Study on timing resolution of APD sensors with test beam

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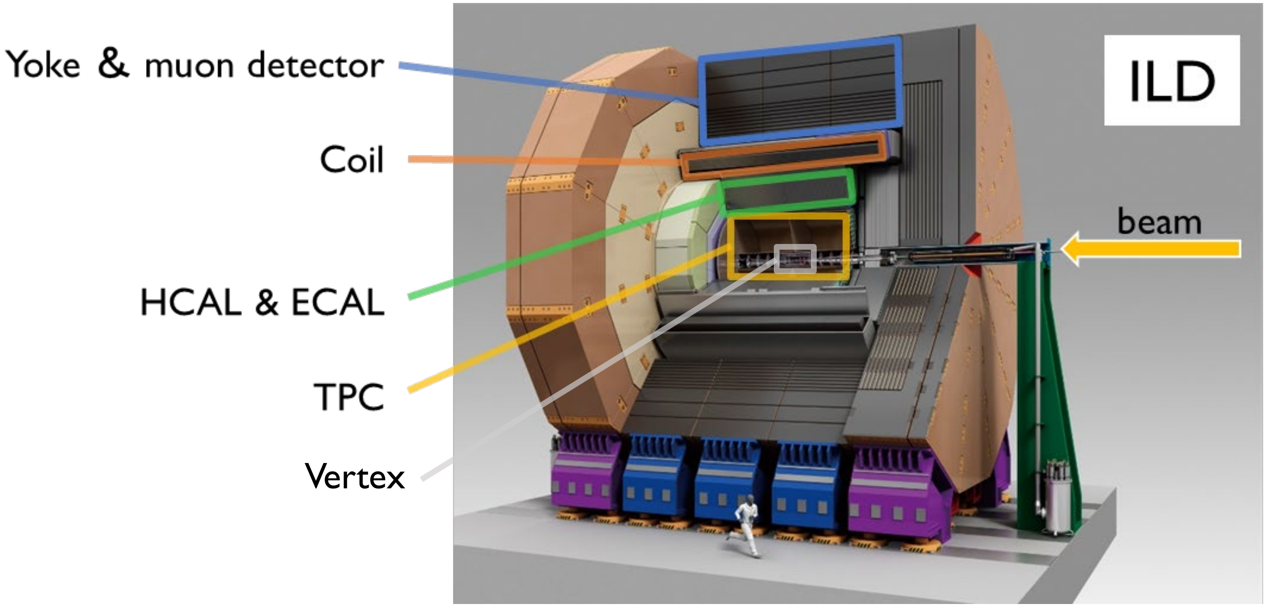
ILD and ECAL

ILD (International Large Detector)

- Detector to be placed at the collision point of the ILC
- Main components:Vertex, TPC, ECAL, HCAL, Coil

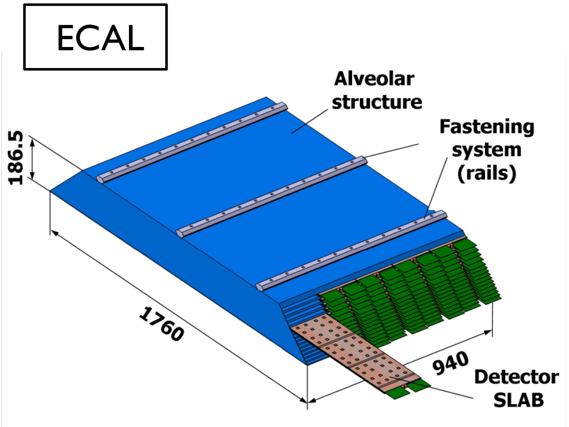


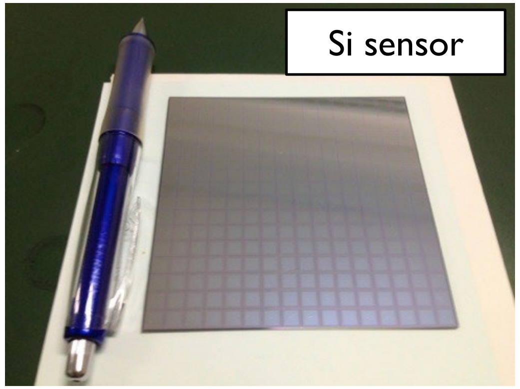
SiW-ECAL

- Sandwich calorimeter (30 layers)
- Absorption layers：Tungsten

  Detection layers：Si（Pixel size: $5 \times 5\ mm^2$ ）

  or Scintillator





5.5 mm x 256 pixels

Particle ID of hadrons and timing resolution

Particle ID of hadrons

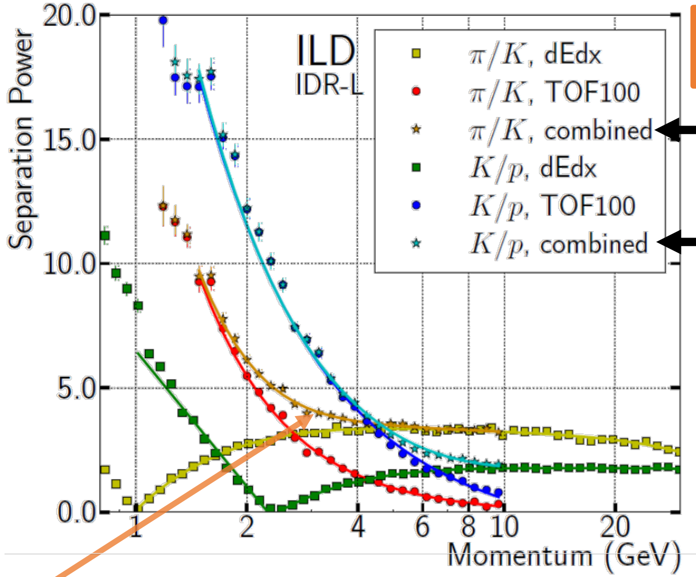
- ➢ Only measurement of dE/dx and momentum
  - ID of K/π ~ 3σ   ID of K/p < 2σ
  - There exists momentum ranges where we can't identify: 1-3 GeV

- ➢ Better separation power can be obtained by adding Time-of-Fright (ToF)
- ➢ Possible to separate (5σ) π/K up to 4 GeV by 20 ps ToF with dE/dx

Timing resolution and momentum range

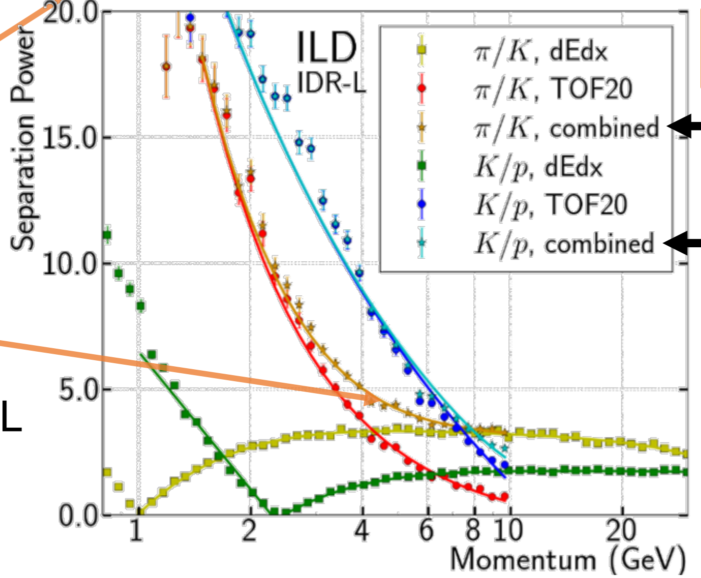
- ➢ ECAL with standard Si: ~100 ps   up to 3 GeV (3 σ)
- ➢ LGAD: 20−30 ps up to 5 GeV (3 σ)

→we are planning to use LGAD to replace sensor of a part of ECAL



100 ps

When adding 100 ps ToF measurement to dE/dx



20 ps

When adding 20 ps ToF measurement to dE/dx

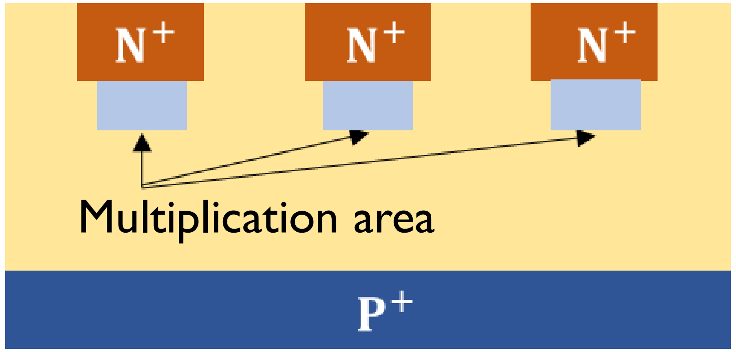
U. Einhaus, arXiv:2110.15115 [hep-ex] 2021.

Type of LGAD

LGAD (Low Gain Avalanche Detector)

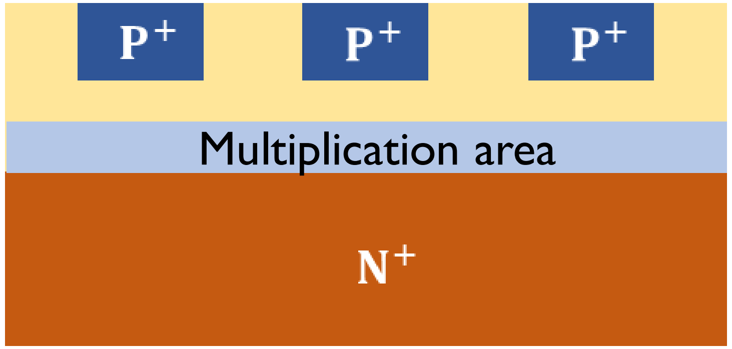
- Silicon sensor with internal avalanche multiplication mechanism
- Studies of LGAD in ATLAS group have achieved timing resolution of about 26 ps

Reach-through type



- Multiplication area is not uniformly formed
- Amplification ratio depends on the hit position of the particle

Inverse type



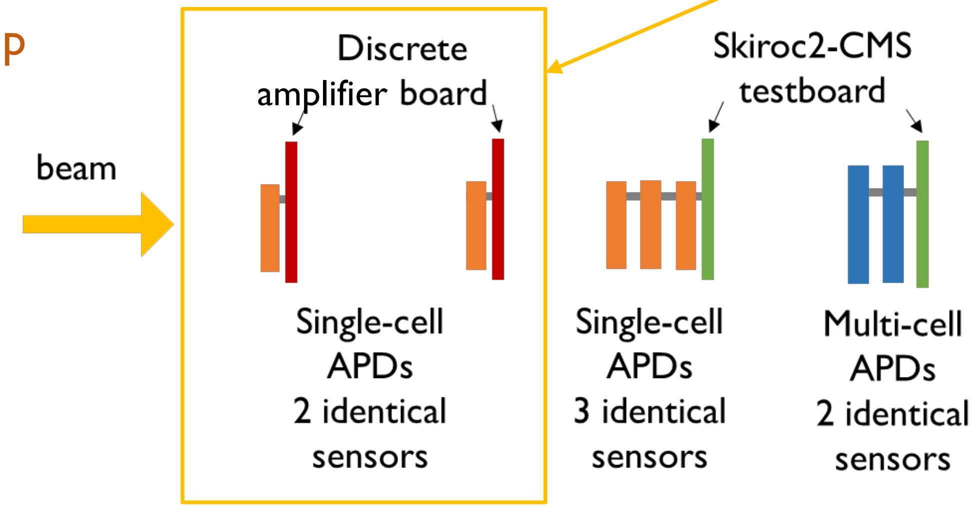
- Multiplication area is uniformly formed
- Uniform response is expected regardless of the hit position

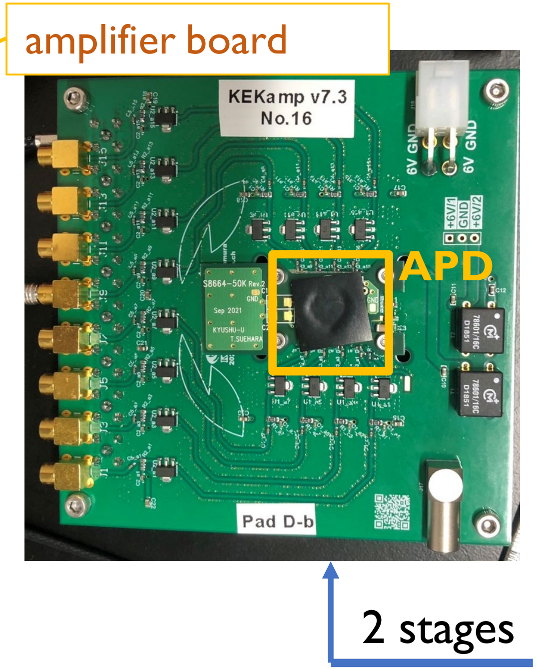
Test beam with discrete amplifier

6-8 Oct. 2021 at ELPH, Tohoku University

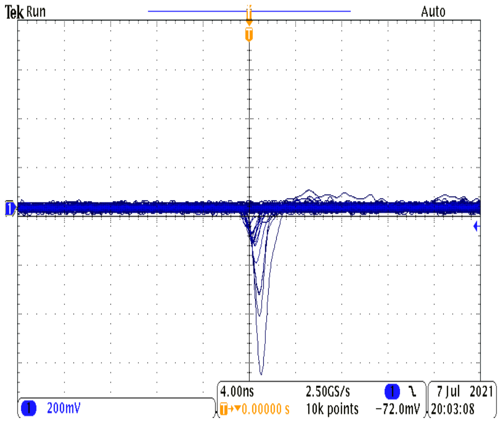
- 3 days ✕ 12 hours positron beam: ~770 MeV

Setup





Waveform output from the amp. board



Rising time ~1 nsec

Amplifier chip

- GALI-S66+ (Mini-circuit)
- Gain: 20 dB
- Wide bandwidth 3GHz

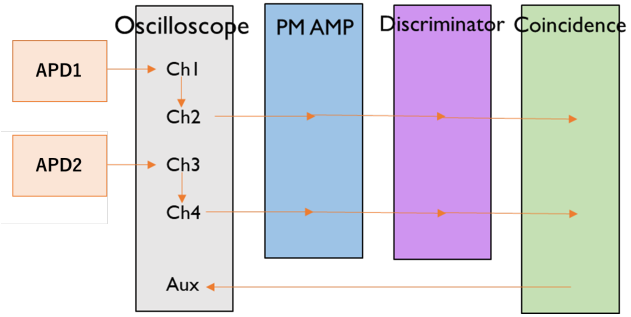
APD

APD No.	Type of APD	V_{br} [V]	size [mm]	capacity [pF]
S8664-50K	Inverse	416	5ϕ	55 pF
S2385	Reach through	160	5ϕ	95 pF

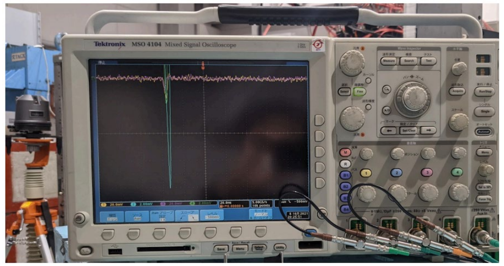
Analysis method

Set up

- The signals from the two APDs (APD1 and APD2) amplified by the amp. board are directly acquired and analyzed by an oscilloscope.



Oscilloscope



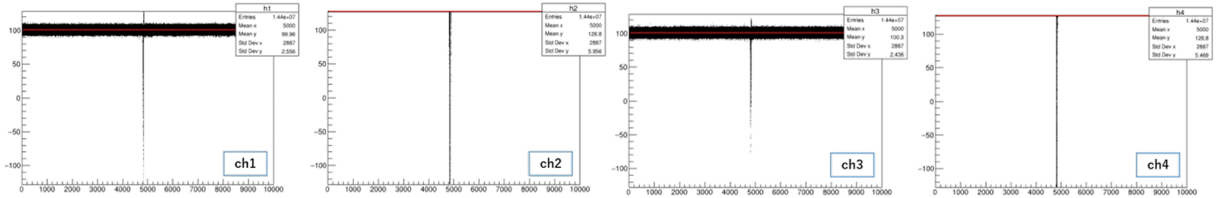
MSO 4104 (Tektronix)
- 1GHz, 5GS/s

Analysis method

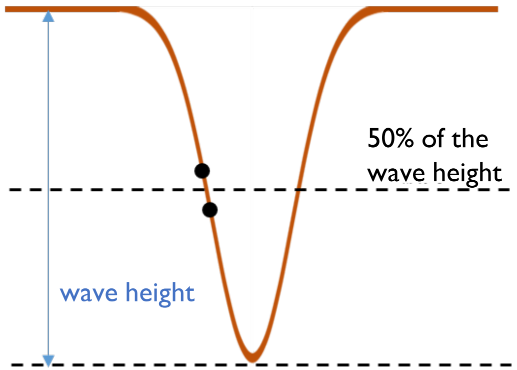
signal from APD1 → ch1(20 mV/div) and ch2(2 mV/div)

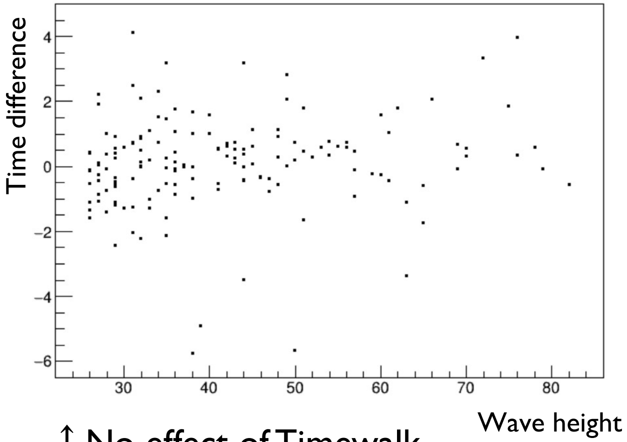
signal from APD2 → ch3(20 mV/div) and ch4(2 mV/div)

- Ch1 and ch3: obtain waveform height and timing information for large signals
- Ch2 and ch4: Obtain more detailed timing information for small signals



Obtain the timing at the point where the voltage is 50 % of the wave height
→Estimate the timing resolution from the time difference between the two APDs.





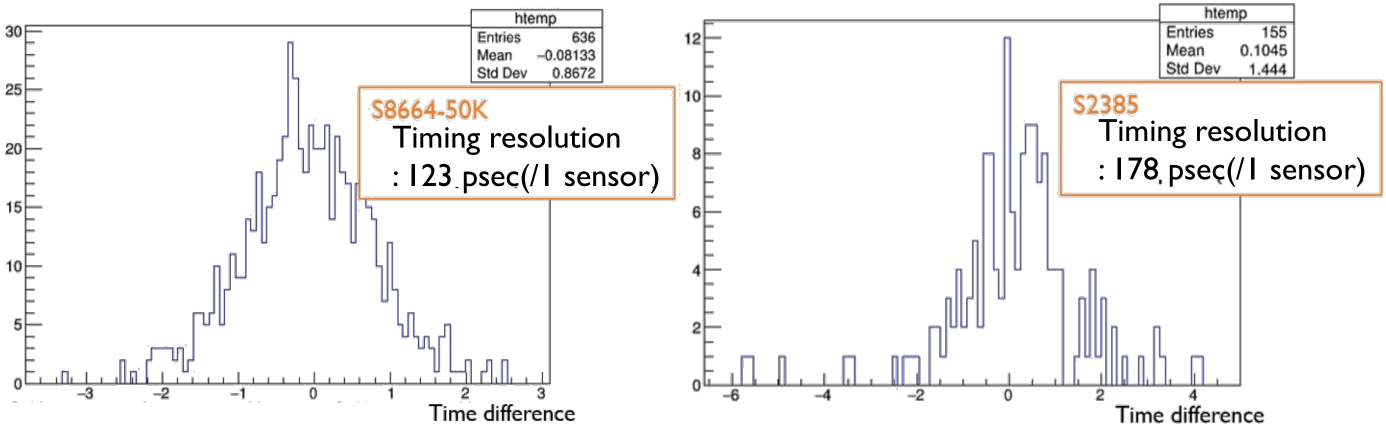
↑ No effect of Timewalk

Result of timing resolution

Result

APD sensor	Cut of charge	Timing resolution
S8664-50K (Inverse type)	> 18 fC	123 ps
	> 36 fC	63 ps
S2385 (reach through type)	> 18 fC	178 ps
	> 36 fC	89 ps

Time difference between the two APDs (charge > 18 fC)



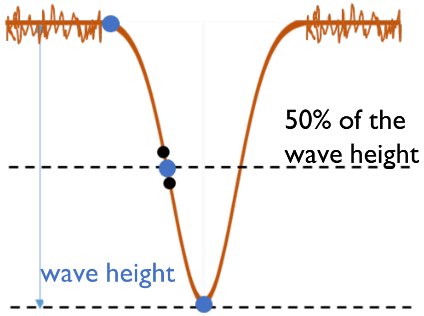
- Timing resolution of S8664-50K is better

  → Difference in capacitance related to signal rising time (S8664-50K: 55 pF S2385: 95 pF)

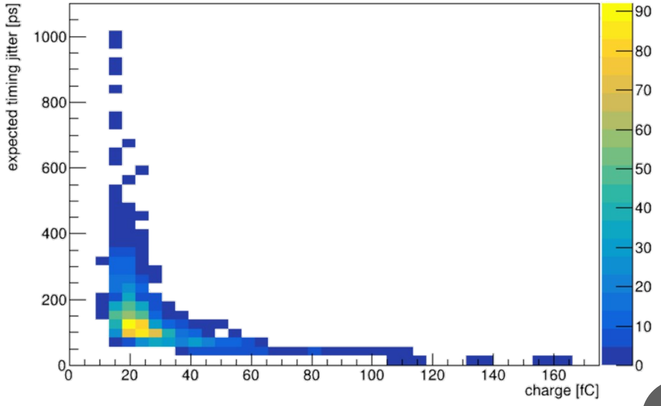
Evaluation of timing jitter due to noise

- Pedestal variation as a noise effect,

  add this effect to the pedestal, wave height, and 50% of wave height points
- Events with charge > 18 fC S8664-50K: 120 ps, S2385: 200 ps
- Events with charge > 36 fC S8664-50K: 62 ps, S2385: 106 ps
- Most of the time resolution is affected by noise caused by sensors and readout circuits



Relation between Charge of signal and Timing jitter due to noise



For achieve high timing resolution

Timing resolution factors: ${\sigma_t}^2 = {\sigma_s}^2 + {\sigma_n}^2$

- ${\sigma_s}^2$: Uncertainty in the timing response of the sensor itself
  - Landau noise: waveform changes depending on whether energy deposit occurs more on the upper side or lower side of the sensor.

    → Making the sensitivity layer thinner decrease Landau noise, but the signal becomes smaller, so the S/N ratio becomes worse.

    (It seem that the thickness of sensitive layer of S8664-50K is 5 μm)
  - Avalanche amplification fluctuation: Uncertainty in time for accelerated electrons to knock out surrounding electrons

- ${\sigma_n}^2$: Uncertainty caused by noise
  - Capacitance of sensor: The smaller the capacitance of the sensor, the smaller the rise time of the waveform.

    → Capacitance is proportional to the size of the sensor → Smaller sensors are less affected by noise.
  - Thermal noise: caused by high temperatures in amplifiers and sensor → need cooling
  - Noise due to disturbance to the conduction path between the sensor and the amplifier or due to HV

    → devise wiring, Stabilization of supply voltage, etc…

Plan for the next year

- Investigate response of the sensor in more detail
  - 2 GHz oscilloscope (R&S RTO64) to check actual rise time
  - Noise study (by temperature, by connection, difference by unit variation, etc.)
  - Dependence on capacitance: check rise time and noise with different size of the sensor
- Current APD (S8664-xx) seems to have too low signal (= too thin active thickness (5 μm?))
  Try other solutions
  - LGADs designed for ATLAS (reach-through)
  - New ones? (need cooperation of Hamamatsu but not too realistic, and having no fund)
  - Other than Hamamatsu? Cooperation with Europe?
- Misc
  - Position dependence (need to operate silicon strip)
    - Multi-cell measurement with SAMPIC (16ch, 1 GHz) module
  - Electronics (ALTIROC?)

Summary

- LGAD have high timing resolution → Introduction of LGAD is expected to improve the timing resolution of ECAL
- Test beam with discrete amplifier to measure the performance of APD
  - Achieved 63 ps timing resolution with inverse S8664-50K using only large signals
  - Improved timing resolution by increasing the statistics of the large signal.
  - Increase the amount of charge by using an APD with a thicker sensitivity layer → Decrease the Jitter
  - Use an oscilloscope with good performance
  - Device to reduce noise...cooling of amplifier board, wiring etc…

BACKUP

Timing resolution of Skiroc2-CMS

- Timing resolution ≅ (rising time)/(S/N ratio) + digitization jitter + Landau noise + timewalk
  - ➢ noise of Skirock2-CMS is large
  - ➢ rising time of Skiroc2-CMS fast shaper is large: 5 nsec
    - Value of S/N ratio ~250 required for 20 ps timing resolution equivalent to 600e- noise → too difficult
    - Fast shaper can be faster but S/N degraded (need detailed study)
  - ➢ Digitization jitter of Skiroc2-CMS: ~30 ps
  - ➢ Landau noise: waveform changes depending on whether energy deposit occurs
    more on the upper side or lower side of the sensor.
  - ➢ Timewalk can be corrected (S.Tsumura's talk)

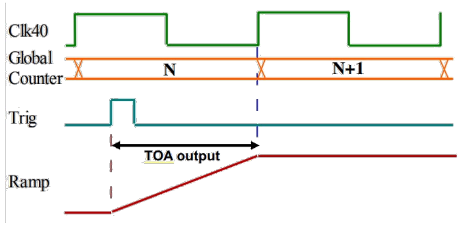
- Noise reduction by better HV treatment
  - However, to achieve timing resolution 30 ps by noise reduction is difficult… → need another reading system

Measurement with Skiroc2-CMS

ASIC for reading signals of silicon sensor

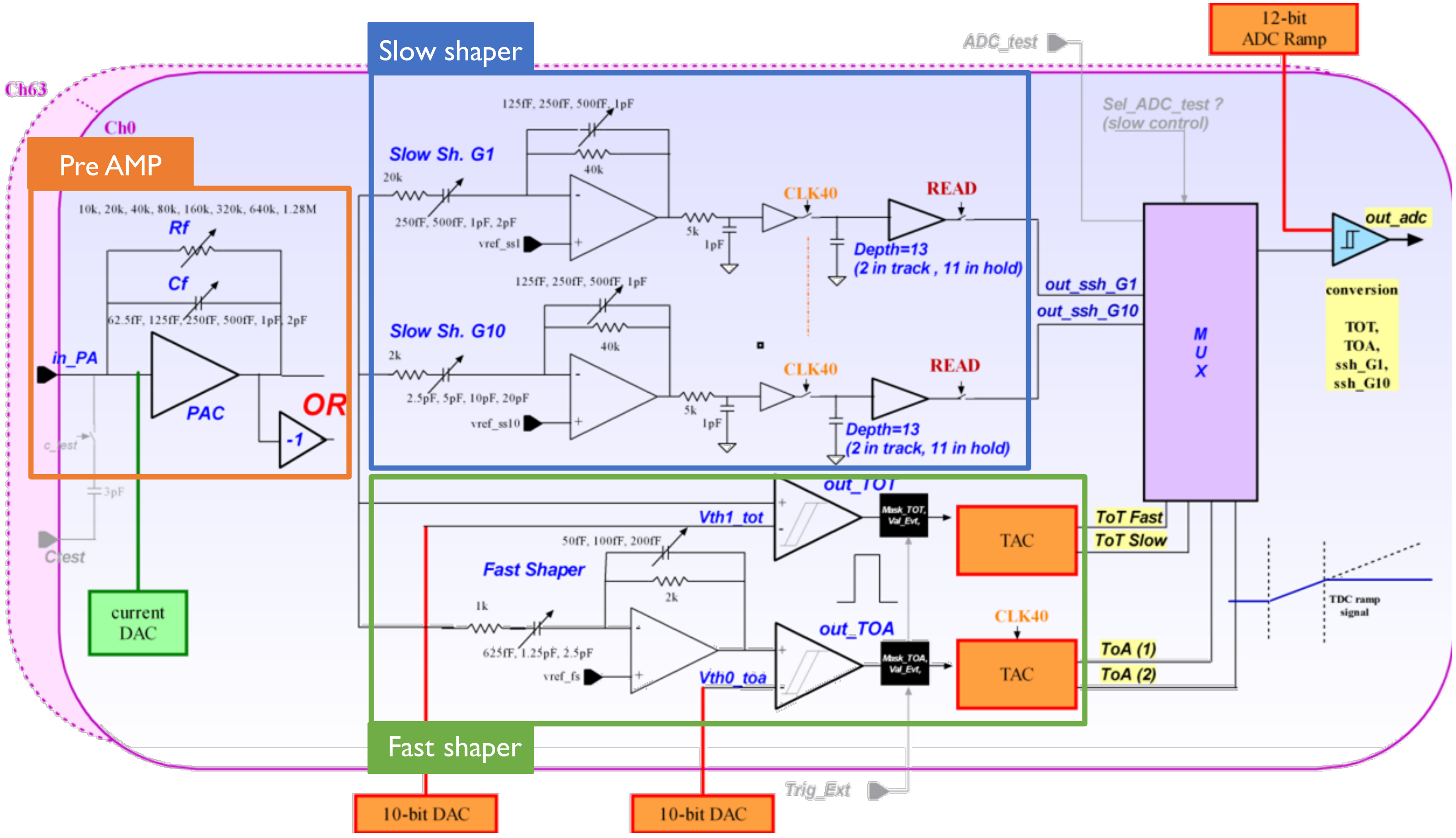
TOA (Time Of Arrival)

- Timing information between the triggered time and the next internal clock



ADC

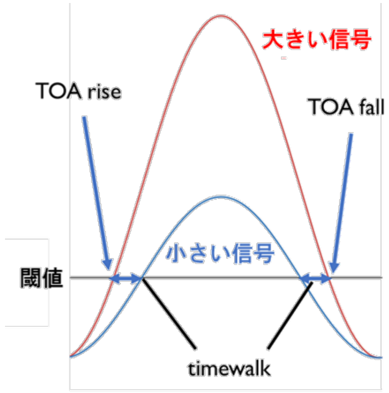
- 13 cells waveform digitizer at 50 MHz ring buffer



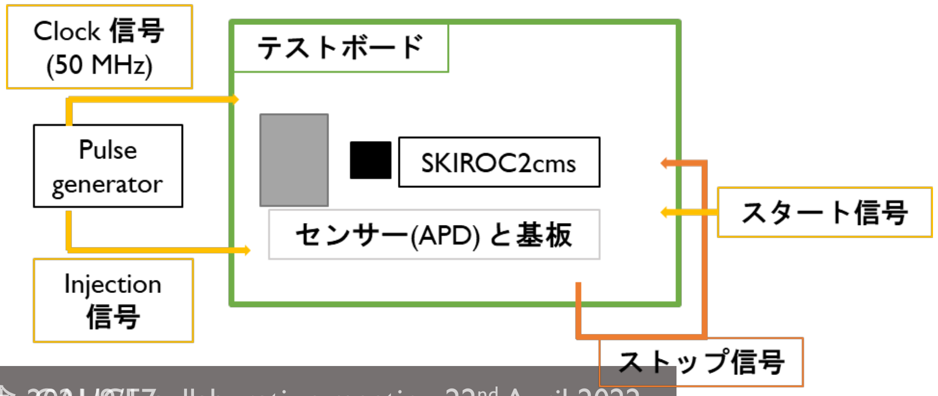
Timewalk measurement

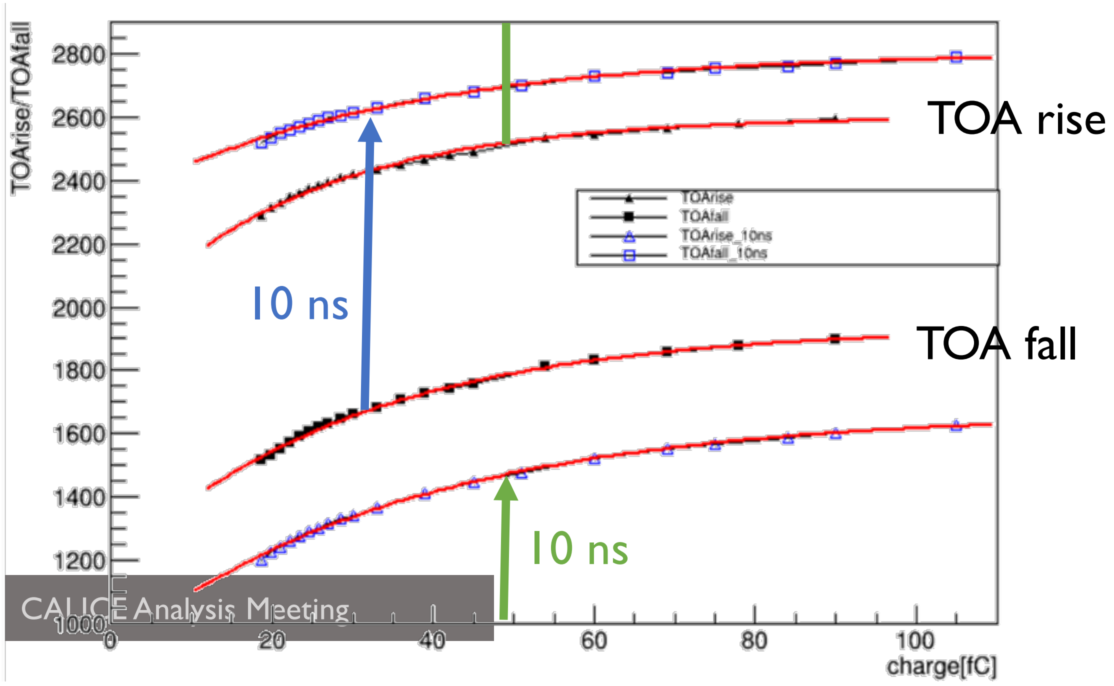
Timewalk

- 入力された信号の大きさによって生じる時間情報の誤差
- 同じタイミングで入力されたとしても
  大きい信号のほうが小さい信号より
  閾値を超えるタイミングが早くなるため
  時間情報に誤差が生じる



- テストボードを用いてInjection信号の電圧を変えながら
  その時のTOAを記録することで、Timewalkを測定



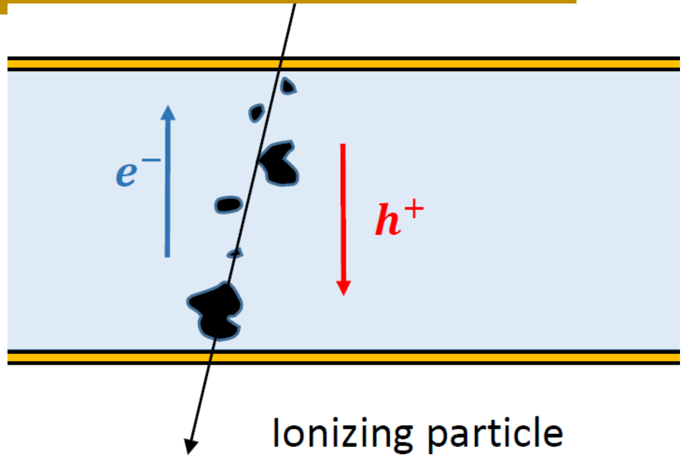


TOAと入力信号の電荷の関係から、
timewalkが従う指数関数を決定

→実験データのtimewalk補正に使用

TIMING LIMITATION FACTORS

- Landau fluctuations
  - Uncertainty on ratio of the energy deposit along the ionizing path
  - ~10% of the drift time
    - Typical silicon sensor (300 μm, 300 V) → drift: 2 nsec → typical contribution of Landau is ~200 psec
  - To reduce the drift time
    - Thin sensors
      - 10 μm, 10 V → drift: 70 psec, Landau fluctuation: 7 psec
      - Electric field in the avalanche region should not count (for avalanche silicon sensors)

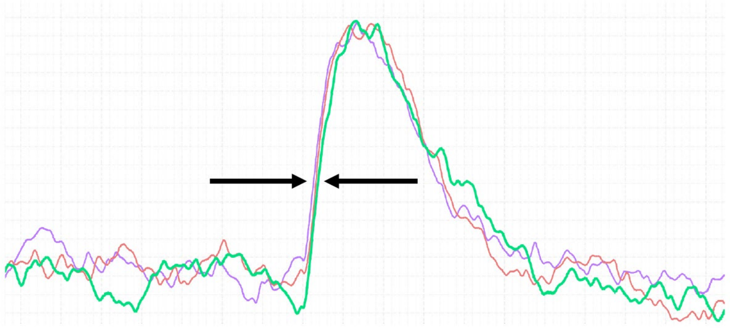


electron mobility 1350 V/cm s^2

TIMING LIMITATION FACTORS

- noise-equivalent electrons
  - Typical (hybrid): 1000 e-
    lower with monolithic
- Both ENC and rise time proportional to C_{in}
  → σ_t is proportional to C_{in}^2
- MIP signal strength
  - 80 e- / μm x gain
    - Difficult to get high S/N ratio with thin sensors
      trade-off with Landau noise

Time jitter



Fast integration

$$\sigma_t = \frac{\sigma_V}{dV/dt} \cong \frac{ENC}{I_{Ind}}$$

eg. rise time 100 psec
and S/N 10 gives
10 psec timing jitter by noise