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10th ICATPP - COMO
On behalf of the Ultra fast timing collaborative group

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Introduction

- Resolution on time measurements translate into resolution in space, which turn impact momentum and energy measurements.
- Silicon strips detectors and pixels have reduced position resolution to few microns.
- Time resolution hasn’t keep pace - not much changed since the 60’s in large scales TOF resolution and technologies (thick scintillators or crystals, PM’s, Lecroy TDC’s).
- Improving time measurement is fundamental, and can affect many fields: Particle and nuclear physics, medical, accelerators, astro, laser imaging ....
- Need to understand what are the limiting underlying physical processes - e.g. sources line widths, photon statistics, e/photon path length variations.
- Initial studies give < few ps for HEP and we guess around 30-40 psec for Medical Imaging
**HEP & PET**

**Similarities and differences**

**Similarities**
- Geometry and granularity
- Detector (Crystals & scintillator)
- Sensor (PM, APD)
- Electronics: Fast (40 MHz), compact
- Data volume (Gbit/s)

**Differences**
- Energy range (10GeV-511keV)
- No synchronisation
  --> free running electronics
- Multiple vertices
- Event Rate 10 MHz

**HEP**

Calorimeter

$M_{Higgs} = 100$ GeV

**PET Camera**

Biomedical Imaging

Counts vs. Energy (keV)

- 28,700 ph/MeV
- ER = 10.1%

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From HEP to Medical Imaging

Where techniques are transferred to developments in bio-medical field
Medical Imaging has only partially benefited from new technologies developed for telecommunications and High Energy Physics detectors

- New scintillating crystals and detection materials →
  - CMS (WPbO4) → Luap ...(Crystal Clear col)
- Photodetectors: Highly segmented and compact → PMT → APD → SiPM
- Electronics & signal treatment → Highly integrated
  - Fast, low noise, low power preamp and sampling
  - Digital filtering and signal analysis
- Trigger/DAQ →
  - High level of parallelism and event filtering algorithms
  - Pipeline and parallel read-out, trigger and on-line treatment
- Computing
  - Modern and modular simulation software using worldwide recognized standards (GEANT) → GATE collaboration
Role of TOF in HEP vs Medical

unique expertise should be more widely available to society.

Three Key Developments since the 60s:
- Fast MCP’s
- 200 GHz electronics and fast sampling chips
- Electronics Simulation Tools

The Need for End-to-End Simulation in Parallel

HEP Needs:
- Particle ID and Flavor Flow,
- Heavy Particles,
- Displaced Vertices, Photon Vertex Determination

MI Needs:
- 3D localization (TOF)
- real-time filtering & reconstruction.
Time-of-Flight Tomograph

- Can localize source along line of flight \textit{depends on timing resolution of detectors}
- Time of flight information can improve signal-to-noise in images \textit{weighted back-projection along line-of-response (LOR)}

\[ \Delta x = \text{uncertainty in position along LOR} = c \cdot \Delta t/2 \]
Benefit of TOF

Better image quality
Faster scan time

- 5Mcts TOF
- 5Mcts
- 1Mcts TOF
- 1Mcts

Karp, et al, UPenn
TOFPET DREAM

- PET without TOF (>99%)
- One Commercial TOFPET System Available with 750 picosec TOF (11.25 cm LOR Resolution)
- 30 picosec TOF
  - 4.5 mm LOR Resolution
- 10 picosec TOF
  - 1.5 mm LOR Resolution
- 3 picosec TOF
  - 0.45 mm LOR Resolution
- Histogramming
- No “Image Reconstruction”
Major advances for TOF measurements in HEP

- Development of MCP’s with 6-10 micron pore diameters
- Ability to simulate electronics and systems to predict design performance
- Oscillator with predicted jitters $\ll 100$ femtosec
- Use Cherenkov light for incoming rel particle
- Custom Anode with Equal-Time Transmission Lines + Capacitative return
- Two cards $2'' \times 2''$ connected to the MCP anode planes (8x8 pads)
- Picosecond card with picosecond Time stretcher SiGe chip includes:
  - Discriminator
  - 2 GHz PLL
  - Time stretcher
- FPGA card includes
  - 200ps TDC
  - Control, calibration, interface

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Best results with 2 TOF counters in tandem:

Two detector resolution (resistor chain #2):

Each detector has $N_{pe} \sim 115-120$ pe:

\[ \sigma_{\text{single detector}} \sim \frac{1}{\sqrt{2}} \sigma_{\text{double detector}} \sim 5.0 \text{ ps} \]

$\sigma \sim 7.0 \text{ ps}$

Running conditions:
1) Low MCP gain operation ($<10^5$)
2) Linear operation
3) CFD discriminator
4) No additional ADC correction

Contribution of the MCP-PMT itself to the above single detector resolution:

\[ \sigma_{\text{MCP-PMT}} < \sqrt{1/2} \left\{ \sigma^2 - \left[ \sigma^2_{\text{Pulser+TAC}_{\text{ADC}}+\text{Amp/CFD}} - \sigma^2_{\text{Pulser}} \right] \right\} < 4.5 \text{ ps} \]

Two Burle/Photonis MCP-PMTs with 10 $\mu$m MCP holes operating at 2.85 & 2.43 kV.
Ortec 9327 Amp/CFD (two) with a walk th. of +5mV & TAC566 & 14 bit ADC11

From J. Va\'vra 10th ICATPP - COMO

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Comparison of read out chains

HEP --> few psec
- Cherenkov light for relativistic Particle
- Transducer: MCP

MI --> 30 - 40 psec
- Scintillator light from fast crystals (LaBr3 !)
- Transducers: PMT, MAPMT, APD, SiPM
  - CFD
  - TDC

Fig. 2: The time stretcher receives signal from MCP, a very low timing jitter walk discriminator will be implemented to generate a "start" signal. The time to measure is the difference between "start" and "Stop", that is a 500ps-1ns time interval pulse. With the following 1:200 time stretching circuit, a stretched pulse (100n-200ns) then be sent to DAQ chip for digitizing by a 11 bit counter with 200ps resolution.
Direction to reach 30-40 psec in MI

- **INPUT** = Somme of PMT signals into High Impedance 50 h cable source
  - Signal characteristic
    - Input = 100 mV x 4 negative polarity
    - Risetime: Few ns  Length 100 ns  Rate 10 KHz
  - Summing circuit bandwidth 300 MHz
  - Timing Estimation Discriminator (TED) with 8 comparators
  - Few mV reproductibility and stability
- **OUTPUT** = 8 differential pairs (Current Mode Logic)
  - ENABLE (DC)

**Diagram**:
- CMOS ASIC
- TED
- Timing Estimation Block
- FPGA
- HEP type Pulse Shape Digitizer 25 psec resol
- Data Treatment

**Graph**:
- Ex: 4 thresholds discriminator

**Notes**:
- INPUT = Somme of PMT signals into High Impedance 50 h cable source
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Semi simulation experiment  
(Results from Chien Min Kao - UC)

Here is description of the experiment: we place a syringe (diameter ~1cm) filled with a small amount of FDG and placed it in between two LSO/PMT module. The two PMT outputs are sampled by a 40GHz digital scope, yielding a 50ps sampling rate for each channel.

- The event time of a pulse is determined as explained in the first slide.
- The second slide shows the resulting histograms of the difference between the determined event time. The single channel timing resolution in the second slide is calculated from the FWHM coincidence timing resolution by $2.35 \times \sqrt{2}$.
A sample pulse generated by LSO/PMT (50ps sampling interval)

- Linear fitting to points determined by a few thresholds (black circles)
- Event time = intercept of the fitted line with the zero voltage (yellow star)
Results include the effects of the sampling rate (50ps), source size (~1cm), and electronic noise.
Full digital Conceptual Architecture

- Trigger logic processes “raw fast information”
- Free-running sampling digitizer
- Digital filter used to extract pulse amplitude and high resolution timing
- Pipelined processing architecture to avoid deadtimes
- Only one “channel” to compute either the energy and time

Trigger logic processes “raw fast information”
Free-running sampling digitizer
Digital filter used to extract pulse amplitude and high resolution timing
Pipelined processing architecture to avoid deadtimes
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The INNOTEP project
Real Time Data treatment

- HEP (LHC)
- MI - Future PET

Digitization
Pipeline
Event Builder
First demonstrator

- Stationary Compact Dual-Panel PET with Very High Sensitivity
- A Benchtop Prototype for High-Throughput Animal Imaging

Courtesy of Kao & Chen/UC
Conclusions

- Improving drastically the timing resolution toward the Psec for HEP and few ten of Psec for MI is hard, but not impossible!
- Adding TOF capabilities will have a fundamental impact on relevant detectors (HEP Particle ID and PET scanners)
- There is a long way to go but the first results are very encouraging.
- Join efforts between HEP and MI community is a very efficient way to reach this challenging goal.

Thanks a lot for your attention!