PHYSICS OF MOLECULAR IMAGING SYSTEMS

Power-efficient high-frequency readout concepts of SiPMs for TOF-PET and HEP

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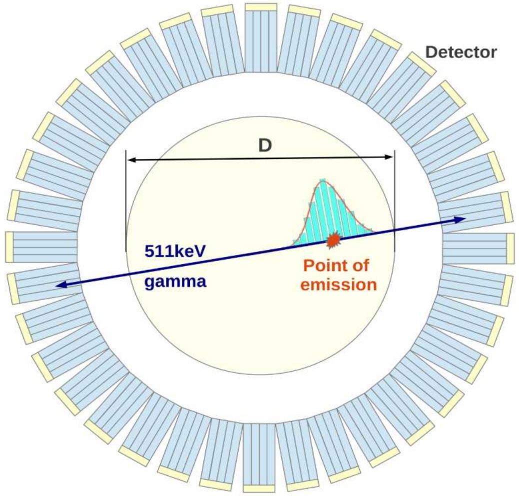
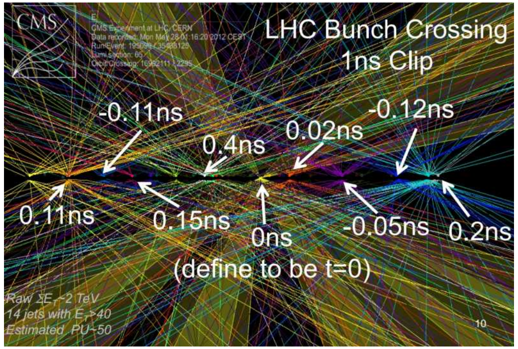
Motivations for ultrafast timing detectors

Time-of-flight positron emission tomography (TOF-PET)
→ https://the10ps-challenge.org/
→ 100 ps is the next big step in systems



In beam dose monitoring for hadron therapy via TOF-PET

High energy physics (HEP) in future high luminosity colliders (25 ns bunch crossing in HL-LHC & pile up effects)

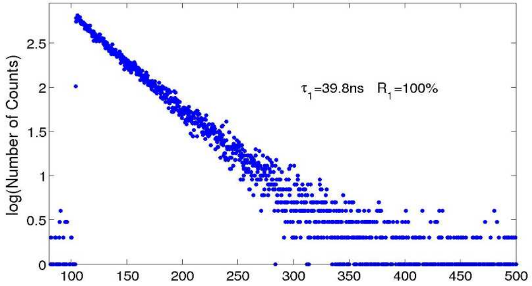


High rate X-ray detection (TOF-CT & Hard X-Ray imagers)

- J. Rossignol et. al, “Time-of-flight computed tomography - proof of principle”, Phys. Med. Biol. 65 085013
- C. Hu et. al, “Spatial Resolution of an Inorganic Crystal-Based Hard X-Ray Imager”, IEEE TNS, Volume: 67, Issue: 6, June 2020

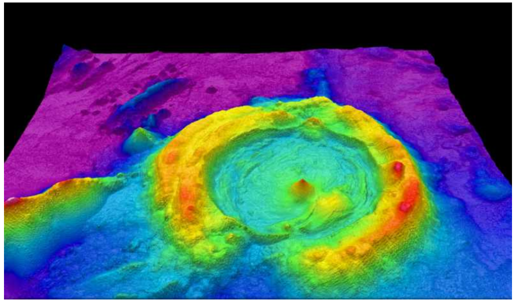
... and ultrafast single photon counting

- Single photon detection:
  - → Time correlated single photon counting (TCSPC) for scintillator research and biomedical applications (eg. fluorescence lifetime imaging).
  - → Single shot light detection and ranging (Lidar).



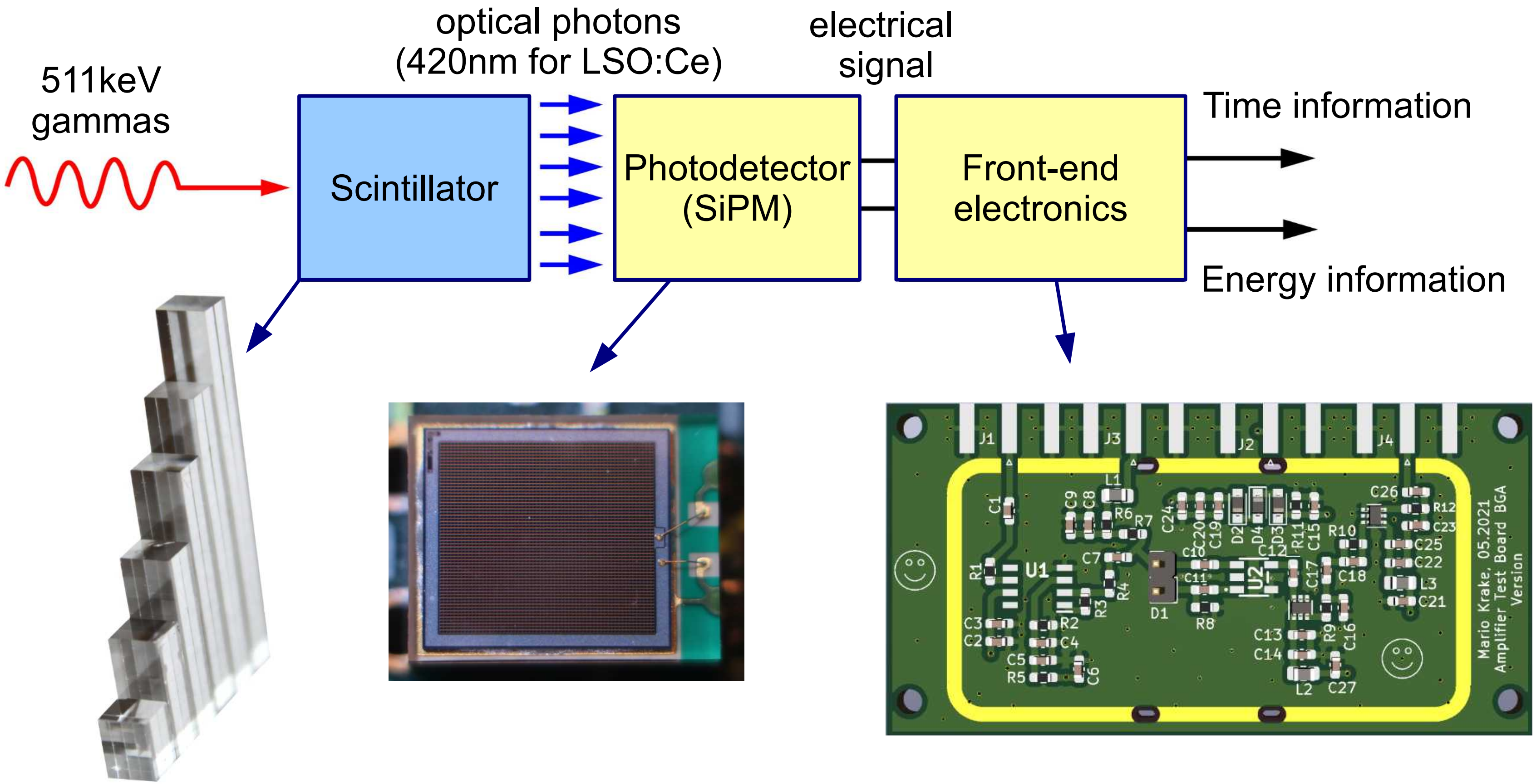
- Few (multi) photon detection: (>1 to 100 detected photons)
  - → Cherenkov emission (TOF-PET, RICH)
  - → Dark matter search
  - → Lidar

The **single photon time resolution (SPTR)** is the defining parameter, which as well influences the timing in scintillator based detectors.

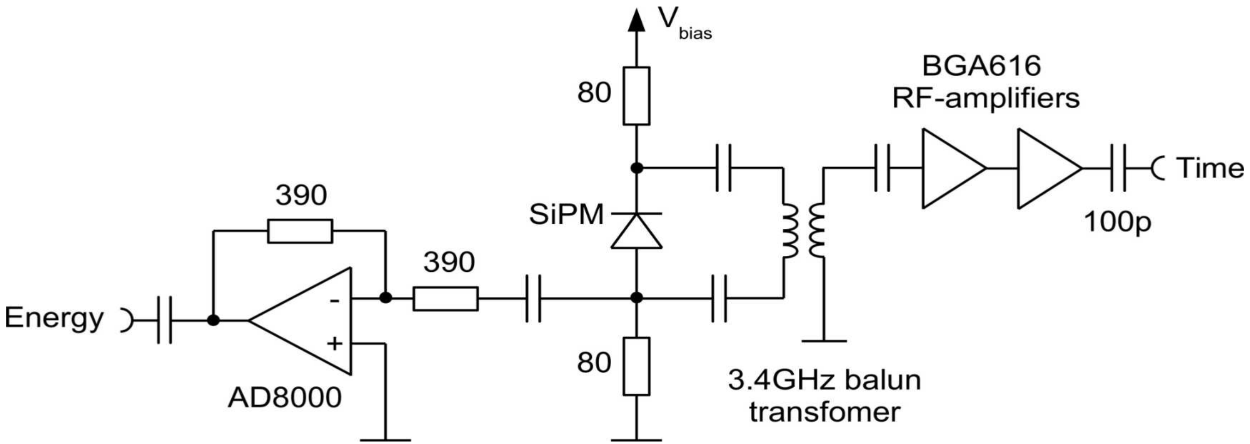


LIDAR image
(https://www.flickr.com/photos/oceanexplorergov/9267768683/)

Components of the radiation detector



High-frequency readout with world record timing



Especially for Cherenkov light detection with bismuth germanate (BGO) this design pushed forward the state-of-the art.

→ BGA616 RF-amplifier reads SiPM differentially via RF balun

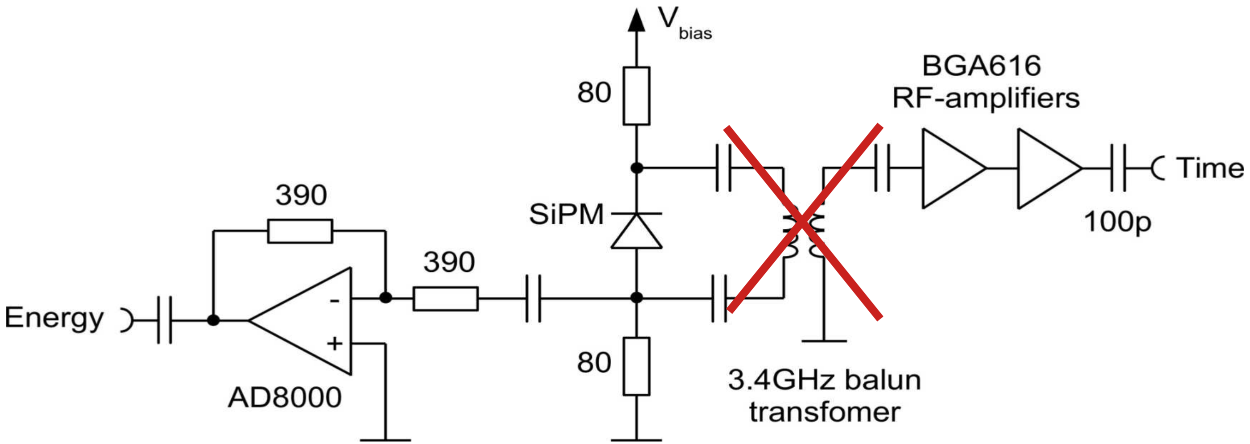
→ High frequency path via single photon avalanche diode (SPAD) quenching capacitance C_q

→ High frequency for time ~1.5 GHz bandwidth

Problem 1: Power consumption >288 mW per channel!

S. Gundacker et.al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET", Phys. Med. Biol. 64 055012, 2019, https://doi.org/10.1088/1361-6560/aafd52

New designs omit the RF balun-transformer



→ BGA616 RF-amplifier reads SiPM differentially via RF balun

→ High frequency path via SPAD quenching capacitance C_q

→ High frequency for time ~1.5 GHz bandwidth

Problem 2: Balun-transformer not compatible with combined PET - magnetic resonance tomograpyh imaging (MRI)

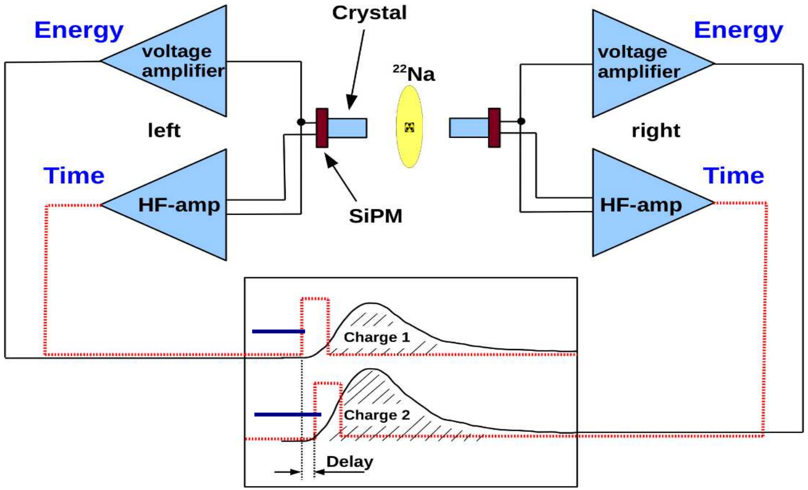
S. Gundacker et.al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET", Phys. Med. Biol. 64 055012, 2019, https://doi.org/10.1088/1361-6560/aafd52

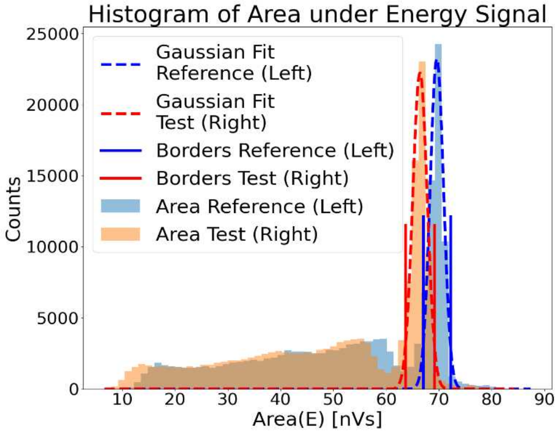
Different amplifier types tested

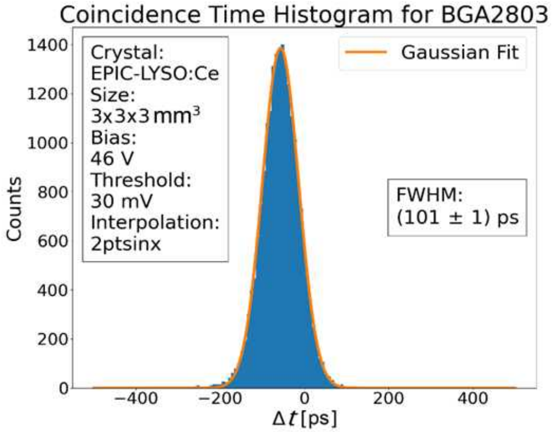
Amplifier	Supply voltage [V]	Supply current [mA]	Power [mW] (single channel)	Gain [dB]	Noise Figure	Price [€/amplifier]
BGA616	6	48	288	19	2.5	1.36
BGA2803	**3**	**5.8**	**17**	**23.6**	**3.6**	**0.291**
BGA2851	**5**	**7**	**35**	**24.8**	**3.2**	**0.32**
BGA2869	5	24	120	31.7	3.1	0.362
MAAL-011139	5	55	275	17	1.4	2.06

→ Bandwidth above 2 GHz for all amplifiers

Coincidence time resolution (CTR) setup



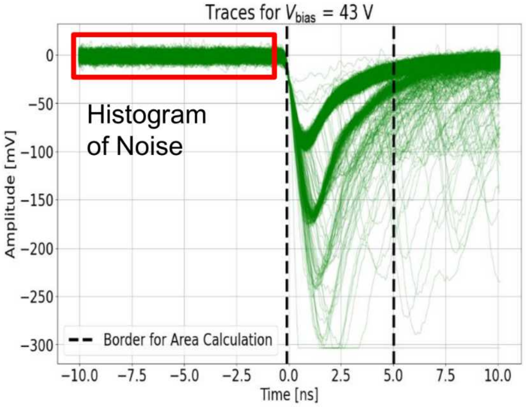




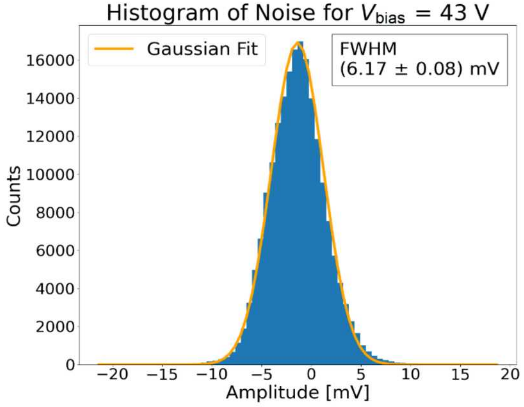
Teledyne LeCroy waverunner 9404M-MS, 40 Gs/s and 4 GHz bandwidth

Setup temperature stabilized at 16°C.
Leading edge discrimination on timing signal set on oscilloscope with linear interpolation.

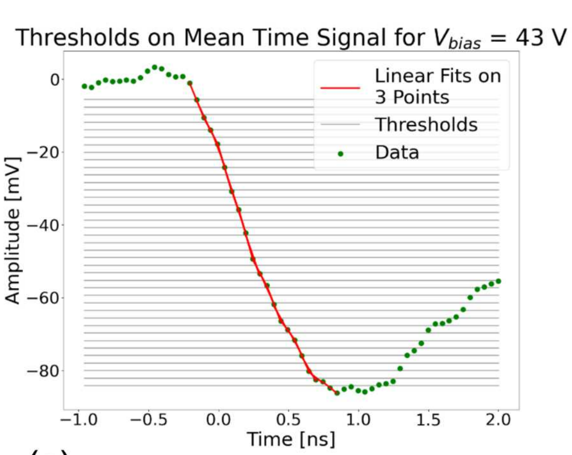
Electronic time resolution with single photons



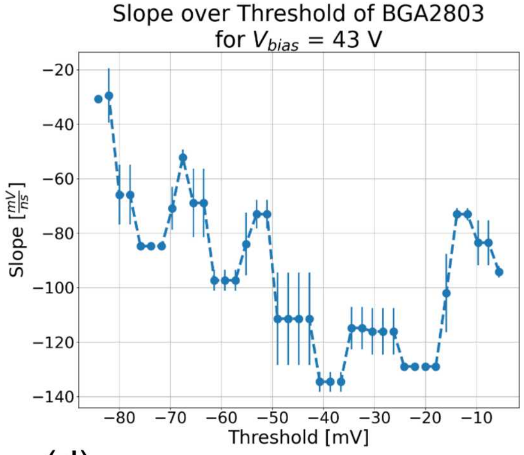
(a)



(b)



(c)

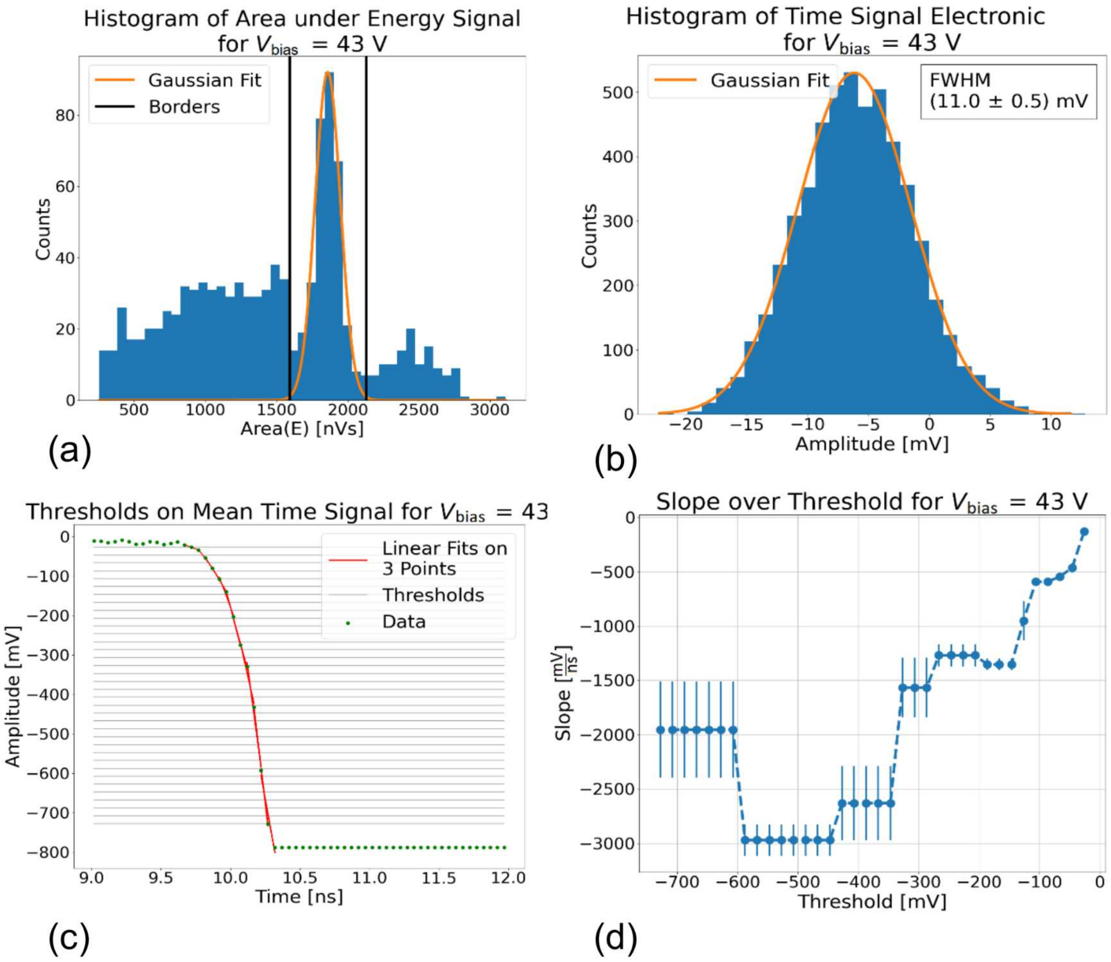


(d)

- → Noise amplitudes before single photon signal (a) inserted into histogram (b)
- → Single photon traces are averaged (c) and dV/dt at different thresholds calculated (d)
- → The electronic time resolution is calculated:

$$TR_{SPAD} = \frac{FWHM_{Noise}}{dV/dt_{@\,threshold}}$$

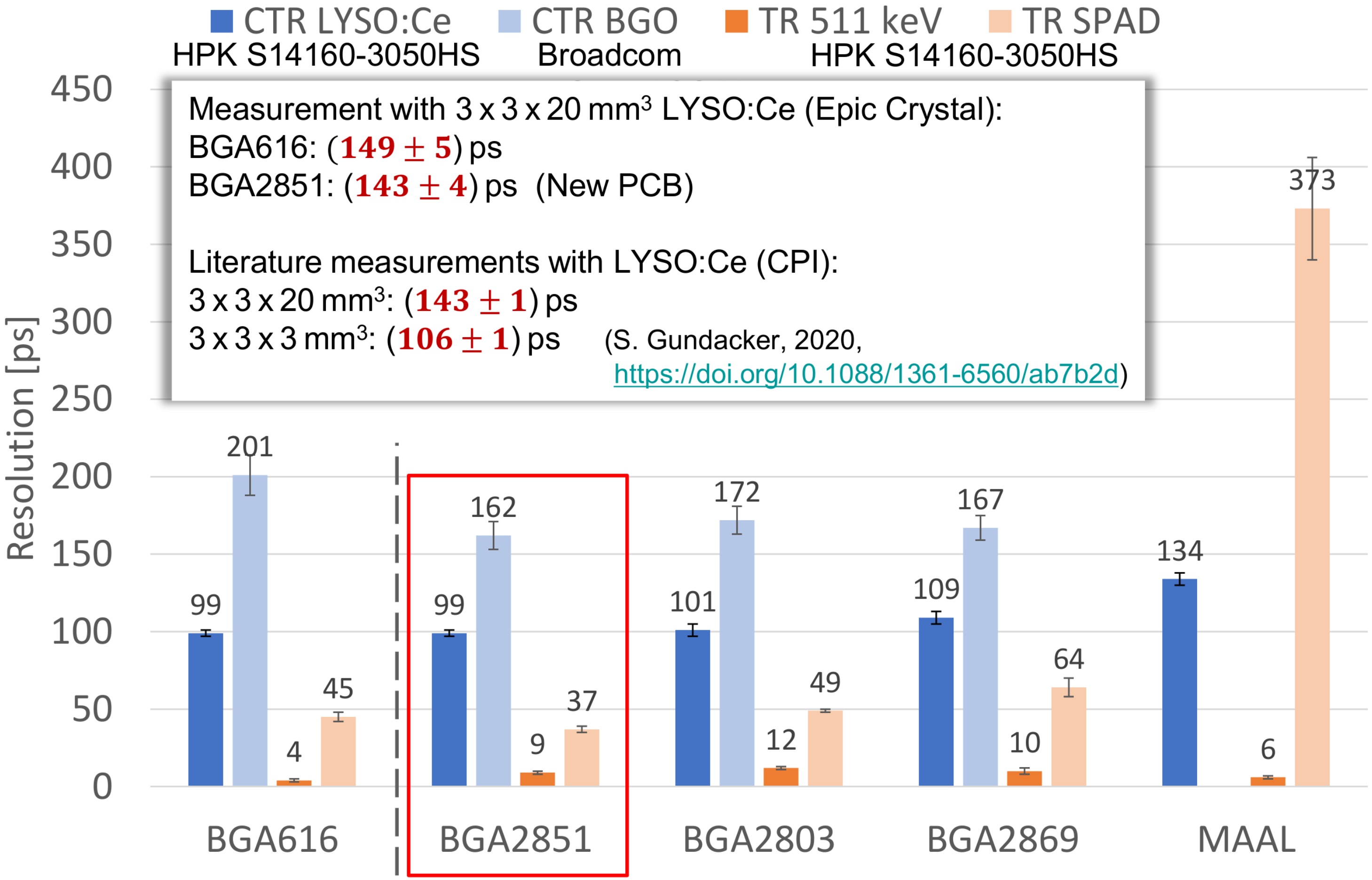
Electronic time resolution with 511 keV signals



- → Selection on 511 keV photopeak events (a)
- → Plot the noise histogram (b)
- → Average signal traces (c) and determine slope dV/dt at different thresholds (d)
- → Calculate the electronic time resolution limits for 511 keV events:

$$TR_{511\,keV} = \frac{FWHM_{Noise}}{dV/dt_{@\,threshold}}$$

Time resolution results with different amplifiers



LYSO:Ce: EPIC 3x3x3 mm³ coupled to Hamamatsu SiPM, 3x3 mm², 50 µm SPAD

BGO: EPIC 2x2x3 mm³ coupled to Broadcom SiPM, 3x3 mm², 30 µm SPAD

Conclusions

- New amplifiers (e.g. BGA2851 and BGA2803) achieve similar or even better CTR with LYSO:Ce and BGO compared to literature values measured with the BGA616.
- The new amplifier types consume up to 10 times less power, with a minimum of 17 mW/channel to be compared with the TOFPET2 ASIC of 8 mW/channel and NINO with 30 mW/channel, whereas the CTR performance is much better (for BGO up to a factor 5).
- This makes it possible to consider HF designs for multi-channel solutions without deterioration of the timing performance in systems.
- New front-end design should ideally be transferred into application-specific integrated circuits (ASICs).

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I am looking forward to your questions,

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