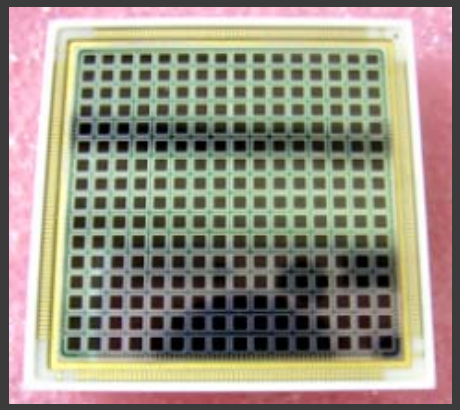
Development of a low-noise analog front-end ASIC for APD-PET detectors

2008.9.4 PSD8@University of Glasgow



256 ch APD-array

8 ch Analog ASIC

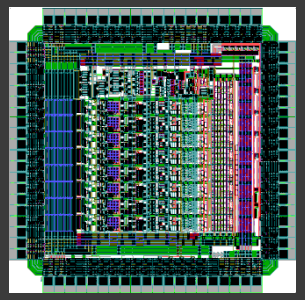
Makoto Koizumi (Tokyo Tech)

J. Kataoka, S. Tanaka, H. Ishibashi, N. Kawai (Tokyo Tech)
H. Ikeda (JAXA)

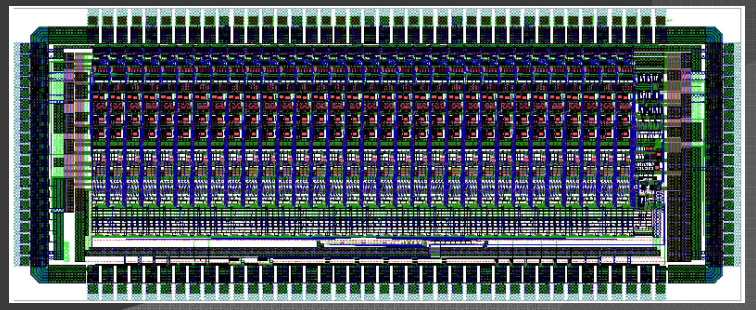
Y. Ishikawa, N. Kawabata, Y. Matsunaga, K. Shimizu (Hamamatsu Photonics)

Outline

- **Development and evaluation of 8-channel ASIC (ver.1)**
  - Introduction
  - Circuit Architecture
  - Performance
- **Future prospects**
  - 32-channel ASIC (ver.2)
  - Mobile PET unit
- **Conclusion**



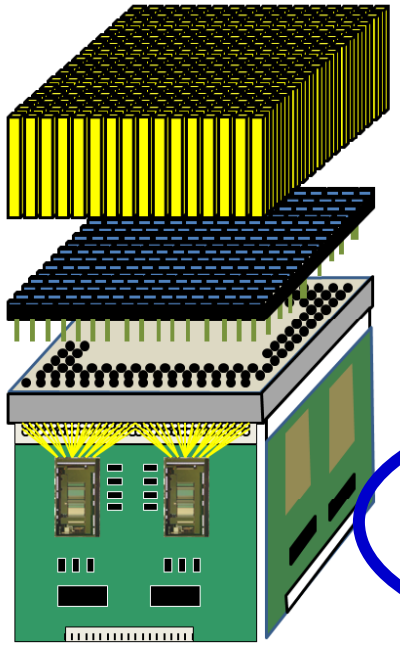
Ver.1
8ch



Ver.2 32ch

Introduction

We are now developing high spatial resolution, low-cost and multipurpose next generation PET detectors by using APD-arrays.

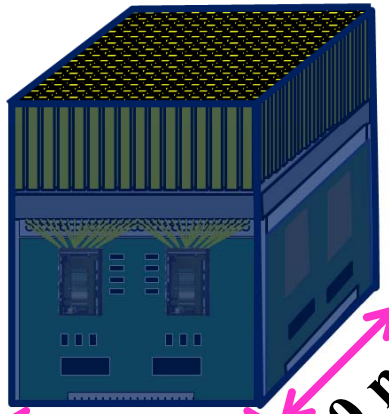


(1) sensor head
(pixel scinti.)

(2) APD-array

(3)Analog front-end
electronics with ASIC

~80 mm



30 mm

30 mm

- ✓ Flexible, low-cost mobile PET w/ sub-mm resol.
- ✓ Application to MRI/PET and TOF-PET.

Woody et al.
(2003)

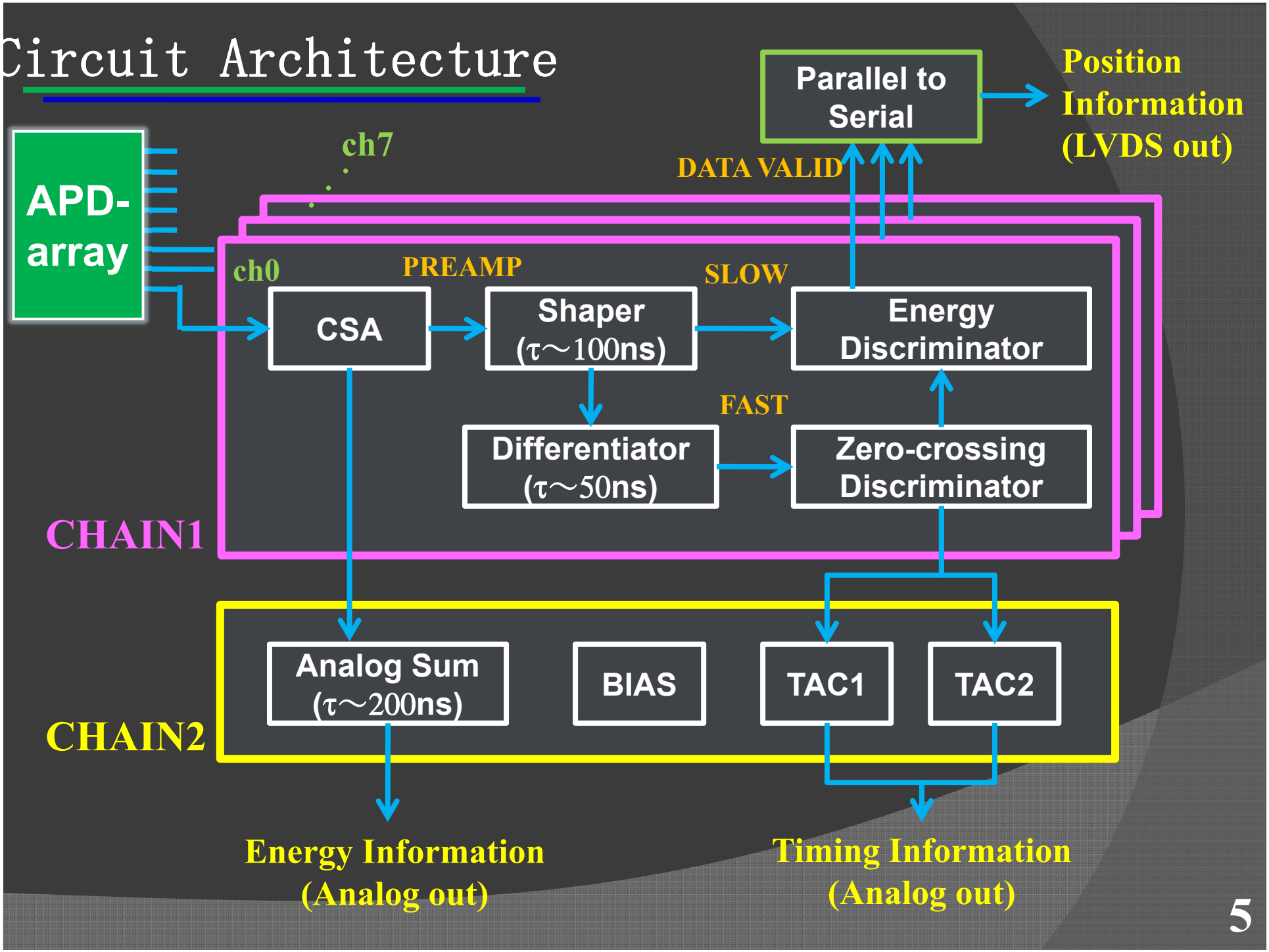
Introduction

Requirements for APD-PET front-end electronics

- Simultaneous processing of multiple channels (> 8-channel)
- CSA gain optimized to APD (～50 times)
- Fast Shaping time optimized to decay time of LYSO (～40ns)
- Time-of-Flight capability (< 1 ns)
- High energy resolution
- Low-noise and low-power consumption

We have developed an analog front-end ASIC which meets these specifications in cooperation with JAXA.

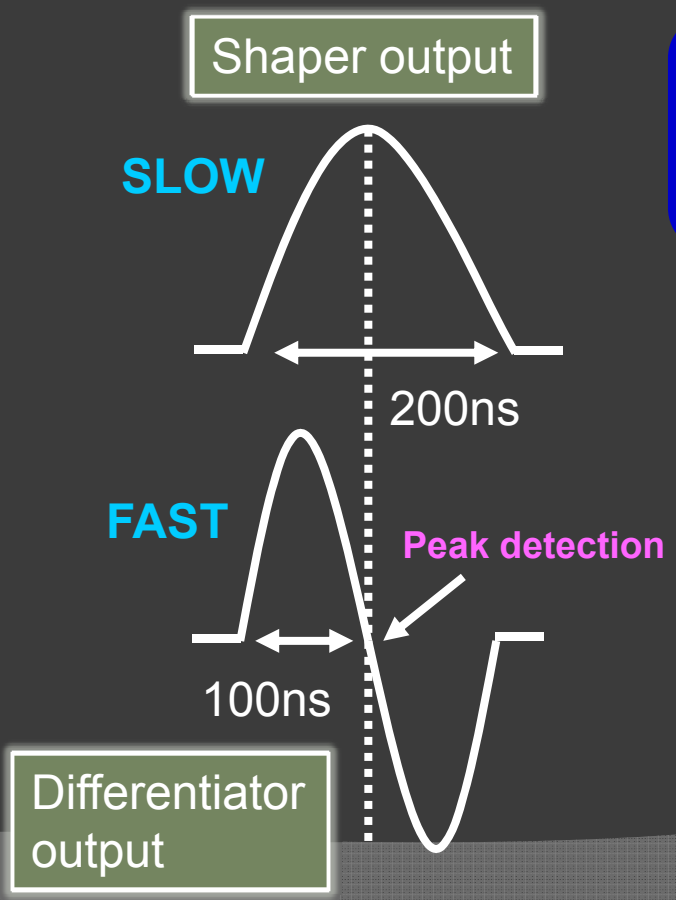
Circuit Architecture



Zero-crossing method

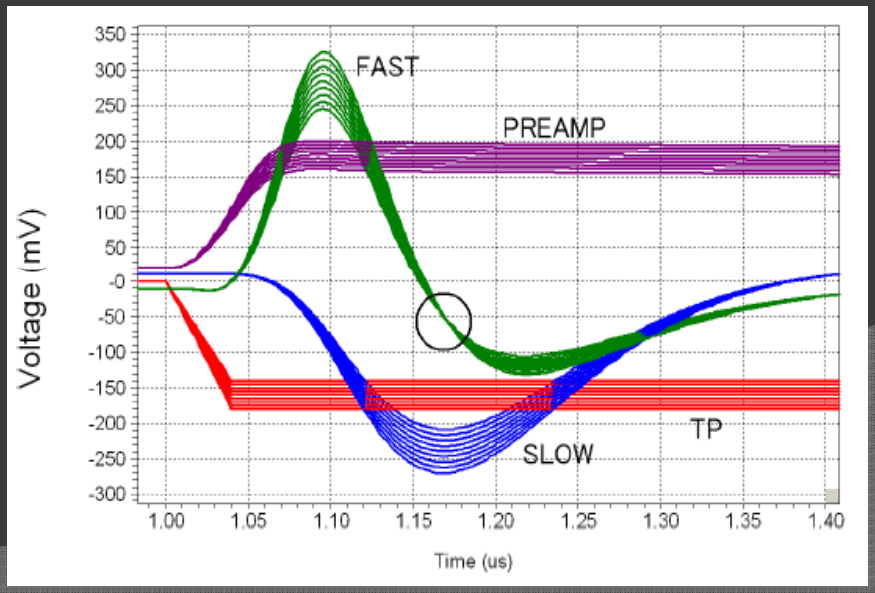
It is very important to obtain **true** hit timing information with various events for Time-of-Flight based PET

Apply the most simple zero-crossing method



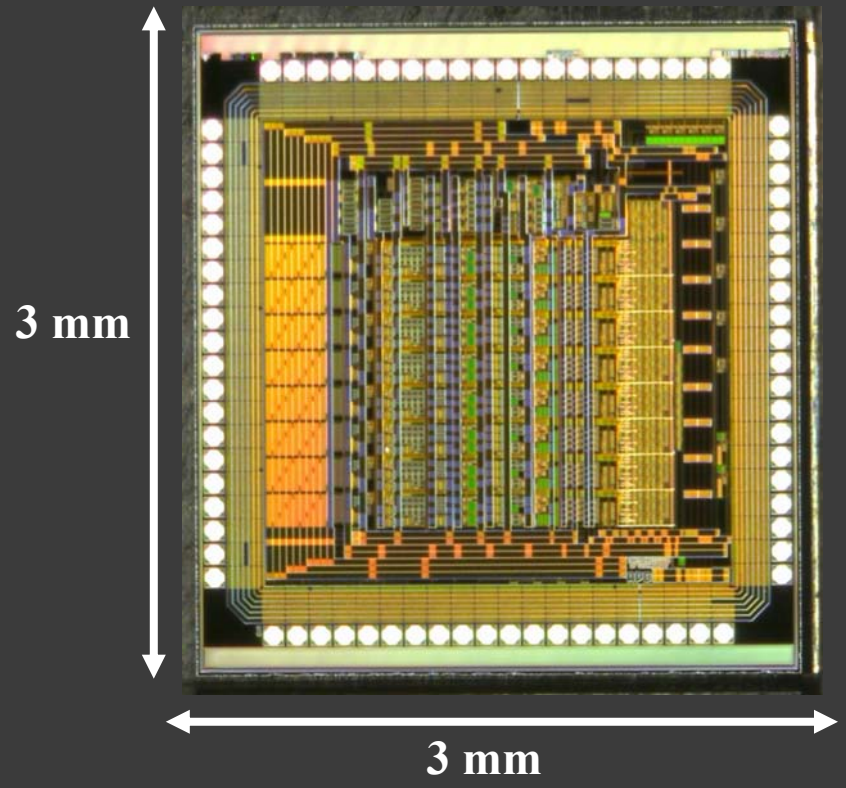
Zero-crossing method

1. **SLOW reaches to signal peak**
2. **Its differential signal FAST crosses zero point**
3. **Zero-crossing comparator turns on to start TACs**

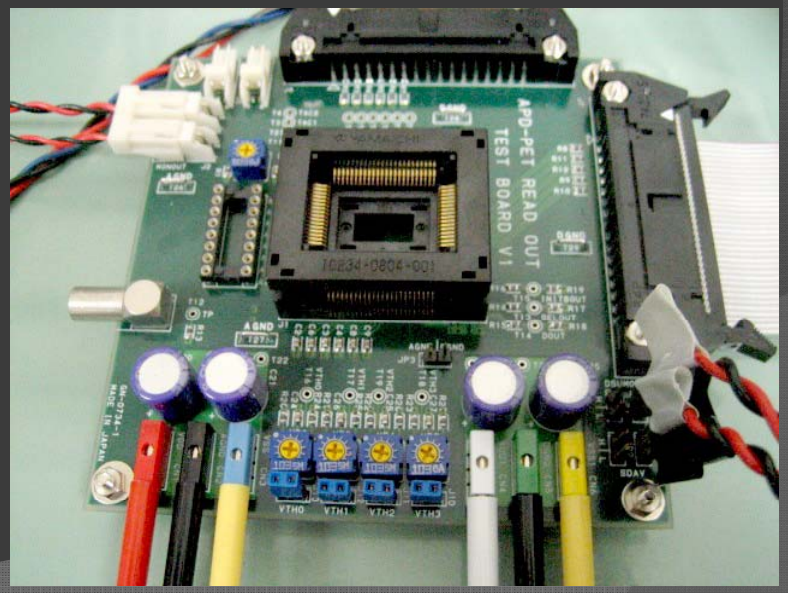


Time walk within 600 ps was expected with 511keV±13%

2007/5/29 : Completed



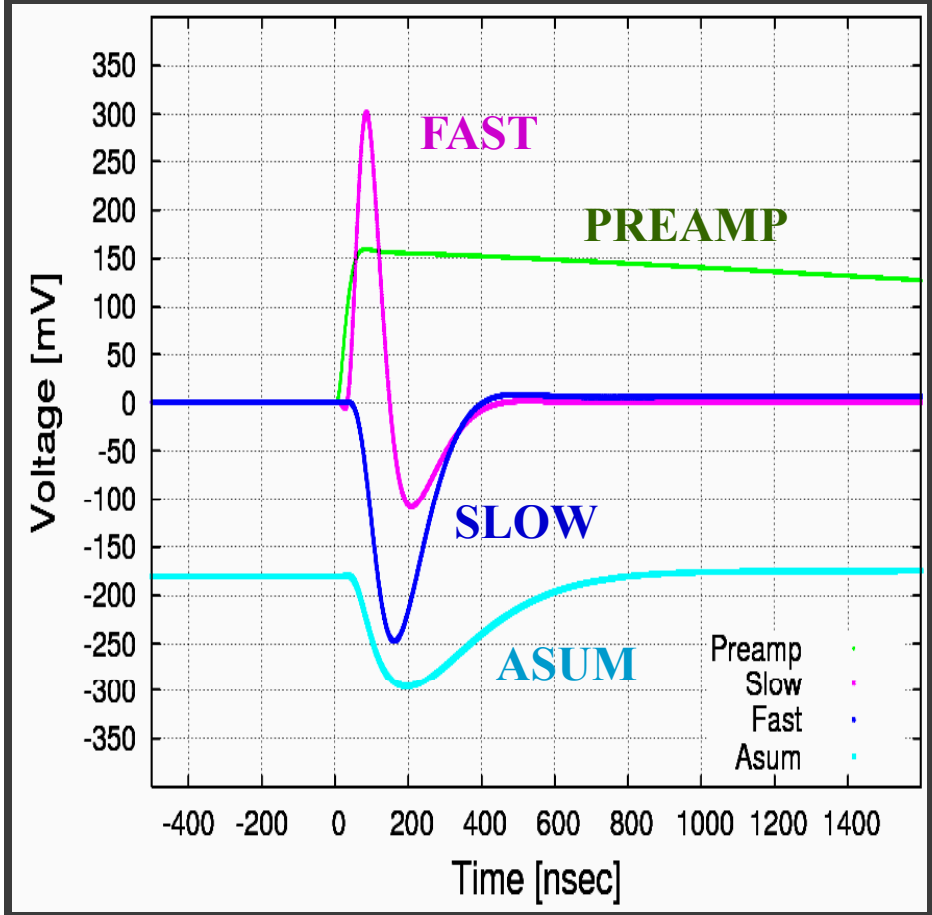
- Process：**TSMC 0.35μm CMOS**
- Chip size：**3mm×3mm**
- Package：**80pin Ceramic QFP**
- Number of channels：**8ch**
- Power consumption:**55mW**
  (6.9mW/ch)



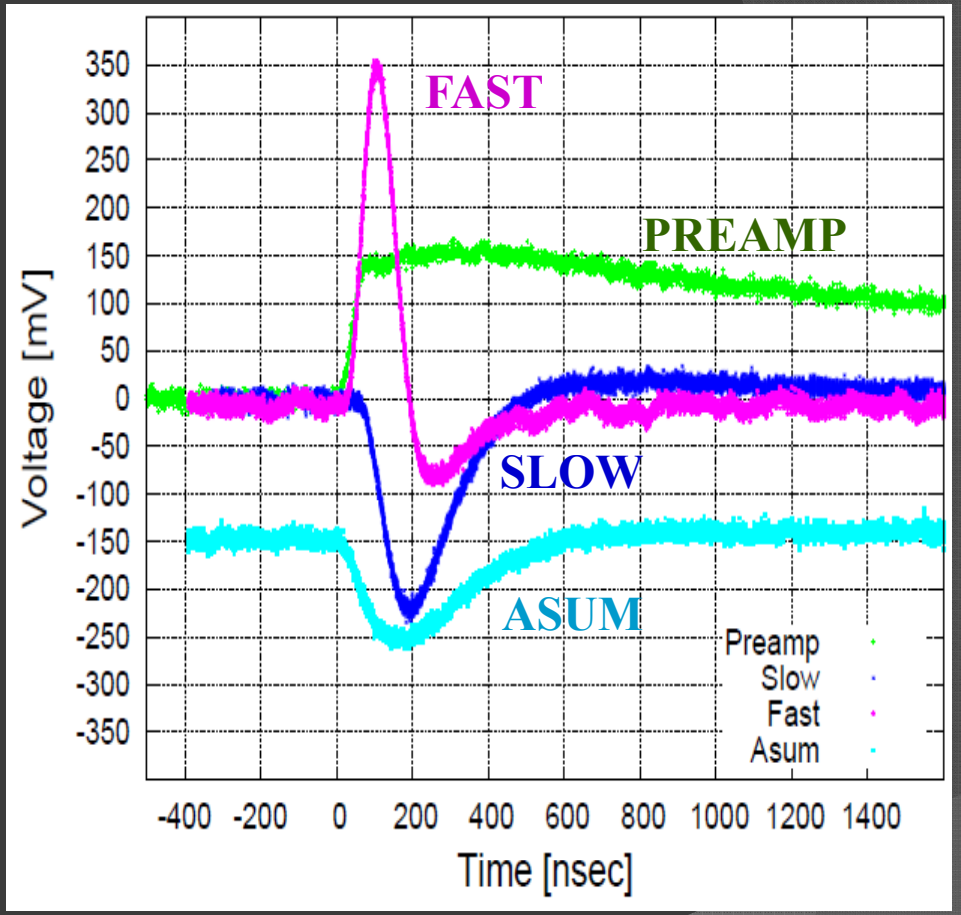
Testing board

Experimental results : Waveforms

Simulation

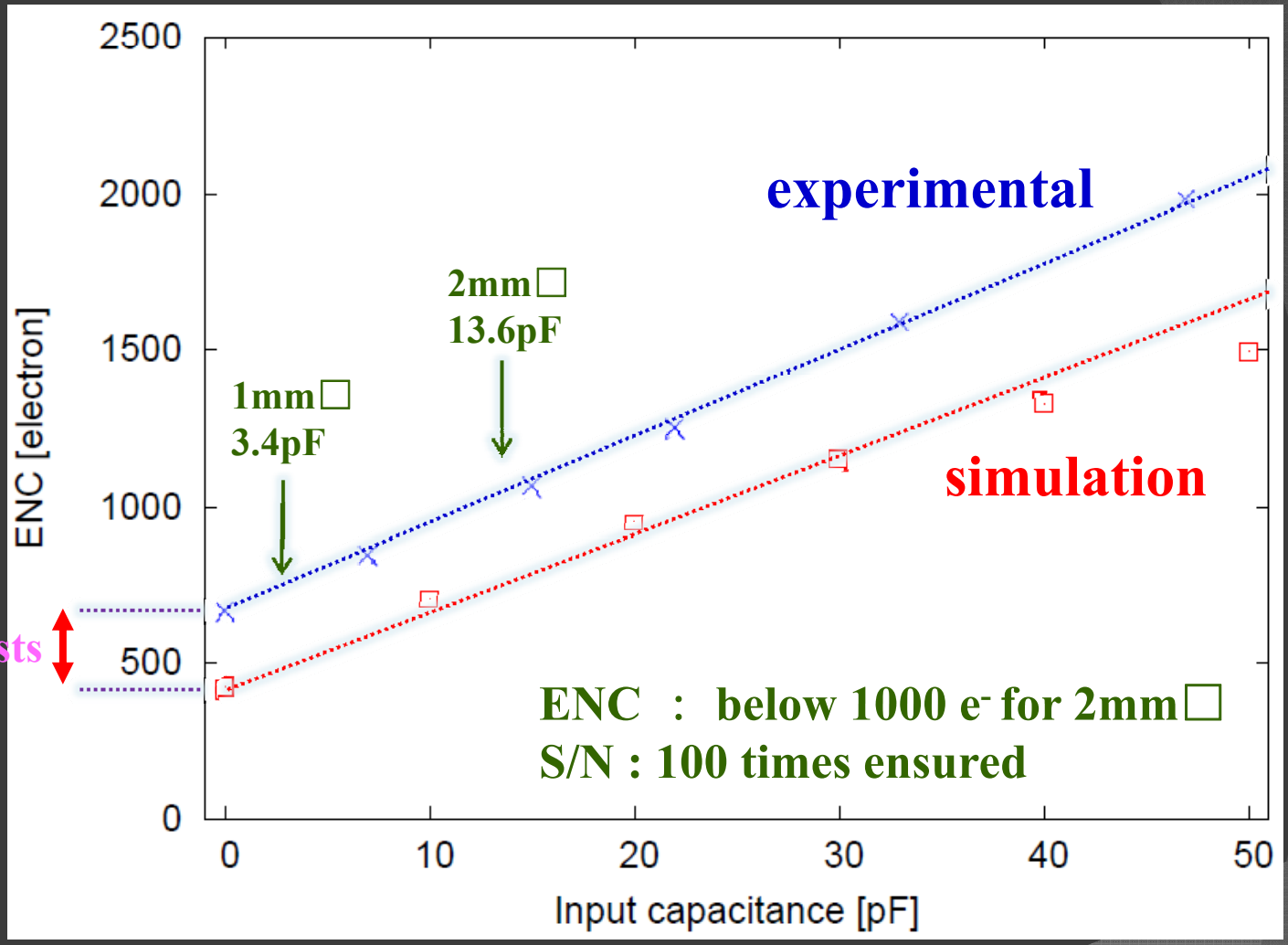


Experimental



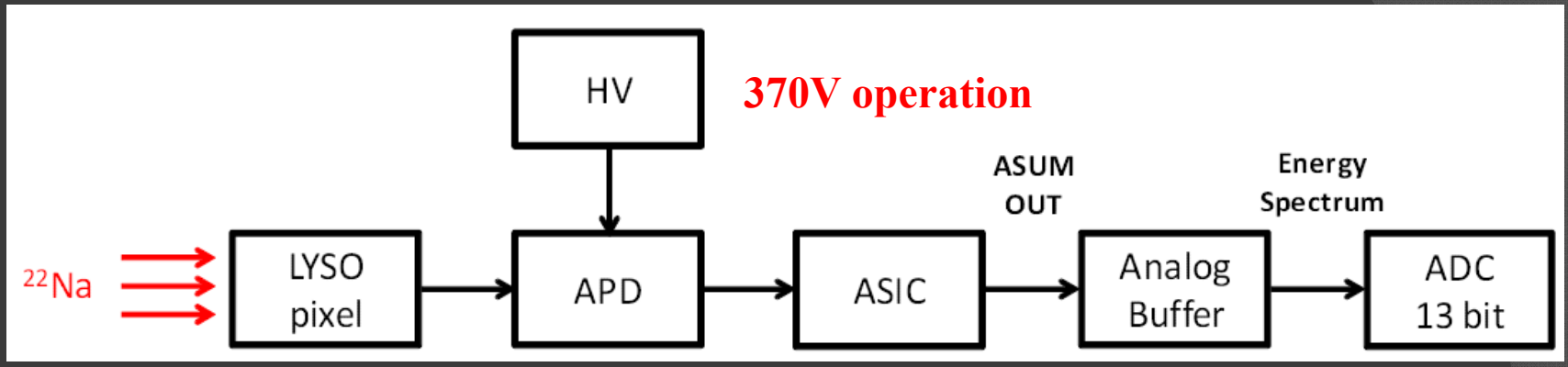
- Experimental waveforms were **consistent with simulation results**.
- Gain dispersion and offset voltages were **within adjustable ranges**.

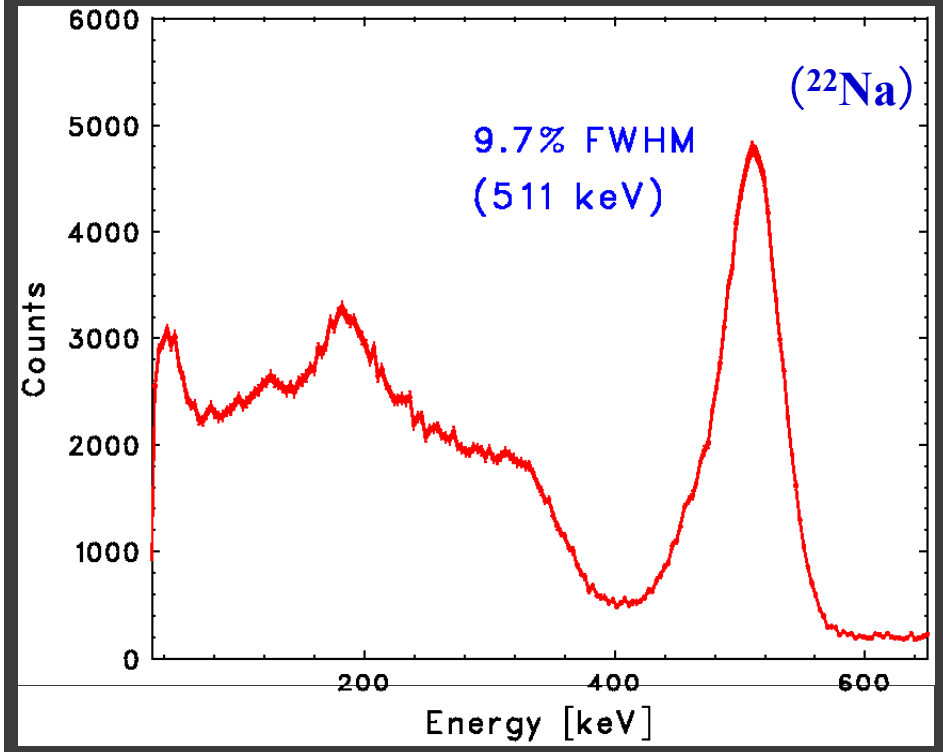
Experimental results : Noise performance



- Equivalent Noise Charge (ENC) : 600 e^- + 28 e^- / pF (RMS)
- Certain excess exists between experimental and simulation results.
  ⇒It might be the floating capacitance of a relatively large package.

Experimental results : Energy resolution

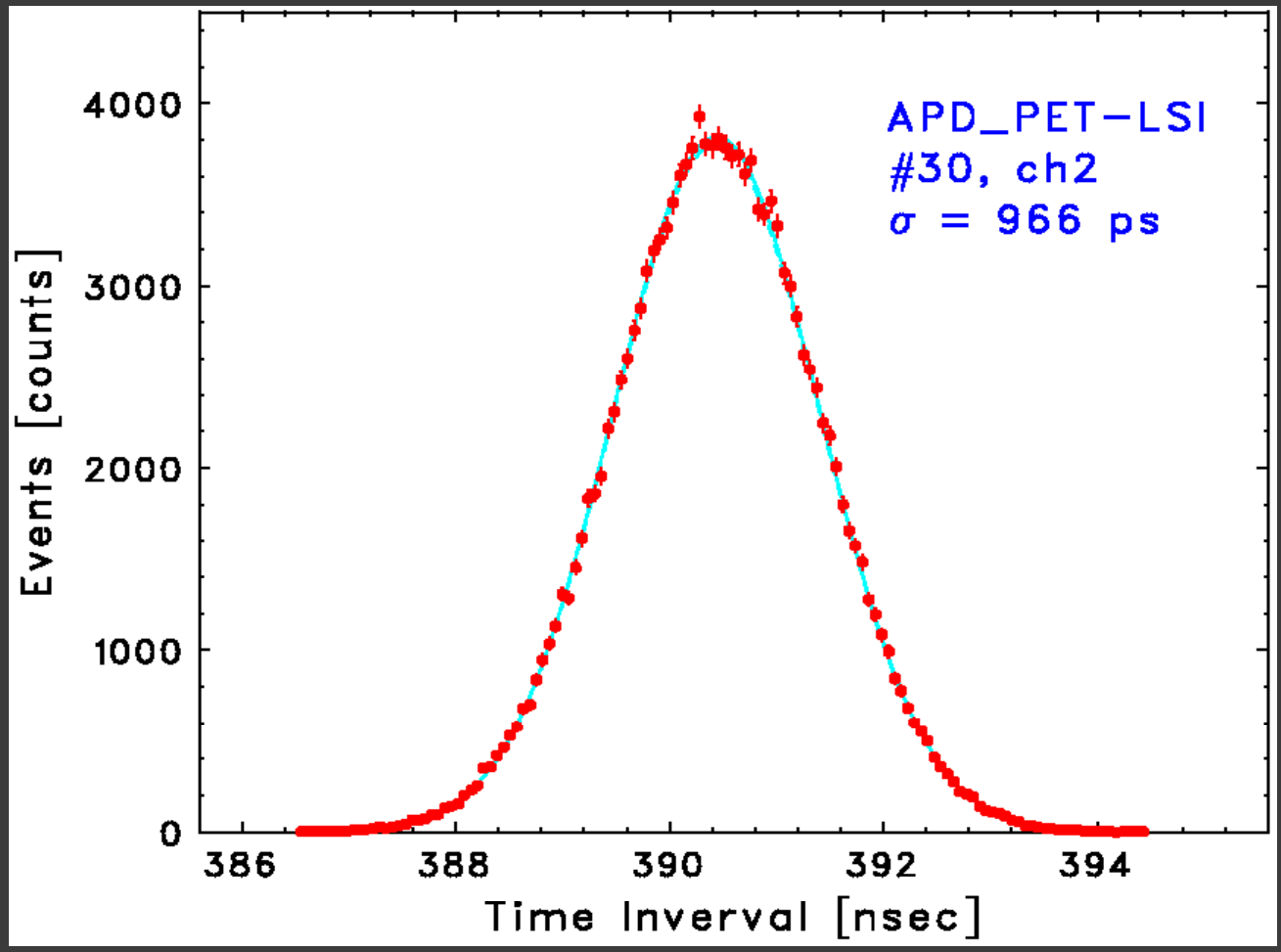




LYSO 2mm□ + **APD 2mm□** + **TIPPET08 No.30_ch2**

- **Resolution : 9.7 % (FWHM) @511keV**
  ⇒Sufficient performance for APD-PET

Experimental results : Time resolution

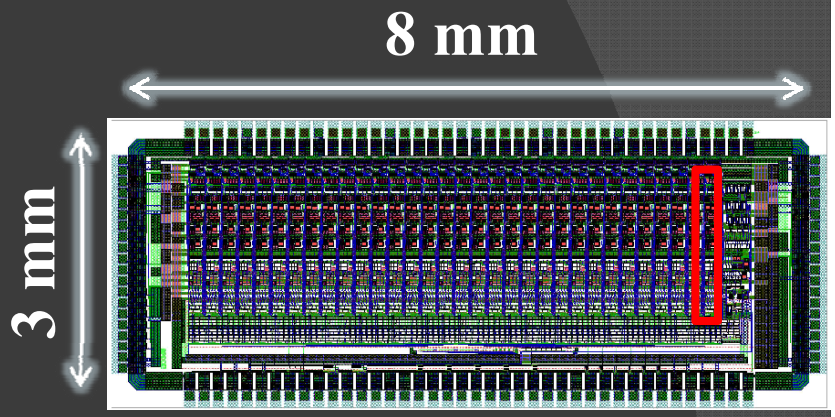


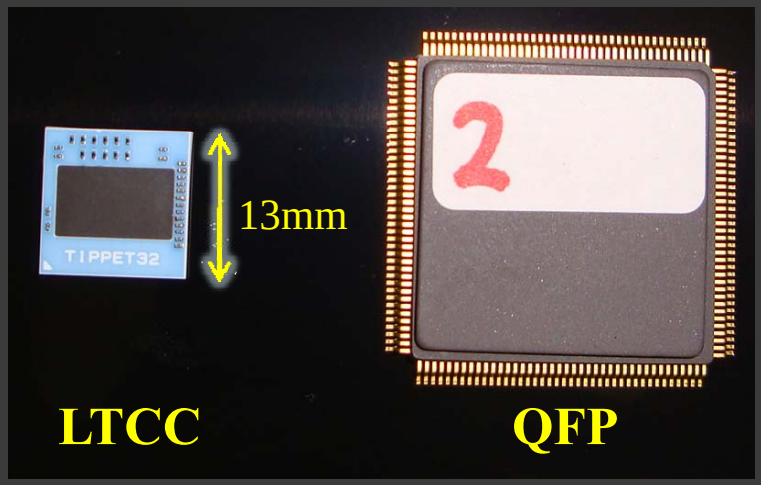
Time Resolution : 970 psec （RMS）
@0pF
⇒achieved by simple zero-cross method.

2nd version ASIC “TIPPET32”

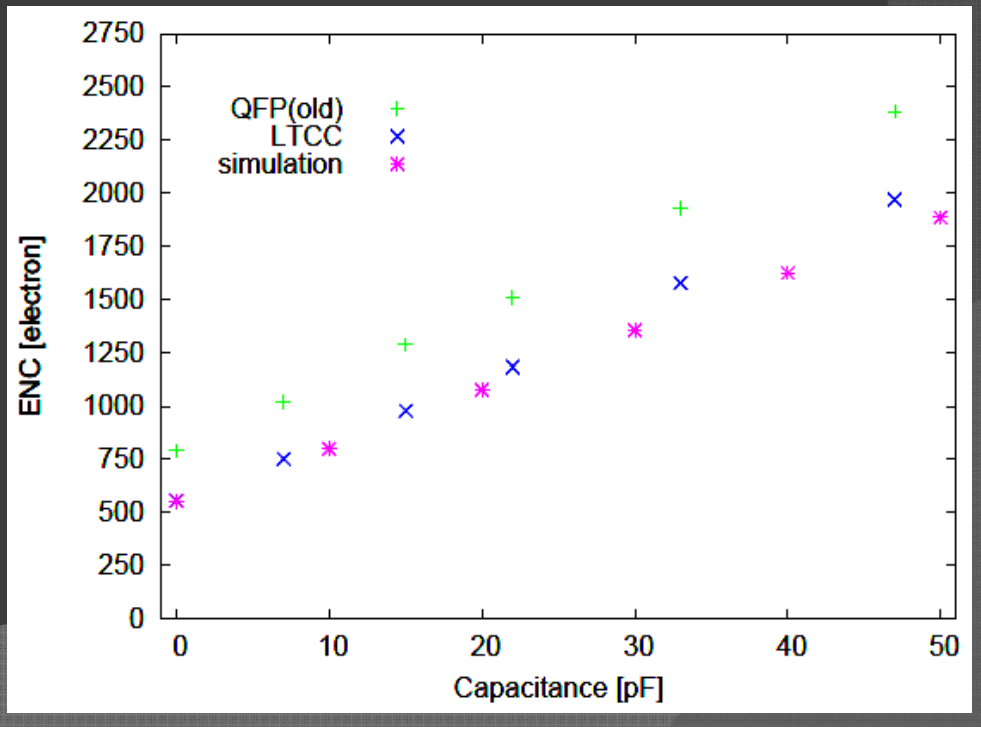
Main differences

- Number of channels : 8 ch → 32 ch
- Order of the shaper : 2 nd → 3 rd
- Time resolution : 970 ps → 570 ps
- Package : QFP → LTCC
- Polo-Zero-Cancellation (PZC)
- Priority chain encoder





Low Temperature Co-fired Ceramics package



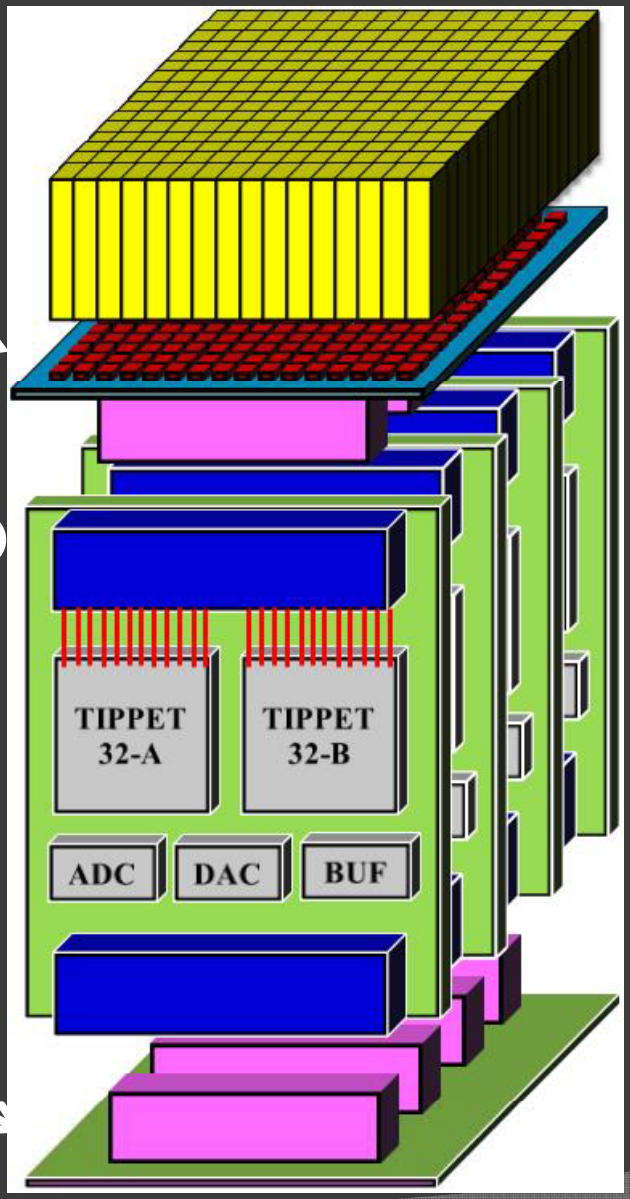
Mobile APD-PET unit

LYSO-array

APD-array

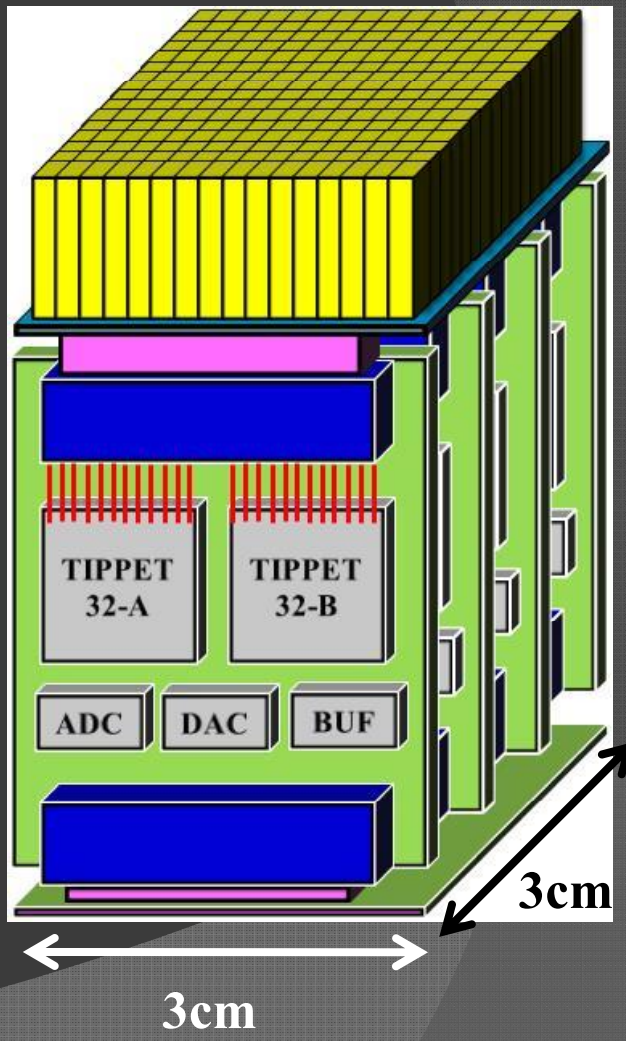
Front-end Card （FEC） ×4

Control Card （CC） ×1



All front-end processing are coverd

⇒It can be connected flexibly !!



Summary

Our goal is to realize a high-resolution, low-cost and multipurpose next-generation PET detectors.

TIPPET08 (1st version)

- We manufactured 8-channel analog ASIC optimized to APD
- Good energy resolution of **9.7%（FWHM） @ 511 keV with APD**
- Good time resolution of **970 ps（RMS） @0pF**
- Low-noise of **600 e^- + 28 e^- / pF** with low-power of **6.9 mW/ch.**

TIPPET32 (2nd version)

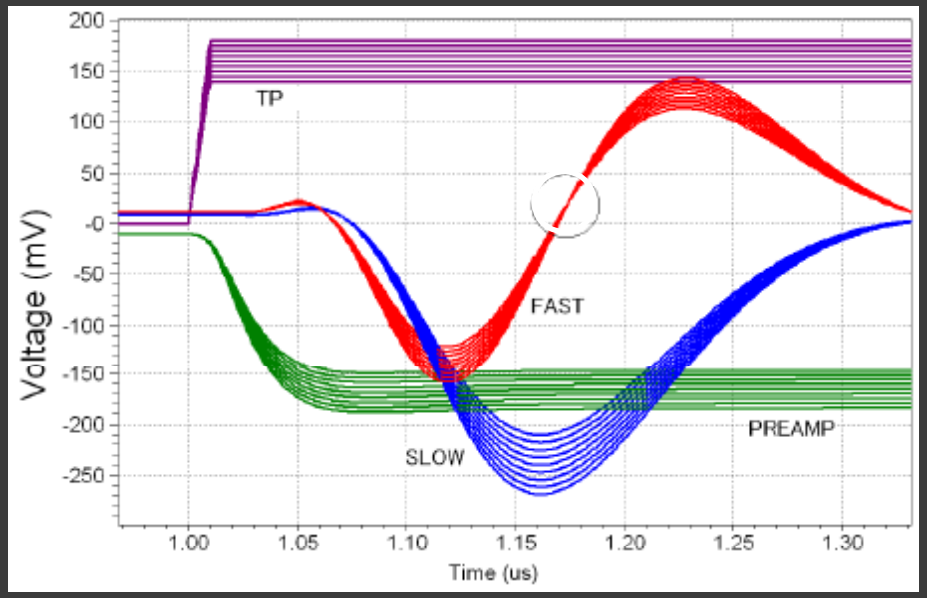
- We are now developing and evaluating 32-channel 2nd version ASIC
- Good time resolution of **570 ps（RMS） @0pF**
- Low-noise of **560 e^- + 30 e^- / pF** with low-power of **6.0 mW/ch.**

We plan to evaluate spatial resolution with one-pair unit

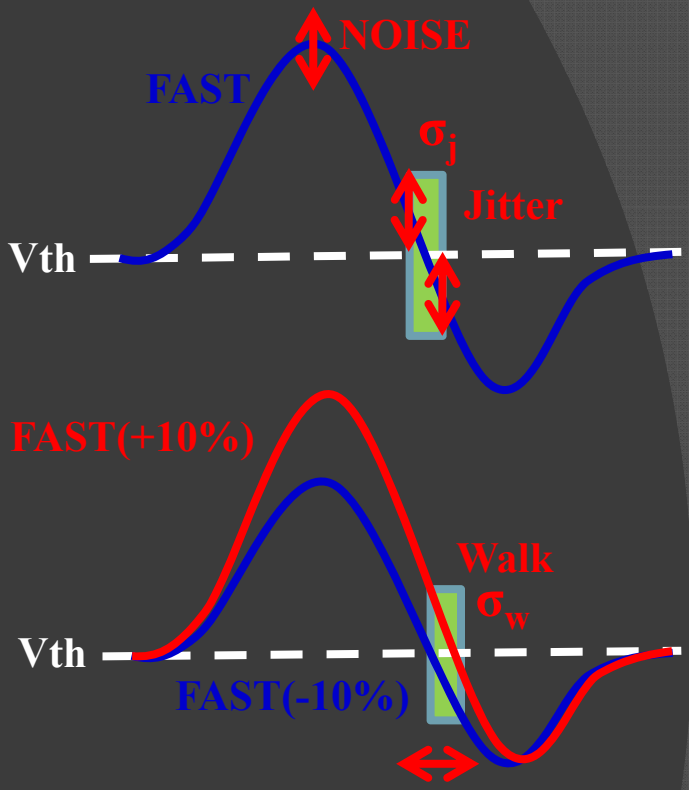
Thank you !

BACKUP

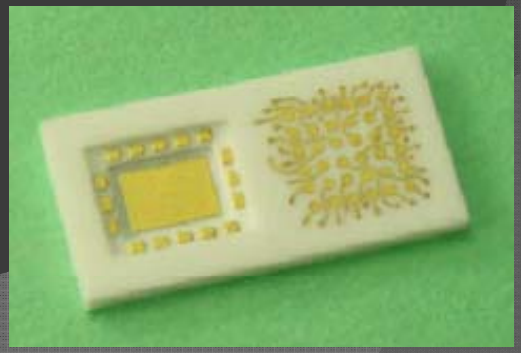
2nd version ASIC “TIPPET32”



Fluctuation of zero-cross point （511keV±10%）

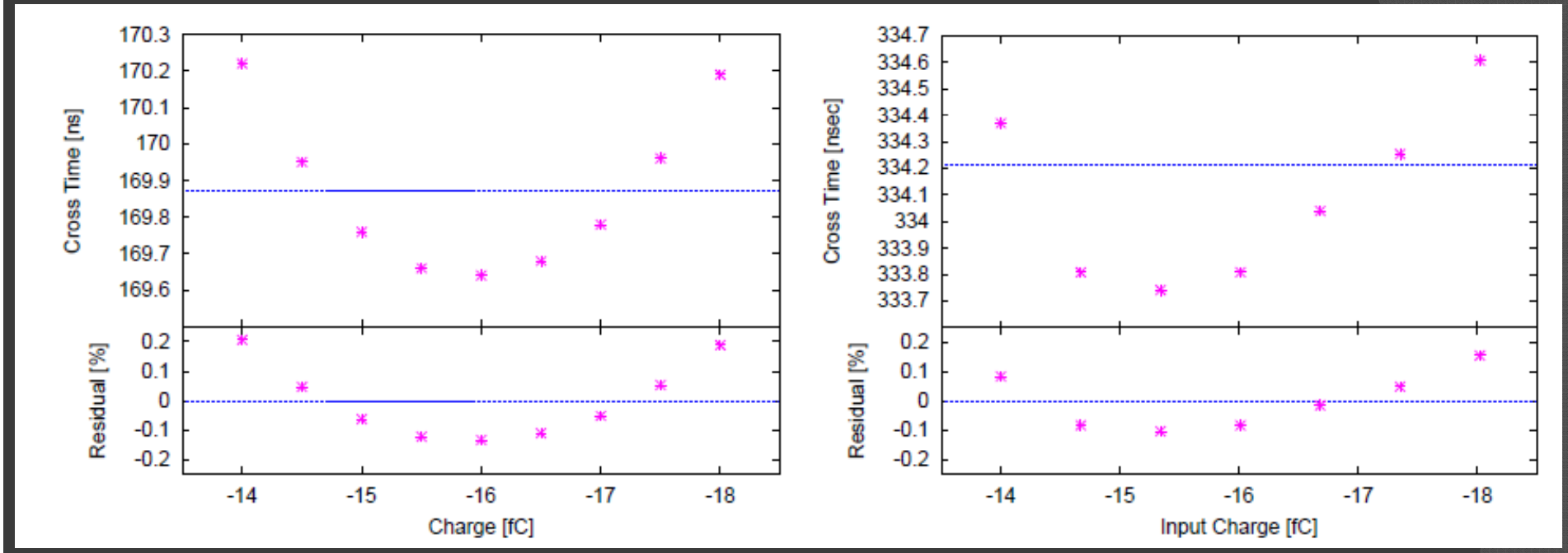


- 8ch (ver.1) → multiplied to 32 ch (ver.2)
- Largely improved time resolution
  - Δt_{jitter} ~ 970 ps → ~ 580 ps (ver.2)
  - Δt_{walk} ~ 600 ps → ~ 60 ps (ver.2)
- Low Temperature Co-fired Ceramics (LTCC) Package is specially used.



LTCC package（KOA）

Time walk

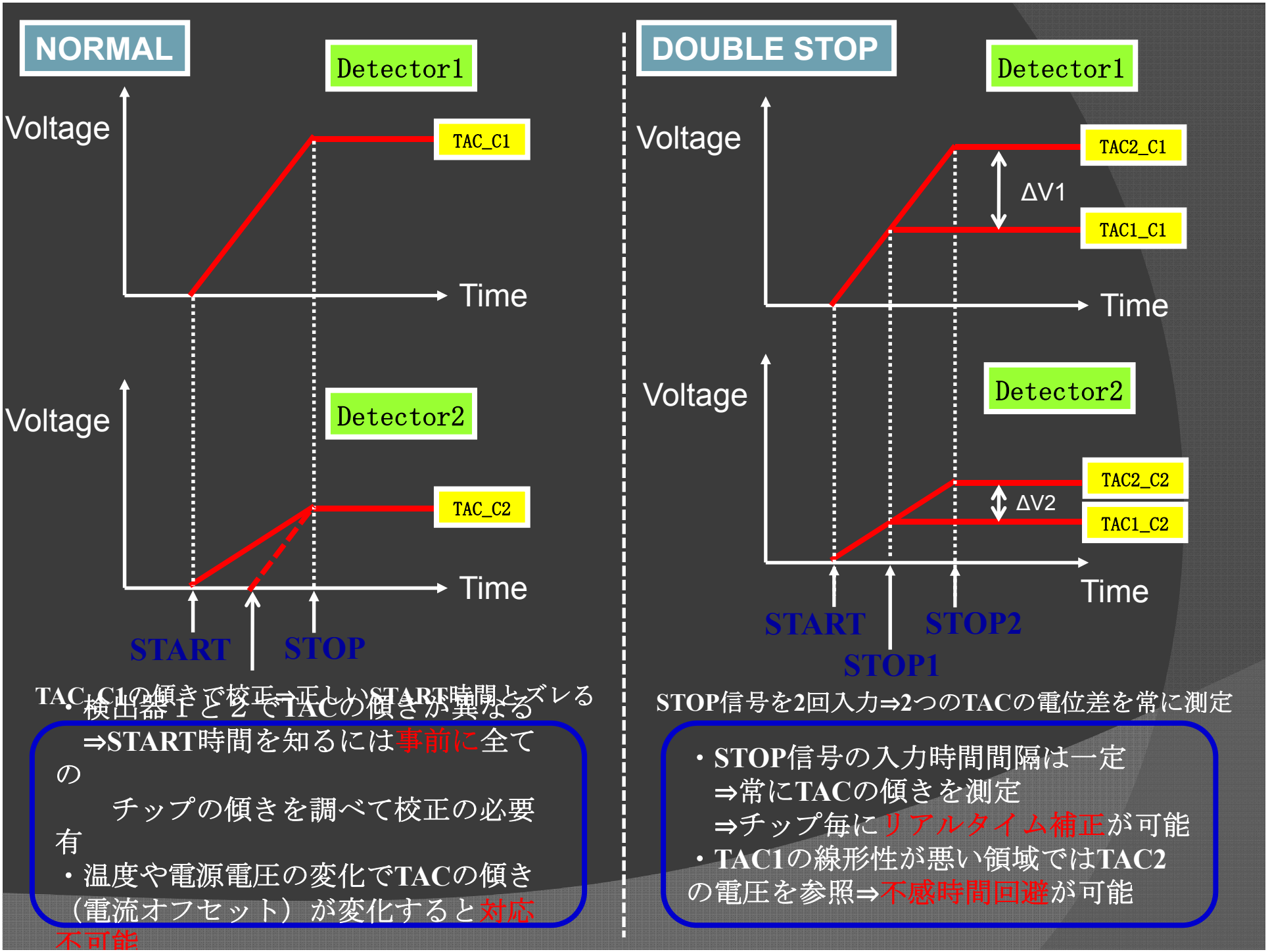


Simulation

600 ps (511 keV ±12.5%)

Experimental

870 ps (511 keV ±12.5%)



TAC_C1の傾きで校正⇒正しいSTART時間とズレる

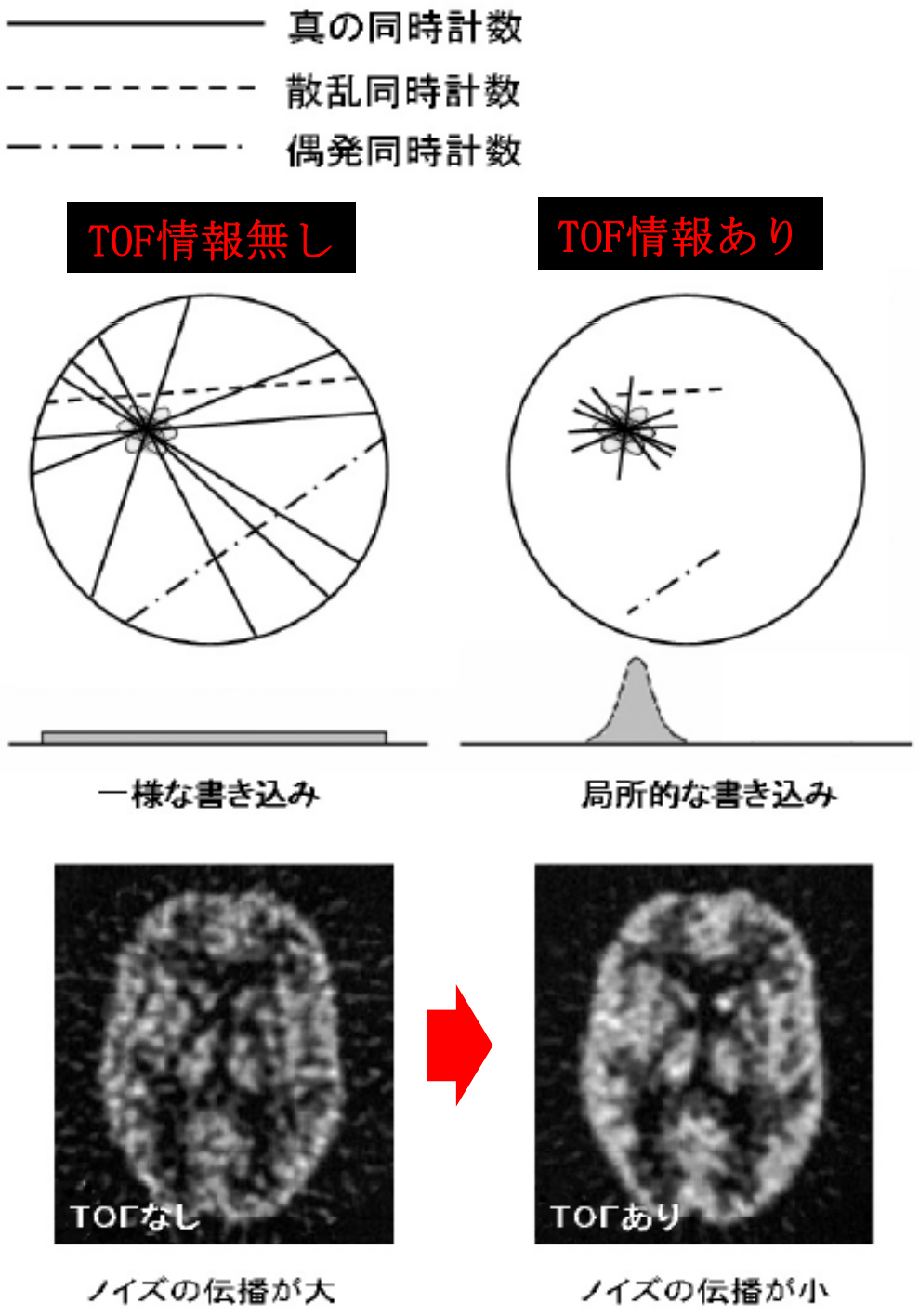
・検出器1と2でTACの傾きが異なる
⇒START時間を知るには事前に全てのチップの傾きを調べて校正の必要有
・温度や電源電圧の変化でTACの傾き（電流オフセット）が変化すると対応不可能

STOP信号を2回入力⇒2つのTACの電位差を常に測定

・STOP信号の入力時間間隔は一定
⇒常にTACの傾きを測定
⇒チップ毎にリアルタイム補正が可能
・TAC1の線形性が悪い領域ではTAC2の電圧を参照⇒不感時間回避が可能

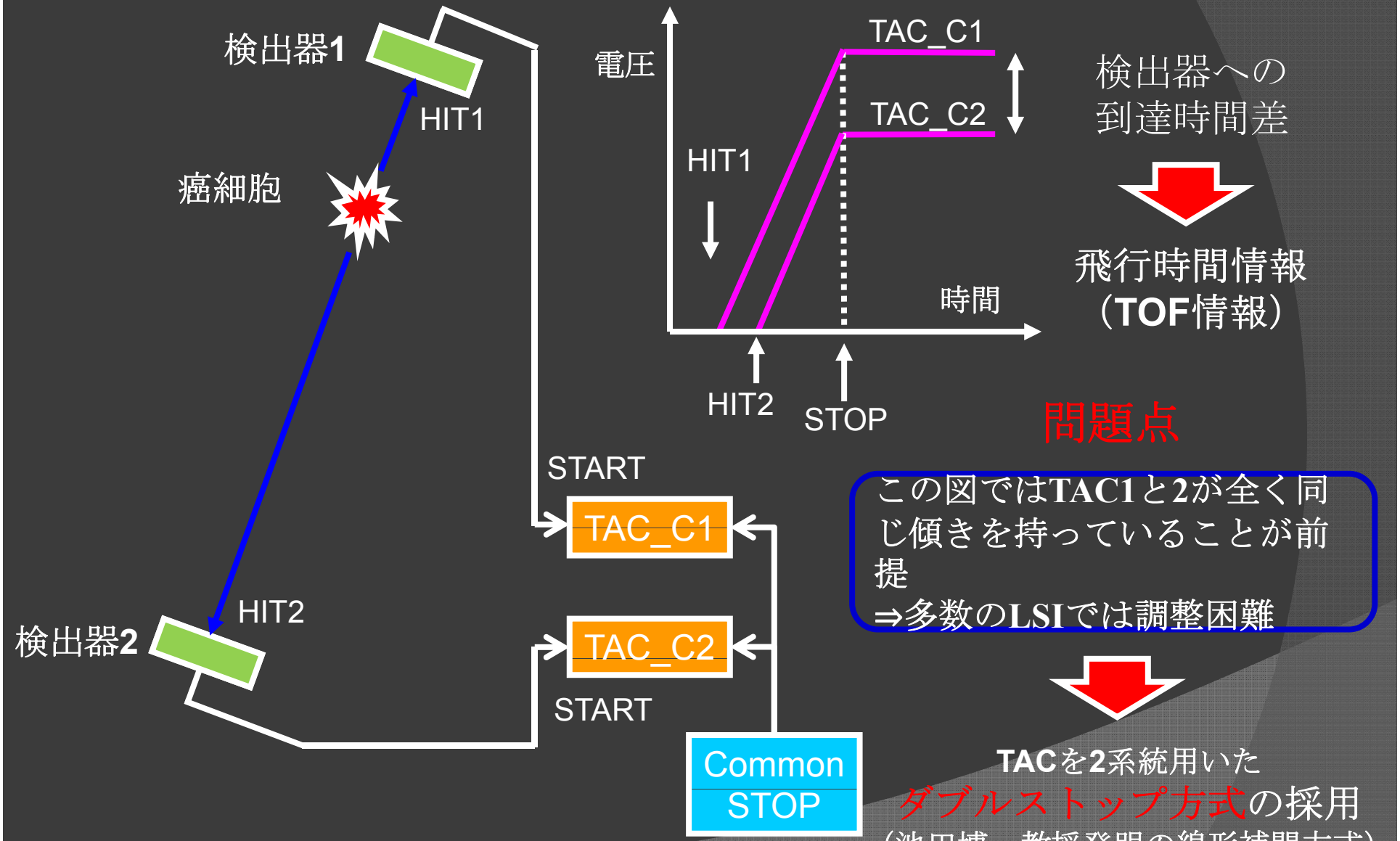
TOFについて

- **Time-of-Flight型PETは、感度を大幅に向上させる最先端の研究テーマ**
- **放医研 村山グループ（澁谷さんほか）による simulation**
- **400 psec (~12cm相当) の TOF 情報があるだけで PET 画像は格段にクリア**
- **2006年にPHILIPSが実用化 LYSOシンチレータ＋PMTで時間分解能～650 ps**



ガンマ線飛行時間測定の原理

TAC回路：START入力からSTOP入力までの経過時間に比例した電圧を出力



検出器への到達時間差

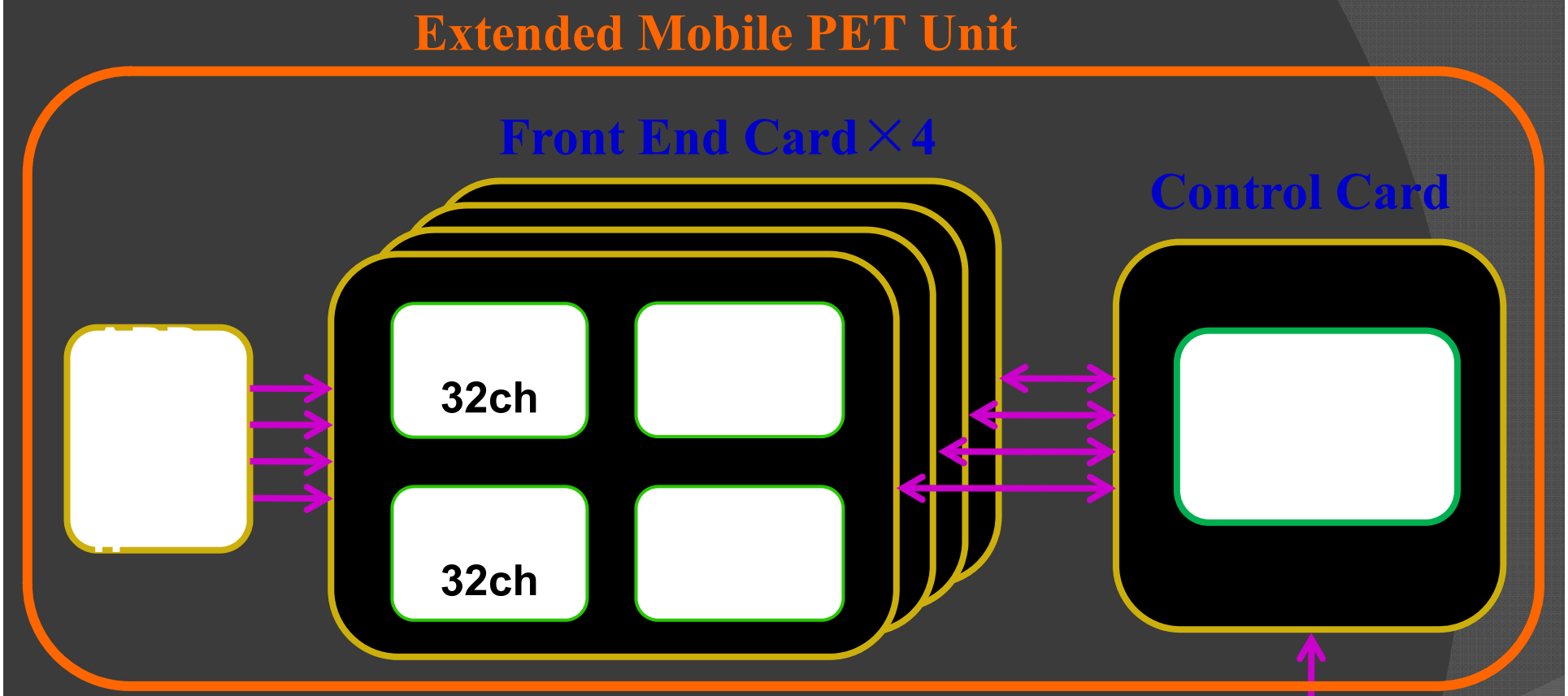
飛行時間情報（TOF情報）

問題点

この図ではTAC1と2が全く同じ傾きを持っていることが前提
⇒多数のLSIでは調整困難

TACを2系統用いた
ダブルストップ方式の採用
（池田博一教授発明の線形補間方式）

APD-PET用LSIver.2：PETシステム全体図

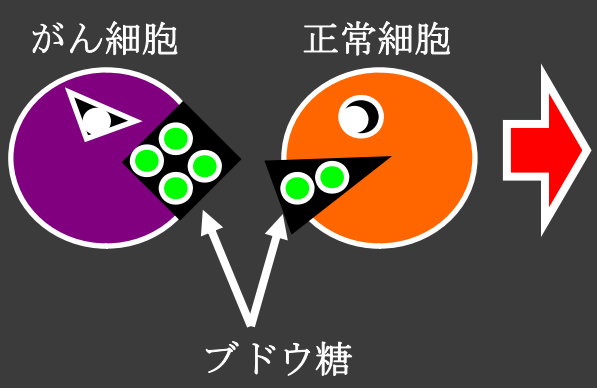


- FEC1枚あたり2chipを搭載し、64 ch分を担当
- CCのFPGAでFEC4枚分、APD 256 ch分を一括処理し、同時計数回路への橋渡しを行う

PET = Positron Emission Tomography

⇒陽電子放出核種を用いた最新のがん検査法

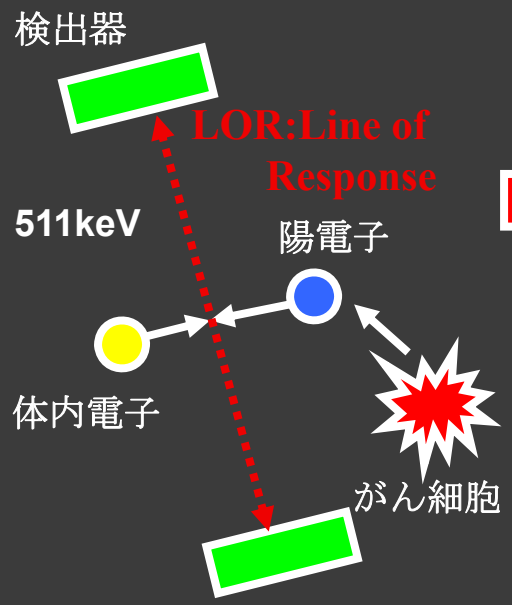
がん細胞は
ブドウ糖が大好物



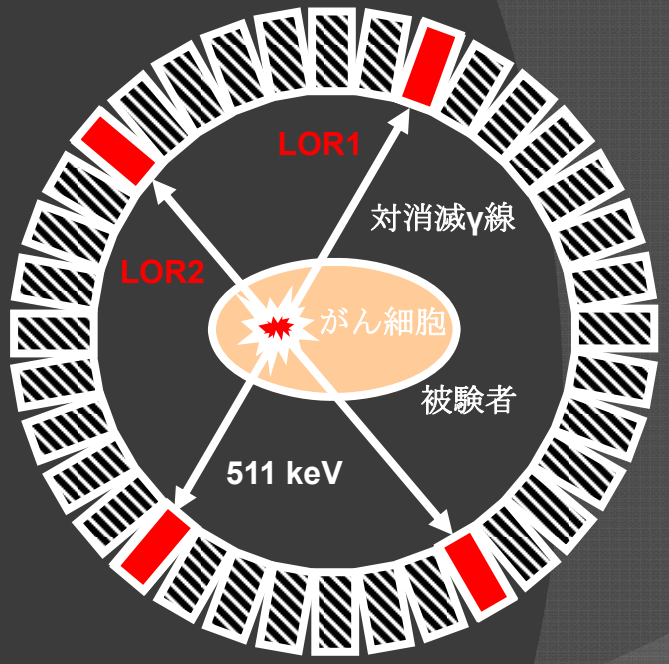
ブドウ糖と陽電子放出核種を合成して注射

FDG:フルオロデオキシグルコース

対消滅γ線をキャッチ



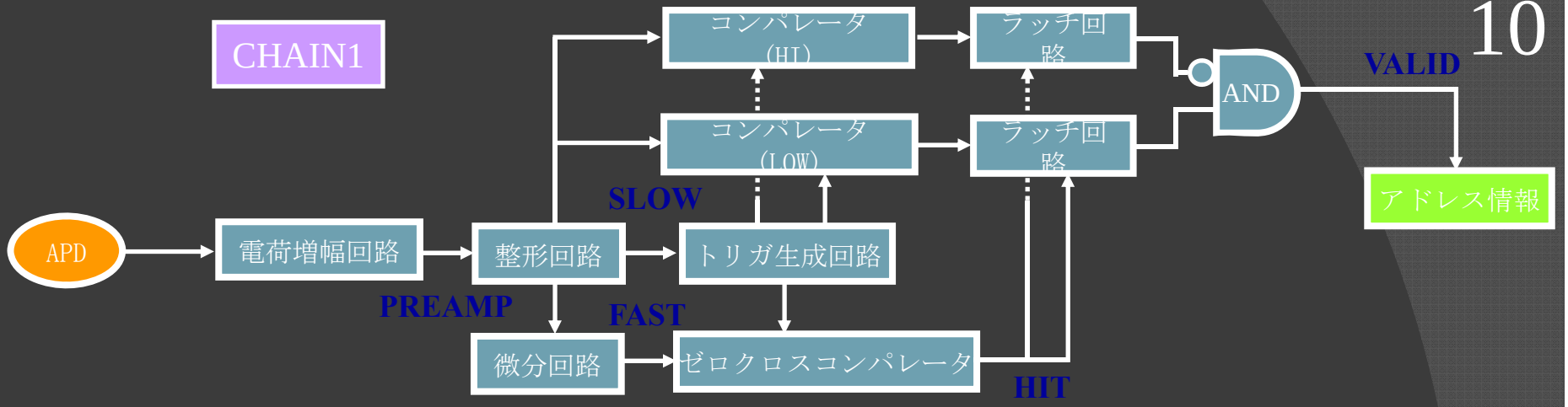
がんの位置情報



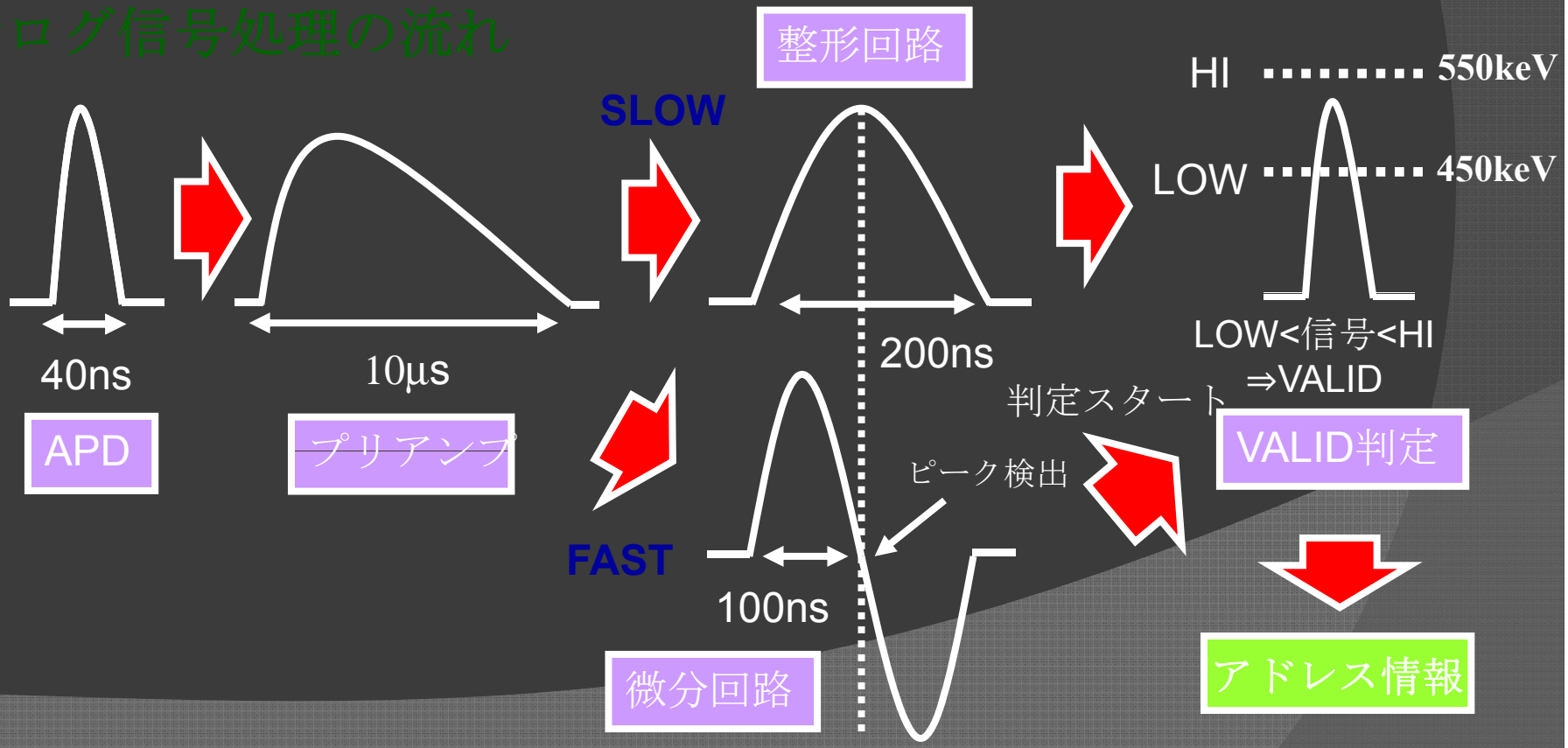
PETの利点

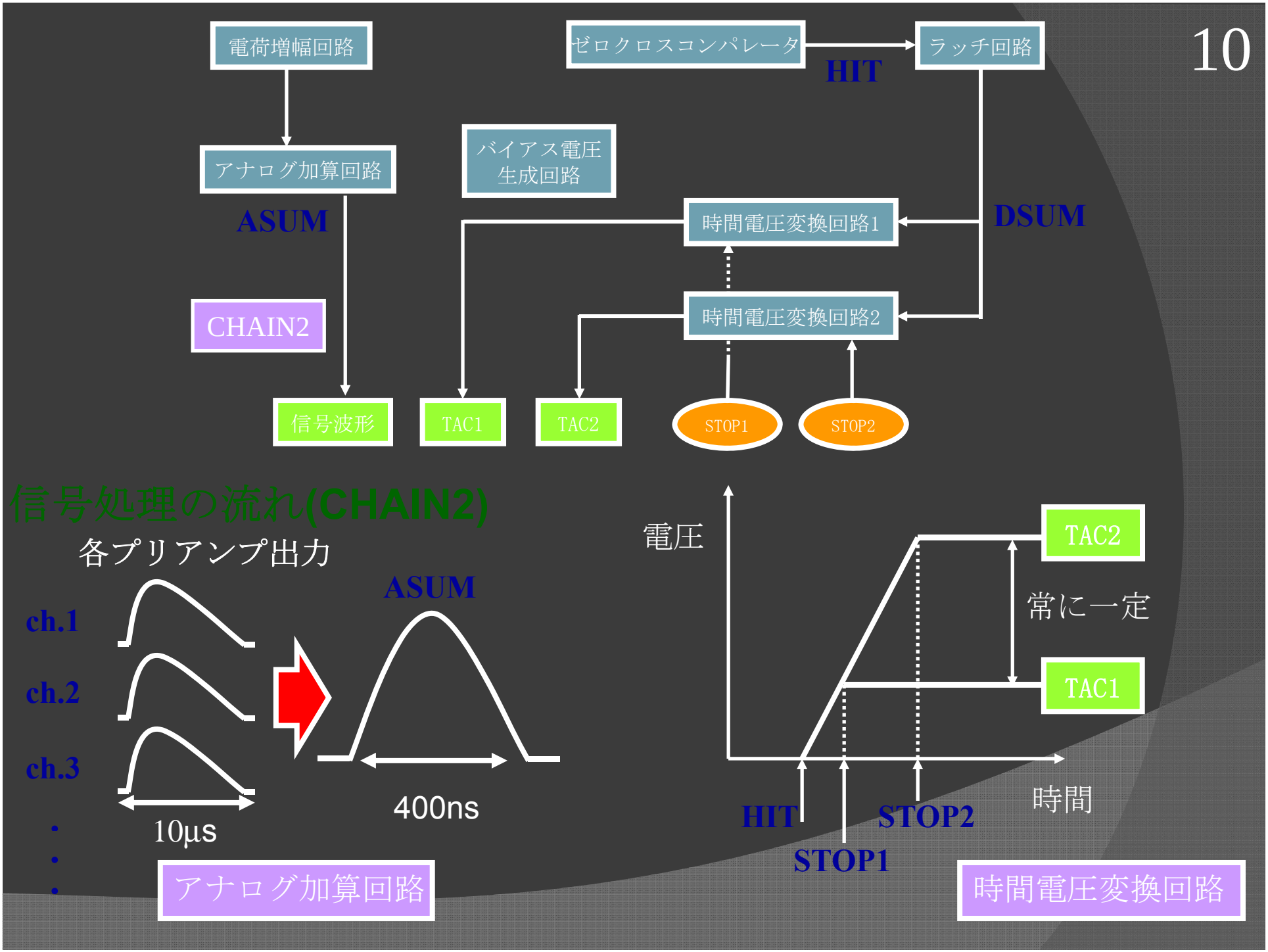
- コリメータが不要　⇒ 低被爆量
- 癌の活動性/悪性度⇒ 機能画像
- 全身を一度に検査 ⇒ 早期発見

積極的に使いたい！
しかし・・・



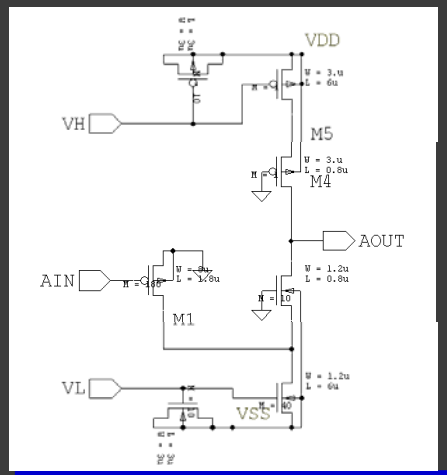
アナログ信号処理の流れ

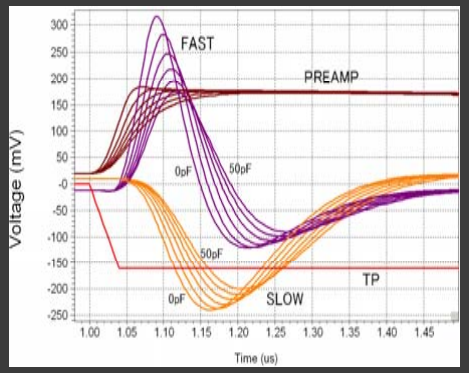


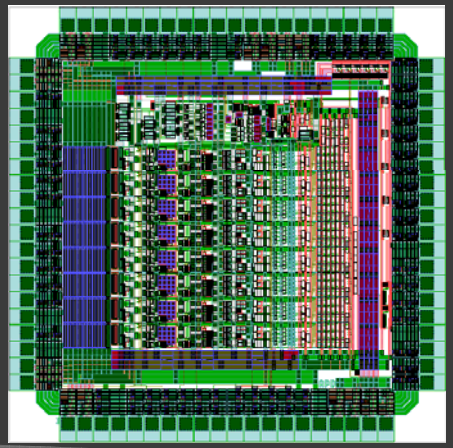

電荷増幅回路
ゼロクロスコンパレータ
HIT
ラッチ回路
アナログ加算回路
バイアス電圧
生成回路
ASUM
時間電圧変換回路1
DSUM
CHAIN2
時間電圧変換回路2
信号波形
TAC1
TAC2
STOP1
STOP2
信号処理の流れ(CHAIN2)
各プリアンプ出力
ASUM
ch.1
ch.2
ch.3
10μs
400ns
アナログ加算回路
電圧
TAC2
常に一定
TAC1
HIT
STOP1
STOP2
時間
時間電圧変換回路

・多チャン　ル化による信号数の増加⇒大　　な処理回路が必要
・新しい検出器であるAPDに対応したLSI⇒ほとん　　しない

APD-PET　用LSIの　発が必要







LSI　発ス　　ール（ver.1）

計　　（2006/10　）

・Open-IPを利用
・回路シ　　レーシ　ン　　3

レイアウト

・シリコン　　上に
回路をレイアウト　　2

（TSMC
）

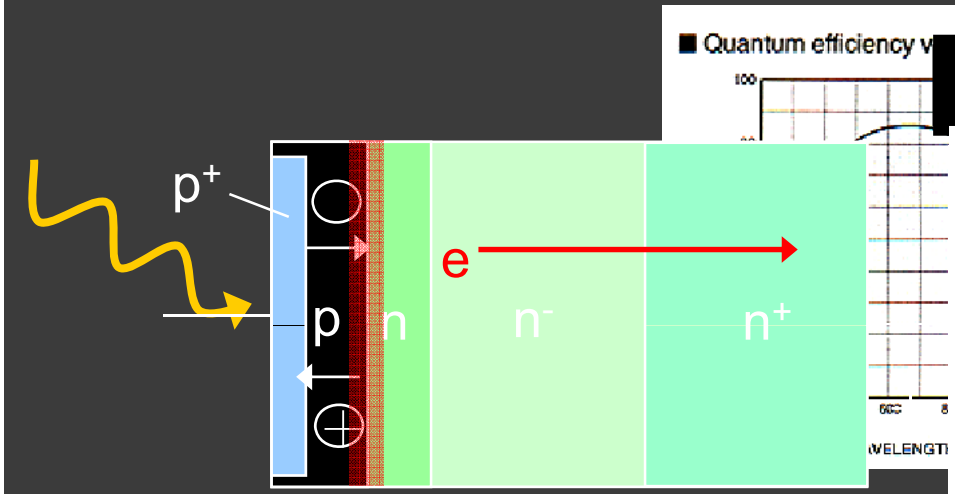
・　アチップをパッ　ー
・　ンデ　ングの　　3

（2007/5　　）

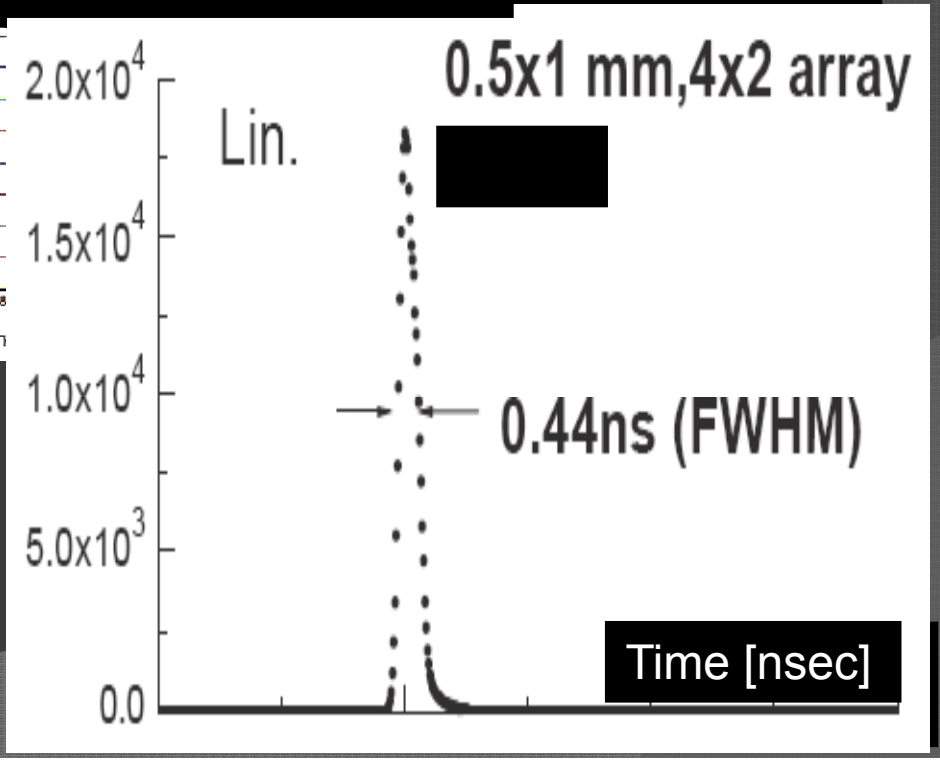
トータル8　　で　　成！

検出器：　　ト　クス APD

- 信号増幅する（G~50-100）フ　トダイオード
- コンパクト、低消　電力、　　に　い
- 500-800 nm の波　域で量子　　80%
- 　い時間応　（　ブ・ナ　　）➡ PMT+PD の　　を　　る

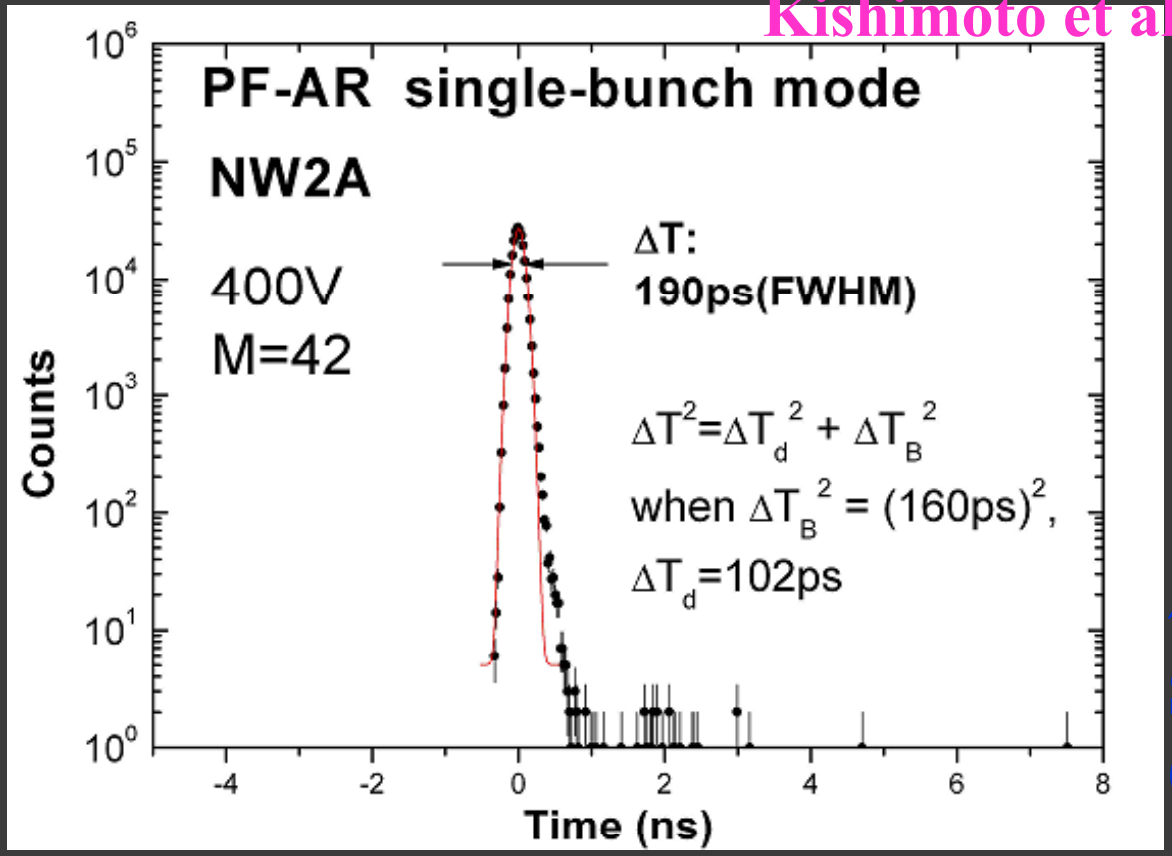


Kishimoto et al. 2003



APDの時間　性（TOFに向けて）

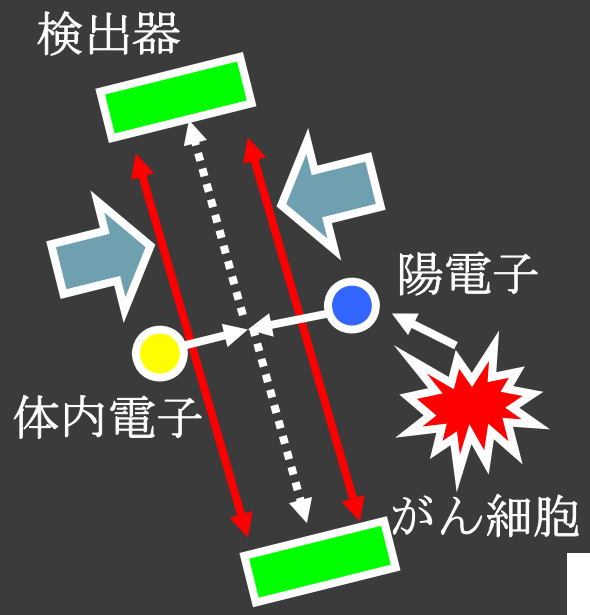
Kishimoto et al. 08



使用APD
S8664-30N
(リバース型)

- 研放射　(PF-ARリング)・シングルバンチでの測定
  (BL-14A　　先生の　　)
  → APD　体としての時間応　は　ΔT = 102 ps

PETの



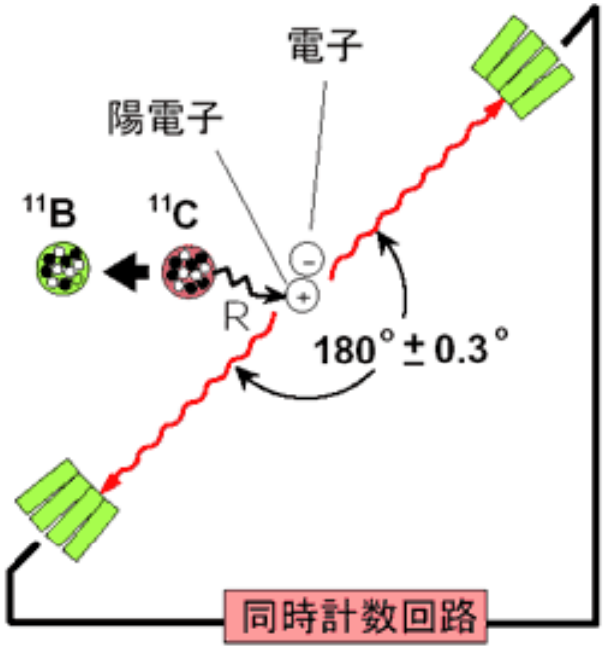
検出器の　イズ

検出器間距離	誤差 (FWHM)
50 cm	1.5 mm
100 cm	3.0 mm

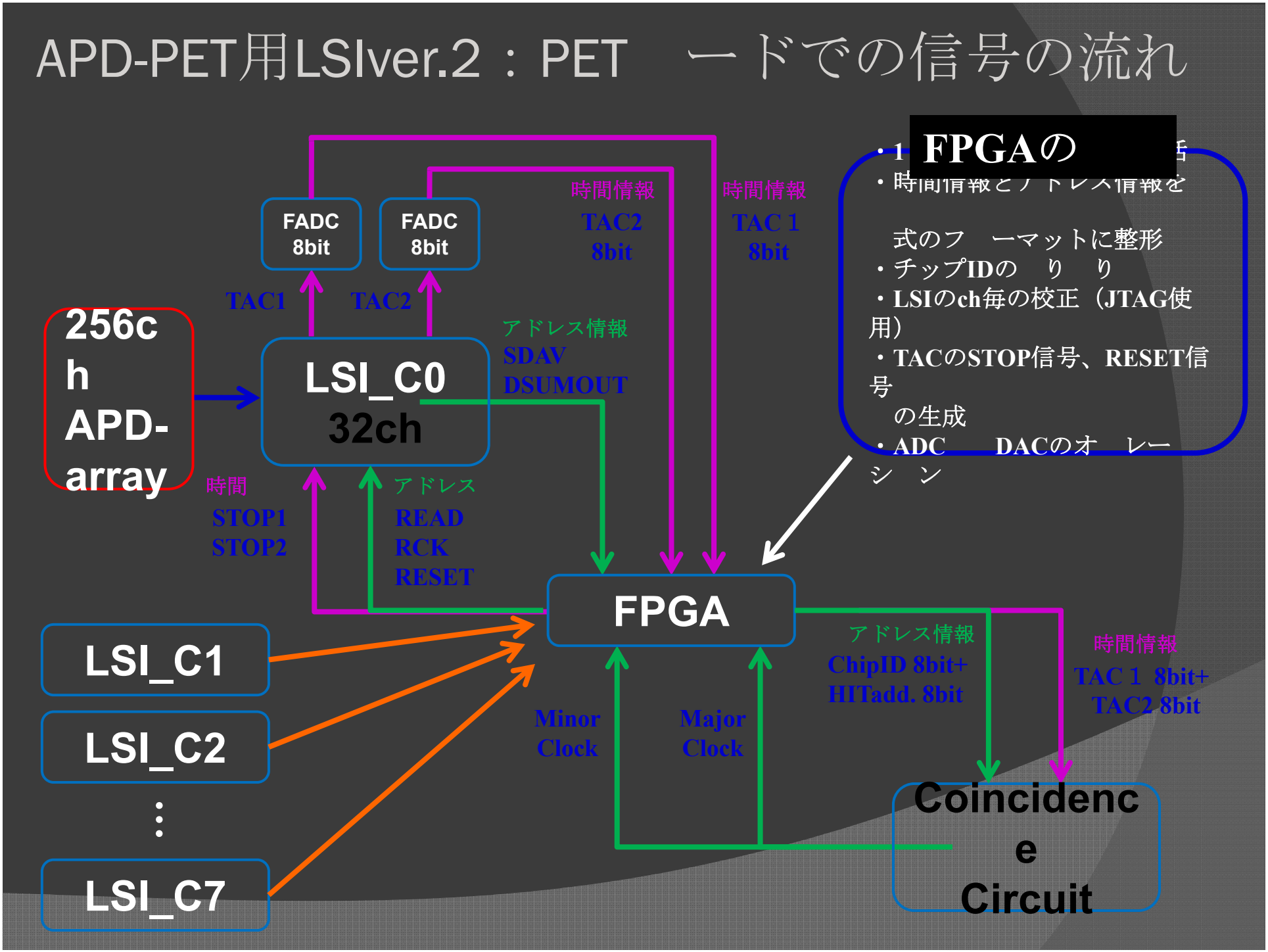
ガンマ線の　度　動

核種	陽電子の最大エネルギー (MeV)	誤差 R
^{11}C	0.961	0.28 mm
^{13}N	1.20	0.60 mm
^{15}O	1.73	1.1 mm
^{18}F	0.634	0.22 mm
^{68}Ga	1.90	1.4 mm

体内に　ける陽電子の飛

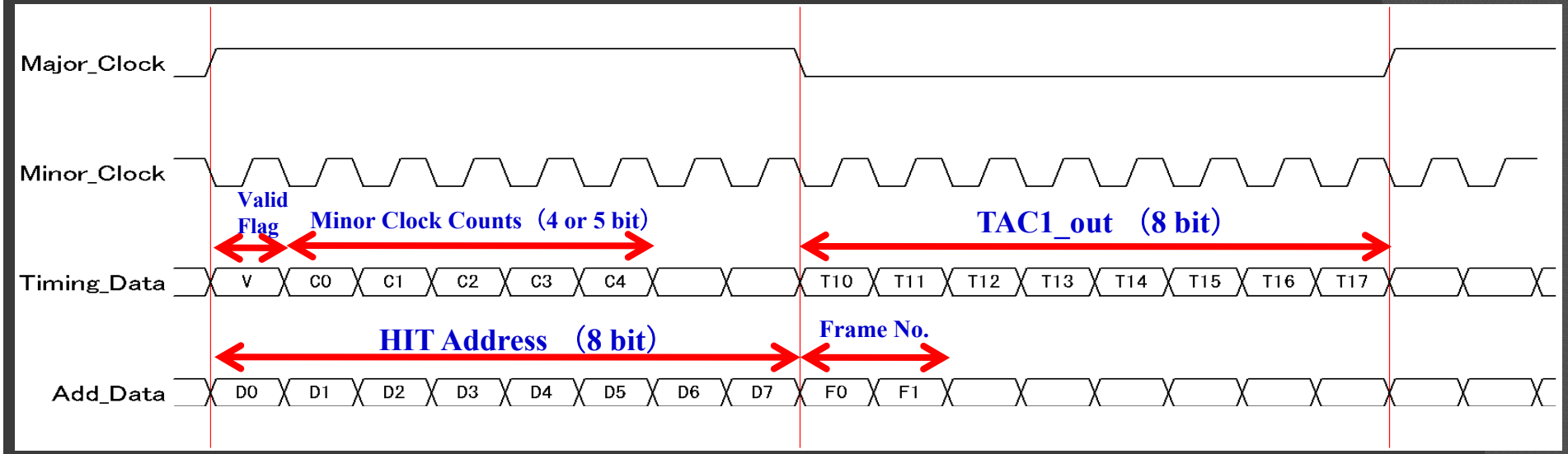


APD-PET用LSIver.2：PET　ードでの信号の流れ

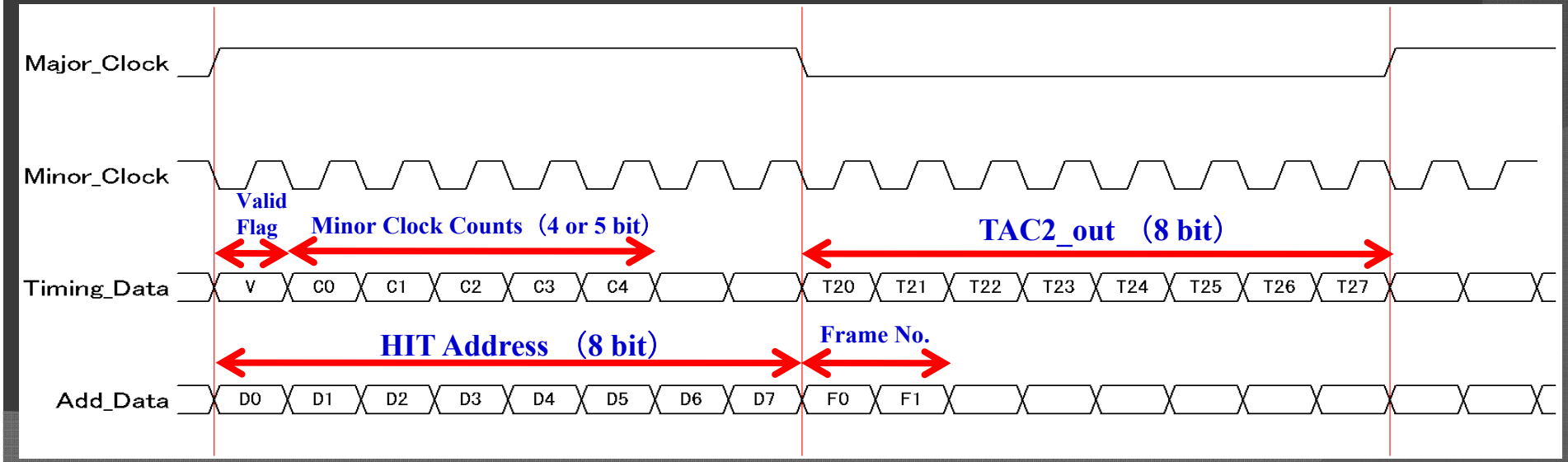


Coincidence Detector Input Format

Frame 1

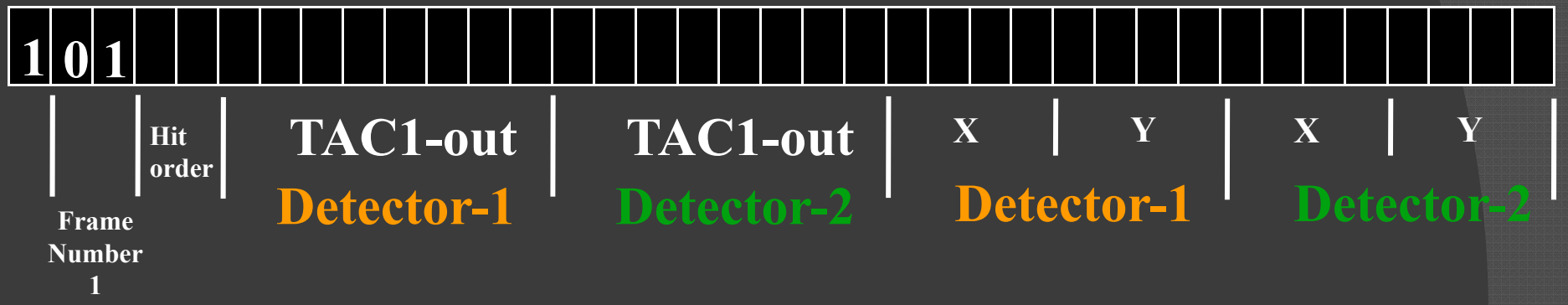


Frame 2



Coincidence Detector Output (IJ-data) Format

Frame 1



Frame 2