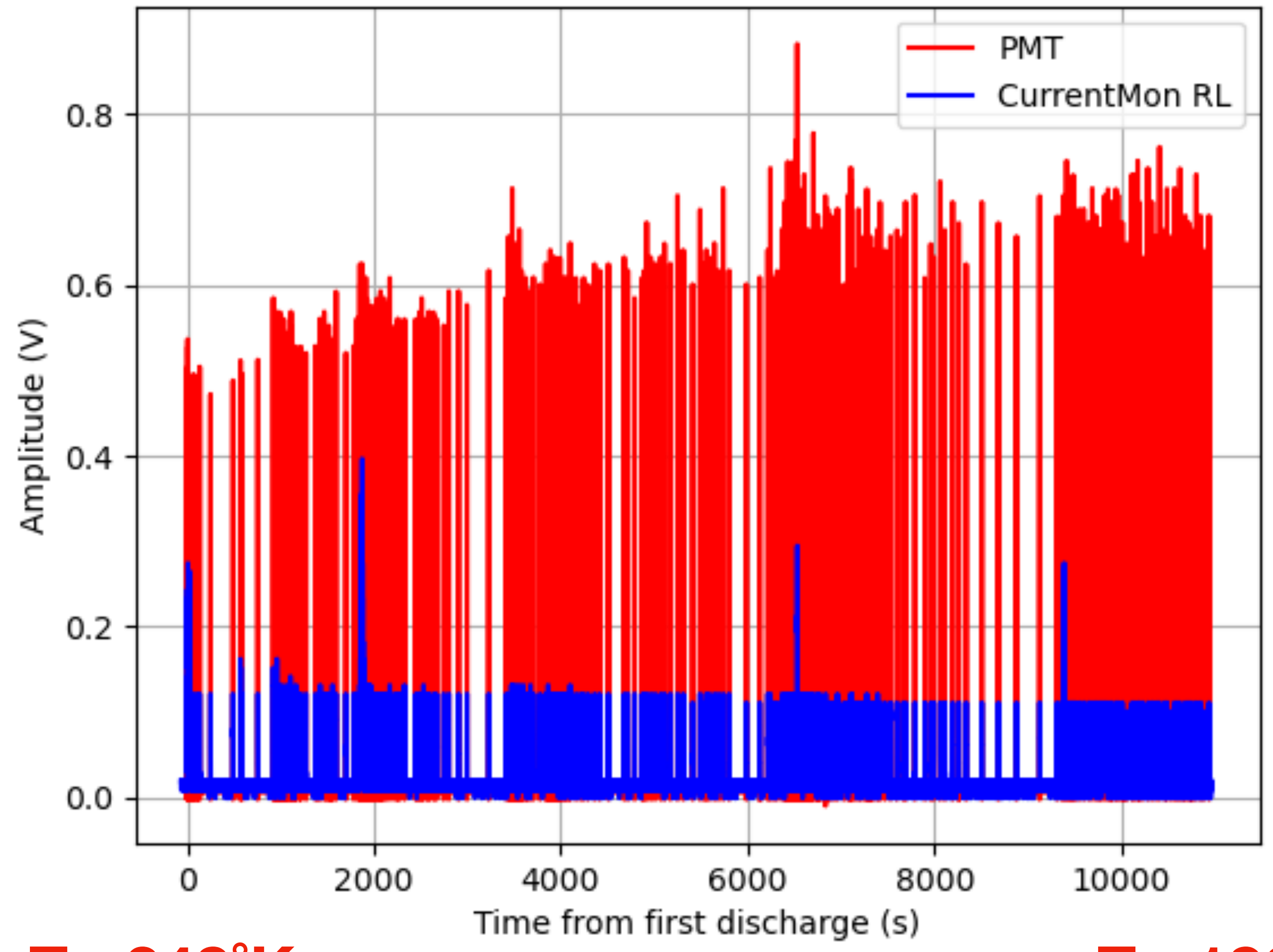
Resistive layer of variable resistivity

Cryogenic temperatures Courtesy of Ryan Felkai

- RWELL with DLC resistive layer*
- Use light signal to disentangle piled up discharges
- Light signal and signal induced on anode are similar in shape and almost constant in values



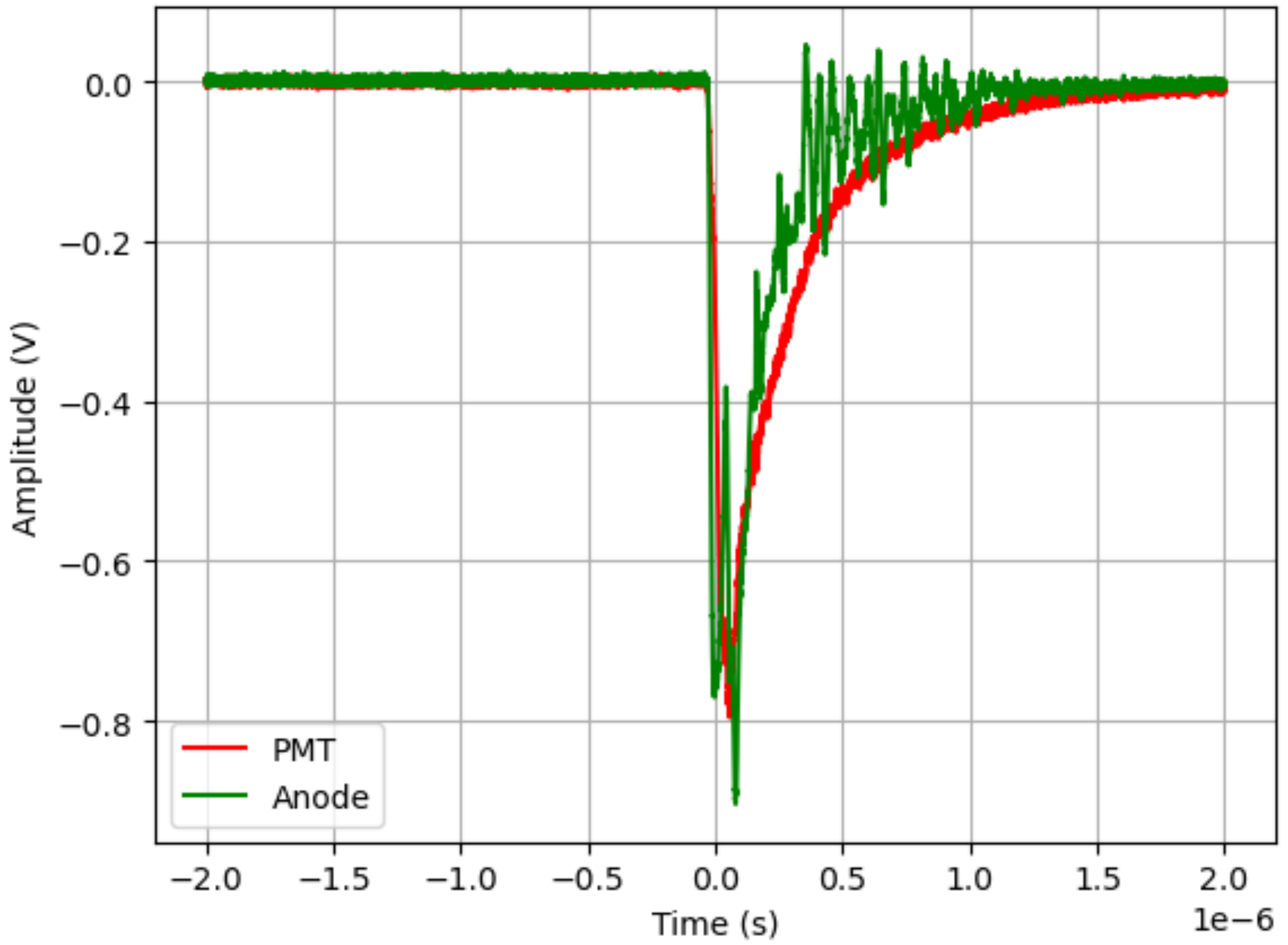
Discharge current & light



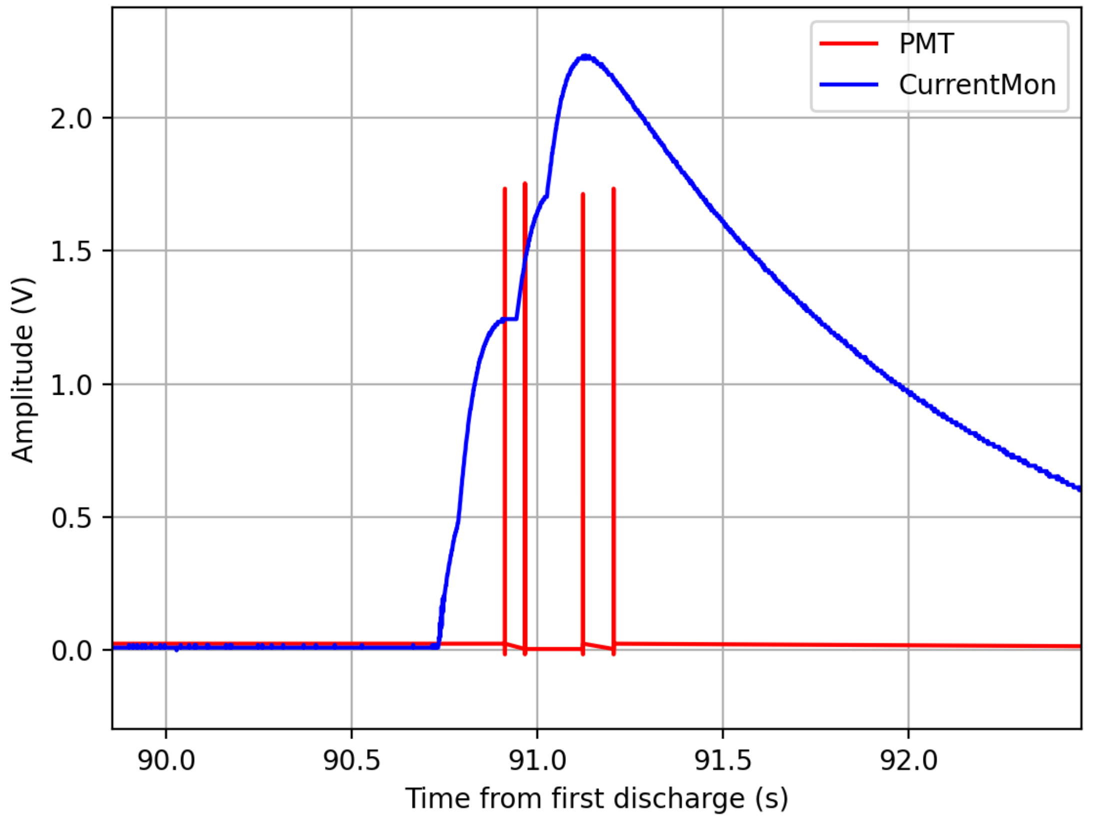
T= 248°K

T= 182°K

Anode induced signal & light



Pileup discharges



Single discharge