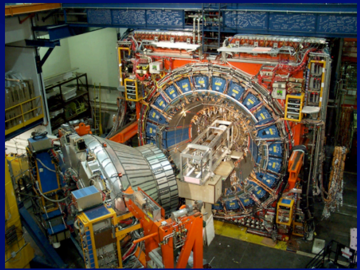
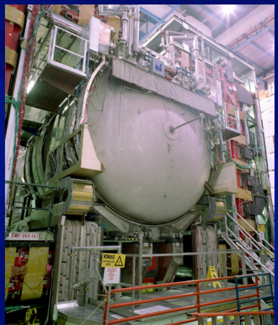
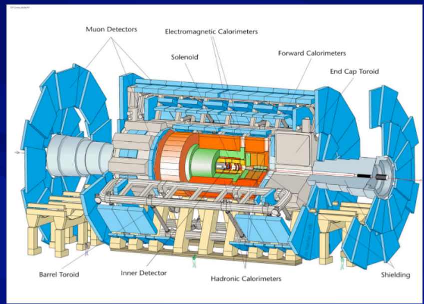
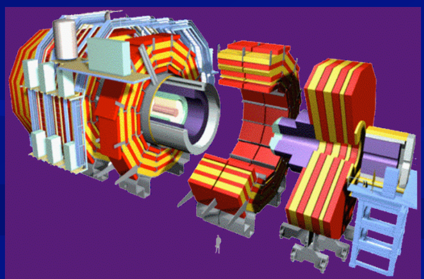
Ultra-fast Timing and the Application of High Energy Physics Technologies to Biomedical Imaging.

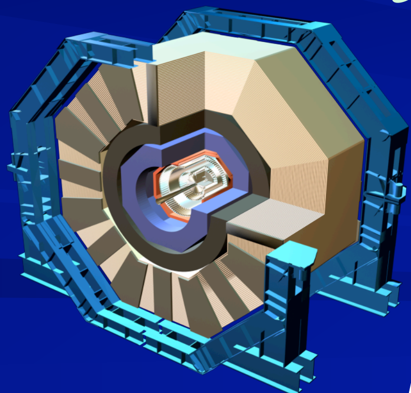






By P. Le Dû





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On behalf of the Ultra fast timing collaborative group

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  - DAPNIA CEA Saclay (France).
- Jean François Genat
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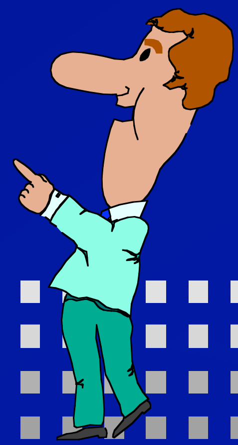
- Jerry Va'Vra
  - Stanford Linear Accelerator (USA)



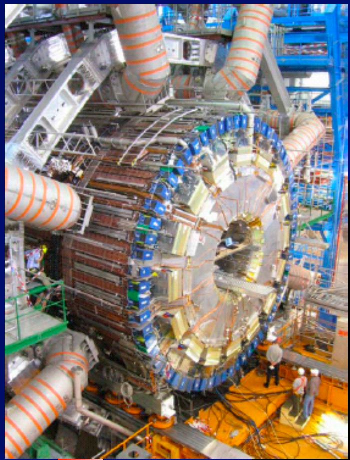
Special thanks for W.W. Moses (LBL,USA)

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 unsderstand what are the limiting underlying physical processes - e.g. sources line widths, photon statistics, e/photon path lengh variations.
- Initial studies give < few ps for HEP and we guess around 30-40 psec for Medical Imaging

HEP & PET

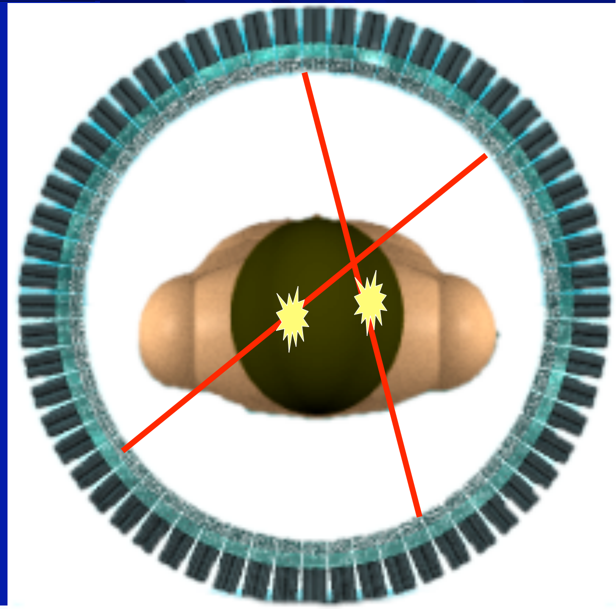
Similarities and differences

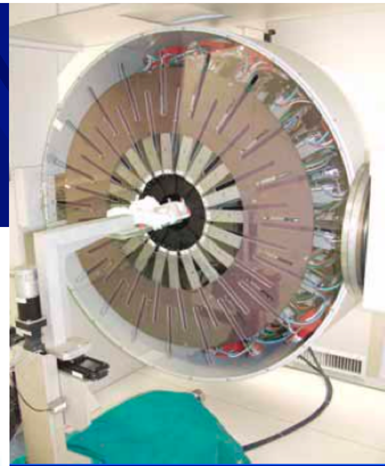


Calorimeter

HEP

M_{Higgs} = 100 GeV





PET Camera

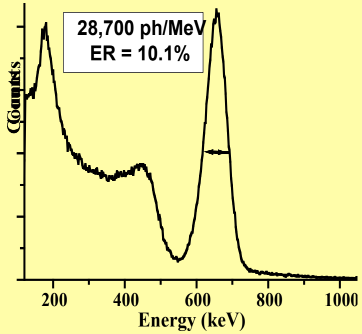
Biomedical Imaging

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



From HEP to Medical Imaging

Where ***techniques*** *are transfered 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
  - APD : SSC/SDC (1991) → CMS (1996) → MicroTEP→ TEP
- Electronics & signal treatemnt→ 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

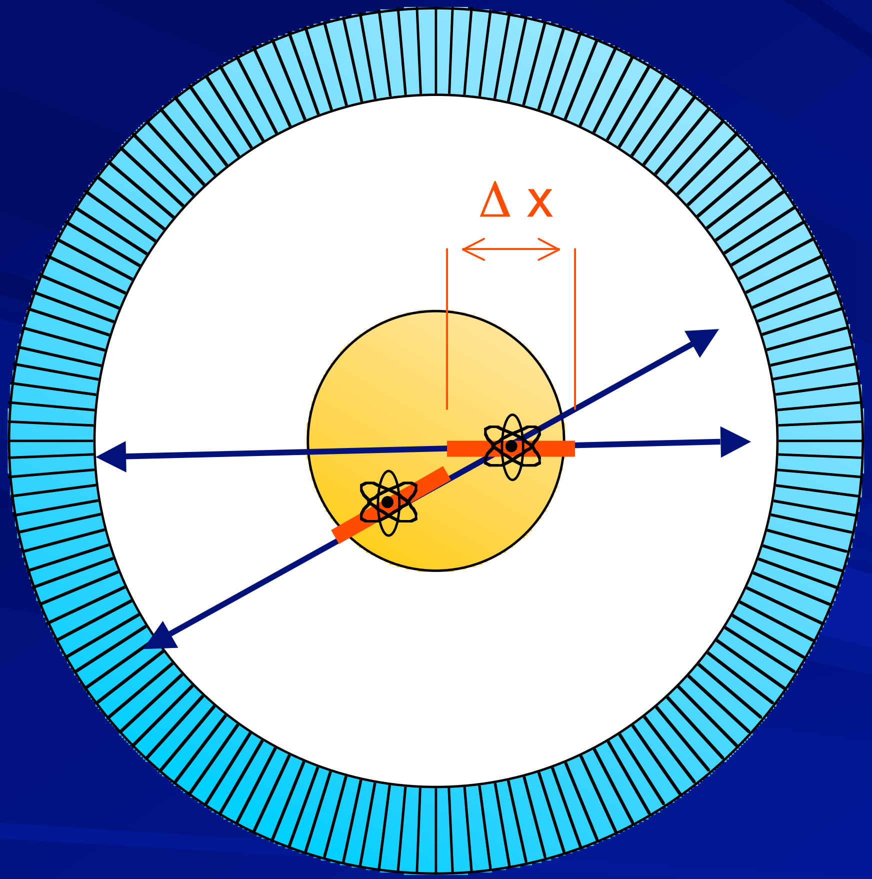
unique expertise should be more widely available to society.

- Three Key Developments since the 60ls:
  - 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

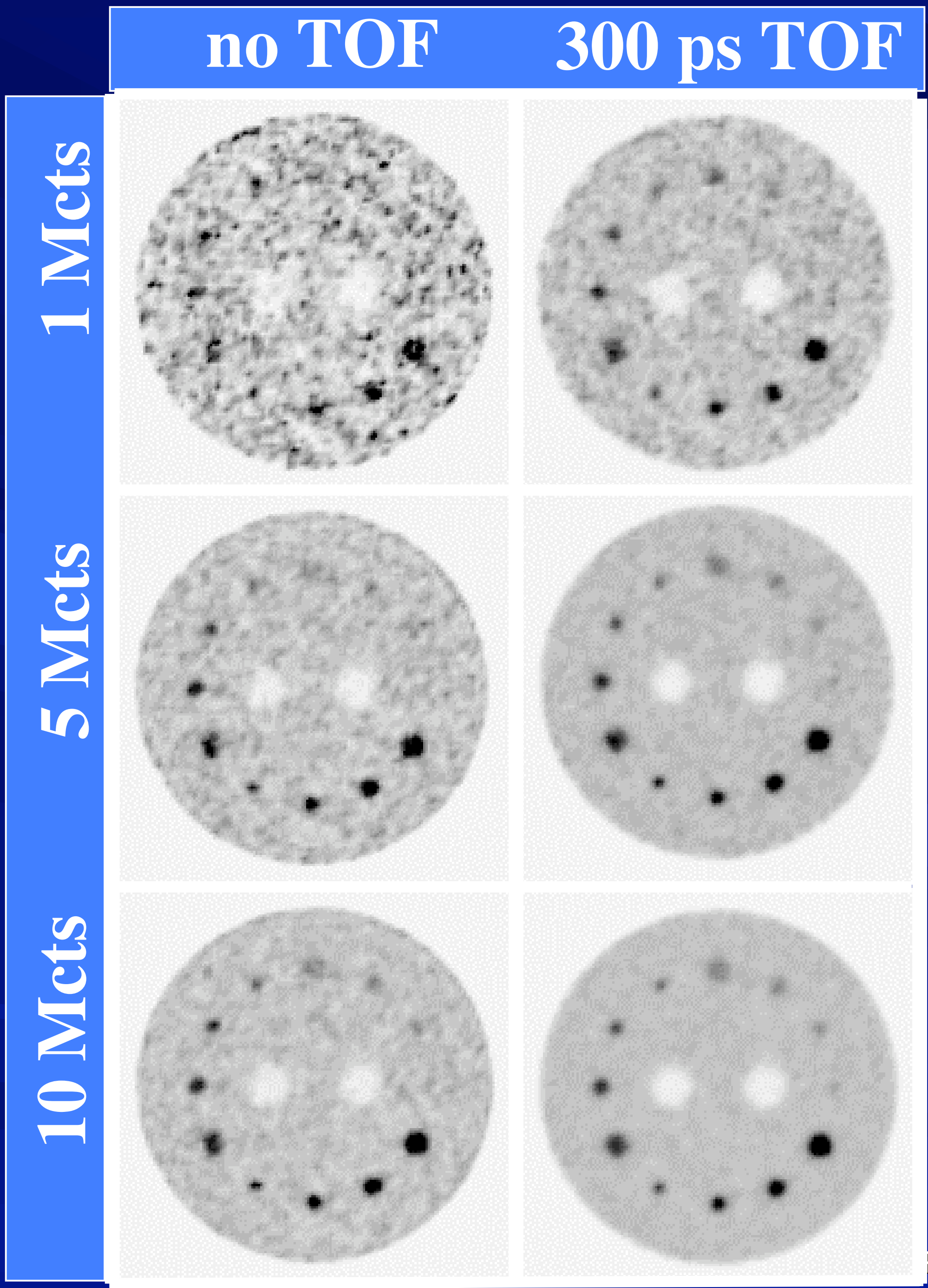


- Can localize source along line of flight – *depends on timing resolution of detectors*
- Time of flight information can improve signal-to-noise in images – *weighted back-projection along line-of-response (LOR)*

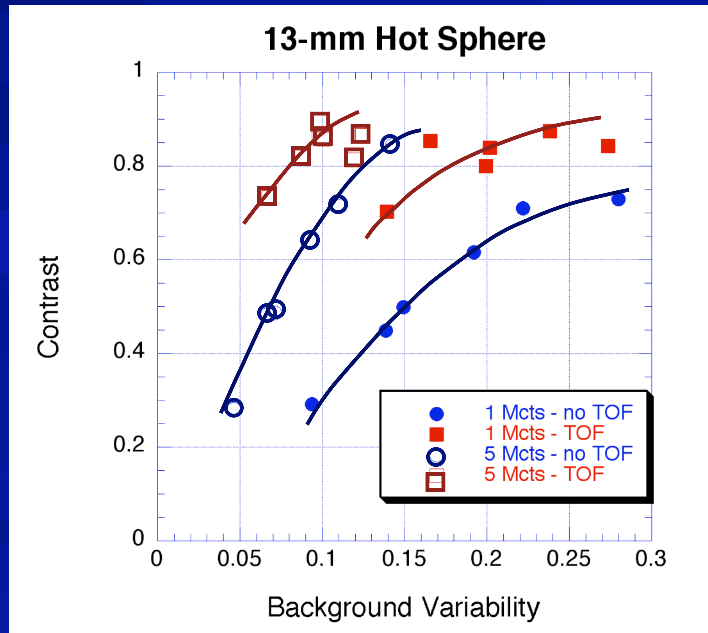
Δx = uncertainty in position along LOR
$= c \cdot \Delta t/2$

Benefit of TOF

Better image quality
Faster scan time



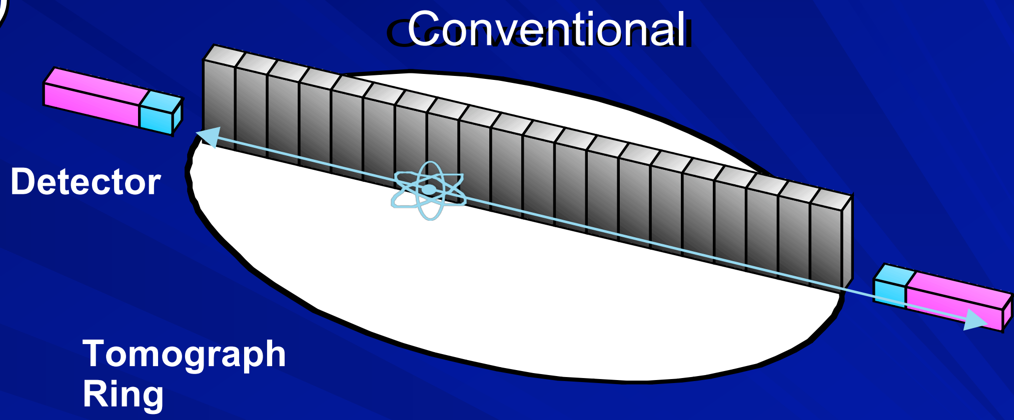
5Mcts TOF
1Mcts TOF
5Mcts
1Mcts

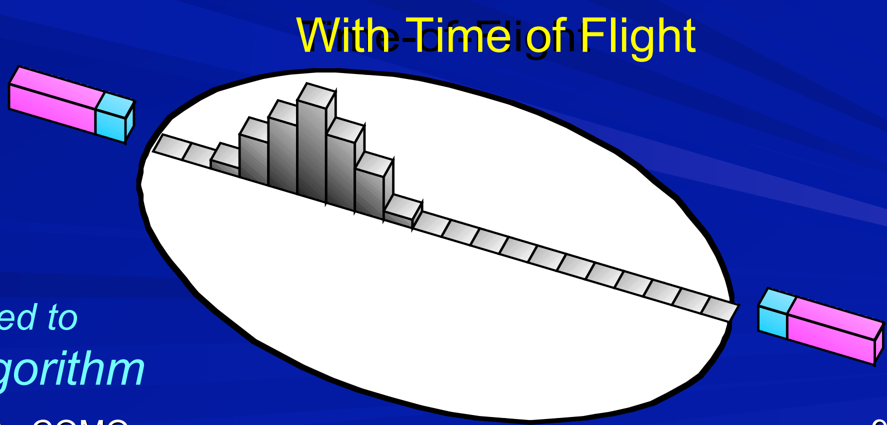


Karp, et al, UPenn

TOFPET DREAM

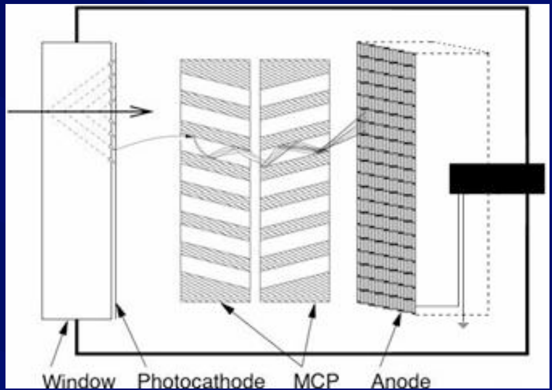
- PET without TOF (>99%)
- One Commercial TOFPET System Available with 750 picosec TOF (11.25 cm LOR Resolution)
- 30 picosec TOF
  - 4.5 mm LOR Resolution
- 10 picosec TOF
  - 1.5 mm LOR Resolution
- 3 picosec TOF
  - 0.45 mm LOR Resolution
- Histogramming
- No " Image Reconstruction"

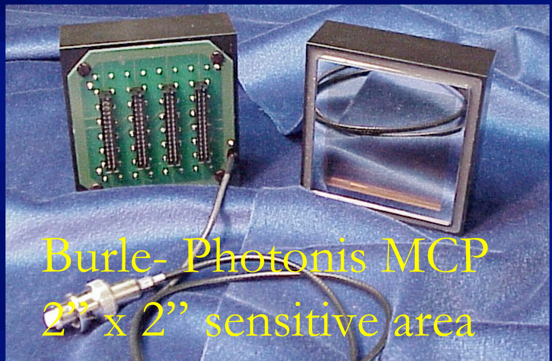


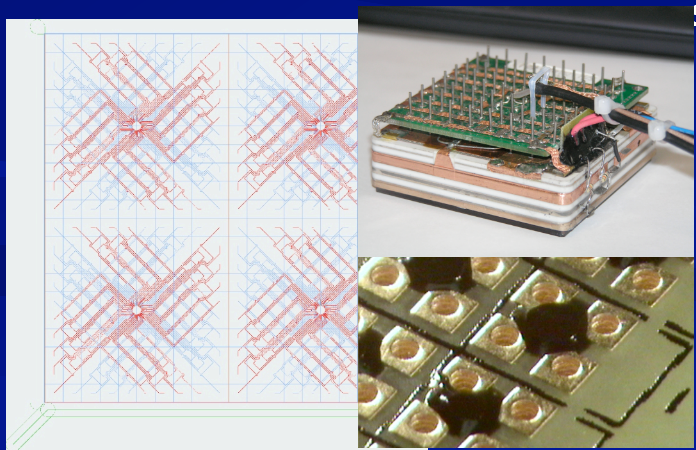


Height represents weight assigned to each voxel by reconstruction algorithm

Major advances for TOF measurements in HEP

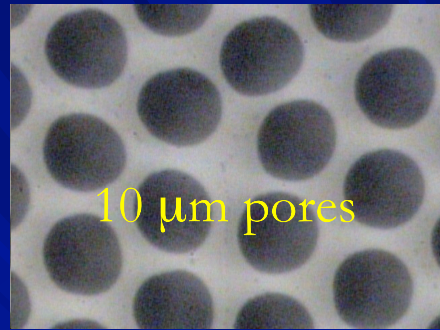


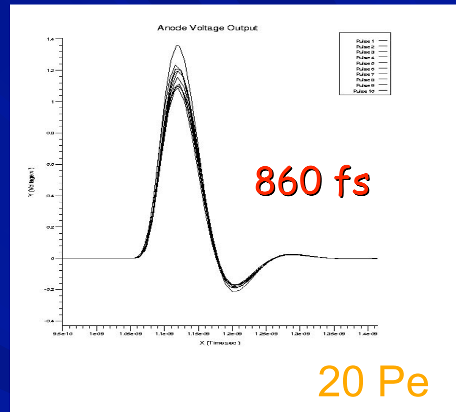


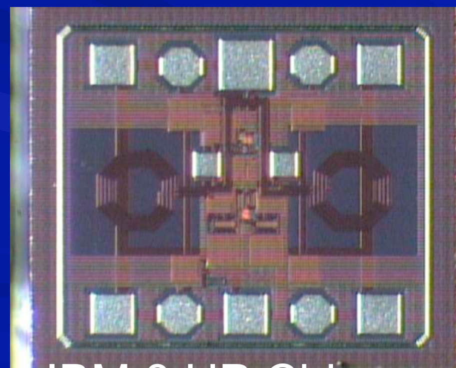


- Development of MCP's with 6-10 micron pore diameters
- Ability to simulate electronics and systems to predict design performance
- Oscillator with predicted jitters << 100 femtosec
- Use Cherenkov light for incoming rel particle
- Custom Anode with Equal-Time Transmission Lines + Capacitative return
- Two cards 2" x 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



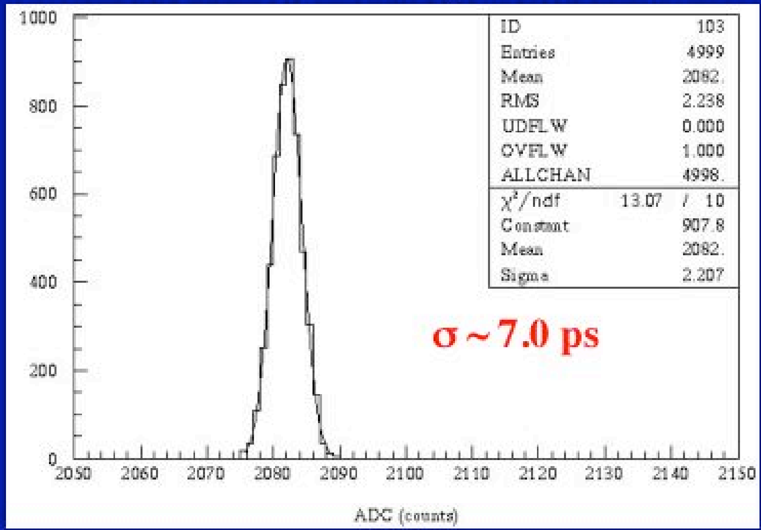




IBM 8 HP Chip

Best results with 2 TOF counters in tandem

Two detector resolution (resistor chain #2):



Each detector has Npe ~ 115-120 pe⁻:

$$\sigma_{\text{single detector}} \sim (1/\sqrt{2})\ \sigma_{\text{double detector}} \sim 5.0 \text{ ps}$$

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

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:

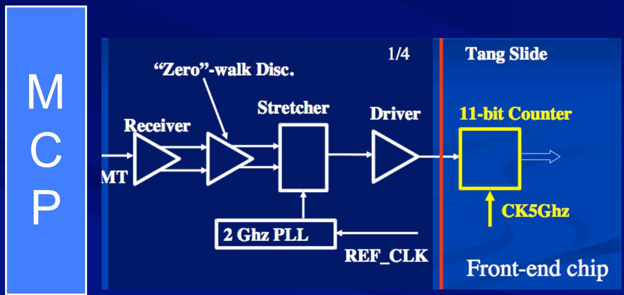
$$\sigma_{\text{MCP-PMT}} < \sqrt{1/2}\ \{\ \sigma^2 - [\sigma^2_{\text{Pulser+TAC\_ADC+Amp/CFD}} - \sigma^2_{\text{Pulser}}\ ]\} < 4.5 \text{ ps}$$

7.0 ps (σ²) 3.42 ps (σ²Pulser+TAC_ADC+Amp/CFD) < 2 ps (manufacturer) (σ²Pulser)

Comparison of read out chains

HEP --> few psec

- Cherenkov light for relativistic Particle
- Transducer : MCP



DAQ Chip

200 MHz TDC (FPGA)

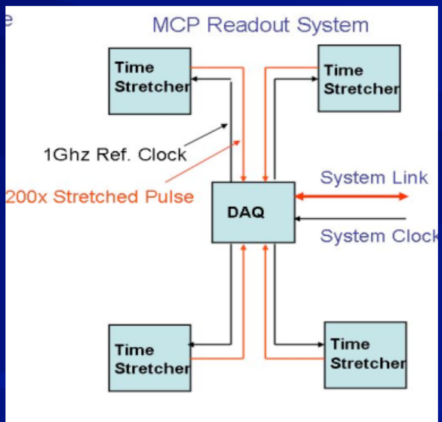


Fig. 2: The time stretcher receives signal from MCP, a very low timing jitter/walk discriminator will be implemented to generate a "start" signal. The time to measure is the difference between "start" and "Stop", that is a 500ps-1ns time interval pulse. With the following 1:200 time stretching circuit,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

MI--> 30 - 40 psec

- Scintillator light from fast crystals (LaBr3 !)
- Transducers
  - PMT,MAPMT,APD, SiPM
- Limiting factor
  (W.W. Moses,IEEE NSS-MIC 2004)
  - CFD
  - TDC

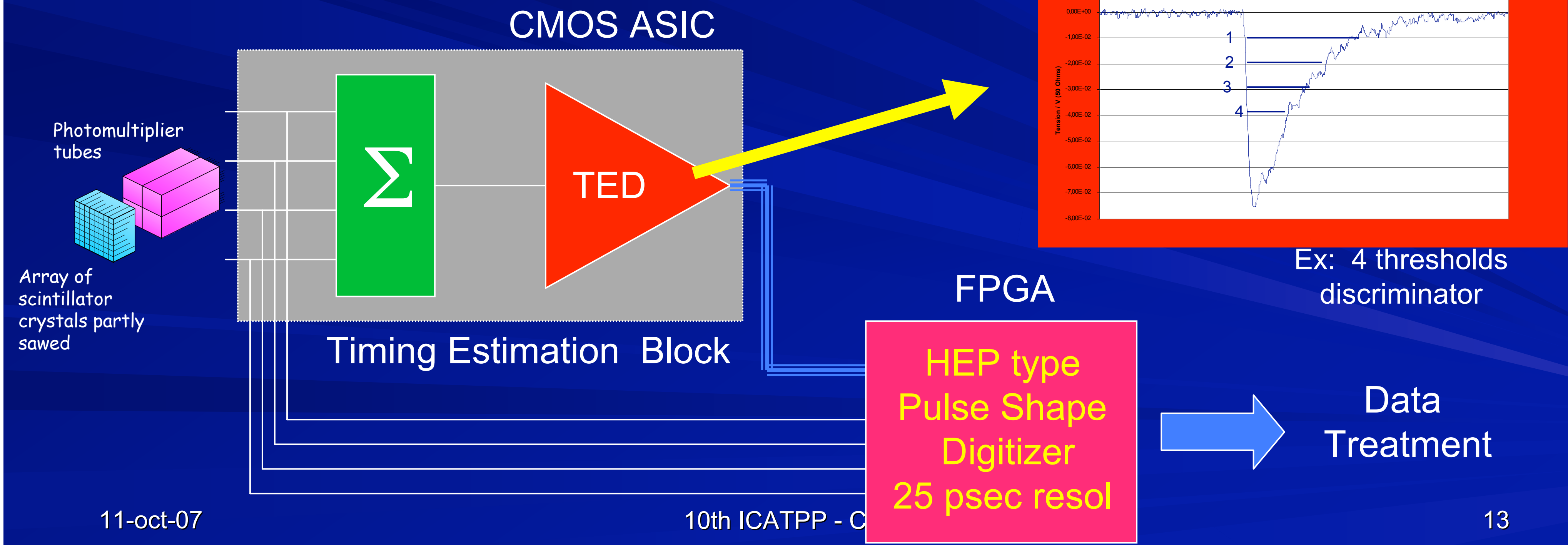
"Reference" chain "Production" chain (CPS ACCEL)

"Production" chain (CPS ACCEL)

COMPONENT	CONTRIBUTION
Crystal (LSO)	336ps
light sharing (block)	454ps
PMT	422ps
PMT array	274ps
CFD	1354ps
TDC	2000ps

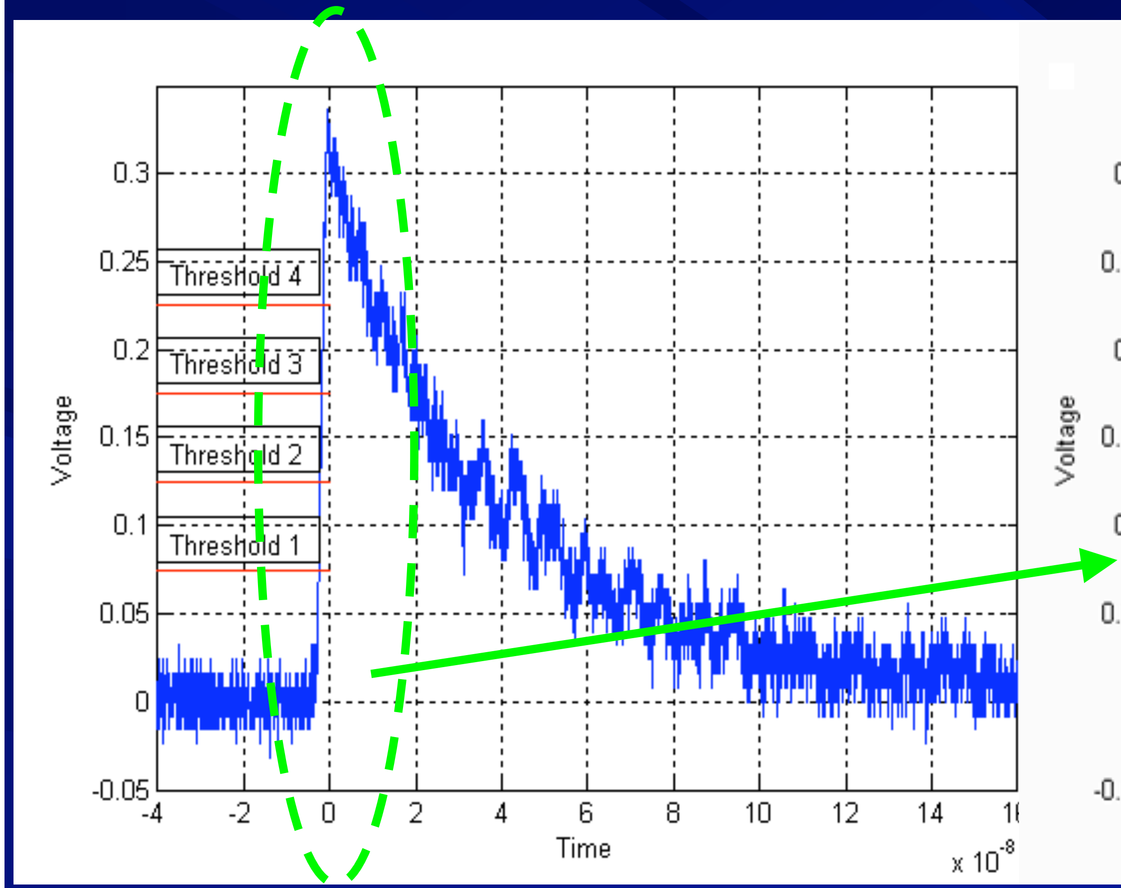
Direction to reach 30-40 psec in MI

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

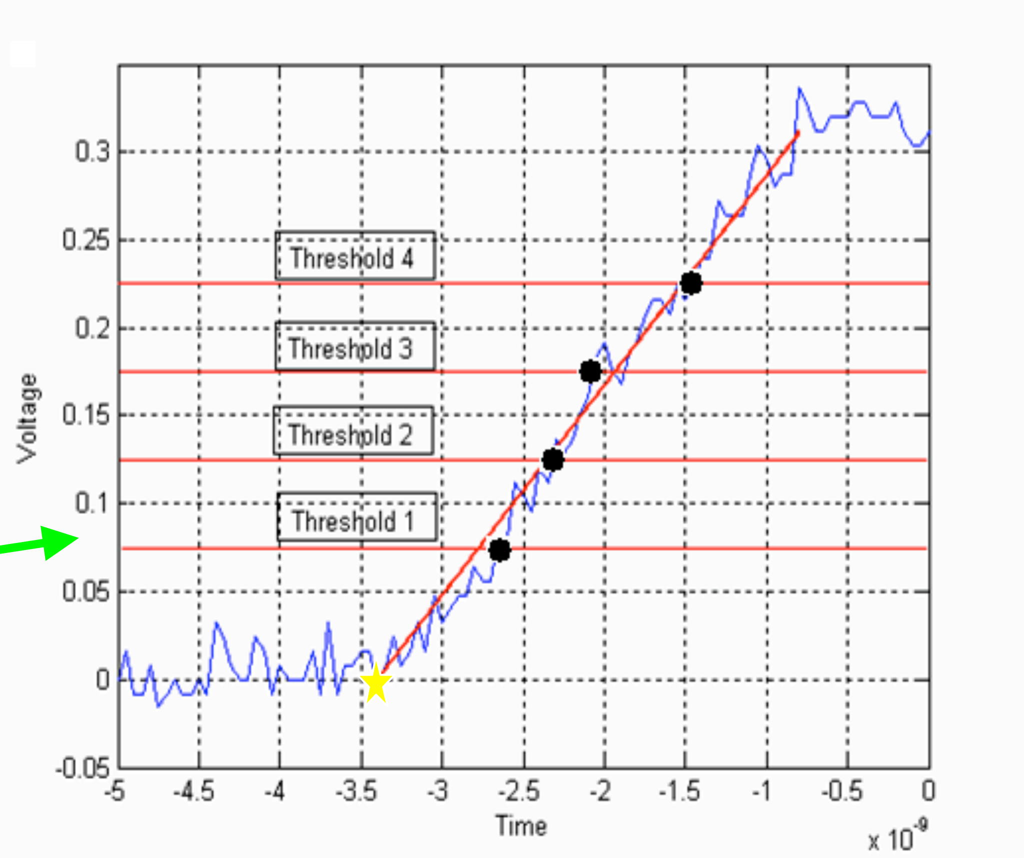


Semi simulation experiement (Results from Chien Min Kao - UC)

- 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*sqrt(2).

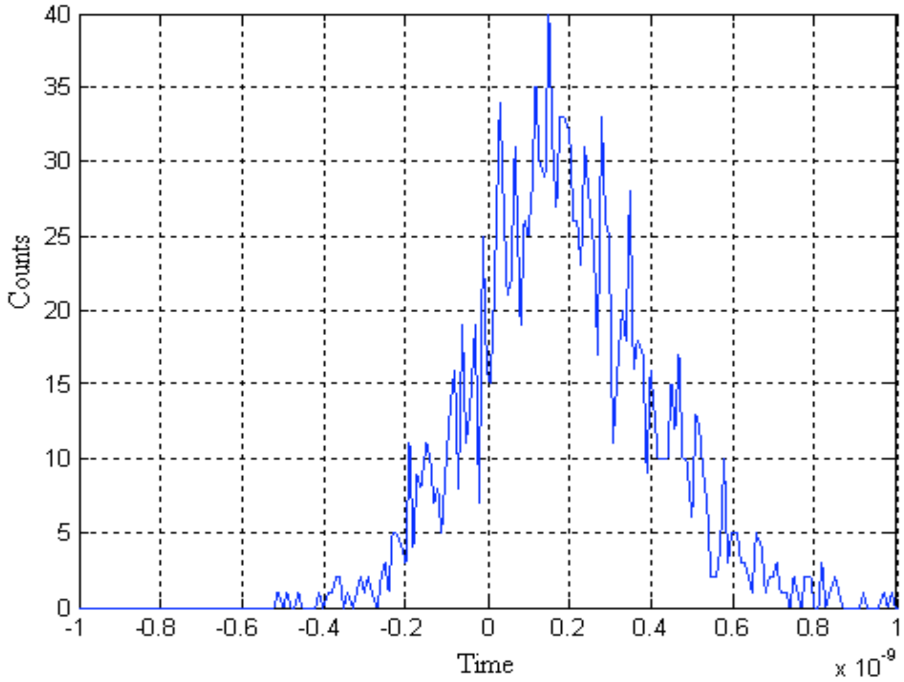


A sample pulse generated by LSO/PMT (50ps sampling interval)



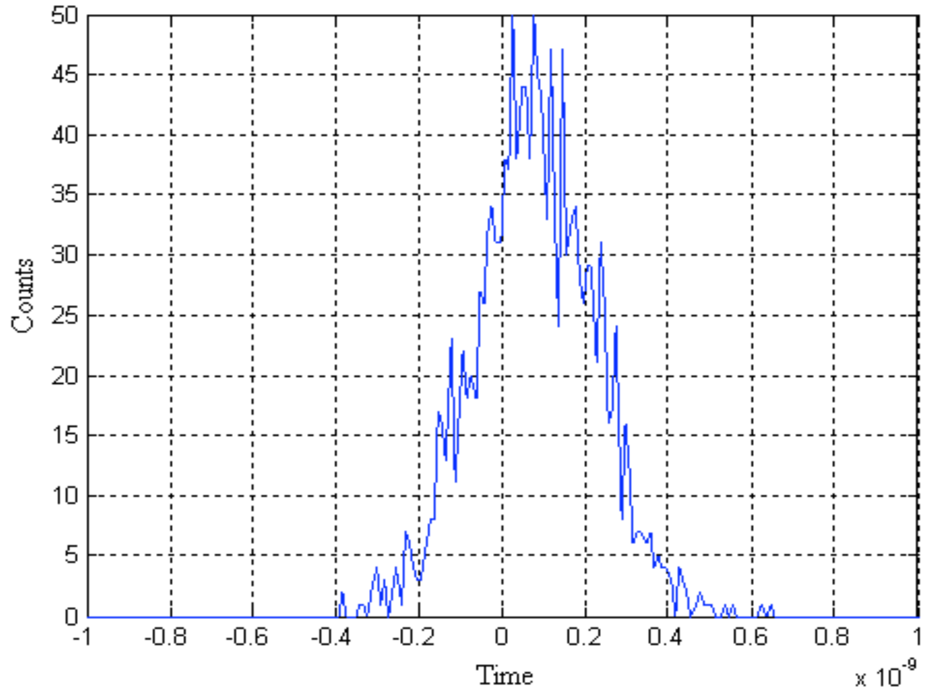
- Linear fitting to points determined by a few thresholds (black circles)
- event time = intercept of the fitted line with the zero voltage (yellow star)

Time Difference Histogram
4 thresholds



~360ps FWHM
coincidence timing resolution
(estimated single channel σ=108ps)

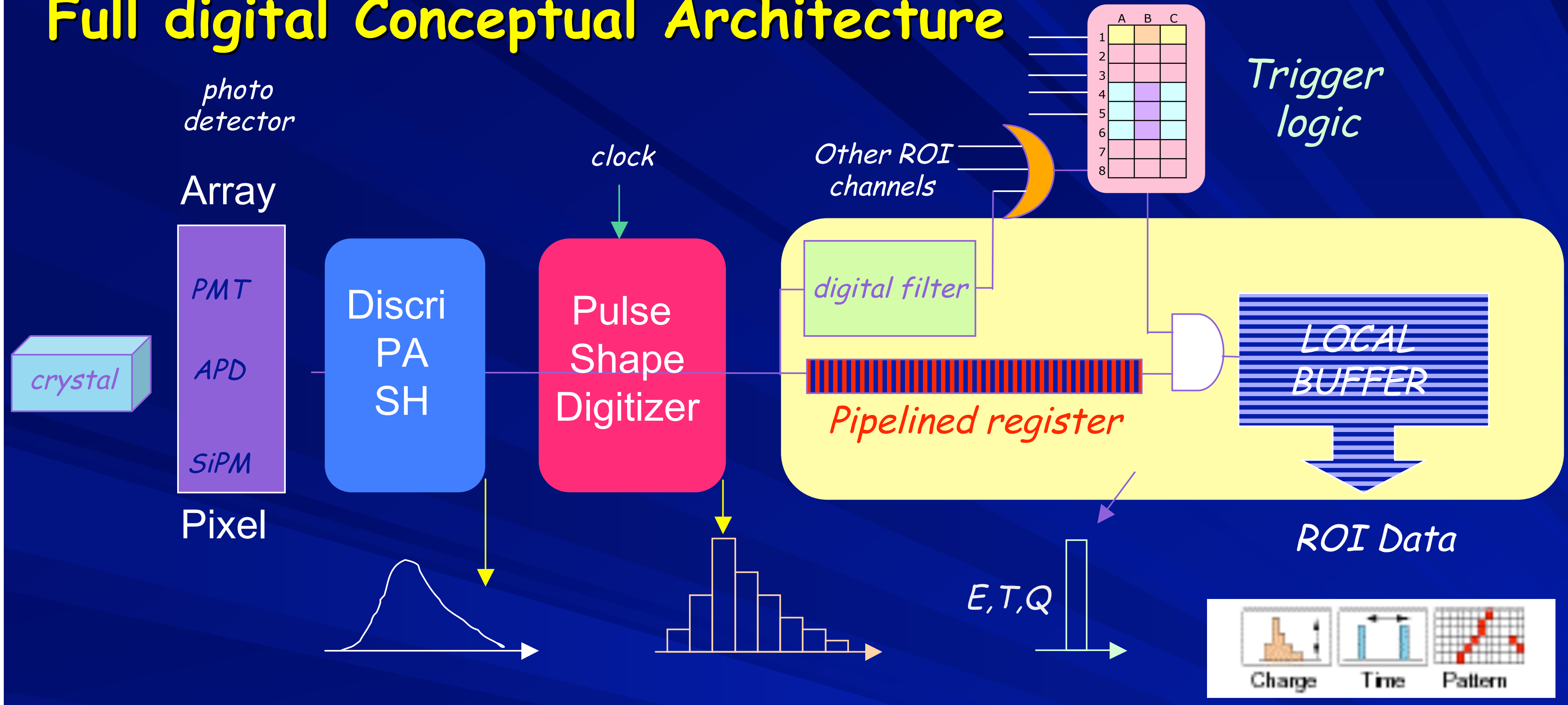
Time Difference Histogram
6 thresholds



~240ps FWHM
coincidence timing resolution
(estimated single channel σ=72ps)

Results include the effects of the sampling rate (50ps), source size (~ 1cm), and electronic noise.

Full digital Conceptual Architecture



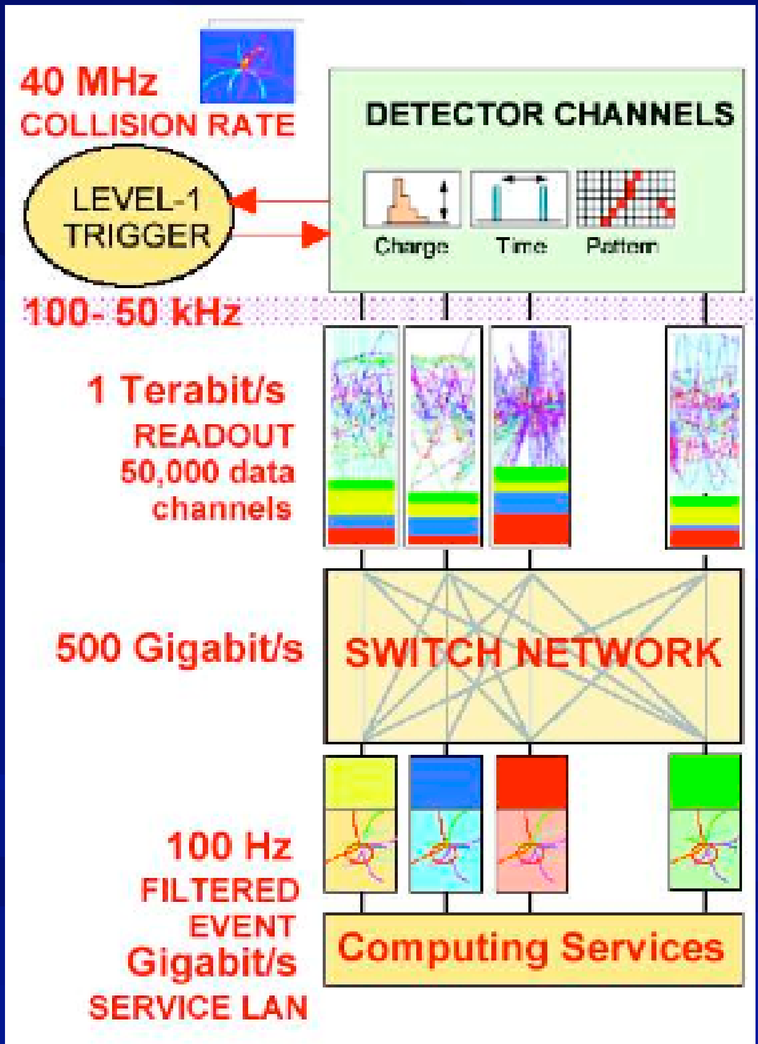
- Trigger logic processes "raw fast information"
- Free-running sampling digitizer
- Digital filter used to extract pulse amplitude and high resolution timing
- Pipelined processing architecture to avoid deadtimes
- Only one "channel" to compute either the energy and time

Data Acquisition

The INNOTEP project

Real Time Data treatment

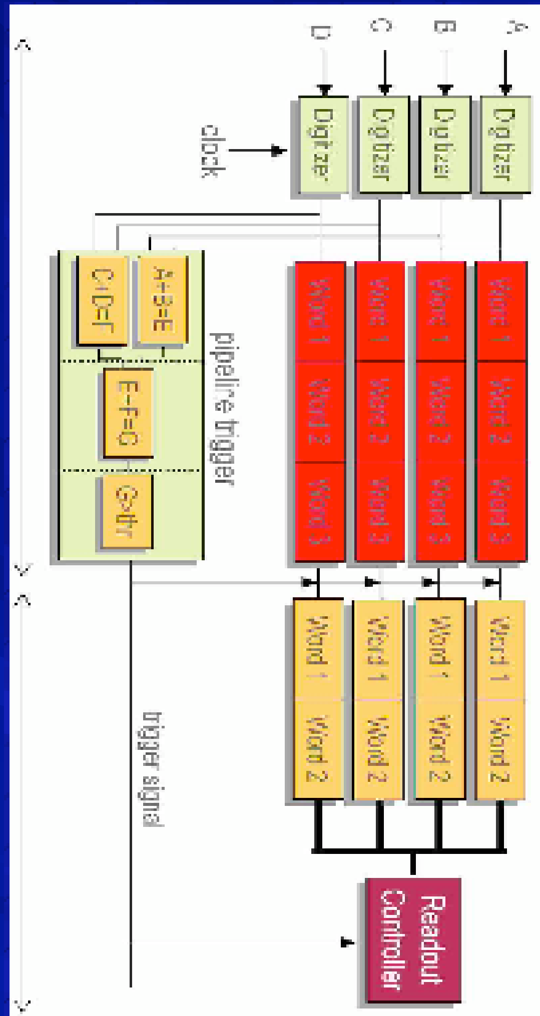
- HEP (LHC)
- MI -Future PET



Digitization

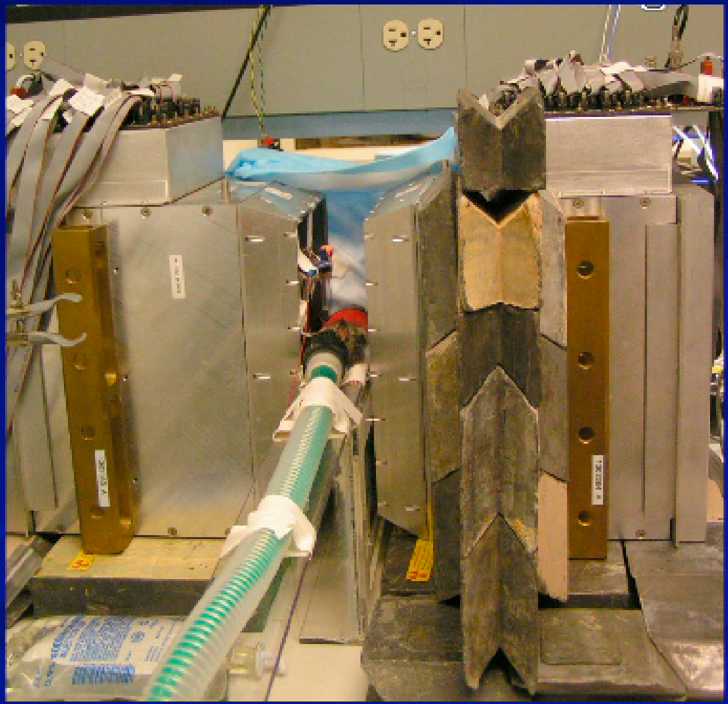
Pipeline

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!