STUDIES OF MPPC DETECTORS DOWN TO CRYOGENIC TEMPERATURES

Andrii Nagai[1], *Nicoleta Dinu*[1], *Adam Para*[2]

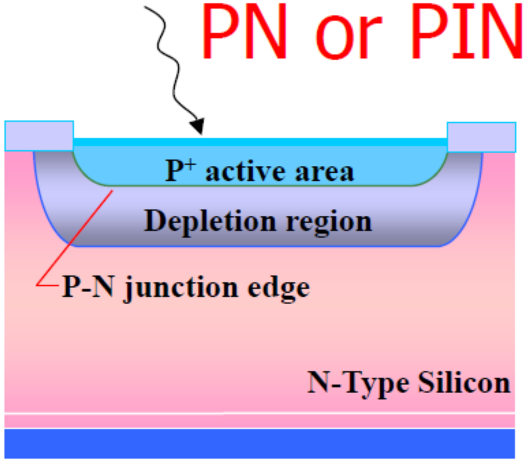
[1] *Laboratory of Linear Accelerator, Orsay France*

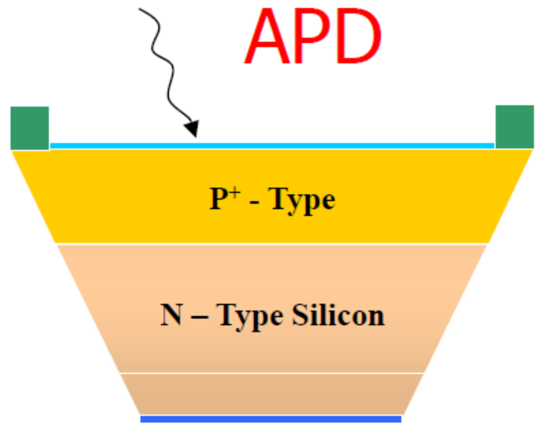
[2] *Fermi National Accelerator Laboratory, Illinois, USA*

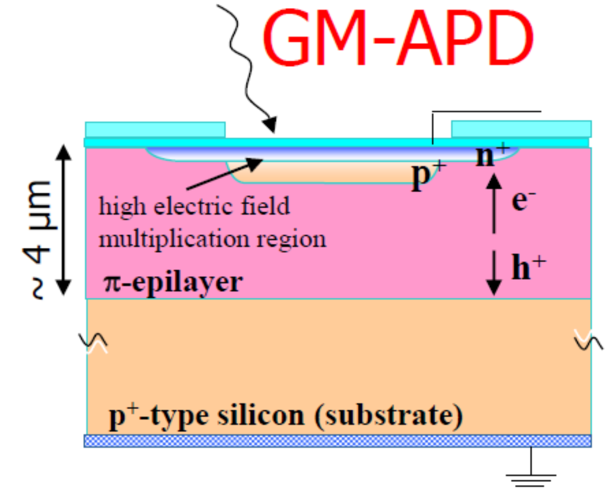
Outline

- Introduction:
  - ✓ Photo-detection silicon detectors
  - ✓ What is MPPC?
  - ✓ The motivation of the present work
- Experimental details
- Main steps of automatic procedure for data analysis:
  - ✓ Baseline restoration
  - ✓ Templates
  - ✓ Peak analysis
- Physics results:
  - ✓ Charge and Amplitude distribution
  - ✓ Gain and Breakdown Voltage
  - ✓ Micro-cell resistance and capacitance
  - ✓ Dark Count Rate
  - ✓ Rise time and recovery time
- Summary

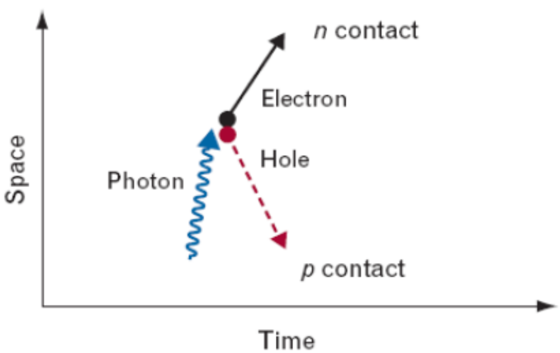
p-n junction for light detection





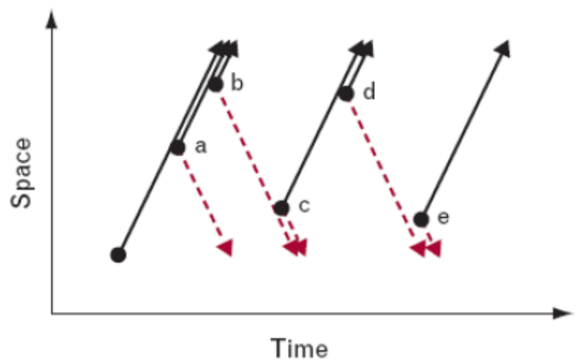


p-n junction, V_{bias} – 0-3 V



Gain = 1

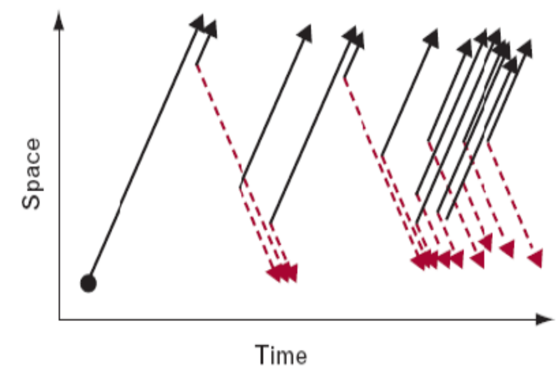
p-n junction, $V_{bias} < V_{BD}$



Gain = M (~ 50-500)

- linear mode operation-

p-n junction, $V_{bias} > V_{BD}$



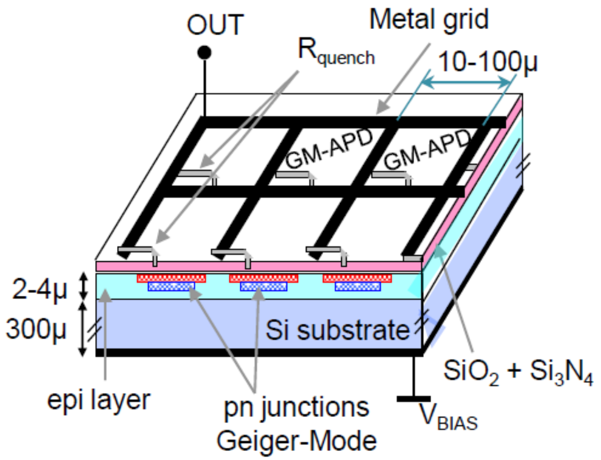
Gain → infinite

-Geiger-mode operation-

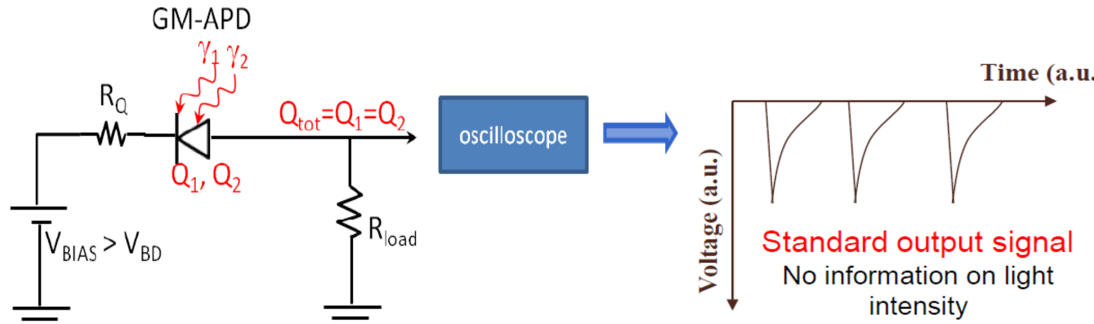
What is a MPPC?

Parallel array of μ-cells on the same substrate

- each μ-cell: GM-APD in series with R_q

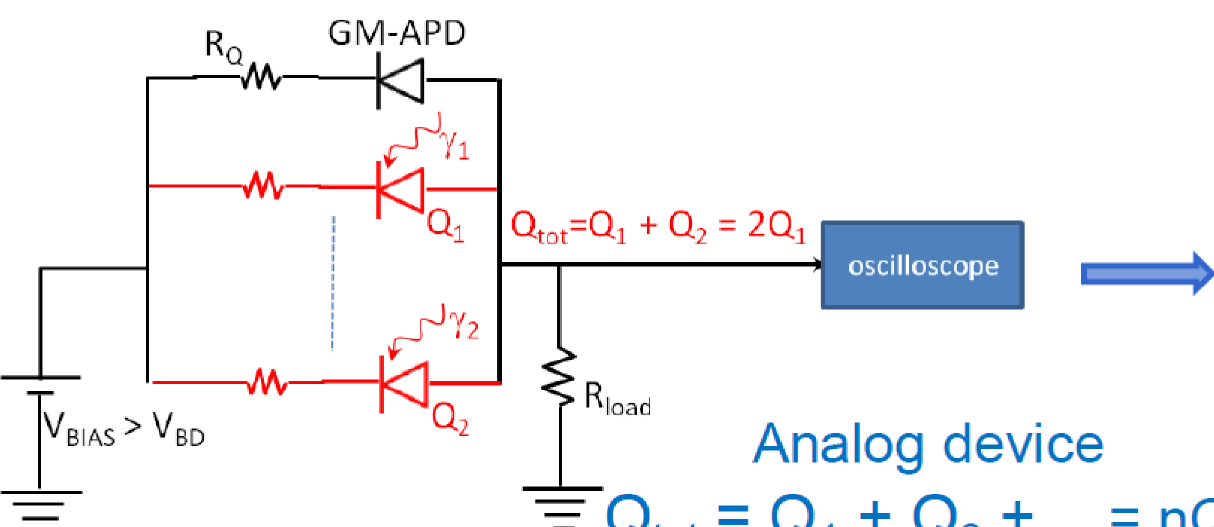


'90s by V.M.Golovin & Z.Sadygov, Russian patents



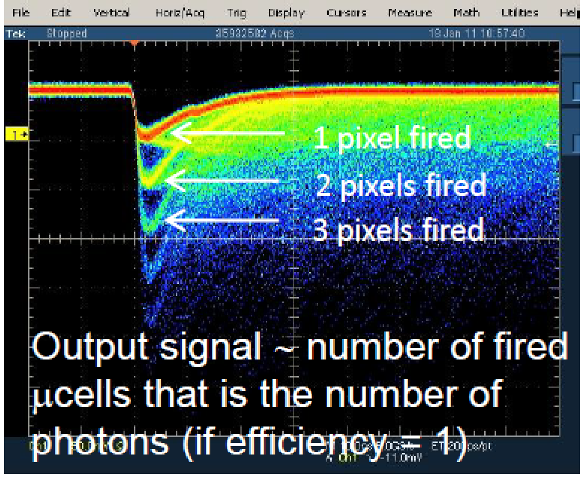
Digital device

$Q = Q_1 = Q_2 = \ldots = Q_n$



Analog device

$Q_{tot} = Q_1 + Q_2 + \ldots = nQ_1$



MPPC detectors

Advantages:

- High gain (10^5 - 10^6) with low voltage (<100V)
- Low power consumption (<50µW/mm^2)
- Fast (timing resolution ~50 ps RMS for single photon)
- Insensitive to magnetic field (tested up to 7 T)
- High photon detection efficiency (30-40% blue-green)
- Compact and light

Possible drawbacks:

- High dark count rate (DCR) at room temperature
  - 10kHz/mm^2 – 1MHz/mm^2
  - thermal carriers, crosstalk , afterpulses
- Temperature dependence
  - Gain, V_{BD}, signal shape, R_q, DCR, PDE

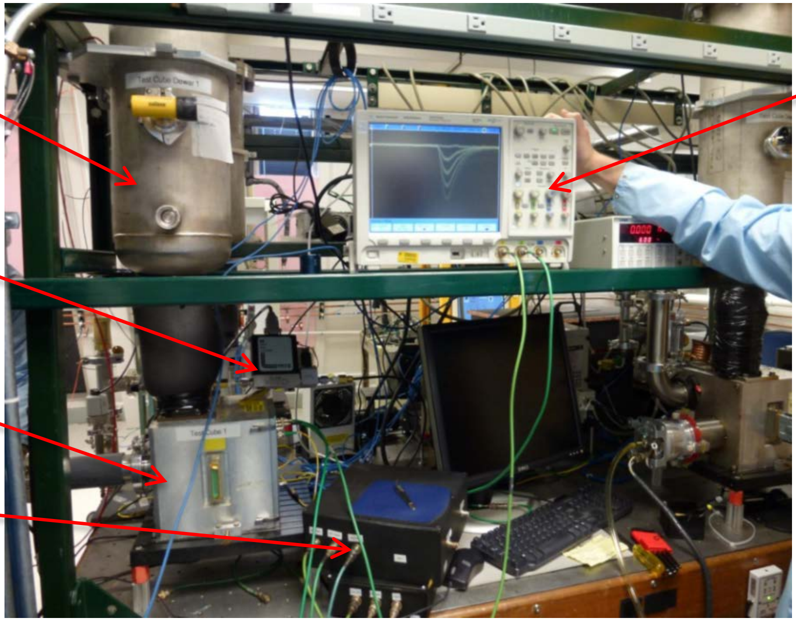
Work motivation:

Temperature:

- affects the characteristics of the MPPC detectors
  - breakdown voltage, signal shape, noise, gain, photon detection efficiency etc
- leads to a variation of the final detection characteristics

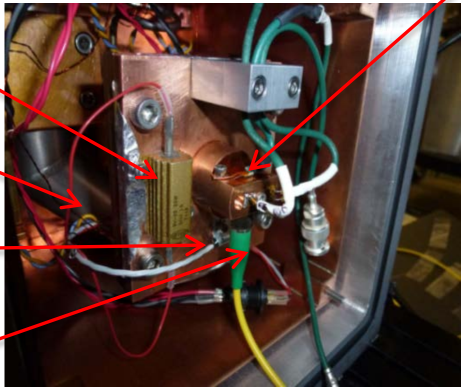
Experimental set-up

N_2 column
N2 flow control
Test cube for MPPC
Amplifier



Oscilloscope for data acquisition (20Mhz)

MPPC in front of light
Heater
Cold finger
Pt100
Optical fiber



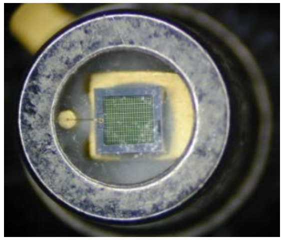
Measurements performed at SiDet, Fermilab

Measurements conditions

- *T from -175°C to 55°C in step of 10°C (24 T values)*
- *at each T:*
  - *12 V_{bias} values for each detector (the same overvoltage independent of T)*

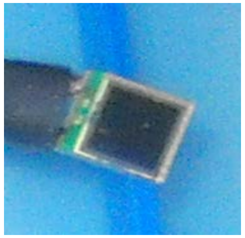
MPPC detectors

Hamamatsu S10362-11-050U



1x1mm^2 total area
50x50μm^2 μcell

Hamamatsu S10931-050P



3x3mm^2 total area
50x50μm^2 μcell

Automatic procedure for calculation of MPPC parameters

Huge amount of experimental data

- 24 values of T
- 12 values of V_{bias} for each T
- 5000 waveforms per V_{bias}
- leading to $1.44 \cdot 10^6$ waveforms per detector

Main steps of automatic procedure based on ROOT analysis framework:

1. Baseline restauration
   - Restore the zero baseline

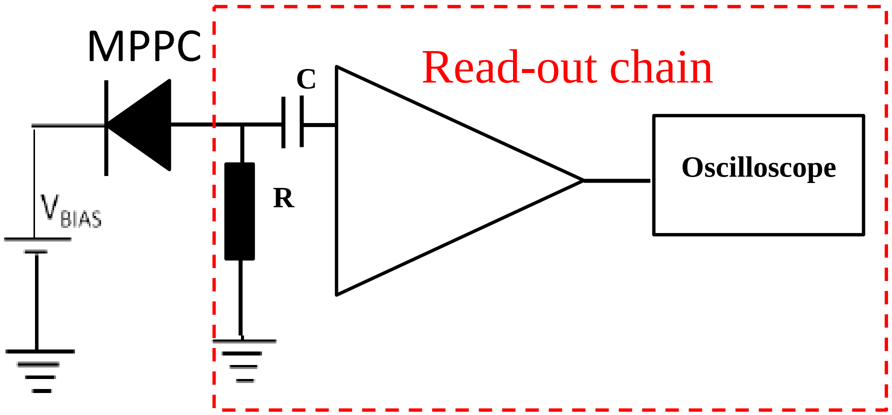
2. Template creation
   - MPPC signal shape is independent of V_{bias}
   - Calculate typical MPPC signal shape at a given T

3. Pulse finding procedure
   - Separate MPPC pulses from high frequency electronic noise

4. Template subtraction
   - Reconstruct MPPC pulses in a train of pulses

5. Pulse characteristics
   - Calculate MPPC pulse characteristics

1. Baseline restoration:



Read-out chain used for data acquisition

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differentiates the signal with the time constant τ

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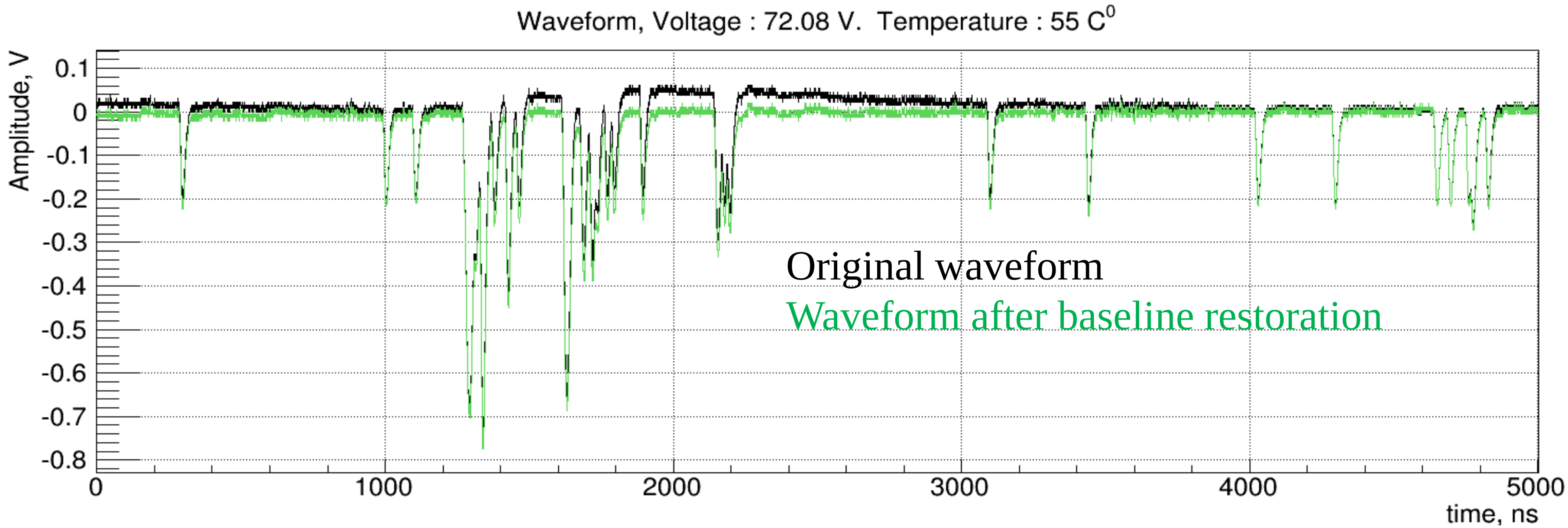
it leads to baseline shift:

- Pulses are siting on shifted baseline
- Pulse shapes are modified (Amplitude, Charge, Trailing edge…)

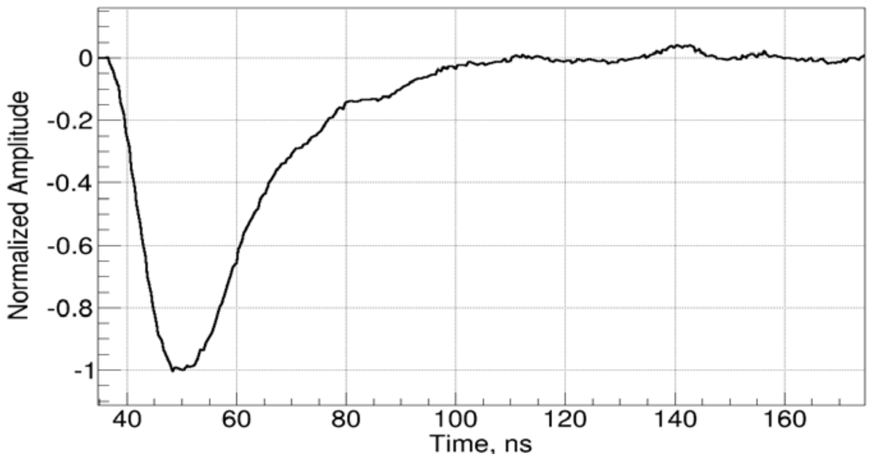


Using such method MPPC charge (Gain) calculation was improved

2. *Template creation*

- Calculate a typical normalized MPPC signal shape at a given T

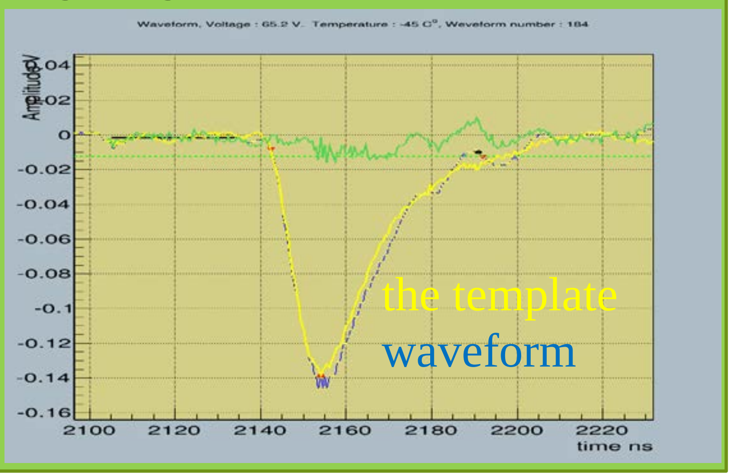
Template, T = -45^{0}C



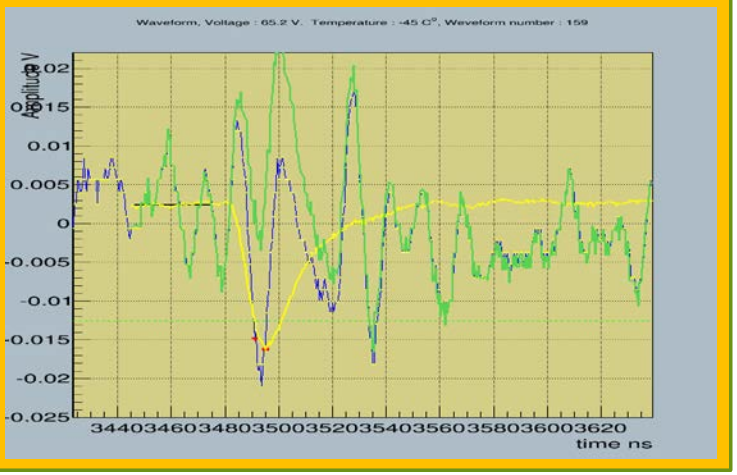
3. *Pulse finding procedure*

- Comparing the template with all pulses we can choose for the analysis only the pulses having the same shape (real MPPC shape)

Single signal:

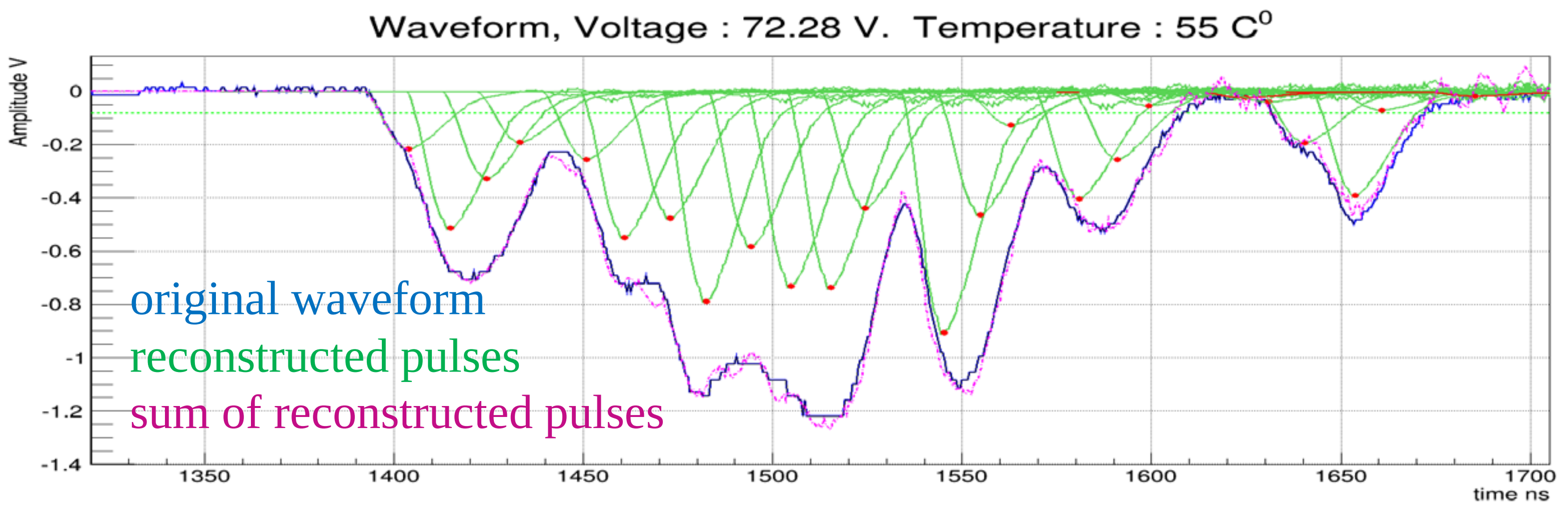


Electronic noise:



4. *Template subtraction procedure*

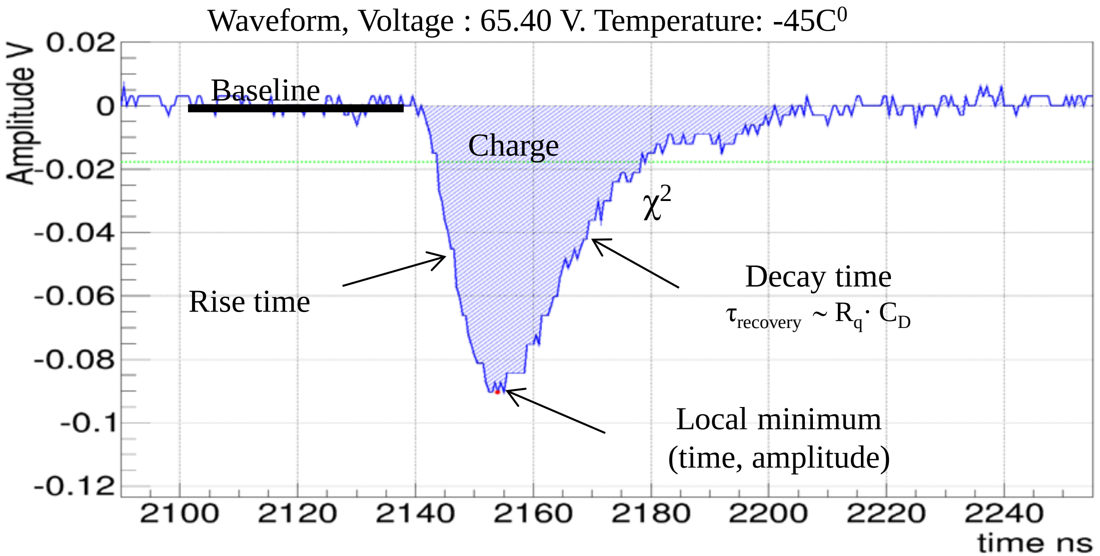
- Reconstruct MPPC pulses within a train of pulses



5. *Pulse analysis*

All calculated parameters saved in Ntuple files (one file at a given T and V_{Bias})

- Baseline
- Riser time
- Decay time
- Charge
- Local minimum (time, amplitude)

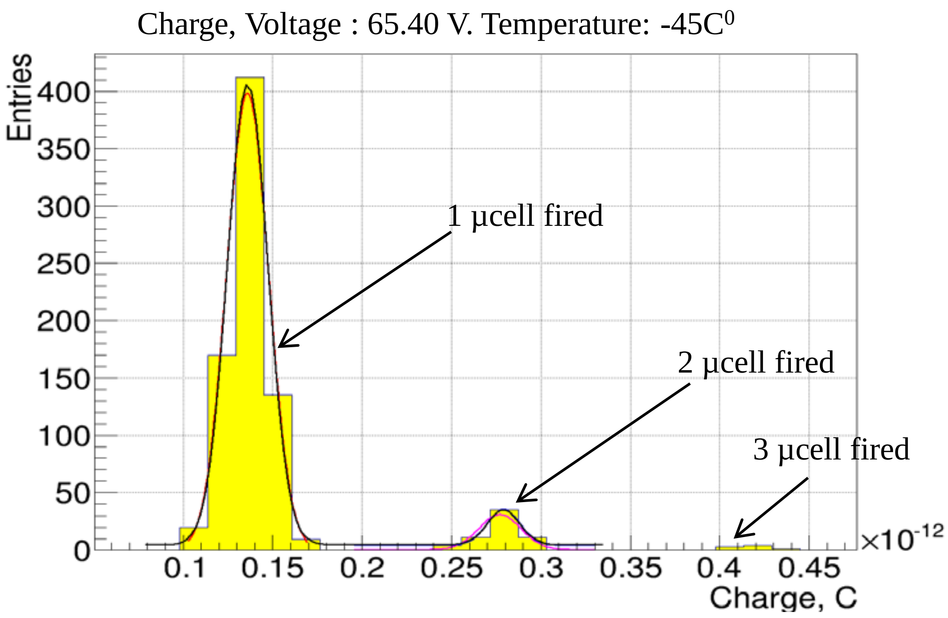


MPPC characteristics

Gain

- number of charges created in one avalanche

$$Gain = \frac{Q_{cell}}{e} = \frac{C_{cell} \times (V_{bias} - V_{BD})}{e} = \frac{C_{cell} \times \Delta V}{e}$$

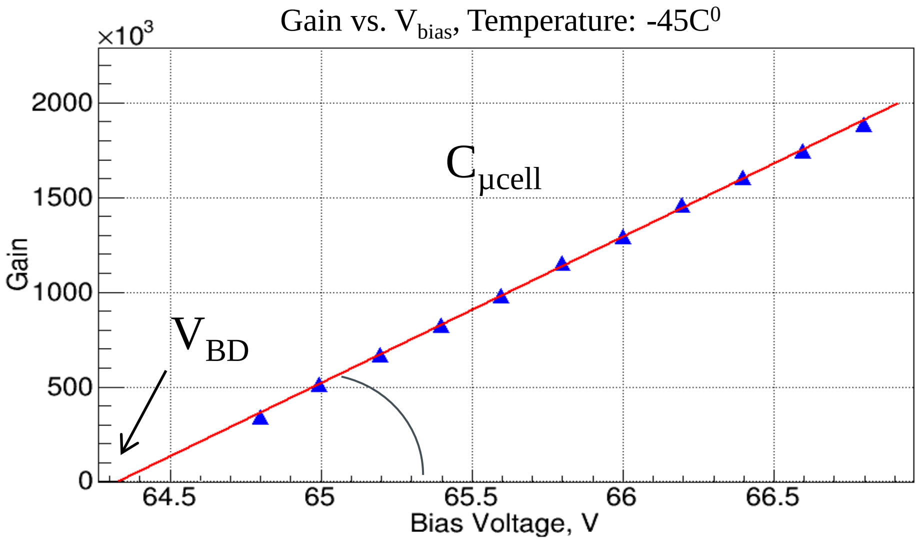


Breakdown voltage

- Linear fit of G vs V_{bias} intercepts of x axis

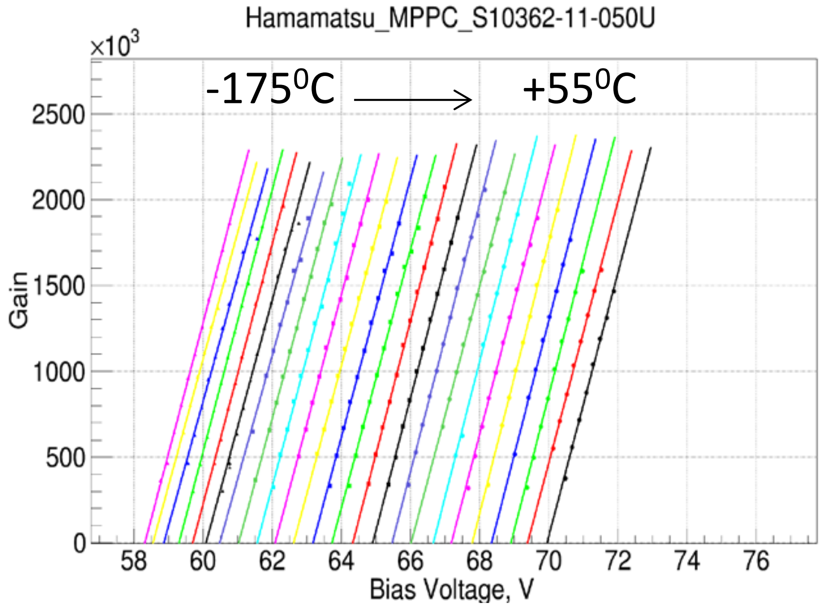
$C_{\mu cell}$

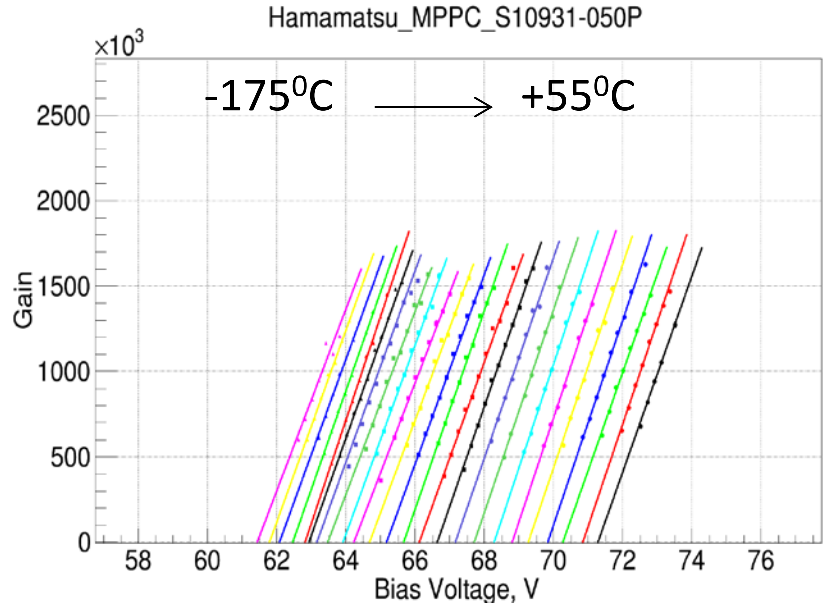
- slope of linear fit



Andrii Nagai, LAL
01/07/2014

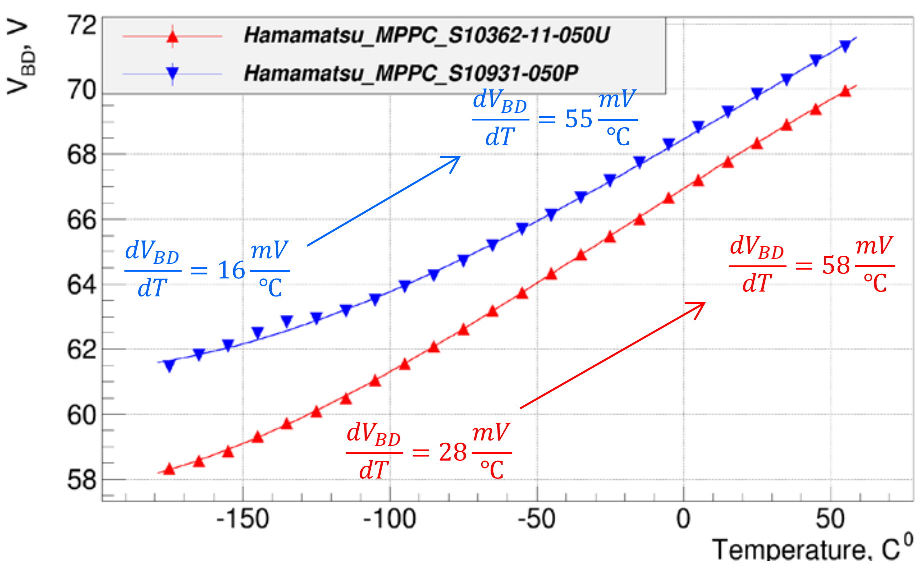
Gain vs V_{bias} and T





@ a given T, G increase linearly with V_{Bias}

Breakdown voltage vs T



Detectors show different temperature dependence

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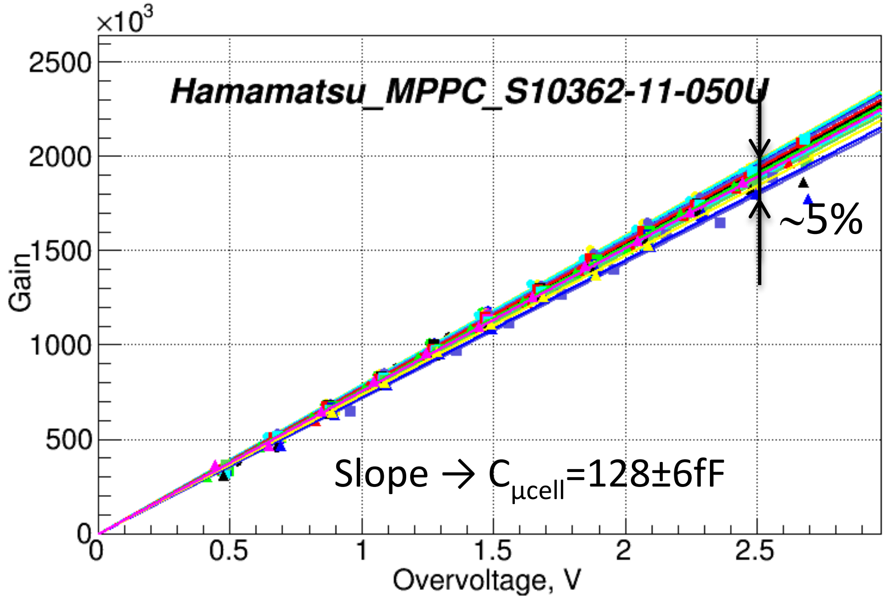
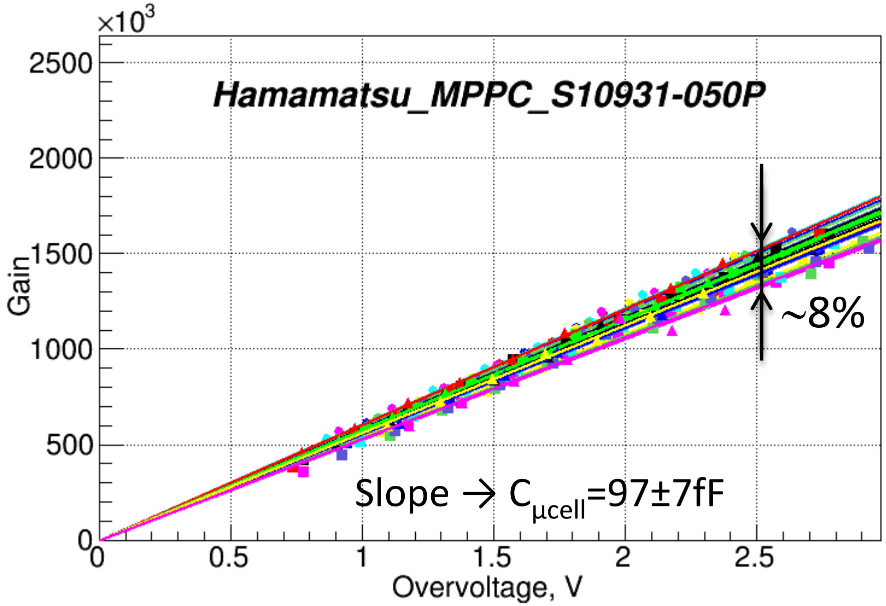
different structural or technological characteristics

(C.R.Crowell and S.M.Sze "Temperature dependence of avalanche multiplication in semiconductors", Appl. Phys. Letters 9, 6(1966))

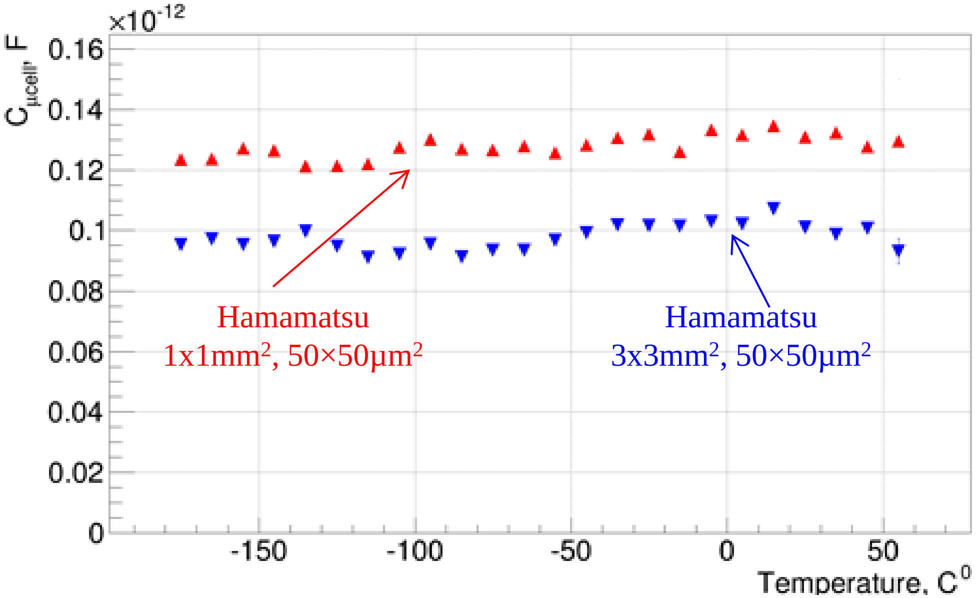
Gain vs ΔV and T





At a given ΔV the G is constant, independent of T

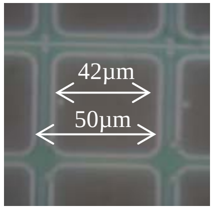
$C_{\mu cell}$ vs T



$C_{\mu cell}$ is constant over all T range

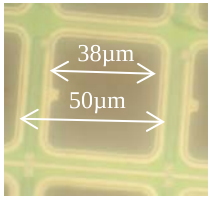
~20% of difference between two detectors

Hamamatsu
1x1mm², 50×50μm²

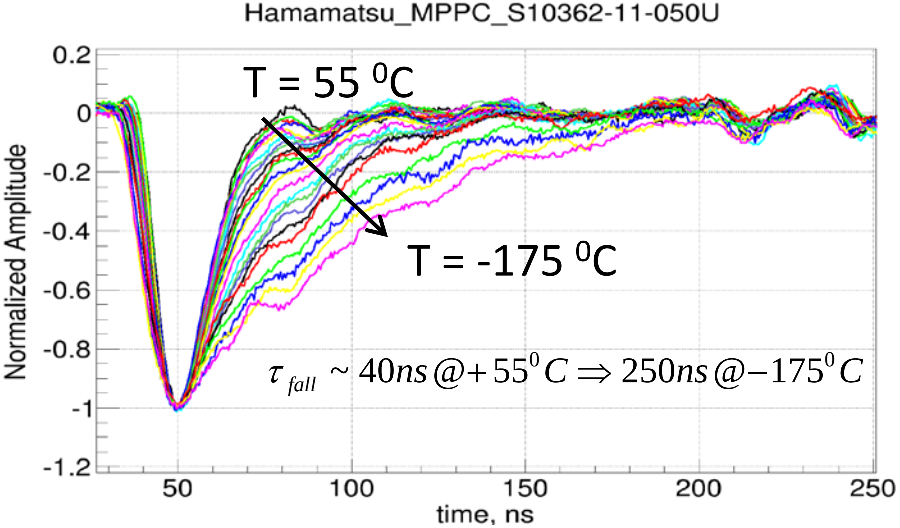


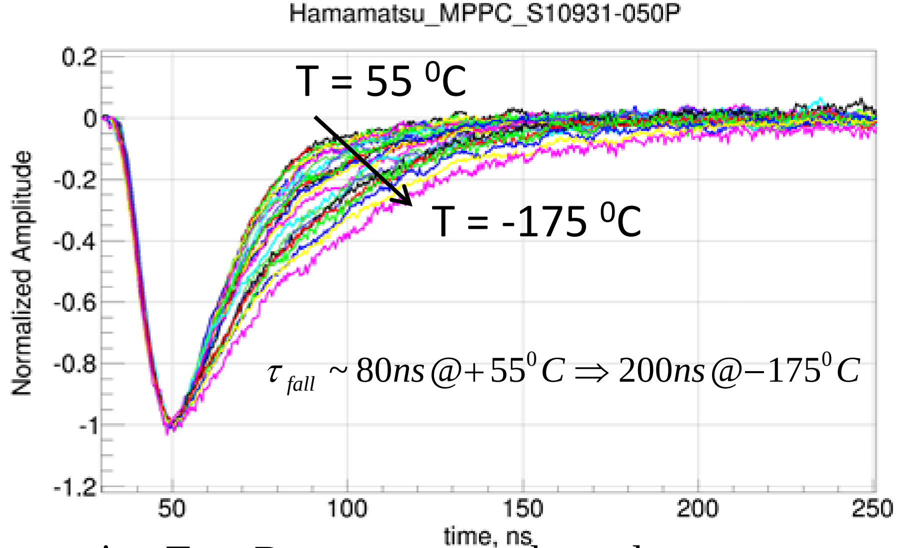
$$C = \varepsilon_{Si}\varepsilon_0 \frac{A}{d}$$

Hamamatsu
3x3mm², 50×50μm²



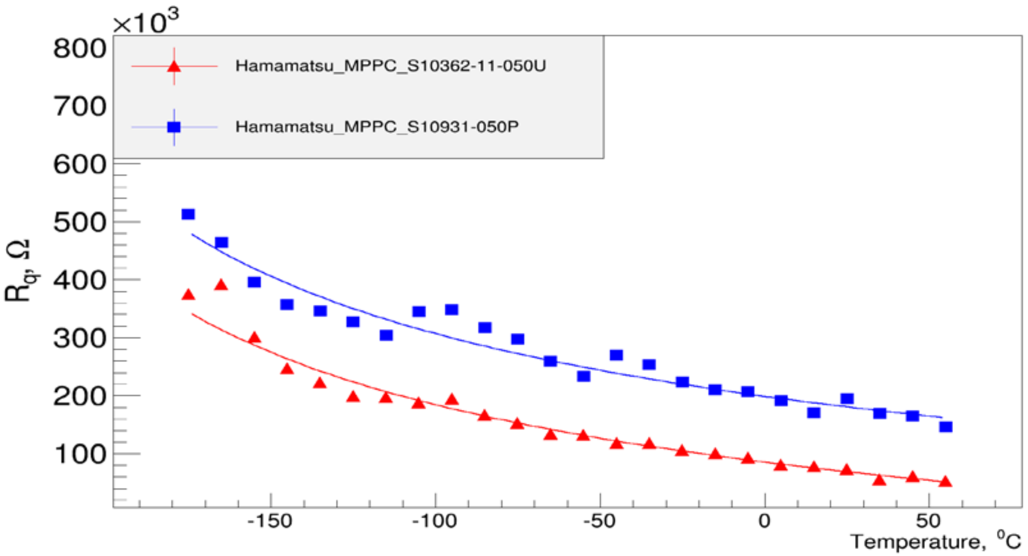
Signal shapes vs T





Pulse falling edge ($\tau_{fall} = C_{\mu cell} \cdot R_q$) increase with decreasing T → R_q temperature dependence

R_q vs T



R_q increase with decreasing T

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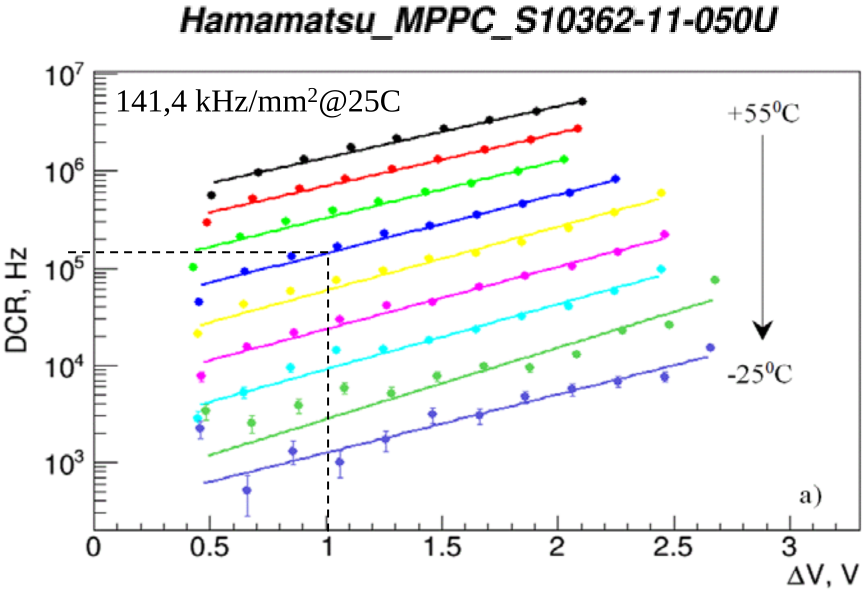
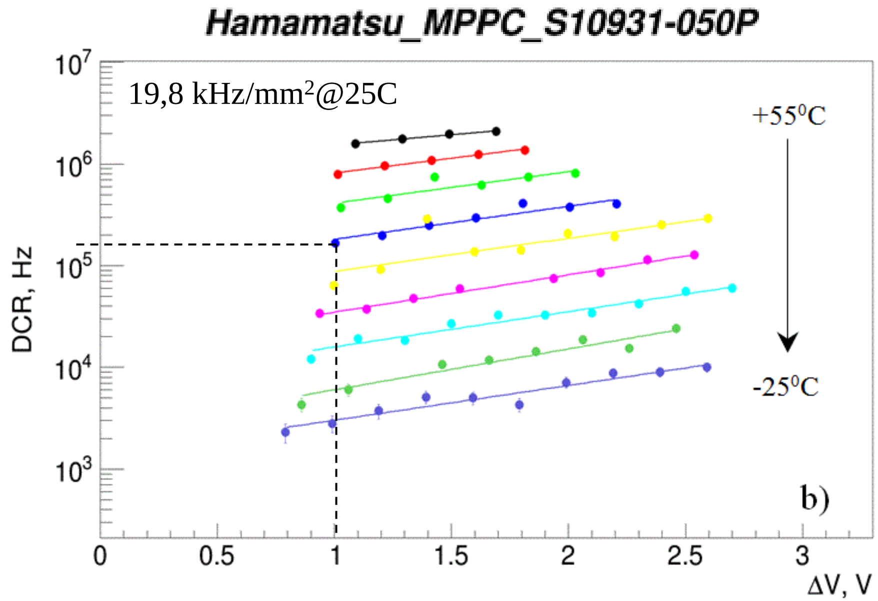
poly-silicon T dependence

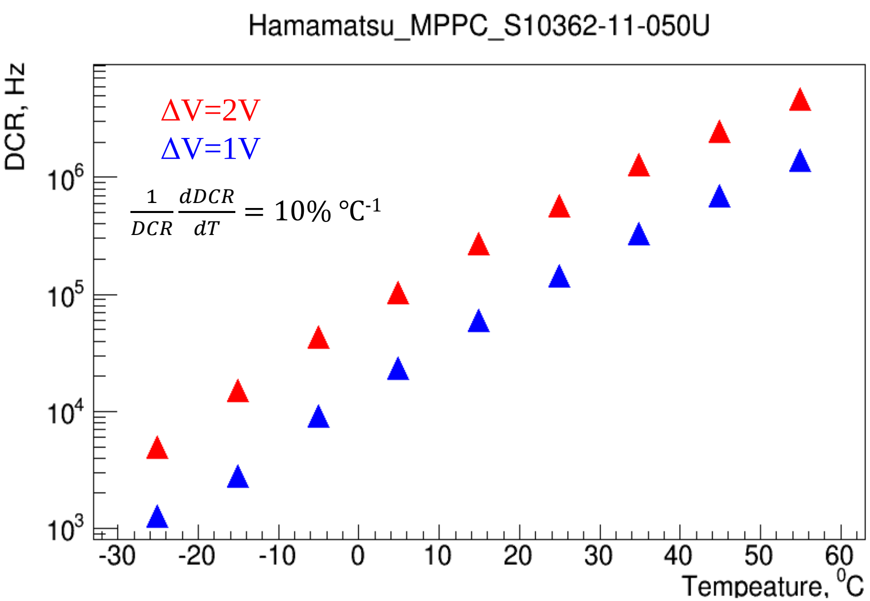
$$R_q(T) = a + b\sqrt{T}\exp\left(\frac{c}{T}\right)$$

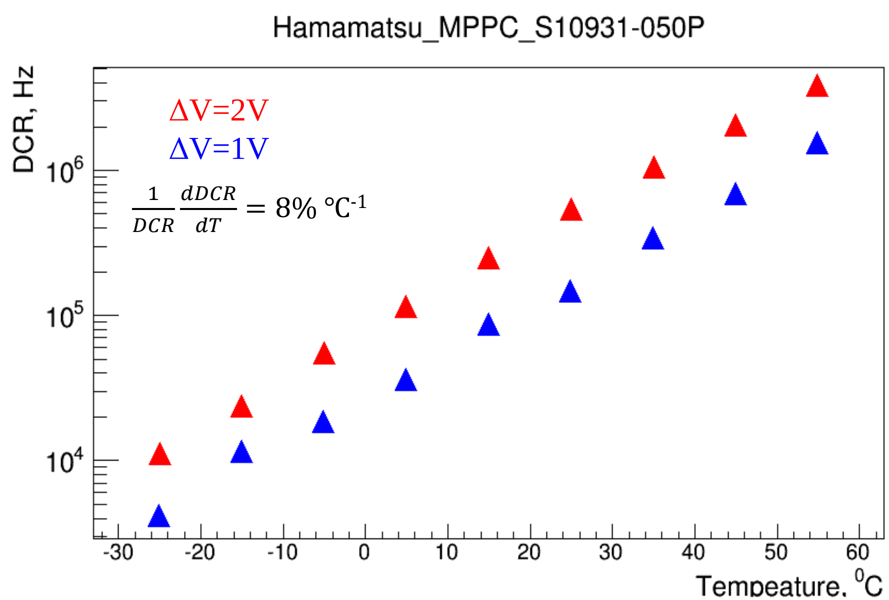
N. C. C. Lu, et al. (1981)
IEEE Trans. Electron Devices, 28, 818

Dark count rate vs T









Decreasing T → DCR decreases (thermal generated carriers decrease)

Summary

- MPPC detectors of 1x1 and 3x3 mm^2 50x50μm cell size
  - T range -175°C to +55°C
  - overvoltage range: 0.5 to 2.5V
- Automatic procedure for calculation of the MPPC parameters
  - baseline restoration
  - pulses characteristics analysis
- T dependence of MPPC parameters
  - breakdown voltage
  - gain
  - dark count rate
  - quenching resistance
  - micro-cell capacitance
  - recovery time
- Future work
  - automatic procedure
    - to be used for the analysis of new detectors from different producers
    - select detectors with best characteristics (noise, T stability) for intra-operative beta probes
  - continue the analysis of MPPC characteristics vs T
    - PDE
    - afterpulses and cross-talk

Additional slides

MPPC characteristics:

Gain : → the number of charges created in one avalanche in one µcell

Noise :
- dark count → pulses triggered by non-photo-generated carriers (thermal/tunneling generation in the bulk or in the surface depleted region around the junction)
- afterpulse → carriers can be trapped during an avalanche and then released triggering another avalanche
- optical cross-talk → photo-generation during the avalanche discharge. Some of the photons can be absorbed in the adjacent cell possibly triggering new discharges

Signal shape :
- Rise time: $\tau_{rise} \sim R_D \cdot C_D$ (read-out chain should be taken into account)
- Recovery time: $\tau_{recovery} \sim R_q \cdot C_D$ (influence the dead time and dynamic range)

Photon Detection Efficiency, Dynamic Range, Timing resolution

Motivation:

- The temperature and bias voltage represent two parameters affecting the characteristics of the MPPC detectors (breakdown voltage, signal shape, noise, gain etc) and consequently leading to a variation of the final detection characteristics
- Use the properties of MPPC for the understanding of fundamental physics: temperature dependence of thermal generated carriers; life time of afterpulses etc.

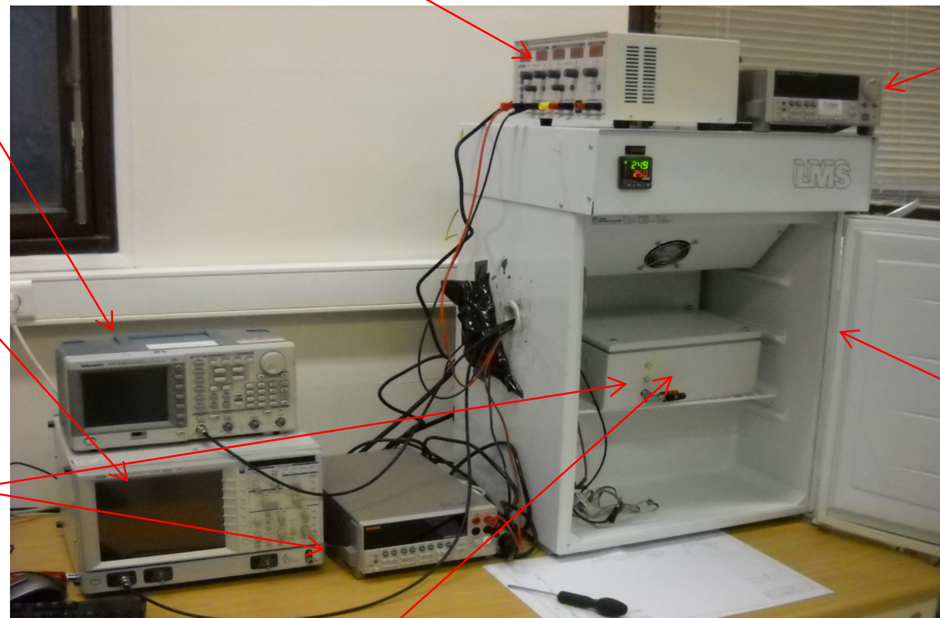
Set-up for new SiPM's measurements as a function of temperature :

Voltage source

Pulse generator

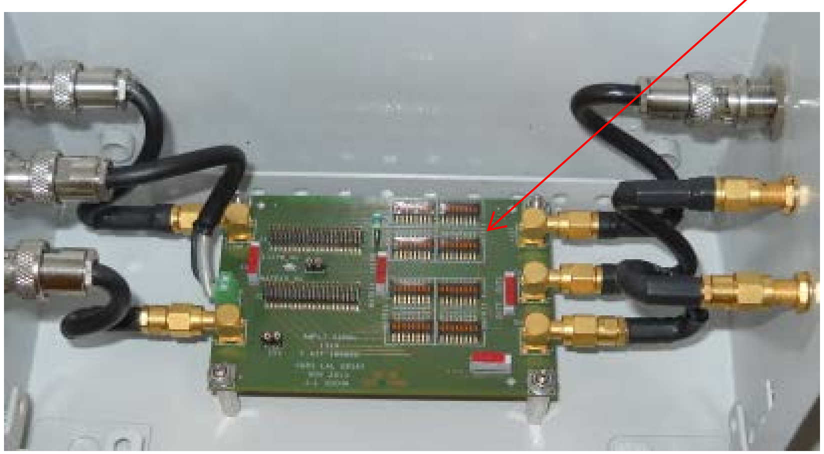
Source meter

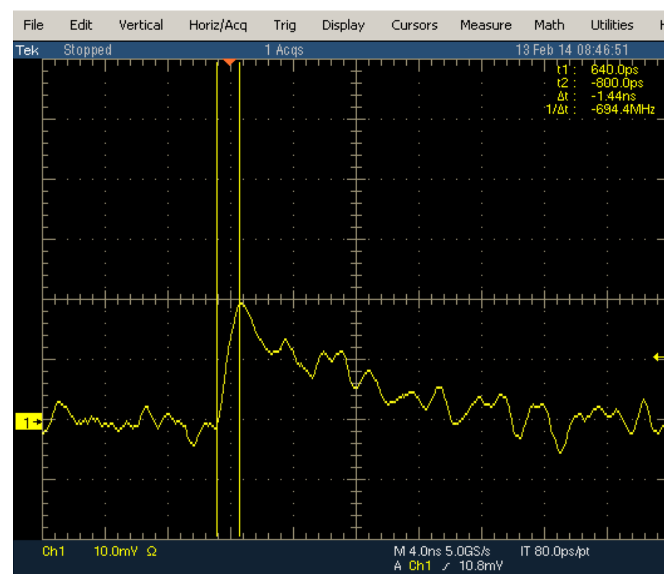
Oscilloscope (500Mhz)



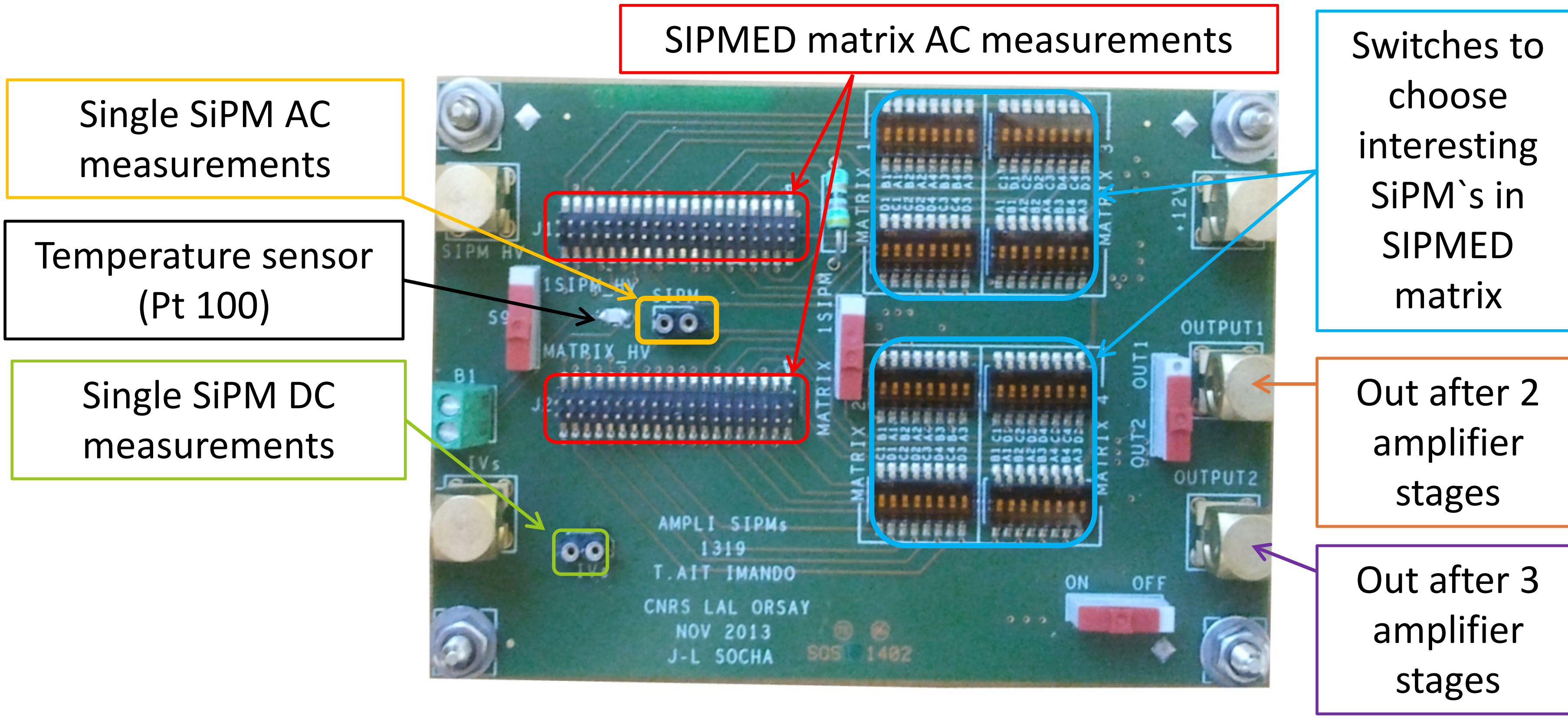
Climatic chamber

Pt100 & multimeter for T monitoring





Board for SiPM measurements:

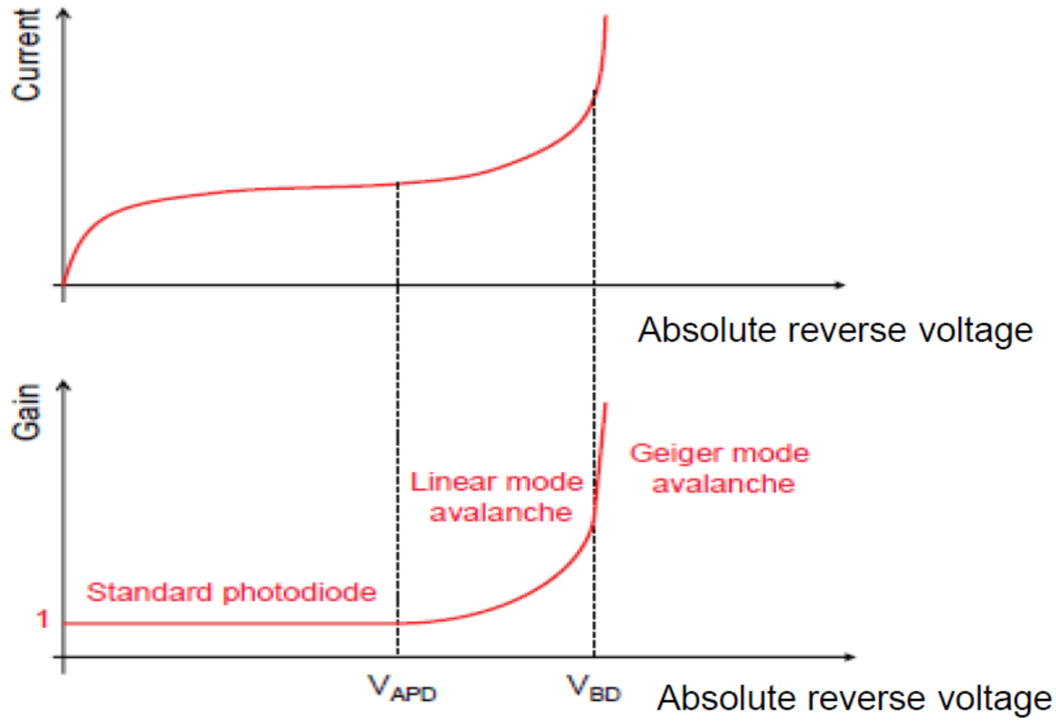


Main characteristics of the board:
- Gali amplifier (G=20dB, BW=2GHz)
- DC and AC measurements of single SiPM
- AC measurements of arrays of SiPM from SIPMED modules

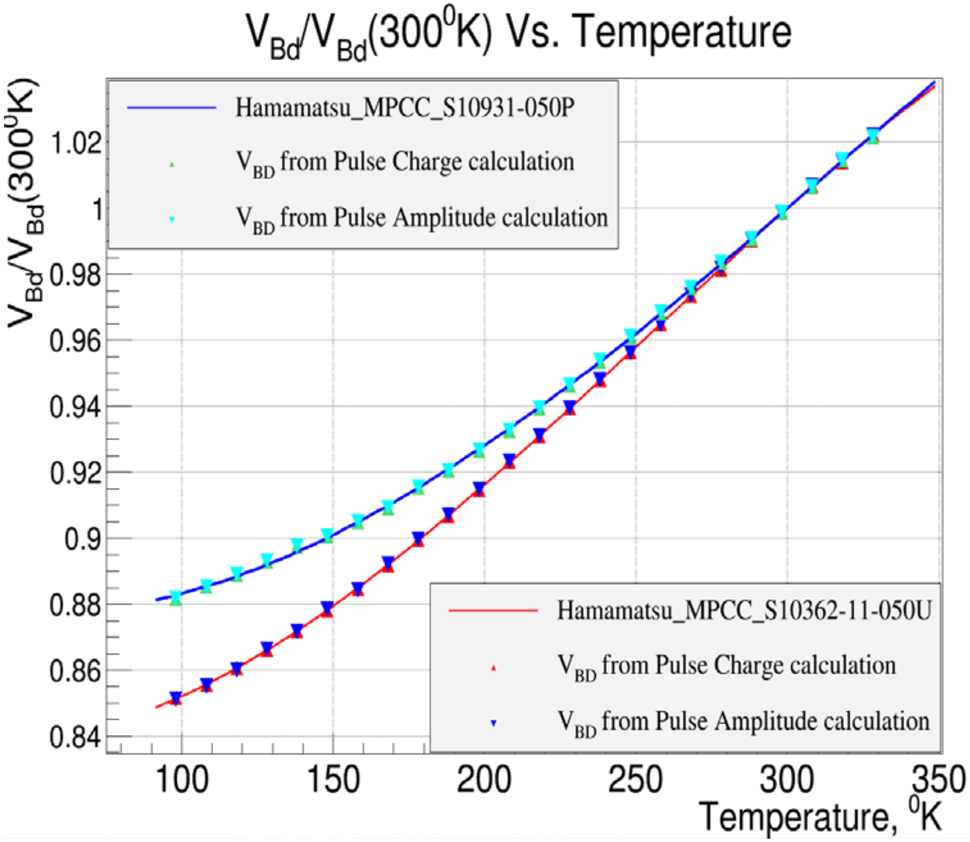
Board design: N. Dinu, T. Imando, A. Nagai, D. Breton
Routing: Jean-Luc Socha
Mechanics: JF. Vagnucci
Cabling: P. Favre, B. Debennerot, F. Campos

Silicon detectors

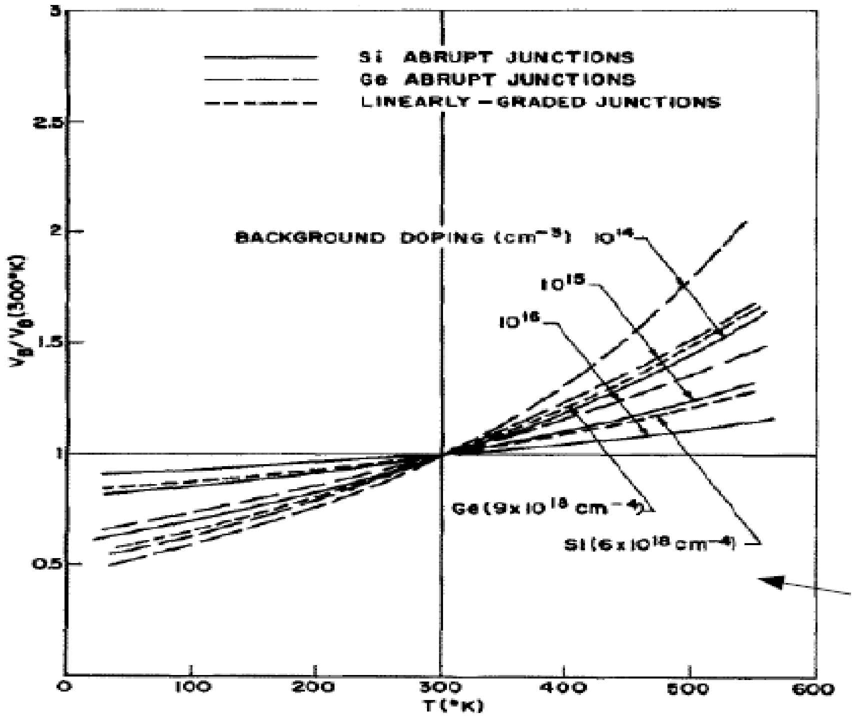
p-n junction working in reverse bias mode



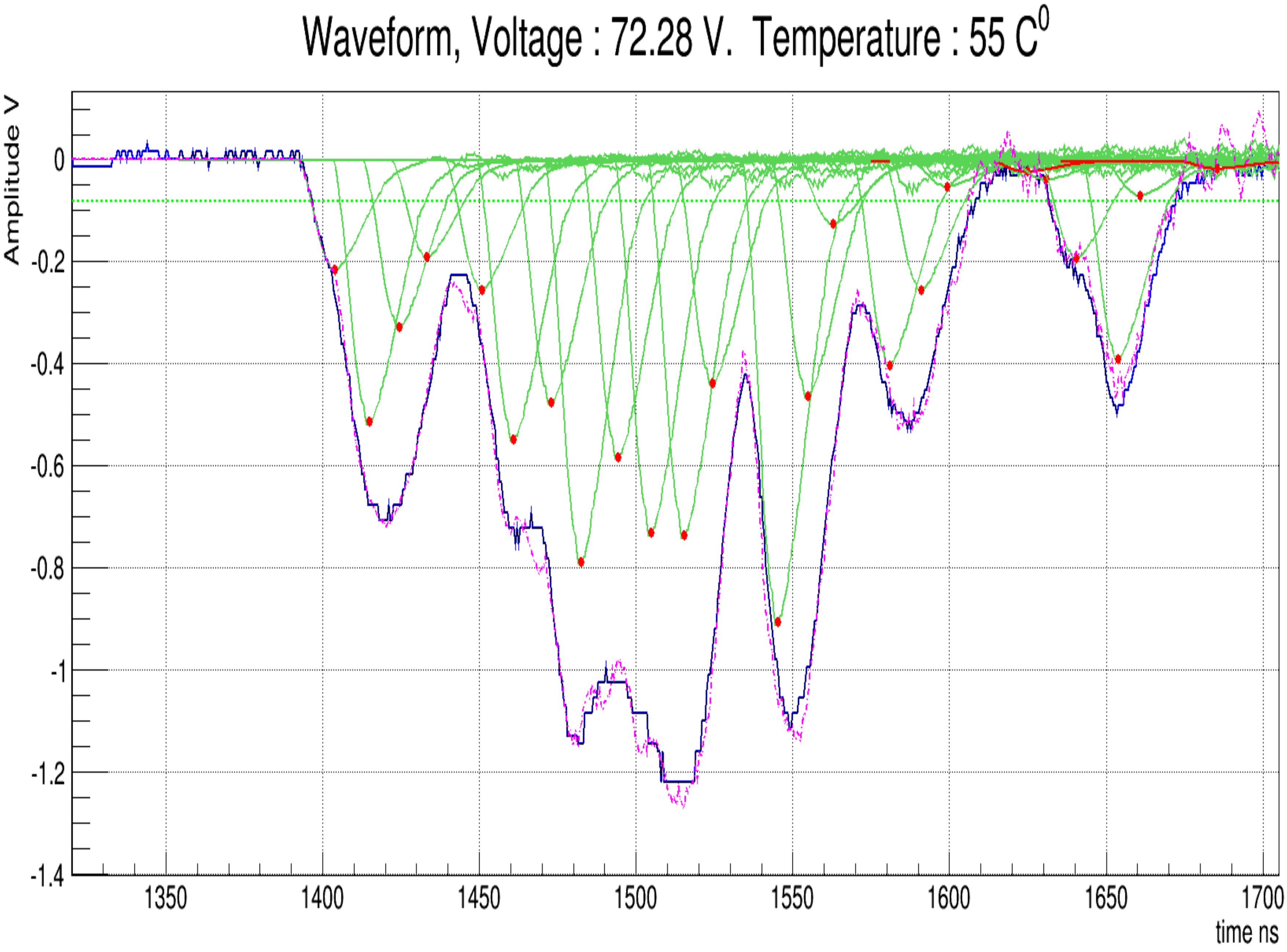
Photodiode	APD	GM-APD
• $0 < V_{bias} < V_{APD}$ • G=1 • Operate at high light level (few hundreds of photon)	• $V_{APD} < V_{bias} < V_{BD}$ • G=50-500 • Linear-mode operating • Operate at medium light level (tens of photon)	• $V_{bias} > V_{BD}$ • $G \rightarrow \infty$ • Geiger-mode operation • Can operate at single photon level



$V_{Bd}/V_{Bd}(300^0K)$ Vs. Temperature
$V_{Bd}/V_{Bd}(300^0K)$
Hamamatsu_MPCC_S10931-050P
V_{BD} from Pulse Charge calculation
V_{BD} from Pulse Amplitude calculation
Hamamatsu_MPCC_S10362-11-050U
V_{BD} from Pulse Charge calculation
V_{BD} from Pulse Amplitude calculation
Temperature, ^0K



Si ABRUPT JUNCTIONS
Ge ABRUPT JUNCTIONS
LINEARLY-GRADED JUNCTIONS
BACKGROUND DOPING (cm^{-3}) 10^{14}
10^{15}
10^{16}
$V_B/V_B(300°K)$
Ge(9×10^{18} cm^{-4})
Si(6×10^{18} cm^{-4})
T(°K)



Waveform, Voltage : 72.28 V. Temperature : 55 C0
Amplitude V
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
1350
1400
1450
1500
1550
1600
1650
1700
time ns

Pulse analysis

All calculated parameters saved in Ntuple files (one file at a given T and V_{Bias})

- Baseline
- Riser time
- Decay time
- Charge
- Local minimum (time, amplitude)