The MIP Timing Detector for the CMS Phase-2 Upgrade

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In collaboration with

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TagusLIP Laboratory

TagusLIP activities:

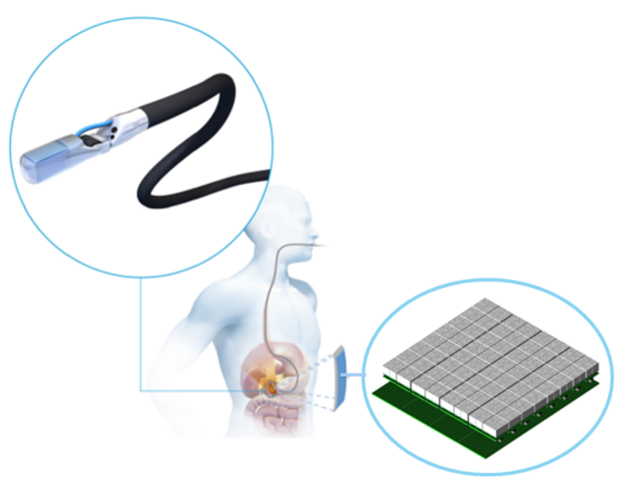
- Development of readout electronics, data acquisition software and firmware for medical applications and HEP

- Design, production and test/validation of detector modules and prototype systems

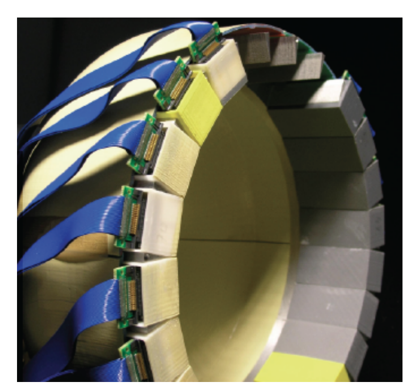
PETsys electronics is a start-up company created at LIP to develop readout electronics for SiPM based PET systems

ClearPEM (2010)

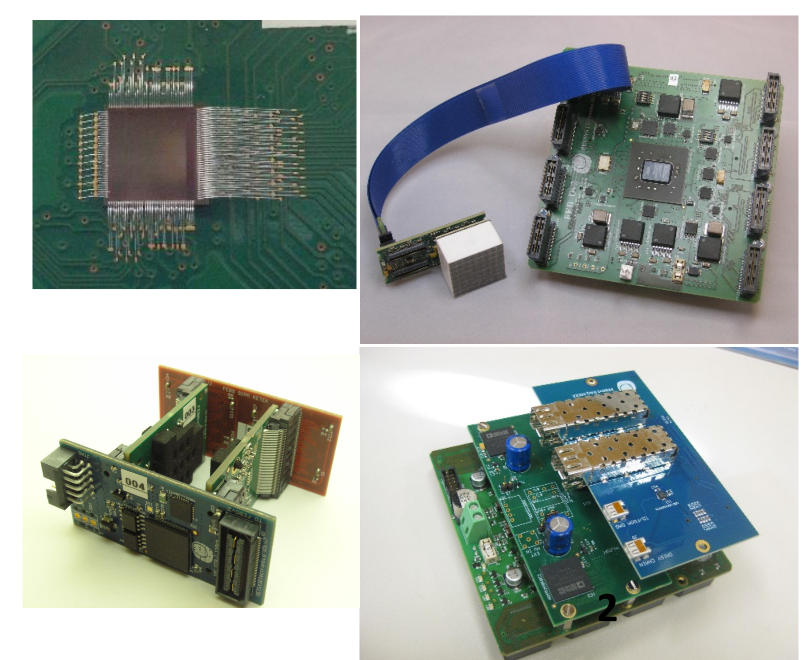
EndoTOFPET (2013)



TOFPET demonstrator (2016)

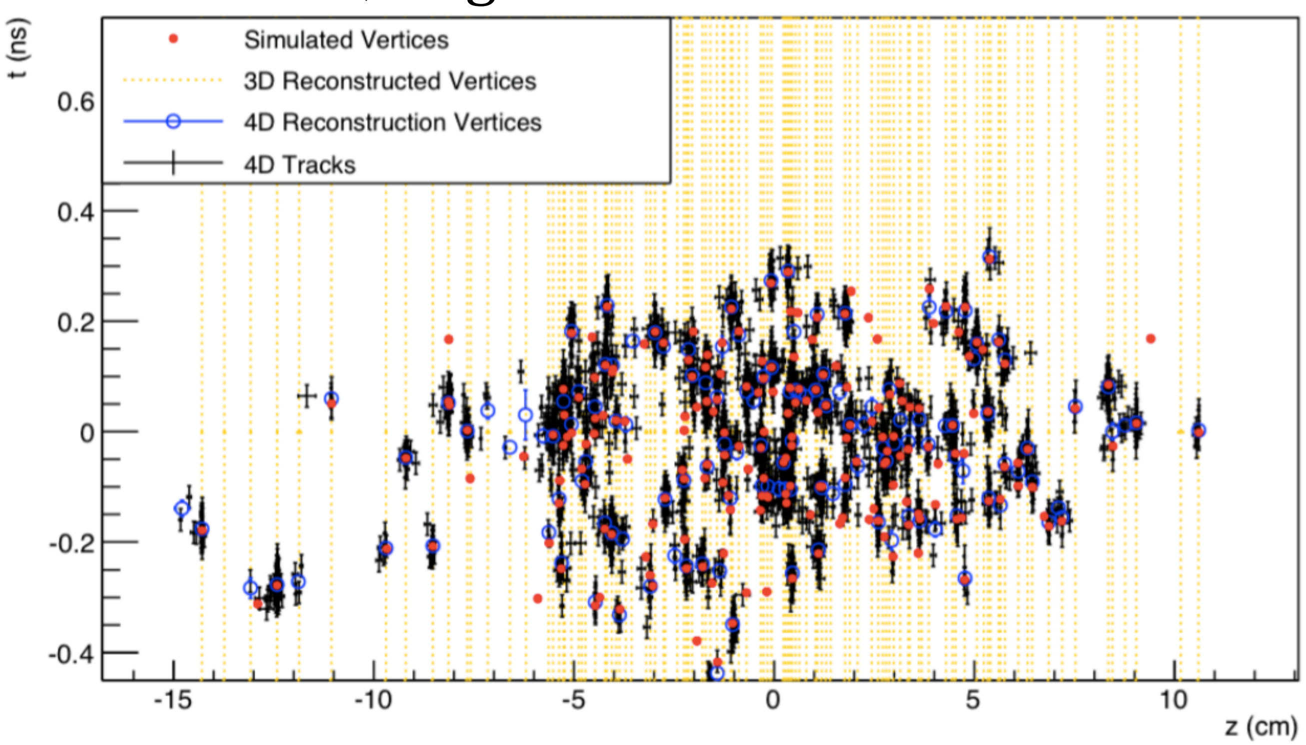


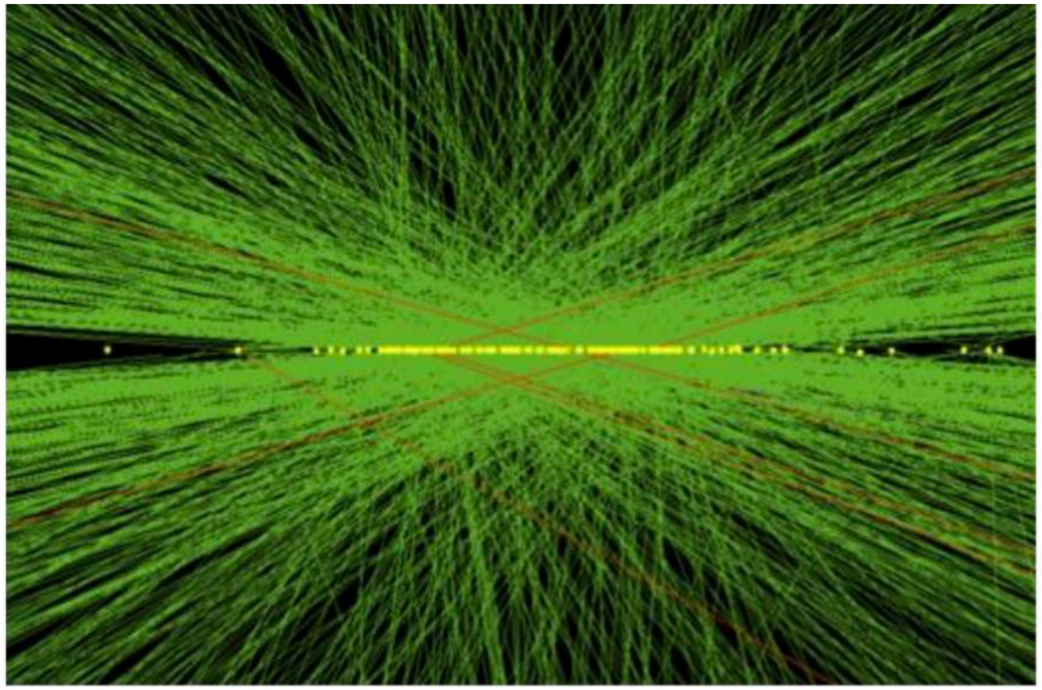
PETsys products



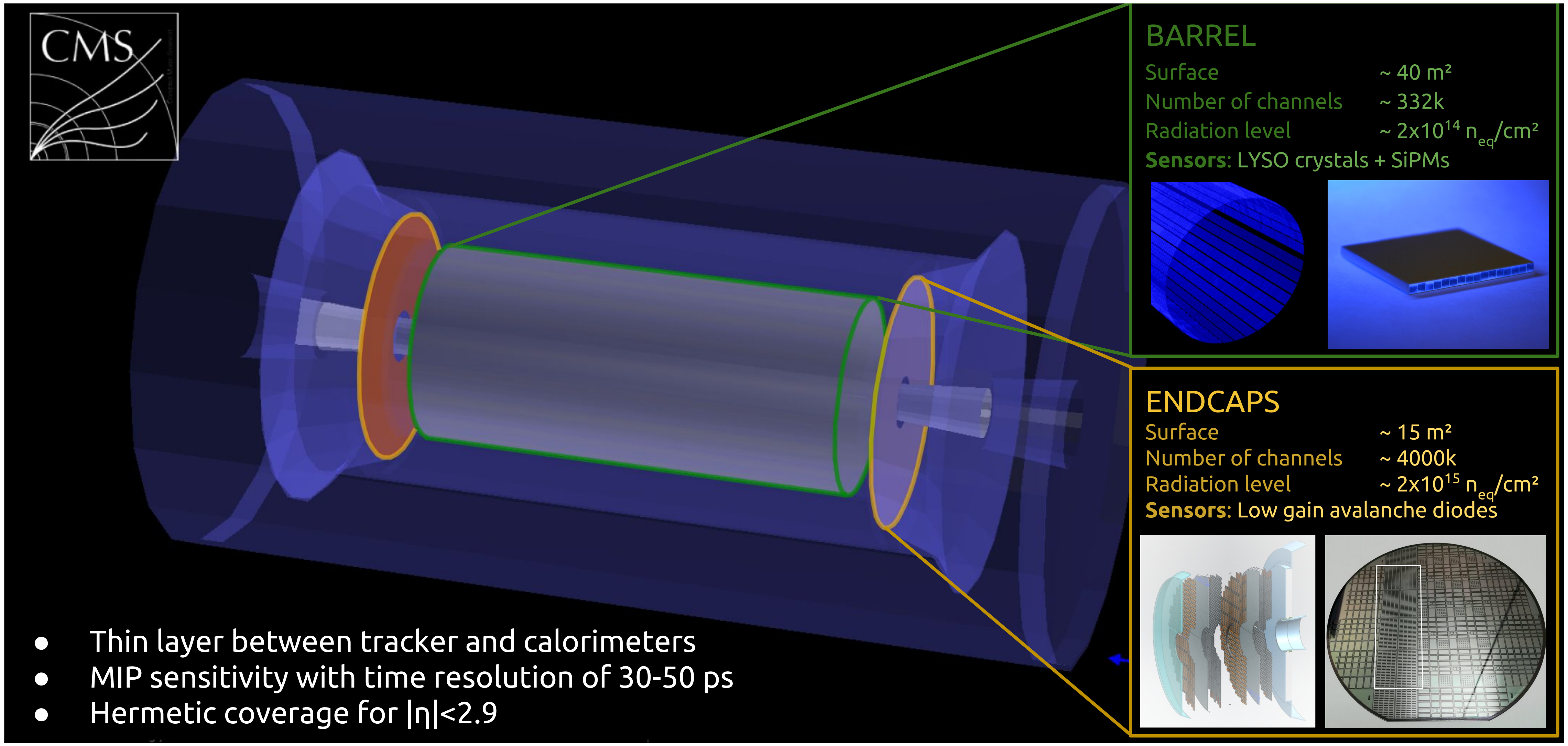
High-Luminosity HL-LHC Challenge

- HL-LHC targeted luminosity for CMS in phase-2 upgrade is (5-7.5)x10^{34} Hz/cm^2 (140-200 pileup events) -> up to 5 times vertex density
- This can degrade the identification and the reconstruction of the interaction
- Exploit the time spread of collision vertices (RMS ~180ps) to provide extra separation power against pileup collisions
- Time resolution of 30-50 ps for charge particles throughout the HL-LHC can be achieved with thin, large area and cost-effective detectors





MIP Timing Detector: Design and Technologies



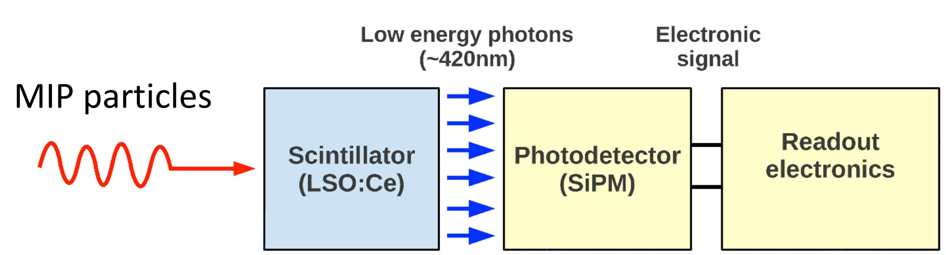
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for $|\eta|<2.9$

Barrel Timing Layer Sensors:

- ➢ LYSO:Ce scintillator crystal bars (~3x3x57 mm^2)
- ➢ SiPM readout (double ended readout)
- ➢ 332k readout channels

BTL Readout Electronics:

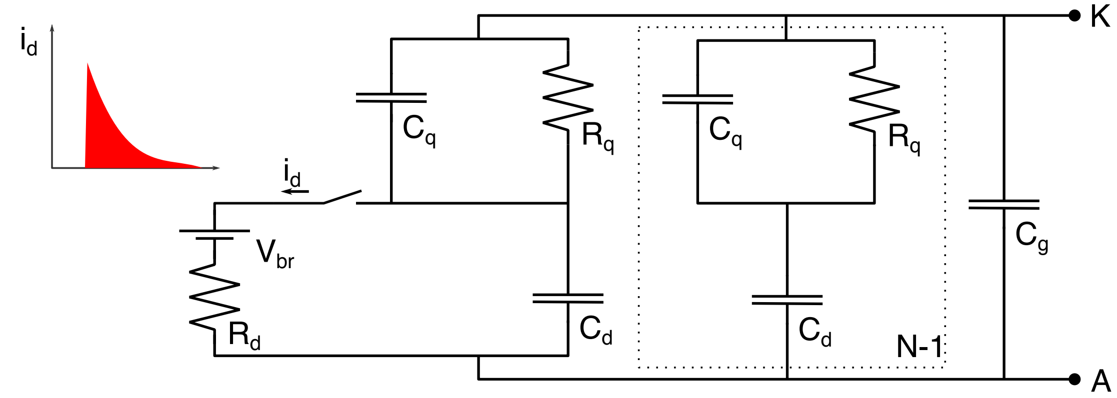
- ➢ Analog processing and digitization of SiPM signals



Operation Conditions

- Radiation has a big impact on the SiPM performance
- Strong increase of dark count noise
- Decrease of QE and gain

Electrical Model of the SiPM



HDR2 parameters along BTL life

Integrated luminosity (fb-1)	Number of p.e.	SiPM gain	DCR (GHz)
0	9500	3.8×10^5	0
500	9000	2.9×10^5	20
1000	8000	2.5×10^5	30
2000	7000	1.9×10^5	45
3000	6000	1.5×10^5	55

HPK HDR2

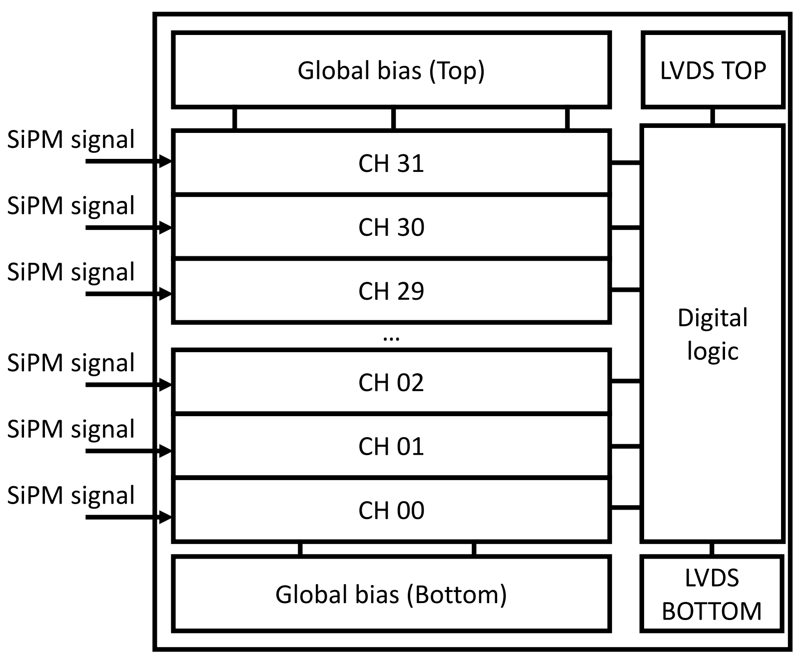
C_d	14.6 fF
C_q	1 fF
C_{grid}	36 pF
R_q	500 kΩ
R_d	1kΩ
N_{cells}	40,000

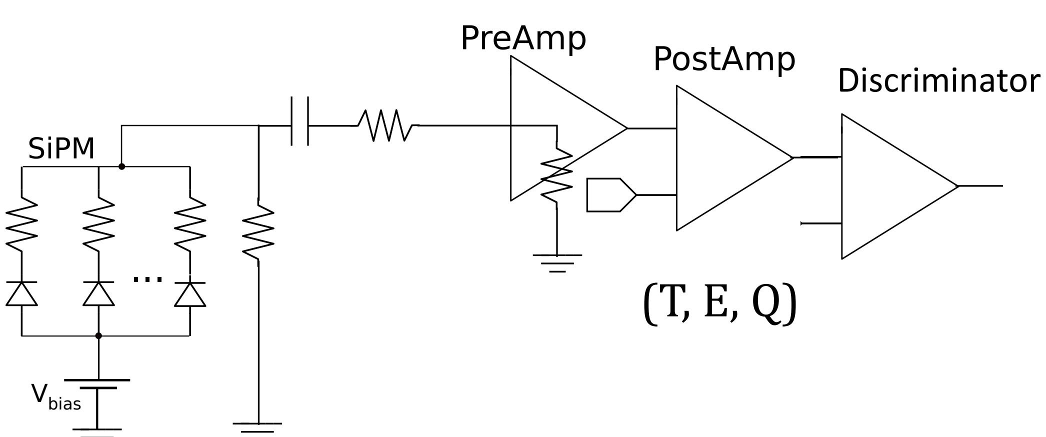
Challenges:

- minimize impact of DCR noise on time resolution
- handle the variation of dynamic range along detector lifetime (factor 4)
- cope with very high rate (2.5 MHz MIP + 5 MHz low E hits per channel)

BTL Front-End Chip (TOFHIR) Versions

- **TOFHIR stands for Time of Flight High Rate!**
- TOFHIR has been developed in collaboration with **LIP** and **PETsys Electronics**
- TOFHiR1 (UMC 110 nm): Available
- TOFHiR2 (TSMC 130 nm): MPW submissions on Feb. 12, 2020





Specification table

	TOFHIR1	TOFHIR2
Number of channels	16	32
Technology	UMC 110 nm	TSMC 130 nm
Voltage	1.2 V, 2.5 V	1.2 V
Radiation Tolerance	No	Yes
Compatibility with lpGBT	Yes	Yes
I/O links	LVDS	CLPS
L1, L0 Trigger	Yes, No	Yes, Yes
10-bit SAR ADC (MHz) (*)	10	40
Bandwidth (MHz)	350	350
Input impedance (Ω)	6	6
DCR noise filter	No	Yes
Number of TACs and QACs	4	8
TDC bin (ps)	20	20
Reference voltages	External	Internal
Maximum MIP rate/ch (MHz)	1	2.5
Max low E rate/ch (MHz)	3	5
Clock frequency (MHz)	160	160

(*) SAR ADC 40 MHz provided by Krakow group

Results with TOFHIR1

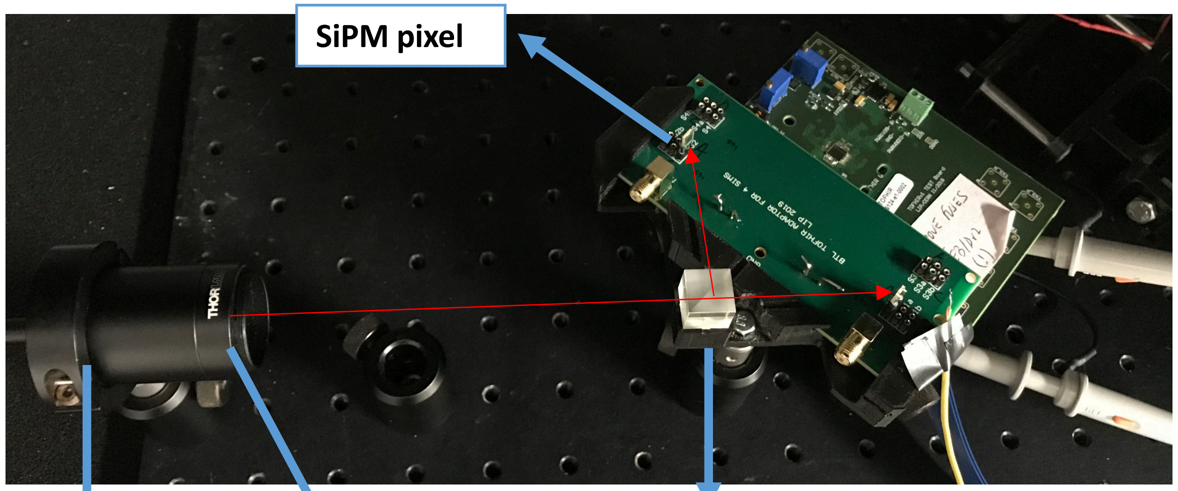
→ SiPM type: HDR2 (BTL type)

- 1 pixel (3x3 mm^2, 15 um cells)
- Typical gain in the order of a few 10^5

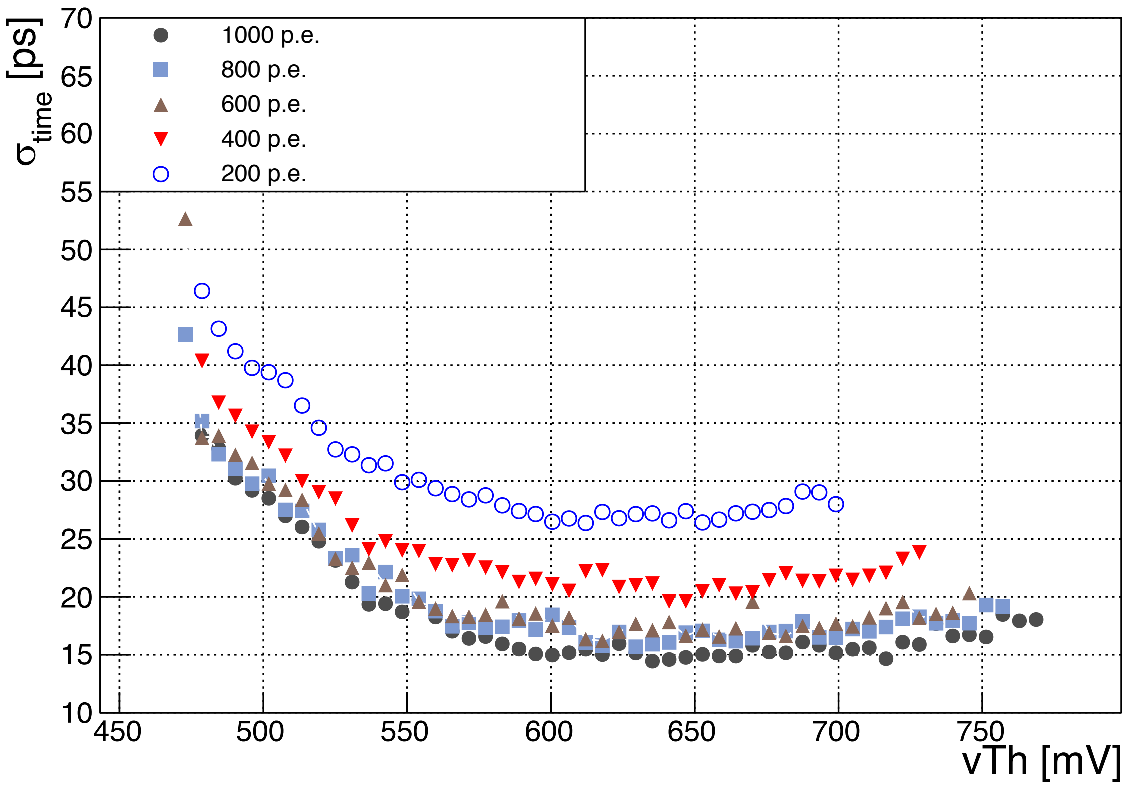
→ SiPMs are triggered by laser pulses (50 ps pulse width)

→ Tests are done at room temperature

→ $\sigma^2_{time1-time2} = \sigma^2_{time1} + \sigma^2_{time2}$



Channel time resolution



→ 200 p.e. laser pulse has the same slew rate as 8000 p.e. LYSO pulse (~ 1 MIP)

→ Single channel time resolution is 26 ps

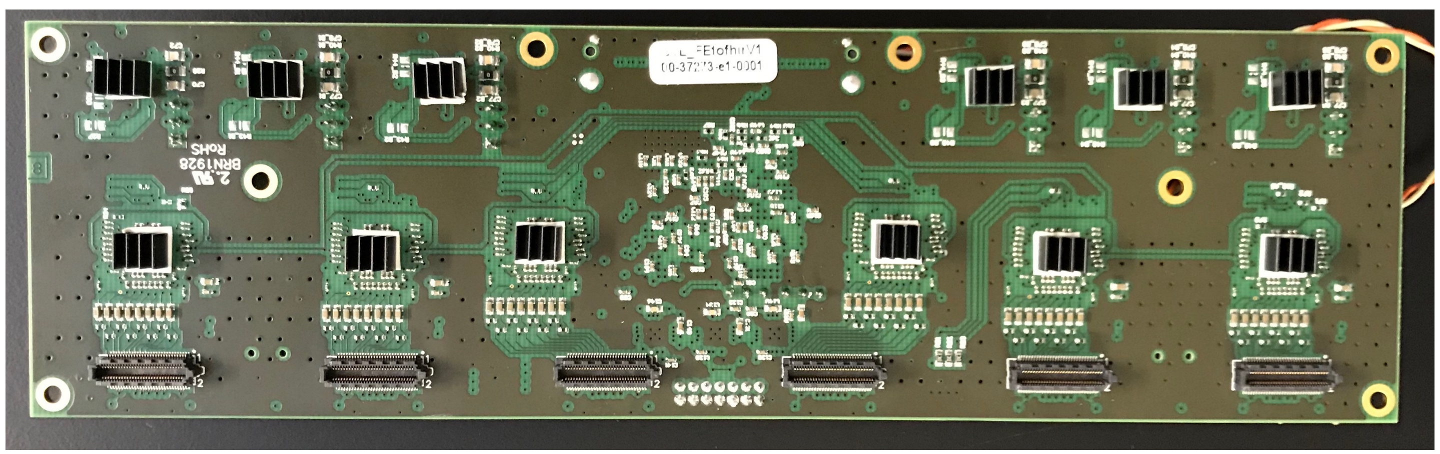
- Laser pulse with 200 p.e.
- ToT selection to remove time walk
- LYSO photostatistics not taken into account

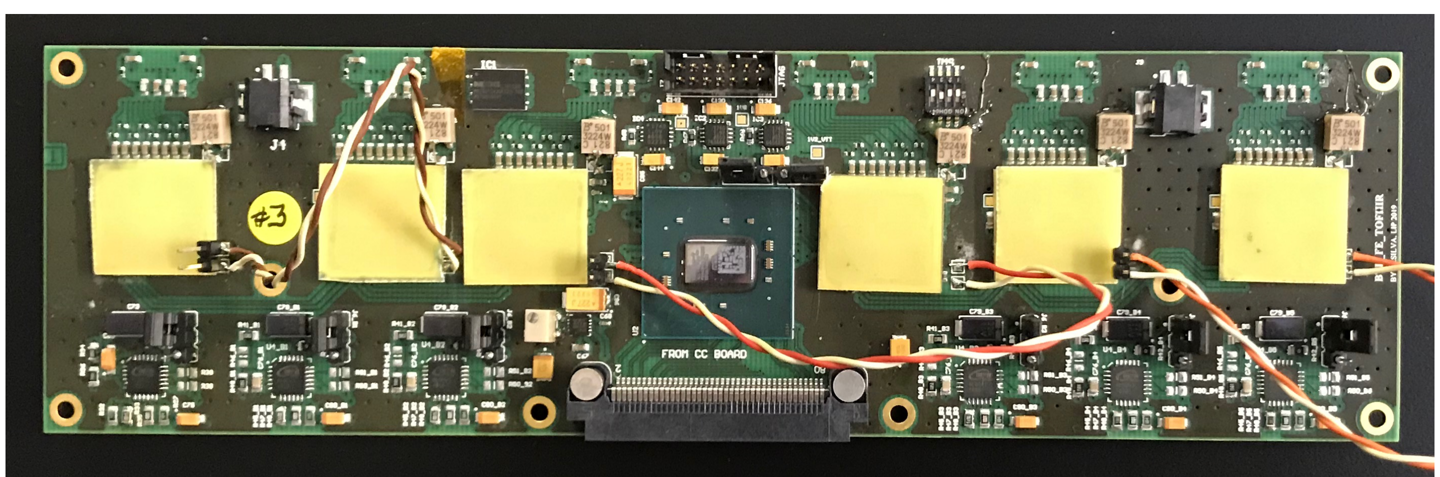
FE Board Prototypes

- FE prototype with TOFHIR1 and ALDO1 ASICs
- 6 connectors for SiPM signals in the back side
- 1728 FE boards in the system, plus spares.

→ 4 FE prototype have been assembled and tested

→ All 4 prototype boards are working

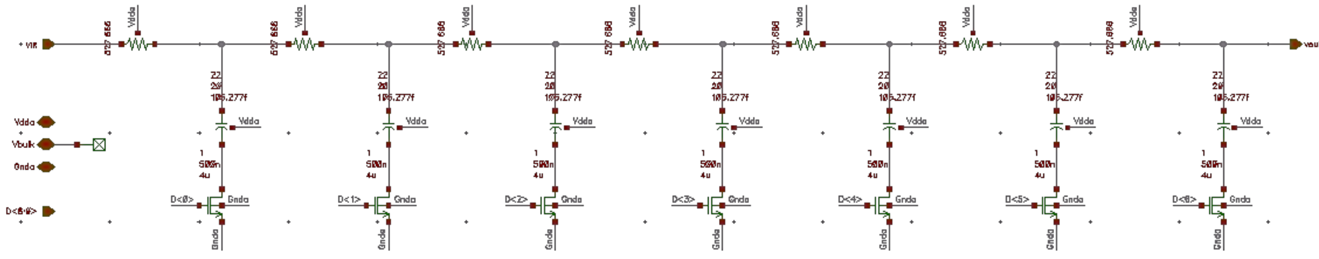




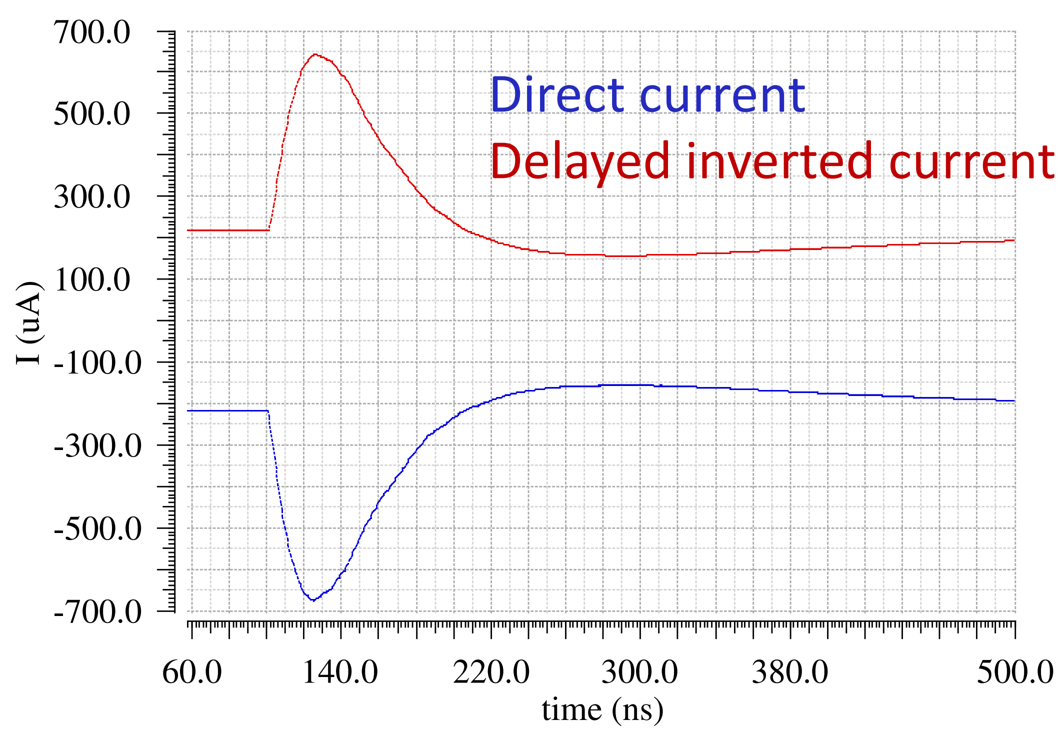
DCR Noise Cancellation in TOFHIR2

Post-amplifier consists of:

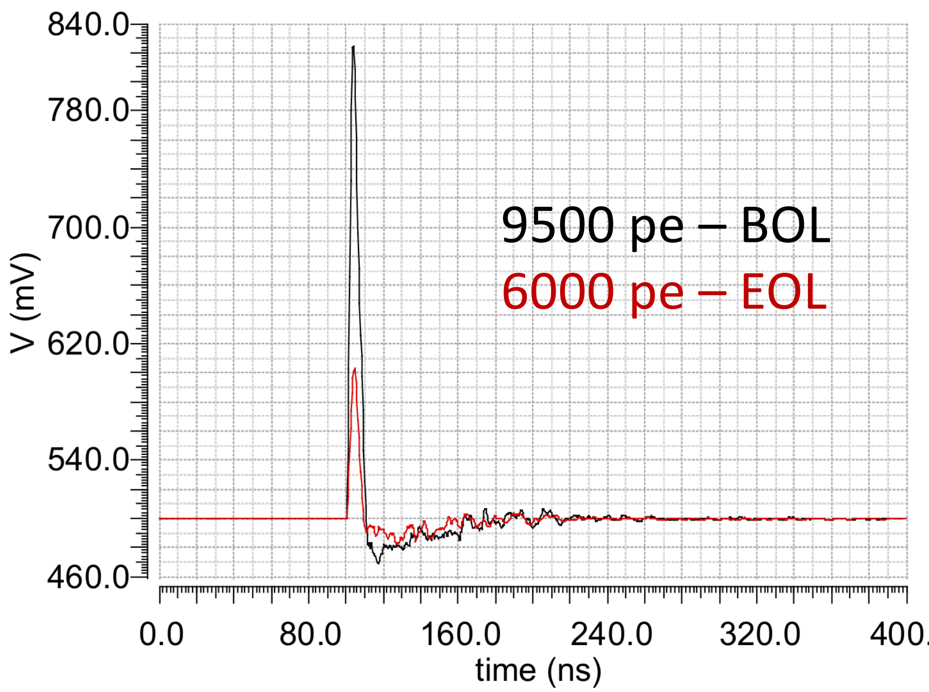
- Analog delay cell that is approximated by a RC net, with a configurable delay
- Current subtraction that adds the inverted delayed pulse to the original pulse
- Baseline holder



PostAmp input current



PostAmp output voltage



- Short output pulse (~20 ns)
  - long tails of LYSO decay are cancelled
- Baseline fluctuation due to pile-up are cancelled

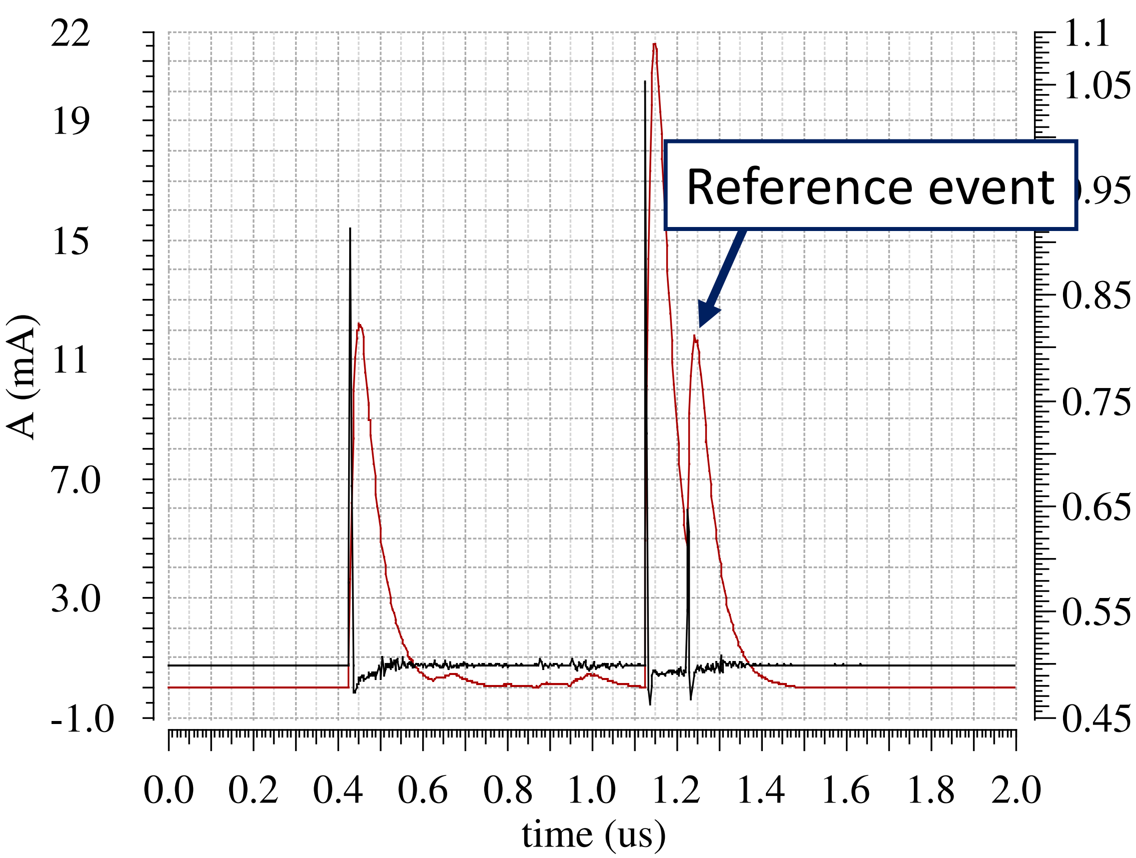
BTL Events Simulation

→ **LHC frequency 40 MHz**

→ **Bunch width 200 ps**

→ **Samples :**

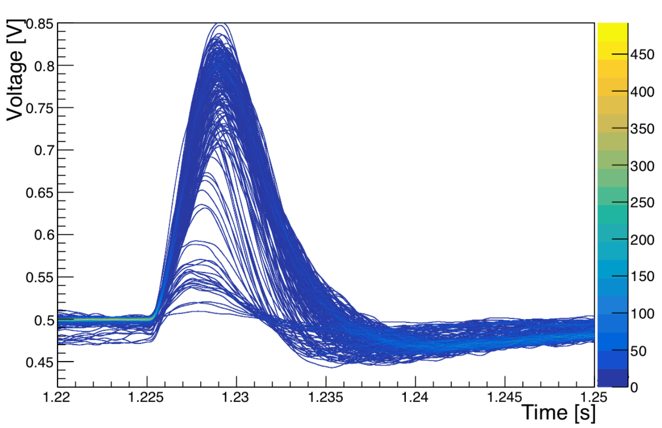
Each sample is a series of events coming randomly every 25 ns with various amplitudes for a fix duration of time, but the last event (50^{th}) is always 1 MIP (reference event).



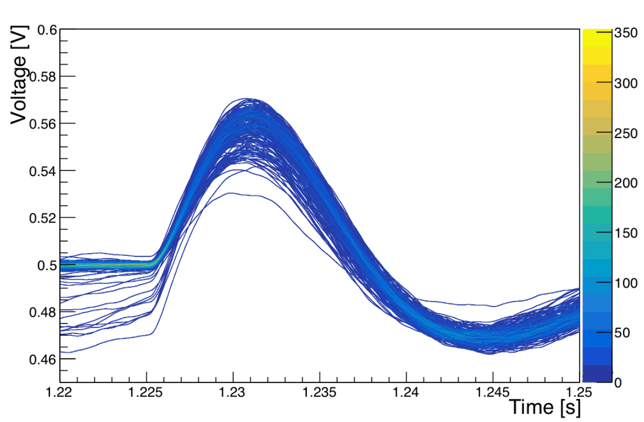
Pulses at the beginning of life:

- 9500 p.e. LYSO pulse
- Gain 3.8×10^5
- No dark count
- SiPM Jitter 100ps
- Temperature 0^o C
- cross talk probability 14%
- Electrical noise
- TDC digitization (20ps)

Distribution of the reference events at the post-amp T branch

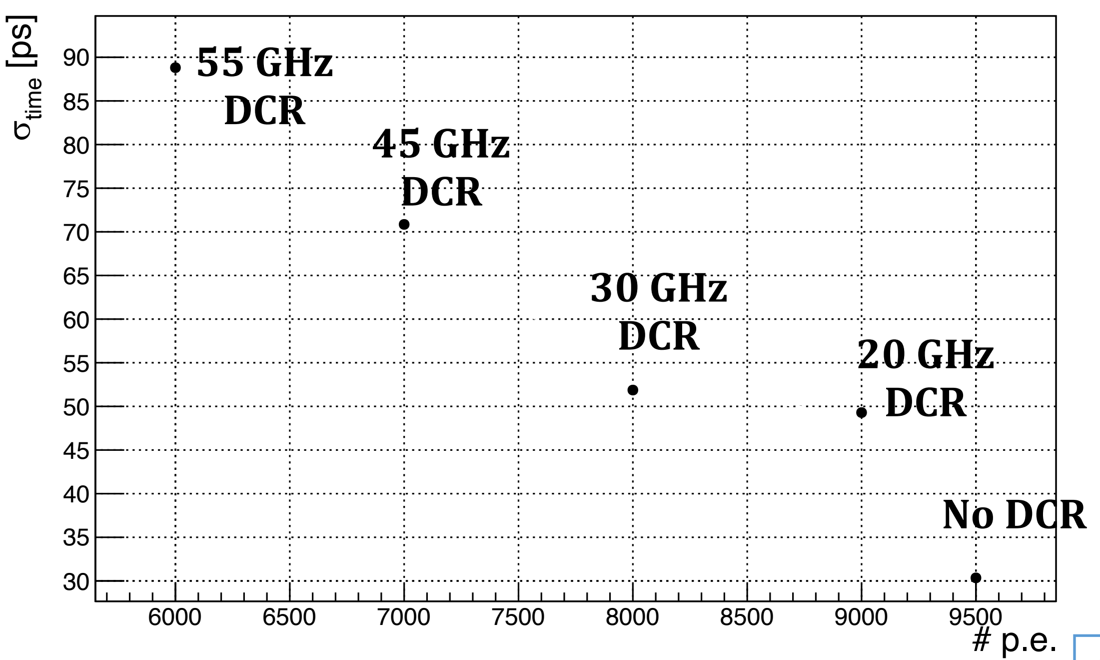


Distribution of the reference events at the post-amp E branch



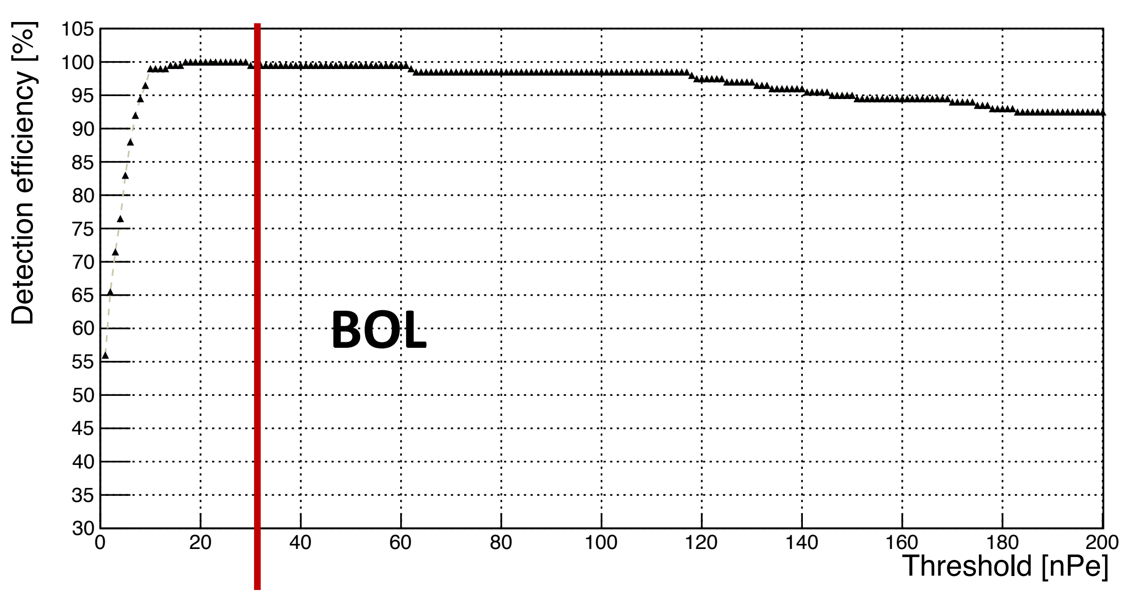
Timing and Efficiency After the Postamp

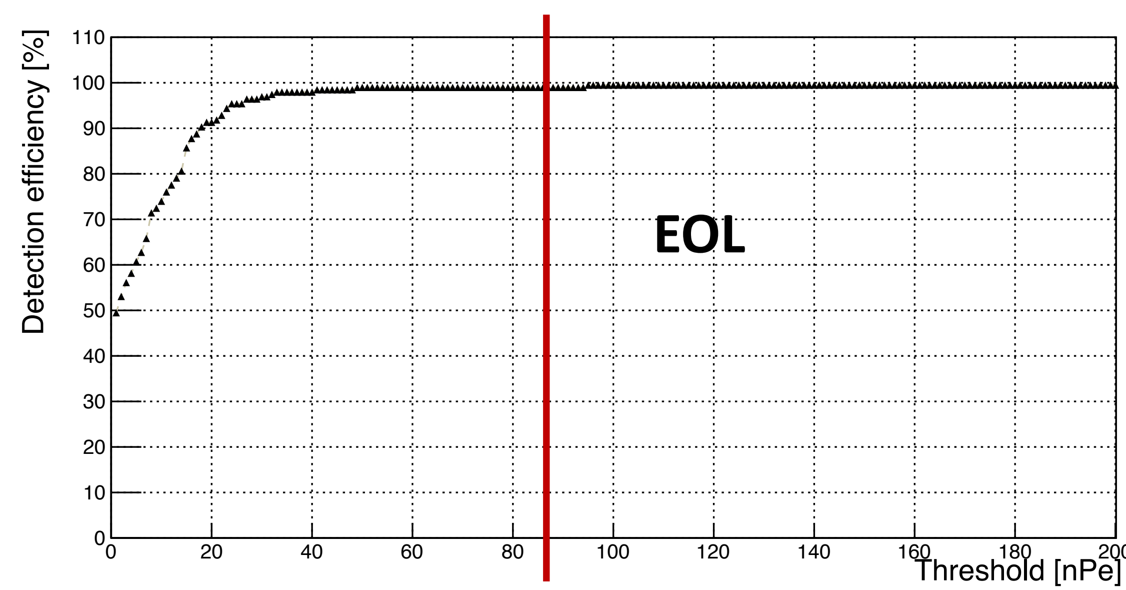
At the discriminator output



- Estimated time resolutions for single-ended readout
- Event detection efficiency at the optimum threshold for timing is ~ 99%
- Good compromise between time resolution and detection efficiency

Efficiency plot





Summary

- Tests of the main TOFHIR1 blocks are successfully concluded
    - performance is matching expectations
    - 10-bit SAR ADC is working
        - Good linearity; noise 0.8 LSB
    - TDC is working
        - Time resolution 15 ps
- TOFHIR1 Single channel time resolution is 26 ps with 200 p.e. laser pulse (~8k p.e. LYSO pulse, wo/ taking into account LYSO photostatistics
- FE prototype has been fabricated and tested. Results are very encouraging
- TOFHIR2_v1 submitted on Feb 12, 2020
- The estimated time resolution with TOFHIR2 at the beginning of life is ~30 ps and at the end of life is ~89 ps for double-ended readout
- The event detection efficiency at the beginning and end of life is ~99%
    - Reasonable compromise between time resolution and detection efficiency in the presence of pileup has been achieved

Thank you for your attention