Fast timing electronics for the CMS MIP Timing Detector

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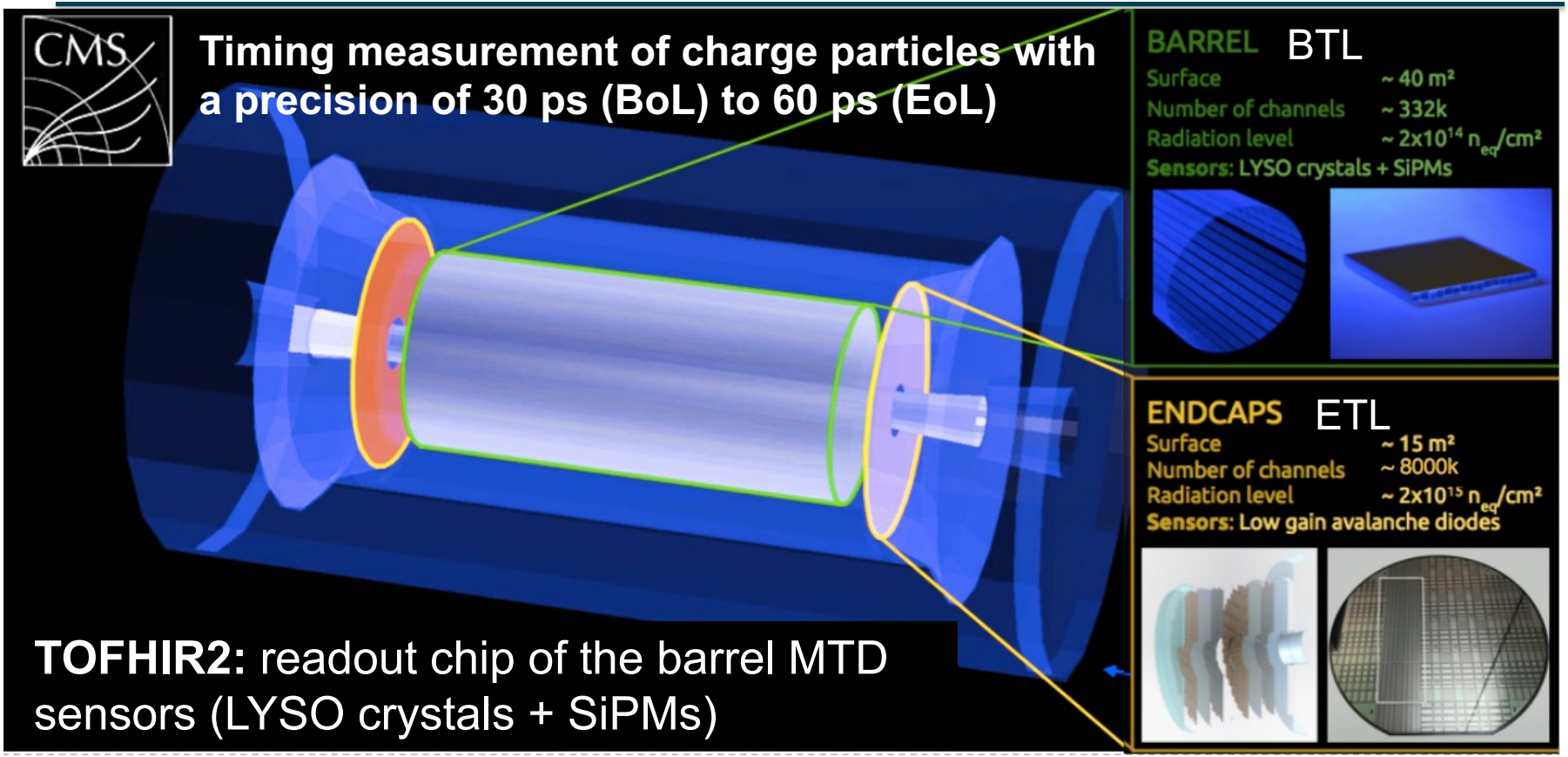
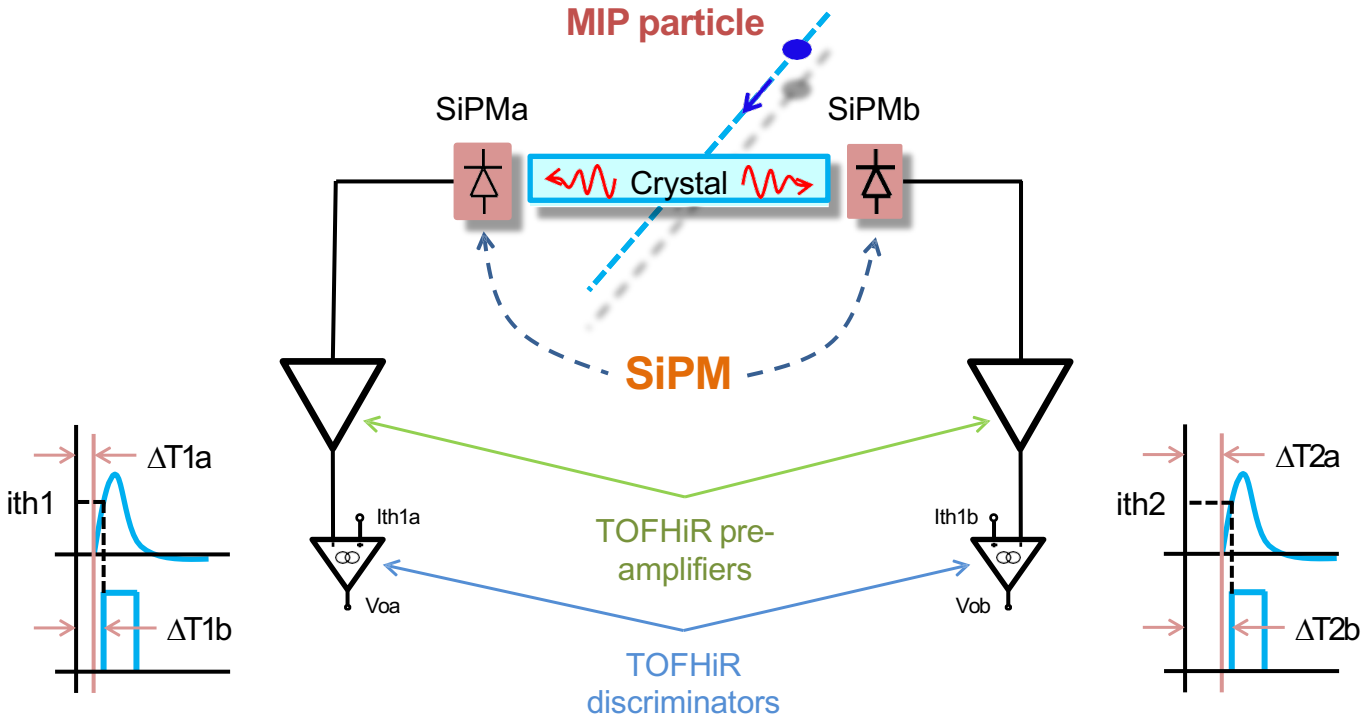
CMS MIP Timing Detector

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)

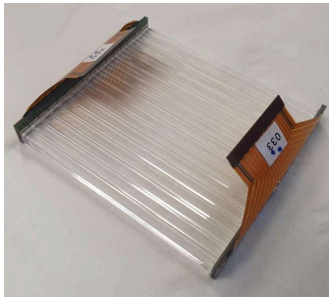
Detector and TOFHiR front-end



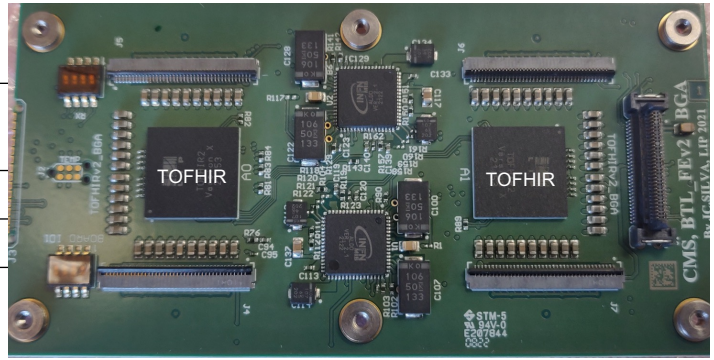
BTL Detector Module

- BTL sensor module: 16 crystal bars + SiPMs
- LYSO Crystal Arrays:
  - MIP deposits ~4.2 MeV
  - Scintillating light 30k photons/MeV
- Silicon Photomultipliers:
  - Large dark current noise due to radiation damage (up to 30 GHz)
  - SiPMs operated at -45°C (using TECs)
  - PDE 20-30% and Gain 1-3x10^5 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 (TDR specs)

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	30

TOFHiR: Key specifications

- Target technology TSMC CMOS 130nm (radiation characterized)
- TOFHIR operating temperature -30ºC (periodic thermal annealing at 50ºC)
- Handle MIP particles at a rate of 2.5 Mhit/channel
- Handle low energy particles (<1MeV) at a rate of 5 Mhit/channel
- Radiation tolerance
  - Total Ionization Dose (TID) of up to 3Mrad
  - Particle fluence of up to 2e14 neq/cm^2

- **Time resolution of 50ps average throughout the 10 years detector lifetime**
  - Beginning-of-life (BoL) time resolution 25ps
  - End-of-life (EoL) time resolution 55ps

- Dark noise suppression up to 30GHz
- Static power dissipation of less than 15 mW per channel
- 32 channels

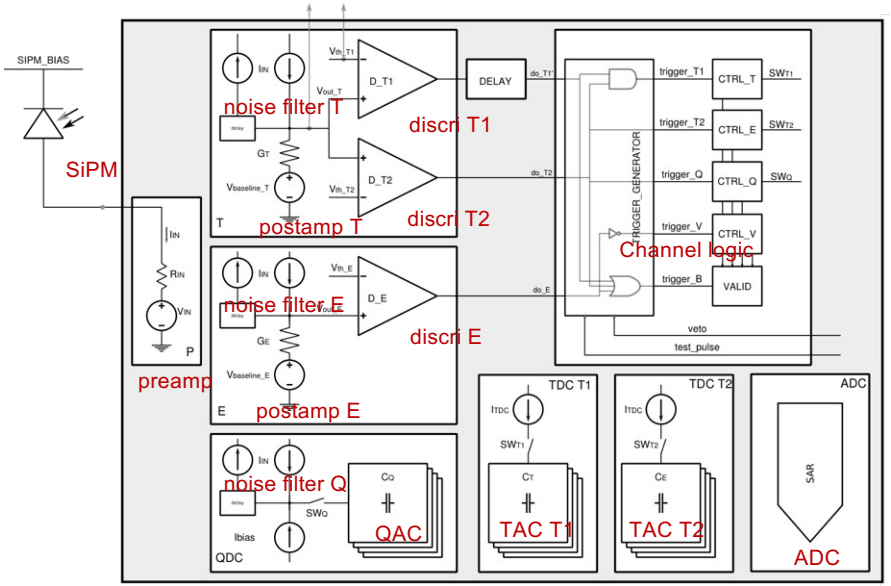
TOFHIR2 channel

Features:

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

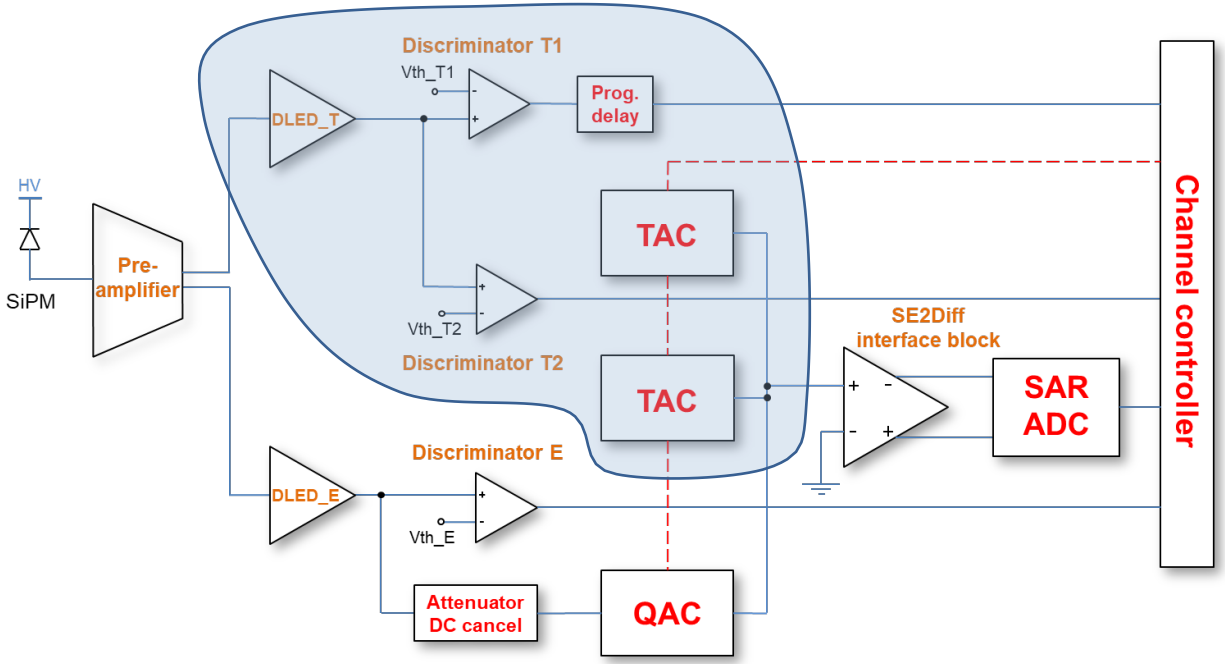
Challenges:

- 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

TOFHiR: Channel architecture – Timing branch



Timing jitter

$$\sigma^{BTL}{}_t = \sigma^{clk}{}_t \oplus \sigma^{disc}{}_t \oplus \sigma^{elec}{}_t \oplus \sigma^{photo}{}_t \oplus \sigma^{DCR}{}_t$$

Digital TOFHiR Crystal & SiPM

- Purpose – detect and time-tag valid MIP events with a time resolution <50ps average throughout the detector lifetime
- There are three main contributors to time resolution
  - Digital clock jitter
  - TOFHiR - Time discritizations in the TDC & electronics noise
  - Crystal photo-statistics & dark counts
- Note (dark counts)
  - Long time exposure to high radiation levels damages SiPM
  - Thermally generated small current pulses at high rates (up to 30GHz)
  - Mitigated, to an extent, by lowering operating temperature (-45ºC)
  - Indistinguishable from true photoelectrons generated by MIP events

Time walk due to baseline drifts

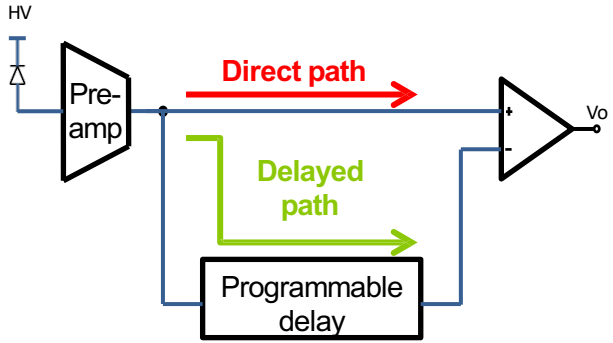
- Stream of pulses
  - MIP events at a rate of 2.6 MHz/channel
  - Low energy events at a rate of 5 MHz/channel
  - Dark counts at a rate as high as 30 GHz
- Impacts:
  - Baseline drifts due to severe piling-up of residual pulse tails
  - Accurate time-tagging is severely impaired due to time walk, since discriminators have fixed threshold
- Baseline must be rock solid for accurate timing

TOFHiR time resolution

- At Beginning of Life (BoL), time resolution is bounded by **electronics noise** (dark noise is negligible)

- At End of Life (EoL), time resolution is degraded and bounded by **dark noise**
  - SiPM current pulses are reduced by **x4** (lower gain and photo-electron yield)
  - Substantial **increase** in **dark noise** (DCR up to 25GHz@-45ºC)
  - Degraded slew-rate/noise ratio
  - To reach the 50ps average time resolution, dark noise must be reduced by at least **x2**

TOFHiR: Dark noise suppression & DLED



DLED signal processing

$$h[f(t)] = f(t) - f(t-\delta t)$$

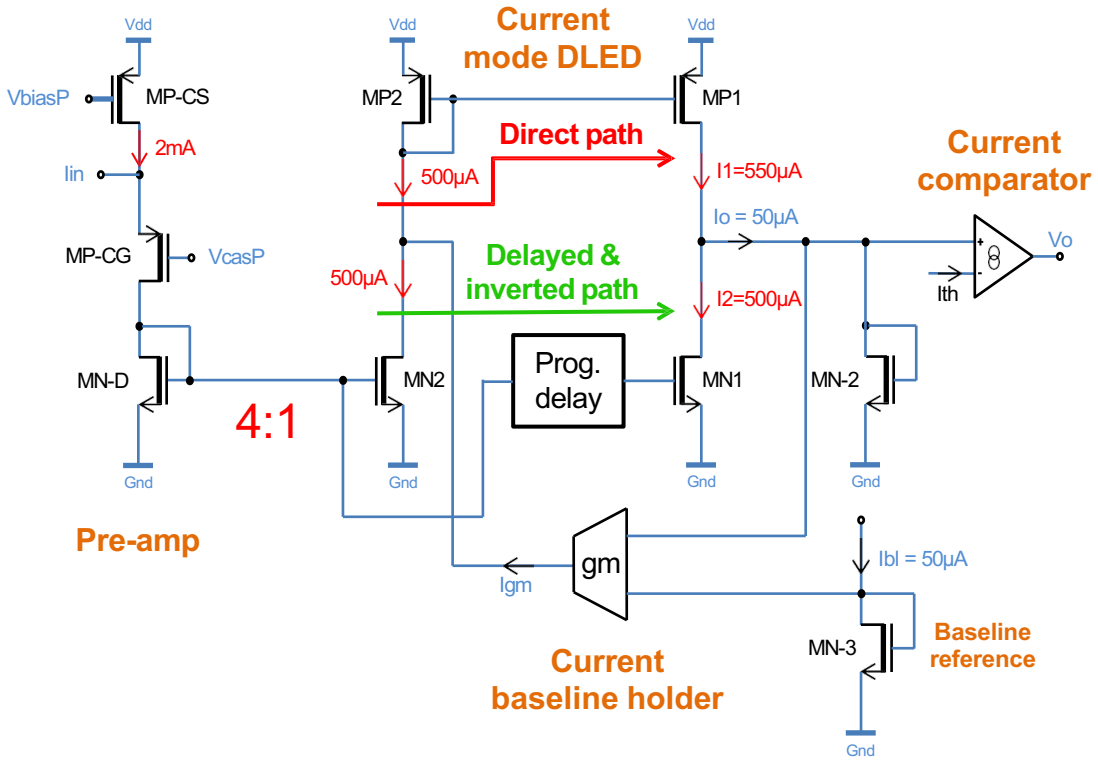
δt = [200 800]ps

Source: MTD Technical design report pp. 30-32

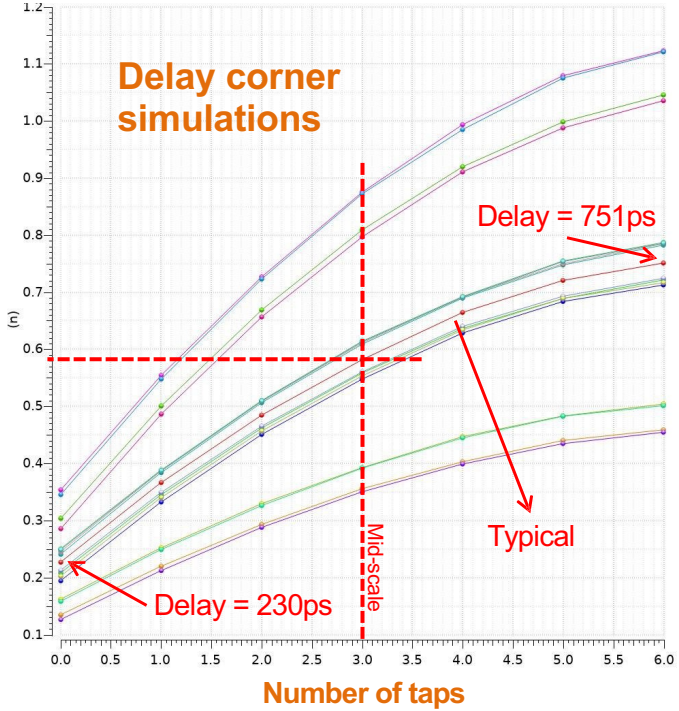
DLED – Differential Leading Edge Discrimination (A. Gola *et. al.* TNS 2013)

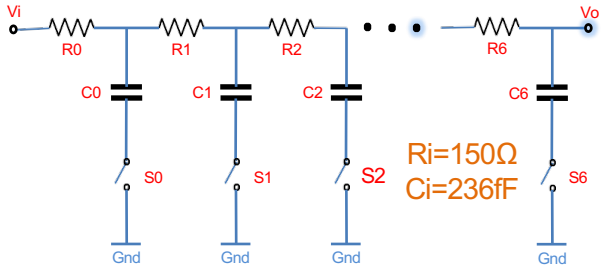
- Cancels an arbitrary portion of the pulse tail (depends on delay δ)
- Preserves the rising edge and hence the timing information
- Reduced pulse amplitude, width and bipolar output pulse shape lead to lower baseline fluctuations
- Mitigate impact of local baseline fluctuations and drifts on time resolution
- Reduces the dark noise impact on time resolution

TOFHiR: Current mode front-end

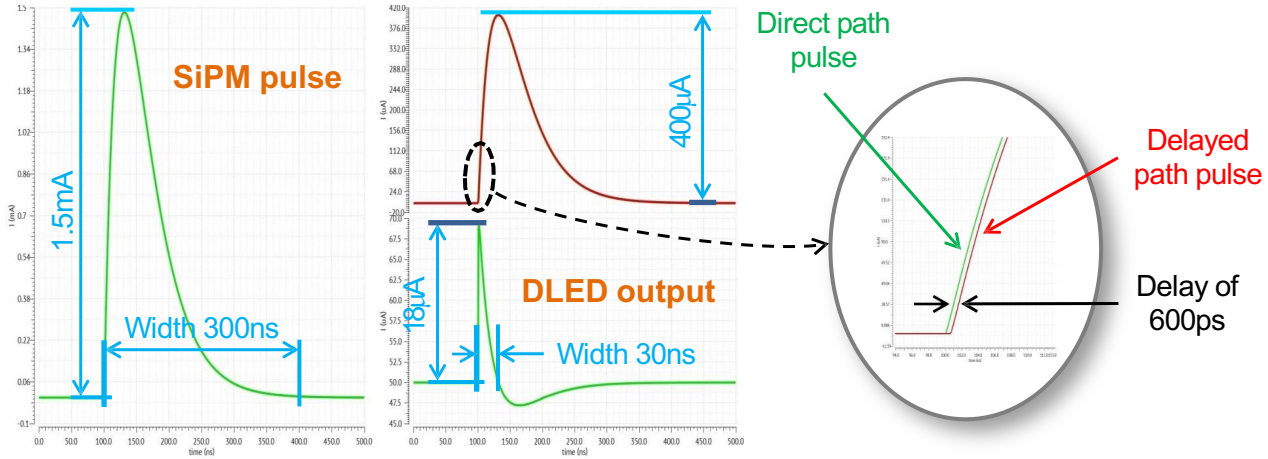


TOFHiR: DLED delay line



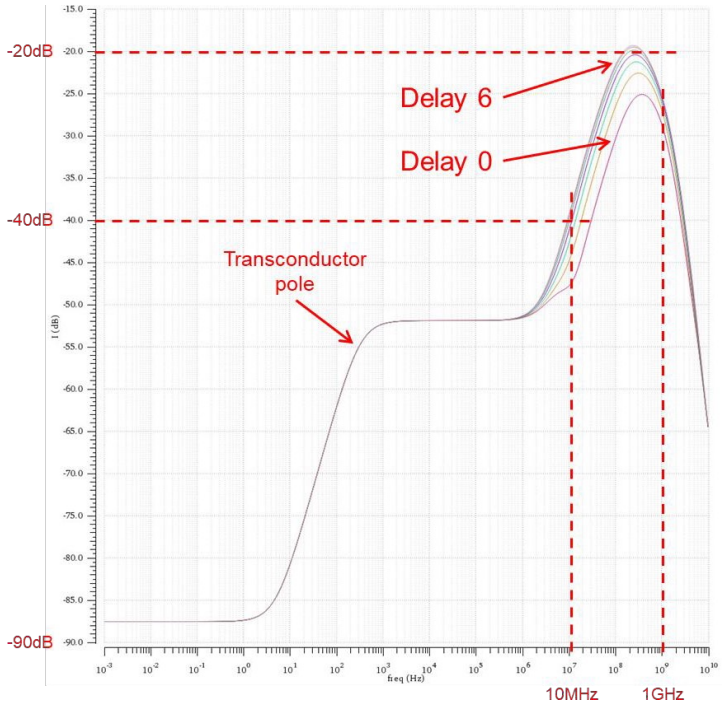


TOFHiR: Dark noise suppression with current-mode DLED



- Preserves pulse rising edge
- Pulse amplitude reduced by **x80**
  - Mitigates baseline drifts and fluctuations from dark noise & residual pulse tails
  - Lower time-walk errors
- Narrower pulse width by at least **x10** - lower pulse pile-up
- Converts the unipolar SiPM pulse into a bipolar pulse
- Reduced dark noise impact on time resolution

TOFHiR: Preamp-DLED frequency response



- High-pass frequency response (from 10MHz to 800MHz)
- Knee frequency 10MHz
- Cutoff by parasitics at 800MHz
- Frequencies above knee (10MHz) are highlighted [-40 -20]dB - Sharp pulse rising edge and timing resolution is preserved
- Frequencies below knee (10MHz) are strongly attenuated to -90dB – Assures solid and stable baseline
- Transconductor dominant pole is at 300Hz – Stability is assured

DCR noise cancellation

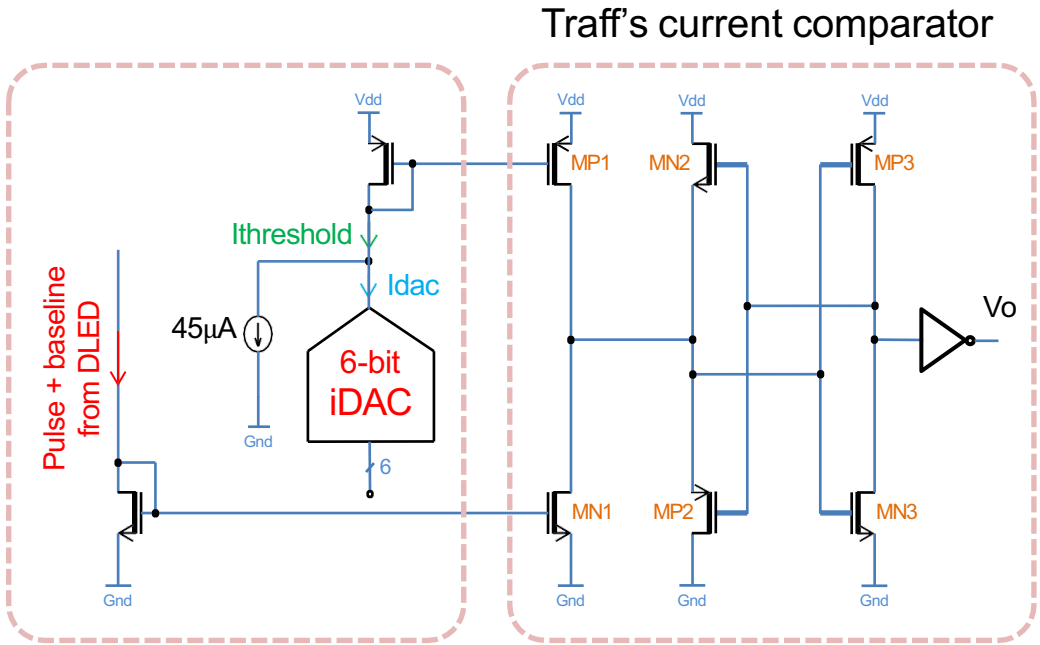
Simulation of time resolution in EoL conditions:

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

	SiPM ouput current	DLED 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

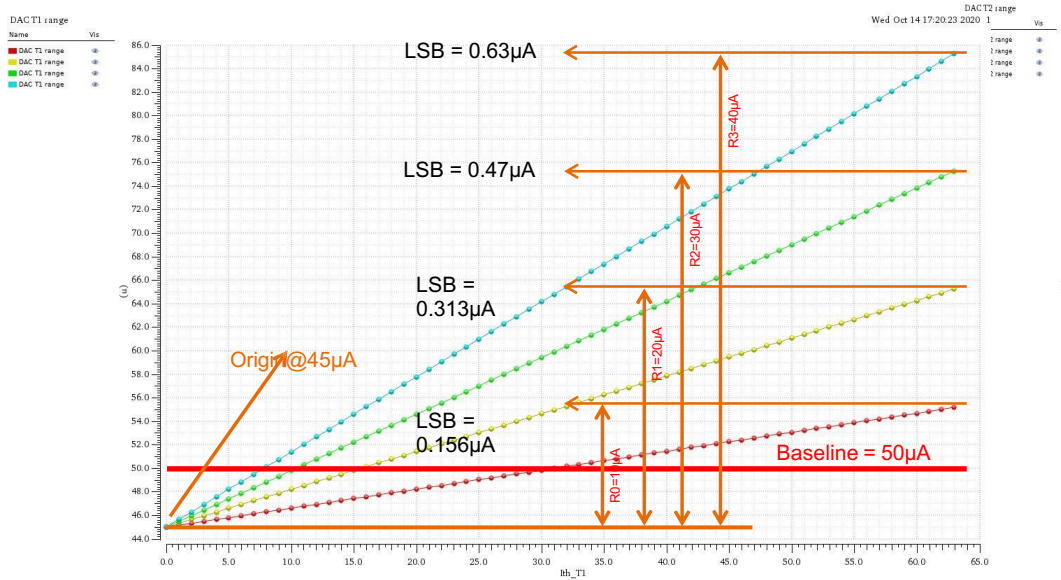
Time resolution is improved by a factor 3.5

TOFHiR discriminators

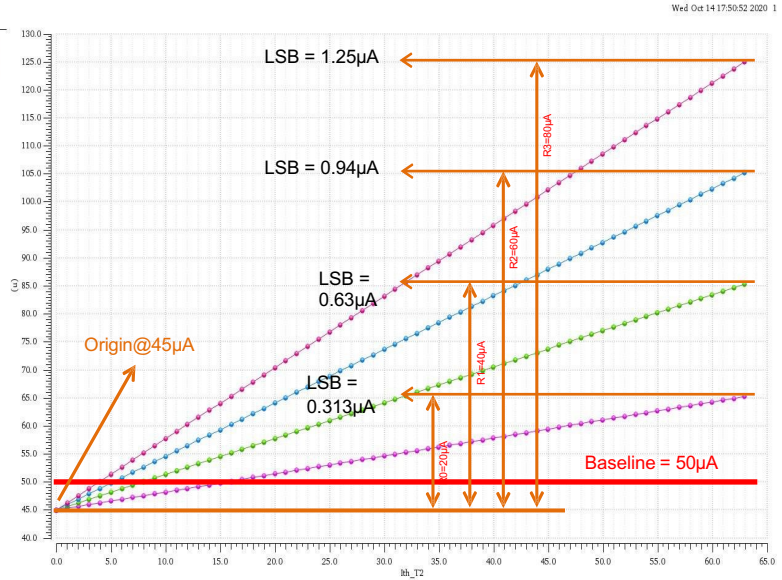


TOFHiR discriminators range

T1 DAC ranges

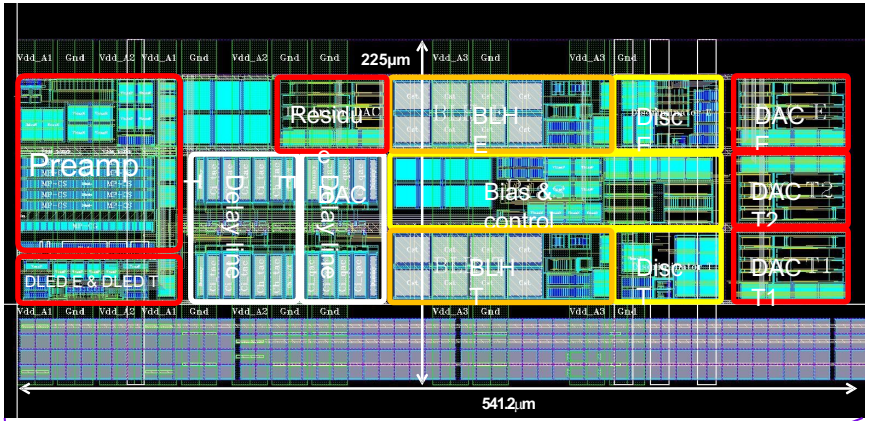


T2 & E DAC ranges

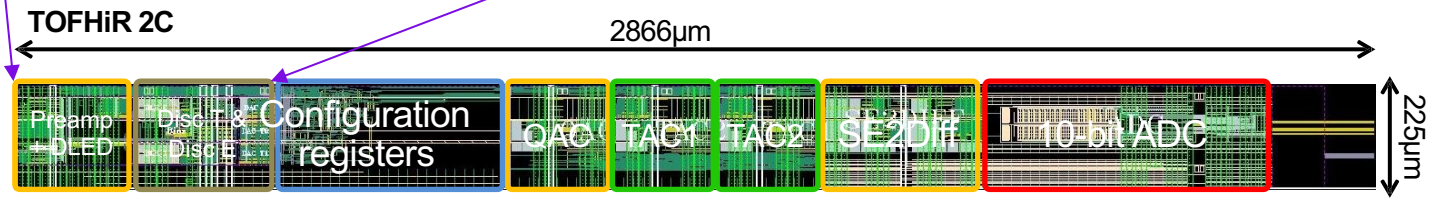


TOFHiR 2C channel layout

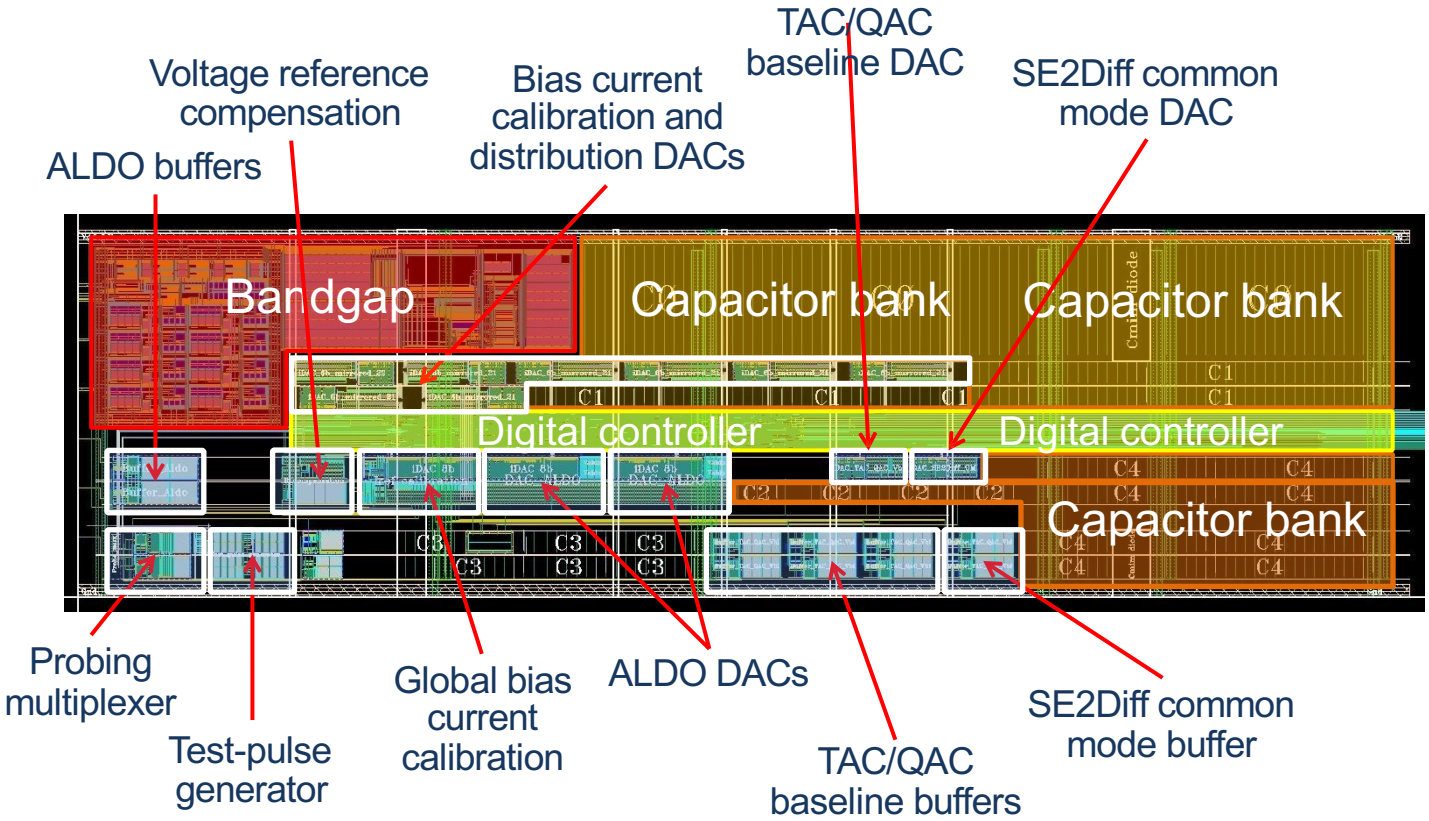
Analog front-end layout



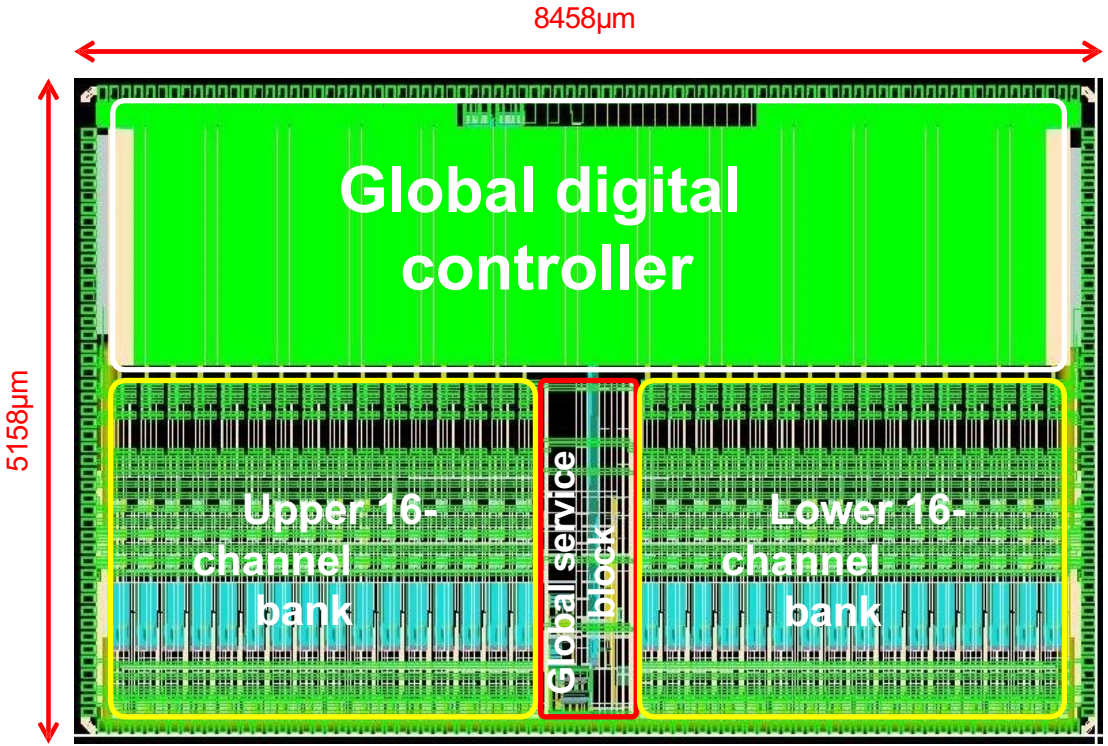
Channel layout and dimensions

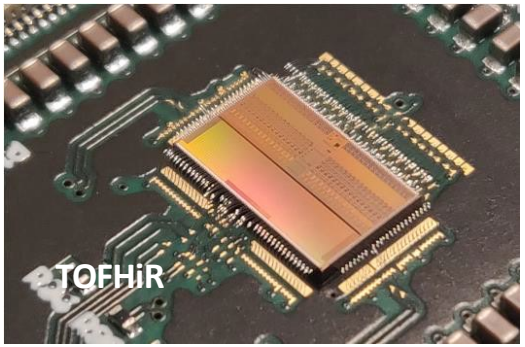


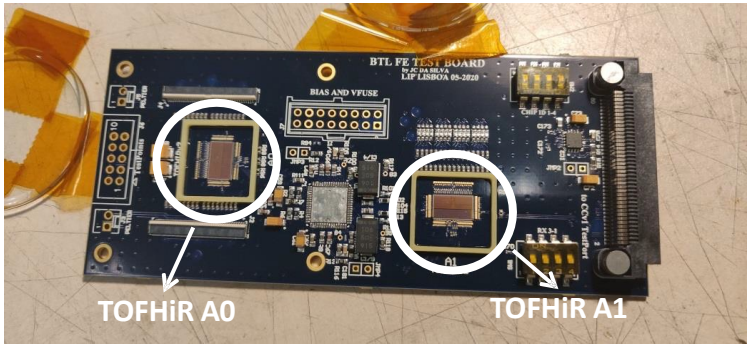
TOFHiR: Global service block



TOFHiR Full Chip





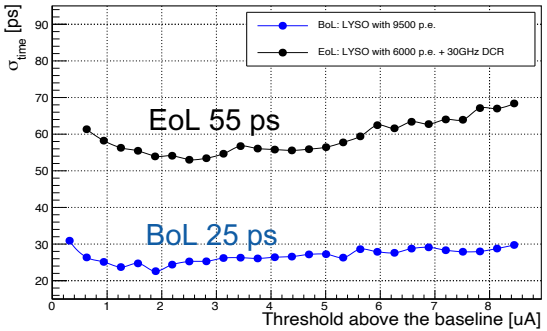


- TOFHiR die area 8.5x5.2=44.2mm2, 258 I/O and power pads

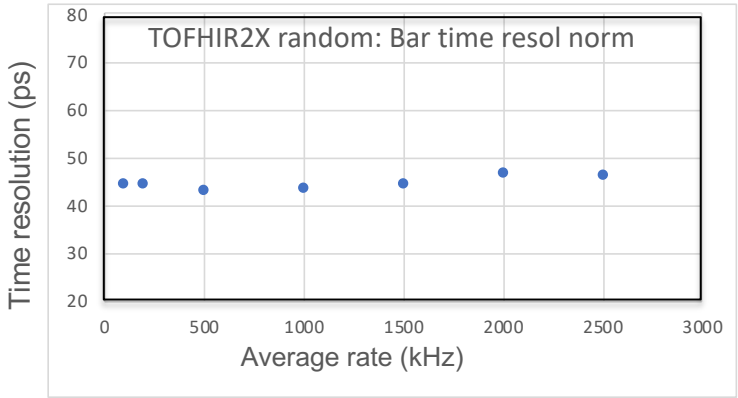
TOFHiR: Key measurement results

Lab measurements with UV laser

Time resolution at BoL and EoL
Time resolution as a function of threshold in BoL and EoL with TDR assumptions

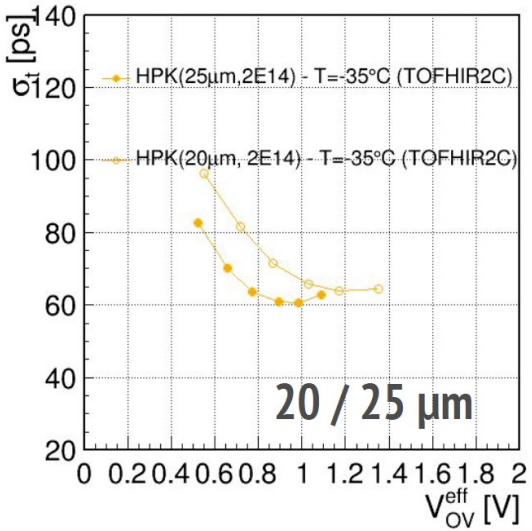


Time resolution as a function of rate
Detector module with TOFHIR2 excited with UV laser (pseudo-random test pulses)



Test Beam

Results with **TOFHIR2 on modules irradiated to 2E14** with 20 and 25 µm SiPMs at T=-35ºC



TOFHiR Conclusions

- TOFHiR front-end ASIC for the MTD/BTL detector at CMS has been developed
- A radiation tolerant full current-mode AFE has been designed:
  - Meets the stringent time resolution specifications
  - EoL time resolution is met thanks to the first silicon implementation of DLED
  - DLED mitigates the low EoL pulse amplitude and high DCR
  - Fits the power budget
  - Has reasonable area for a 32 channel ASIC
  - Provides high yield
  - Has low channel-to-channel spread
- Extensive measurement campaigns show that the average time resolution of 50ps is met throughout the 10 years detector lifetime
- These achievements have been critical to the commissioning of the MTD/BTL detector

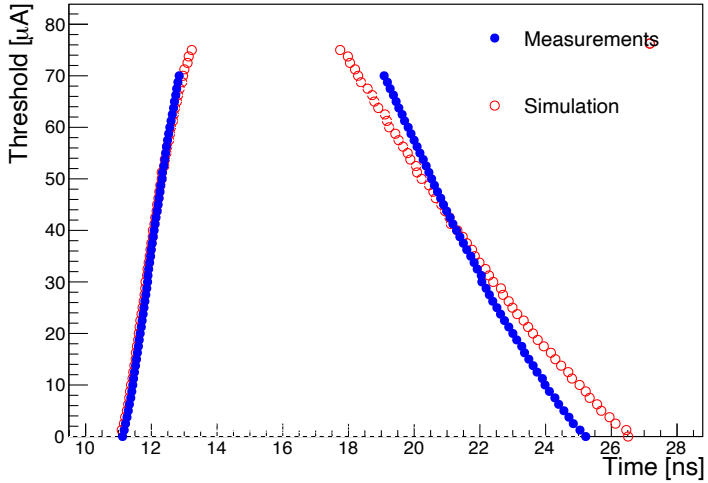
Thank you for your attention

Backup

Pulse shape

Pulse shape of LYSO excited with UV laser

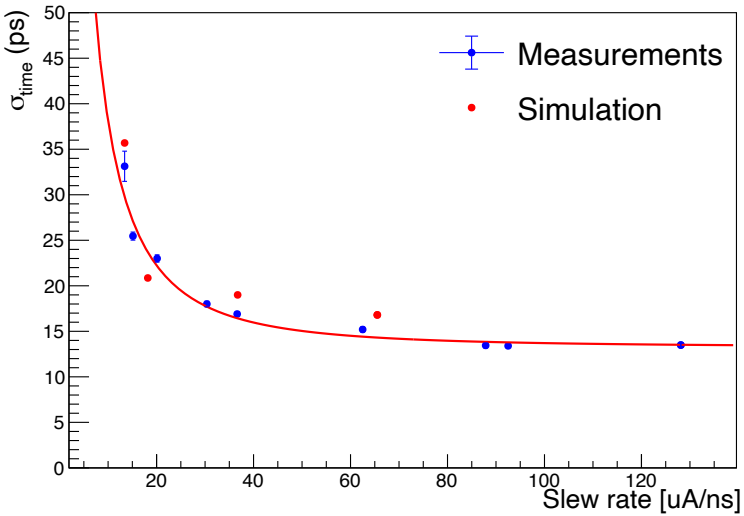
- LYSO pulse: 9500 pe, SiPM gain 3.8×10^5
  - UV laser tuned to generate a LYSO pulse with a given number of photoelectrons
- Pulse shape derived from discriminator threshold scan
  - The time of the leading and trailing edges are measured by the TDC1 and TDC2
- Good agreement between simulation and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

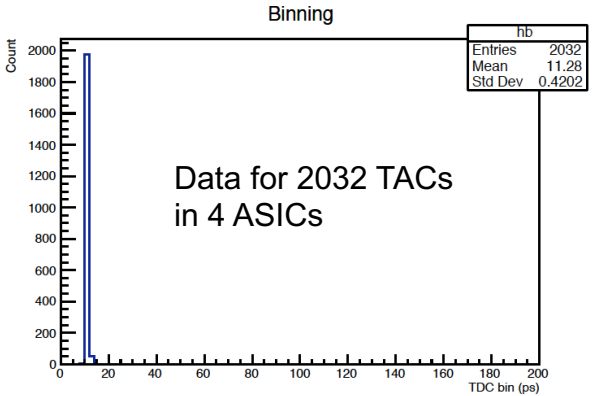
$$\sigma_t^{elect} = \frac{\sigma_{noise} = 0.36\ \mu A}{SR = 28.6\ \mu A/ns} = 13\ ps$$



TDC performance

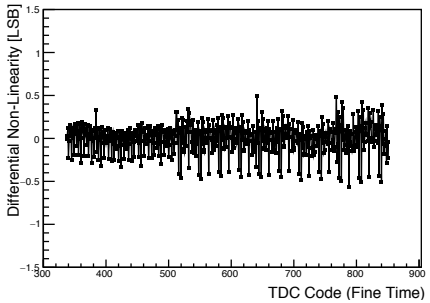
TDC binning:

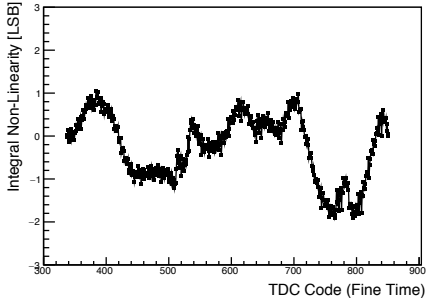
- **Typical binning is 11 ps**
  - 10 ps expected
- Low dispersion of binning
  - sigma=0.4 ps



TDC linearity:

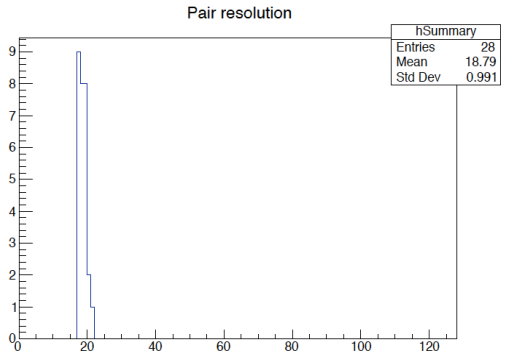
- DNL < ± 0.5 LSB
- INL < ± 2 LSB





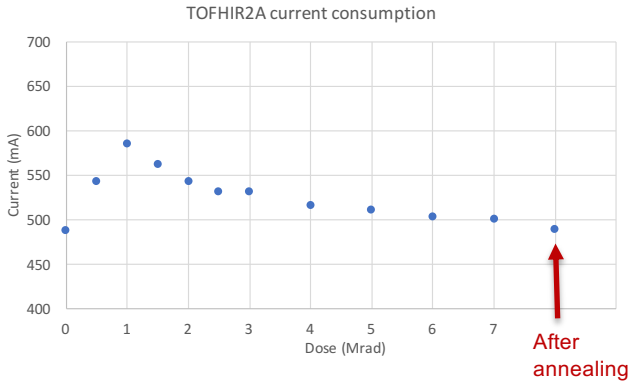
TDC resolution:

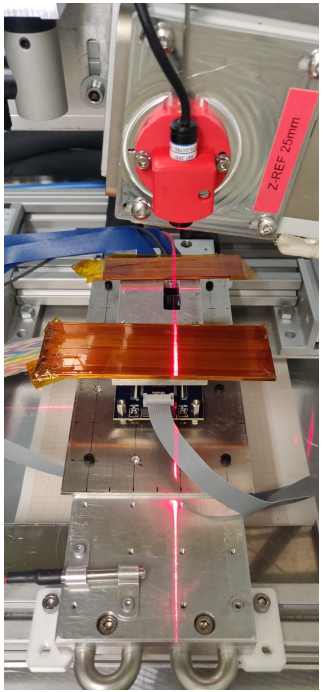
- Coincidences between TDC pairs used to cancel common jitter (e.g. clock jitter)
- **TDC resolution is 13 ps**
  - 5% dispersion



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.

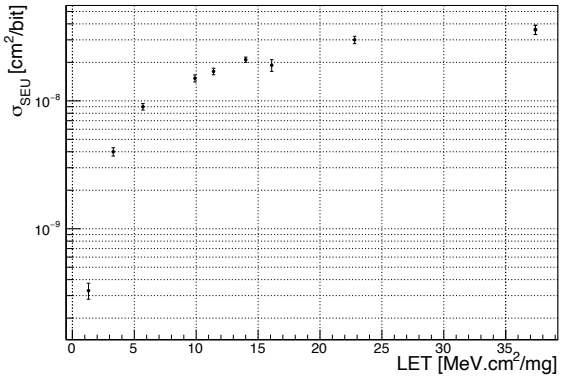
SEE radiation test

- **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

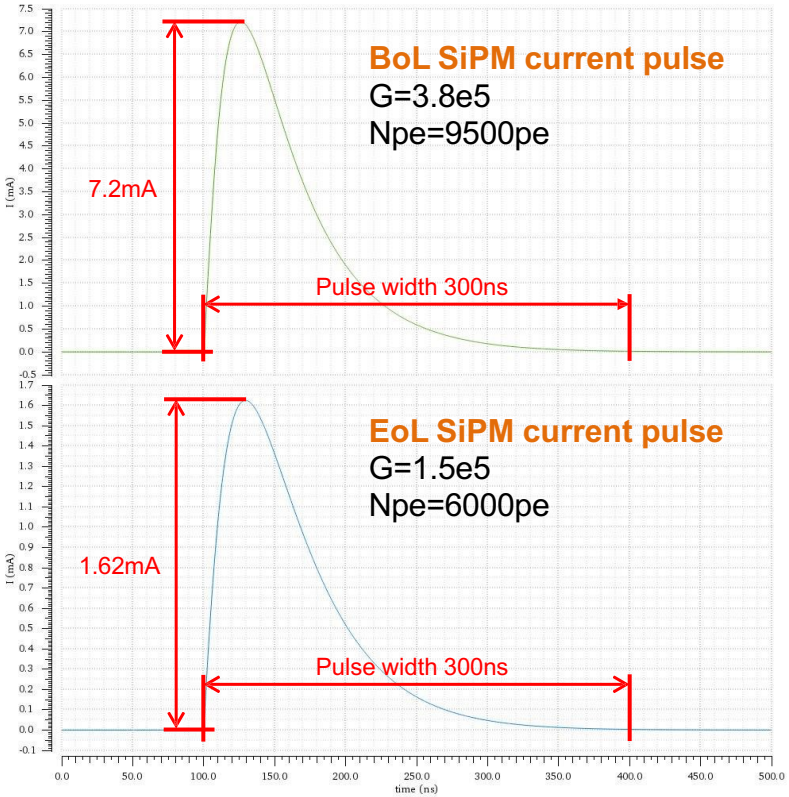
Results:

- 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

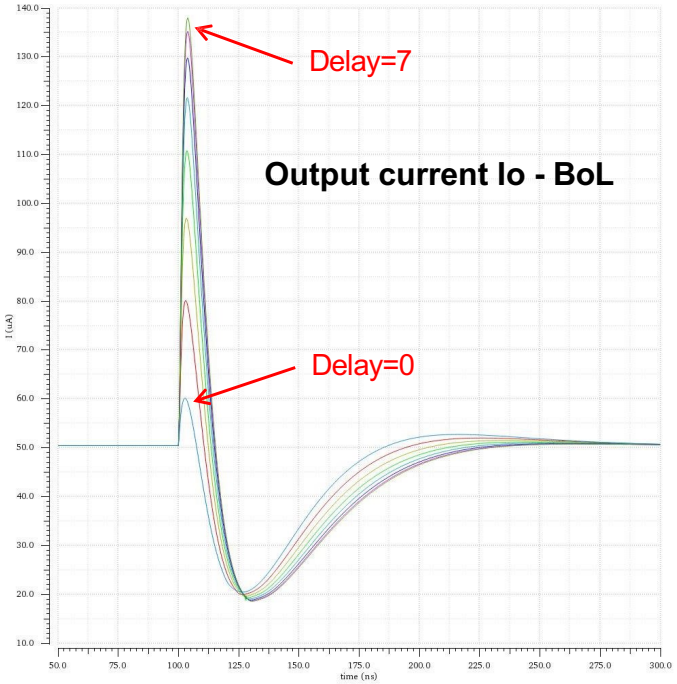
Cross-section of corrected SEU errors

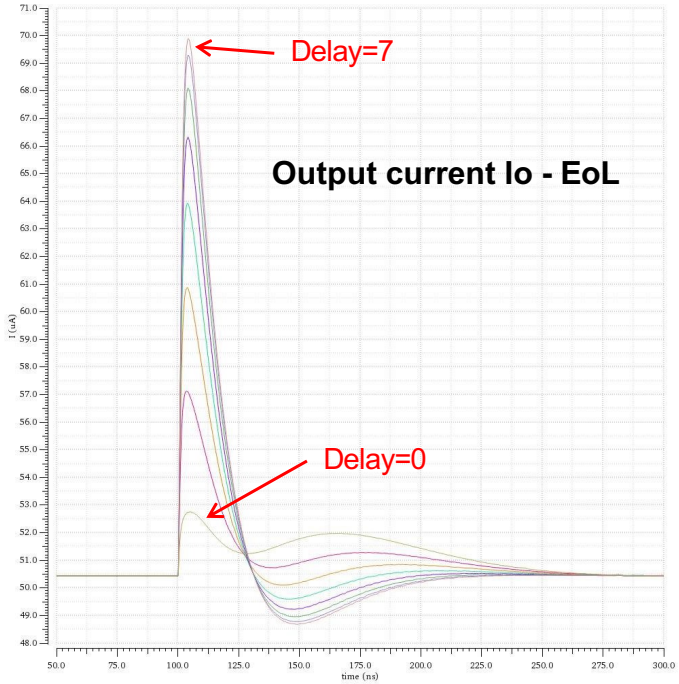


TOFHiR: Typical BoL & EoL SiPM current pulses

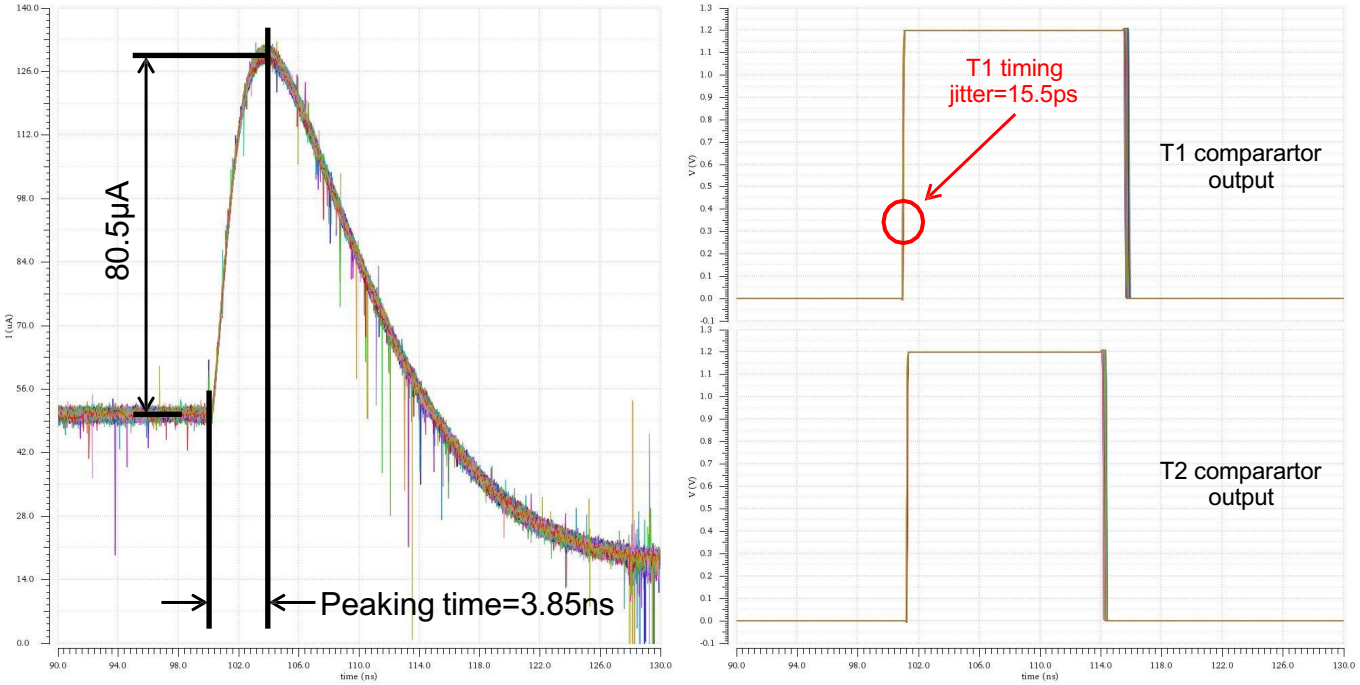


TOFHiR: Current pulse vs delay

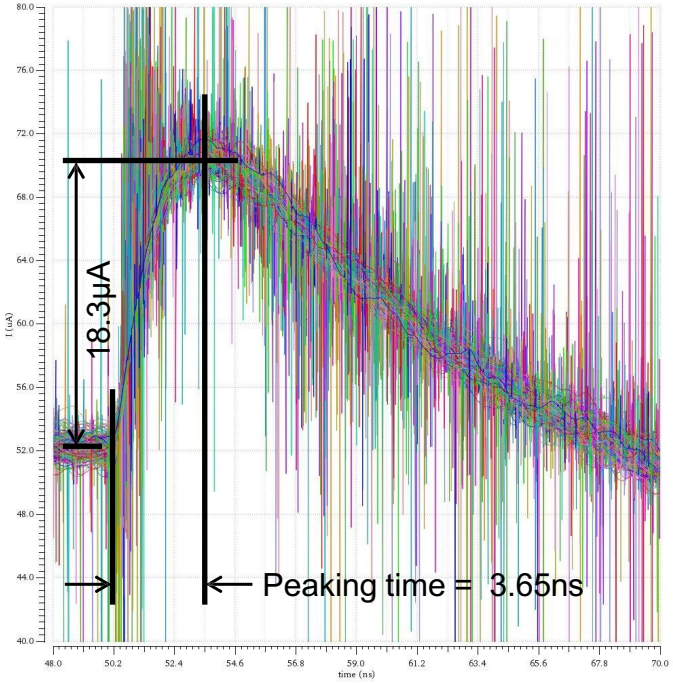


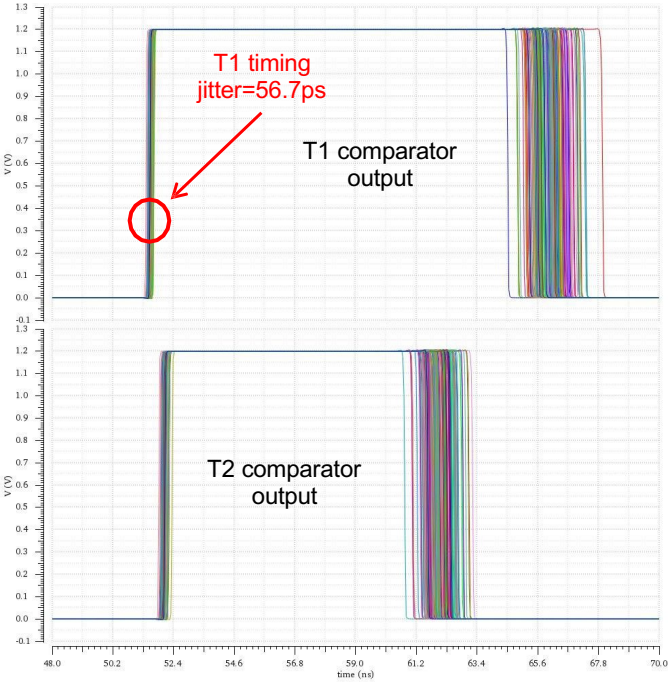


Timing resolution (BoL with electronics noise)



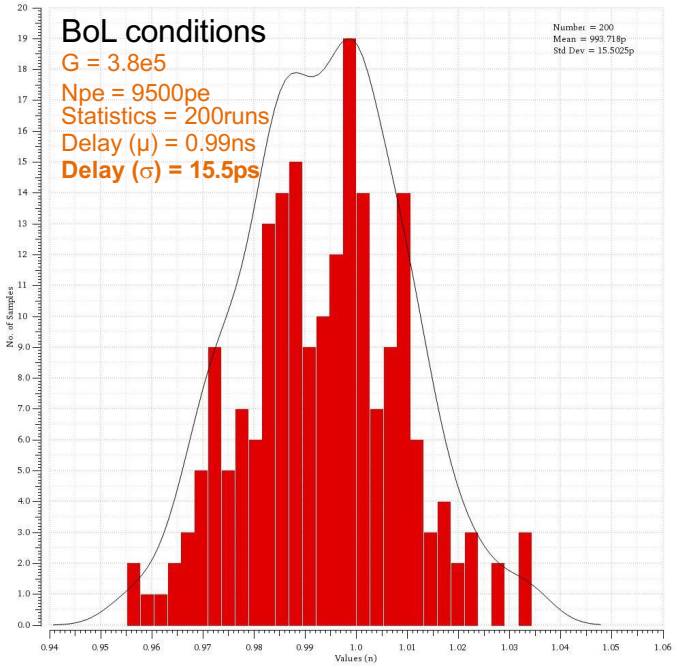
Timing resolution (EoL with DCR)

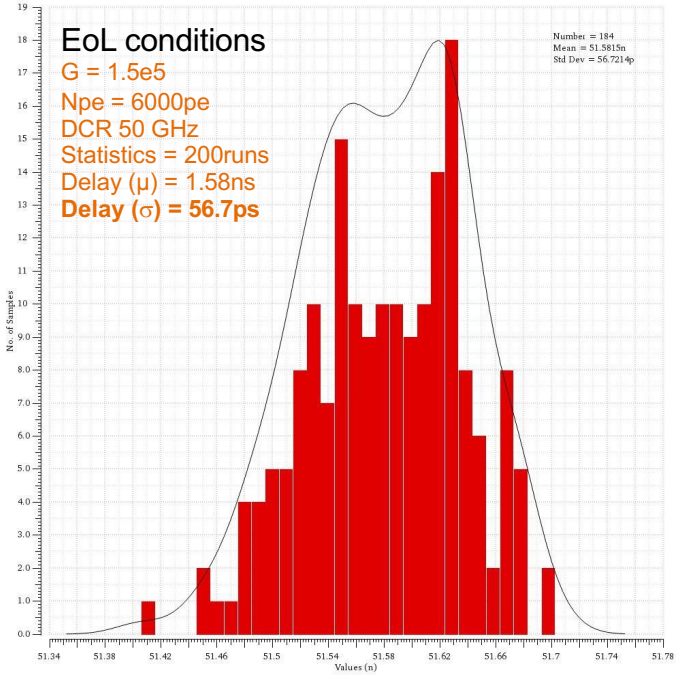




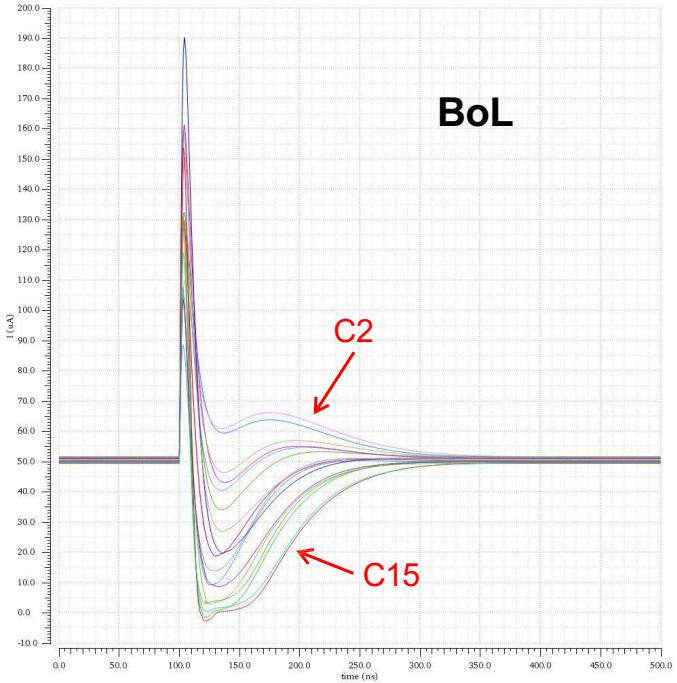
TOFHiR channel timing resolution (noise and DCR)

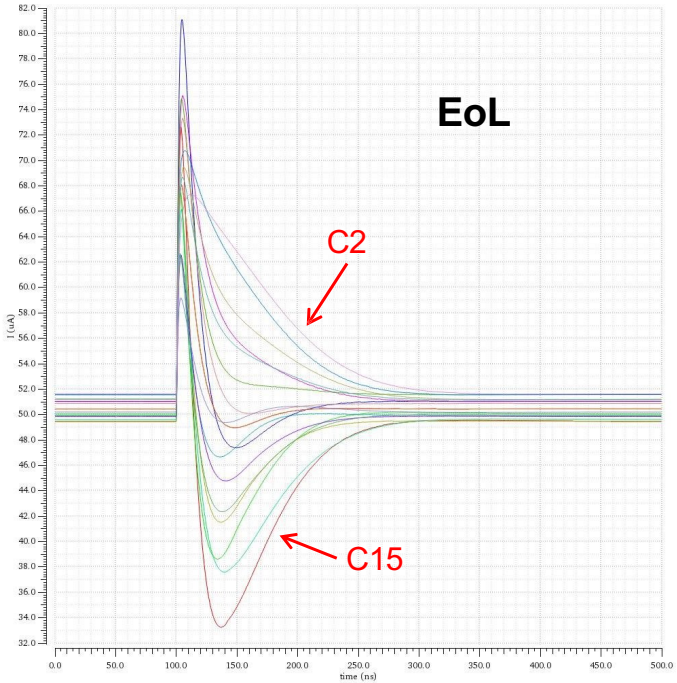
Single channel time resolution



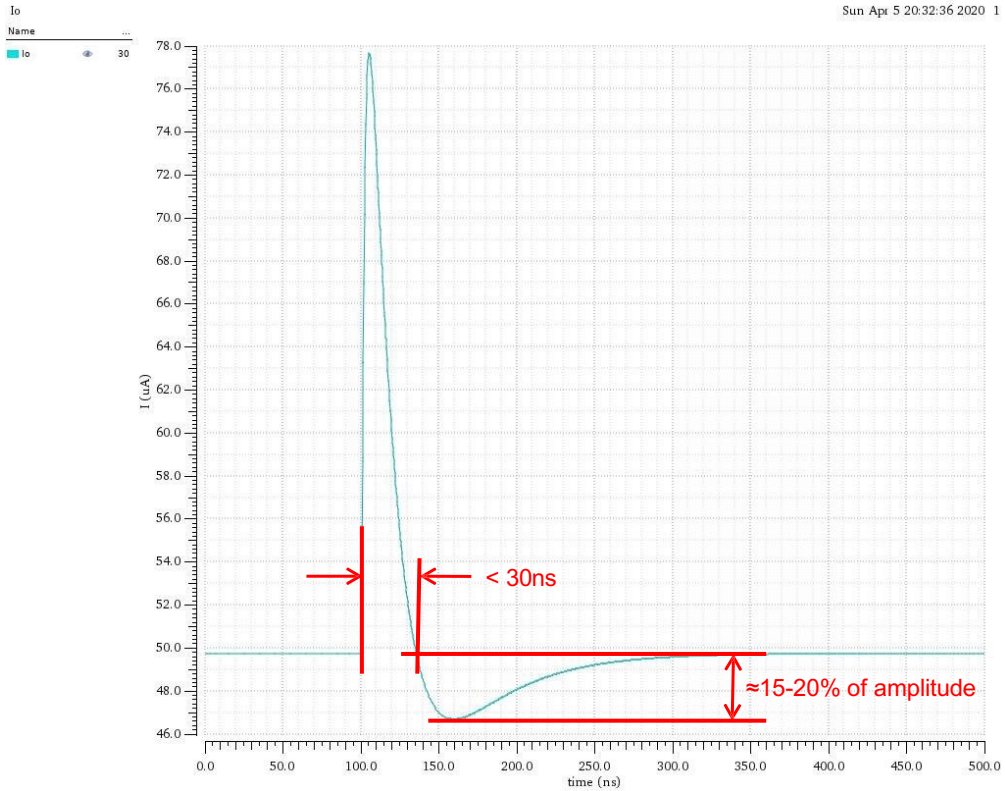


TOFHiR: Output current pulses through corners

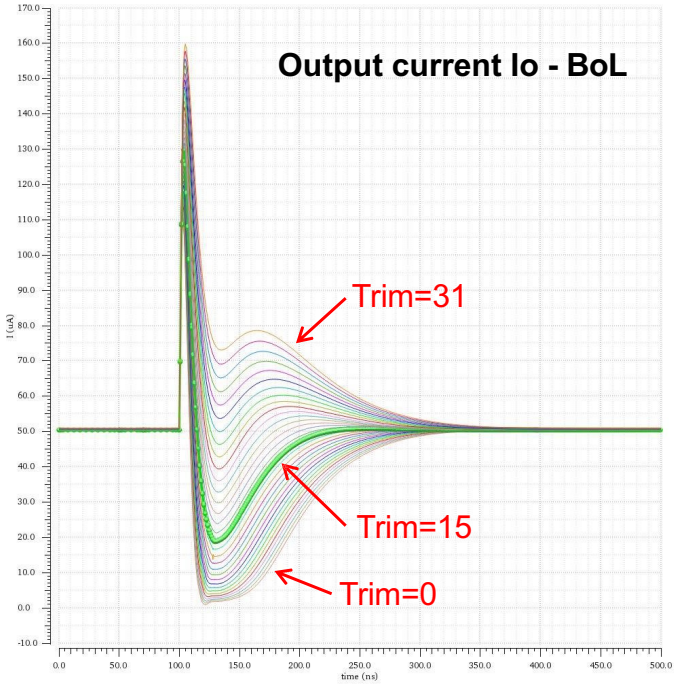


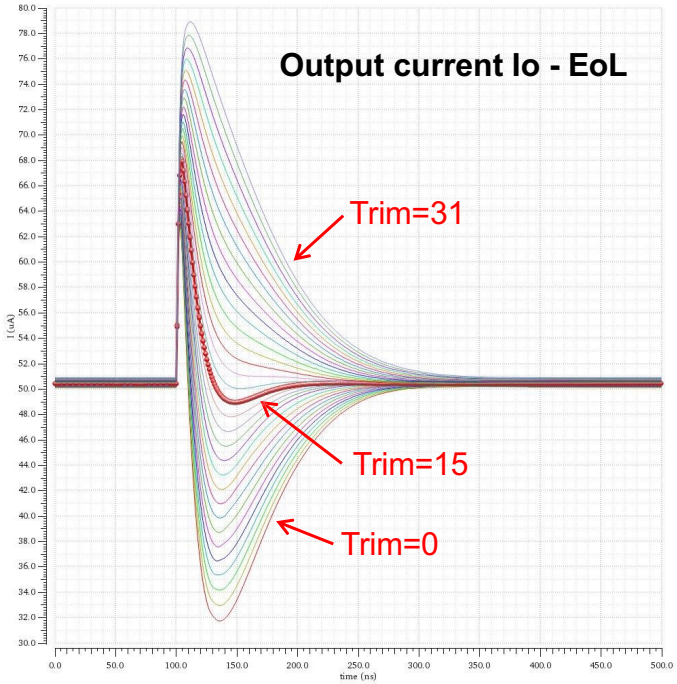


TOFHiR: Ideal pulse shape

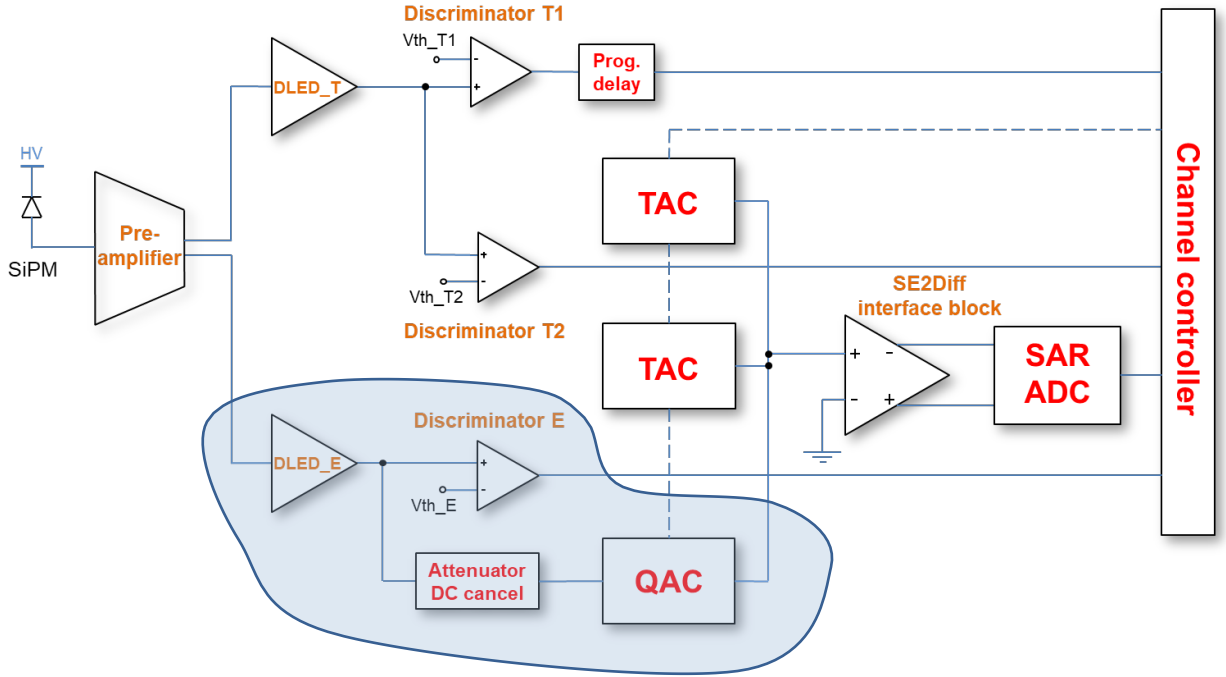


TOFHiR: Pulse shape calibration

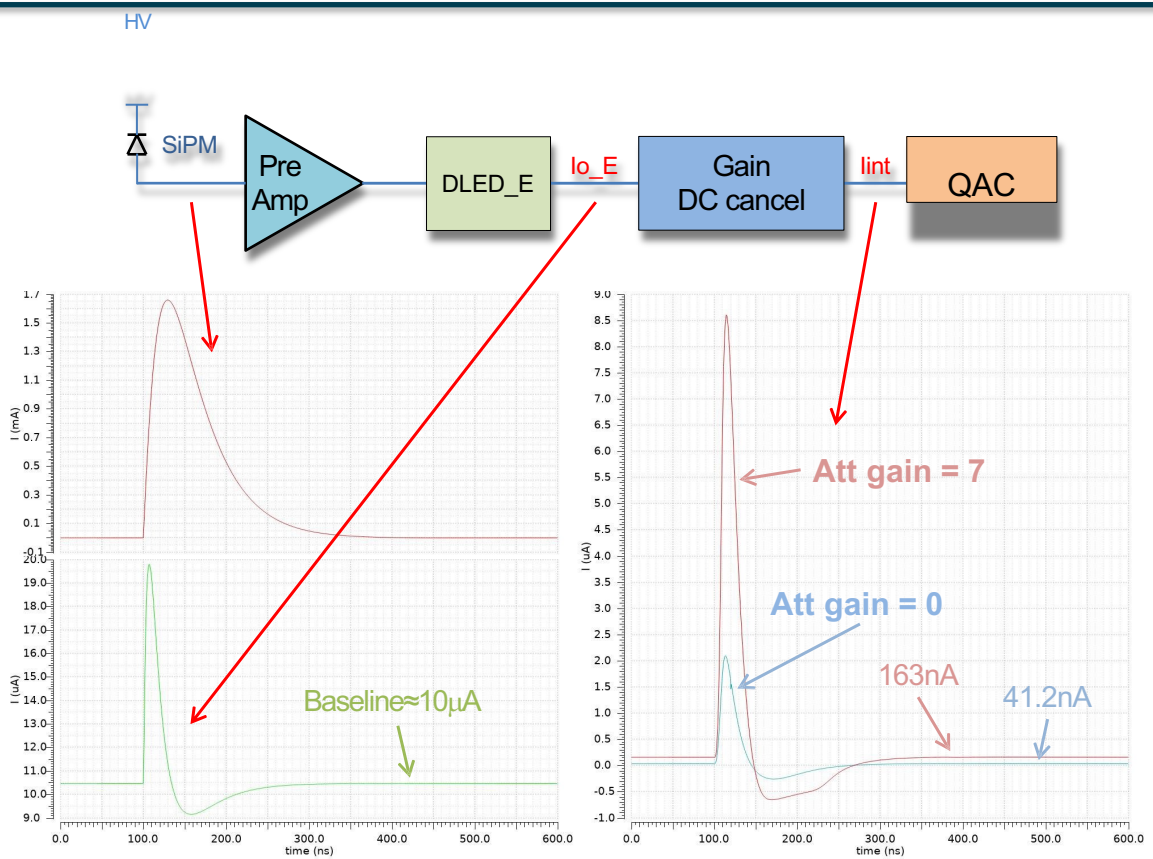




TOFHiR: Channel architecture – Energy branch

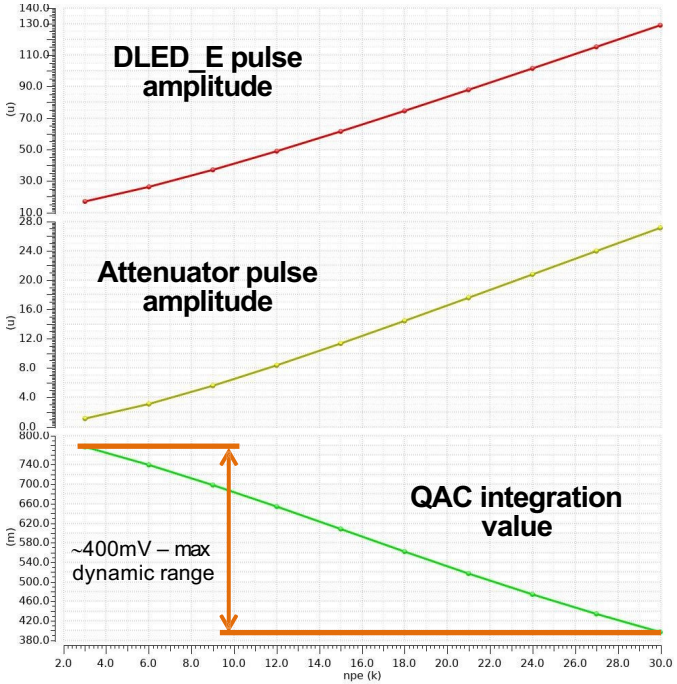


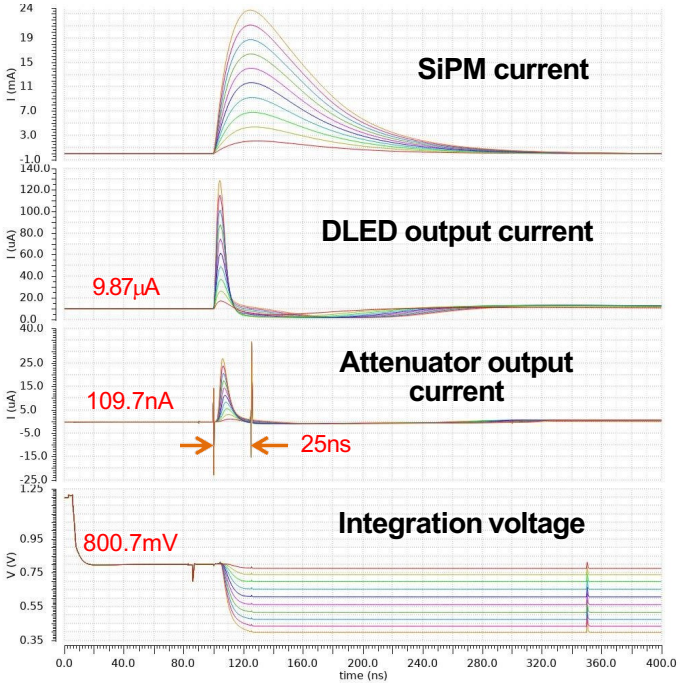
TOFHiR QAC signal processing



TOFHiR: QAC linearity vs. Npe (BoL)

- Att=0, Delay_E=2, Pulse_trim_E=7
- Integration window = 25ns
- SiPM gain = 3.8e5
- Npe range = [0 30000]pe





TOFHIR: Energy measurements

- TOFHIR2 has a DAC to calibrate the baseline, allowing it to be set at zero
- Charge integration block has been validated
  - Good linearity in energy dependence on number of photoelectrons
  - Energy resolution below 5% in the range of pulse amplitude of interest