# HGTD hybrid performance test at USTC

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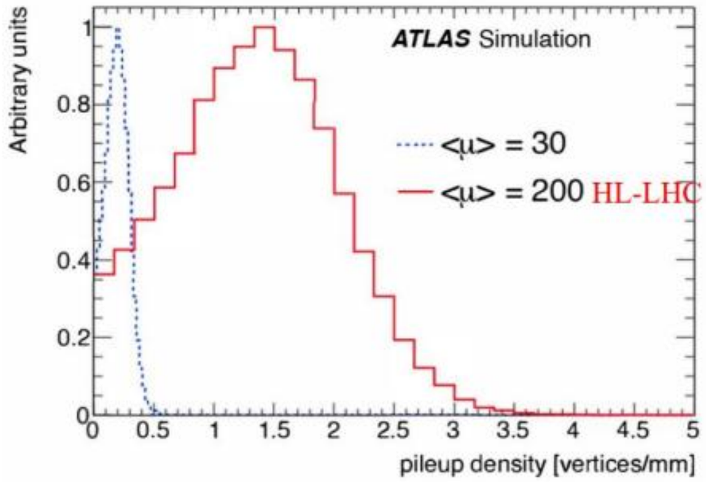
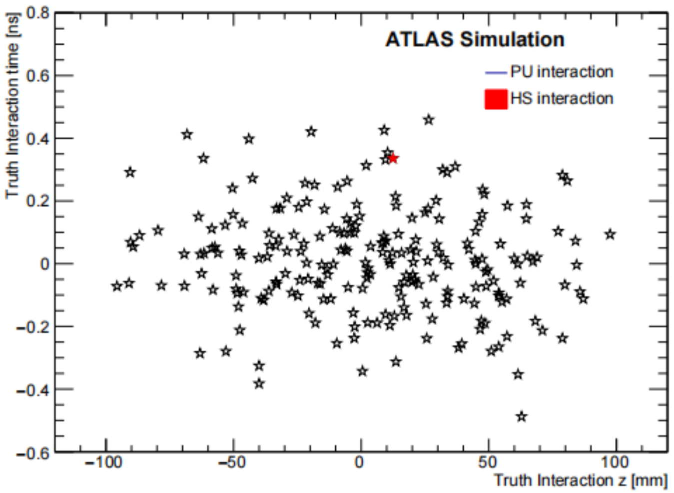
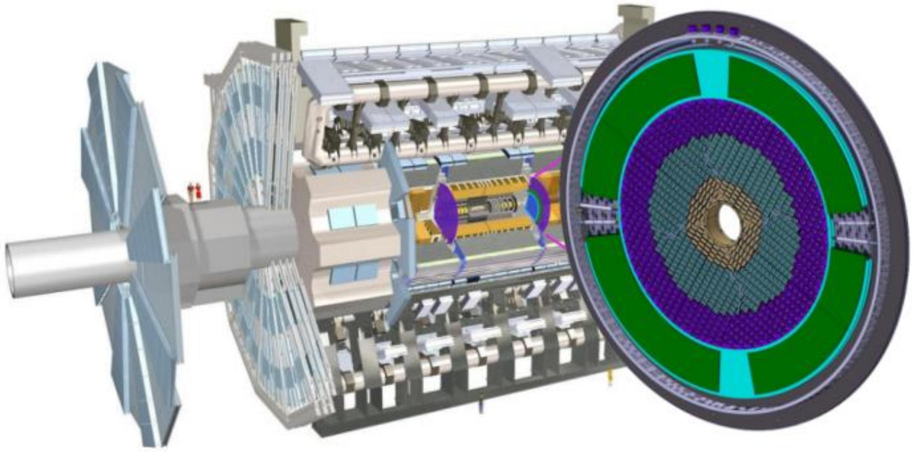
30/10/2025

# ATLAS High Granularity Timing Detector (HGTD)

- HL-LHC upgrade will increase the luminosity: $2.1 \times 10^{34}$ ==> $7.5 \times 10^{34}\ cm^{-2}s^{-1}$, and also increase the pile-up events: 30 ==> 200 every bunch crossing
- To reject those pile-up events, only using vertex position information is not enough
- HGTD project: providing vertex timing information for each track with about 40 ps resolution



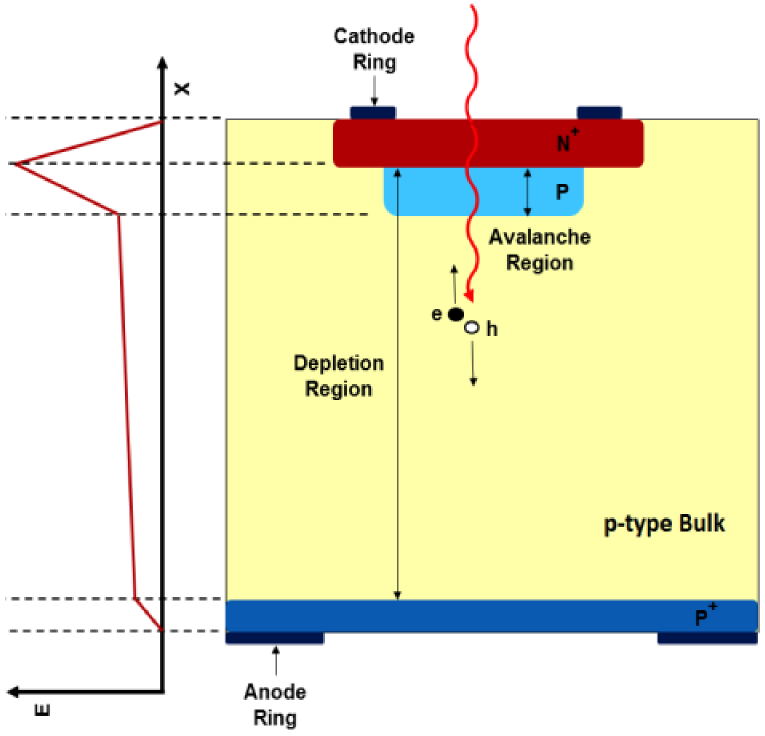



HGTD key requirement

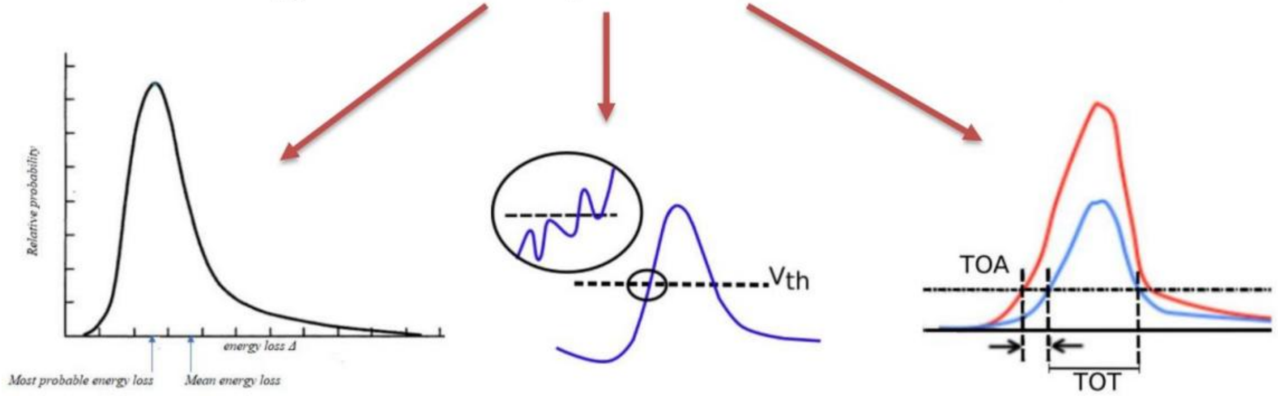
- Hit efficiency > 95%
- Time resolution per hit > 35 ps
- Radiation hardness
  - Maximum fluence: $2.5E15\ n_{eq}/cm^2$
  - Total Ionising Dose: 2 MGy

# LGAD and time resolution composition

- Low Gain Avalanche Diodes are used as the sensor of HGTD
- $N^+ - P - P^- - P^+$ structure with a moderatly doped P-layer to produce a high electrical field
- The gain is realized by the impact ionization of migrating carriers which acquire enough energy in the high electrical field during charge collection process

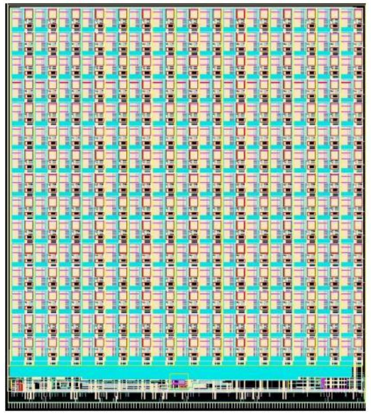



$$\sigma^2_{T_{hit}} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{TW} + \sigma^2_{clock} + \sigma^2_{TDC}$$

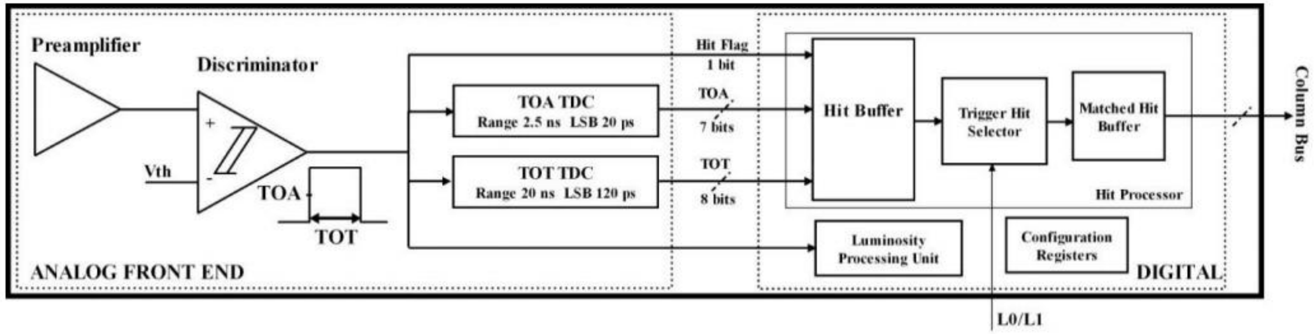



- $\sigma_{Landau}$, Landau fluctuation from charge deposition non-uniformity
- $\sigma_{jitter} \sim \frac{t_{rise}}{(S/N)}$, where $t_{rise}$ is the rise time and $S/N$ is signal to noise ratio
- $\sigma_{TW} \sim [\frac{V_{th}}{S} t_{rise}]_{RMS}$, from amplitude variation
- $\sigma_{clock}$, uncertainty of reference
- $\sigma_{TDC}$, TDC binning resolution

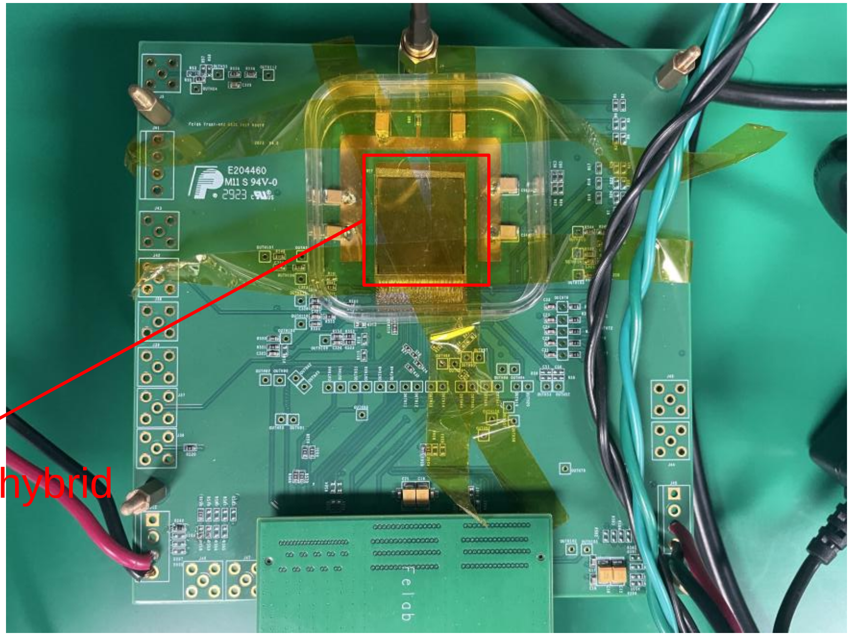
# ASIC and hybrid at USTC



15*15 Altiroc layout (size~20mm*22.3mm)




Altiroc on-pixel electronics

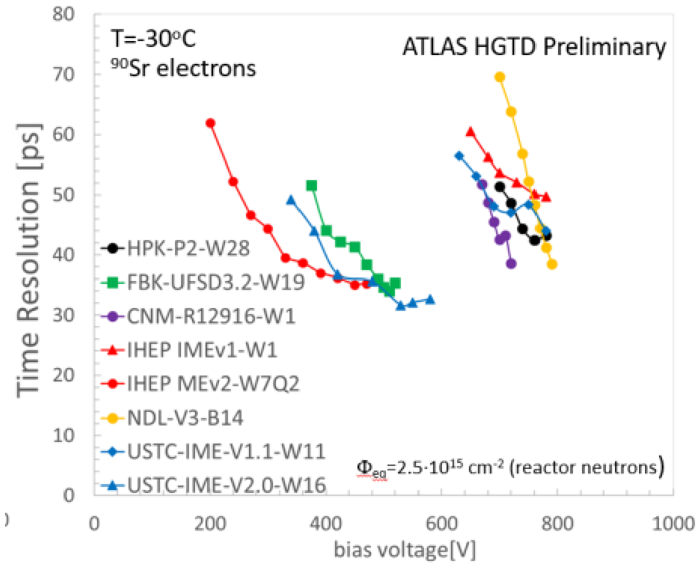


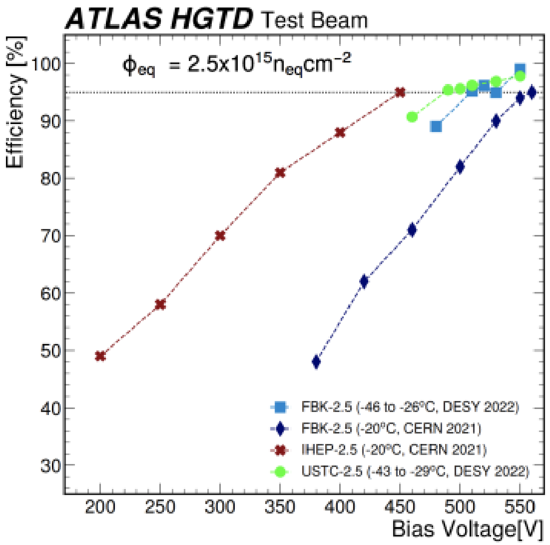
15*15 hybrid

testboard top view

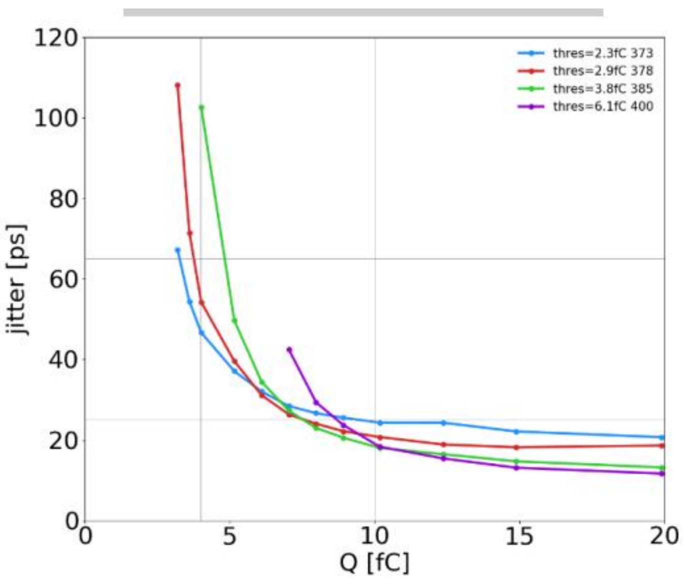
- The ASIC used in HGTD is called Altiroc
- In USTC, we have Altiroc3 chip + USTC-IME LGAD sensor hybrid
- To measure the time resolution performance, we integrated the 15*15 hybrid into the testboard for signal readout

# HGTD time resolution measurement



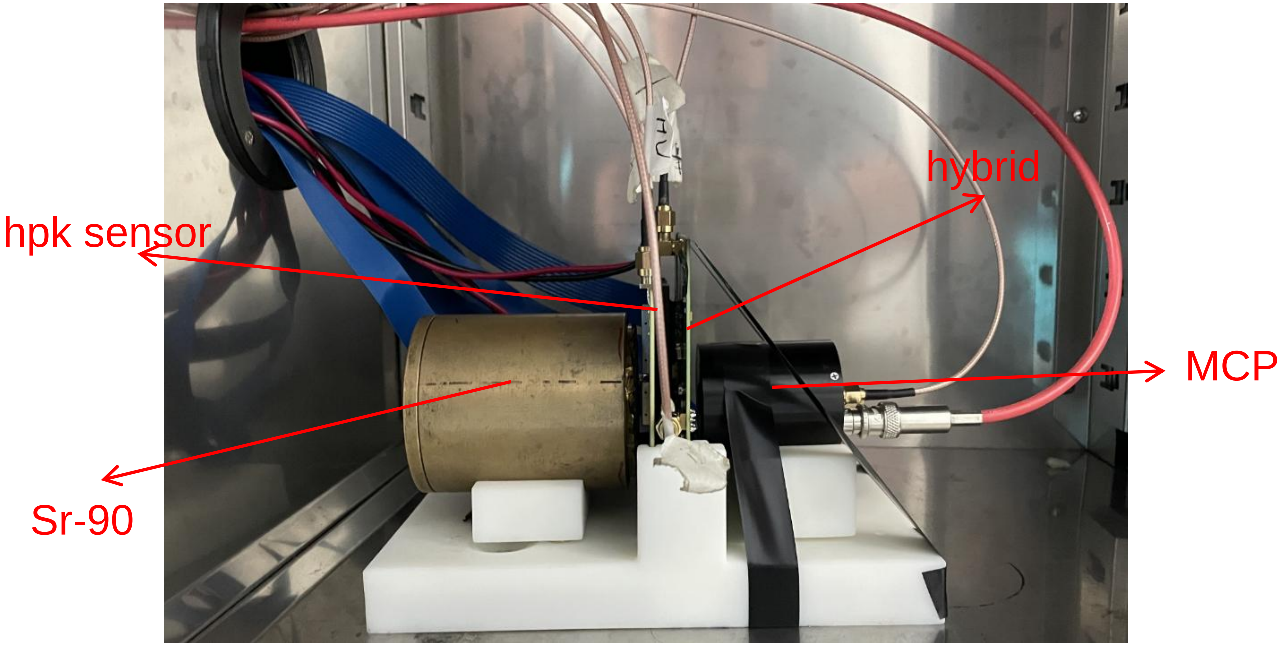

LGAD alone, time resolution (left) and efficiency (right)




Altiroc alone jitter

- The high time precison is the characteristic and also the most important key requirement for HGTD
  - target time resolution per hit: 35 ps at the start of lifetime and not worse than 70 ps at the end of lifetime
- The stand alone performance of LGAD sensor and Altiroc are sufficiently tested and satisify the requirement
- Combined performace test ongoing
  - testbeam
  - Sr-90 source test (convinent in lab and can serve as the complement to module QA/QC)

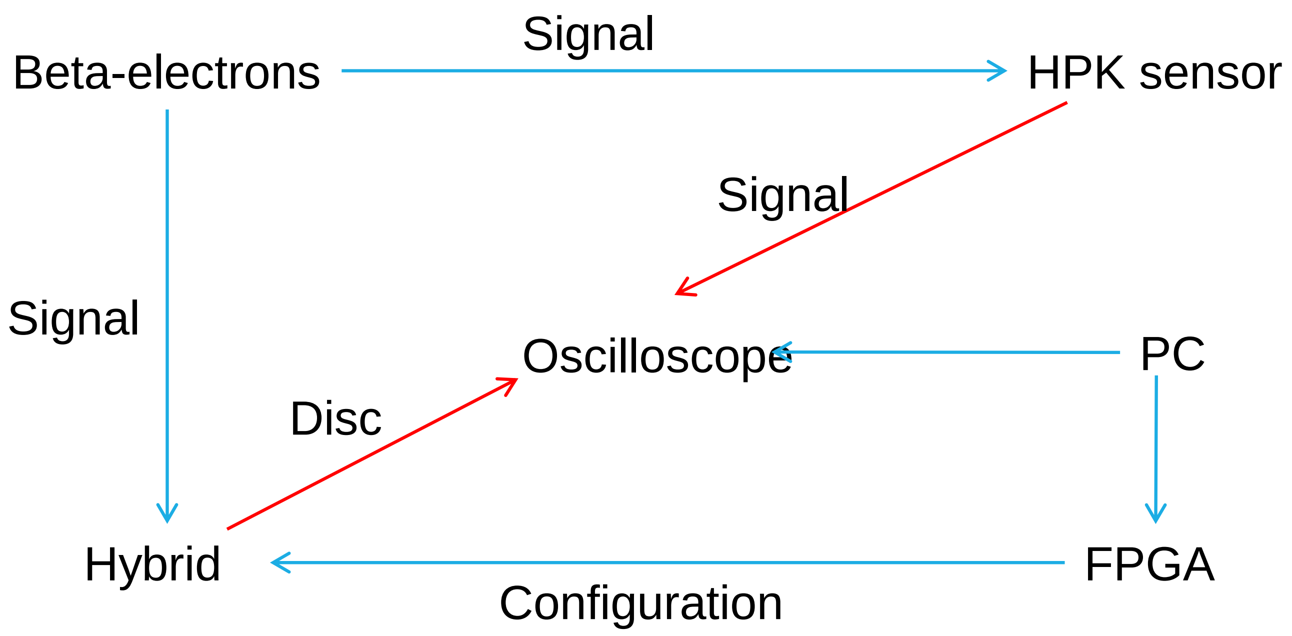
# Hybrid time resolution scope test at HGTD

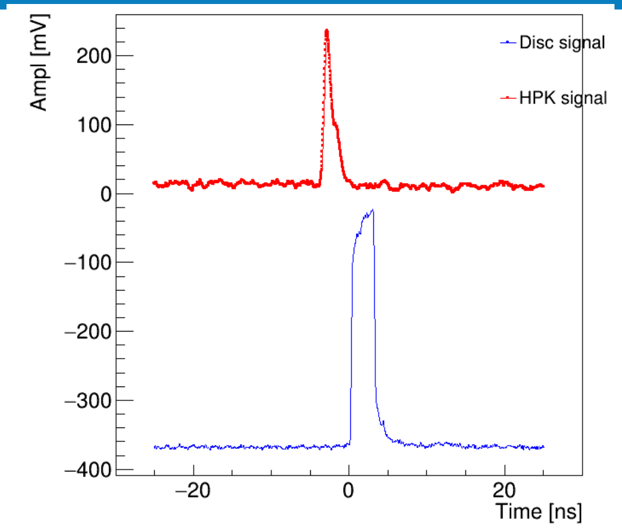



measurement setup

- Setup at USTC: radioactive source => reference sensor (single pad LGAD sensor) => hybrid => MCP
- Using MCP to calibrate the single LGAD sensor, and using single LGAD as the reference to the hybrid
  - The variation of ΔTOA mainly originates from detectors' time uncertainty
  - $\sigma_{hybrid} = \sqrt{\sigma_{\Delta TOA}^2 - \sigma_{Ref}^2}$

# Data taking logic



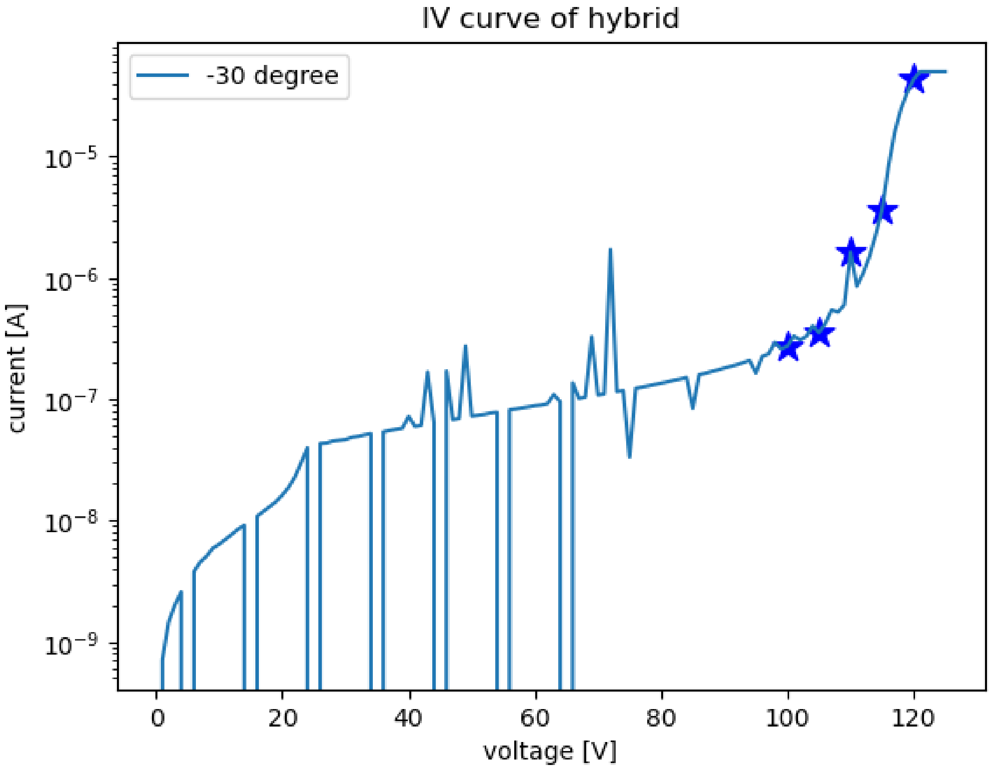

waveform in oscilloscope, the red curve is the reference signal and the blue curve is the hybrid Disc signal

- Extract the Altiroc's discriminator signal using the testboard probe pin
- Collect waveform when disc signal and HPK signal reach their trigger level within 10ns in oscilloscope
- Use PC to contral FPGA register to loop over pixels

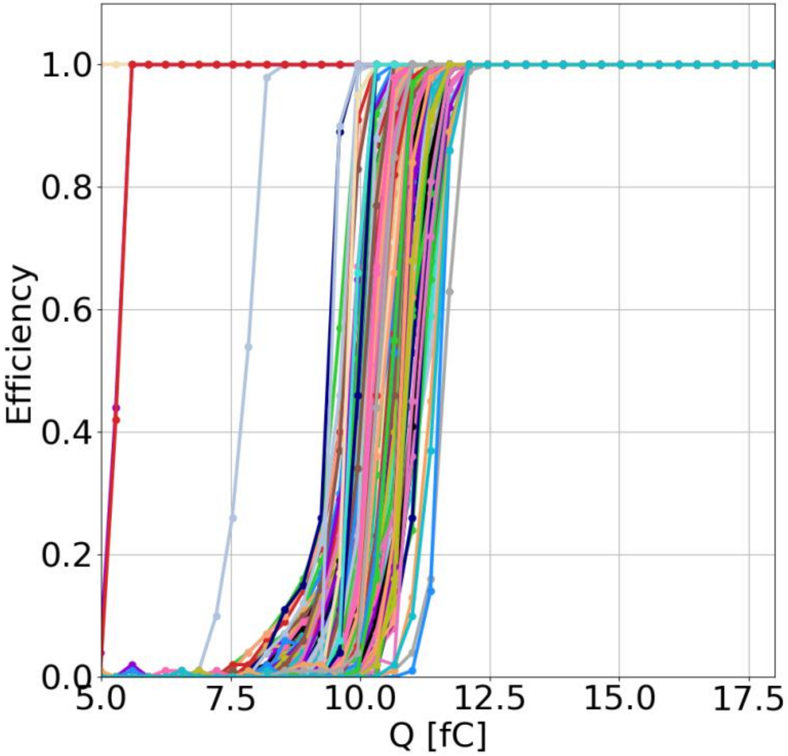
$$\sigma^2_{T_{hit}} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{TW} + \cancel{\sigma^2_{clock}} + \cancel{\sigma^2_{TDC}}$$

- Since the uncertainty of reference sensor will be substracted and the signal is directly extracted from disciminінator without digitalization, the contribution from $\sigma_{clock}$ and $\sigma_{TW}$ can not be seen

# Hybrid status



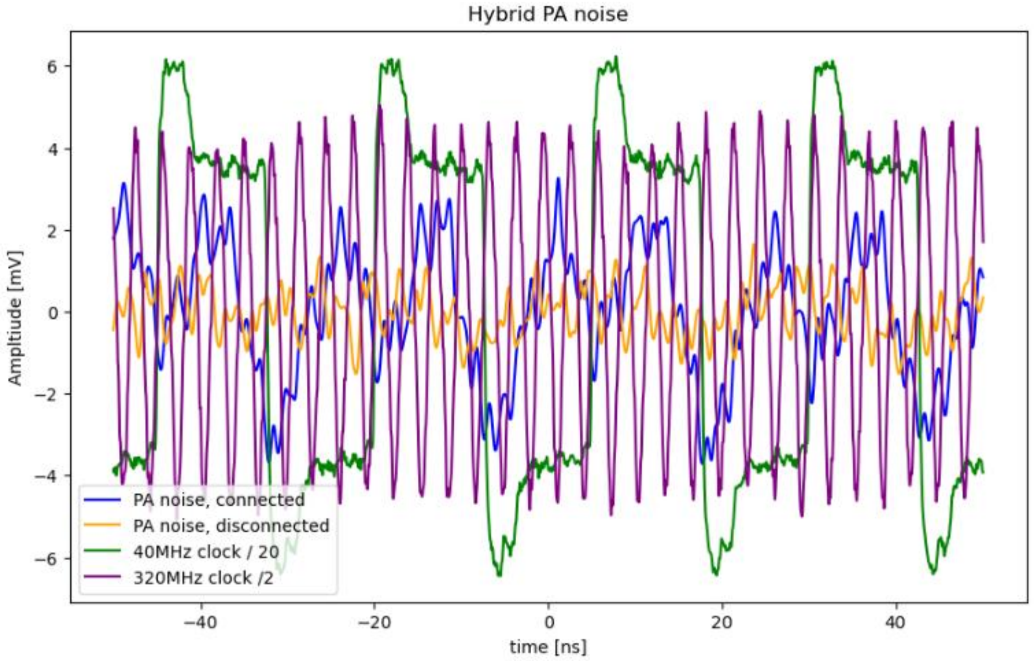

hybrid IV @-30degree



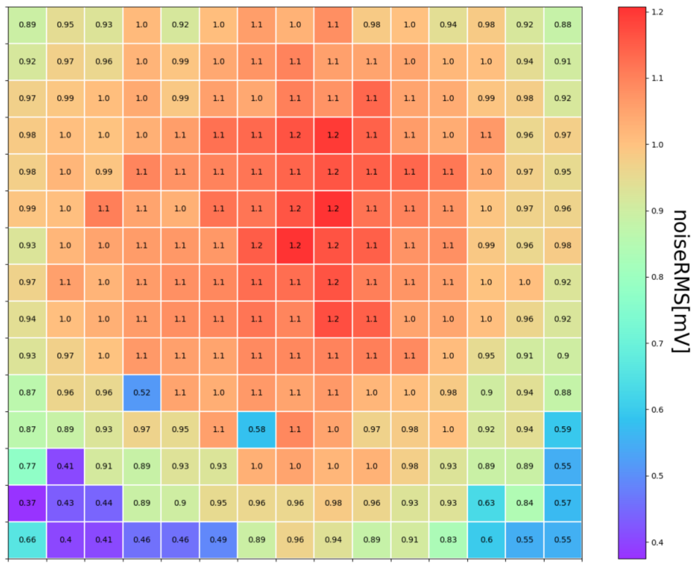

Disc charge threshold after tunning @ -30degree

- Temperature = -30degree, Vbd ~ 123 V
- break down voltage ~ 123 V; 5 HV settings were tested: 100, 105, 110, 115, 120 V
- Tuned the discriminator threshold at ~ 10fC

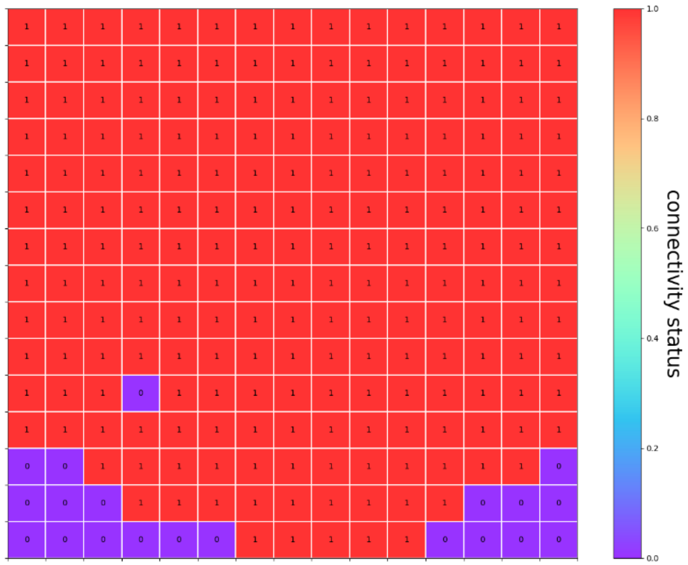
# Hybrid noise




noise waveform




hybird noise RMS map

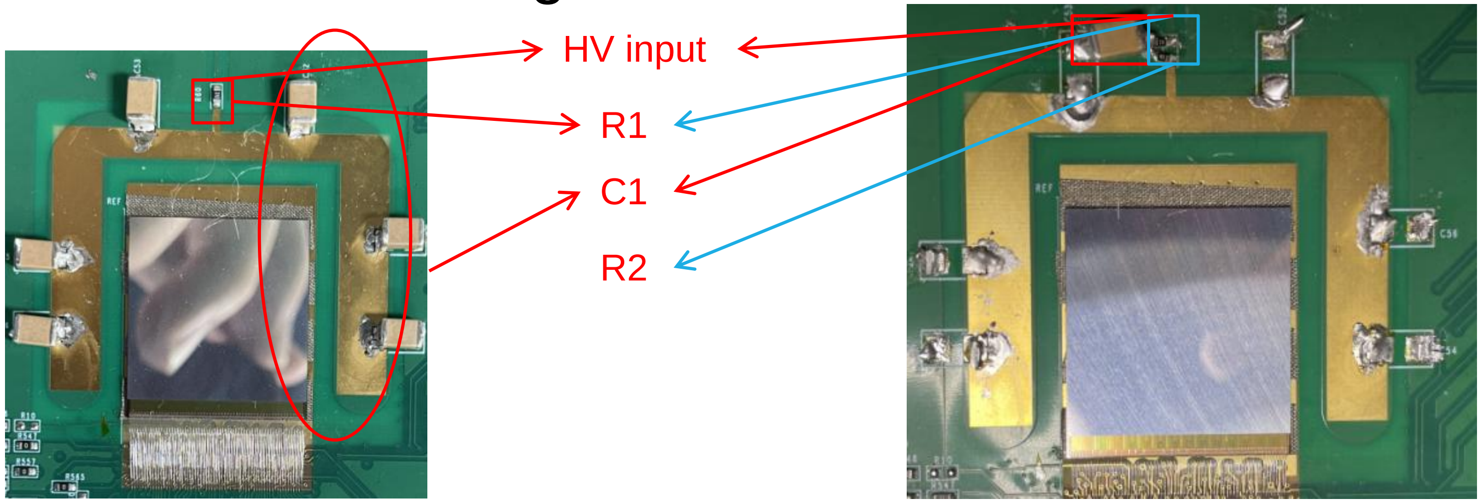


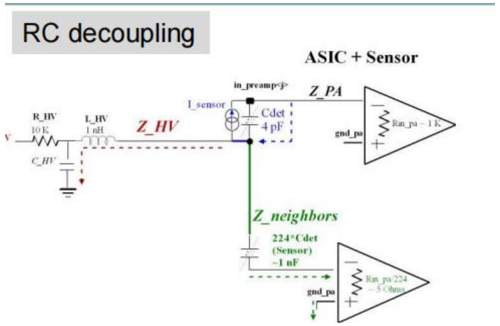

hybird connnectivity map tested by source test. red channels are connected while the purple channels are disconnected

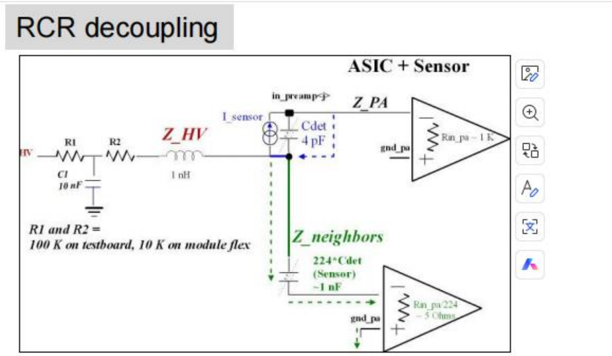
- When we tested the pre-amplifier output without signal, the noise RMS in each channel is obviously not zero
- The noise's main frequency is 40MHz ==> induced by internal 40MHz clock
- The noise amplitude highly correlate with the hybrid connectivity situation
  - The noise disappears when the sensor does not connect to the Altiroc (also does not exist in the digital module / Altiroc alone )
- To get a better performance, we made a HV decoupling on testboard to surpress this noise

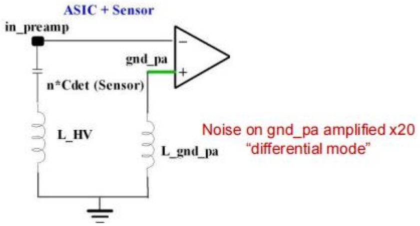
Before HV decouling

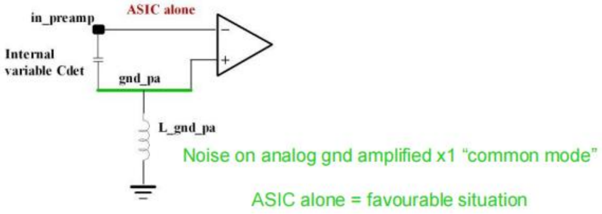
After HV decouling



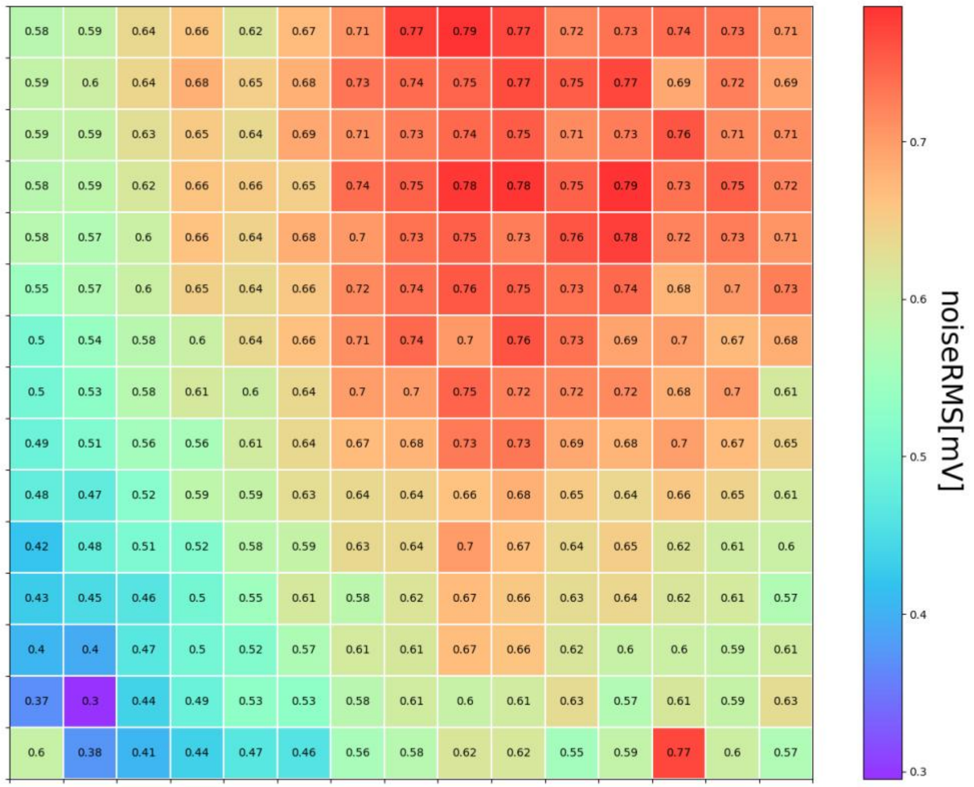



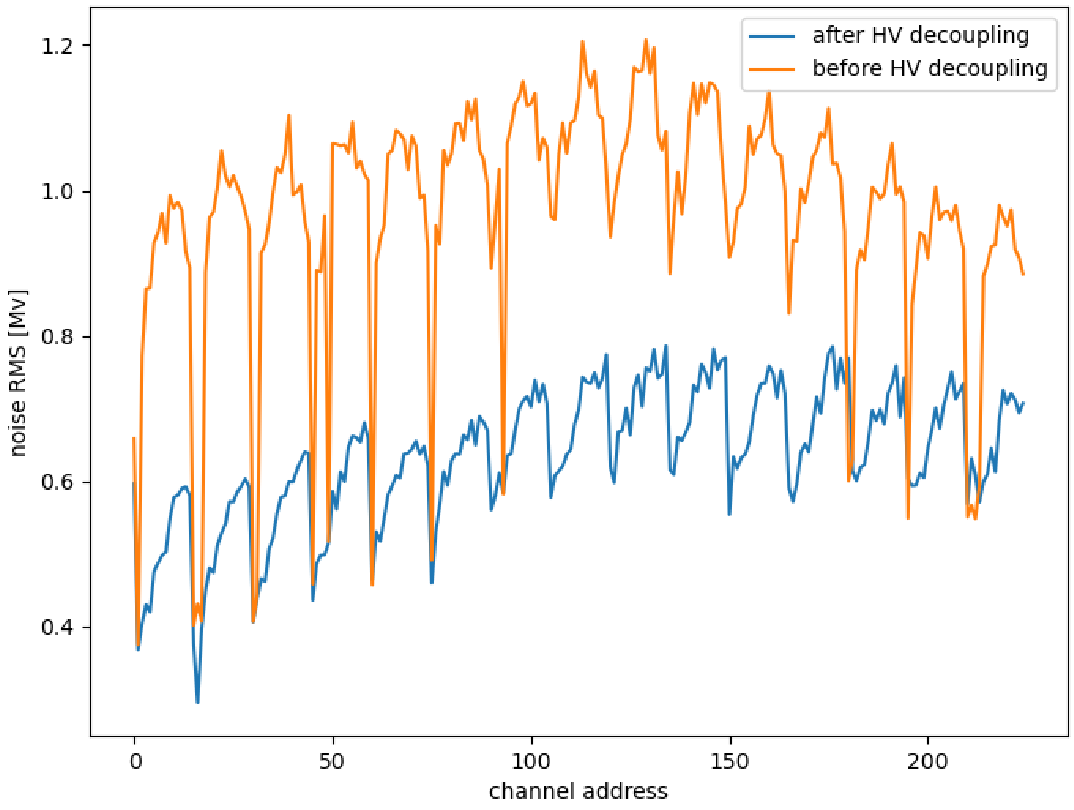



# Noise level after adjustment



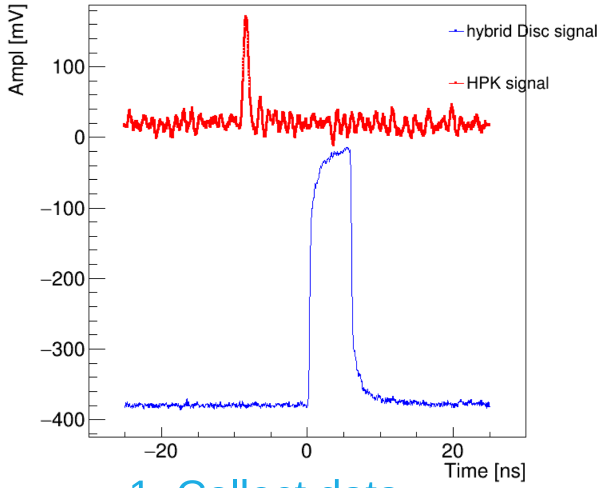

noise RMS map after decoupling



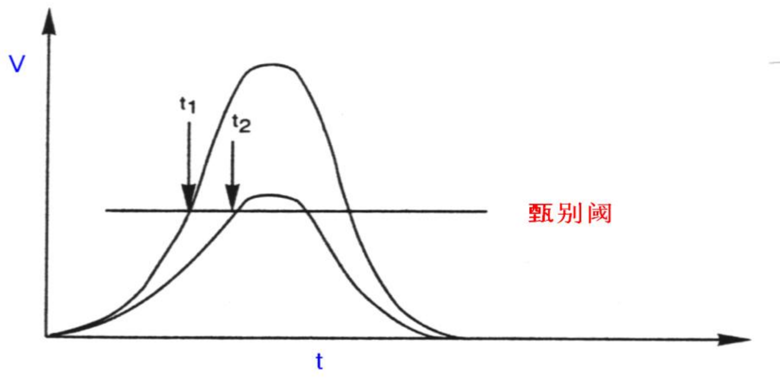

noise RMS vs channel

- After the adjustment, the noies RMS of disconnected channels keep the same while the noise RMS of connected channels decrease much
- The noise level of disconnected channels could be thought as the best noise level we can achieved. After the adjustment, the main reason of the relative larger noise at connected channels is the capacitor of HV layer (yellow layer at the plot of page 10)
- The similar change has been implemented in the module flex

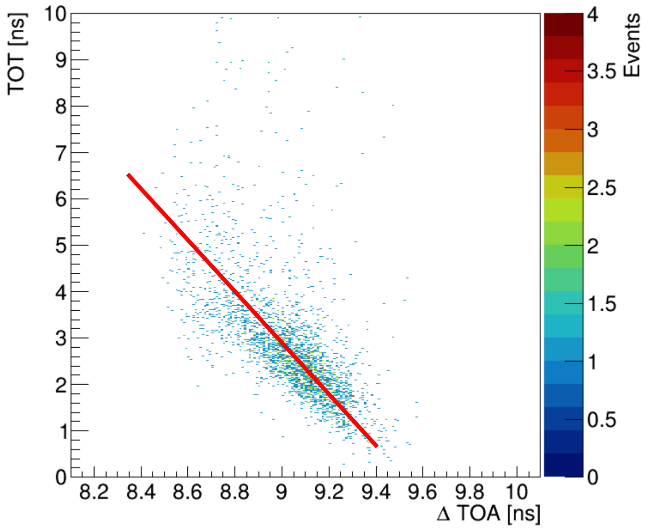
# Resolution extraction work flow



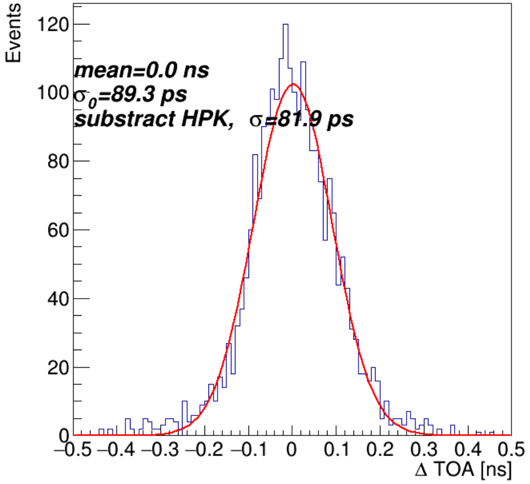

1. Collect data



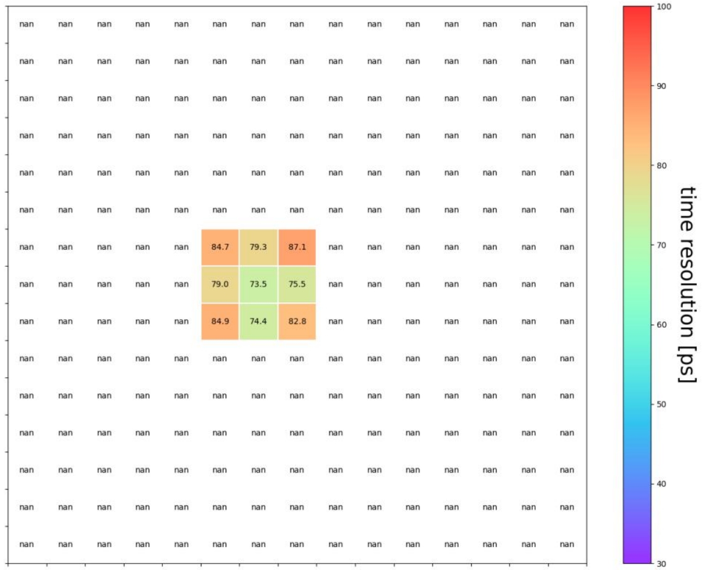

2. Determine the TOA for the waveforms; Font edge timing is used for Disc signals while the constant fraction timing is used for HPK signals




3. Do the time walk correction for Disc TOT vs ΔTOA

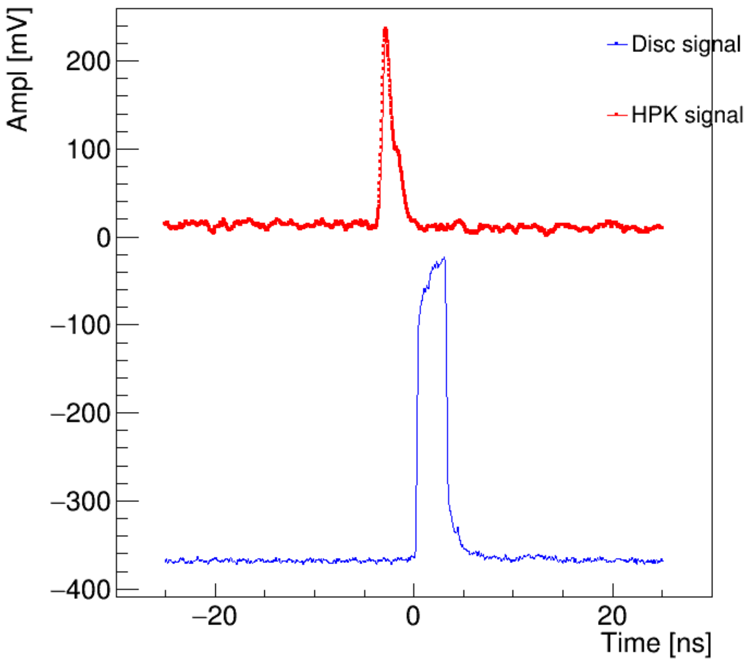



4.Get the uncertainty and substract the reference's contribution

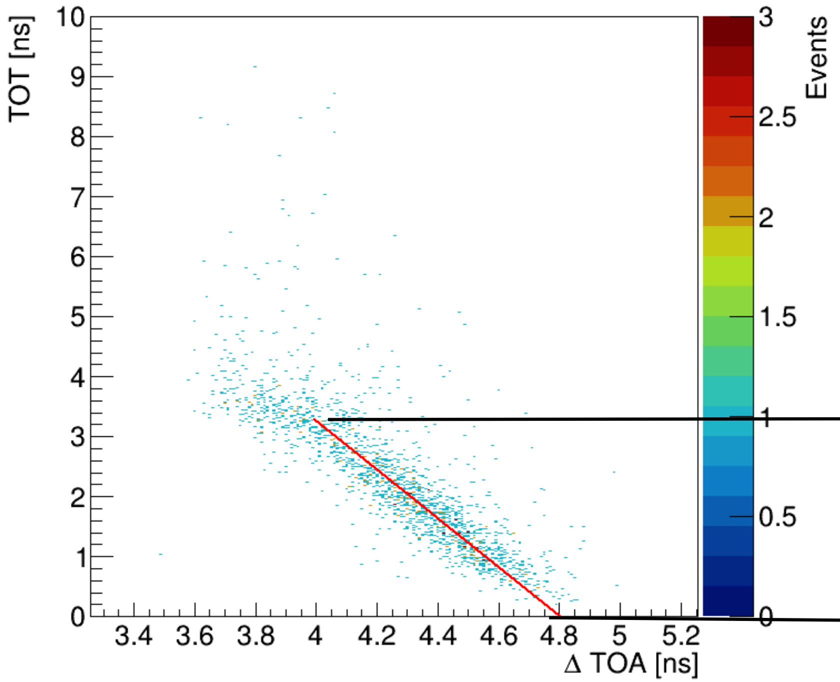



4.Loop over different pixels

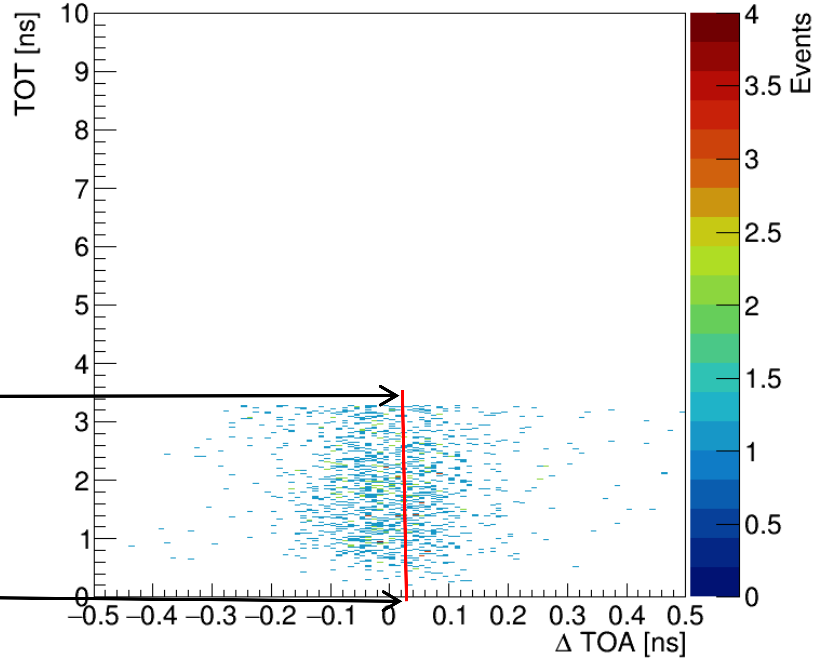
# Detail of timming and TW walk correction




Signal event waveform



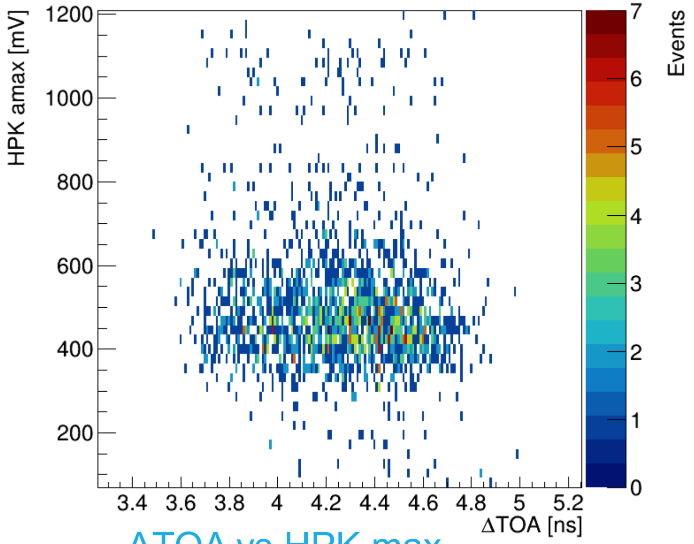

Event distribution in ΔTOA vs ToT



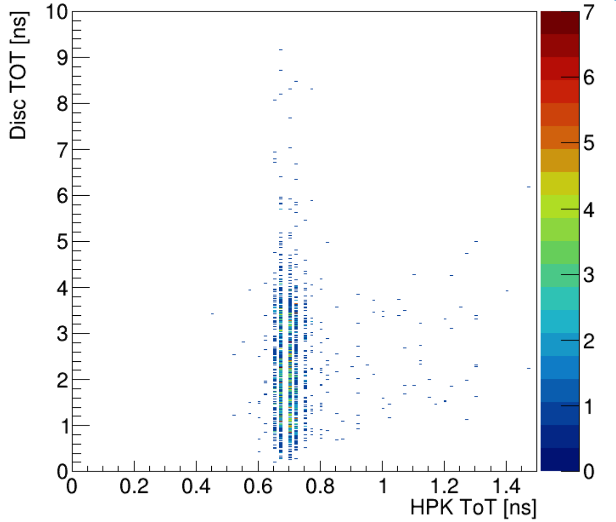

ΔTOA distribution after TW correction

- Font edge timing is used for Disc signal to get the TOA1 and ToT
- Constant fraction timming is used for the HPK signal to the TOA2
- ΔTOA=TOA1-TOA2
- Draw all the events in the ΔTOA vs ToT map. The time walk effect (Δ TOA mean value vs ToT) is obvious
- A linear TW correction is done

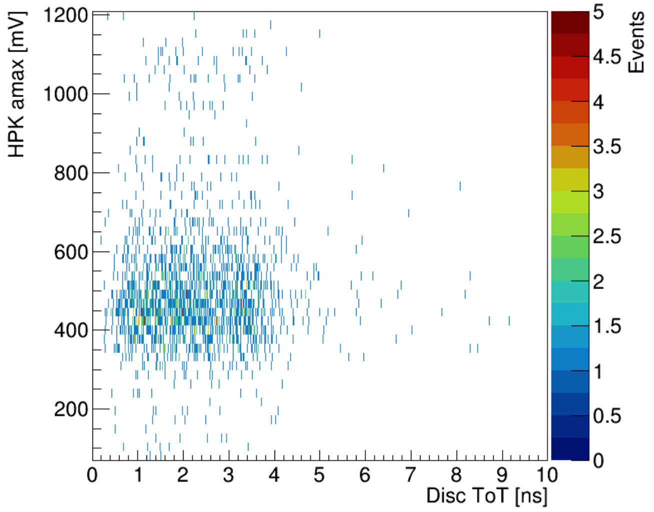
# Event distribution



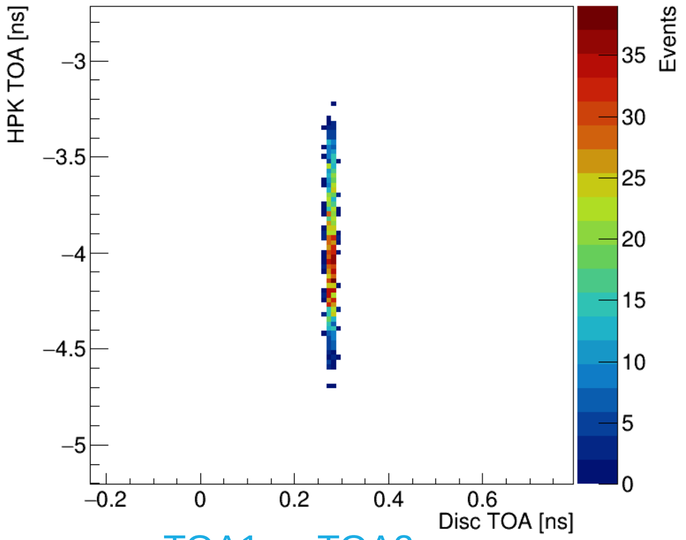

ΔTOA vs HPK max




Disc ToT vs HPK ToT

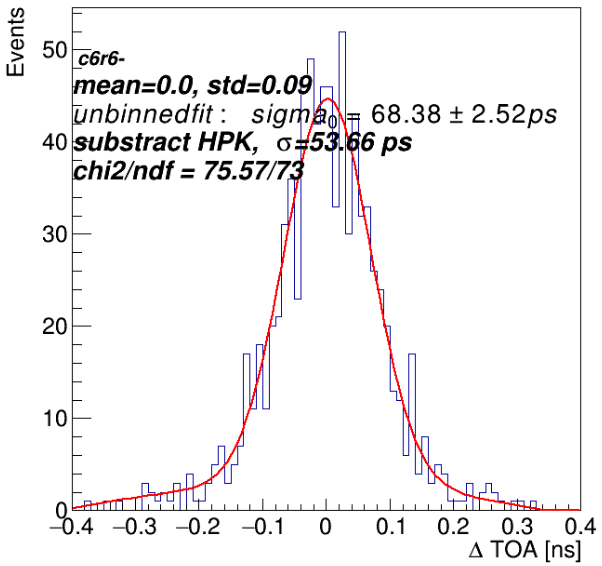



Disc ToT vs HPK max

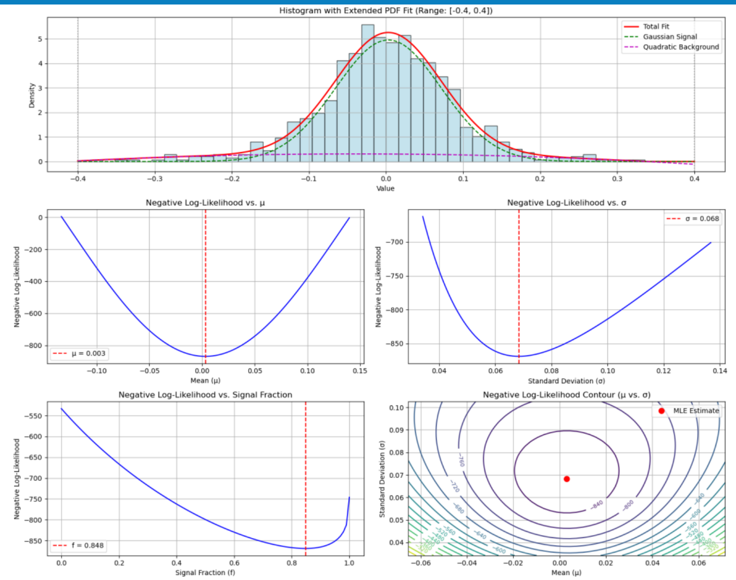



TOA1 vs TOA2

# Time resolution extraction: unbined fitting



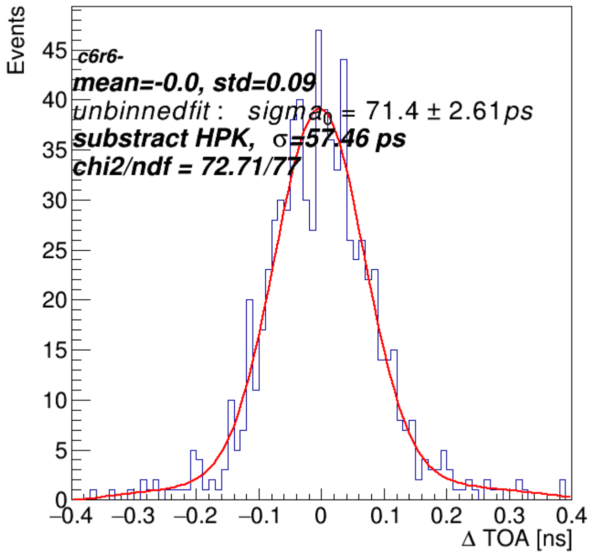

unbinned fit result



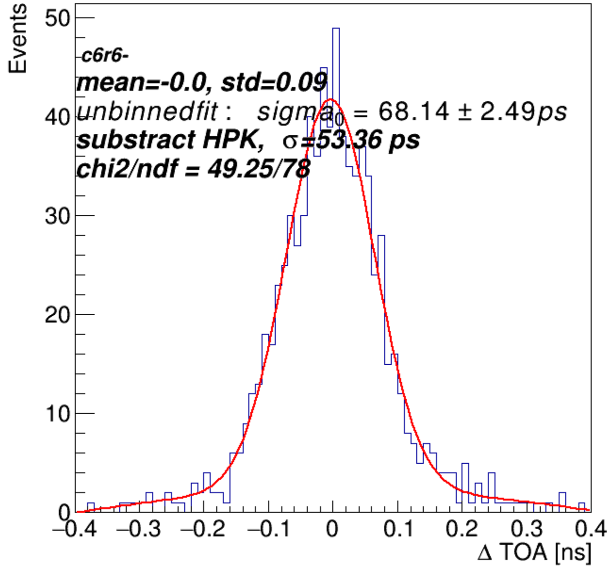

NLL vs parameters

- Using c6r6 @ HV = - 110 V as the example
- To account for the coincidence matching events, the Δ TOA distribution is composed of Gaussian signal + quadratic coincident background
- unbinned fit: $pdf(\Delta TOA) = f * Gau(\Delta TOA; \mu, \sigma) + (1-f) * [a * \Delta TOA^2 + b * \Delta TOA + c]$
  - 6 parameters to be fitted: $f, \mu, \sigma, a, b, c$
- The chi2/ndf and NLL vs parameters plots show that the fitting is stable

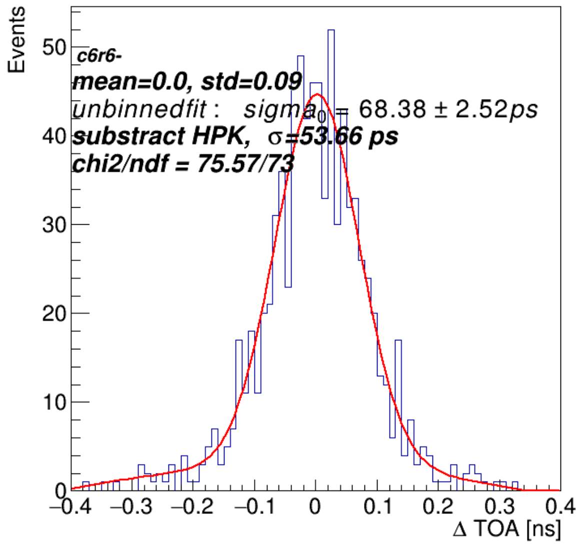
# Single pixel resolution vs HV



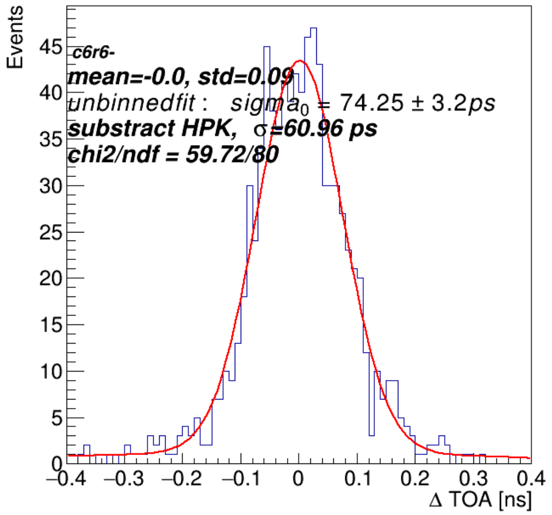

HV = -100 V



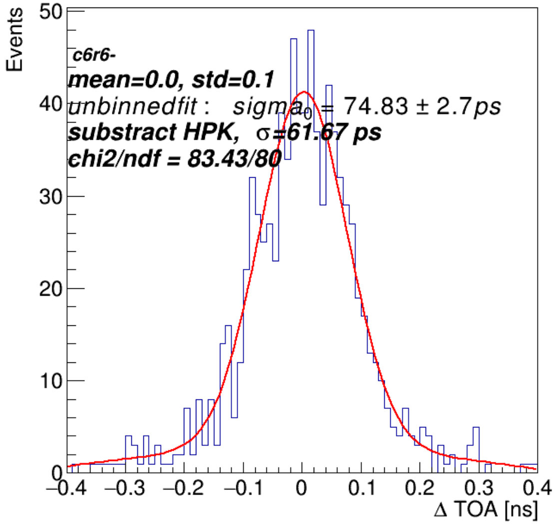

HV = -105 V




HV = -110 V



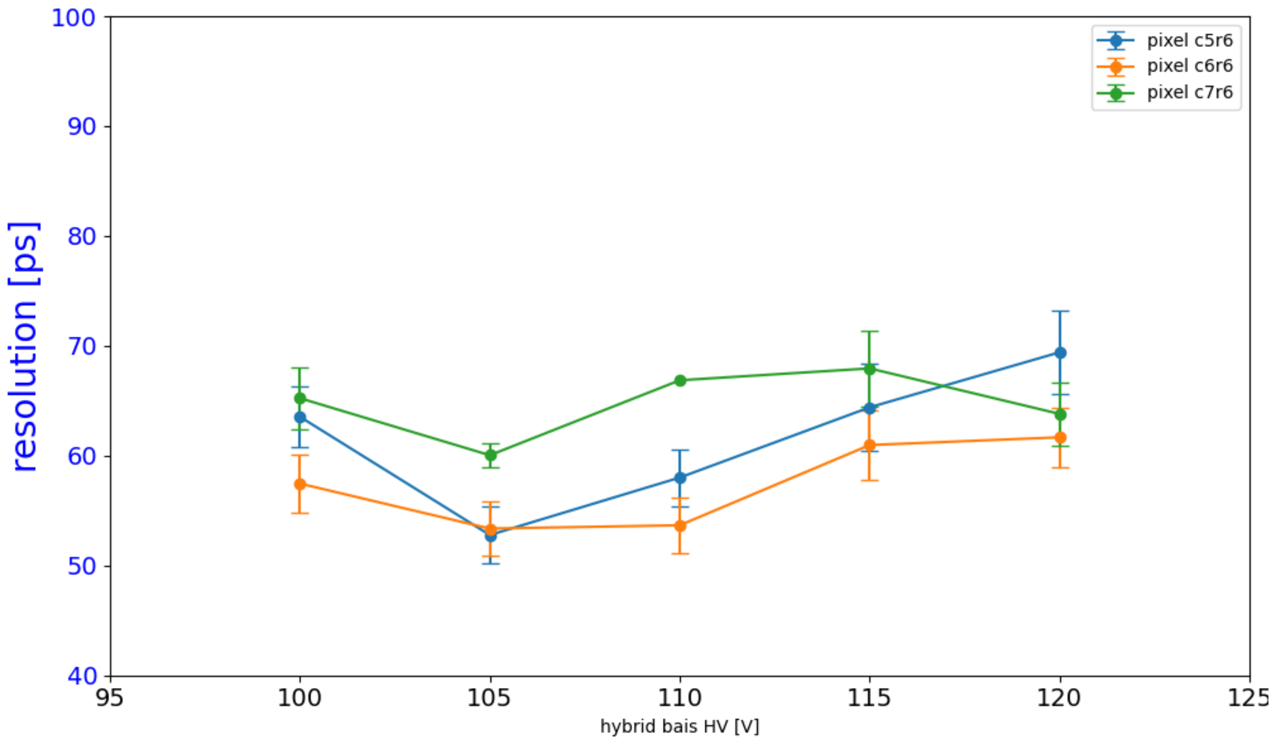

HV = -115 V




HV = -120 V

- The time resolution results vs HV of coloumn 6 row 6

# Time resolution result



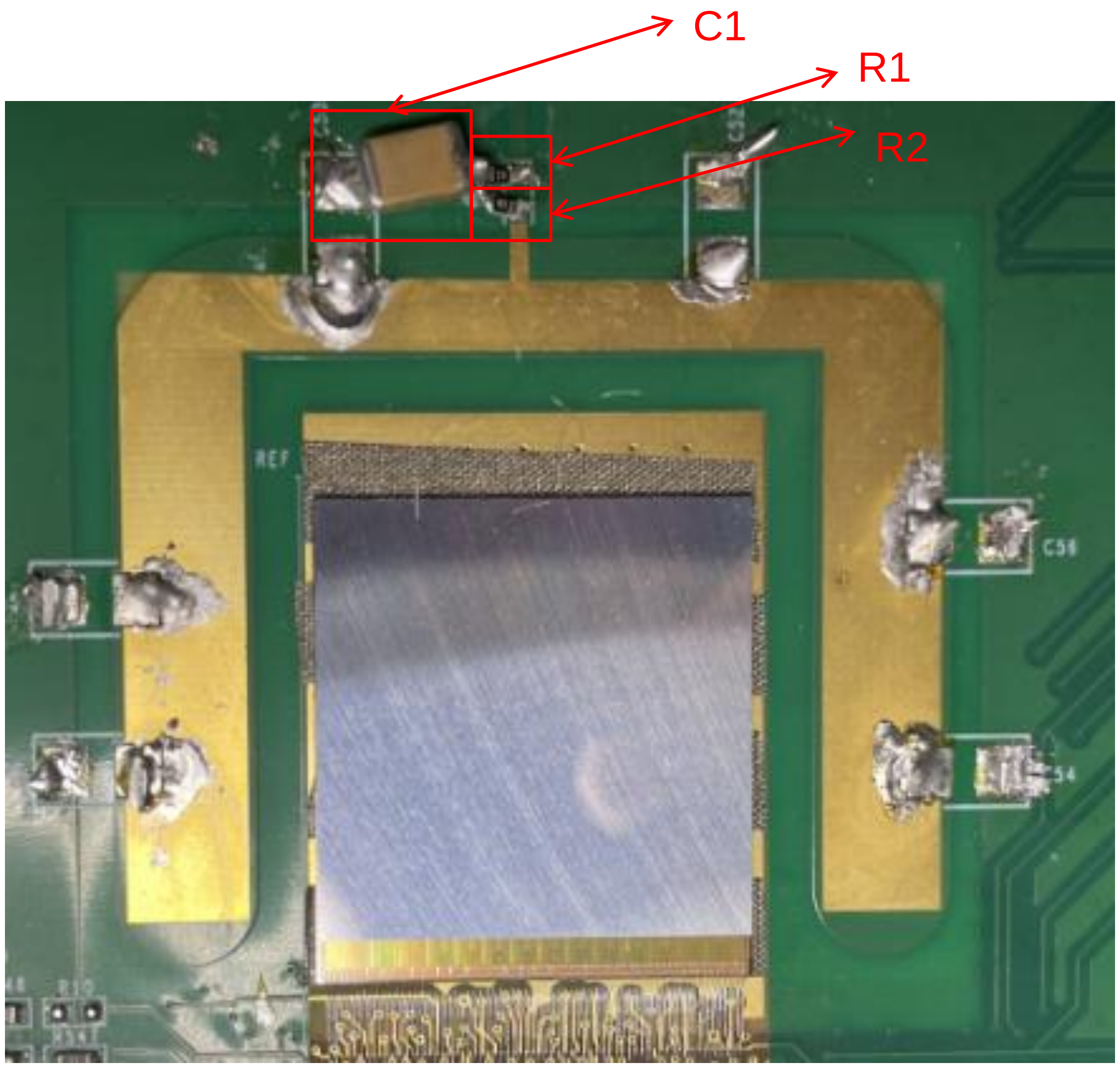

- 3 pixel (c5r6, c6r6, c7r6) were tested
- The time uncertainty first decrease then increase with HV. It is because HV = -120V is too close to breakdown voltage
- The best time resolution performance ~ 53 ps is achieved at HV = -105 V

# Summary

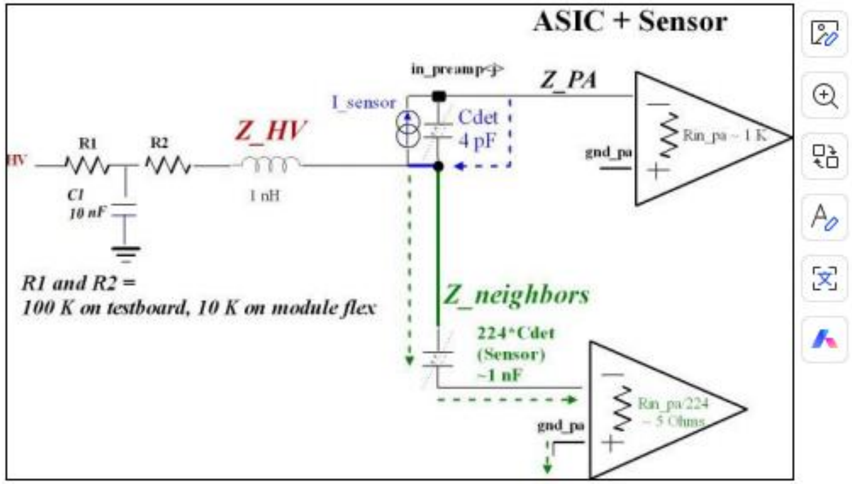
- The time resolution performance is the key requirement of HGTD. Sr-90 source test is a necessary complement to the testbeam
- The set up to measure the time resolution for HGTD module and hybrid has been established at USTC
  - Design a stable frame to get the maximum flux with our Sr-90 source
  - A problem on testboard inducing large jitter is found and fixed
  - Finish the script to loop over pixel and find trigger
- We test the analog time resolution performance of Altiroc3 + USTC-IME sensor hybird is measured, with the best time resolution ~53 ps, which is worse than the target resolution
- Outlook:
  - Loop over more pixels to see the uniformity of resolution
  - Extract the signal after digitalization and meausre its resolution

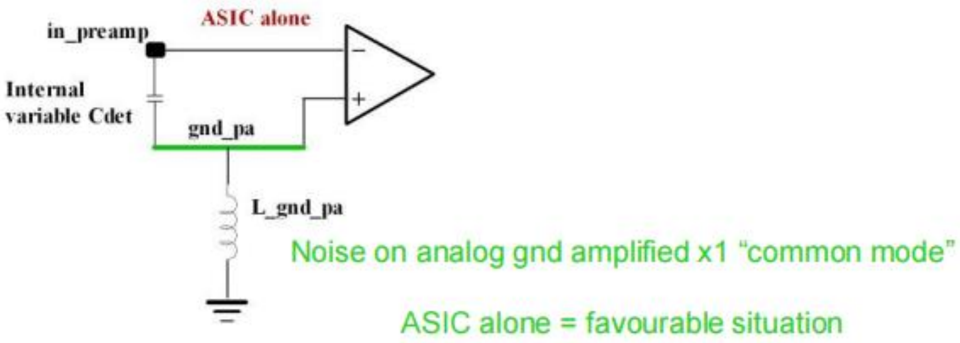
# Backup

# HV decoupling



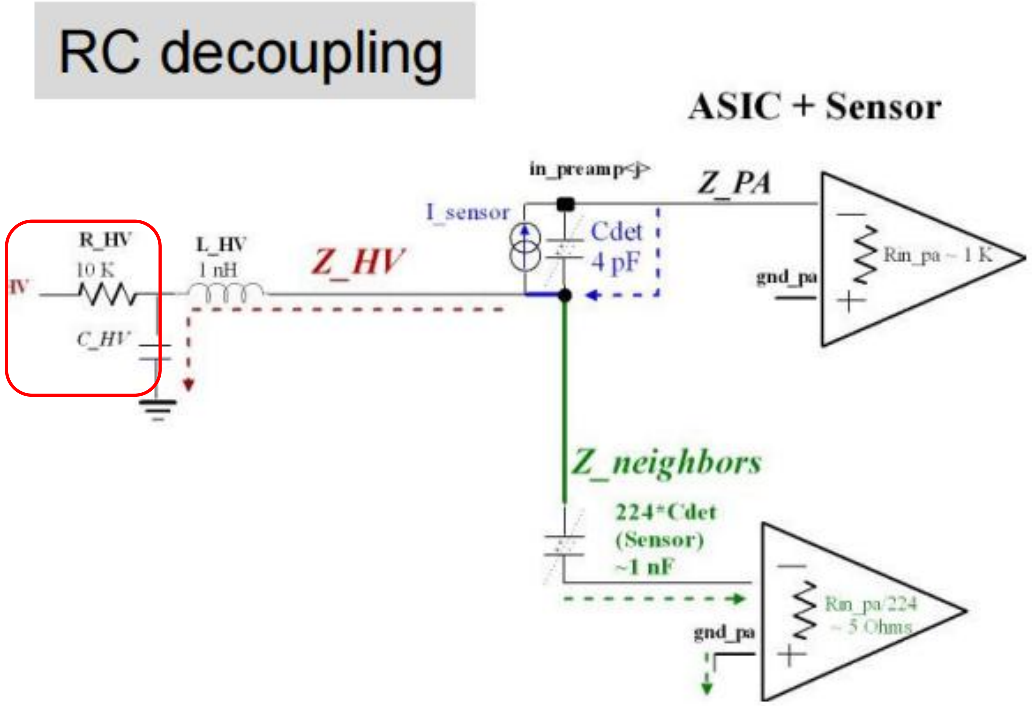

RCR decoupling

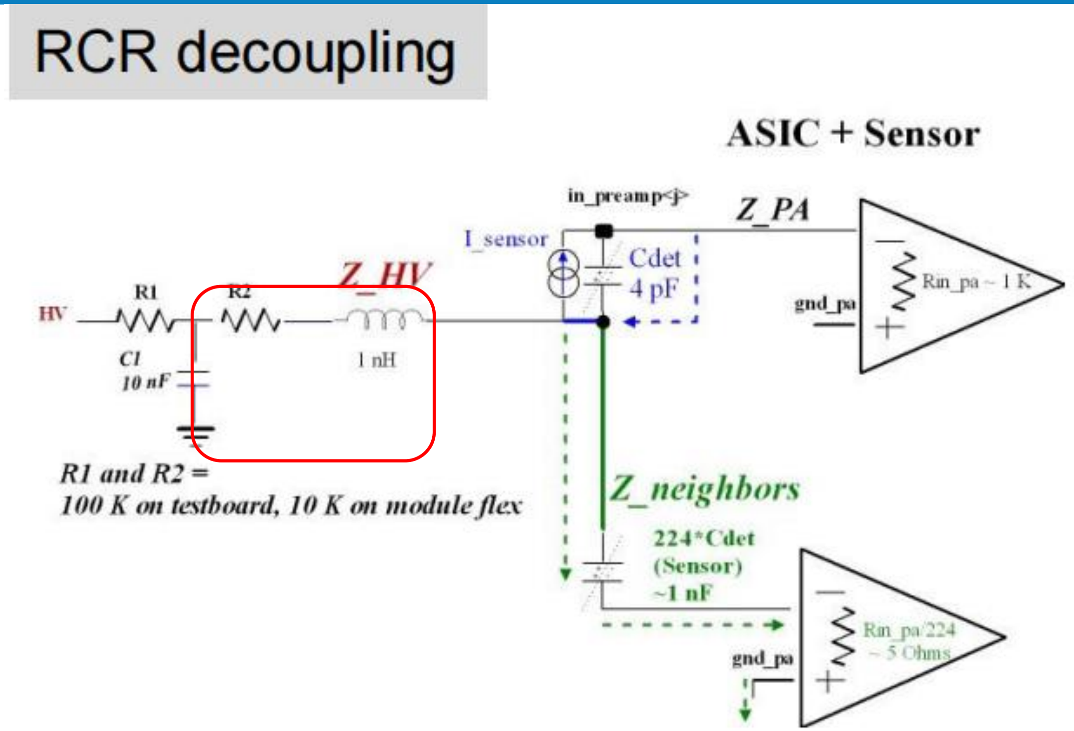



- By RCR decoupling, we can surpress this noise
- The reason of the noise and the effect of the RCR decoupling can be found at back up

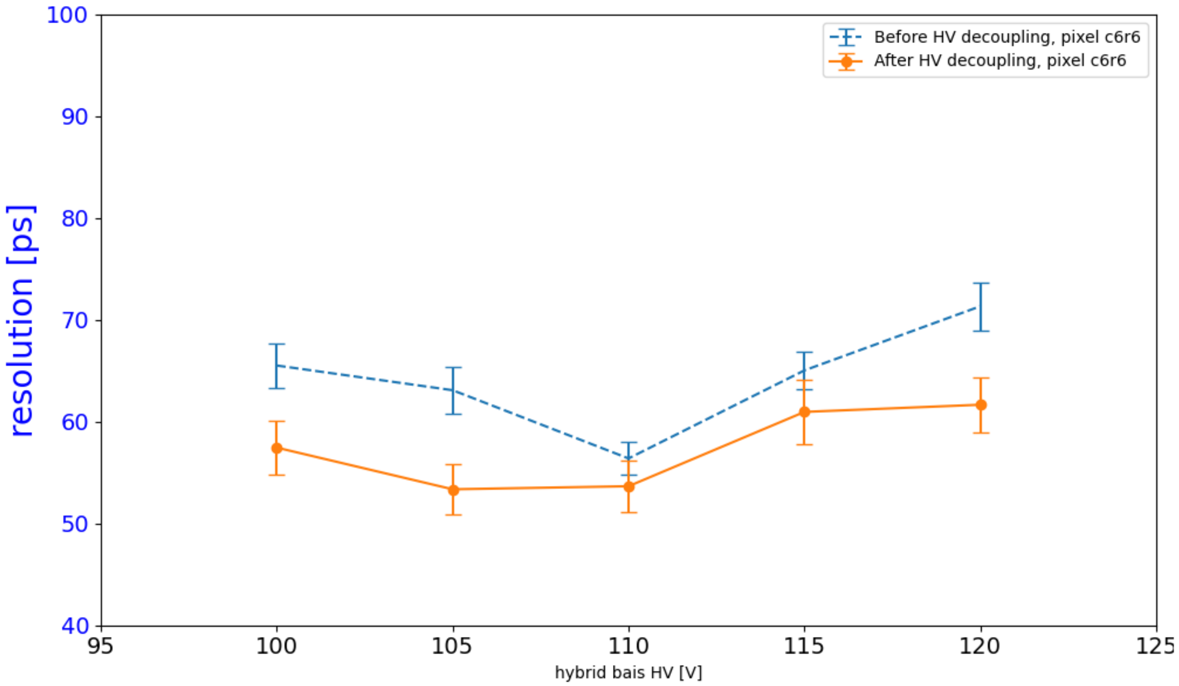
# HV decouple



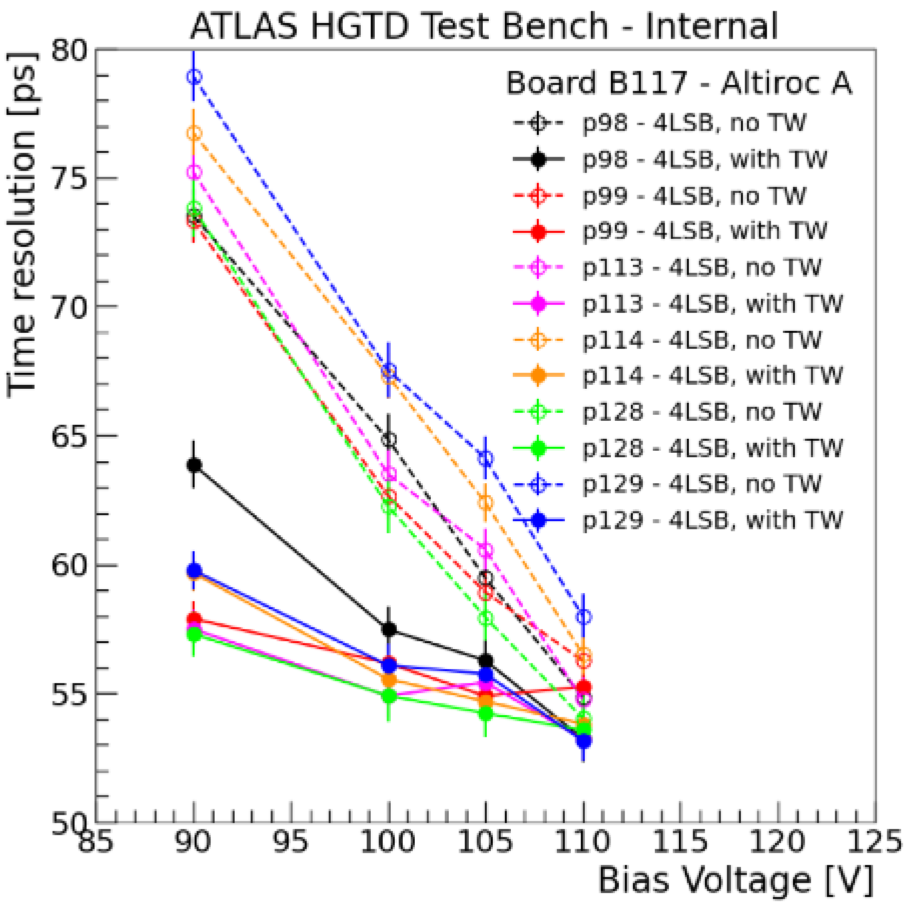

- A  way to reduce the noise is to change the RC decoupling to the RCR decoupling
- This is because the pre-amplifier negtive input (Z_PA) can connect to the gnd_pa through the neighbor channels
- In RC decoupling, considering the noise frequency is around 40MHz
  - impedance to the chip ground: $Z \approx \sqrt{R^2 + (\frac{1}{\omega C})^2} = \sqrt{5^2 + (\frac{1}{2\pi * 4e7 * 1e-9})^2} = 6\ \Omega$
  - impedance to the testboard ground: $Z \approx \omega L = 2\pi * 4e7 * 1e-9 = 0.25\Omega$
- To make sure the Z_PA close to the chip ground instead of testboard ground, we need to increase the impedance to the testboard ground (block this circuit) ==> adding the R2 ==> RCR decouple

# time resolution improvement after HV decoupling

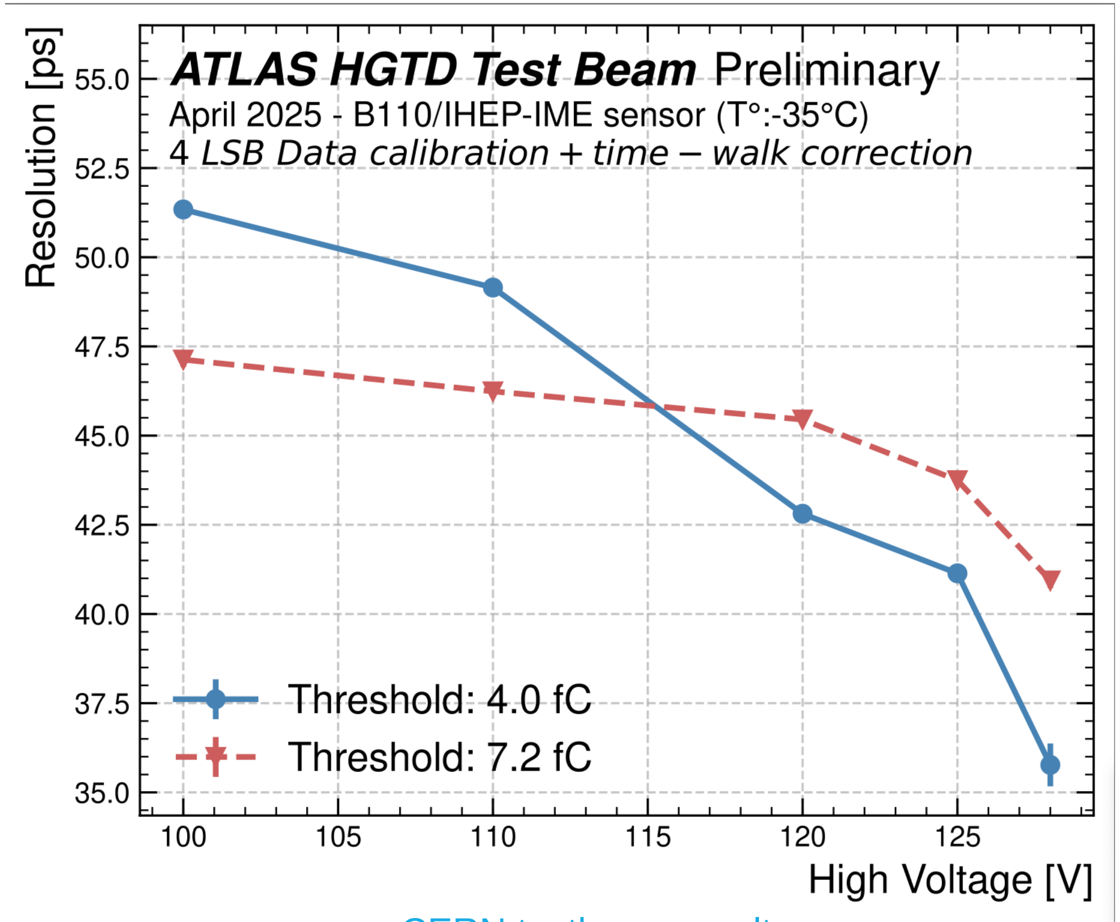



- The same work flow is used for one pixel before and after HV decoupling
- There is an improvement of about ~10 ps

# Resolution result of CERN




CERN Sr-90 result




CERN testbeam result