Electrical discharges and their mitigation in Thick-GEM based WELL detector

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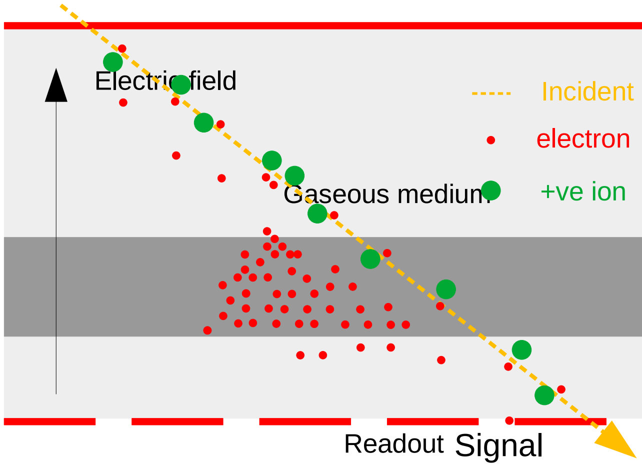
Gaseous particle detector

- Ionizing radiation (μ^-, π^-, p, e^-, X-ray, γ-ray ...) passing through a medium looses its energy and ionizes the medium (e^- + positive ion). N_0 → number of primary ionizations.
- Application of electric field helps to separate the two kind of charges. The velocity of the moving charges depends on the field value.
- Readout electronics can detect a charge only if it is above a threshold. It is produced via charge multiplication:
    - High electric field (e.g. application of 4000 V across 1 mm gap) helps the electrons to move with very high kinetic energy and ionize further.
    - Townsend avalanche: $N = N_0 e^{\alpha x}$

      ($\alpha \rightarrow$ First Townsend coefficient, $x \rightarrow$ distance traveled by the charge)



Electrical discharge in gas detectors

- Production of large charge makes a detector efficient in detecting the passing particles.
- It is achieved by efficient charge multiplication.
    - Use a gas with high Townsend coefficient.
    - Apply high electric field.
- If the total produced charge becomes greater than a certain value (Raether limit [1]) discharge occurs within the detector. The maximum achievable gain of a detector is limited by this criterion.
    - Ionizations are accompanied by excitations producing photons during their de-excitation. The photons also ionize the medium.
    - Too much ionization give rise to a lot of photons creating further ionizations, finally leading to discharge in the detector i.e. formation of electrically conducting paths between electrodes kept at different potentials.

Ref [1]: H. Raether, Electron Avalanches and Breakdown in Gases, *Butterworths (1964)*.

Thick-GEM (THGEM)

- Thick-GEM: a thicker version of the Gas Electron Multiplier developed at Weizmann Institute of Science [2].
- Cu layer coated on both faces of a 0.4-0.8 mm thick FR4 (PCB) material.
- Cylindrical holes drilled through the plate. ~0.5 mm diameter holes arranged in square/hexagonal pattern with ~1 mm pitch.

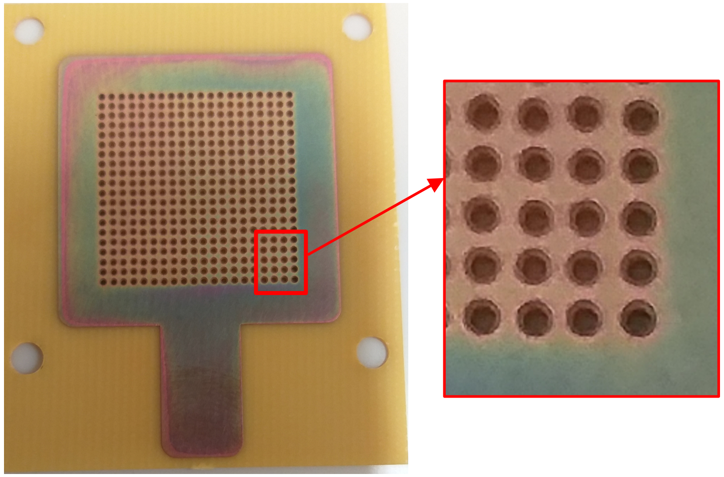


Fig: A 2 cm × 2 cm THGEM foil

<u>GEM</u>

- Thickness ~ 50 µm
- Hole diameter ~ 70 µm
- Excellent position resolution, good imaging capability.

<u>THGEM</u>

- Thickness ~ 500 µm
- Hole diameter ~ 500 µm
- Easy to prepare and handle, robust, can sustain multiple discharges.

Ref [2]: R. Chechik et al., Thick GEM-like hole multipliers: properties and possible applications, *Nucl. Instrum. Meth. A* ***535*** *(2004) 303*.

IGNORE: Animation for previous slide

Flash the GEM first
Disappear and show THGEM foil at the same place.

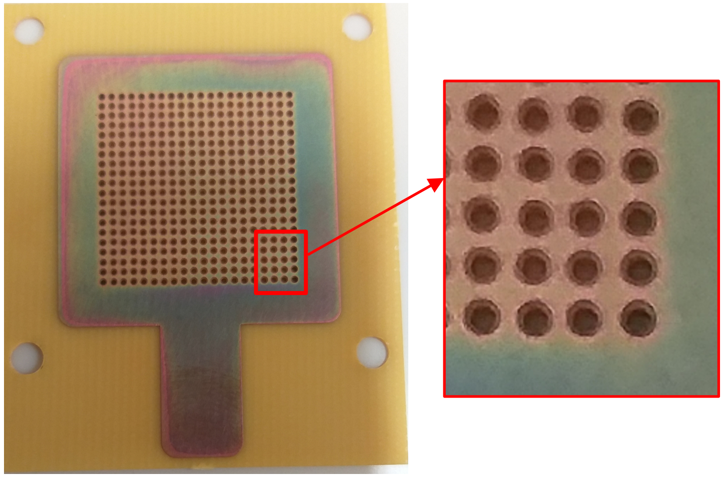


Fig: A 2 cm × 2 cm THGEM foil

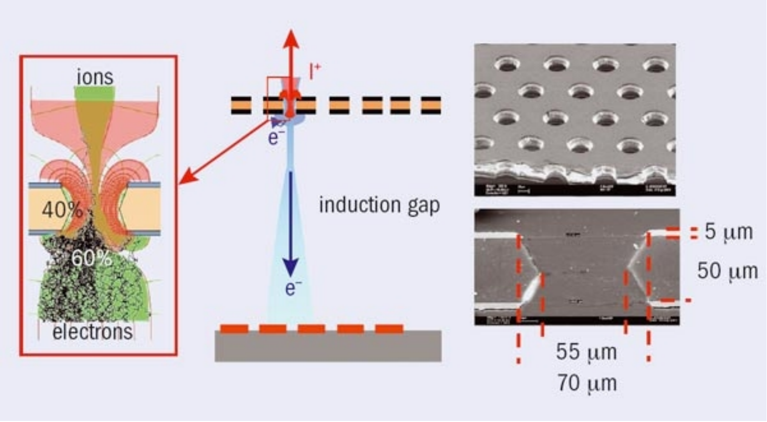


Fig: Structure and operation of a GEM.

WELL detector

- WELL [3]: a single-faced THGEM coupled to an anode. Primary ionization in the 3 mm transfer gap, electron multiplication within the well-shaped holes (~0.4 mm thick).
  - Closed geometry restricts photo-induced ionization at a distant point.
  - Thin geometry suitable for DHCAL.
- Geometry of the tested prototype -
  - 2 cm × 2 cm active area. Square array of 500 µm dia holes in 1 mm pitch.
  - Possibility of readout from anode and WELL top.
  - Single plane readout or strip readouts of width 2.8 mm, 3 mm pitch. Each strip covers 3 rows of holes.

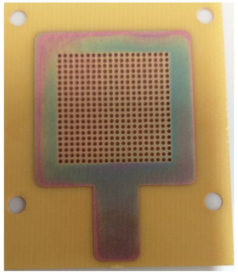


Fig: Top side of THGEM foil

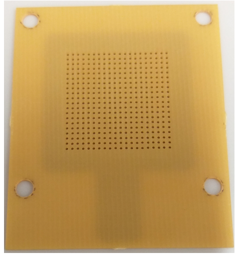


Fig: Bottom side of THGEM foil.

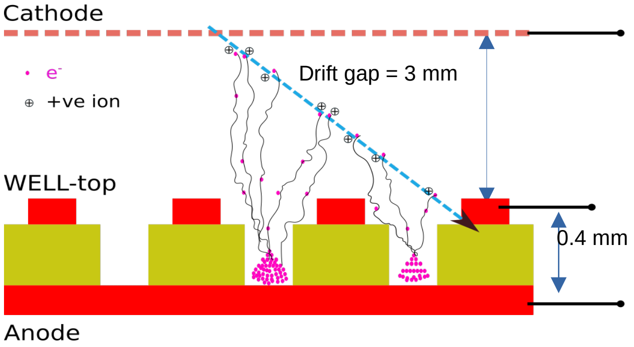


Fig: Schematic of a WELL detector.

Ref [3]: L. Arazi et. al, THGEM-based detectors for sampling elements in DHCAL: laboratory and beam evaluation, *JINST* ***7*** *(2012) C05011.*

Detector response

- Gain is calculated from the position of K_α peak of X-ray source as found by Gaussian fit.
- Gain of WELL increases exponentially with the applied voltage across the THGEM (ΔV_{WEll}).
- In a regular WELL, a maximum **gain ~ 8 × 10^3** is achieved at ΔV_{WEll} = 730 V above which strong discharges ($I_{electrode}$ = 100-500 nA, forcefully limited by power supply settings) appear and the detector can not be operated.

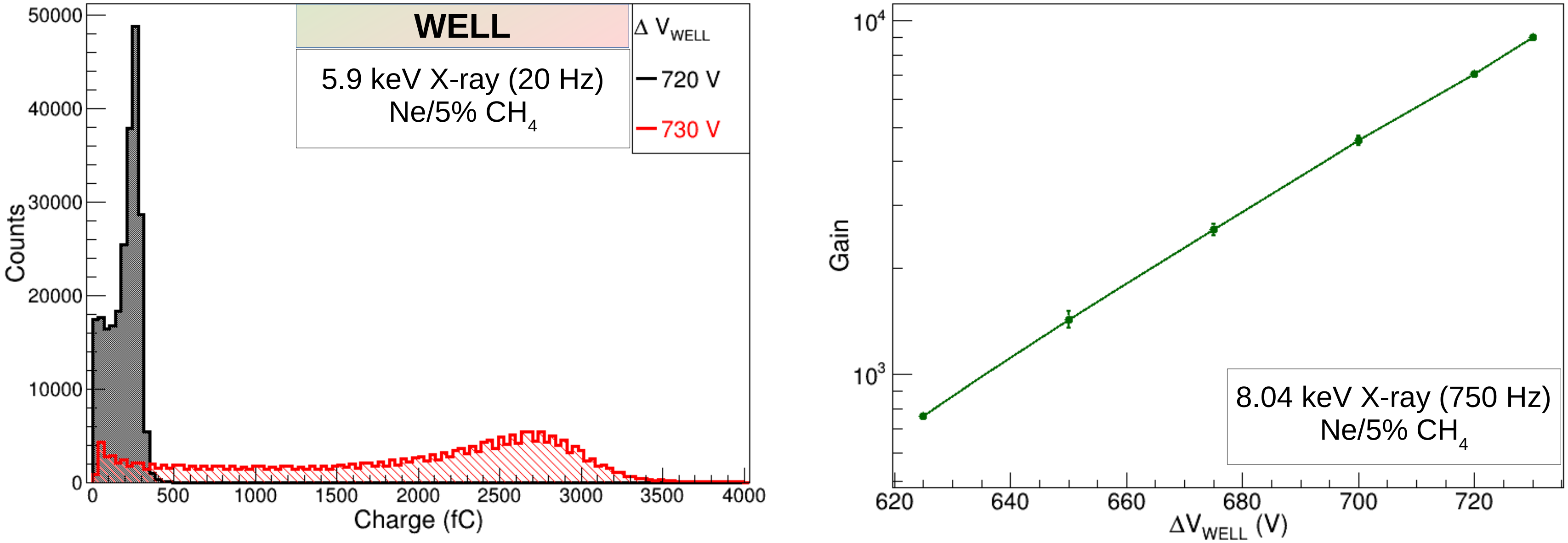


Fig: (left) MCA spectrum and (right) gain curve of WELL as a function of voltage across THGEM.

Electrical discharge in WELL

- Production of a discharge is indicated by currents in participating electrodes.
- The safety settings in the power supply forces the current to stay below a limit by lowering the applied voltage.
- Without such restrictions, the effect of discharge can be catastrophic. Damage to detector, readout electronics.

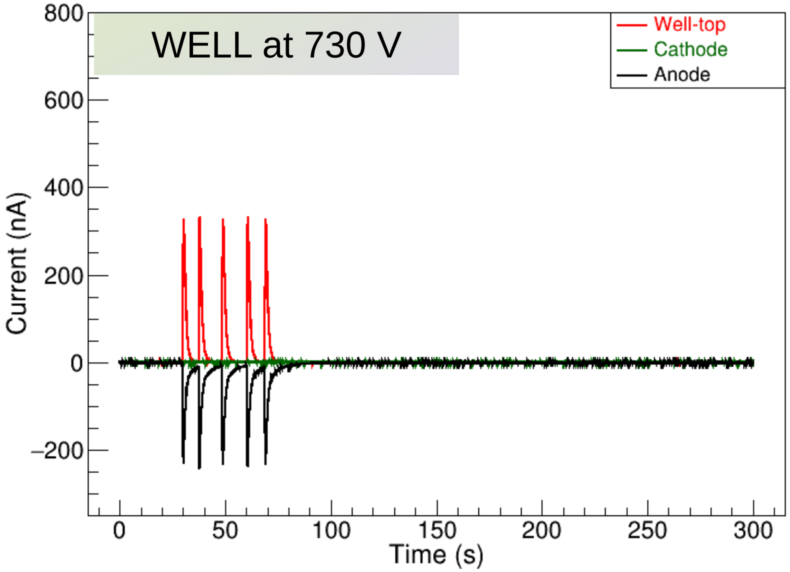


Fig: Monitored currents from all the electrodes of WELL at ΔV_{WELL} = 730 V .

Discharge mitigation in WELL → RPWELL

- A resistive plate (resistivity~ 10^9 – 10^{12} Ω-cm) is inserted between the THGEM and the anode: **RPWELL** [4].
- It is based on the idea of slow charge evacuation via a resistive plate (same as in RPC).
- The residual charges from an avalanche residing on the resistive plate reduces the field locally lowering the gain, thus mitigating a potential discharge.
- Also, covering the bare anode helps the process.

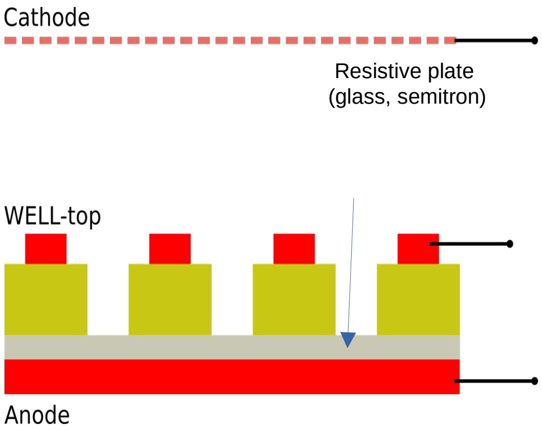
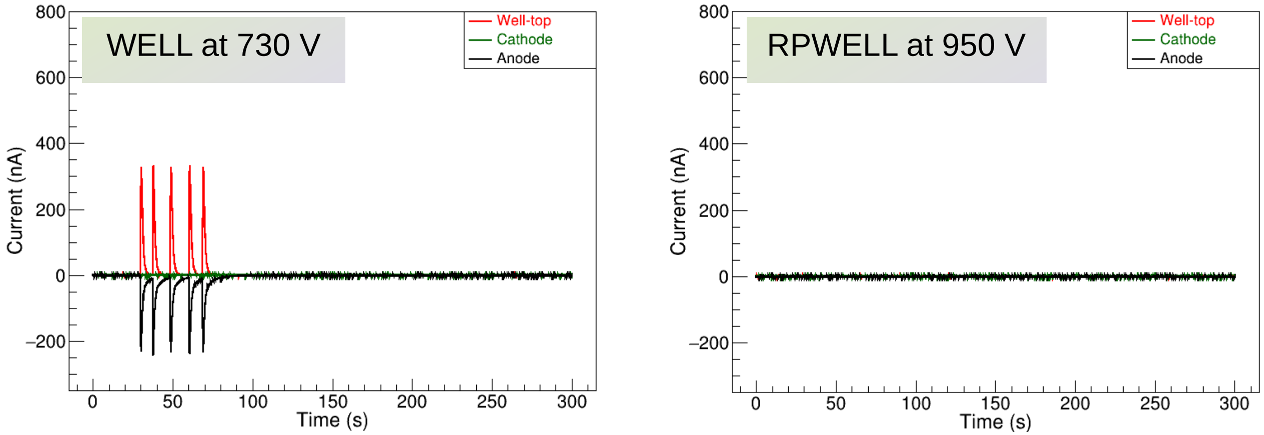


Fig: Schematic of an RPWELL detector.



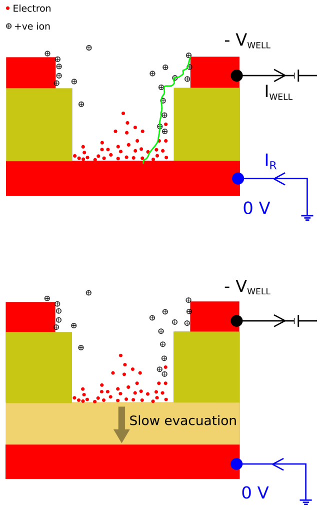


Fig: Monitored currents from all the electrodes of WELL and RPWELL.

Ref [4]: A. Rubin et. al, First studies with the Resistive-Plate WELL gaseous multiplier, *JINST **8** (2013) P11004.*

Detector response

- Discharge mitigation in RPWELL allows application of higher voltage, producing a larger gain. Maximum gain > **10^4** can be achieved with the used electronics (rate dependent).
- Higher voltage application produces higher gain but with some amount of feeble discharges (not detectable as electrode current. Visible as large signal on oscilloscope, saturates preamp).
- The deviation of the RPWELL gain from exponential nature is due to the voltage drop across RP which increases with voltage.

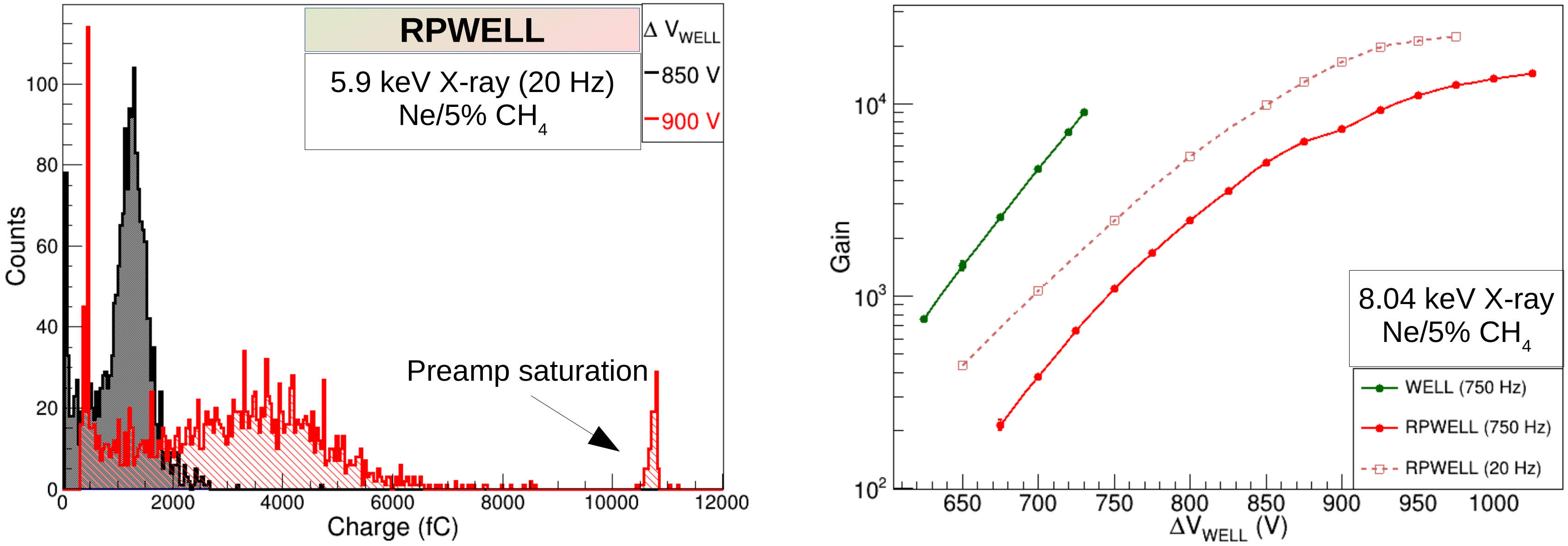


Fig: (left) MCA spectra for RPWELL, (right) Gain curves as a function of voltage across THGEM.

What is the effect of discharges in RPWELL performance?

Goal & requirements

- Although the discharges in RPWELL are very week, they still appear at high voltages.
- What is their effect on the detector performance?
    - Localization
    - Recovery time

Requirements for the study

- Produce discharges at a known localized region inside RPWELL.
- Control the production of discharge, its intensity and number.

Localized discharge production: method

Total charge at bottom of WELL = primary charge × WELL gain

- For a known source, we operate an RPWELL with strip readouts at a voltage which produces a total charge slightly less than the Raether limit. We introduce large primary charges at a specific location pushing that location to produce discharges.

- A specially designed **localized charge injector** is used for this purpose.

- Electrons can pass only through the open holes, X-rays can pass through all holes (25 µm Al foil).

- Electrons produced via primary ionization in the top-most gap gets multiplied in injector open hole. A second stage multiplication occurs in the WELL hole just below the open injector hole.

- Total charge at the bottom of the WELL crosses Raether limit producing localized discharge.

- The efficiency of the tool is verified in a WELL detector, from the monitored electrode currents.

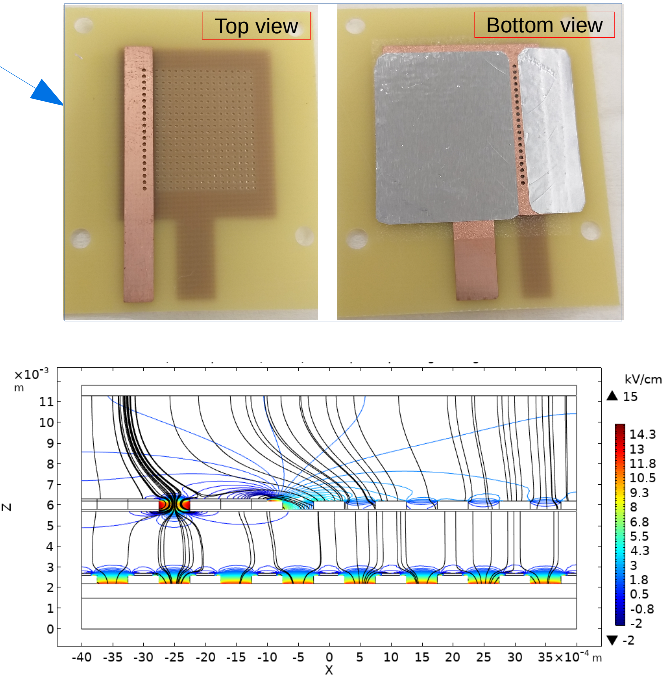


Fig: Used localized charge injector, and simulated field lines through it.

Effect of discharge: method

- Assembly of a RPWELL with a localized charge injector with its **open row of holes at the position of readout R_D.**

- Gas mixture: Ne/5% CH_4.

  ΔV_{WELL} = 850 V, $\Delta V_{transfer}$ = 150 V (0.5 kV/cm), $\Delta V_{injector}$ = 600 V, ΔV_{drift} = 500 V (1 kV/cm).

- A high rate X-ray source (**X_{WELL}**: 500 Hz Cu target X-ray tube) irradiates a WELL hole at the location of readout R_m ($R_m \neq R_D$). Gain shift due to charging up/down effect in FR4 was taken care of [5].

- Acquire regular charge spectrum from R_m in absence of any discharges i.e. injector OFF.

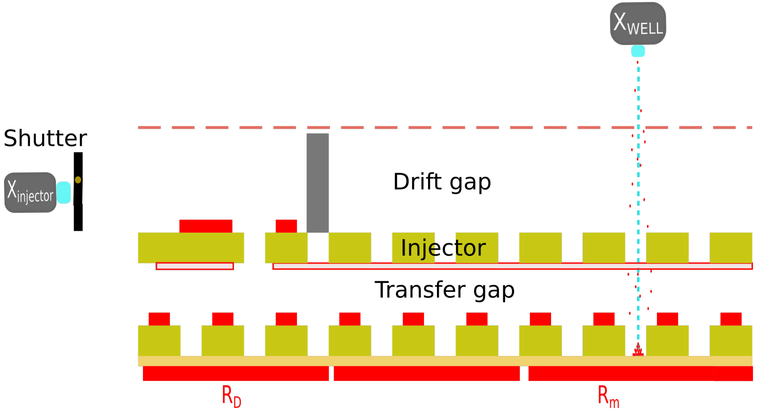


Fig: A regular spectrum is obtained when X_{WELL} irradiates R_m and injector is OFF.

Ref [5]: D. Shaked Renous et. al, Gain stabilization in Micro Pattern Gaseous Detectors: methodology and results, *JINST **12** (2017) P09036.*

Effect of discharge: method

- Switch on injector by opening the shutter in front of $X_{injector}$ to produce discharges at R_D.
- Acquire R_m spectrum. Any modification will indicate effect of discharges at the location of R_m.
- Choose R_m at different distances from R_D to quantify the localization of the effect.
- For a fixed R_m, recovery time is found by switching off $X_{injector}$ and monitoring the time taken by R_m spectrum to recover its original position.

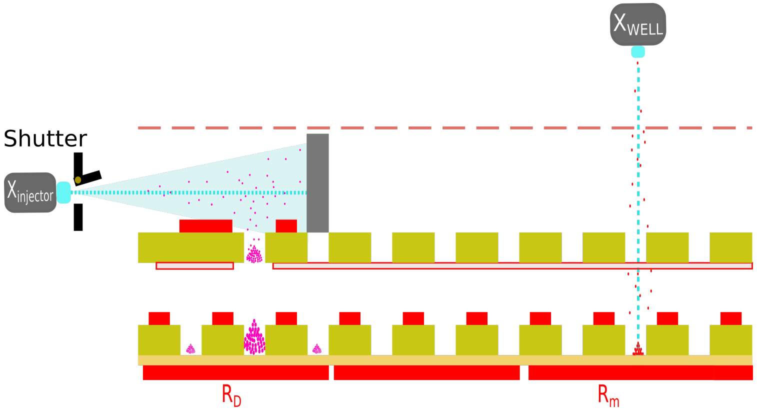


Fig: Switching on $X_{injector}$ produces discharges at R_D which modifies the initial R_m spectrum.

Observed effect

- Regular WELL: discharge at R_D **does not influence** the R_1 (3 mm from R_D) spectrum.
- RPWELL: discharge at R_D **reduces the gain** at R_m .
- The second peak at the lower channel number and the bad resolution of spectrum is due to the presence of the charge injector in front of the detectors.

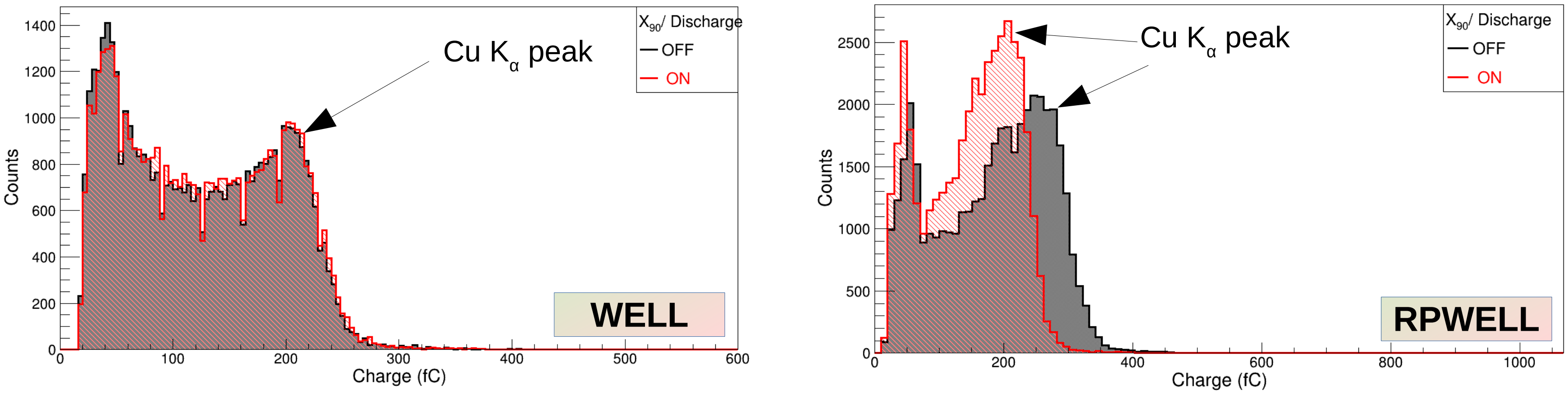


Fig: MCA spectra from R_m with and without discharge at R_D in (left) WELL, (right) RPWELL.

Observed effect

- Repeated spectra acquisition (each for 5 seconds) in a cycle of discharge OFF and ON for different exposure times.
- Error bars are from the Gaussian fit.

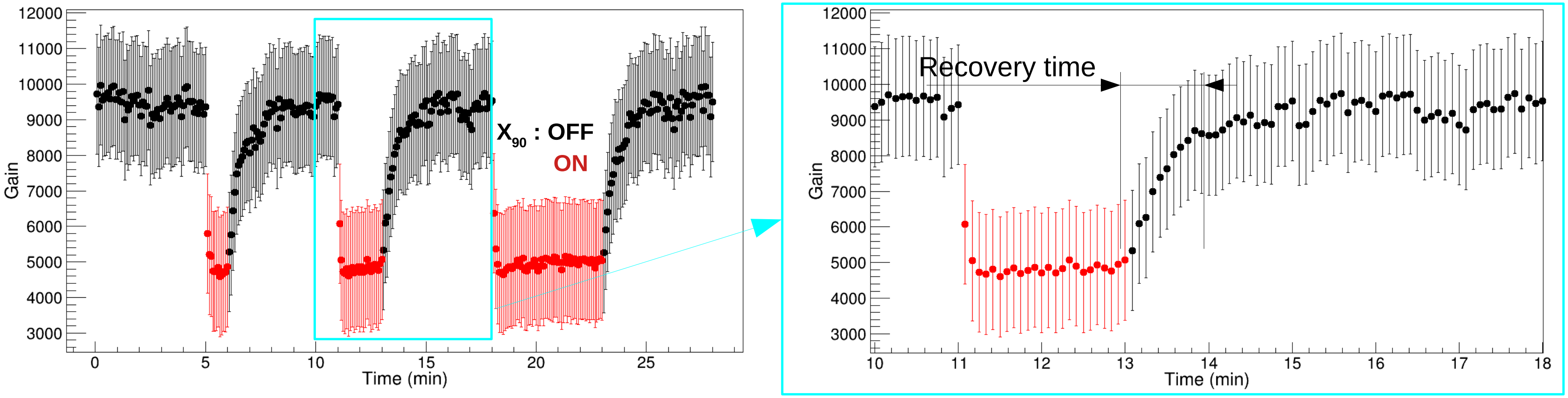


Fig: Variation of gain as a function of time in a cycle of X_{injector} off and on.

- Switching on X_{injector} reduces the gain very fast (~ 5 seconds). The **recovery time is about 1 minute**.

Effect of discharge intensity

- The reduction in gain is higher at higher voltage across the injector.
- Larger amount of charge insertion through the open injector holes creating larger amount of charge deposition on R_D. Producing stronger effect.

$$Gain\,shift\,(\%) = \frac{Gain_{OFF} - Gain_{ON}}{Gain_{OFF}} \times 100$$

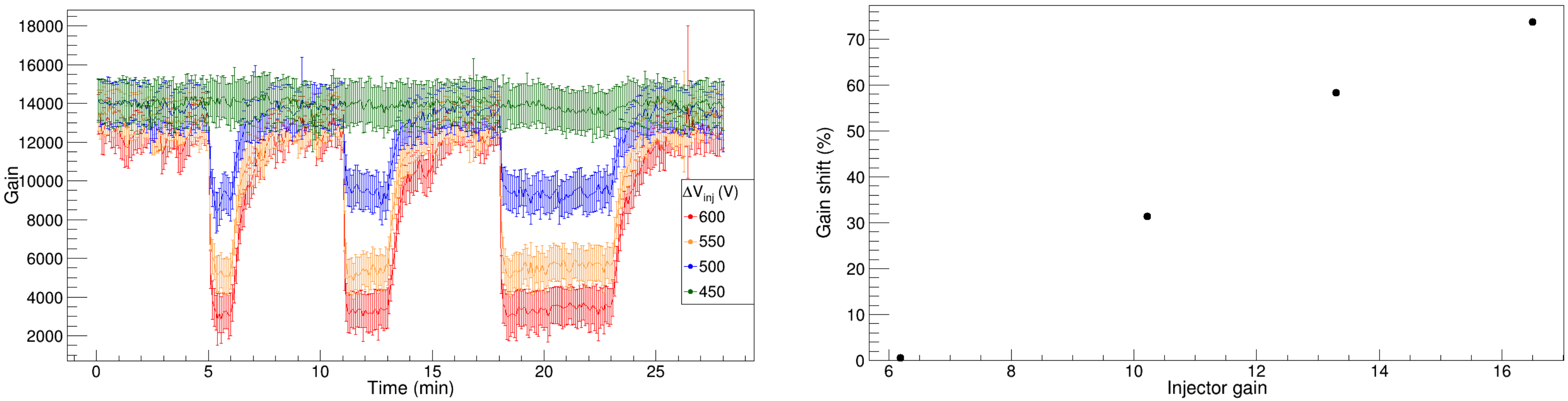


Fig: (left) Variation of gain in a cycle of $X_{injector}$ off and on for different $\Delta V_{injector}$, (right) variation of gain shift as a function of injector gain.

Effect of distance

- The shift in gain reduces with distance from R_D. The **closer points are affected the most**.
- The shift is higher for well spectra as it feels the effect of larger area of resistive plate.

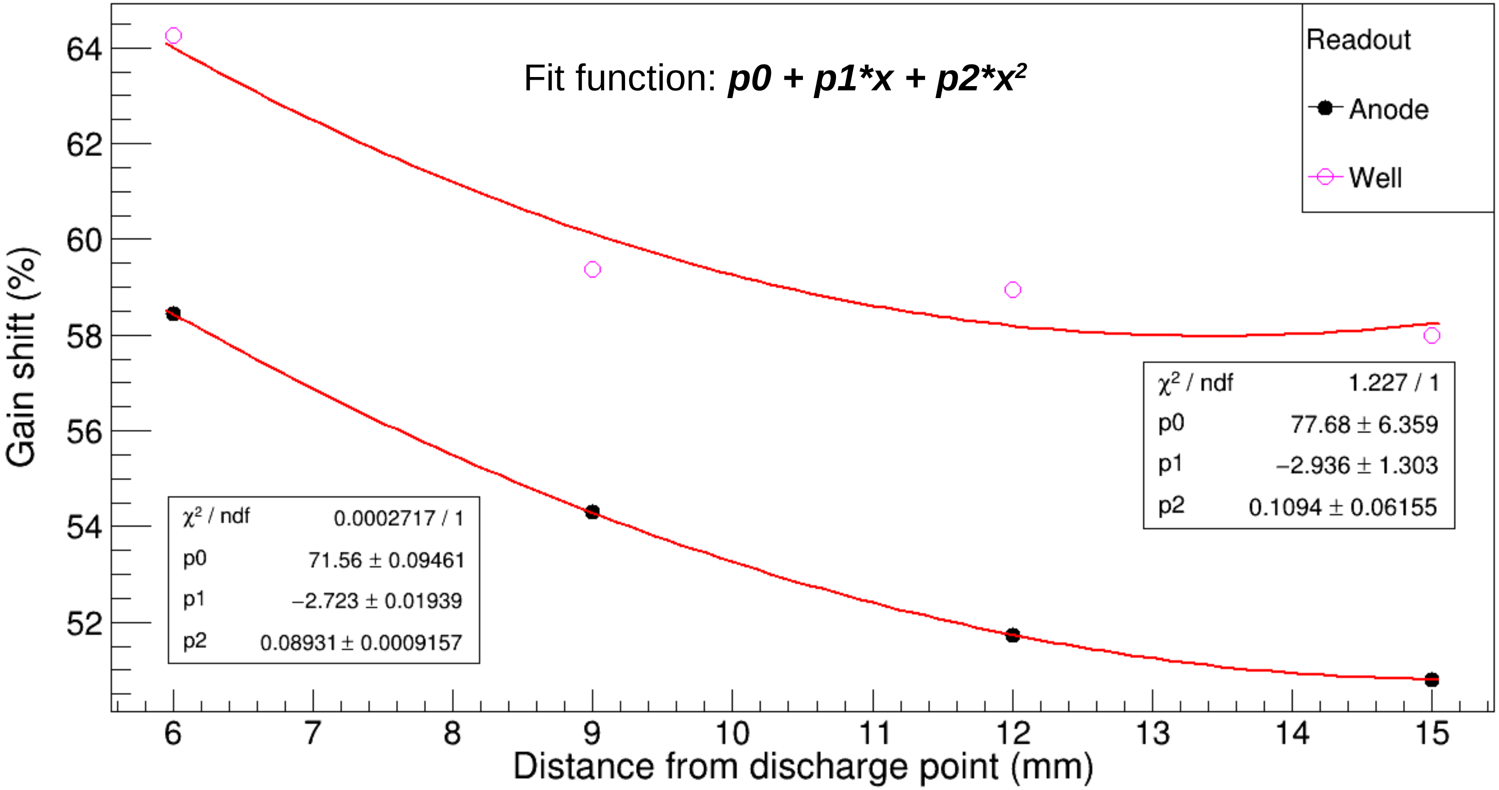


Fig: Variation of gain shift as a function of distance from discharge production point.

Qualitative explanation

- The gain of the WELL stage depends on the effective voltage across the WELL, ΔV_{eff}.
- The charges deposited on the resistive plate at the location of R_D (when injector is switched ON) diffuses to the anode (at 0 V) through the volume of resistive plate.
- This produces a voltage drop across the RP (V_{RP}) which acts in opposite to $\Delta V_{applied}$.

$$\boldsymbol{\Delta V_{eff} = \Delta V_{applied} - \Delta V_{RP}}$$

- ΔV_{RP} is higher for large charge deposit and for a closer point.
- The effect can be estimated using an equivalent R-C circuit for the resistive plate.

Fig: Charge deposited at a point evacuates to anode through the volume of resistive plate. This has an effect at other regions also.

Circuit simulation of resistive plate

- The current flow through the RP produces a voltage drop across RP which reduces effective gain.
- The resistive plate is modeled in terms of a set of resistors (bulk and surface) and capacitors.
- Evacuation of the deposited charge is equivalent to a current flow.
- The voltage drop across the resistive plate at different distances from input current is simulated in **ORCAD PSpice**.
- As a first step, some typical inputs as estimated from the geometry are used.
  - Bulk resistance (R_b)= 0.2 MΩ, surface resistance (R_s) = R_b/5, C_b = 53 pF, C_r = 4 pF.
  - I (t) = 100 µA DC current.

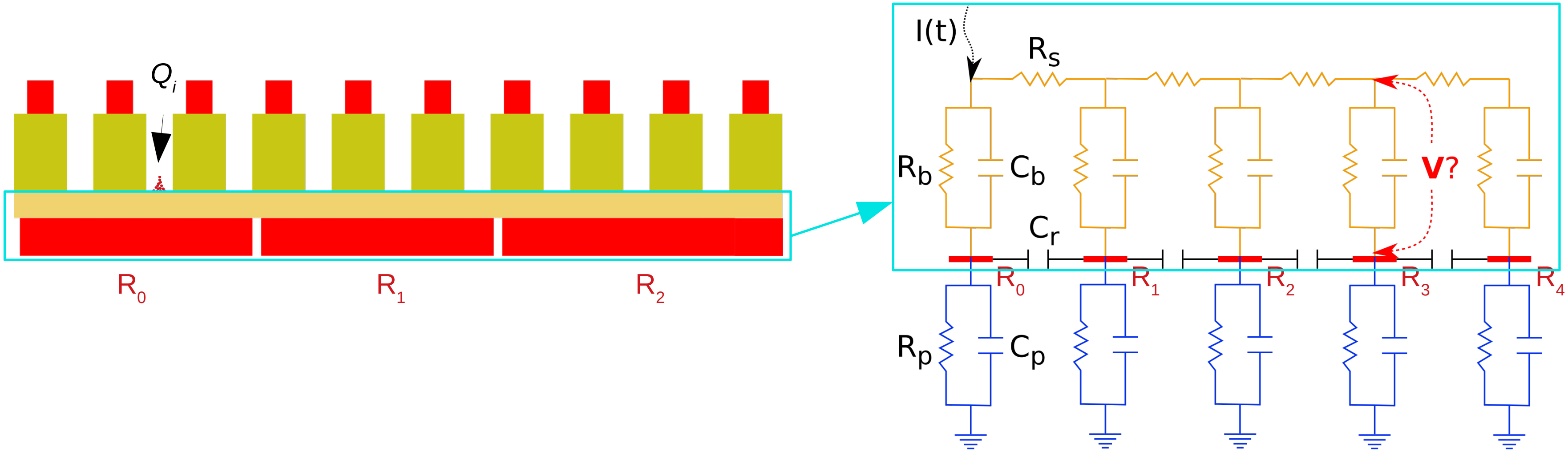


Fig: Equivalent electric circuit for the resistive plate.

Circuit simulation of resistive plate

- The voltage drop reduces with distance from the charge deposition point. This qualitatively explains the reduction in gain as a function of distance.
- **The calculation need to be performed with measured values of bulk and surface resistances and correct charge deposition model.**

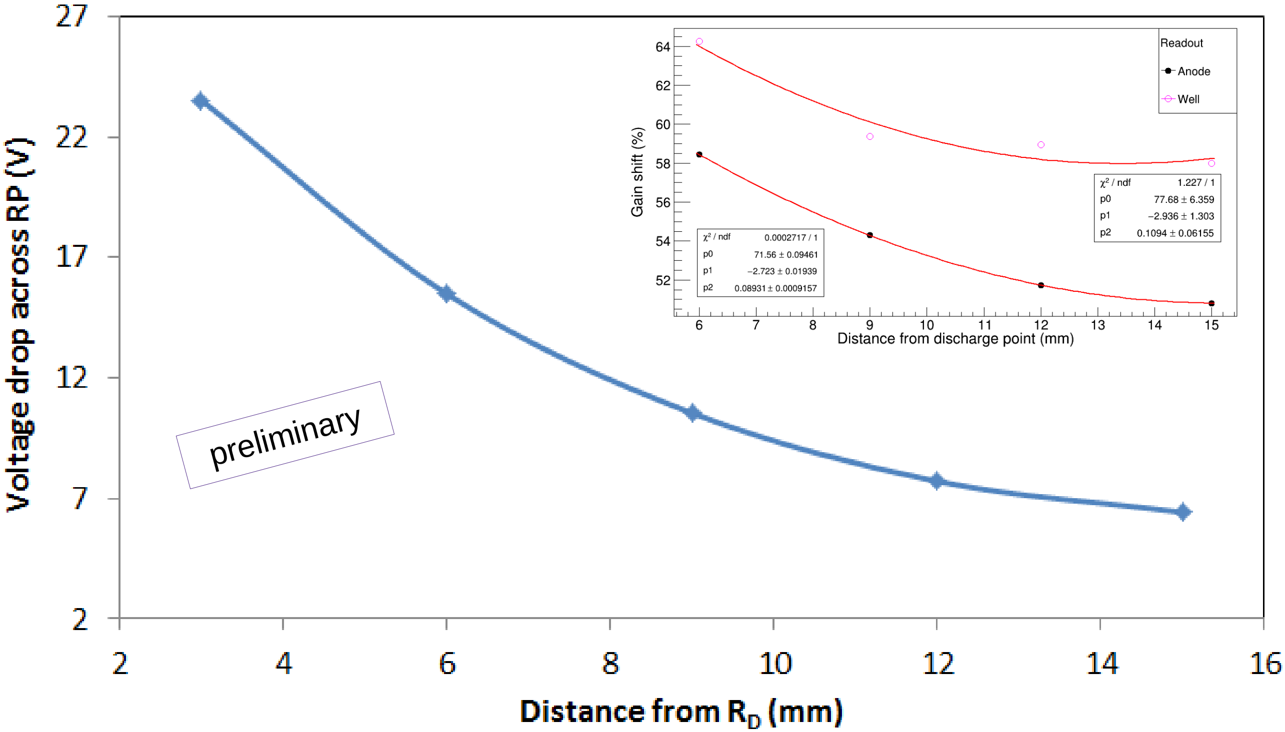


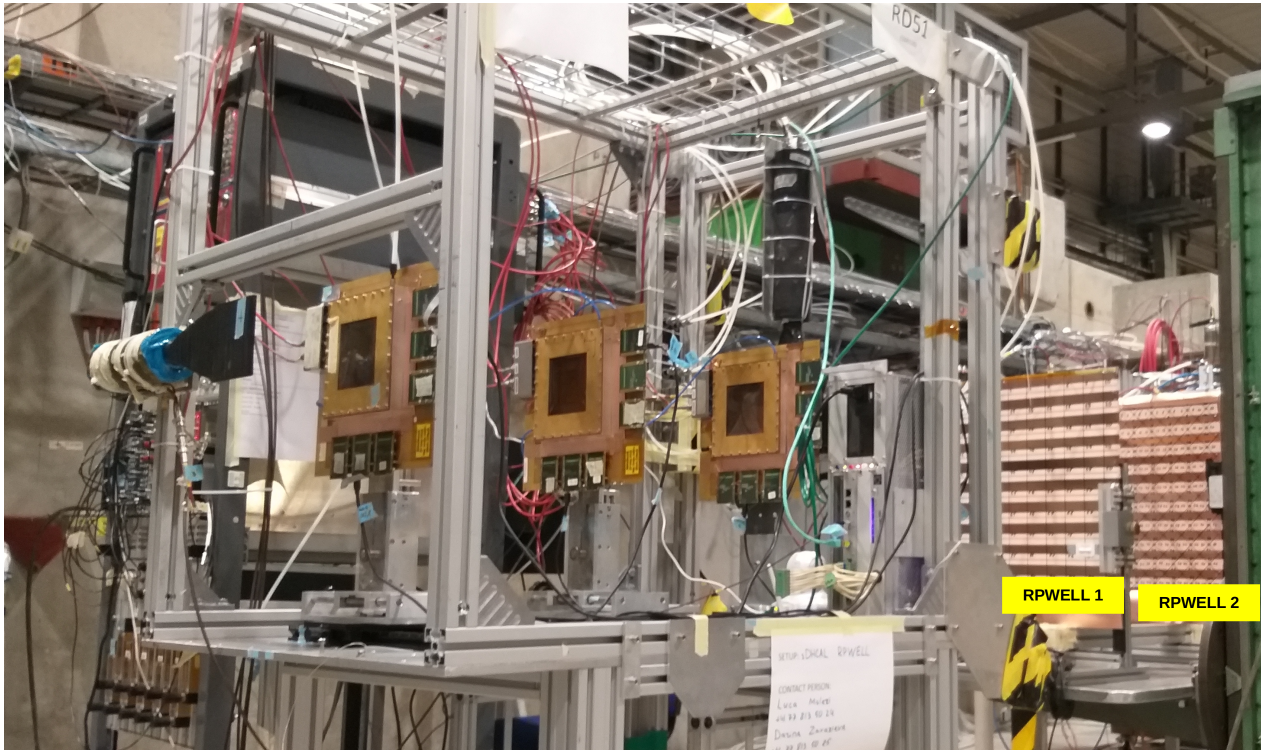
Fig: Variation of voltage drop across resistive plate as a function of distance from entry point of input current. (inset) experimental observation of gain shift with distance from R_D.

Conclusion

- Introduction of a resistive plate in the WELL-like detector mitigates the violent discharges. It helps to achieve higher gain.
- Production of discharges inside an RPWELL reduces the gain at and around its production point. Self discharge-quenching mechanism offered by the resistive plate.
- Discharge mitigation using resistive plate comes at the price of position-dependent gain change for highly ionizing events.
- The effect depends on the amount of deposited charge.
- The recovery time is found to be around 1 minute. Does not seem to depend on distance. We are limited by the 5 second acquisition time.
- The shown results are for multiple discharges. Study of effect of a single discharge is in progress.

Present status with RPWELL

- Small prototype RPWELLs have shown satisfactory performance in the lab under X-ray and cosmic radiations.
- Performance evaluation of 2 large (50 cm × 50 cm) RPWELLs is ongoing using muon beam in CERN SPS/H4 RD51 beam-line.



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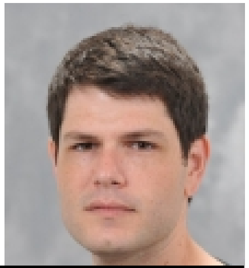
Dan Shaked
Renous


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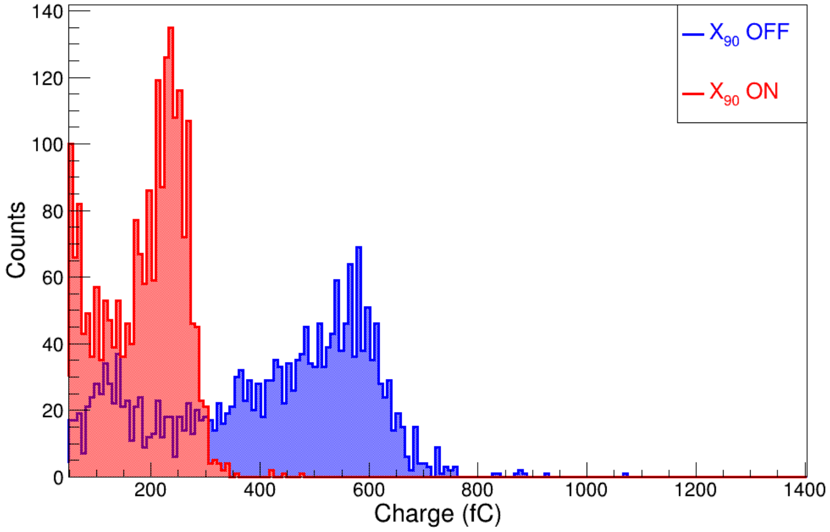
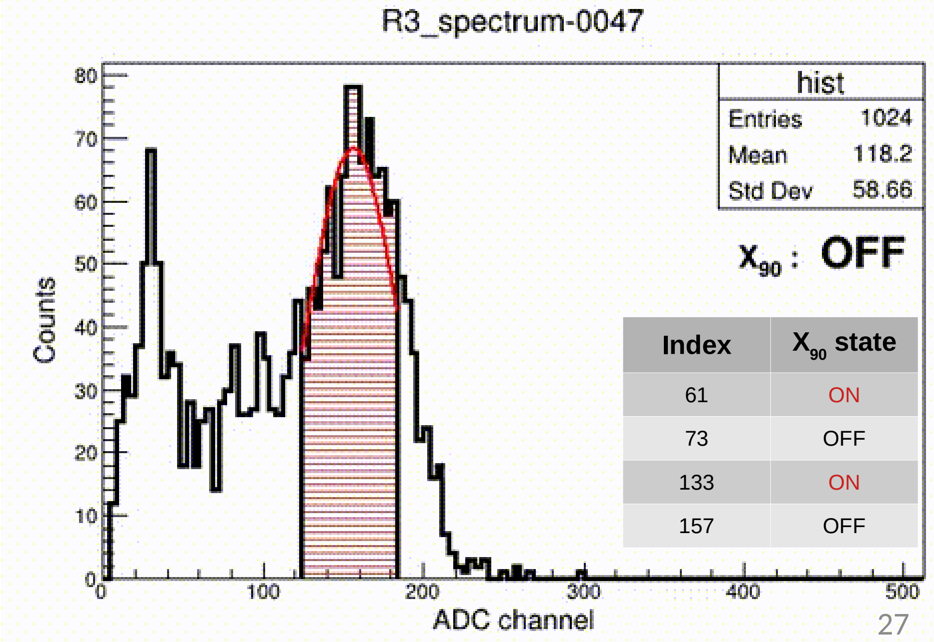
Thank You

BACKUP

Observed effect

- Production of discharges ($X_{injector}$ ON) at R_D reduces the gain at regions around R_D.
- Studying the same in a normal WELL (i.e. no resisitive plate) confirmed that this effect is due to the presence of resistive plate.
- Repeated spectra acquisition (each for **5 seconds**) in a cycle of discharge OFF and ON for different exposure times.
- Gain is calculated from the position of Cu K_α peak as found by Gaussian fit (ignore the second peak at lower channel number).

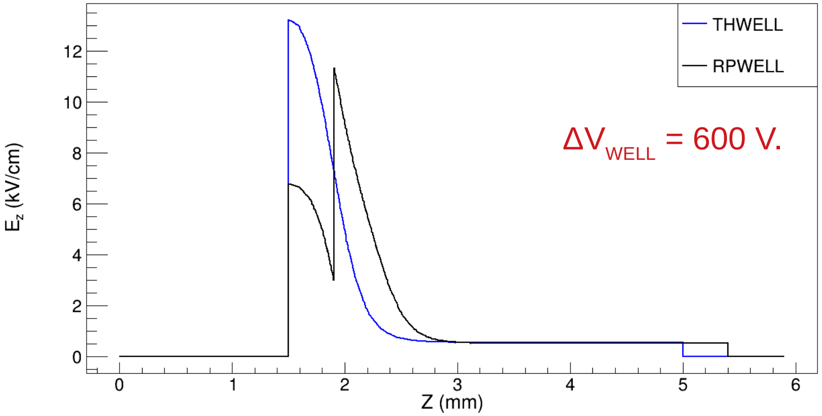


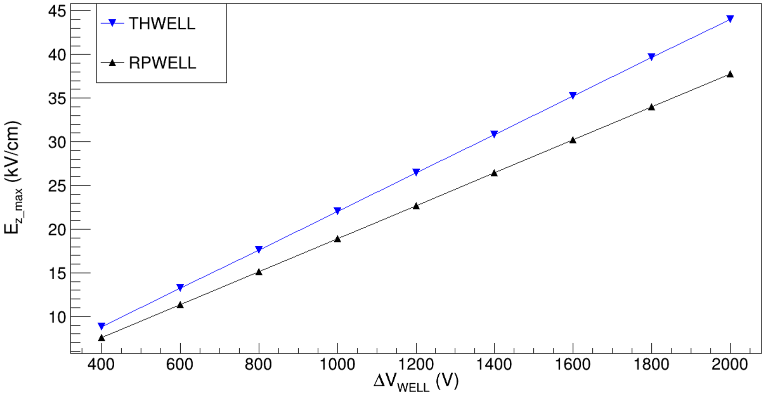


Index	X_{90} state
61	ON
73	OFF
133	ON
157	OFF

Field calculation using COMSOL

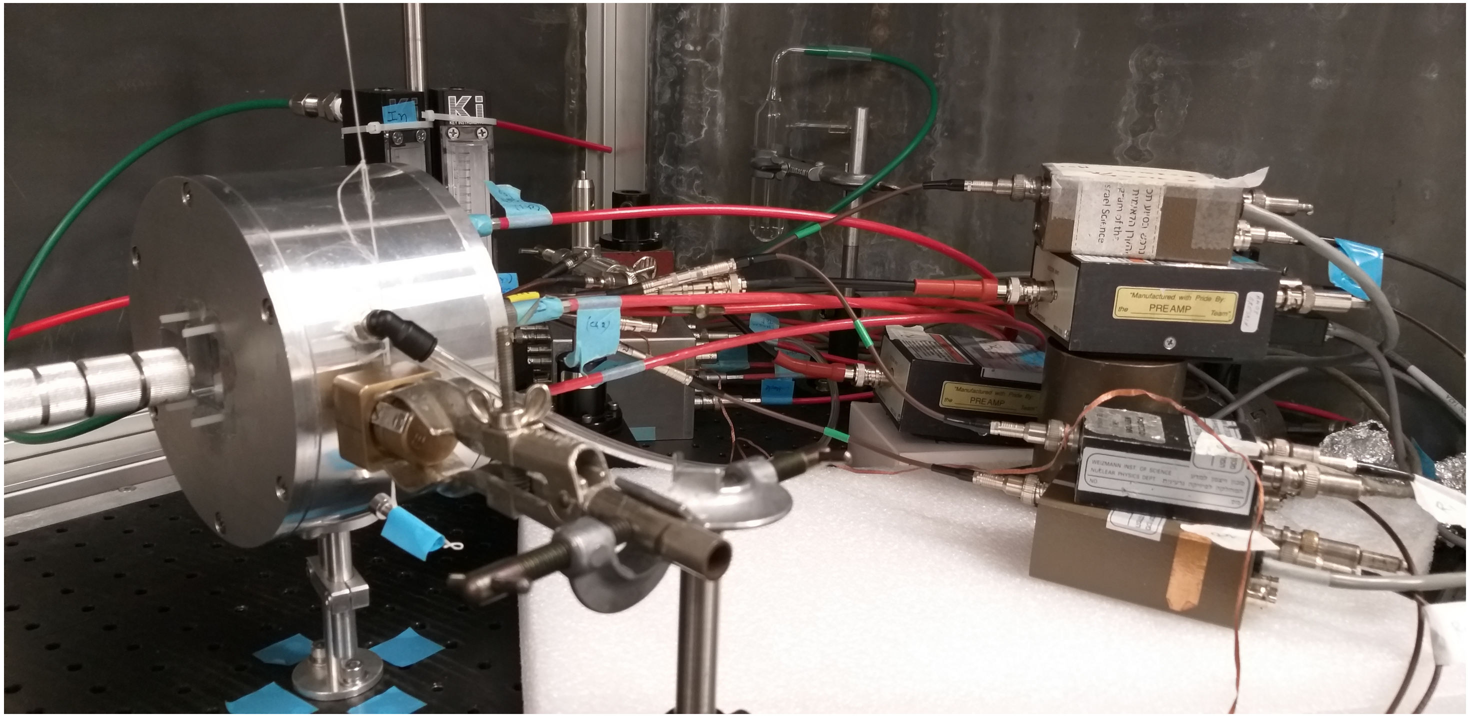
- For the same applied voltage, field in the RPWELL hole is lower than that for a regular WELL detector because of increased thickness between anode and WELL top.





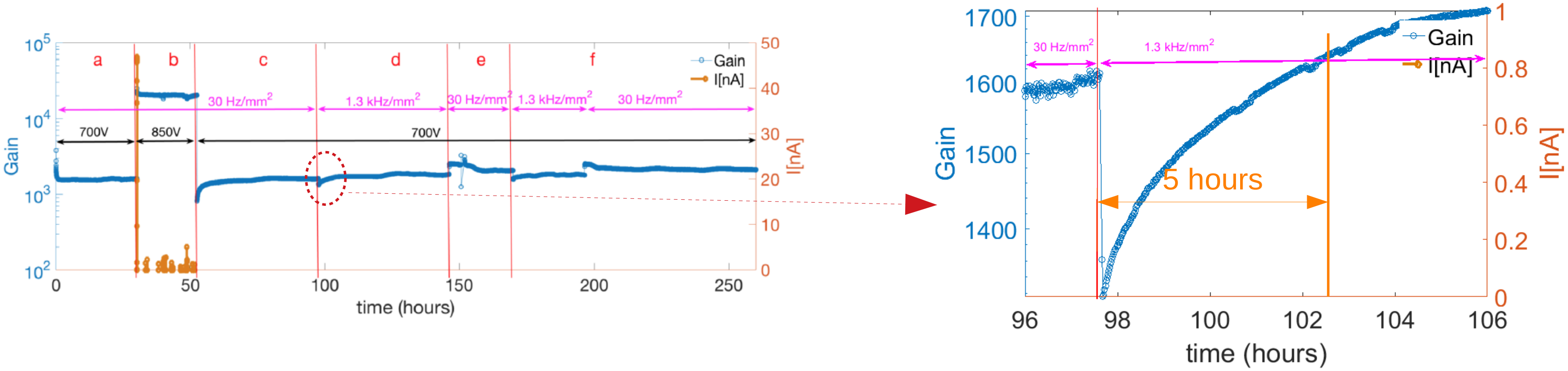
Experimental setup

- Setup.



Charge up/down in FR4 – published result

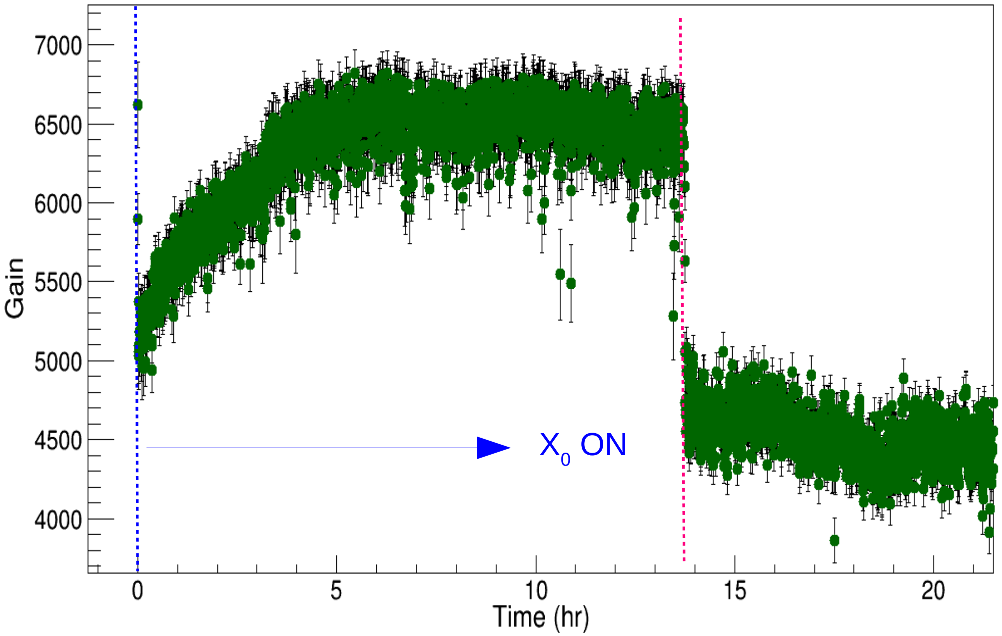
- Due to increase in X-ray rate, the initial fall in gain occurs in about 5 minutes. The gain recovers to its initial value in about 5 hours.



Ref [1]: “Gain stabilization in Micro Pattern Gaseous Detectors: methodology and results”, *D. Shaked Renous et al 2017 JINST 12 P09036*.

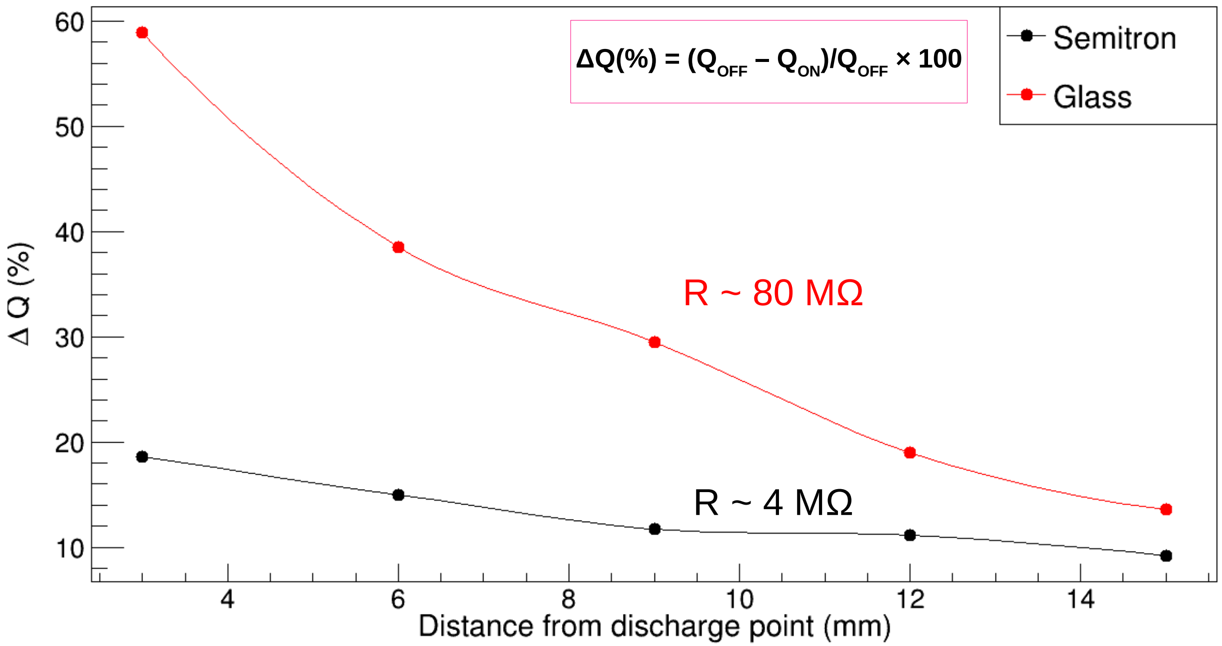
Charge up/down in FR4 – present study

- Charge up/down process in FR4 completes in 5 hours for the used source rate and voltage configuration.



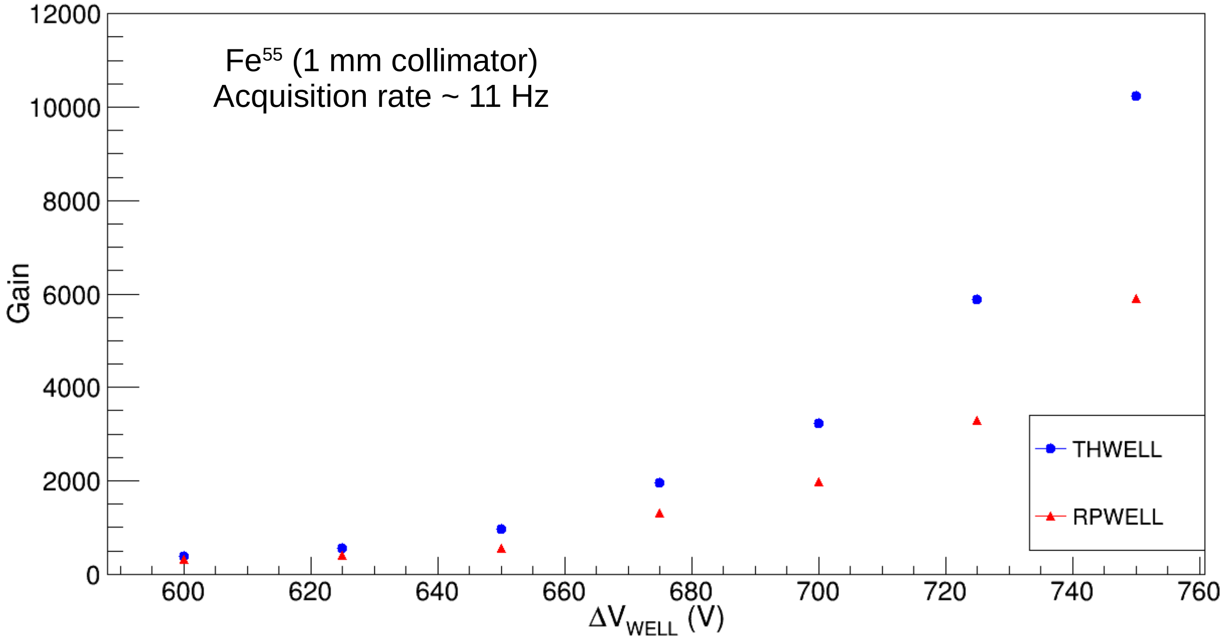
Discharge effect for different RP

- It was a preliminary result.
- But it showcases the effect of resistance and at per with the theoretical model.



Voltage drop across RP by charge deposit

- Comparison of gain vs ΔV_{WELL} curves between THWELL and RPWELL at different radiation rates to find a relation between deposited charge and voltage across the resistive plate.
- At the same voltage the gain is always lower in case of RPWELL. The difference increases with voltage.
- Possible explanation: Charge deposition on RP creates a voltage drop across RP which reduces the effective field at the hole.



Electrical discharge

- Very high potential difference between 2 close points → high electric field in the medium ($E \sim \Delta V/d$).
- Strong electric field can extract electrons from the atoms/molecules of the medium.
- Free electrons gain kinetic energy from the field. While moving, they collide with other molecules liberating more and more electrons.
- Finally, a large amount of charge movement between the 2 points, creating a conducting plasma between the 2 points → a spark/ electrical discharge.
- The phenomenon relies on ease of ionizing the medium. It becomes easier in presence of radiation as it supplies the primary ionization.

Why is it important and relevant in gas detectors?