Results with the TOFHIR2 front-end ASIC of the CMS MTD Barrel Timing Layer

A. Boletti, E. Albuquerque, R. Bugalho, L. Ferramacho, M. Firlej, T. Fiutowski, R. Francisco, M. Gallinaro, M. Idzik, J. Moron, T. Niknejad, L. Oliveira, J. C. Silva, R. Silva, M. Silveira, K. Swientek, J. Varela, and the CMS MTD group

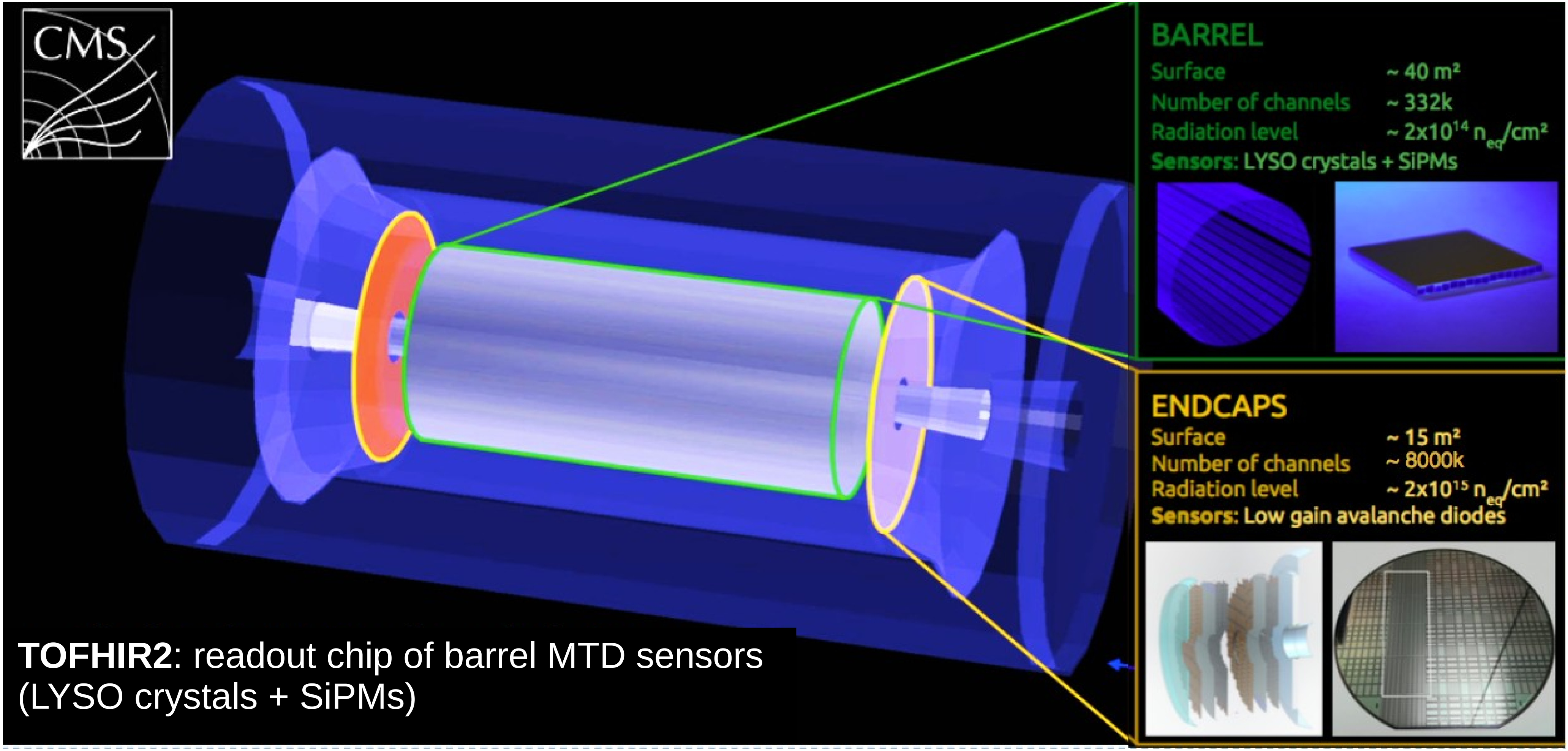
TWEPP 2022 – Bergen (Norway)

Outline

- CMS MIP Timing Layer detector
- Design of TOFHIR2 and front-end electronics
- Measurements of timing and energy resolution
- Results from high-rate and irradiation tests

CMS MIP Timing Detector

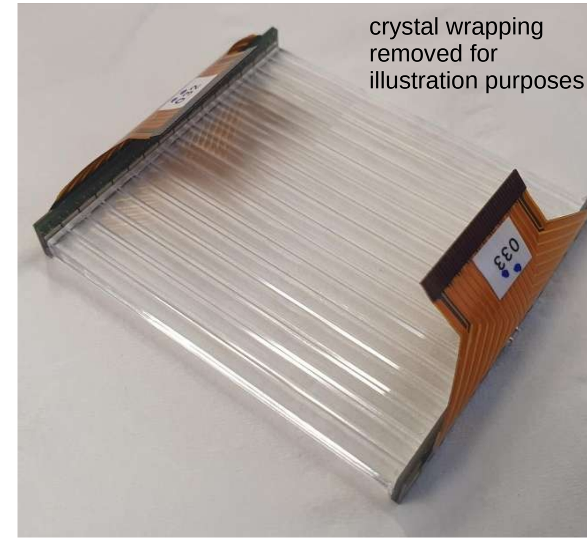
Timing measurement of charge particles
Precision from 30 ps (Begin of Life) to 60 ps (End of Life)



TOFHIR2: readout chip of barrel MTD sensors (LYSO crystals + SiPMs)

BTL detector module

BTL sensor module: 16 crystal bars + SiPMs
- LYSO bar: 3x3x57 mm^3, with two 3x3 mm^2 SiPMs glued at each end
- MIP deposits ~4.2 MeV



Silicon Photomultipliers as photo sensors:
- PDE 20-34% and gain (1-3)e5 for OV 1.5-3.5 V
- Large dark current noise due to radiation damage
- Detector operated at -35^{o}C (SiPM @ -45^{o}C using TECs)

Readout ASIC: TOFHIR2
- 32 independent channels
- BTL requires 10k TOFHIR2 chips

Front-End board:
- Supports two sensor modules
- Contains two TOFHIR2 and two ALDO2 (Low voltage and SiPM bias voltage regulators)

Front End requirements

Timing measurement
- Two timing measurements per event (<30 ps at BoL; <60 ps at EoL)

Amplitude measurement
- Charge integration and ToT   (< 5% resolution)

Dark counts and **out-of-time pileup**
- Mitigate degradation of time resolution due to large SiPM dark count rate (DCR)
- Cancel long LYSO signal tails to minimize pulse pile-up

MIP rate
- MIP rate: 2.5 MHz/channel
- Low energy hit rate: 5 MHz/channel

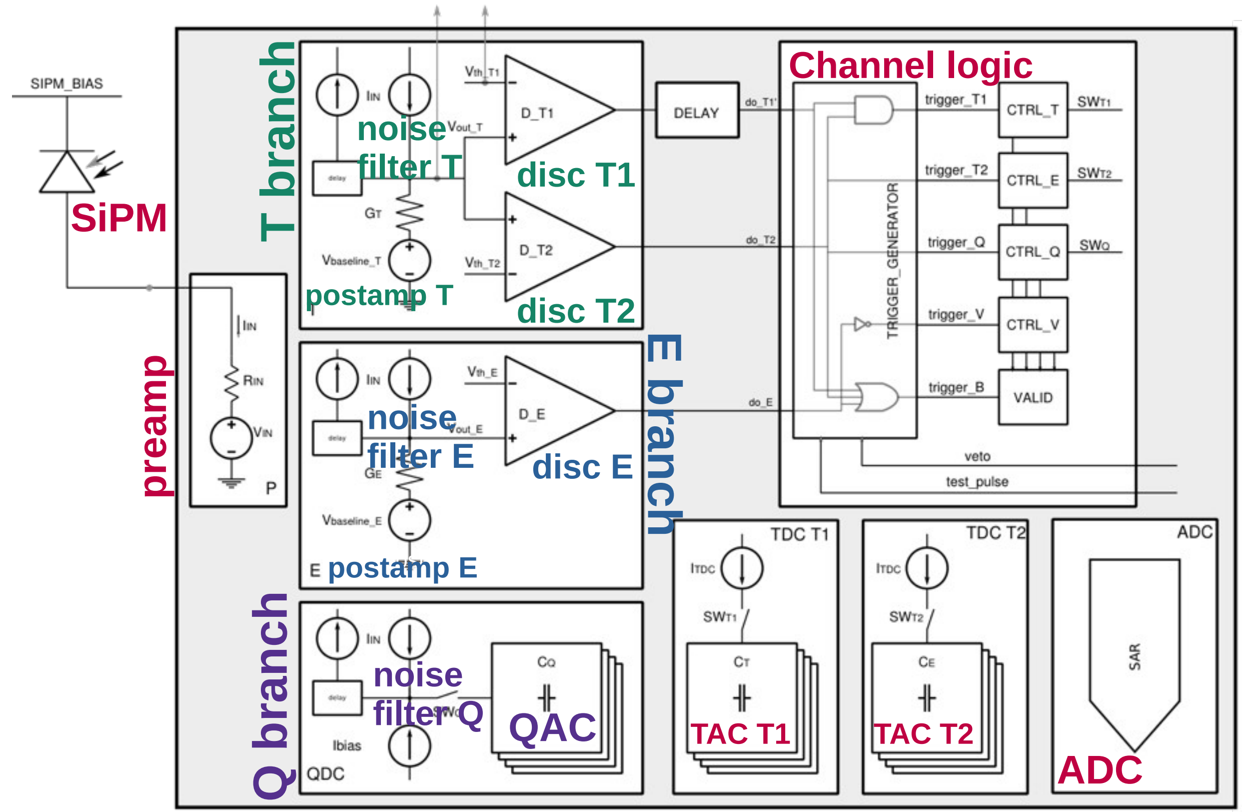
TOFHIR2

Features per channel:

- Branches: T, E and Q
- Three leading edge discriminators
  - Full current mode implementation
- Two TACs and one QAC sharing 40 MHz SAR ADC

Challenges:

- Minimize the impact of DCR noise and pileup on time resolution
- Cope with high rate



TOFHIR2 characteristics			
Number of channels	32	TDC bin (ps)	10
Technology	CMOS 130nm	10-bit SAR ADC (MHz)	40
Voltage supply	1.2 V	I/O links	CLPS
Reference voltage	Internal	L1, L0 Trigger	Yes, Yes
Radiation tolerance	Yes	Maximum MIP rate/ch (MHz)	2.5
DCR noise filter	Yes	Max low E rate/ch (MHz)	5
Number of analog buffers	8	Clock frequency (MHz)	160

Measured power consumption:

- 330 mA (~400 mW) with active chip, no events
- 463 mA with active chip, high-rate events

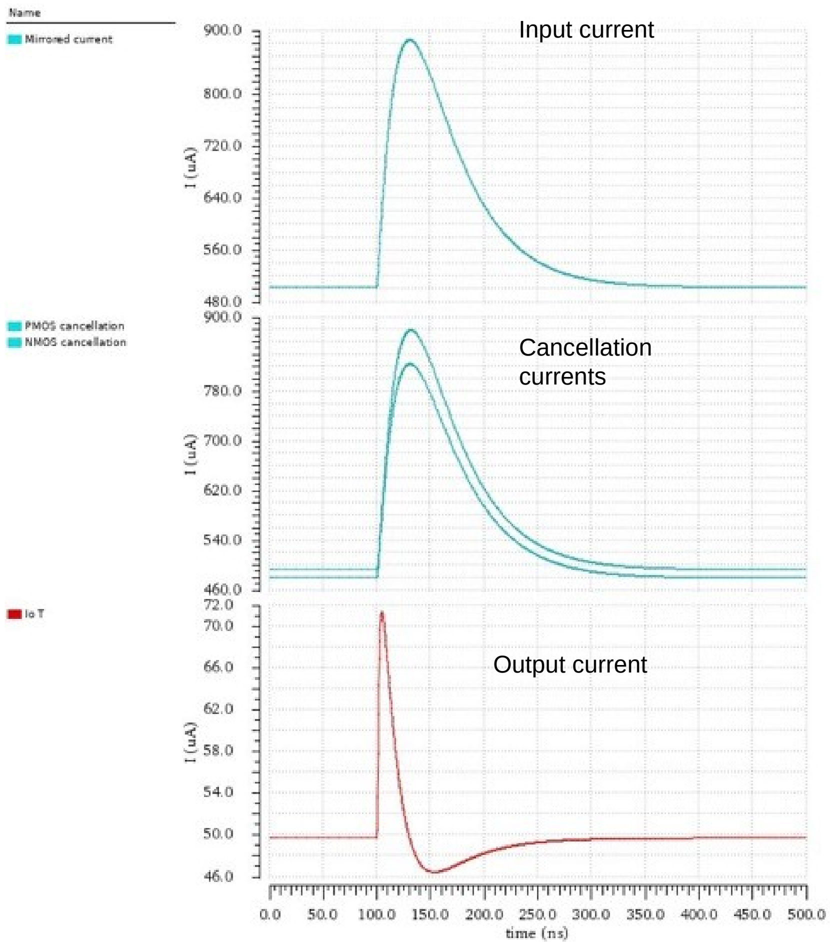
DCR noise cancellation

DLED method (*):
- Inverted and delayed current pulse is added to the original pulse
- Delay line is approximated by a RC net (200-1800 ps)
- Short output pulse (< 25 ns)
- Noise and baseline fluctuations are mitigated

Simulation of time resolution (EoL conditions):
- Dark Count Rate: 55 GHz
- MIP pulses with 6000 p.e.
- SiPM gain: $1.5 \cdot 10^5$

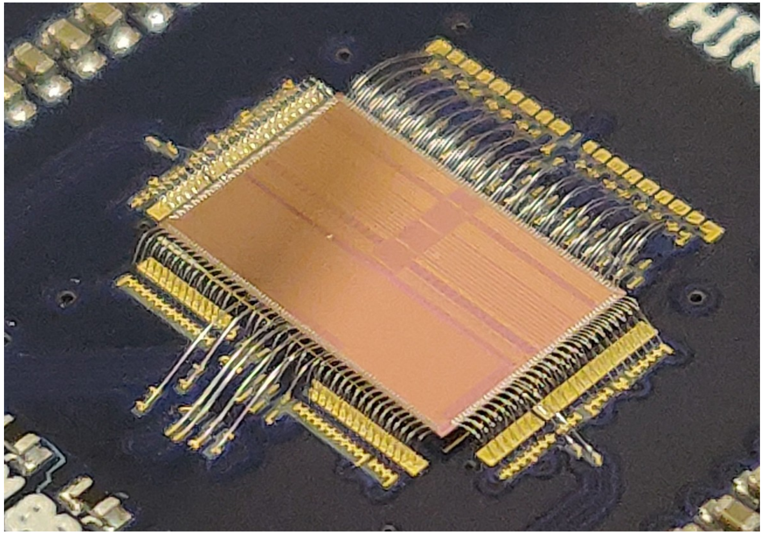
	SiPM ouput current	DCR module output current
Slew rate (μA/ns)	135.9	9.93
Noise r.m.s (μA)	24.5	0.51
σ_{noise}/ SR (ps)	180	52

Improvement factor: 3.5



(*) A. Gola, C. Piemonte and A. Tarolli, "Analog Circuit for Timing Measurements With Large Area SiPMs Coupled to LYSO Crystals," in IEEE Transactions on Nuclear Science, vol. 60, no. 2, pp. 1296-1302, April 2013.

TOFHIR prototyping cycle

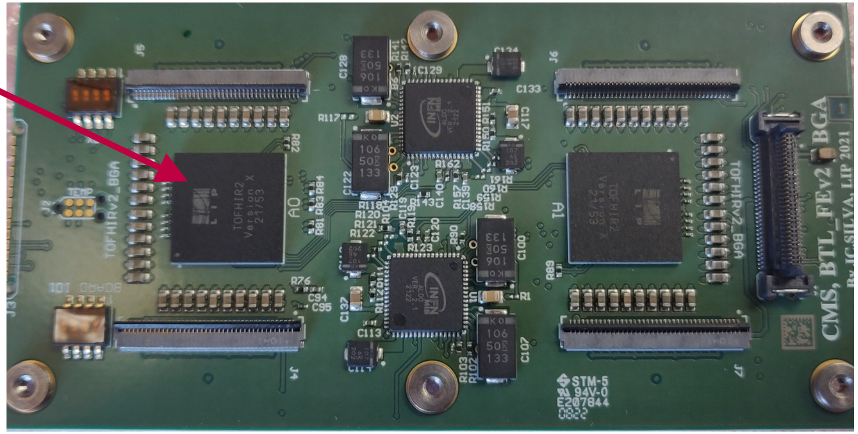


TOFHIR1 (UMC 110 nm):
- Quick adaptation from TOFPET2

TOFHIR2 (TSMC 130 nm):
- New design, DCR noise cancellation circuit

- **TOFHIR2A** (2020)
  - Full chip (32 channels) and functionality

- **TOFHIR2X** (2021)
  - Current mode DCR cancelation and current discriminator
  - BGA packaging designed and under assembly and test



- **TOFHIR2B** (2021-2022)
  - New DAC to improve charge integration response
  - Improved TMR for SEE protection

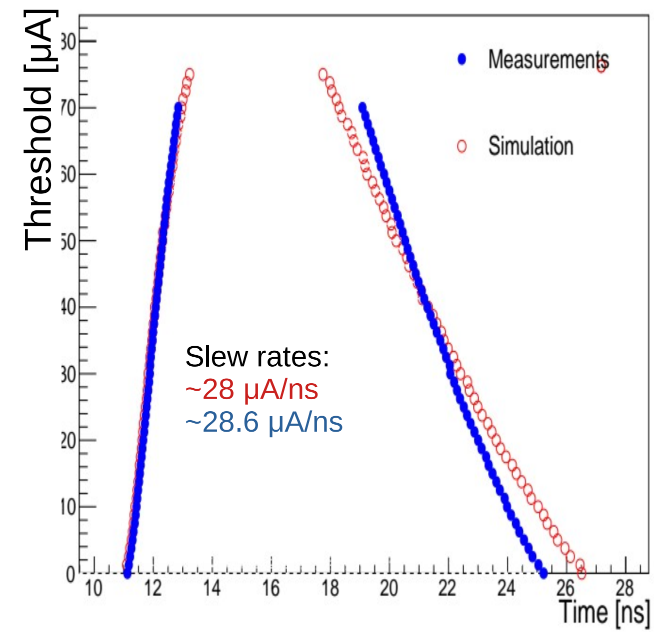
ASIC design done by PETsys Electronics
Integration in BTL done by LIP (Lisbon)

Performance tests

Pulse shape

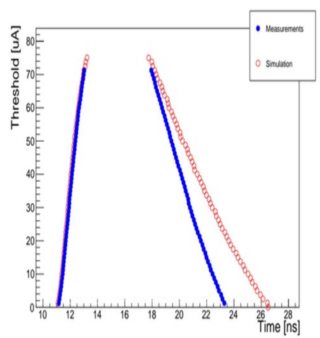
Pulse shape of **LYSO excited with UV laser**

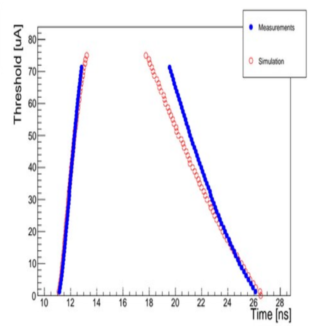
- UV laser tuned to generate a LYSO pulse with a given number of photoelectrons
  - 9500 pe, SiPM gain 3.8×10^5
- Pulse shape derived from **discriminator threshold scan**
  - The time of the leading and trailing edges are measured by the TDC1 and TDC2
- Good agreement between simulation and data
  - The slew rate in the rising edge is 28.6 μA/ns (BoL)



Pulse shape trimming

- Pulse shape depends on matching between N and P branches in DLED block
- Programmable trimming of pulse shape was introduced in TOFHIR2X

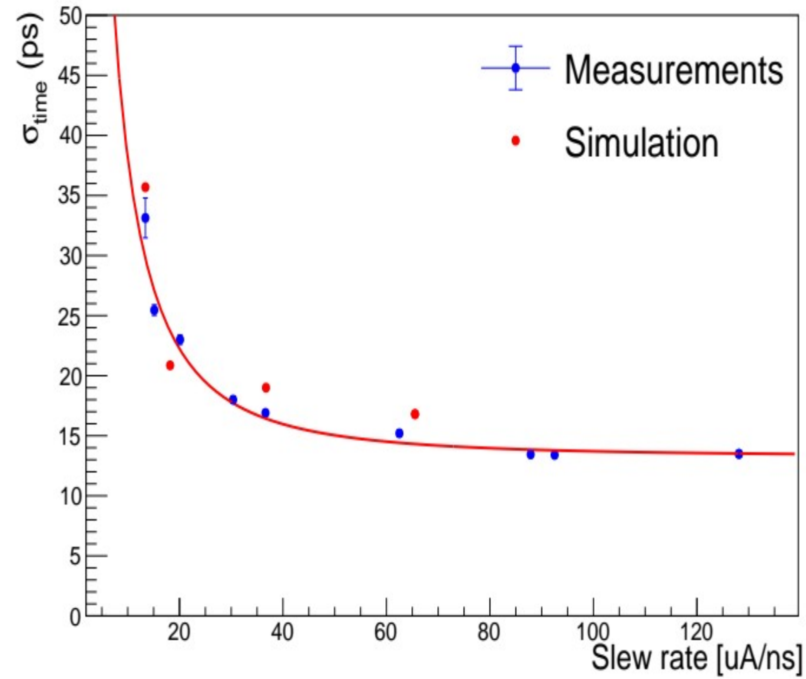




Solid state noise

- The contributions of the **amplifier noise** and **TDC noise** to the time resolution are estimated with laser light shining on two naked SiPMs (using a beam splitter)
- The channel time resolution is derived from the CTR (width of the time difference between the pulses in the two channels)
- Fit function: $\sigma_t = \sigma_{noise} / (dI/dt) \oplus \sigma_{TDC}$
- Fit results:
  - σ_{noise} = 0.360 μA
  - σ_{TDC} = 12 ps

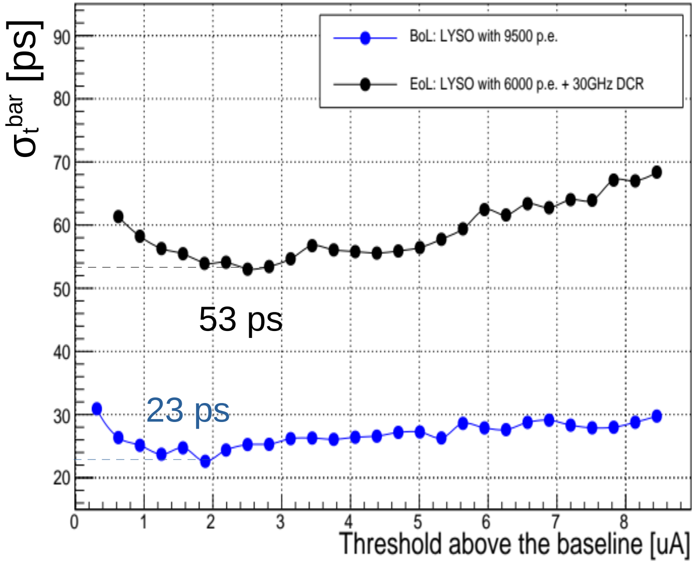
Electronics noise contribution to time resolution



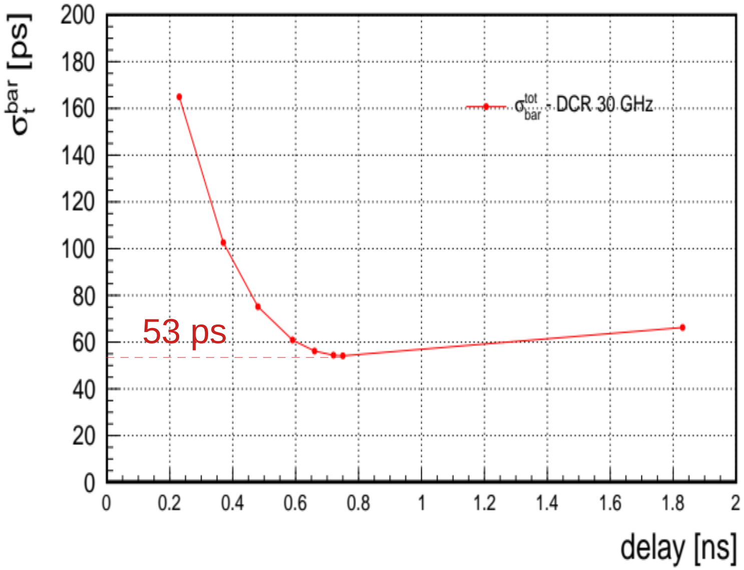
Time resolution of MIP pulses

- The timing of a MIP is obtained from the average of the two measurements in a LYSO bar
- Bar time resolution is derived from the CTR of two channels in the crystal bar (σ_{bar} = CTR/2)

Time resolution as a function of the discriminator threshold for LYSO pulses in BoL and EoL conditions.



Time resolution of LYSO pulses characteristic of EoL for DCR of 30 GHz as a function of the delay line in the DCR cancellation circuit.



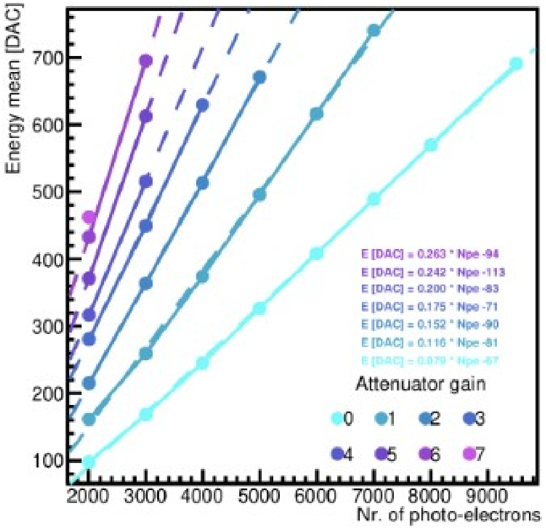
BoL and EoL conditions compatible with requirements

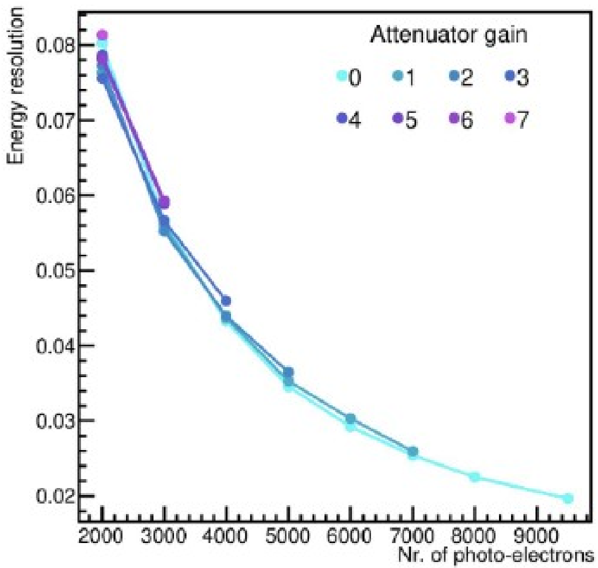
Energy measurement

Integration of the pulse charge to estimate the MIP energy

Test with UV laser to validate linearity of the response and resolution as a function on number of photoelectrons
- TOFHIR2B has a DAC to calibrate the baseline, allowing it to be set at zero for a good linearity in energy response
- Energy resolution below 5% in the range of pulse amplitude of interest

Final chip will have better resolution:
- filtering capacitor added to reduce digital noise in energy baseline holder

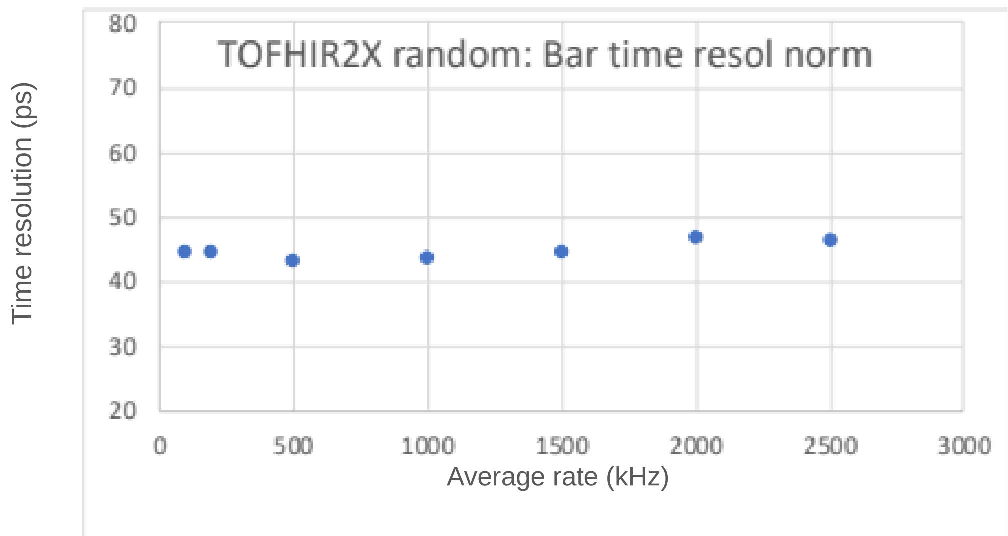




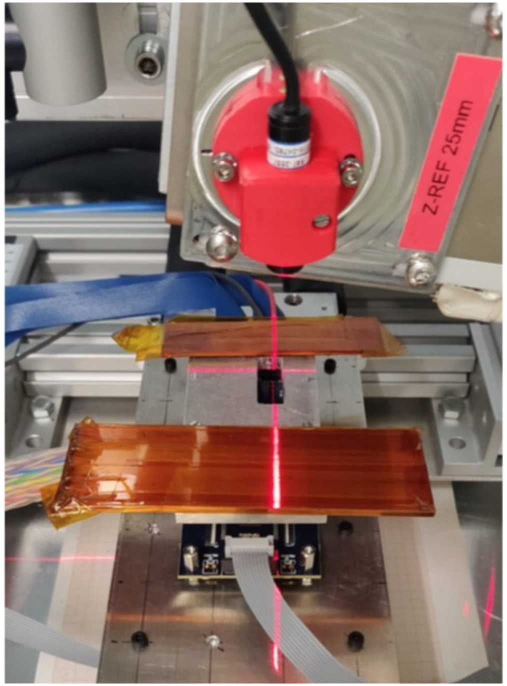
High-rate tests

TOFHIR2 performances tested as a function of the rate
- Laser triggered by pseudo-random sequence of test pulses

Time resolution is stable up to 2.5 MHz/channel
- Small degradation above 2 MHz (not seen with internal analog test pulses) may be due to measurement conditions (insufficient SiPM cooling)



Irradiation tests



TID radiation test

- TOFHIR2 irradiated up to 7 Mrad
- Max expected dose in BTL is 2.9 Mrad
- Radiation and annealing cycles emulated
- Voltages, noise, and TDC and QDC calibrations monitored
- Negligible effects observed (<1% after annealing cycles)

Single Event Effects radiation test

- Tests performed at Heavy Ion Facility (HIF) Louvain-la-Neuve
  - Different ions ($^{53}Cr^{16+}$, $^{36}Ar^{11+}$, $^{27}A^{18+}$, $^{22}Ne^{7+}$, $^{13}C^{4+}$, $^{84}Kr^{25+}$) and different incident angles (0^o, 30^o, 45^o) covering a wide range of linear energy transfer (LET)
- TOFHIR2 features TMR protection of configuration bits, clock, resync and automatic SEUs correction
- Very small number of non-corrected errors and loss of sync
  - <1 conf bit corruption and loss of sync per fill, at LHC conditions

Summary and conclusions

- TOFHIR2 front-end ASIC for the CMS Barrel Timing Layer detector has been presented:
  - Expected conditions of operation and requirements
  - Chip design
  - Results of performance measurements:
    - Timing resolution
    - Energy measurement
  - Results of high-rate and radiation tests
- Measurement results show good performance of TOFHIR2
  - Requirements on time and energy resolutions are met
  - Good resilience to high-rate events and radiation
- Timeline for the Engineering Run is under discussion in CMS

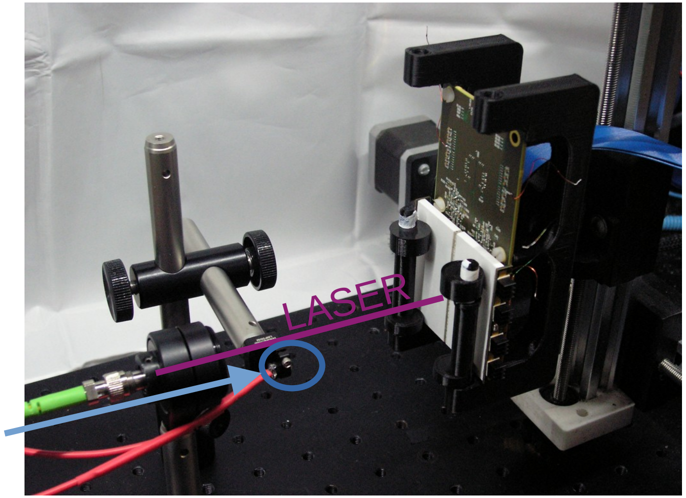
Backup

Test facilities

Lase test setups installed in Lisbon, Milano and CERN
- Colling and light tight test boxes
- Blue (405nm) and UV (370nm) laser systems
- DAQ system based on FEB/D board (PETsys Electronics)

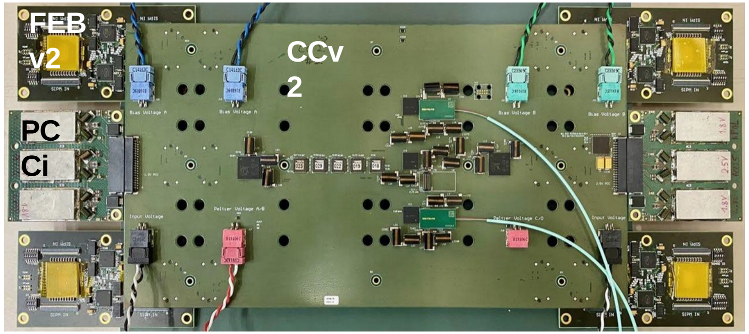
TOFHIR2 Test Board
- Two TOFHIR2 and ALDO2 (LV/BV regulator)
- SiPM input connectors
- Access to probing pads in TOFHIR2
- Access to data with DAQ system

Picosecond laser
- Blue light shinning directly on SiPMs
- UV light exciting scintillation in LYSO crystals

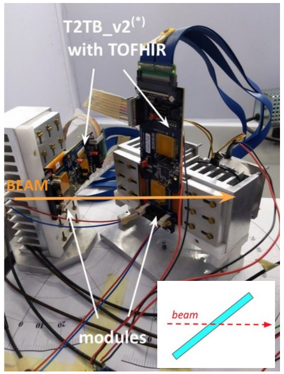


Blue LED emulating DCR noise

Integration test of Readout Unit:
- validate the full acquisition chain, assess the impact of the system noise, check the compatibility of the various components from the assembly point of view

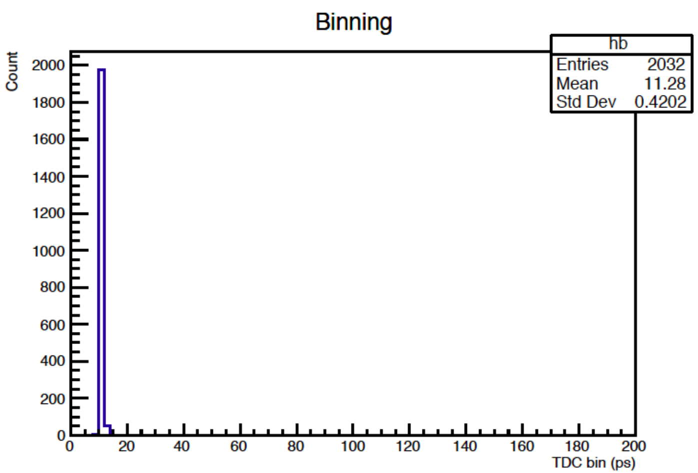


Test beams at CERN
- CERN North Area H8 beam lines (Oct 21 & Jun 22)
- Detector modules with non-irradiated and irradiated (2e14 neq/cm2) SiPM arrays

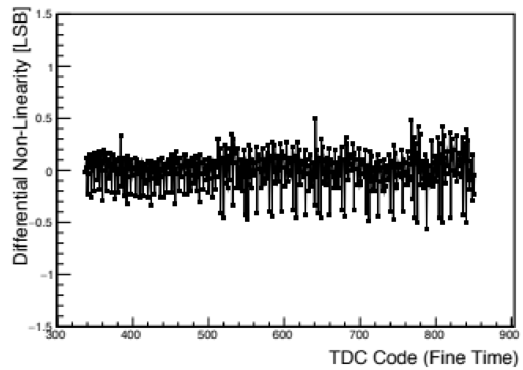


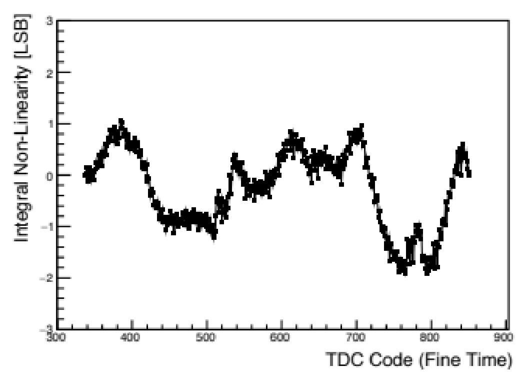
TDC performances

TDC binning:
- Typical binning is 11 ps
  - 10 ps expected
- Low dispersion of binning
  - sigma=0.4 ps

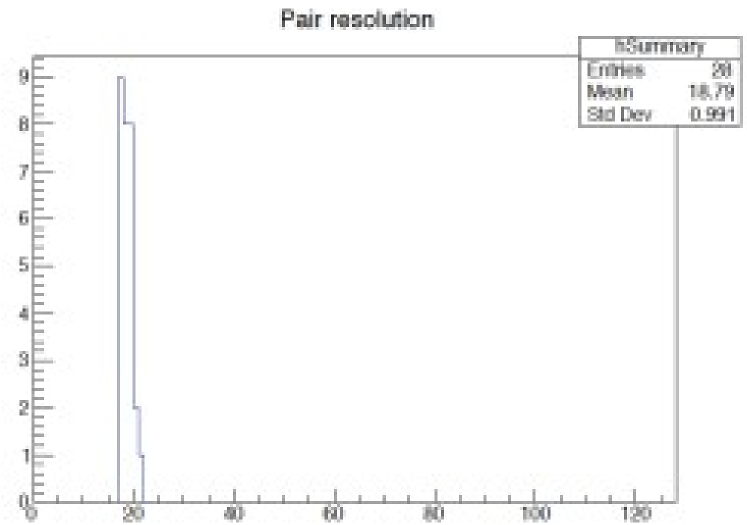


TDC linearity:
- DNL < ± 0.5 LSB
- INL < ± 2 LSB





TDC resolution:
- Coincidences between TDC pairs used to cancel common jitter (e.g. clock jitter)
- TDC resolution is 13 ps
  - 5% dispersion

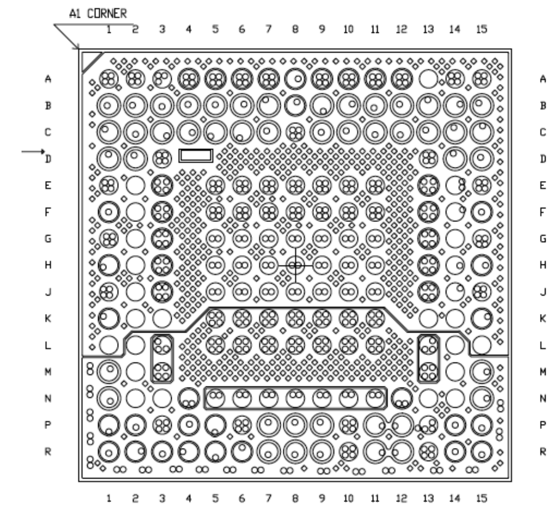


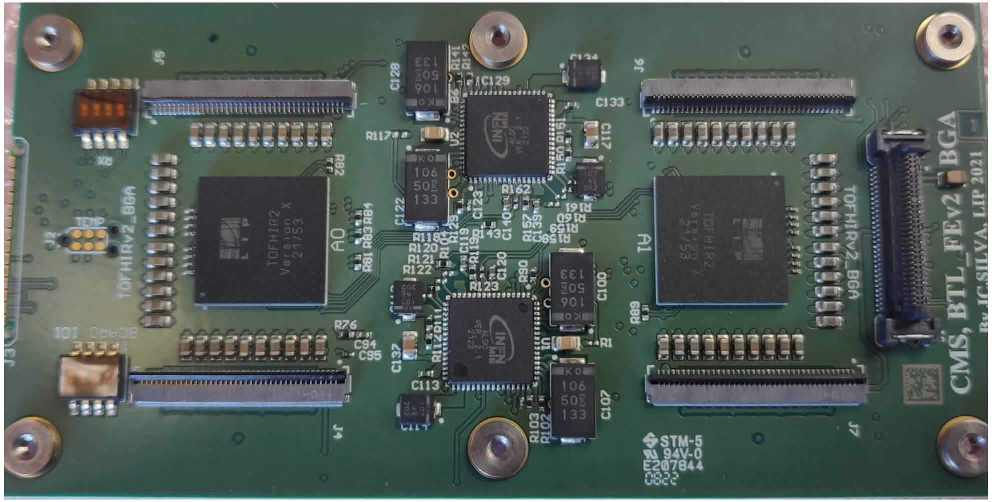
TOFHIR2 BGA package

Design and production by external company (IMEC/ASE)
- Design concluded. Simulation of input inductance
- Substrate production concluded
  - 15,000 substrates

Prototype assembly
- 300 BGAs with TOFHIR2X available

Performance in COB- or BGA-based boards measured to be the same
- Pre-production of 130 FE-BGA boards is on-going





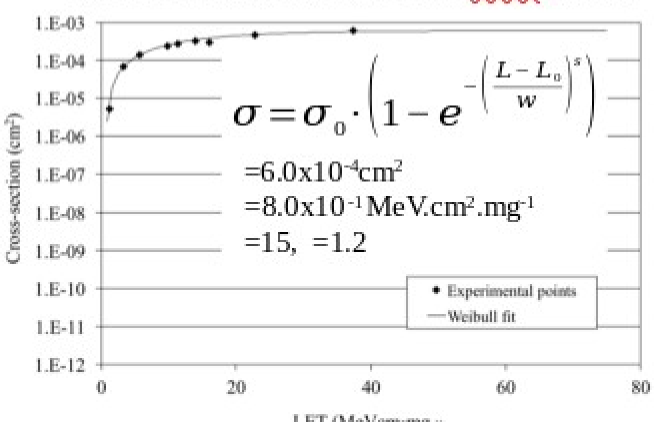
SEE radiation result

SEE radiation test: TOFHIR2B

- TMR protection of the clock and resync tree added in TOFHIR2B
- Heavy-ions irradiation (Louvain) on 22 April 2021
- The protection works fine, very small number of non-corrected errors and loss of sync
- **Extrapolation to LHC:**
  - **In the whole BTL, less than one configuration bit corrupted and one loss of sync per fill**

run number	Ion	Flux (part/s/cm2)	Fluence (part/cm2)	Angle	LET (MeV/mg/cm2)	Configuration: Corrected errors (bits)	Configuration: Uncorrected errors (bits)	Bad events: CH ID	Bad events: T1 Coarse (Sync loss)
1	Cr-505	4 000	2 260 000	45		957	1	0	2
2	Cr-505	4 000	720 000	45		274	2	0	0
3	Cr-505	4 000	1 040 000	45		600	0	1	1
4	Cr-505	4 000	2 720 000	45		1 980	2	2	1
sum	Cr-505	4 000	6 740 000	45	22.8	3 811	5	3	4
5	Cr-505	4 000	1 460 000	0		672	0	0	78 127
6	Cr-505	4 000	1 600 000	0		813	0	0	0
sum	Cr-505	4 000	3 060 000	0	16.1	1 485	0	0	1
7	Ar-353	8 000	8 760 000	45	14.0	2 810	5	1	0
8	Ar-353	10 000	10 650 000	30	11.4	3 495	0	1	1
9	Ar-353	12 000	13 020 000	0	9.9	4 098	3	0	2
12	Al-250	15 000	22 875 000	0	5.7	5 820	3	1	4
14	Ne-238	15 000	16 725 000	0	3.3	886	0	3	4
15	C-131	15 000	4 200 000	0	1.3	0	0	0	0
16	Kr-769	200	114 000	30	37.4	82	0	0	0
18	Kr-769	1000	565 000	30	37.4	357	0	1	0

Cross-section of corrected SEU errors



TID radiation results

- **No effects larger than 1% after annealing**

TOFHIR2X