The timing performance of the TOFHIR2 ASIC

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on behalf of the TOFHIR team

Fast Timing in Medical Imaging

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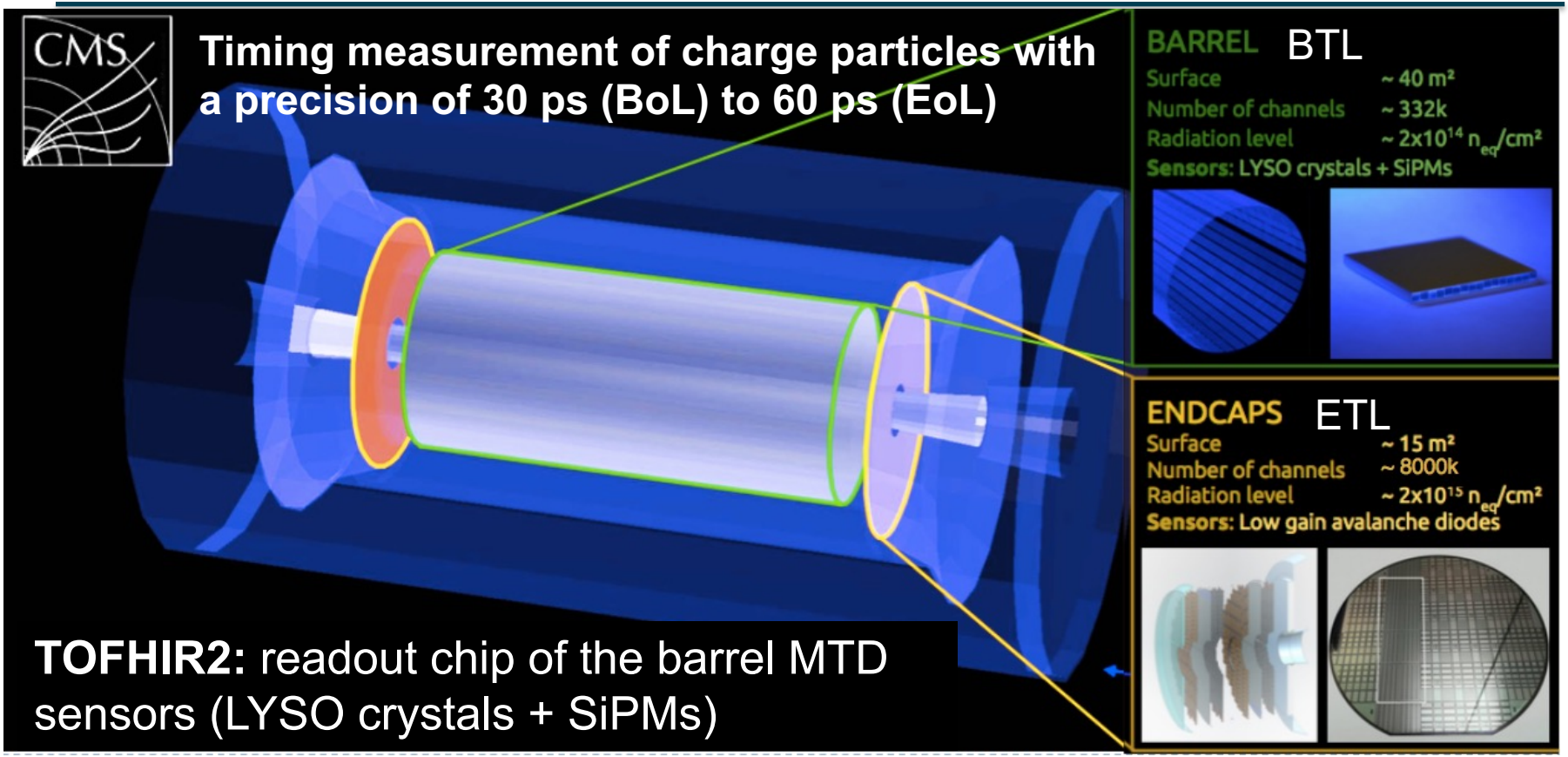
Warning

In this talk time resolution is given in standard deviation (r.m.s.)

CMS MIP Timing Detector

Timing measurement of charge particles with a precision of 30 ps (BoL) to 60 ps (EoL)

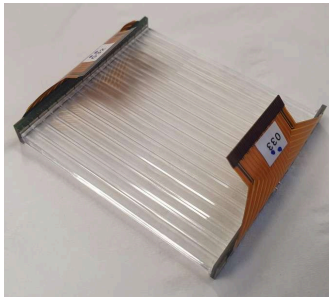


TOFHIR2: readout chip of the barrel MTD sensors (LYSO crystals + SiPMs)

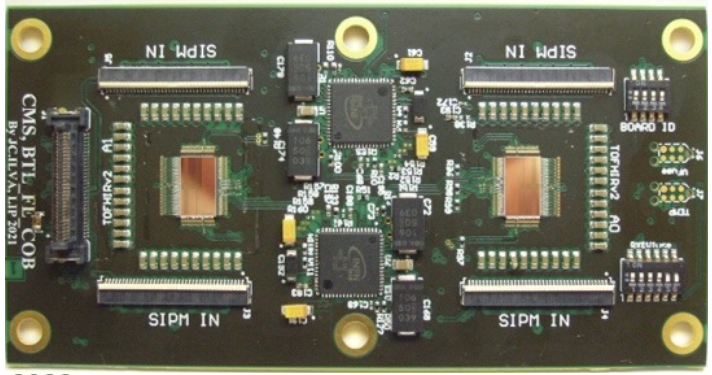
BTL Detector Module

- BTL sensor module: 16 crystal bars + SiPMs
  - Each bar 3x3x57 mm^3 LYSO; two 3x3 mm^2 SiPMs glued at each end
- LYSO Crystal Arrays:
  - MIP deposits ~4.2 MeV
- Silicon Photomultipliers as photo sensors:
  - Large dark current noise due to radiation damage (up to 50 GHz)
  - Detector operated at -35ºC (-45ºC using TECs under development)
  - PDE 20-30% and Gain 1-3e5 for OV 1.5-3.5 V
- Readout ASIC: TOFHIR2
  - Each Front-End board has 2 ASICs
  - Each ASIC has 32 independent channels

BTL sensor module



Front-End board



Nominal parameters along BTL life

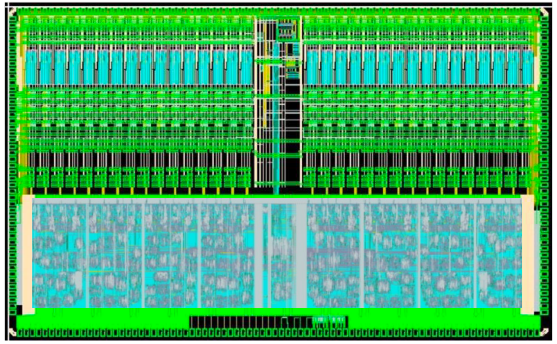
Integrated luminosity (fb-1)	Number of p.e.	SiPM gain	DCR (GHz)
0 (BoL)	9500	3.8×10^5	0.001
3000 (EoL)	6000	1.5×10^5	55 (30)

Front-end requirements

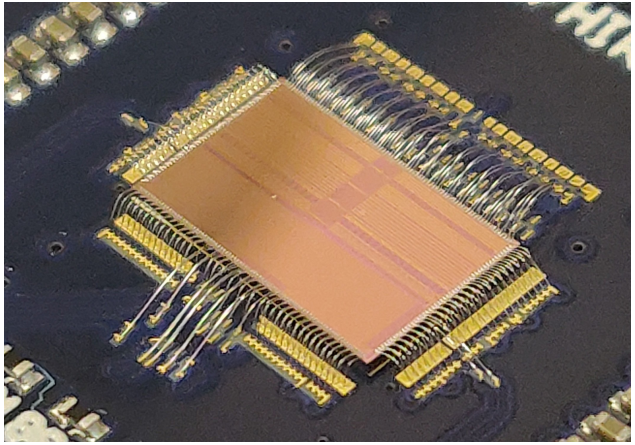
- MIP rate
  - MIP rate: 2.5 MHz/channel
  - Low energy hit rate: 5 MHz/channel
- Timing measurement
  - Two timing measurements per event
- Amplitude measurement
  - Charge integration and ToT
- Dark counts and out-of-time pileup
  - Mitigate degradation of time resolution due to large SiPM dark count rate (DCR)
  - Cancel long LYSO signal tails to minimize pulse pile-up
  - Stabilize baseline to allow good timing with leading edge discrimination

TOFHIR prototyping

- **TOFHIR1 (UMC 110 nm):**
  - Quick adaptation from TOFPET2
  - Enabled system testing in 2019
- **TOFHIR2 (TSMC 130 nm):**
  - New design, DCR noise cancellation circuit
  - TOFHIR2A
    - Full chip (32 channels) and functionality
    - Tested in 2020
  - TOFHIR2X
    - Improved DCR cancelation and current discriminator
    - Tested in 2021
  - TOFHIR2B
    - Improved TMR for SEE protection
    - Under test
- ASIC design done by PETsys Electronics; Integration in BTL done by LIP



Chip dimensions: 8.5x5.2mm^2



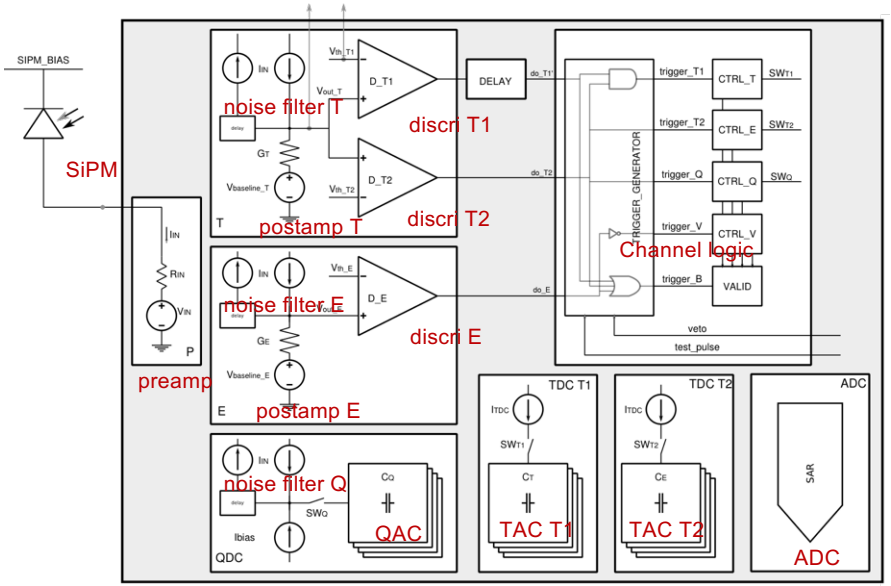
TOFHIR2 channel

Features:

- 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



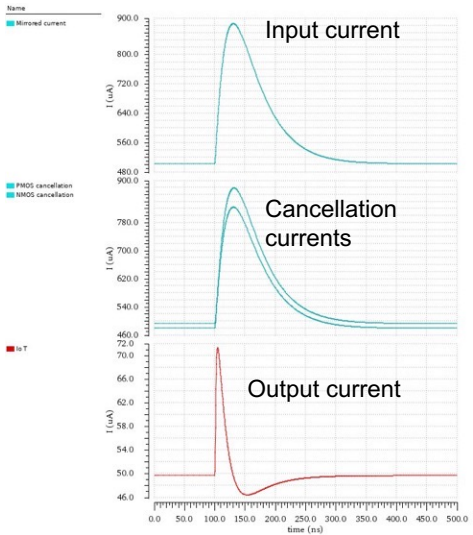
TOFHIR2 characteristics	
Number of channels	32
Technology	CMOS 130nm
Voltage supply	1.2 V
Reference voltage	Internal
Radiation tolerance	Yes
DCR noise filter	Yes
Number of analog buffers	8
TDC bin (ps)	10
10-bit SAR ADC (MHz)	40
I/O links	CLPS
L1, L0 Trigger	Yes, Yes
Maximum MIP rate/ch (MHz)	2.5
Max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

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

*) 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.



Simulation of time resolution in EoL conditions:

- Dark Count Rate: 55 GHz
- MIP pulses with 6000 p.e.
- SiPM gain: $1.5 10^5$

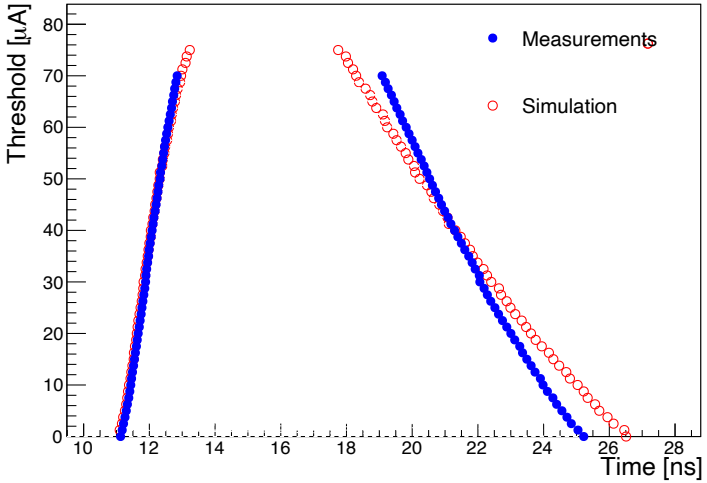
	SiPM ouput current	DCR module output current
Slew rate (μA/ns)	135.9	9.93
Noise r.m.s (μA)	24.5	0.51
σ_{noise}/ SR (ps)	180	52

Time resolution is improved by a factor 3.5

Pulse shape

Pulse shape of LYSO excited with UV laser

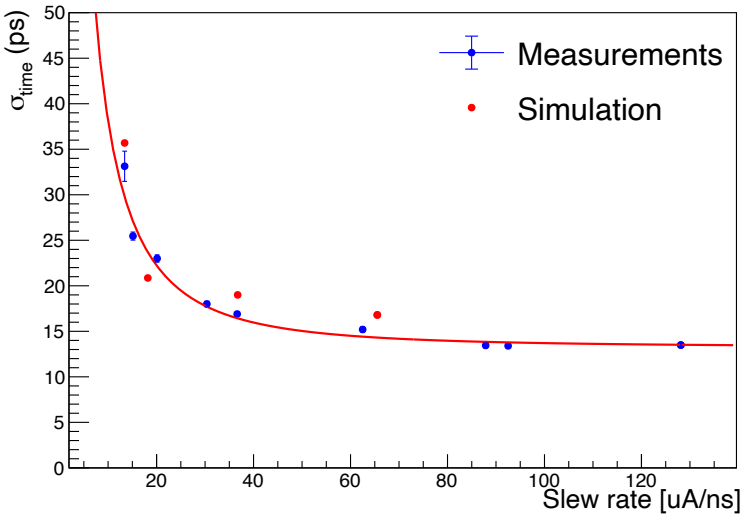
- LYSO pulse: 9500 pe, SiPM gain 3.8×10^5
  - UV laser tuned to generate a LYSO pulse with a given number of photoelectrons
- Pulse shape derived from discriminator threshold scan
  - The time of the leading and trailing edges are measured by the TDC1 and TDC2
- Good agreement between simulation and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



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 measured CTR
- Fit function: $\sigma_t = \sigma_{noise}/(dI/dt) \oplus \sigma_{TDC}$
- Fit result: σ_{noise}= 0.360 µA and σ_{TDC}= 12 ps.
- Electronics noise contribution to time resolution:

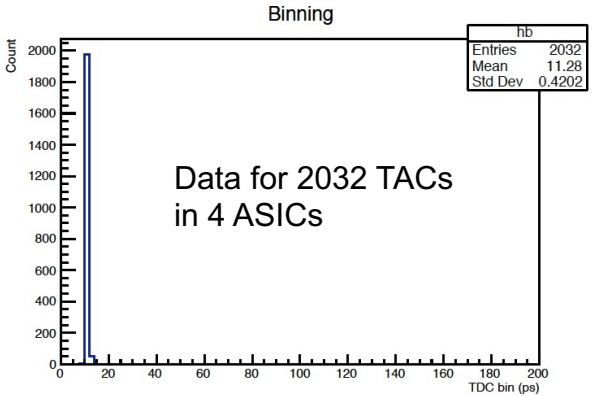
$$\sigma_t^{elect} = \frac{\sigma_{noise} = 0.36\ \mu A}{SR = 28.6\ \mu A/ns} = 13\ ps$$



TDC performance

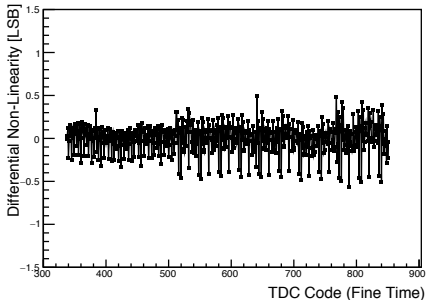
TDC binning:

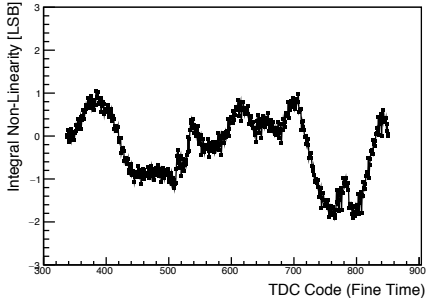
- **Typical binning is 11 ps**
  - 10 ps expected
- Low dispersion of binning
  - sigma=0.4 ps



TDC linearity:

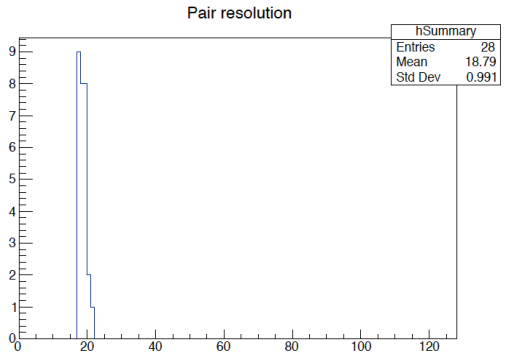
- DNL < ± 0.5 LSB
- INL < ± 2 LSB





TDC resolution:

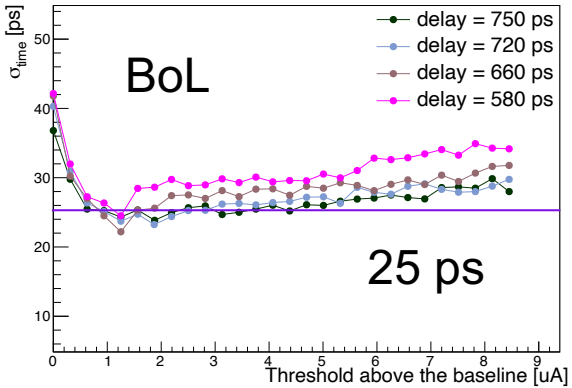
- Coincidences between TDC pairs used to cancel common jitter (e.g. clock jitter)
- **TDC resolution is 13 ps**
  - 5% dispersion



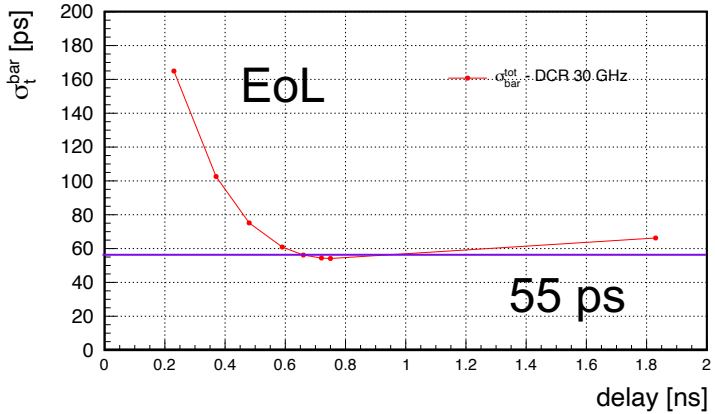
Time resolution of MIP pulses

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

Time resolution as a function of the discriminator threshold for LYSO pulses with 9500 photoelectrons, typical of BoL conditions.

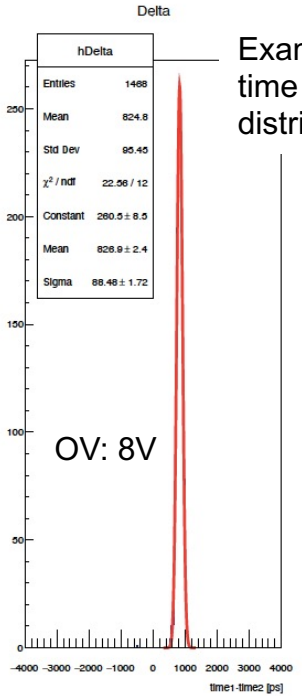


Time resolution of LYSO pulses characteristic of EoL for DCR of 30 GHz as a function of the delay line in the DCR cancellation circuit.



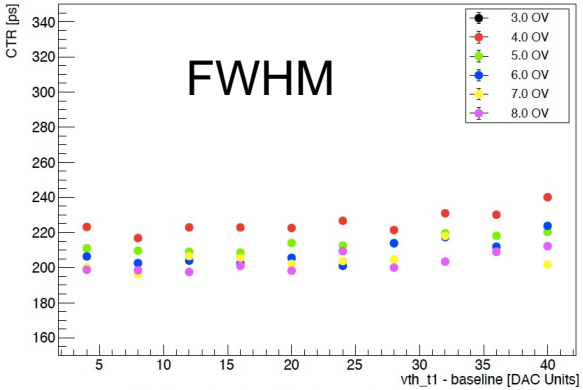
Time resolution with PET modules

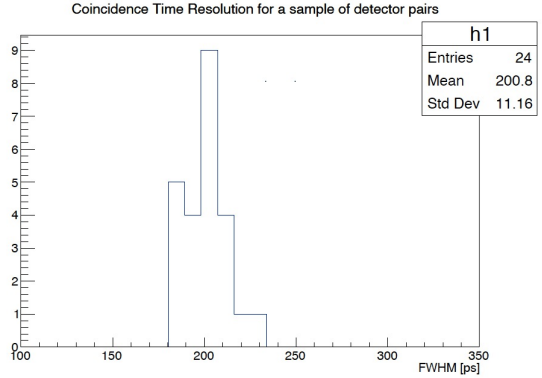
- Preliminary measurements with PET modules
  - Hamamatsu 8x8 SIPM array coupled to LYSO 15mm 8x8 array
- Caveats:
  - TOFHIR2 is not optimized for PET
  - Non-optimized PET module
- Comparison with TOFPET2:
  - No degradation of CTR with OV.
  - No satellite peaks in time distribution at large OV.



Example of time distribution

CTR as a function of OV and Threshold





Summary

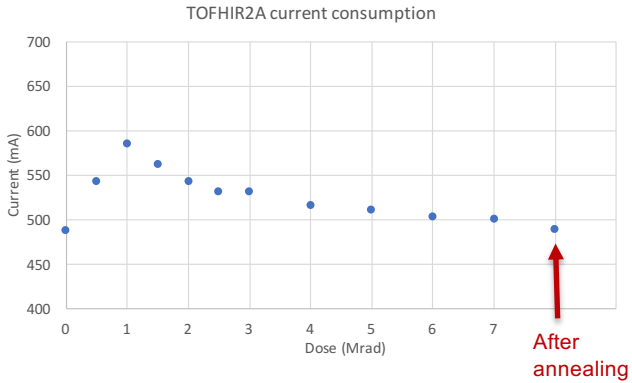
- The TOFHIR2 readout chip for the CMS barrel MIP Timing Detector was developed
- Measurements with sensor modules associated to TOFHIR2 match the expectations
  - Timing resolution of 25 ps is measured at nominal BoL conditions
  - Timing resolution of 55 ps is measured at nominal EoL conditions and 30 GHz DCR achievable with T=-45oC
- DCR cancellation and baseline stabilization allows good timing at large OV

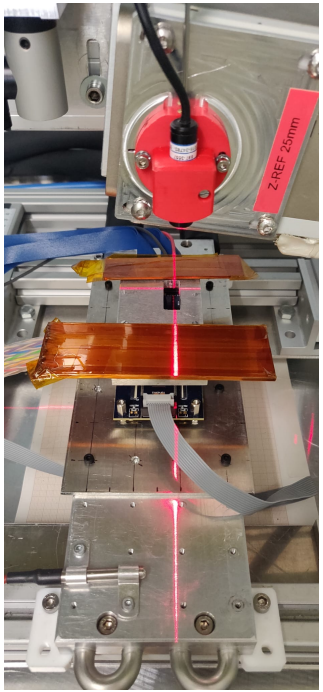
Thank you for your attention

Backup

TID radiation test

- **TID tests done at the x-ray irradiation facility at CERN**
- Max expected dose in barrel MTD is 3 Mrad
- ASICs irradiated up to 7 Mrad





Results:

- We observed effects due to large leakage current in TSCM 130nm (fab 14) at dose ~1 Mrad:
  - 20% increase of current consumption
  - 15-20% decrease of DAC's voltage range
- Full recovery after 10h annealing
- Negligible effects up to 7 Mrad in the frontend amplifiers, TDC and QDC.

SEE radiation test

- **Tests of Single Event Effects (SEE) performed at Heavy Ion Facility (HIF) Louvain-la-Neuve**
- SEE protection in TOFHIR2:
  - TMR on configuration bits (15'558 flip-flops) and automatic correction of SEUs
  - Transients (SETs) in the clock and resync are protected in TOFHIR2B

Results:

- Measured cross-section of corrected SEU errors
  - match well the expectations
- Observed two uncorrected SEU errors
  - with large LET (37.4 MeV/mg/cm^2) and fluence of 4.5 M ions/cm2
- Extrapolation to LHC:
  - <<1 uncorrected error/chip/year

Cross-section of corrected SEU errors