A Time Driven Readout Scheme
For PET and CT...

...using APDs and SiPMs
Outline of Presentation

• Why a new readout technique?
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- Why a new readout technique?
- The “Time Based” approach.
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• The “Time Based” approach.
• APD detector & TB readout.
• TOF capability?
• SiPMs and TB readout.
• Summary.
Clinical goals:

- **Multimodality**: CT, PET, MRI, US, ...
  - Reduce patient exposure time;
  - Compensate for patient/organ motion;
  - Facilitate image fusion (PET/CT);
  - Simultaneous imaging of tumor response and responsiveness, as well as dose delivery in vivo.
Why a New Readout?

• Clinical goals:
  – Multimodality: CT, PET, MRI, US, ...
    • Reduce patient exposure time;
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    • Facilitate image fusion (PET/CT);
    • Simultaneous imaging of tumor response and responsiveness, as well as dose delivery in vivo.

• Technical goals (“From HEP to PET”):
  – Use technologies & techniques devel’d for HEP
    • State-of-the-art electronics;
    • Compact and reliable data processing;
    • System integration and cost.
Why “Time” Based?

- Leads to simple readout architectures:
  - Only digital pulses ⇒ simple electronics
  - No flash ADCs (running at > 500MHz, power)

- Simple timing circuits:
  - Need only discriminators and TDCs;

  → Derive time and energy information from one digital pulse.
    - Time over threshold (T.o.T.), pulse width modulation;

- Build on in-house experience from large experiments.
Time Based Readout: How?

P.A. \( \Rightarrow \) i(t) \( \Rightarrow \) Discr. \( \Rightarrow \) V(t)

FEDC05

NINO

Threshold

\( V(t) \)

\( i(t) \)

\( t \)
Time Based Readout: How?

LSO-like Test Pulse

FEDC05

P.A.

\( i(t) \)

Discr.

\( V(t) \)

Threshold

\( i(t) \)

\( V(t) \)

Time Walk

\( t \)
Time Based Readout: How?

LSO-like Test Pulse

P.A.

FEDC05

Discr.

NINO

i(t)

V(t)

Threshold

Time Walk

i(t)

V(t)

2009 Pisa Meeting on Instrumentation
La Biodola, Italy - May 24 - 30, 2009
Time Based Readout: How?

Timestamp from leading edge after time walk correction. Photon energy from falling edge (pulse width). Need only discriminator and TDC for both.
**FEDC05 chip:**
- Preamplifier developed for ATLAS Silicon Tracker
- 400 electrons ENC (r.m.s.)
- Gain = 4mV/fC
- 16 channels
- 13ns peaking time

**NINO chip:**
- Very fast discriminator (3GHz BW)
- Signal peaking time: <1ns
- Output time jitter: \(\leq 25\)ps
- 8 channels
- Power consumption: 27mW/ch.
The NINO Chip

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"SPICE" of Readout Chain

LSO-APD Pulses

FEDC05 Output

NINO output (+)

Time Stamp

Energy

Hamamatsu S8550

FEDC05 (ATLAS)

NINO (ALICE - TOF)
Energy Resolution & Dynamic Range With APDs & NINO

- 57Co (122keV)
- 176Lu Background

Raw data
[Pulse Width]

Corrected data
[Charge/Energy]

Look-up Table

Linearity after correction

Energy resolution

- 22Na (511keV, 1275keV)
- 137Cs (662keV)

Raw data [Pulse Width]

Look-up Table

Corrected data [Charge/Energy]

Linearity after correction

Energy resolution

- 57Co
- 22Na
- 137Cs

Energy resolution

- $y = 775.54x$
- $R^2 = 0.9979$
Timing Resolution With APDs & NINO

- How “fast” are APDs in the time encoded ‘NINO’ setup?
- What are the limitations?
- What are the alternatives?
- The road to TOF-PET…
Timing Resolution With PMT (Reference)

No corrections applied; CFD is free of Time Walk.

470ps FWHM
Timing Resolution With PMT–APD

Photo-peak Selection
And
Time Walk Correction
on APD Setup

470ps FWHM

1180ps FWHM
Timing Resolution With Dual APD

Photo-peak Selection
And
Time Walk Correction
on both APD Setups

Raw data
After photo-peak selection
+ Time walk correction

470ps FWHM
1180ps FWHM
1600ps FWHM
1. Front end electronics noise together with the APD dark current contribute ~ 20% to the total time jitter.
Time Jitter of Detector and Readout

\[ \sigma_{\text{Total}} = \sqrt{\sigma_{\text{crystal}}^2 + \sigma_{\text{APD}}^2 + \sigma_{\text{electr}}^2} \]

1. Front end electronics noise together with the APD dark current contribute \( \sim 20\% \) to the total time jitter.
2. Non-uniformities in avalanche amplification in the APD account for \( \sim 30\% \).

<table>
<thead>
<tr>
<th>TOTAL</th>
<th>Crystal</th>
<th>APD</th>
<th>Electronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>340</td>
<td>230</td>
<td>220</td>
</tr>
<tr>
<td>1130</td>
<td>800</td>
<td>540</td>
<td>517</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>30</td>
<td>20</td>
</tr>
</tbody>
</table>

[ps] rms  [ps] FWHM  [%]
1. Front end electronics noise together with the APD dark current contribute \(~ 20\%\) to the total time jitter.

2. Non-uniformities in avalanche amplification in the APD account for ~ 30\%.

3. The principal jitter component of the total jitter is attributed to
   a) the Poisson-like photon production in LSO within the crystal decay
time of 40\text{ns}, and
   b) the high threshold sensitivity of the APD being N \sim 20\text{ p.e.}
      (R = 2200\text{ p.e.}, t_N = 340\text{ps}, \tau = 40\text{ns})
From HEP we know:
- Event patterns congested by background;
- “Space” points help to remove confusion and improve reconstruction efficiency;
- Charge division, Stereo view, delay lines, cathode readout are known methods;

In PET similar problems arise:
- Count rate contaminated with scattered and random photons;
- TOF reduces randoms and increases sensitivity.

\[ \text{NECR} = \frac{T}{1 + \frac{S}{R} + \frac{2R}{T}} \]

(D denotes patient diameter)

```
TOF timing (psec)  SNR squared
0    300   600    900    1200    1500    1800
1.0  1.5   2.0   2.5   3.0   3.5   4.0

Lesion Detectability
```

```
D = 27cm
D = 35cm
APD
SiPM
“S”catter
“R”andom
“T”rue
```

“Space” coordinate from \( t_2 - t_1 \)
100ps \( \rightarrow 15 \text{mm} \)
SiPMs (MPPCs, etc.)…
• combine the advantages of conventional PMTs: fast and high gain, and
• those of solid state devices: compact, insensitive to magn. fields, low cost;
• are sensitive to single photo-electrons;
• are binary devices (photon counting)

But have …
• low fill factors;
• high thermal (dark current-) count rates;
• high terminal capacitance.
Non-commercial 1 x 1mm² (400 pixels) SiPM test structure of STM – Catania:

Laser pulse: 50ps, 405nm

Delay [ns]

Pulse height [µA]

Noise
1 SPAD
2 SPADs
3 SPADs
4 SPADs

σ_jitter = \sigma_{ele}^2 + \sigma_{SPAD}^2 \frac{dI}{dt}

\approx \sigma_{SPAD} \frac{dI}{dt}

= 4.6 \mu A

= 35 \mu A/\text{ns}

σ_n = n \times \sigma_{SPAD} \frac{dI}{dt} = \frac{dI}{dt}

= 130 ps

FWHM:
425ps (1p.e.)
306ps (2p.e.)
256ps (3p.e.)
\[ \sigma_{\text{jitter}} = \sqrt{\sigma_{\text{ele}}^2 + \sigma_{\text{SPAD}}^2 \frac{dI}{dt}} \]

\[ \approx \frac{\sigma_{\text{SPAD}}}{\frac{dI}{dt}} = \frac{4.6 \mu A}{35 \mu A/\text{ns}} = 130 \text{ps} \]

\[ \sigma_n = \frac{\sqrt{n} \times \sigma_{\text{SPAD}}}{n \times \frac{dI}{dt}} = \frac{\sigma_{\text{jitter}}}{\sqrt{n}} \]
Laser Timing With NINO

Non-commercial 1 x 1mm² (400 pixels) SiPM test structure of STM – Catania:

Without time walk corrections:

Use look-up table for correcting data.
Laser Timing With NINO

Non-commercial 1 x 1mm\(^2\) (400 pixels) SiPM test structure of STM – Catania:

NINO has little if any influence on timing precision.

FWHM:
- 430ps (1p.e.)
- 320ps (2p.e.)
- 275ps (3p.e.)
- 221ps (4p.e.)

With time walk corrections:
SiPM: Energy Resolution

Hamamatsu S 10931-050 P: 3 x 3mm², 3600 pixels

LSO 3 x 3 x 20 mm³ crystal

NINO spectrum normalized from pulse width to energy (algorithm derived from SPICE simulations).

- SiPM output FWHM: 30%
- NINO output FWHM: 29%
- SiPM: Hamamatsu S 10931-050 P
  - 3 x 3 mm, 3600 pixels
- LSO: (3 x 3 x 20 mm³)
- Na-Source: (3 x 3 x 20 mm³)
SiPM: Timing Resolution

Hamamatsu S 10931-050 P: 3 x 3mm², 3600 pixels

Preliminary conclusion:
• SiPM timing resolution better than that of fast PMTs.
• SiPM resolution still contaminated by jitter from time walk (corrections to come).
• Time walk in energy window, expected from SPICE, to be $\sigma \sim 120\text{ps}$ (280ps FWHM)

$\sqrt{\sigma_{\text{PMT}}^2 + \sigma_{\text{SiPM}}^2} = 251\text{ps}$
$\sigma_{\text{PMT}} = 185\text{ps}$
$\sigma_{\text{SiPM}} = 170\text{ps}$

$FWHM_{\text{SiPM}} = 400\text{ps}$
**Summary**

- **Experience from BioCare (FP6) Work:**
  - Validation of *Time based Readout* Scheme (patented).
  - Understand limitations in sensor performance (PMTs & APDs).
  - Timing resolution intrinsically limited by photon statistics and insufficient APD gain.

- **CERN time-based electronics well adapted to SiPMs:**
  - Simple architecture around NINO discriminator (no additional amplification needed);
  - Single detector time resolution of \( \leq 400 \text{ps } FWHM \) \( (\sigma = 170 \text{ps}) \) achieved.
  - Time walk corrections \((\sim 280 \text{ps } FWHM)\) still pending;
  - Resolution intrinsically limited by photon velocity in crystal \((\sim 200 \mu\text{m/ps})\)
    \( \Rightarrow 100 \text{ps maximum in 20mm } \Rightarrow 50 \text{ps } FWHM \) in chosen LSO crystal.
“Timing Precision” vs. $N_{p.e.} (Q)$

(Westcott, Knoll, Lynch, Wright)
The time evolution of the SiPM signal is shown in the graph. The parameters are as follows:

- \( I_0 = 34 \mu A \)
- \( N_{pe} = 2000 \)
- \( \tau_{crystal} = 40 \text{ ns} \)
- \( \tau_{RC} = 5 \text{ ns} \)

The graph shows the current \( I_{SiPM}(t) \) as a function of time \( t \). The inset highlights the 1 p.e. response of the SiPM.