

Performance of the SiPMs operated at low temperature for the JUNO - TAO detector

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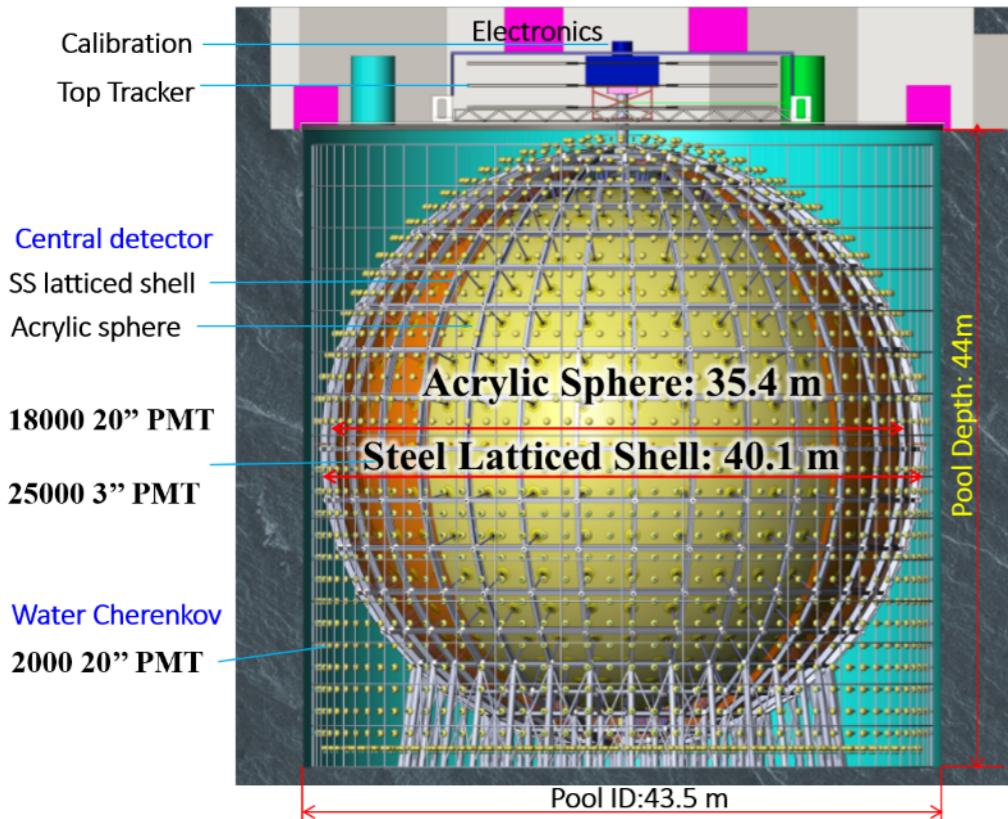
on behalf of the JUNO - TAO Working Group (JUNO Collaboration)

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Outline

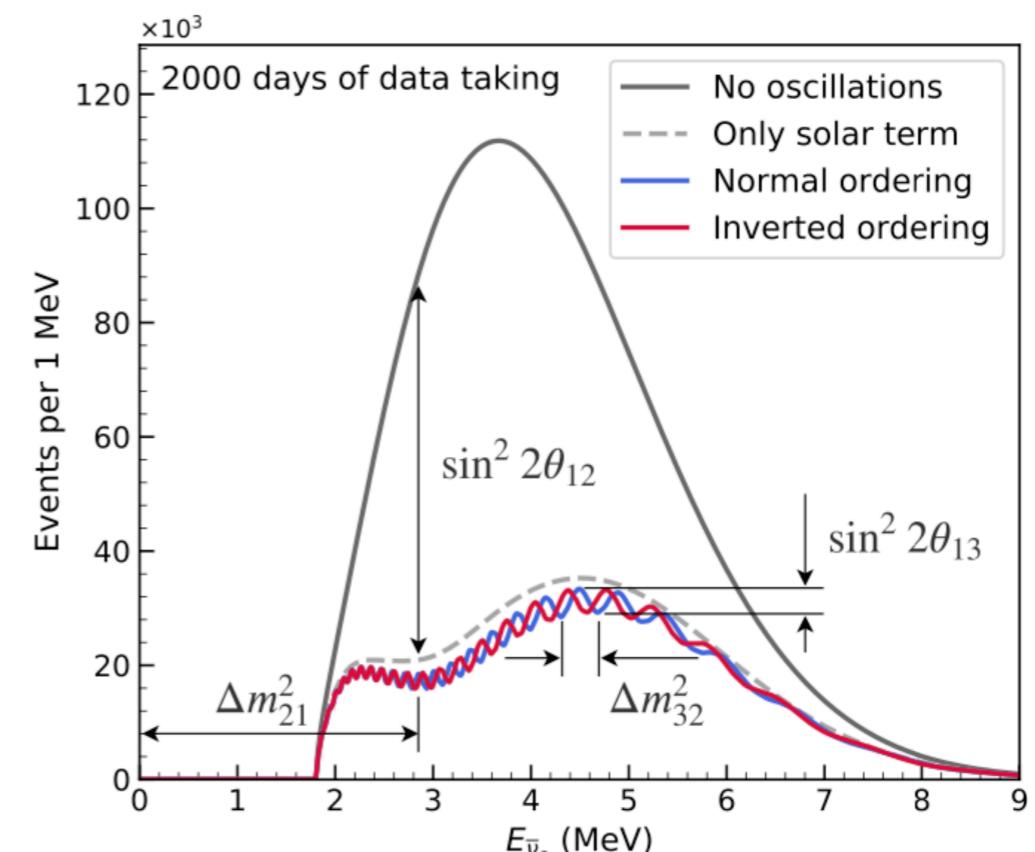
- The JUNO & JUNO - TAO experiments;
- Silicon Photomultipliers for the TAO detector
- Performance of SiPMs
- Conclusions

JUNO & JUNO - TAO Experiment

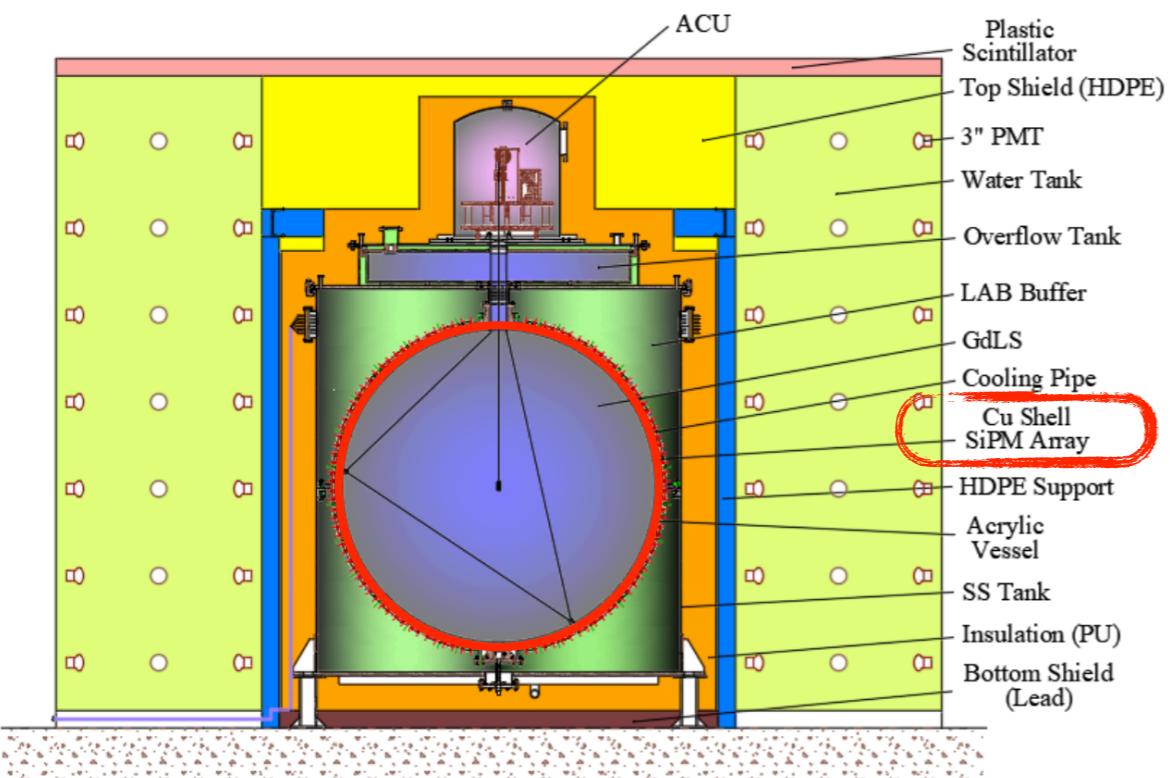


- Current models cannot provide a reliable reference spectrum of the reactor anti- ν input flux
- Since existing measurements have not enough resolution to reveal fine structures
- **A near detector can reduce model dependecies of the unknown fine structures providing more robust measurements**

- **Jiangmen Underground Neutrino Observatory:**
 - a **medium-baseline (53 km) reactor neutrino** experiment under construction in China (data taking foreseen in 2023)
- **Goals:** to measure the neutrino mass hierarchy, neutrino oscillation parameters and other astroparticle rare processes

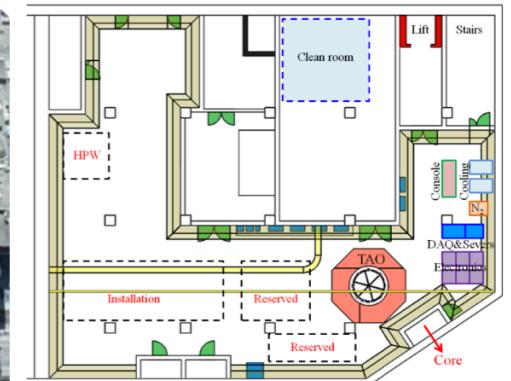
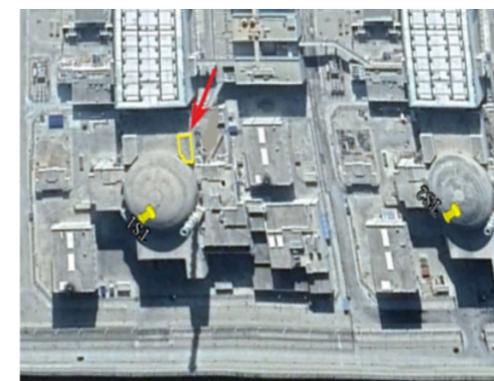


JUNO & JUNO - TAO Experiment

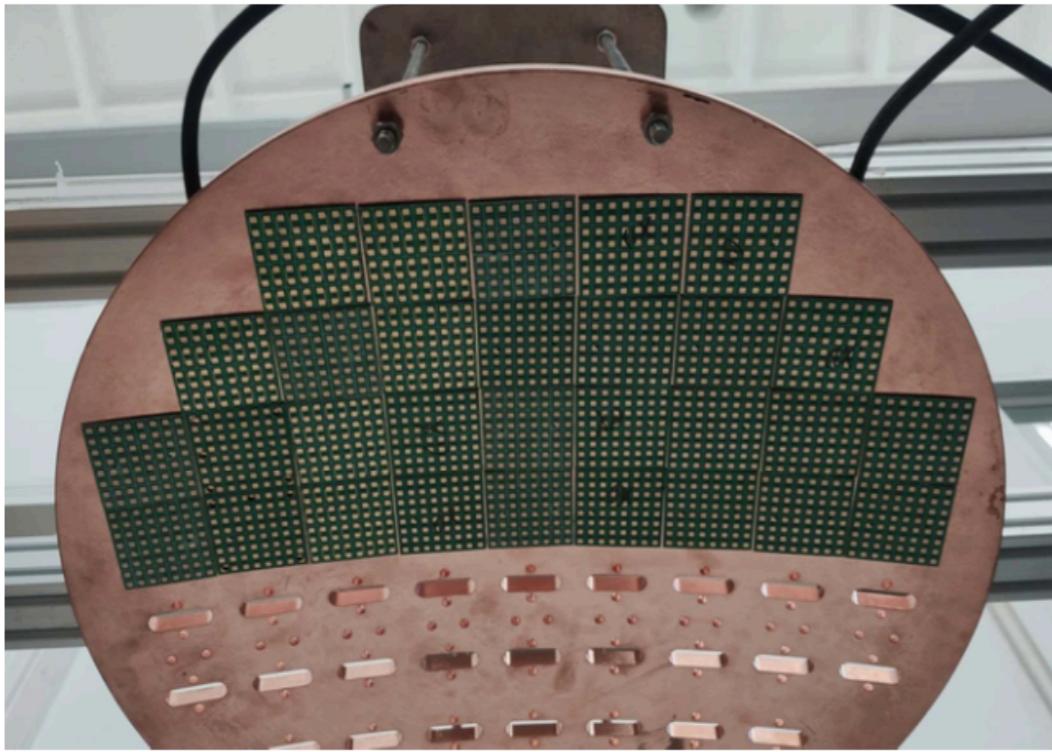


- Nuclear Power Plant in Taishan city in Guangdong province
 - **53 km away from the JUNO experiment**
 - All reactor cores are European Pressurized Reactor of 4.6 GW power
- **TAO detector will be located 30 m away from core #1**, outside of the concrete containment shell of the reactor core in a basement at about 9.6 m underground

- Taishan Antineutrino Observatory is a satellite experiment of JUNO
- **State-of-art liquid scintillator detector with high energy resolution**
- **Goals:** measure reactor anti-neutrino spectrum with sub-percent energy resolution
 - Provide a reference spectrum for JUNO
 - Provide a benchmark measurement to test nuclear databases
 - Reactor monitoring, sterile neutrino, etc..

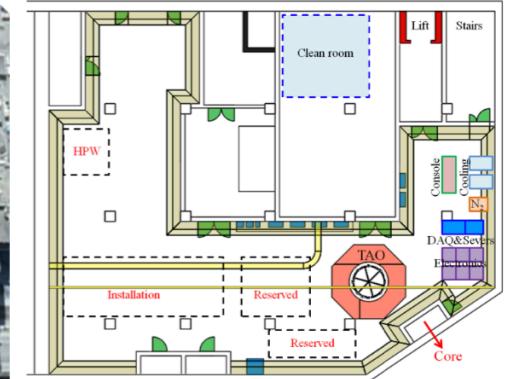
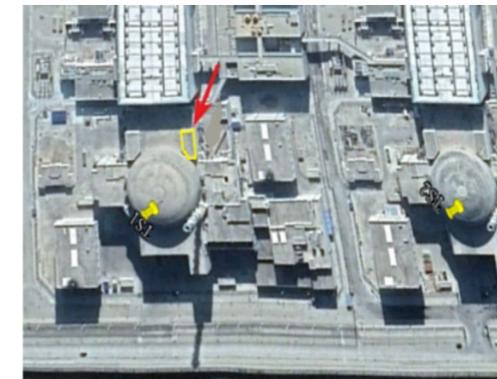


JUNO & JUNO - TAO Experiment



- Since the desired high energy resolution, SiPMs are preferable wrt PMTs because of their higher efficiency
 - Detectors capable to counts single photoelectrons (PE)
 - The Dark Count Rate (DCR) can be lowered if the devices will work at very low temperature (working temperature for the TAO detector will be -50°C)
- TAO will be readout in total by ~ 4000 SiPMs arrays (tiles) of 5x5 cm² size with ~ 94% total coverage w/o fill factor

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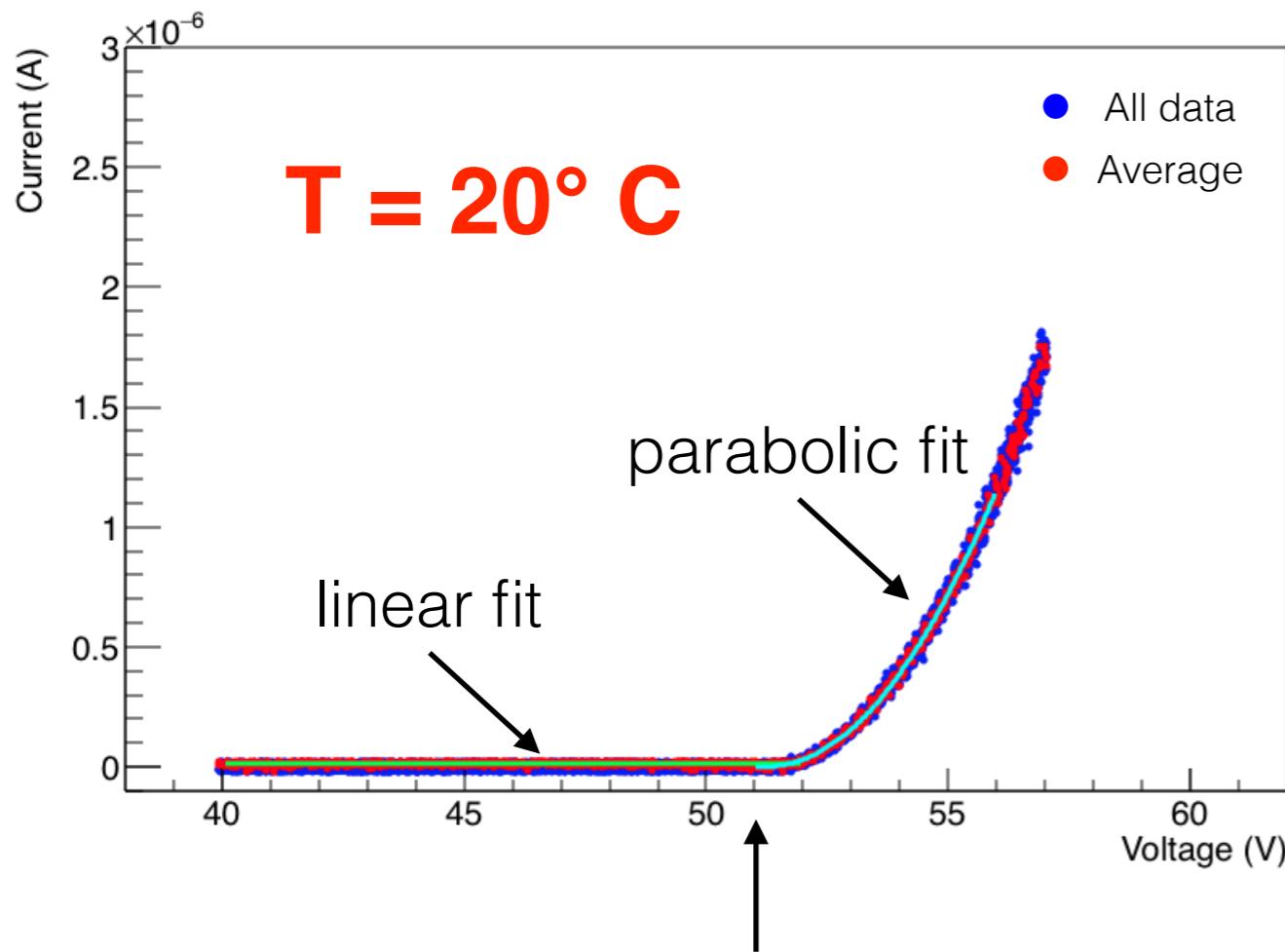
SiPMs: the requirements

Parameter	Specification	Comments
PDE	$\geq 50\%$	at 400 nm
Dark counts rate	$< 100 \text{ Hz/mm}^2$	at -50°C
Correlated noise	$< 20\%$	cross-talk and afterpulses
Uniformity of V_{bd}	$< 10\%$	to avoid bias voltage tuning
SiPM size	$\geq 6 \times 6 \text{ mm}^2$	for simplicity and high coverage
SiPM tile size	$\sim 50 \times 50 \text{ mm}^2$	reduce number of channels
SiPM coverage in a tile	$> 90\%$	not included in PDE

- Higher coverage (~ 94% w/o fill factor) and efficiency wrt PMTs
 - Needed for the desired energy resolution (< 2% @ 1 MeV)
 - PDE correlates with Dark Noise and correlated noise
- Low background materials are needed for both SiPMs cells and Front-end Electronic Boards (FEBs) to meet the overall requirement on radioactivity budget less than 100 Hz
- Studies on performance on going with different SiPMs producers (HPK, FBK and SenSL)

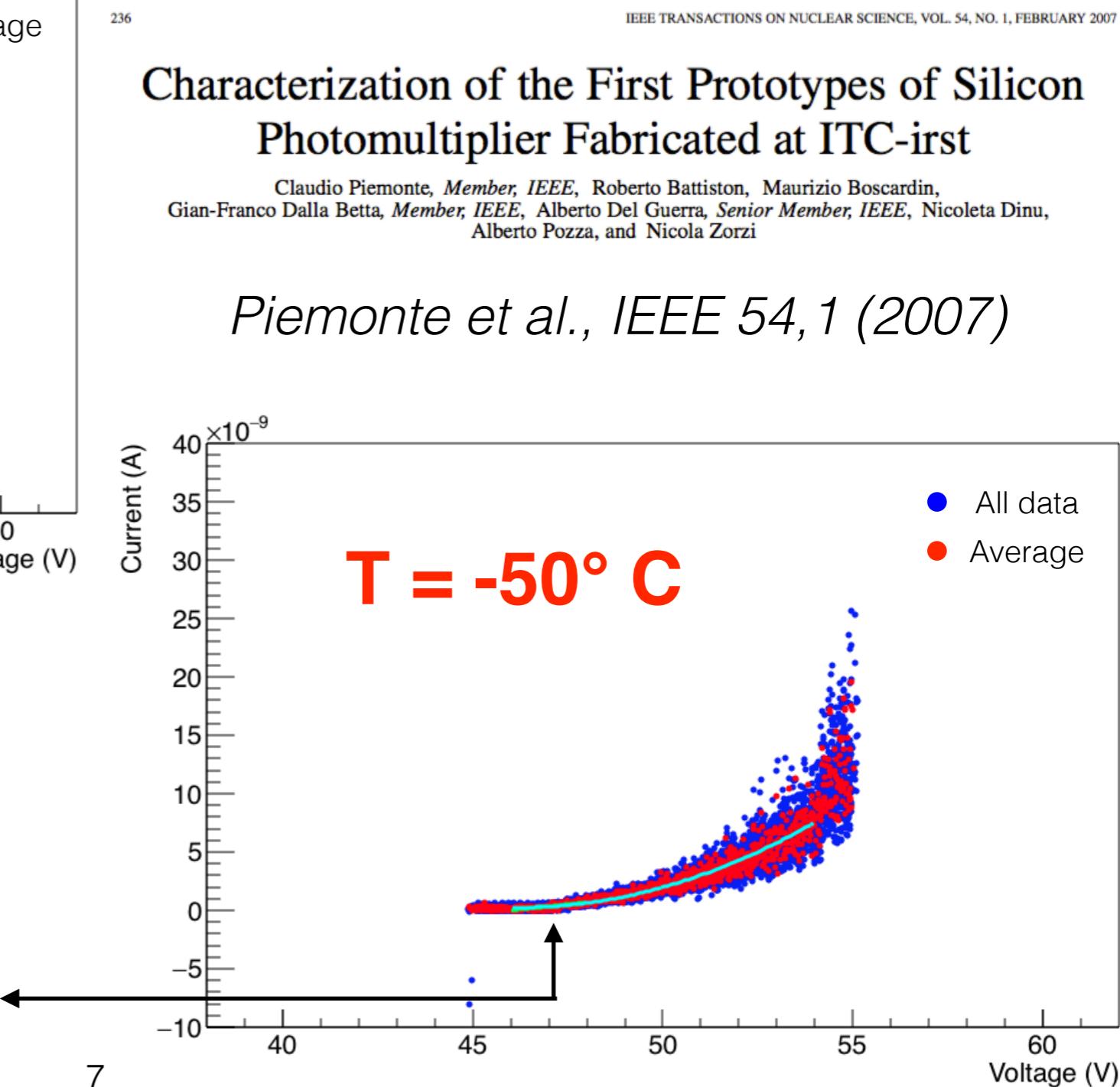
Vendor	Pixel pitch (μm)	Active area (mm^2)	V_{BD}^* (V) at 20° C	V_{Bias} (V) at -50° C	V_{ov} (V)
Hamamatsu Photonics (HPK) s13360-6075PE	75	36	51.5	50.5	3
Fondazione Bruno Kessler (FBK)	75 double/triple trench	36	26.6/27.2	27.5/27	3

Breakdown voltage calculations I-V curves on Hamamatsu cells



The vertex of the parabola
is the breakdown voltage
 $V_{BD} \approx 51.6 \text{ V}$

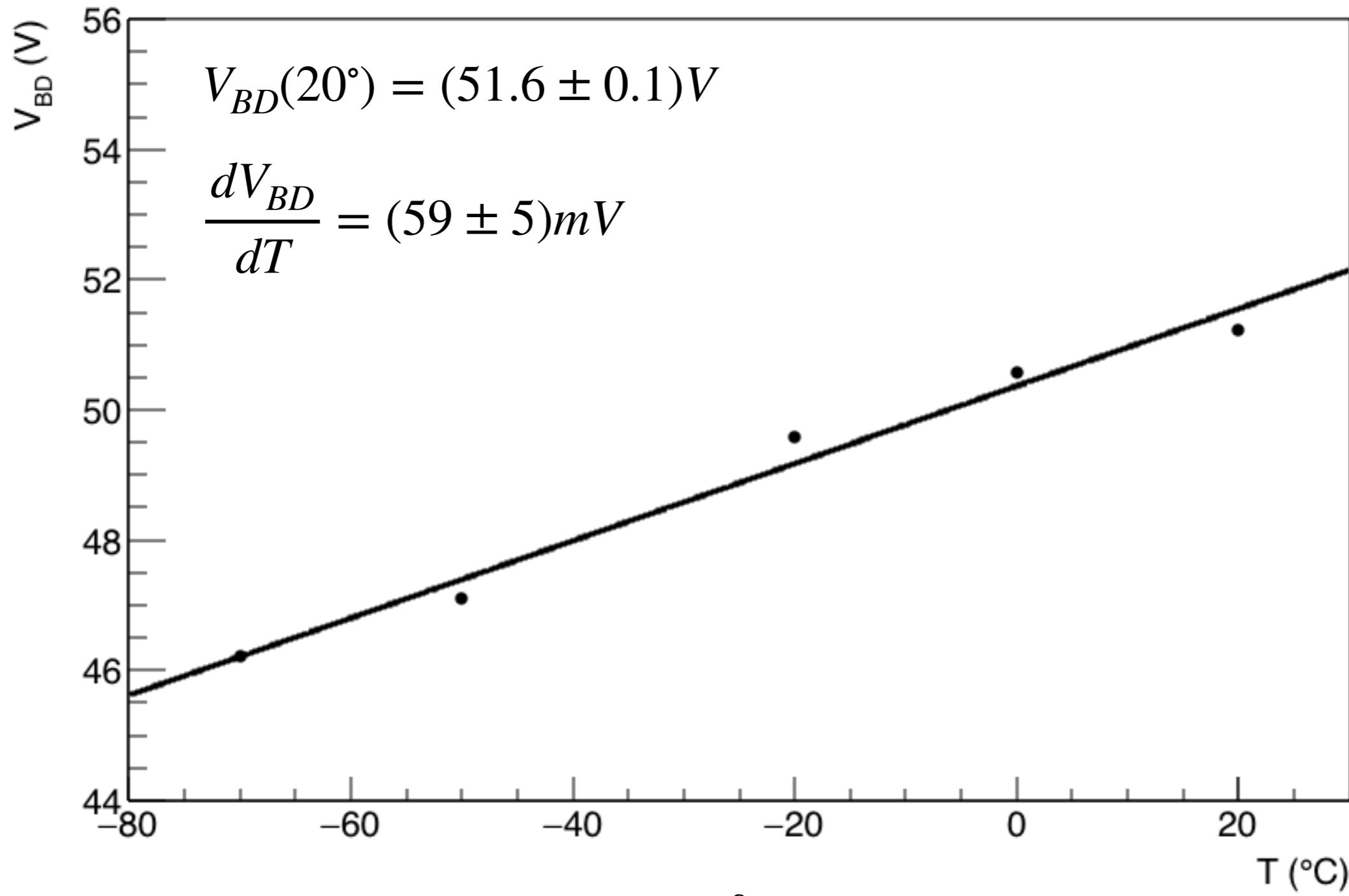
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$V_{BD} \approx 47.1 \text{ V}$

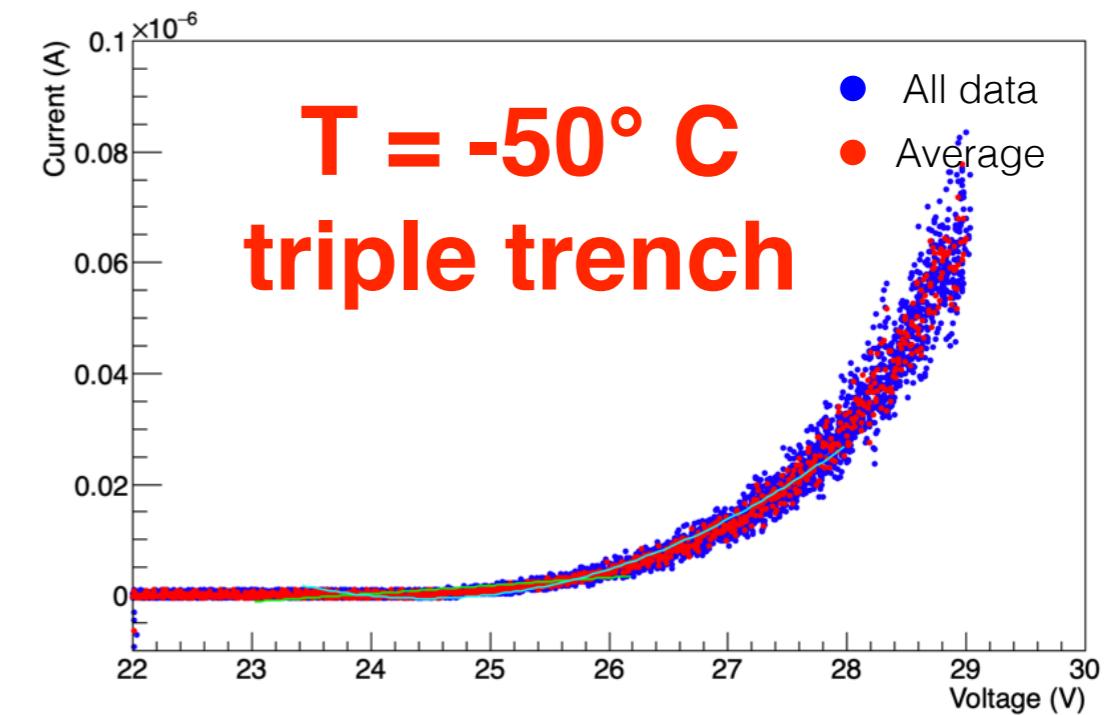
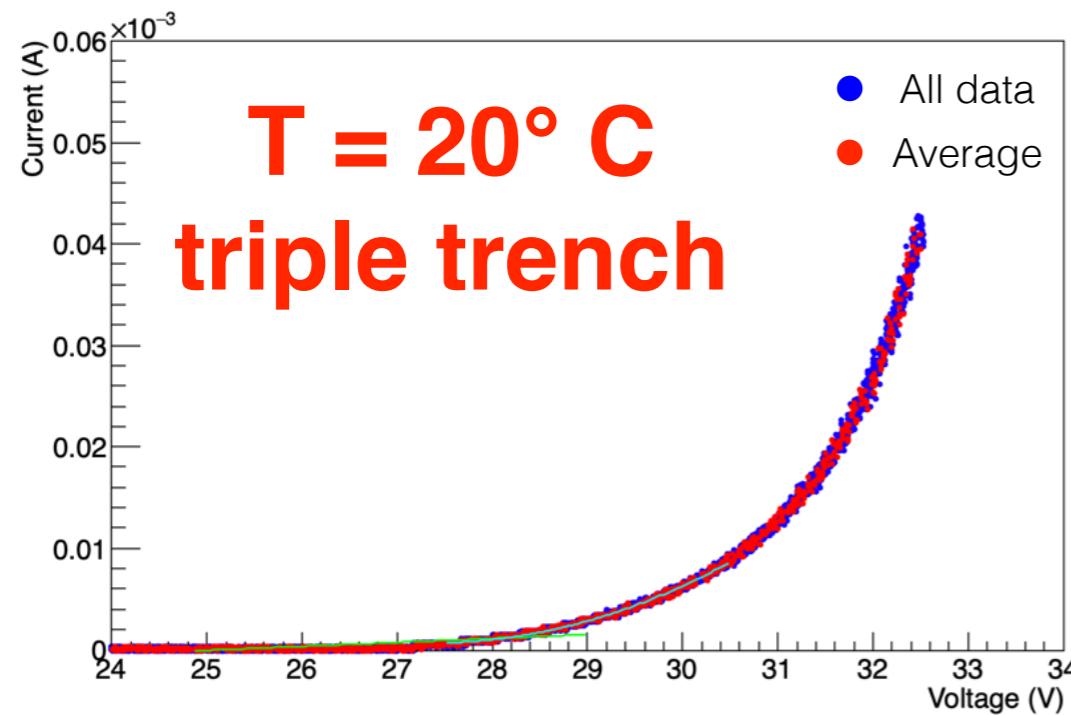
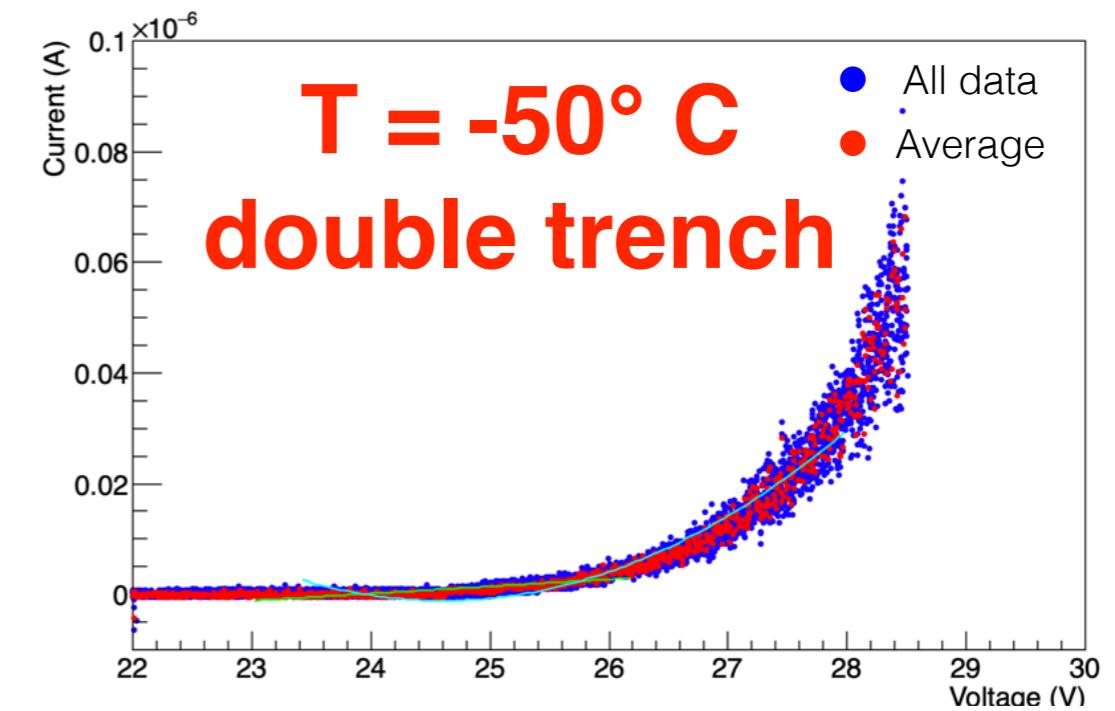
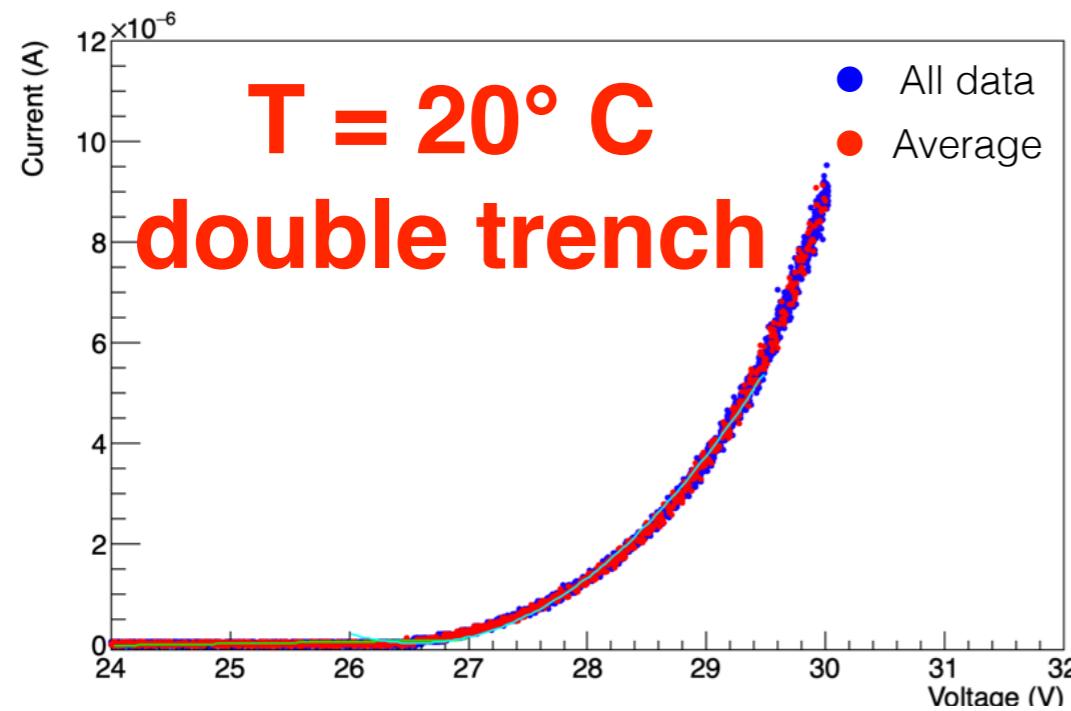
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Breakdown voltage calculations I-V curves on Hamamatsu cells



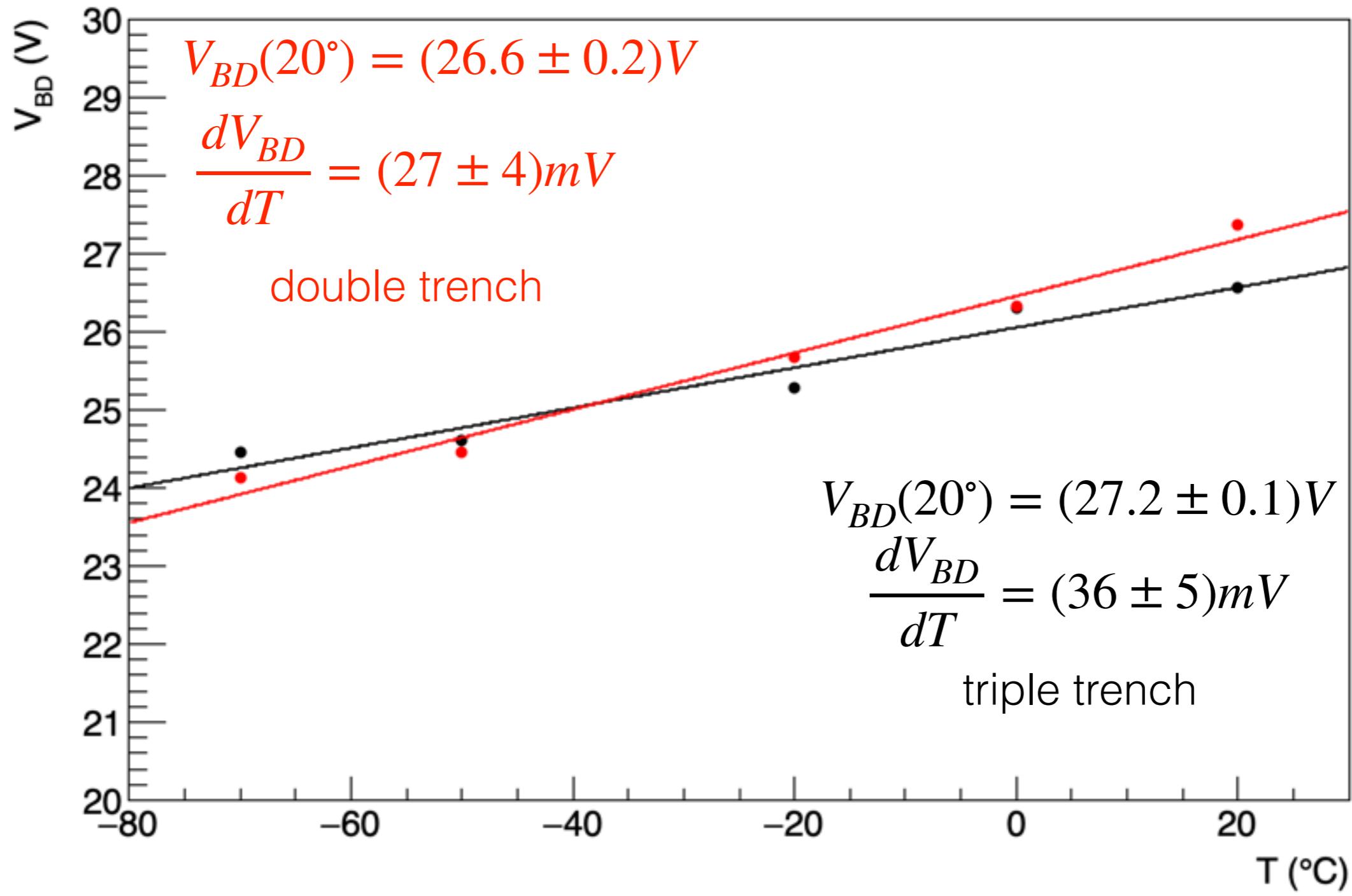
Breakdown voltage calculations

I-V curves on FBK cells



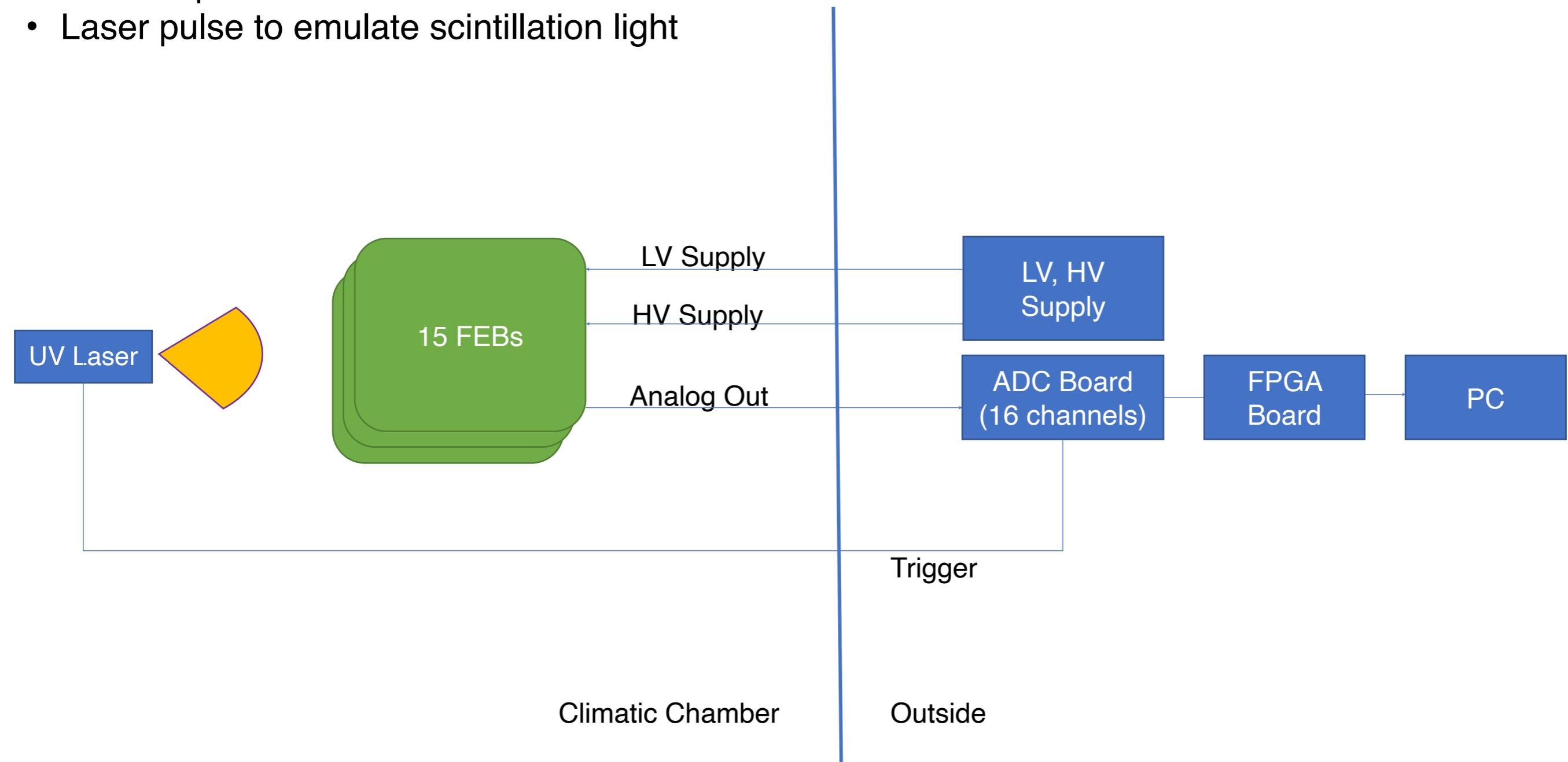
Breakdown voltage calculations

I-V curves on FBK cells



The setup: block scheme

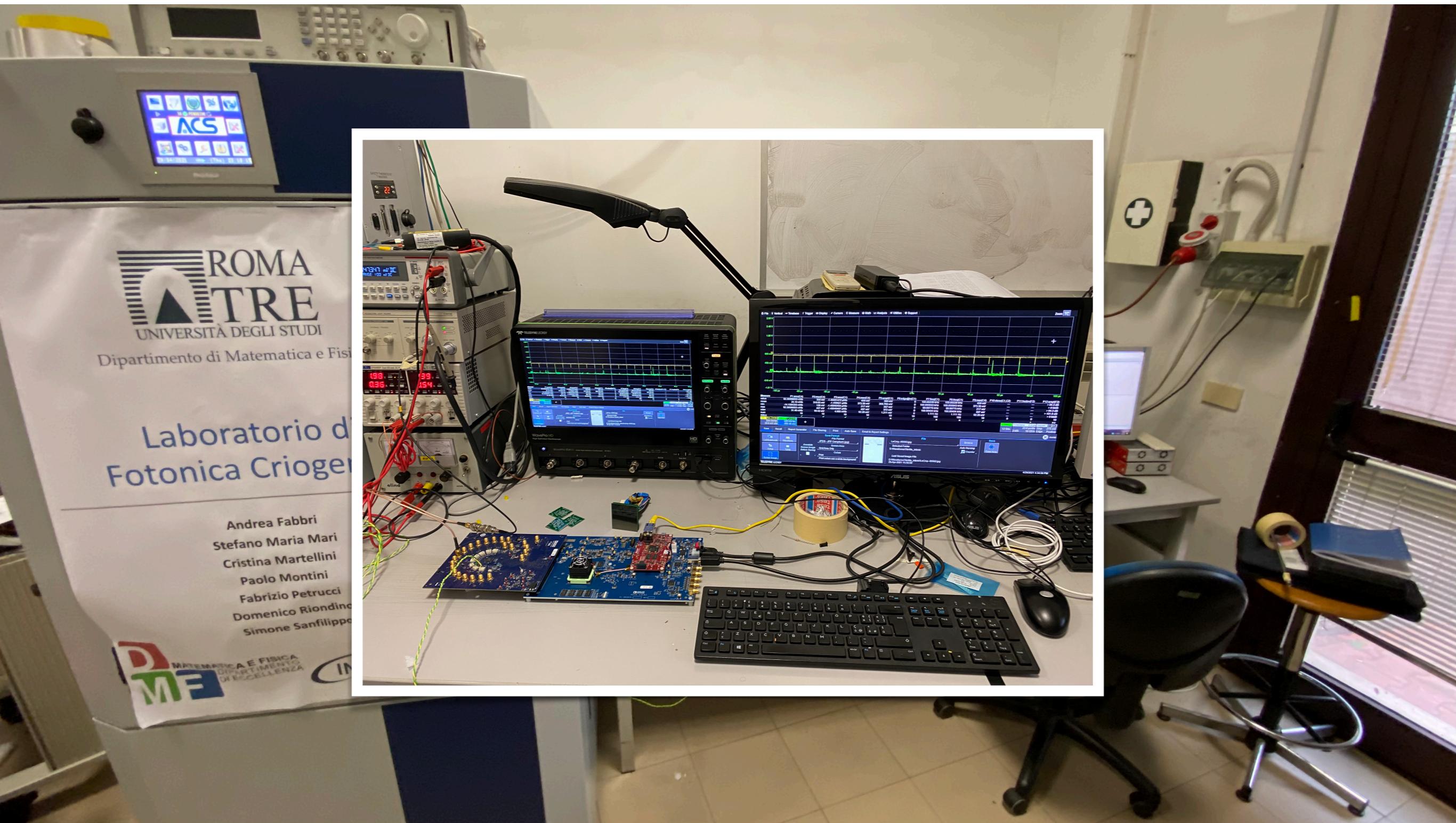
- Up to 15 FEBs can be mounted on a spherical sector ($R = 50$ cm)
- Hamamatsu and FBK SiPMs were used
- AD9083 ADC board
- Data acquired down to -50° C to emulate the final detector behaviour
- Laser pulse to emulate scintillation light



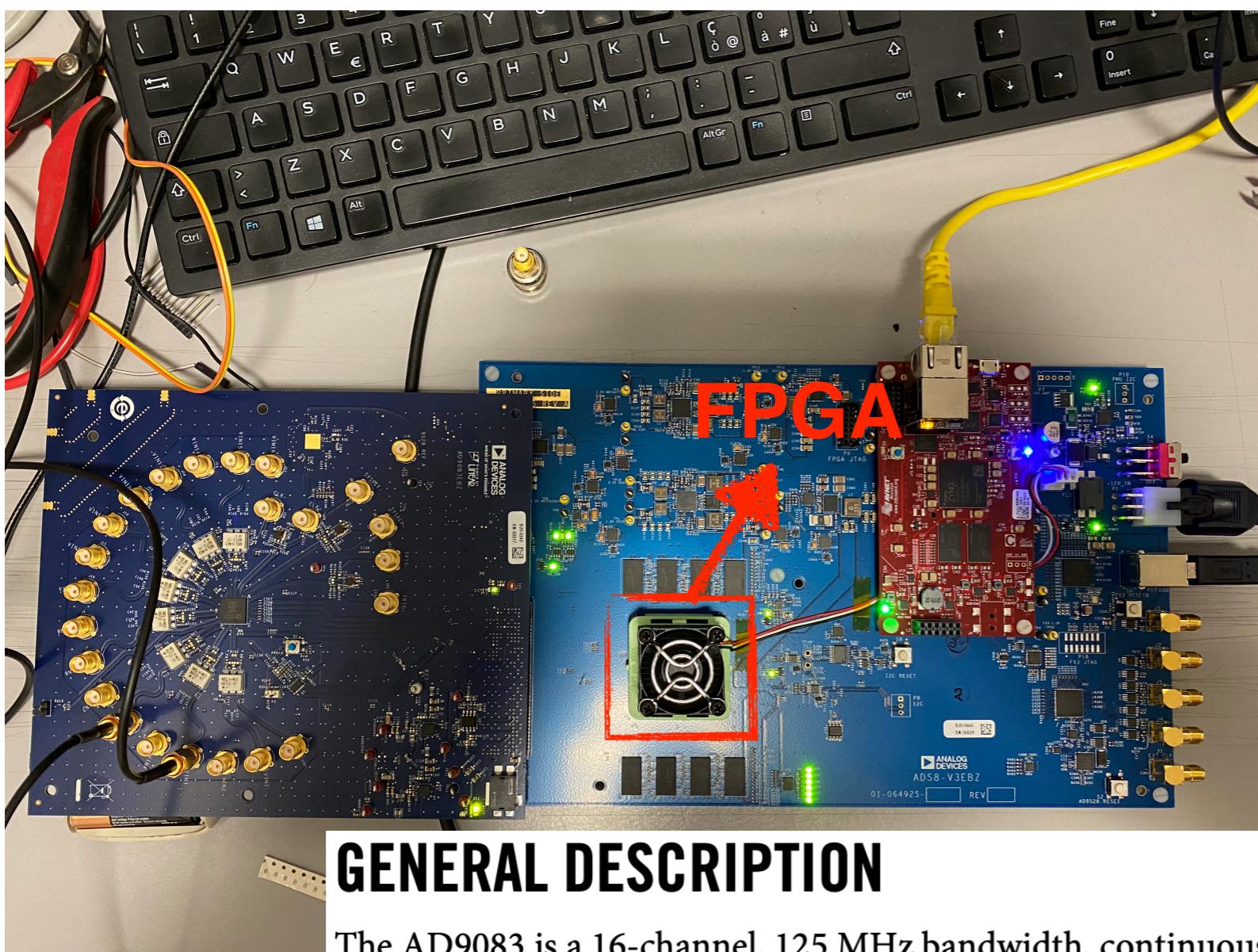
The test setup



The test setup



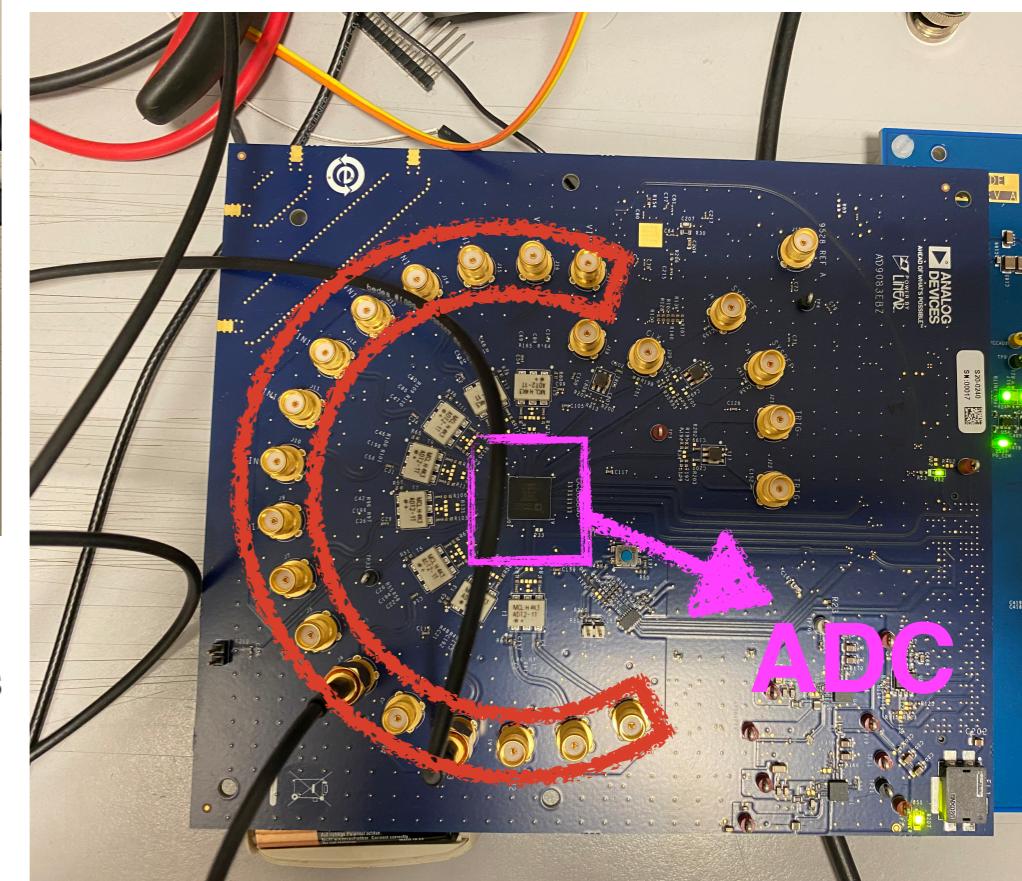
Analog Devices AD9083 ADC



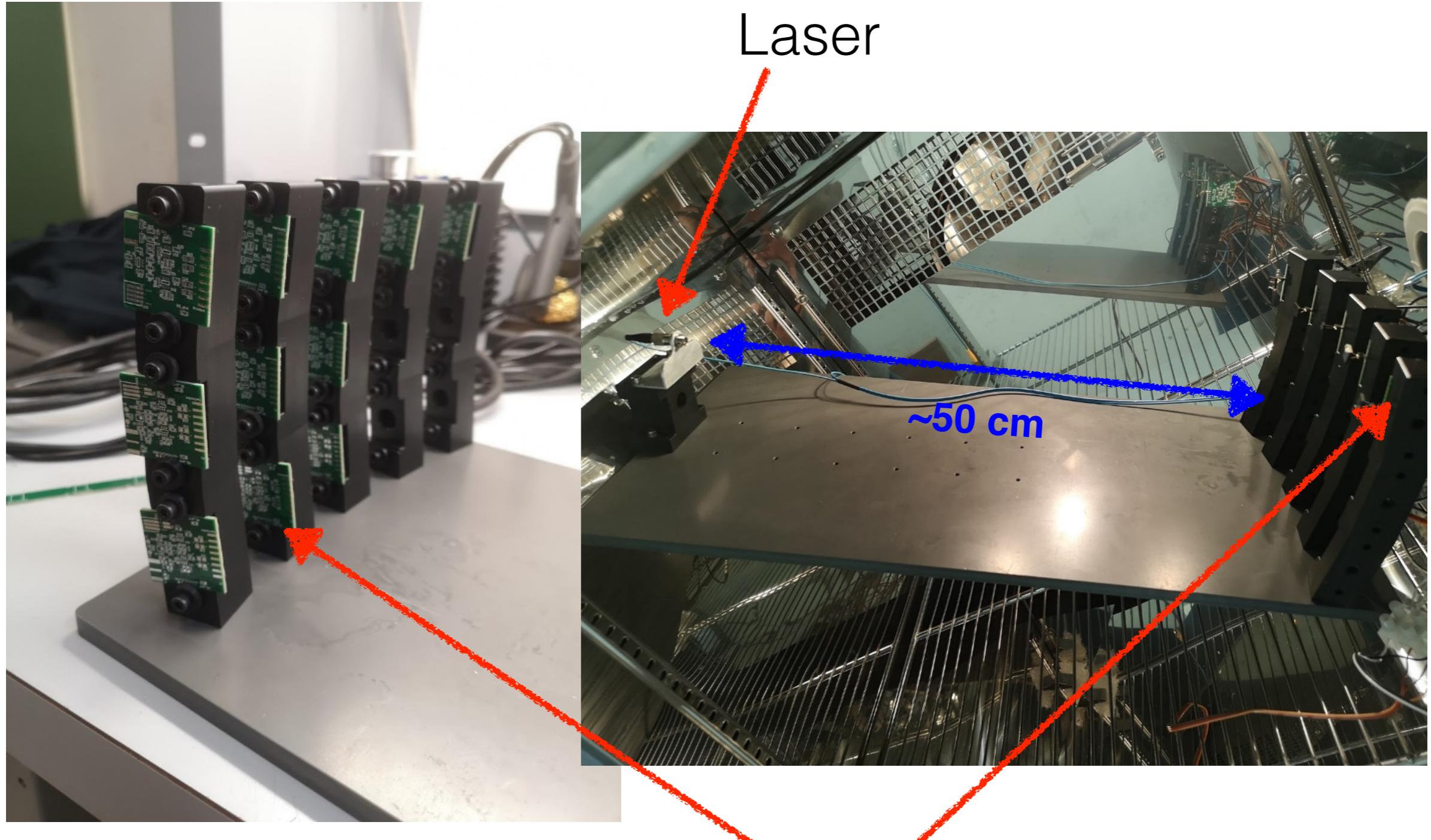
GENERAL DESCRIPTION

The AD9083 is a 16-channel, 125 MHz bandwidth, continuous time $\Sigma\Delta$ (CTSD) ADC. The device features an on-chip, programmable, single-pole antialiasing filter and termination resistor that is designed for low power, small size, and ease of use.

The 16 ADC cores features a first-order, CTSD modulator architecture with integrated, background nonlinearity correction logic and self cancelling dither. Each ADC features wide bandwidth inputs supporting a variety of user-selectable input ranges. An integrated voltage reference eases design considerations.



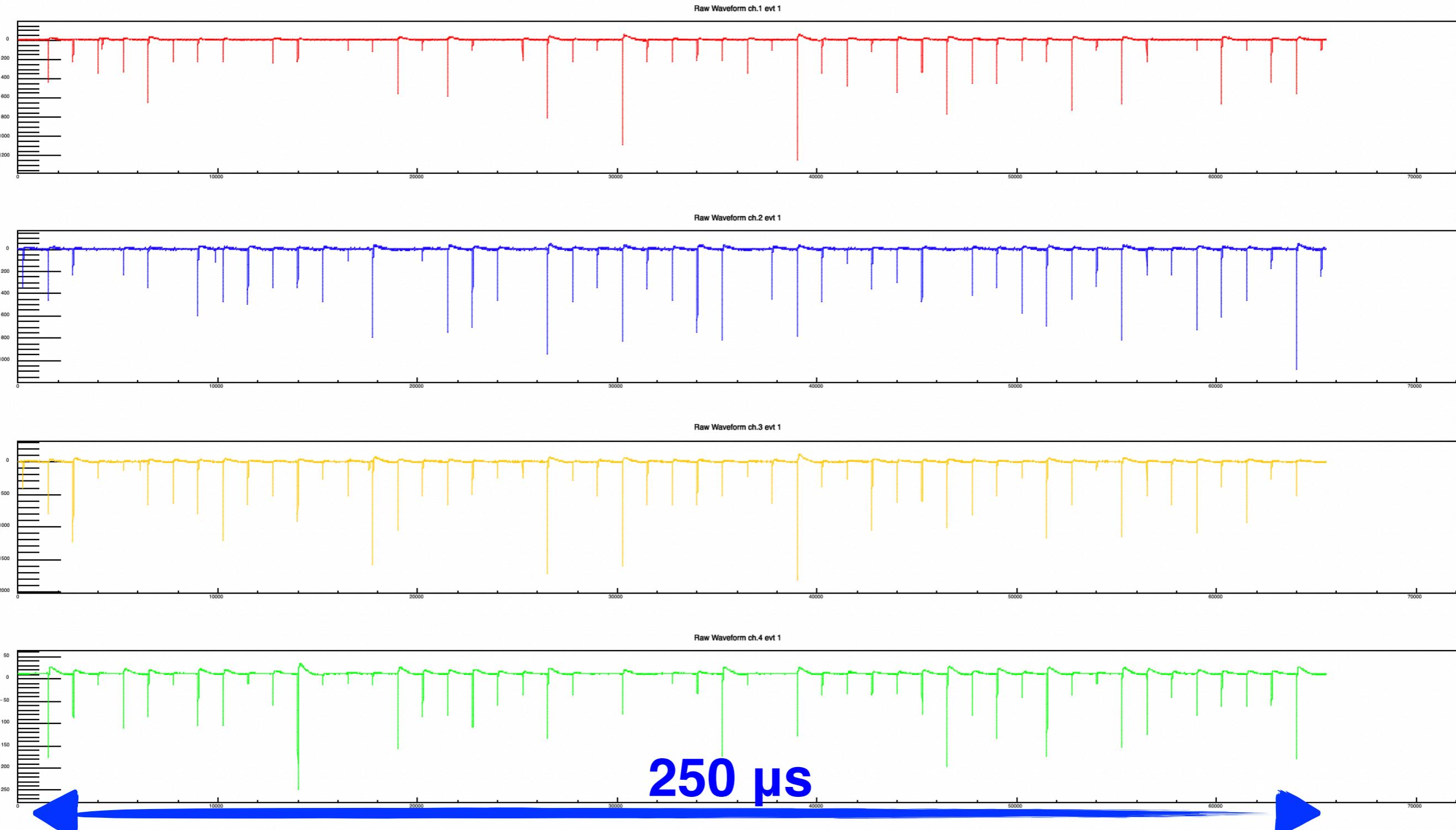
Inside the climatic chamber



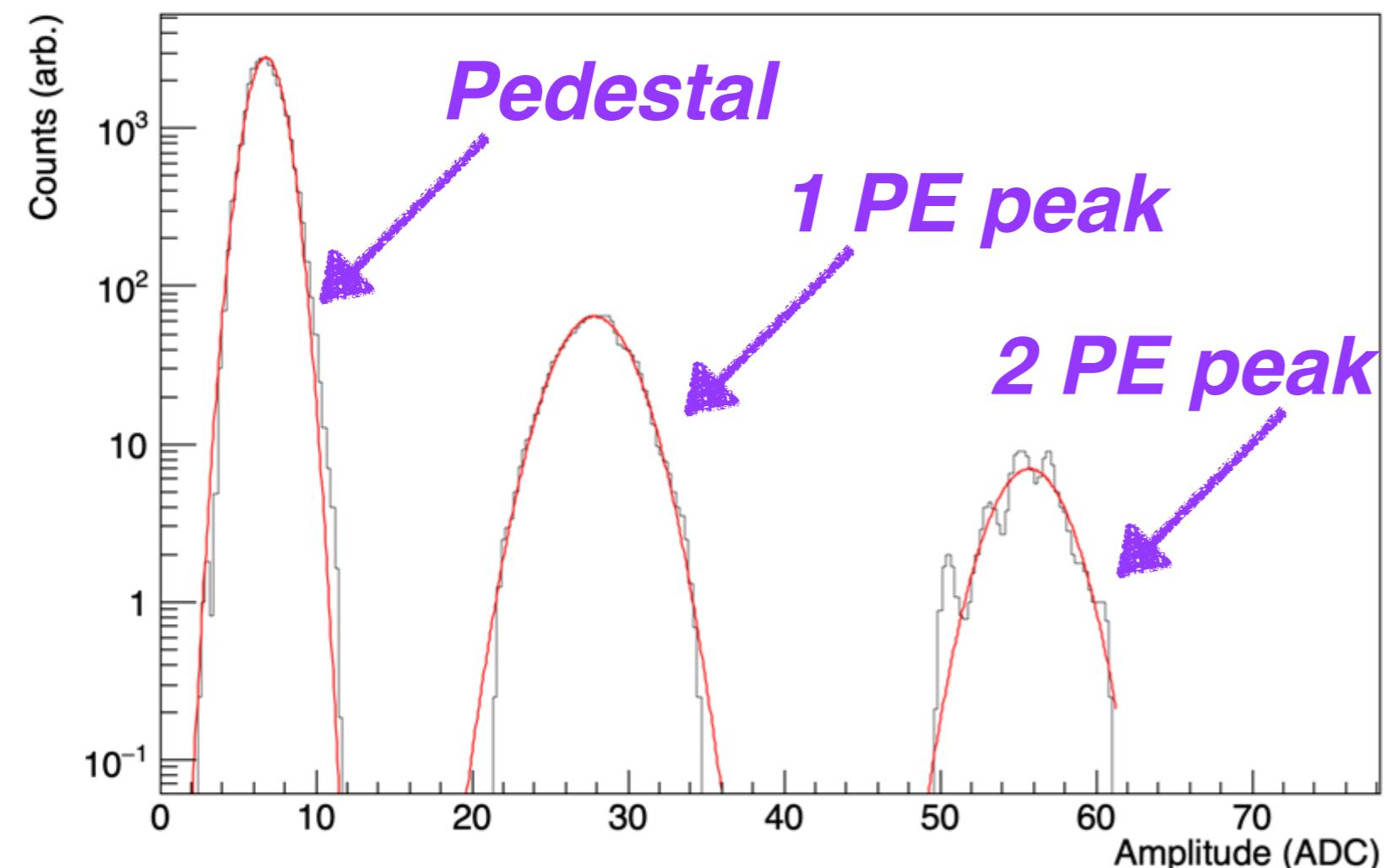
Front-end Electronic Boards (FEBs)

*for more details on the used electronic scheme
see P. Montini contribution at the poster session*

Waveforms @ -50° C



SiPMs characterization: Single Electron Response Spectrum



$$P(ct) = \frac{N_{2PE}}{N_{1PE}}$$

where N_{1PE} is the integral of the 1PE events population and N_{2PE} the one of 2PE population.

$$P(ap) = \frac{N_{meas} - N_{fit}}{N_{meas}}$$

where N_{meas} is the integral of the 1PE peak and N_{fit} is the number of events from a gaussian fit of the same population.

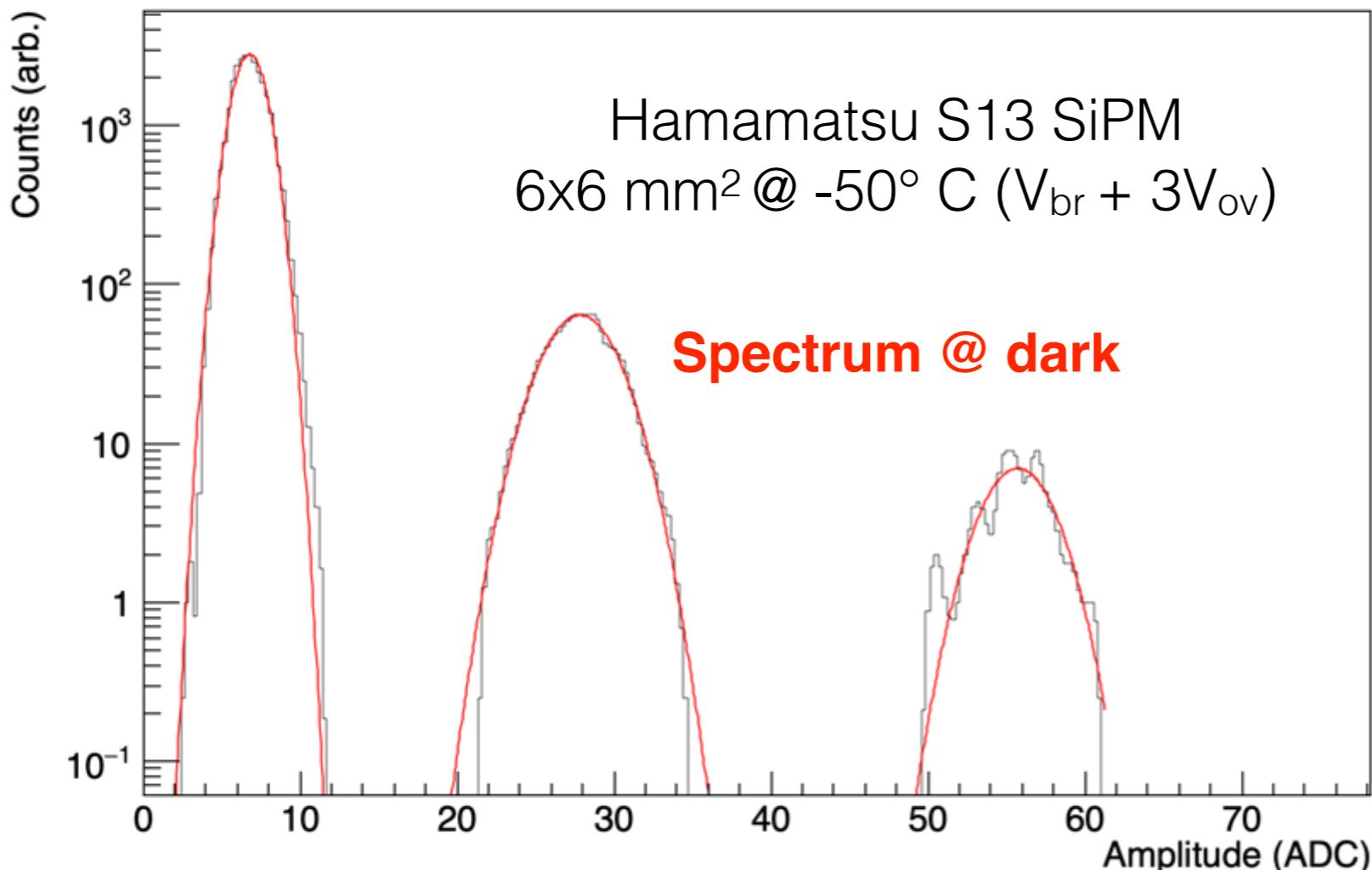
Typical Single Electron Spectrum (SER): here different peaks correspond to the amplitude of the signals due to 1 or more photoelectrons (PE). The very first peak usually refers to the noise pedestal.

From this, several informations such as Dark Count Rate (DCR) and correlated noise of SiPMs (cross-talks and after-pulses) can be extracted.

$$P(N) = \frac{N_{DCR}^N \times e^{-\mu_{DCR}}}{N!}$$

N_{DCR} is the number of photoelectrons observed in a time window Δt , μ_{DCR} is the average of photoelectrons expected in the same time window and N the total number of detected photoelectrons.

Hamamatsu S13 6x6 mm² @ -50°C (V_{br} + 3V_{ov})



$$P(ct) = \frac{N_{2PE}}{N_{1PE}}$$

$$P(ap) = \frac{N_{meas} - N_{fit}}{N_{meas}}$$

- Direct Cross-talks probability is ~ 12%

- After pulses probability is ~ 1.%

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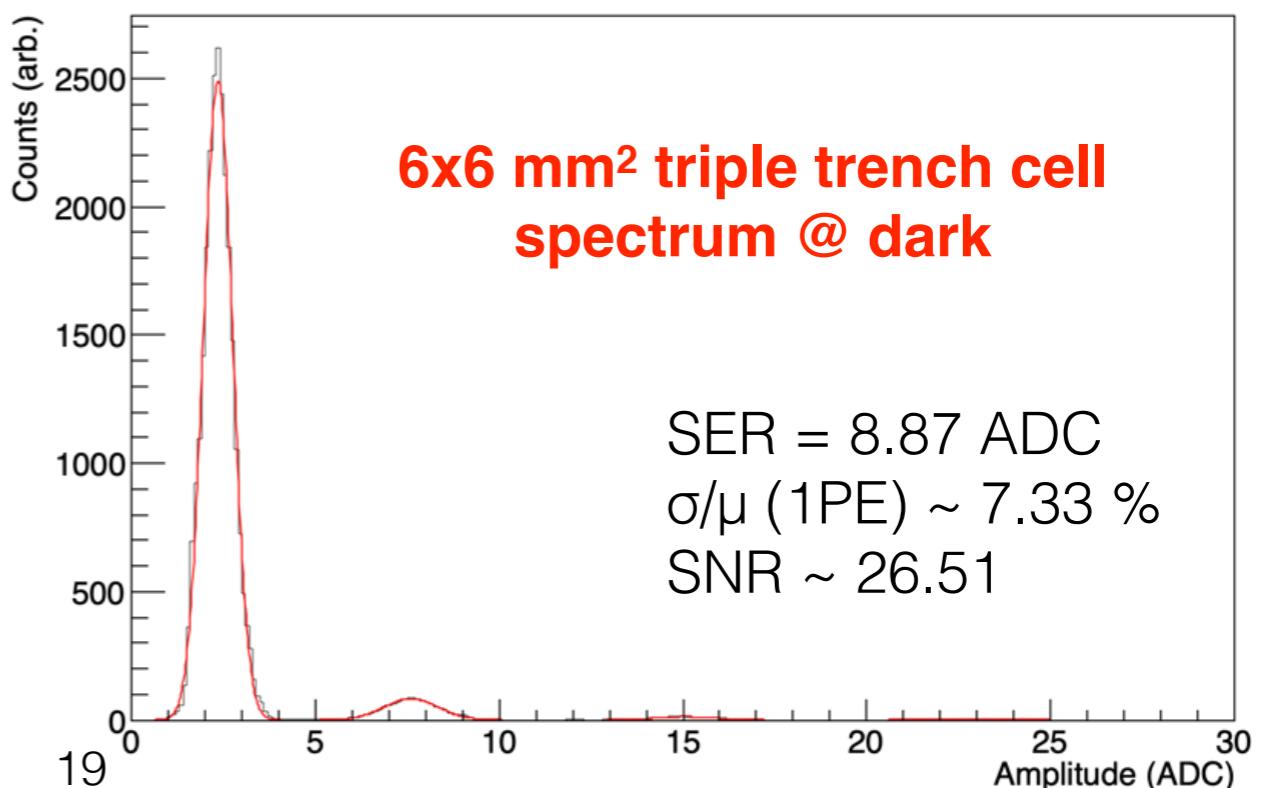
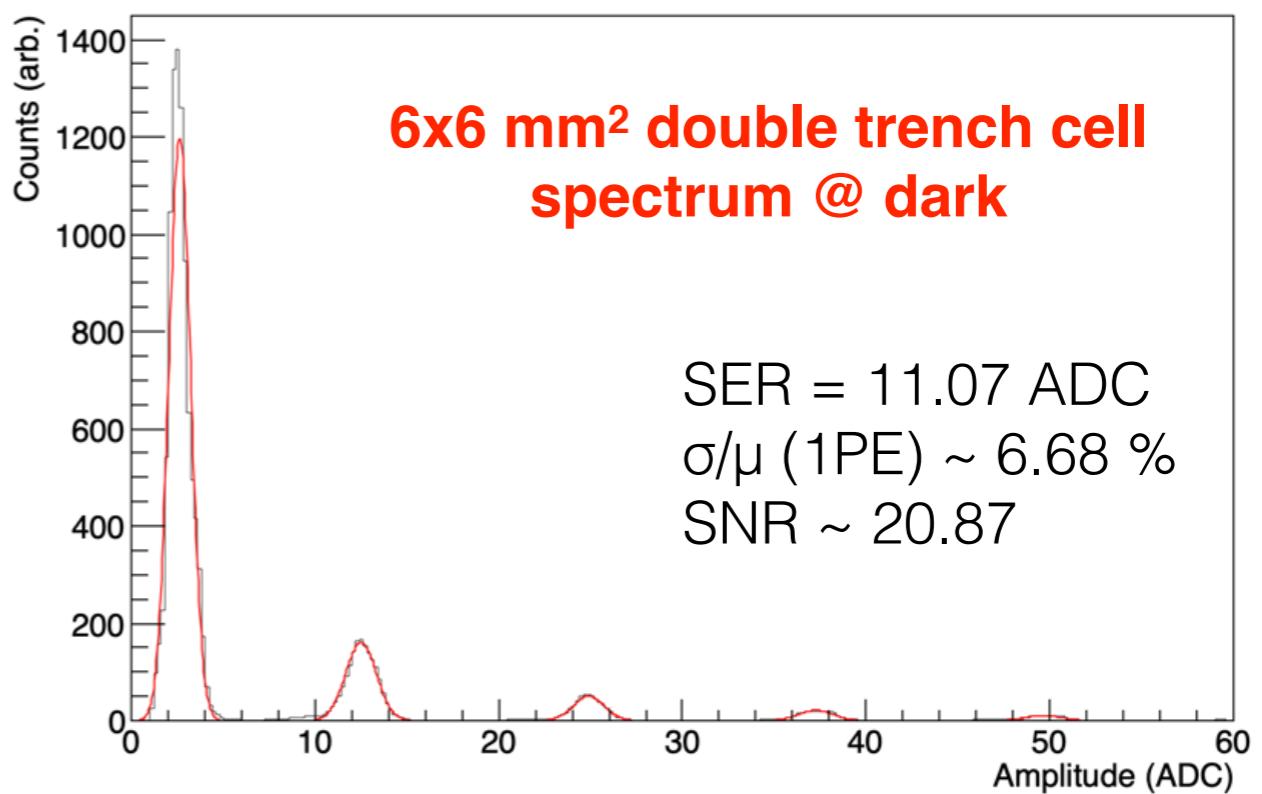
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$$P(N) = \frac{N_{DCR}^N \times e^{-\mu_{DCR}}}{N!}$$

- Dark Count Rate is ~ 60 Hz/mm²

FBK NUV-HD Low-CT 6x6 mm² @ -50° C (V_{br} + 3V_{ov})

- Direct Cross-talks probability ~ 22% triple trench and ~ 28% double trench
- After pulses probability is ~ 1.4% triple trench and ~ 1.8% double trench
- Dark Count Rate is ~ 150 Hz/mm² triple trench and ~ 112 Hz/mm² double trench



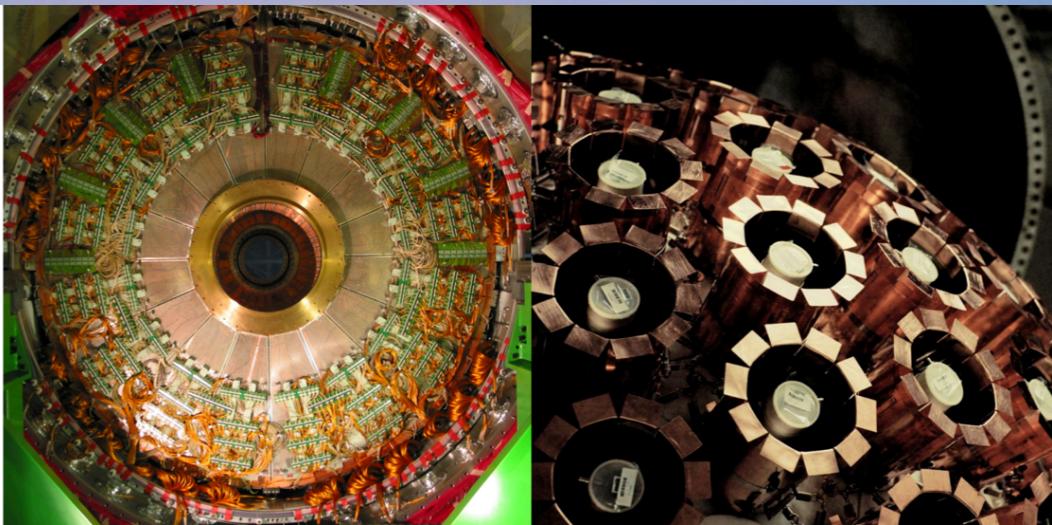
Conclusions

- JUNO - TAO will be a ton-level LS (near) detector with sub-percent energy resolution
 - Located ~ 30 m away from one core of the Taishan NPP (China) and 53 km away from the JUNO detector
 - A lot of challenges to reach the goals of a new concept detector:
 - Reference *anti-v* spectrum for JUNO
 - Testing nuclear databases
 - New physics?
- It will be read out by ~ 4000 SiPMs tiles (5x5 cm² size each):
 - The working temperature will be -50° C in order to lower Dark Count Rates
 - Preliminary results from commercial Hamamatsu and Fondazione Bruno Kessler (FBK) SiPM single cells are quite promising wrt the requirements
- 1:1 prototype by the end of 2021 at IHEP in China
 - Mainly to validate CD design and possible LS studies
- Commissioning phase will start by the end of 2022

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Online format



Thank you!