Extremely Fast Detector for 511 keV Gamma

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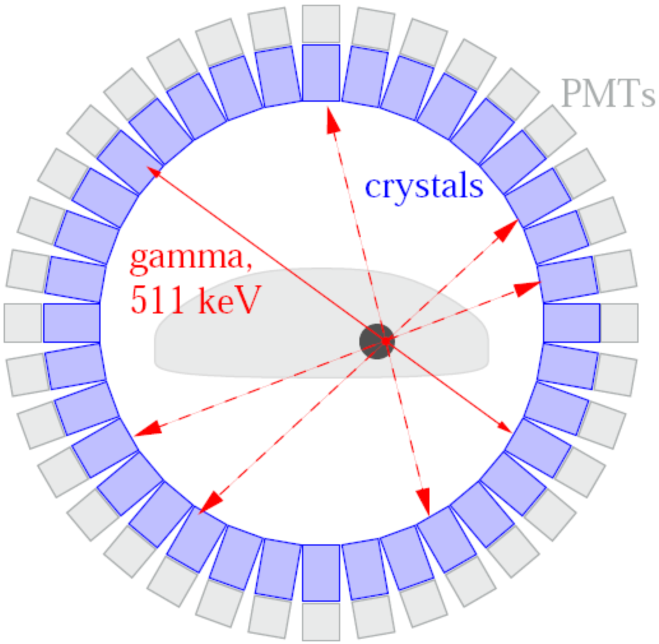
Positron Emission Tomography



- PET is a nuclear imaging technique used widely in oncology, cardiology and neurology.
- Use radioactive tracer (e.g. ^{18}F-FDG, $\tau \sim 110$ min) emits positrons ⇨ annihilation with an electrons ⇨ two 511 back-to-back gamma.
  - Full body dose ~ 3 to 5 MBq/kg
- Main issues
  - Backgrounds: Compton scattering in the subject, random coincidence
  - Reconstruction: need corrections for scattering and attenuation
  - Contrast of the image directly correlated to the S/B and available statistics. Better spatial precision requires more statistics for an image.

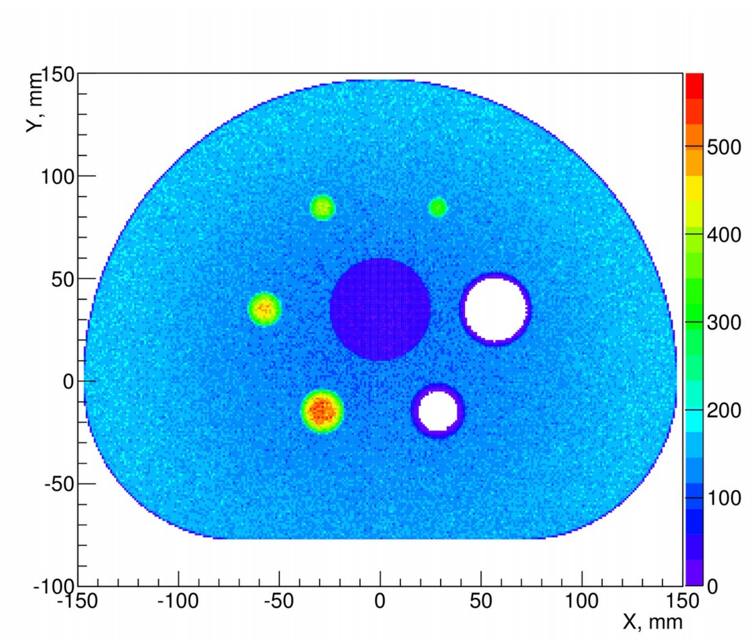
Better image quality for the same dose requires:
- *Higher efficiency*
- *Better Spatial Resolution*
- *Better S/B*

- TOF techniques: using the difference in time between two photons ⇨ improve S/B
  - Simple estimation: $G = \frac{S/N_{TOF}}{S/N_{noTOF}} \sim \sqrt{\frac{D}{\delta x}} \sim \sqrt{\frac{D}{c/2\ \delta t}}$ ⇨

D=30 cm
CRT=350 ps ⇨ G~1.9
CRT=100 ps ⇨ G~3.6
⇨ 12x lower dose

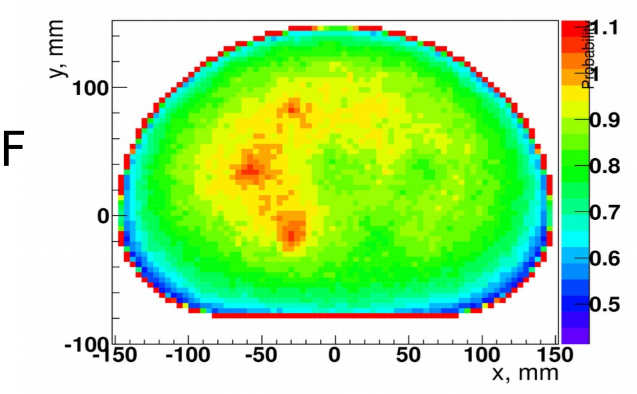
Phantom Simulation: importance the TOF

2D simulated body phantom.
Red regions: hot spheres.
Blue and white: cold spheres

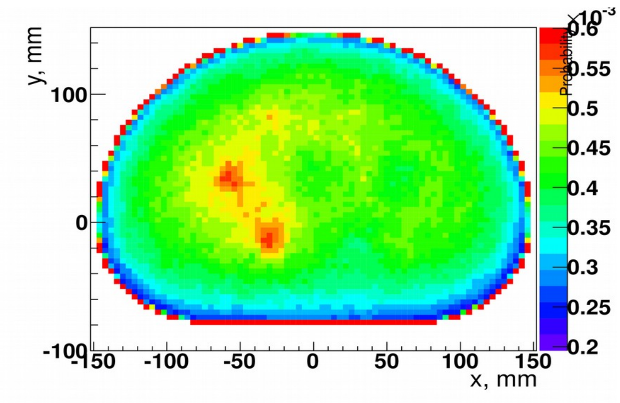


2D back-projection

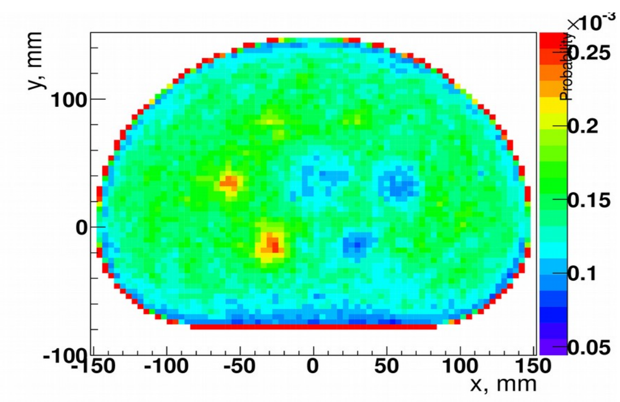
no TOF



TOF 500 ps



TOF 100 ps



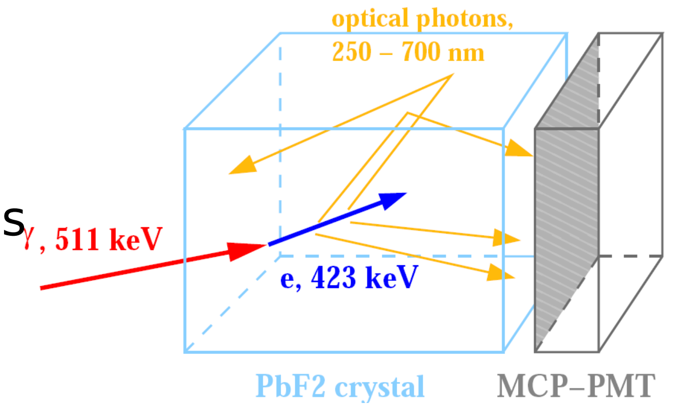
Project

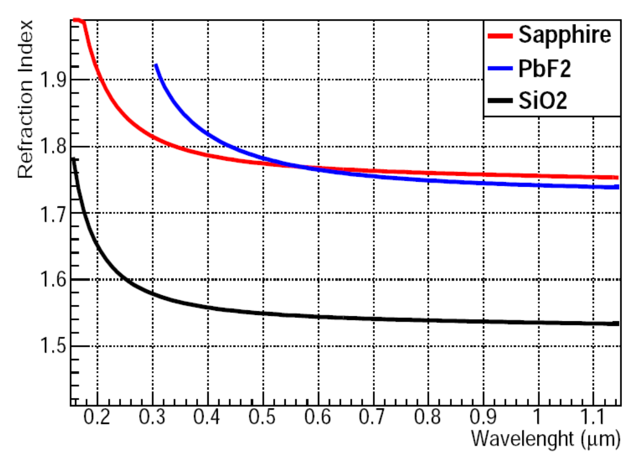
- Goal of the project: design a detector with the excellent time resolution and high efficiency.
- Main idea: use Cherenkov light instead of scintillation. Will compare two approaches: use of lead fluoride / lead tungsten crystals.
- PbF_2 crystal + MCP-PMT + Fast flash ADC (SAMPIC)
  - Excellent time resolution, low dark count rate.
  - High price.
- $PbWO_4$ crystal + Si PM + Fast flash ADC (SAMPIC)
  - Good timing performance, not expensive.
  - High dark count rate in the single-photon detection mode.

PbF_2 Detector

	Plastic	BaF_2	$LaBr_3$	$PbWO_4$	PbF_2
Density, g/cm^3	~1	4.9	5.3	8.3	7.8
Photoelectric fraction	0.001%	22%	15%	48%	46%
Attenuation length (511 keV)	~ 10cm	22 mm	21 mm	9 mm	9 mm
Light Yield, ph/MeV	~10K	1800	63k	200	~60
Light emission time	2 – 4 ns	0.8 ns	25 ns	6/30 ns	~1ps

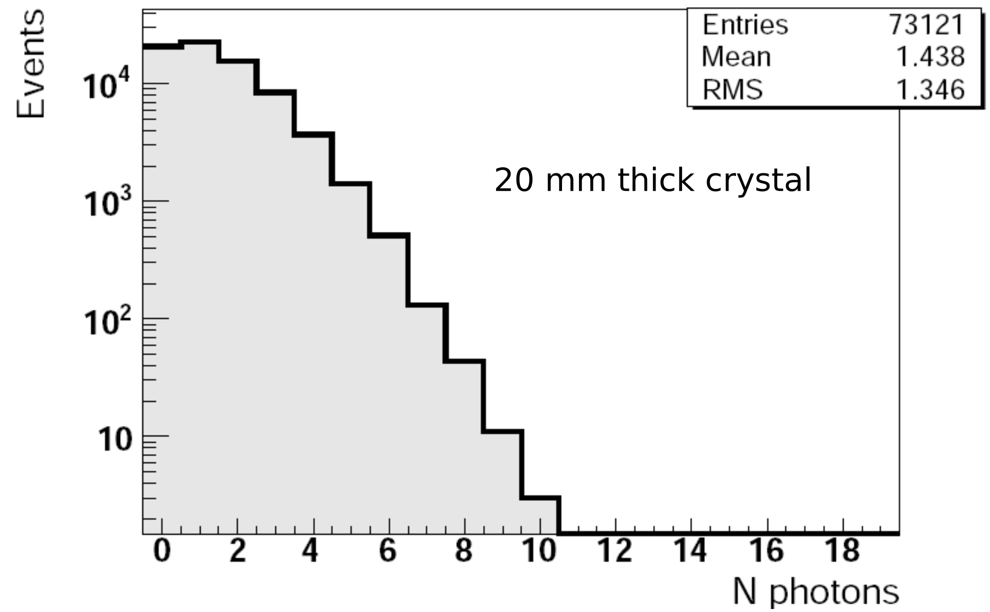
- Similar to Korpar et al. TIPP 2011 1531–1536 (2012).
  - Efficiency $\leq$ 8% $\Rightarrow$ too small for PET applications
- Goal: improve efficiency at least by a factor of four by improving the optical interface:
  - MCP-PMT with Sapphire Window
  - Use of the molecular bonding to glue MCP-PMT with the crystal (no optical grease)
- This idea is patented by CEA:
  - D. Yvon, CEA, French Patent 136103, November 12, 2013



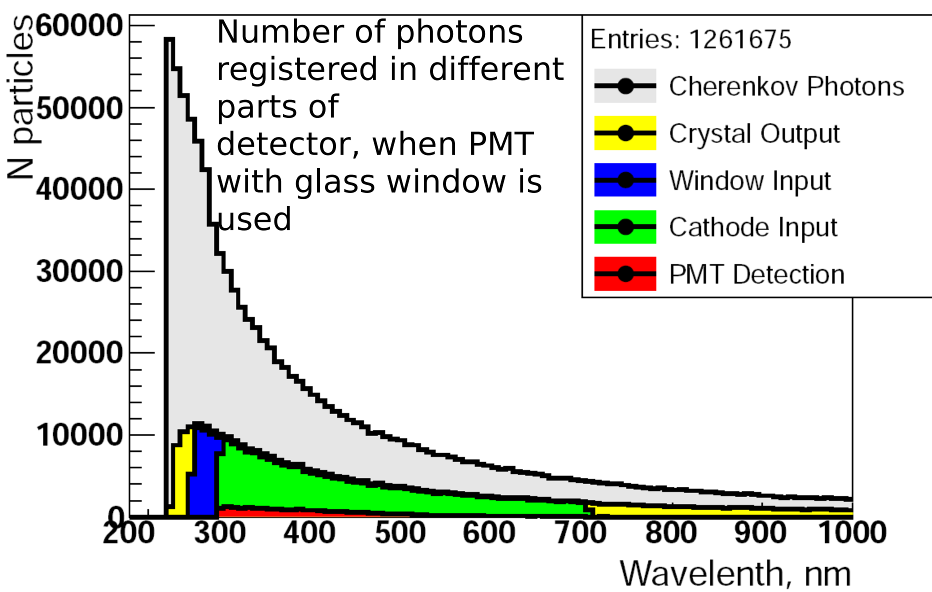


Geant 4 Simulation

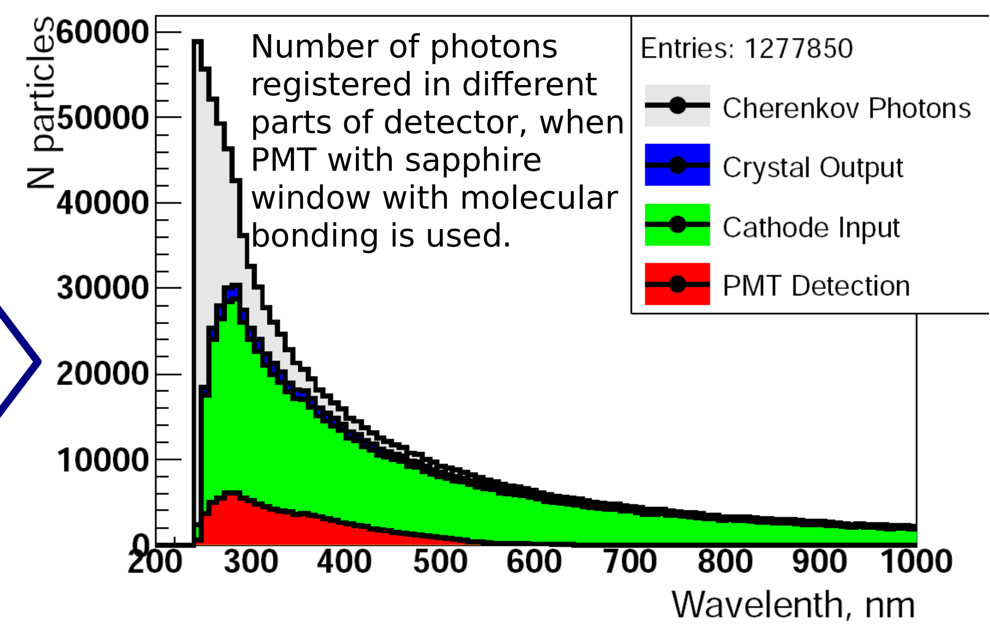
- Use Geant4 to simulate detectors with different geometries and different optical interfaces.



Conventional optical interface



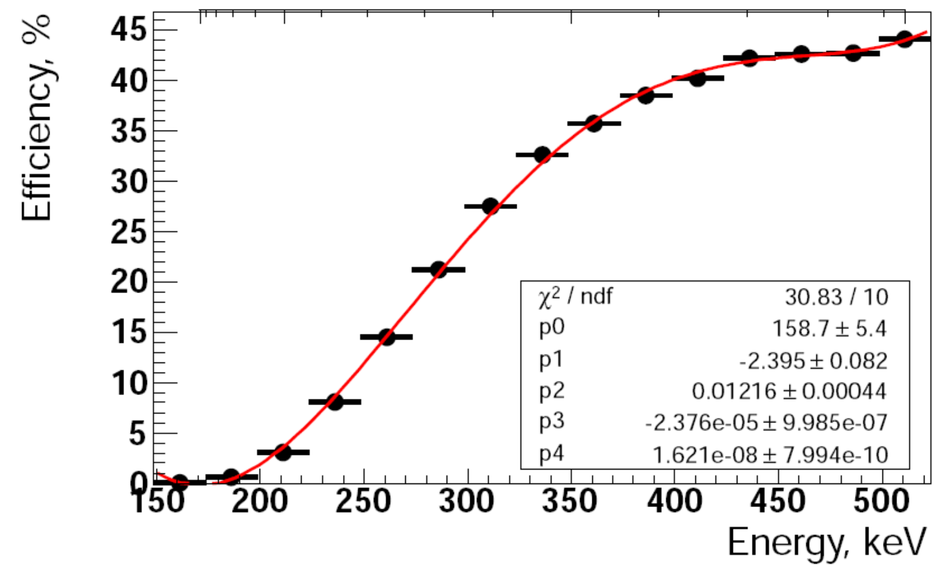
Improved optical interface



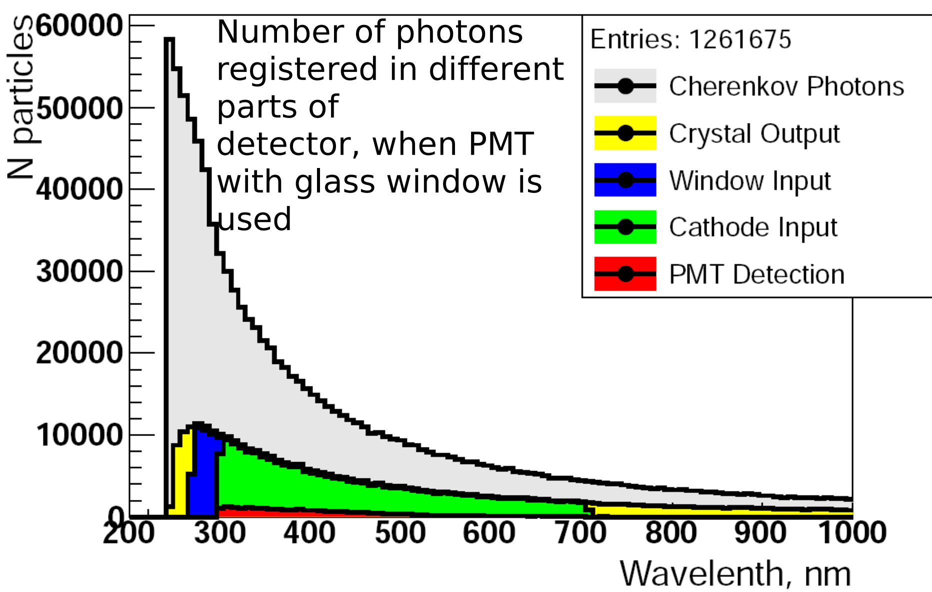
Geant 4 Simulation

- Use Geant4 to simulate detectors with different geometries and different optical interfaces.

Detection efficiency. 10 mm thick crystal painted in white.



Conventional optical interface



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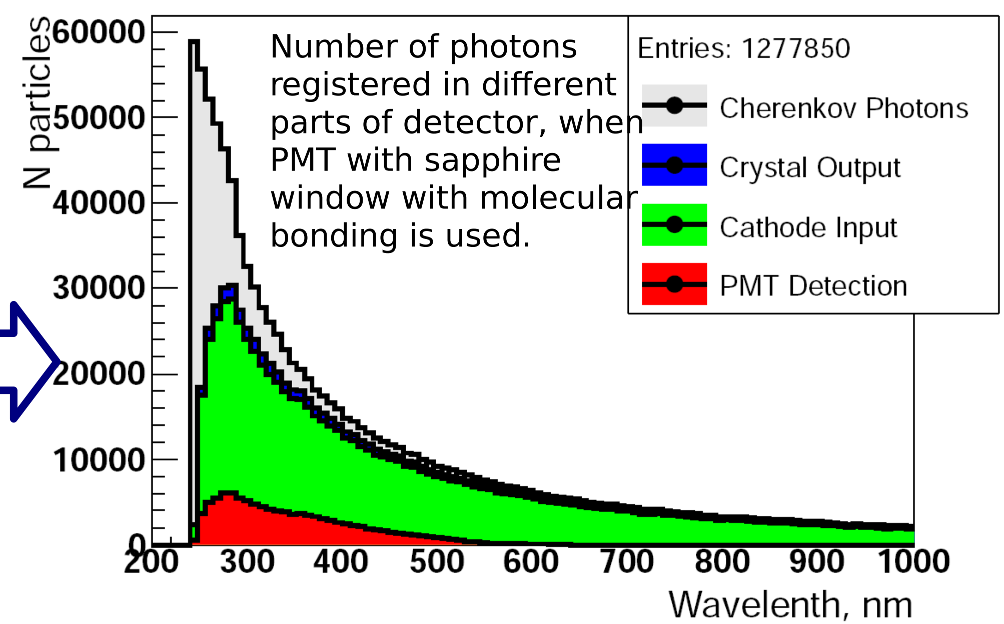
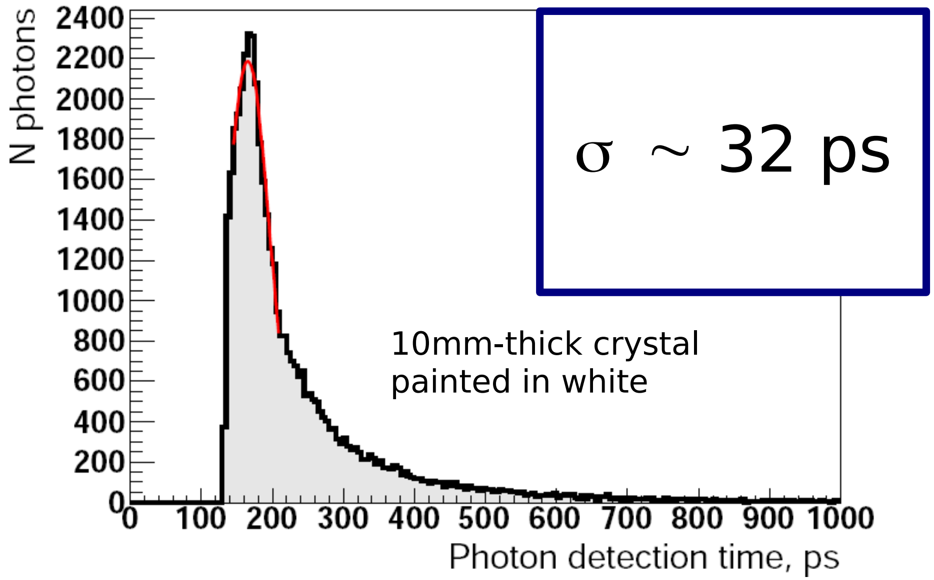
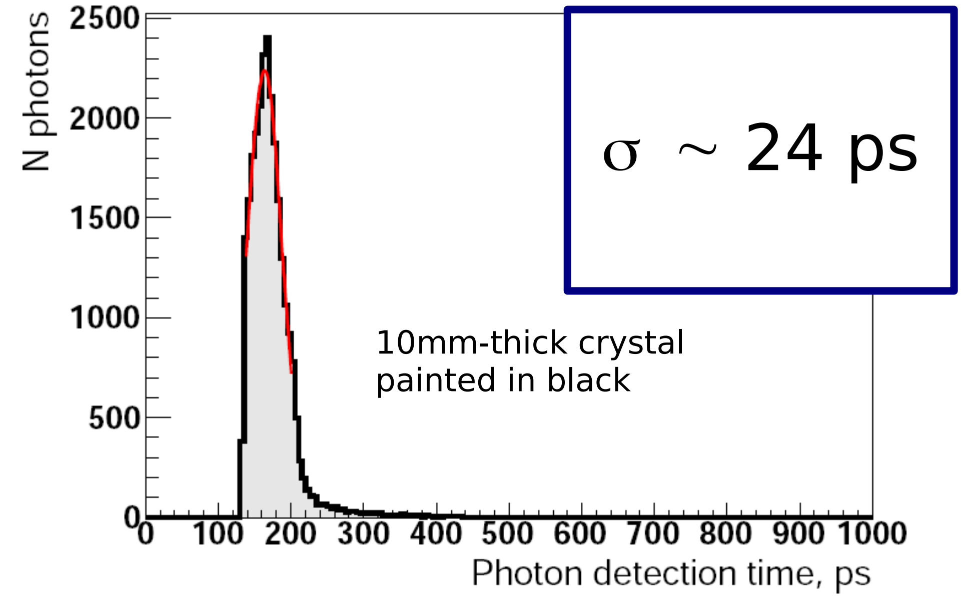
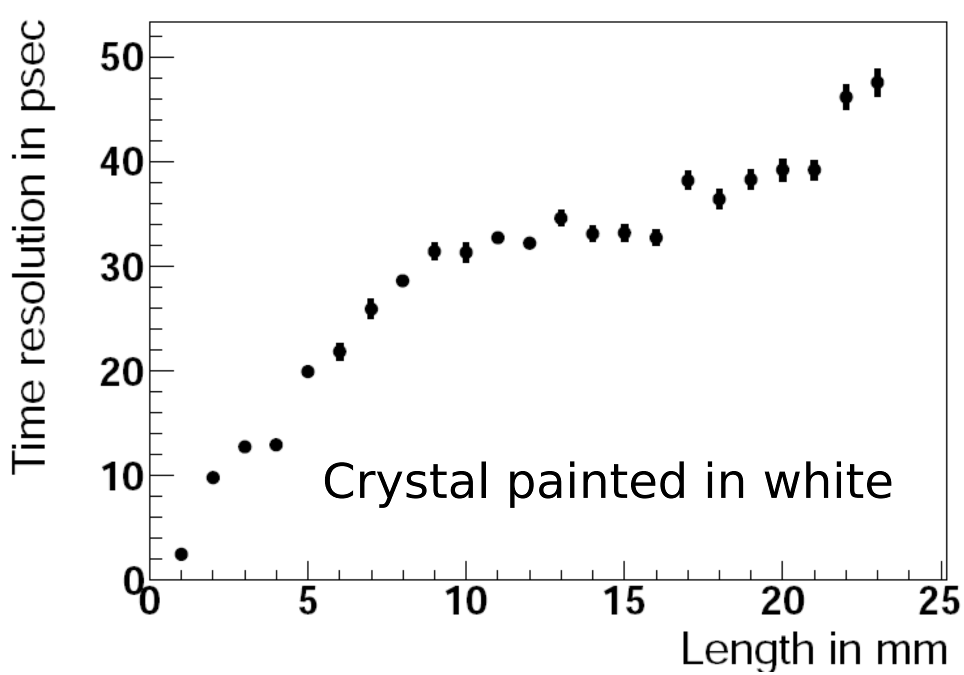
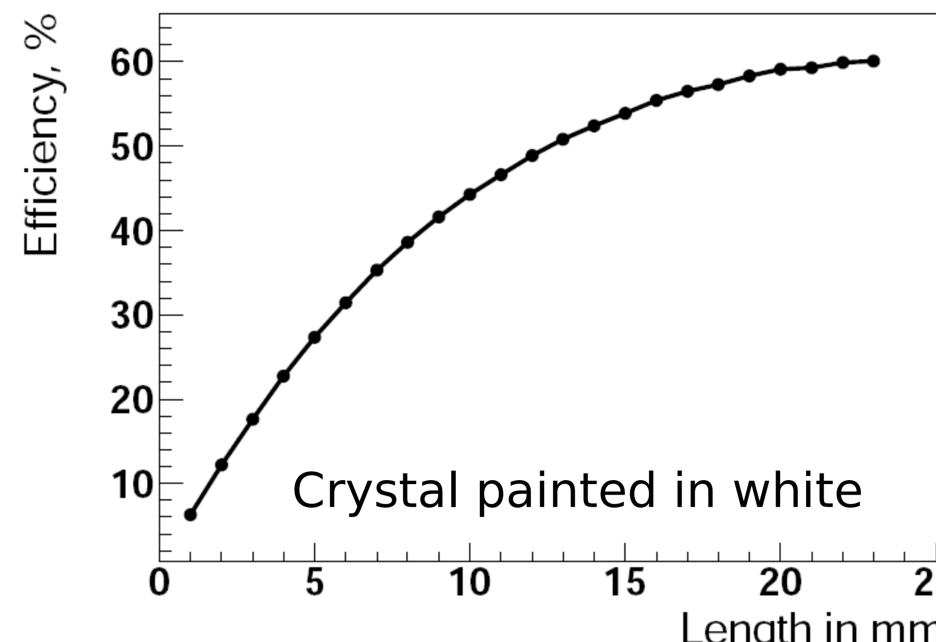


Efficiency versus timing



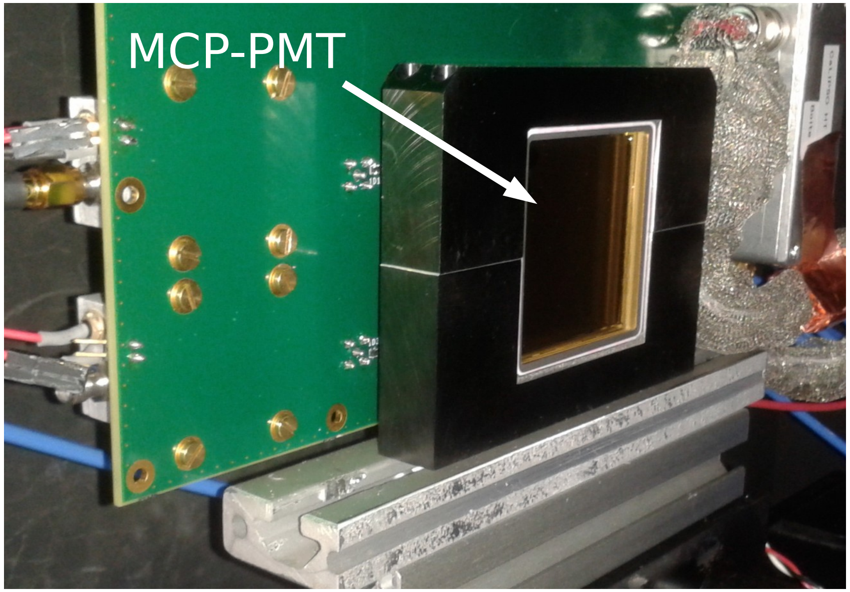






Current Status

- Started development of the fast readout chain
  - Test of the MCP-PMT with the Sapphire wndow (not yet with the optimal timing performance).
- First step: commission and test the read-out chain using PbF_2 and MCP-PMT + conventional optical interface.
- Prepare the the working place for the molecular bonding development.
- Will compare performance of the different detector configurations using Na^{22} test bench.



$PbWO_4$ Detector

	Plastic	BaF_2	$LaBr_3$	$PbWO_4$	PbF_2
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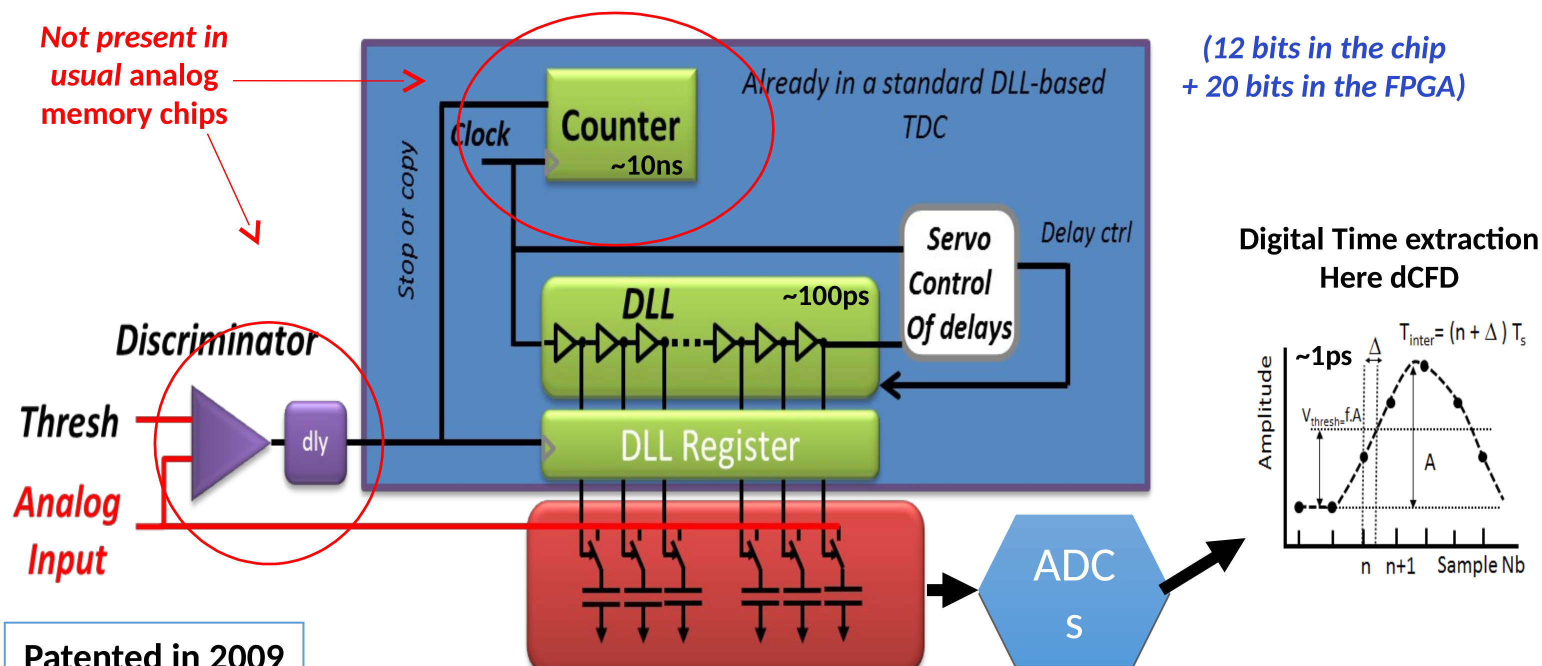
- $PbWO_4$ crystal + Si PM + Fast flash ADC (SAMPIC).
- Contains fast Cherenkov component + rapid Scintillation component
- Idea : distinguish between signals from a single photo-electron (PMT noise) and from the signal of longer duration from the scintillation using unique feature of the SAMPIC.

SAMPIC: the « Waveform TDC » Concept (WTDC)

- **WTDC: a TDC taking a snapshot of the relevant part of the analog waveform**
- Overall time information is obtained by combining 3 times :

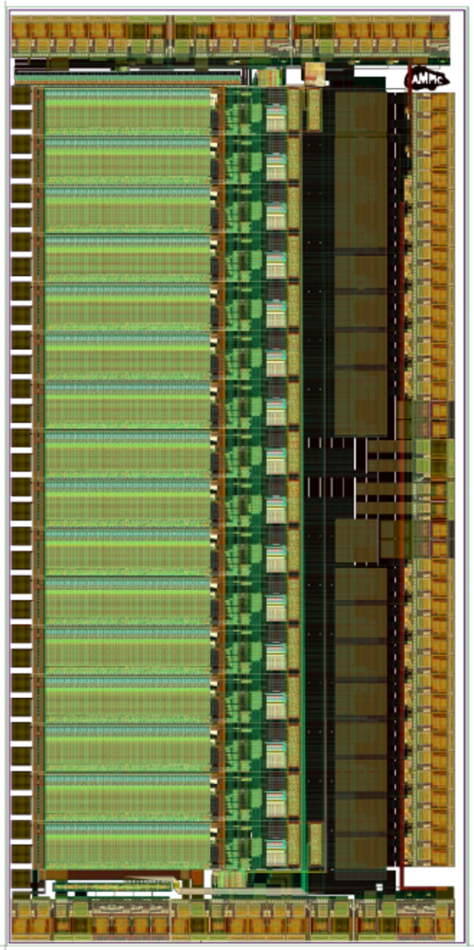
TDC [
- **Coarse** = Timestamp Gray Counter (few ns step)
- **Medium** = DLL locked on the clock to define region of interest (~100 ps step)
- **Fine** = samples of the waveform (**digital algorithm** will give a precision of a few ps)

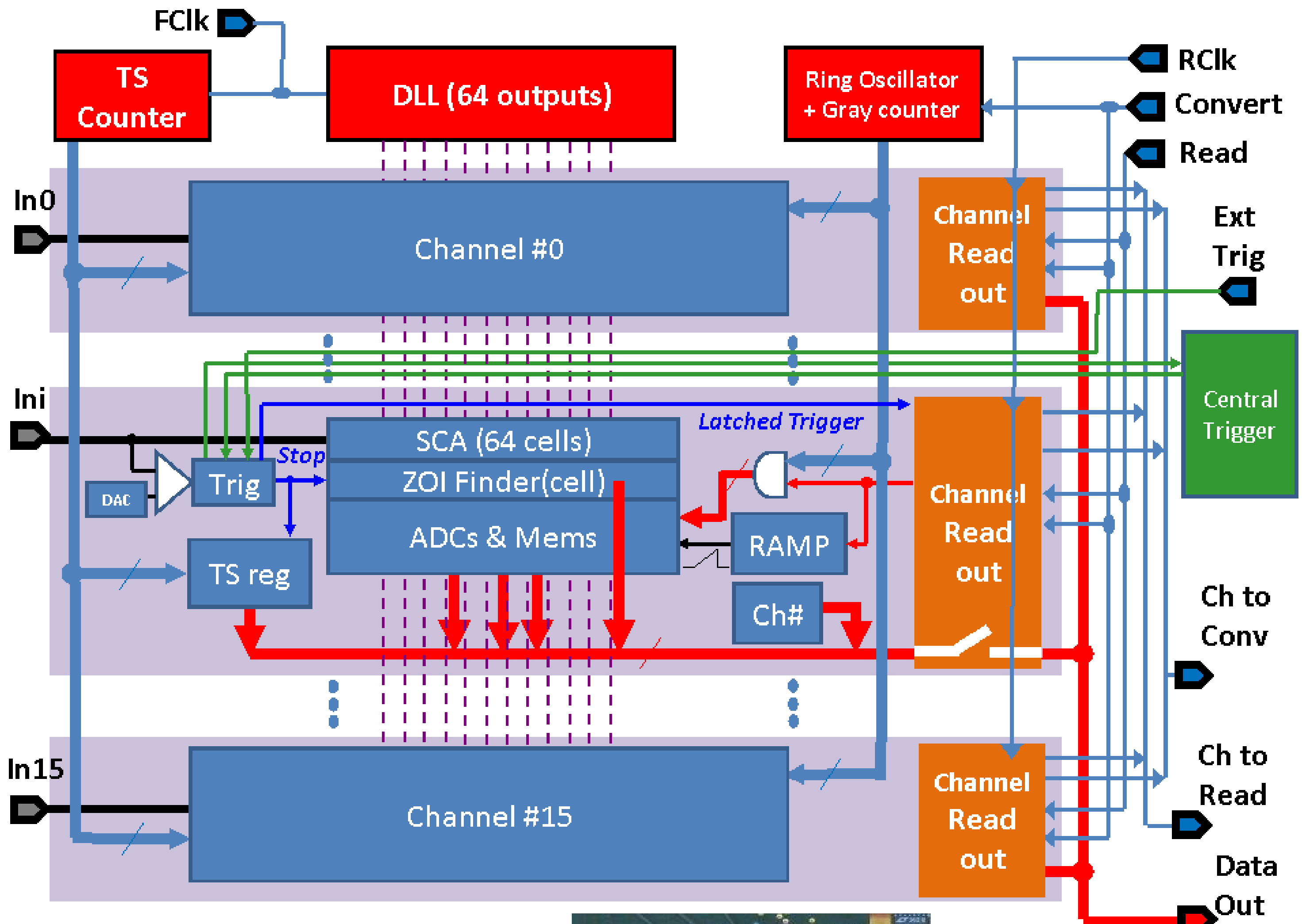
- **Discriminator is used only for triggering, not for timing => no jitter added on measurement, low power**
- **Digitized waveform available to extract other parameters (Q, amplitude,…)**



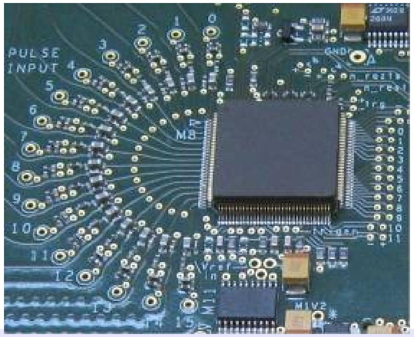
Patented in 2009

Global Architecture of SAMPIC



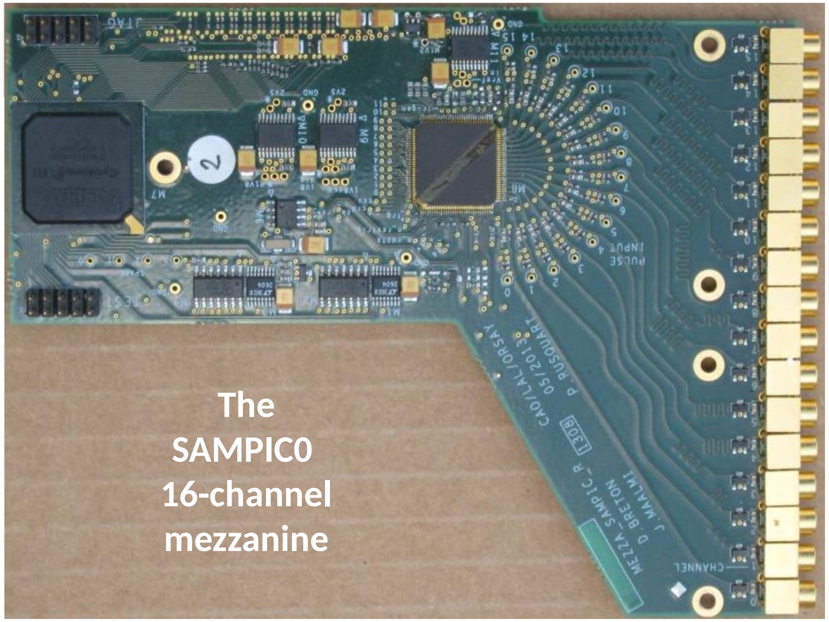


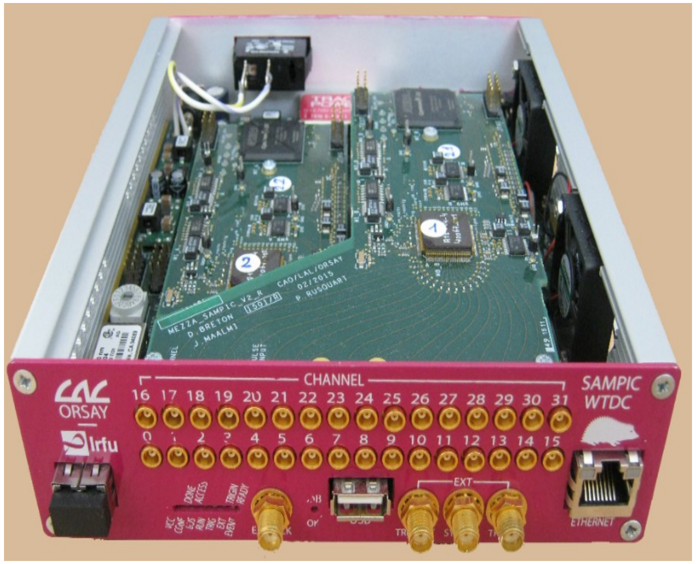
- Technology: AMS CMOS 0.18µ
- Size: 8 mm^2
- Package: 128-pin QFP, pitch of 0.4mm



32-Channel Module & Acquisition Software

- **Chip prototyped in AMS 180nm CMOS (8mm²)**
- **First version: SAMPIC0. Now using SAMPIC1.**
- **32-channel module integrating 2 mezzanines**
- **1 SAMPIC/mezzanine**
- **USB, Ethernet UDP**

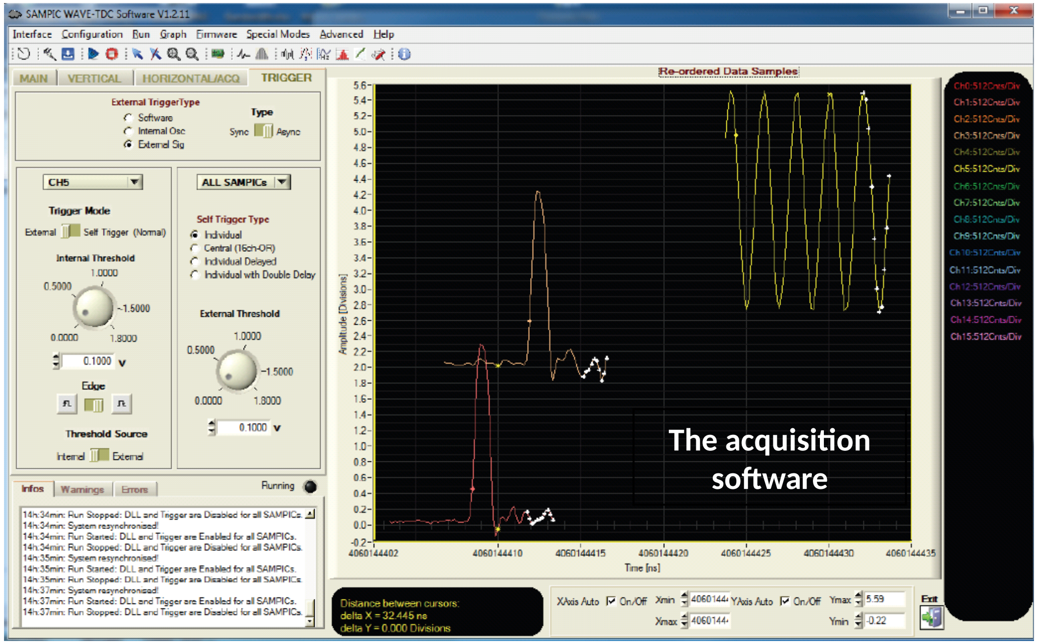




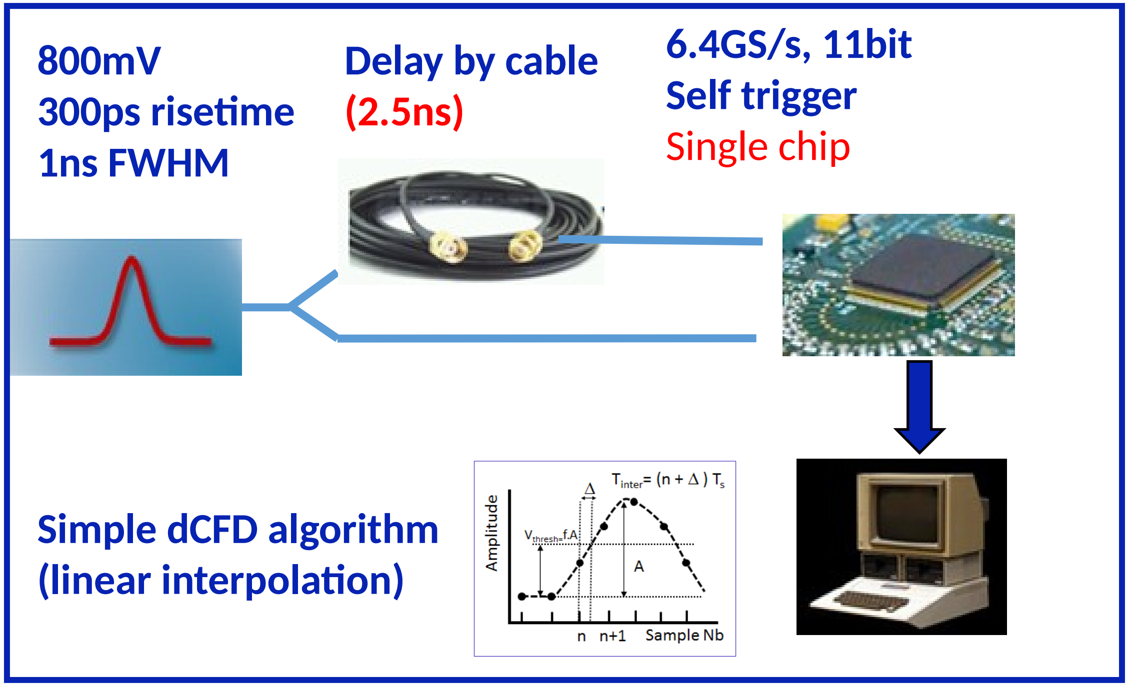
- **Acquisition software** and C libraries

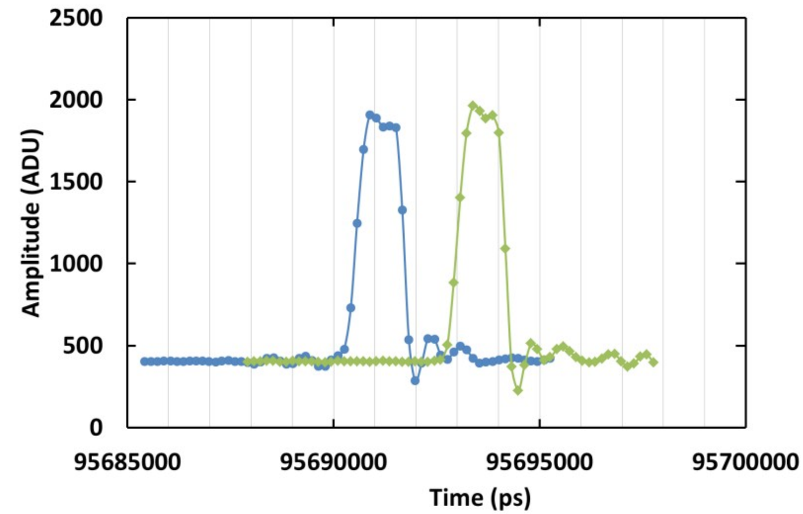
=> full characterization of the chip & module

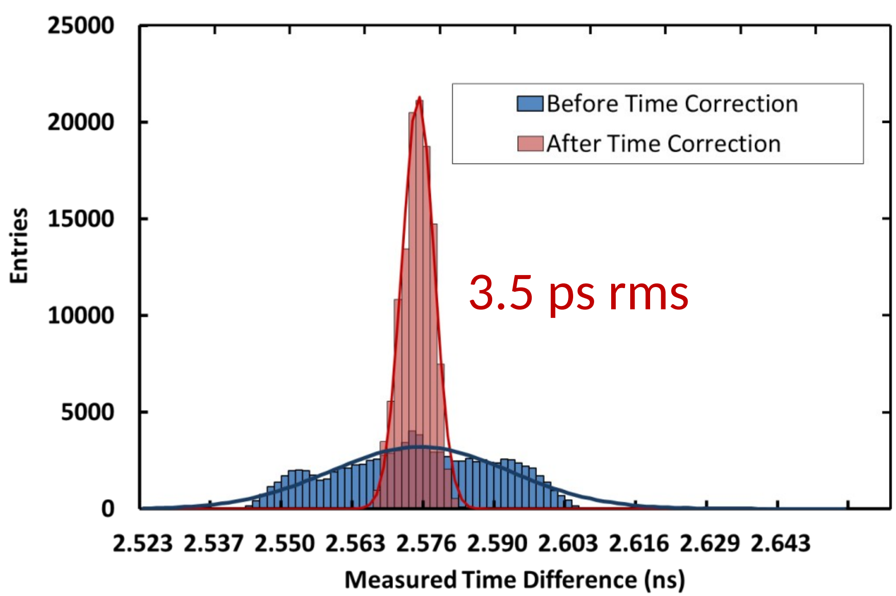
- Timing extraction (dCFD, interpolation…)
- **Special display** for **WTDC mode**
- Already used for small scale experiments



Timing Difference Resolution (TDR)





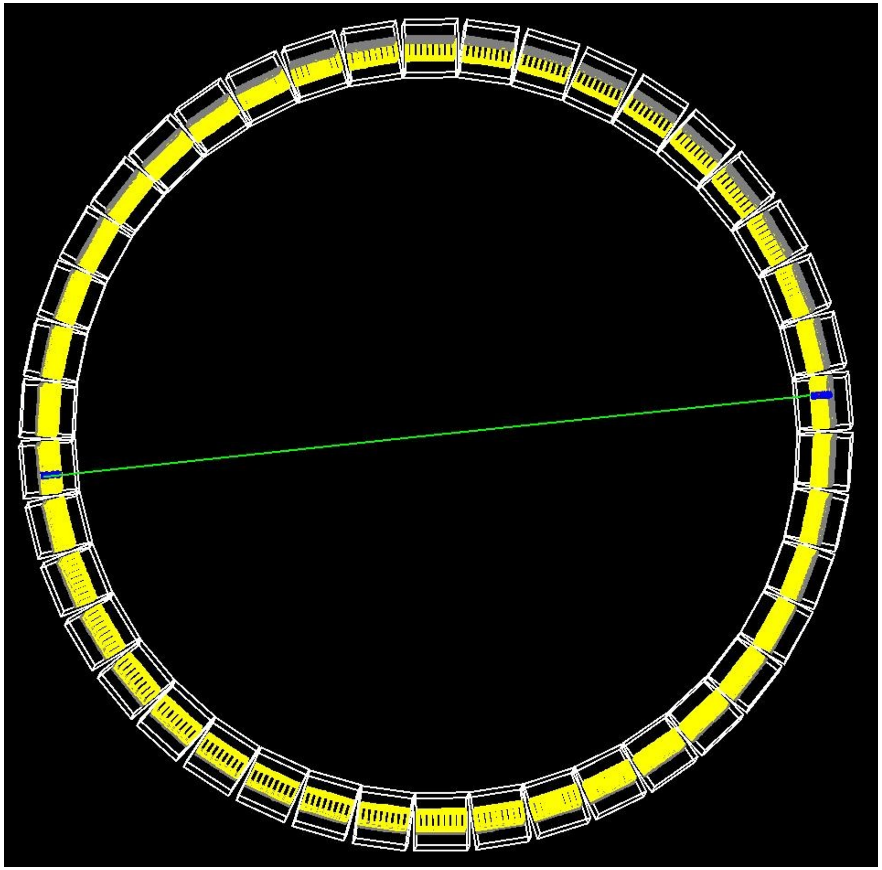


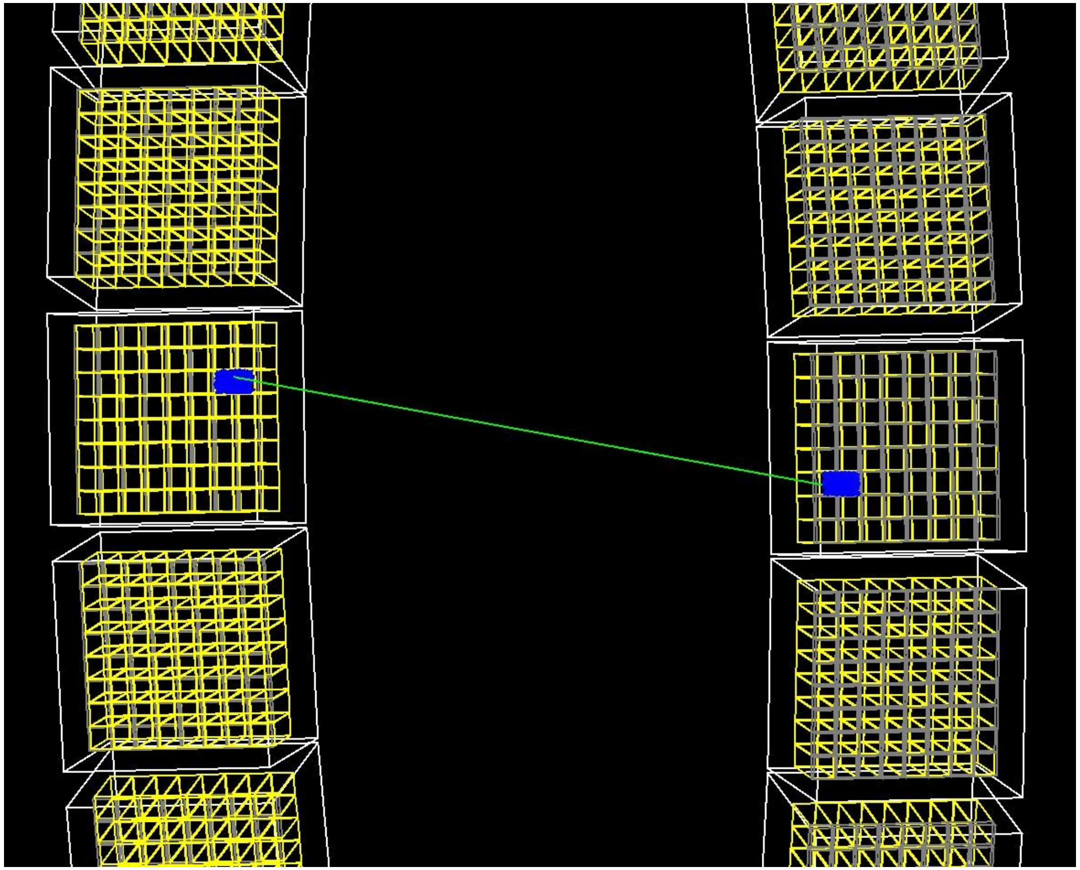
- TDR = 18 ps rms before any time correction
- Non gaussian distribution due to DLL non uniformity (TINL)
- Can be easily calibrated and corrected (sinewave crossing segments method [1])
- TDR = 3.5 ps rms after simple correction

[1] D. Breton et al, TWEPP 2009, p149

Scanner Simulation With Gate

- GATE is Geant4 based software dedicated to simulations in medical imaging and radiotherapy.
- Allow to estimate the scanner parameters (spatial and time resolution, noise equivalent count rate, image contrast recovery).
- Will be used to chose the best detector configuration with optimal efficiency / time resolution combination.





Conclusion

- Started the development of the detector with the extremely high resolution in time and good efficiency.
  - Devoted for use in TOF-PET, but also suitable for any application where timing is important, e.g. material studies using positron annihilation lifetime spectroscopy.
- Started first tests with MCP-PMT and the development of the fast read-out chain.
- Prepare tests with the molecular bonding.
- Work on SAMPIC development is ongoing.
- Started the work on the full scanner simulation with GATE and will use simulation results to choose the optimal technology and parameters of the gamma detector.