Innovative design of a camera for IACT telescopes

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The context

- The Cherenkov Telescope Array will be composed of 3 different sizes of telescopes: Large (LST), Medium (MST) and Small (SST)
- Different optics and a camera designs are proposed for these telescopes
- The Geneva group is the leader of one of the proposed SST telescopes using a Davies-Cotton single mirror design and proposing an innovative fully digital camera based on SiPM
- The camera presented here is the design proposed for this Single mirror Small Size telescope (SST-1M)

Why SiPMs

Large scale mass production **No Ageing**

Lightweight

High yield

Low Op. Voltage

Higher PDE over larger spectral range

Robust **Insensitive to Magnetic Field**

Compact

Very good Single Photon Response

Small variation sample-by sample

Why SiPM

- High Quantum Efficiency
- Single Photon sensitivity
- Fast pulses
- Low noise
- High Fill factor
- Robustness
- Uniformity
- High dynamic range
- Large area to be covered
- Linear response

Why SiPM

Improve

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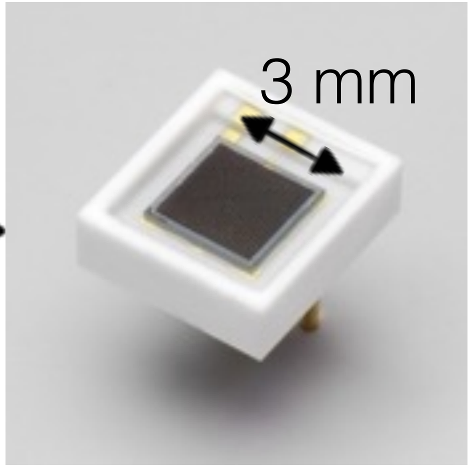
Worse

40 mm



Why SiPM

Improve Worse

- High Quantum Efficiency
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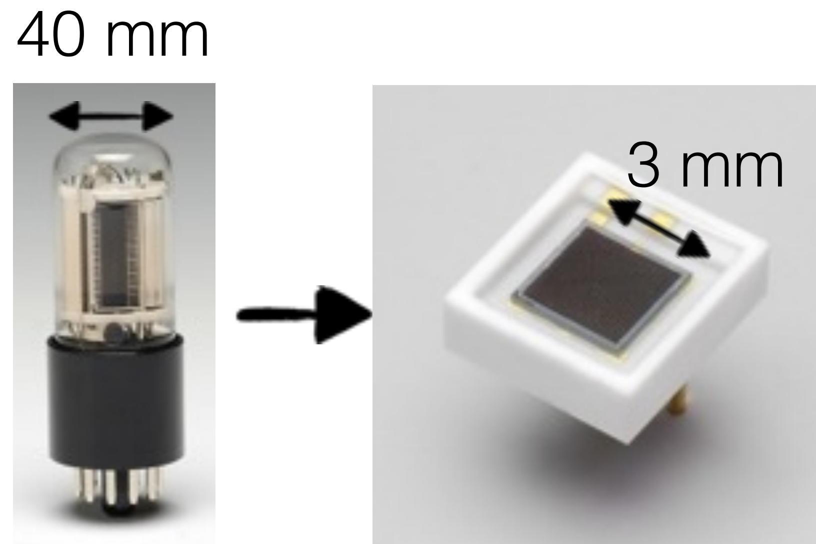
- Large area to be covered
- Linear response (optical cross talk, pile up)



- Lower voltage and easier cooling
- Lightweight
- High potential for performance improvement and cost decrease
- Characteristics depend on operation temperature

Why SiPM

Improve

Worse

- Fast pulses
- Low noise (dark count, afterpulses)

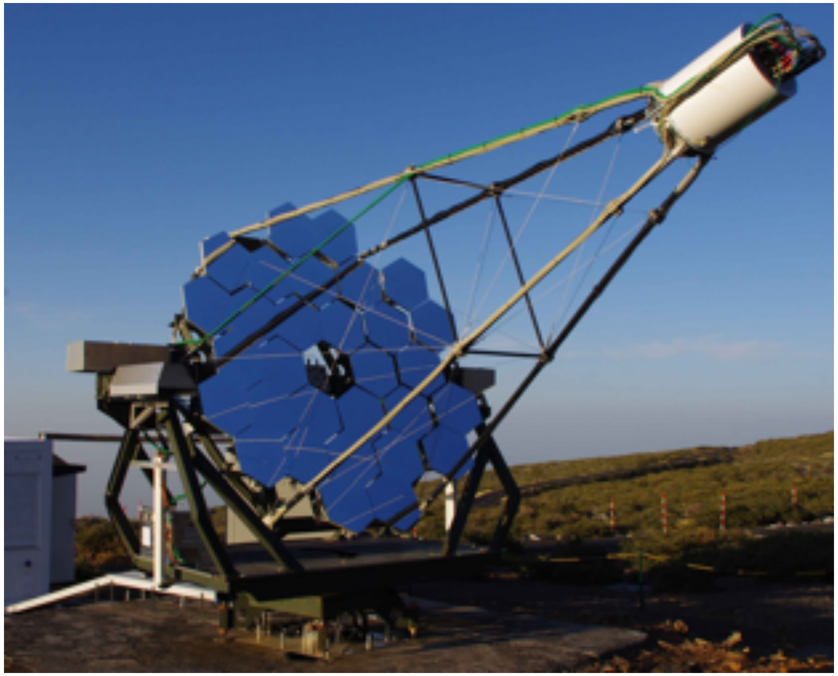
Are these parameters worrisome for gamma ray astronomy ?

- Large area to be covered
- Linear response (optical cross talk, pile up)

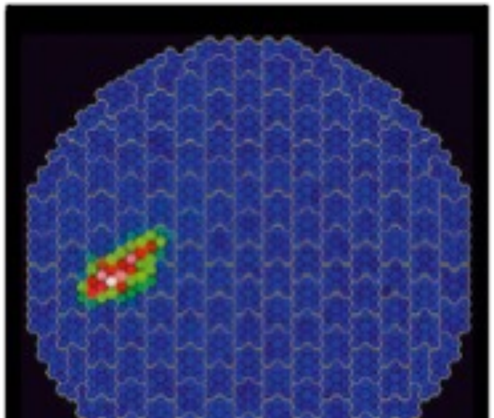
- Characteristics depend on operation temperature

Why SiPM in gamma-ray Astronomy

- Excellent single PE sensitivity
- Lightweight and robust cameras
- No evidence of ageing after 18 months
- Night Sky Background (NSB) rate dominates wrt Dark noise (MHz)
- Current Photo-Detection Efficiency > 40%.
- Operation during Moonlight: ~30% larger duty cycle
- As demonstrated by FACT, SiPM work on the field and with moonlight!)



New approach, use fully digital SiPM-based camera on a Davies-Cotton telescope.



Recorded showers during full moon, CERN Courier Nov 2011:

Telescope Design Drivers

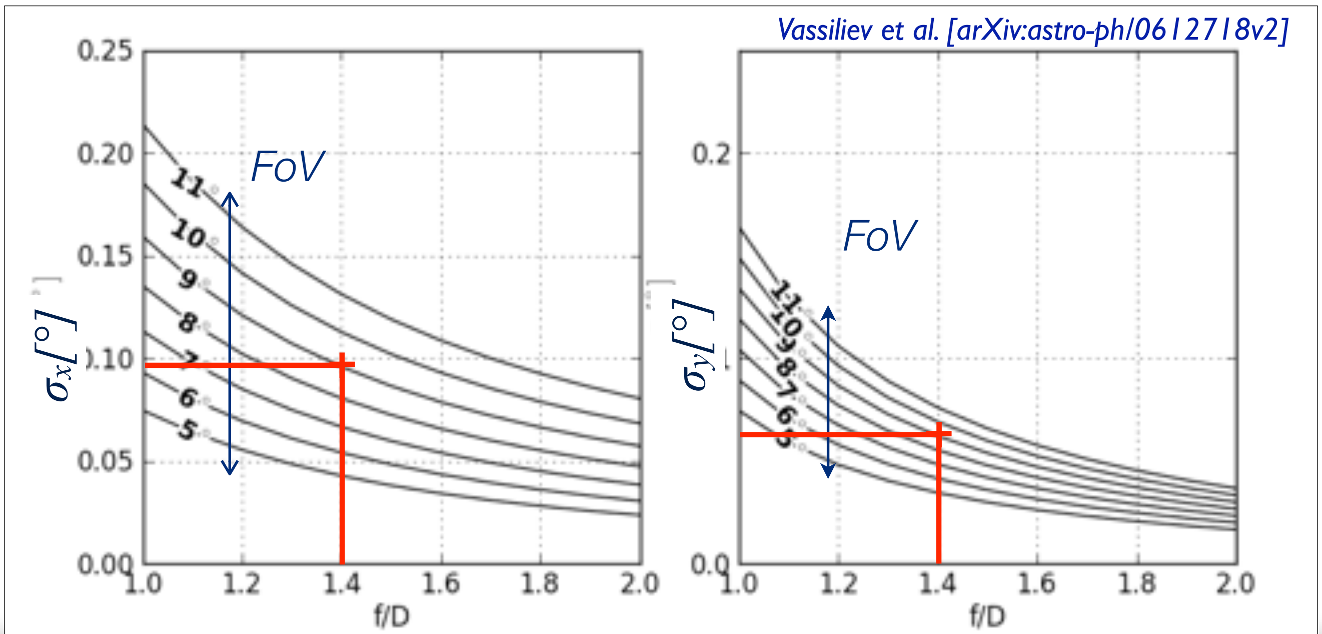
Conditions:

Dish = 4 m → ***energy threshold***

FoV = 9° → ***explore the galactic center, map extended source***

f/D = 1.4 → ***suitable angular resolution***

PSF OF A 4M DAVIES-COTTON



Telescope Design Drivers

Too big for a SiPM!!

Conditions:

Dish = 4 m

FoV = 9°

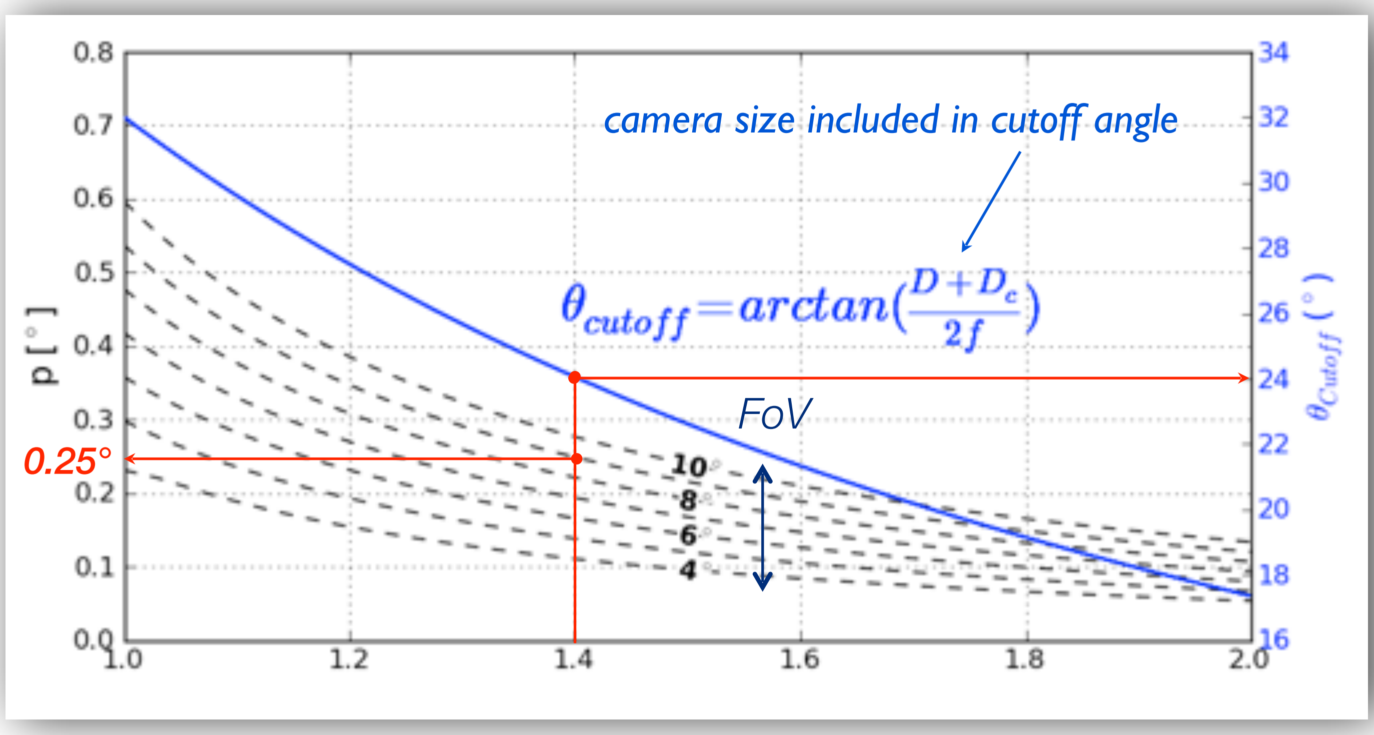
f/D = 1.4

pixel size = 4· min(σ_x, σ_y) = 0.25°

pixel size (linear) = 2.44 cm

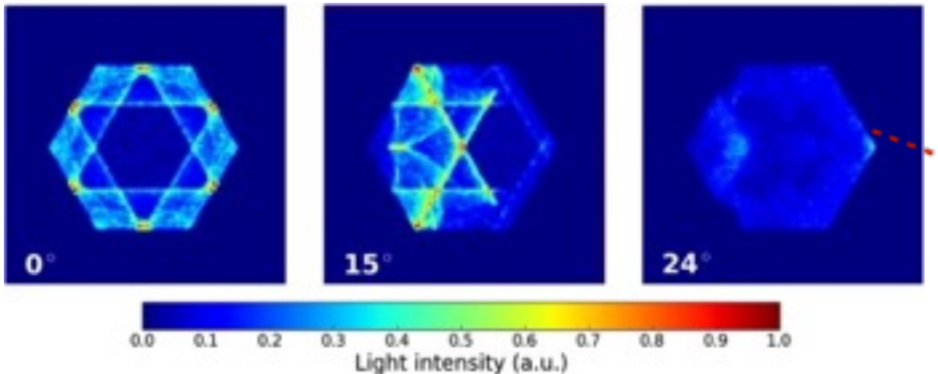
n_p = 1296 pixels

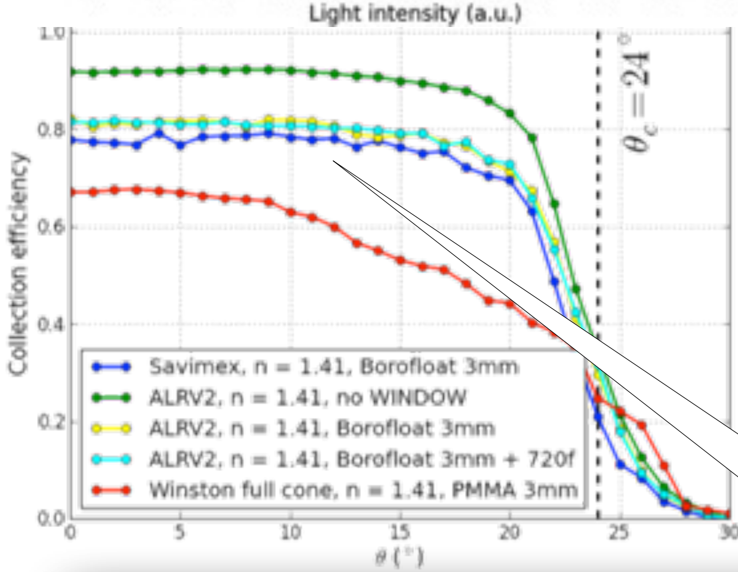
Camera size (D_c) = 88 cm

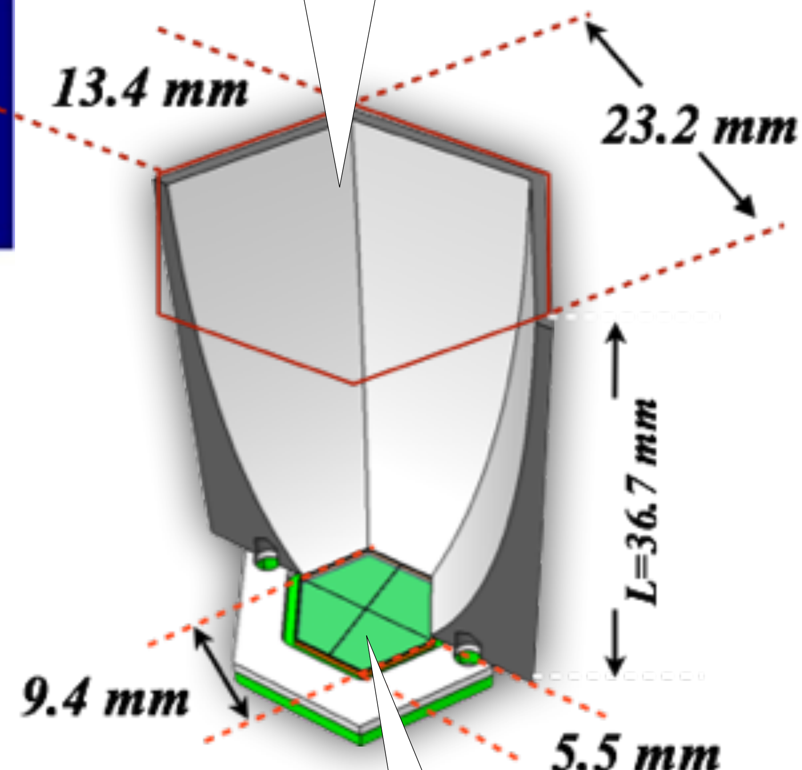


Winston cones

We need an Hollow cone to improve the response in the UV





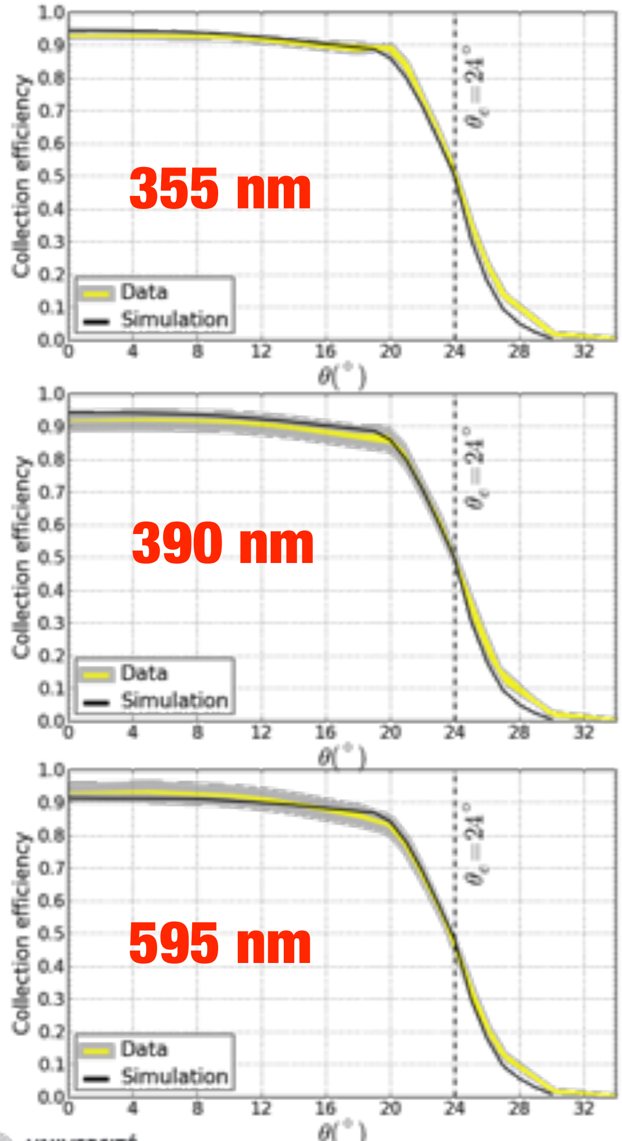


It's all about coating!

A new type of sensor!

Point Spread Function	➡	angular pixel size: 0.25°	➡	Top physical size
f/D and Camera diameter	➡	Cutoff angle: 24°	➡	Cone Height

Prototypes and first measurements



- ➡ Measurement done for different wavelengths
- ➡ Simulation of the set-up to validate the coating
- ➡ Very good agreement between simulation and measurement
- ➡ Coating qualified also with 40 thermal cycles (from -15° to +30°) - no measurable effect
- ➡ The collection efficiency shown here does not take into account the effect of the entrance window

Related paper:
J.A. Aguilar et al., *Design, optimization and characterization of the light concentrators of the single mirror small size telescopes of the Cherenkov Telescope Array, Astroparticle Physics, doi:10.1016/j.astropartphys.2014.05.010*

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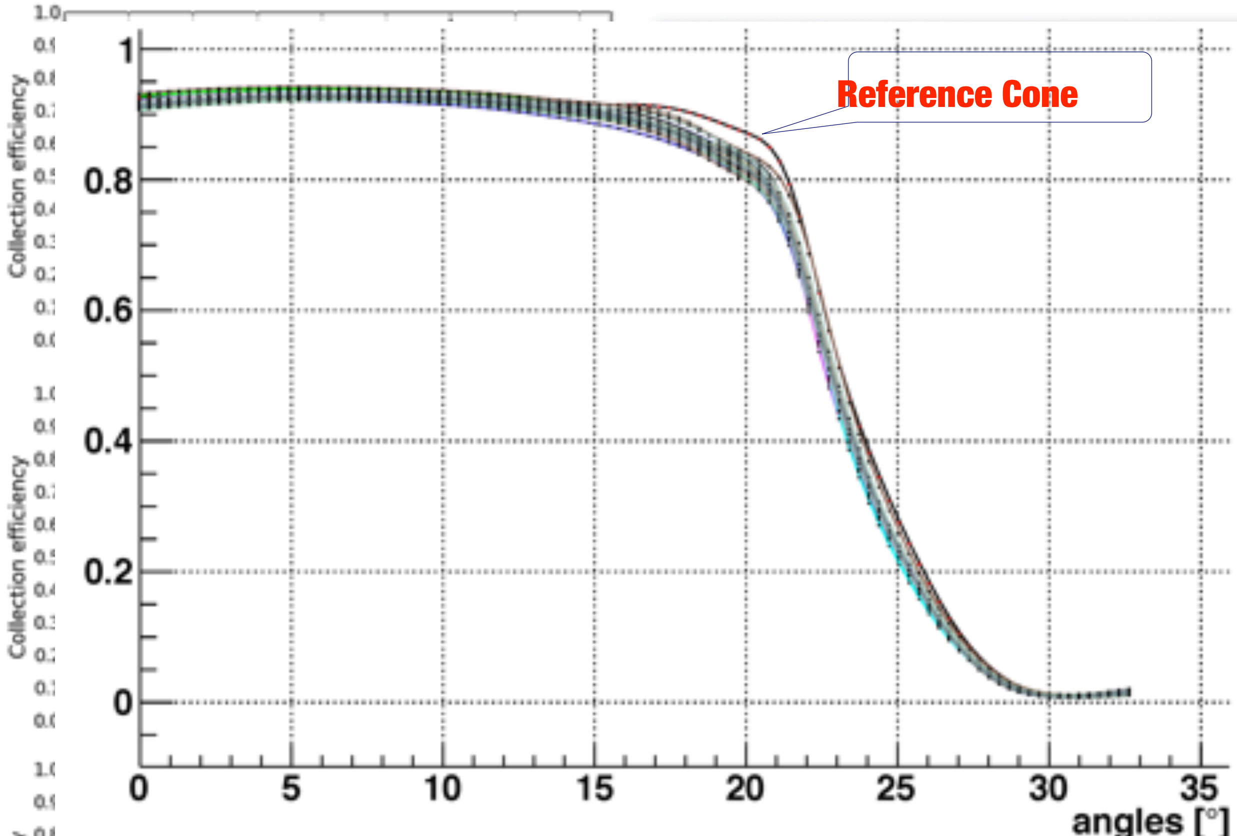

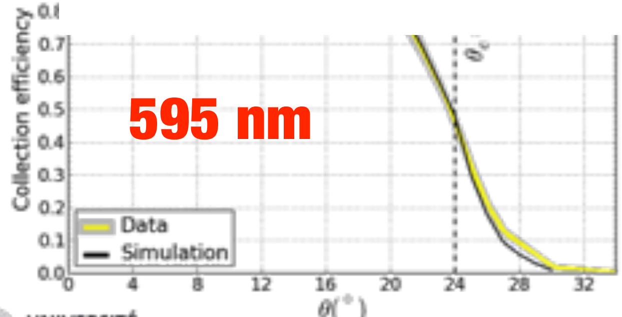

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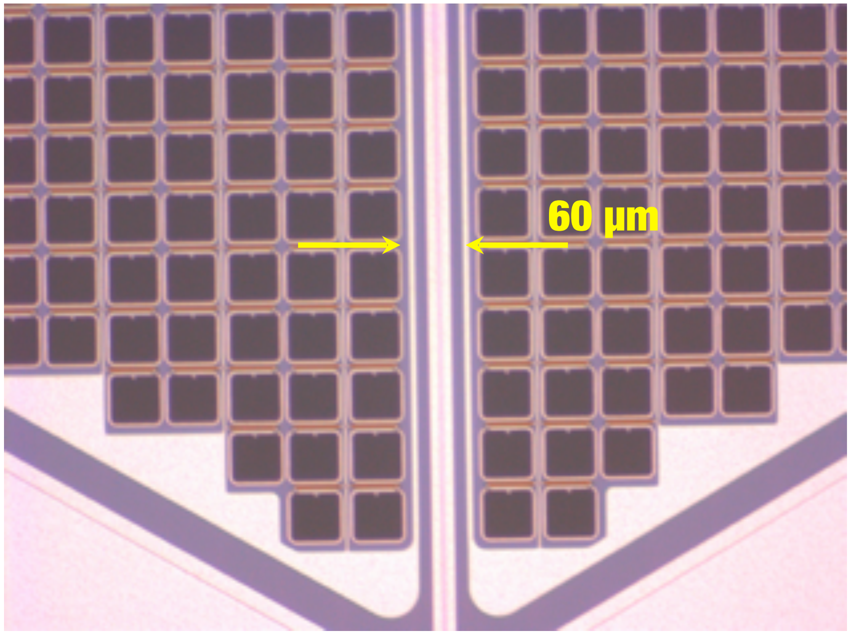
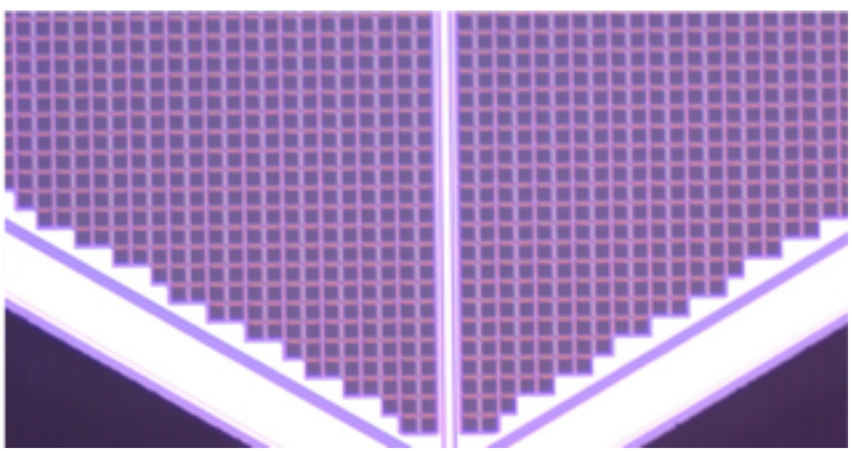
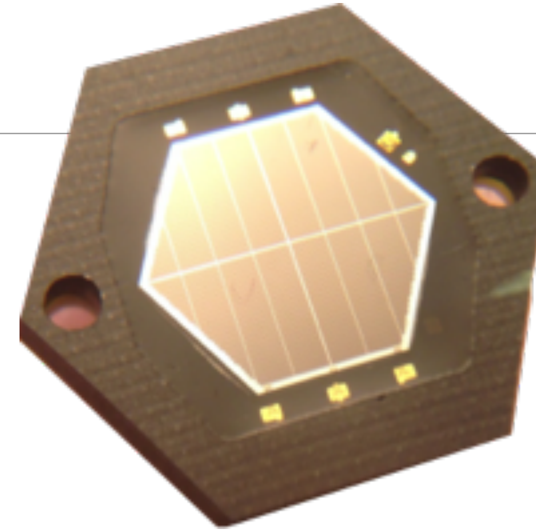
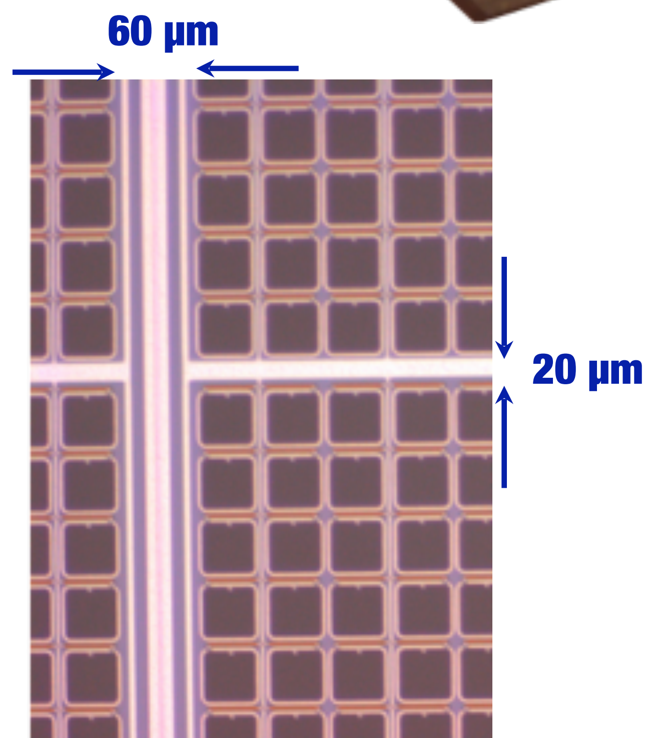
The S12516-050 sensor

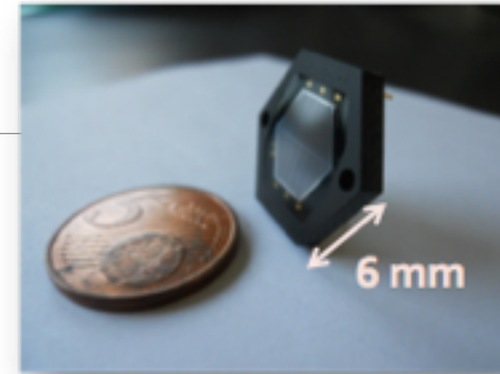




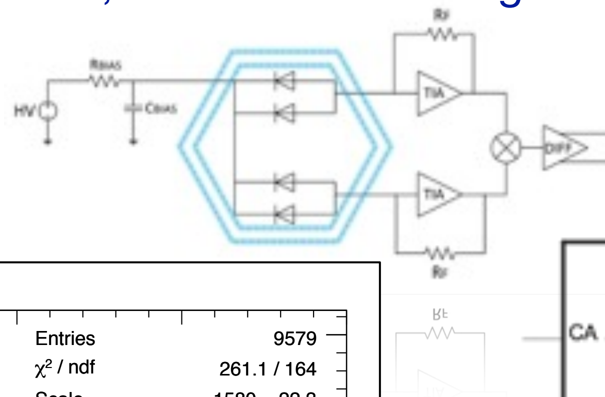




The Hexagonal Sensor

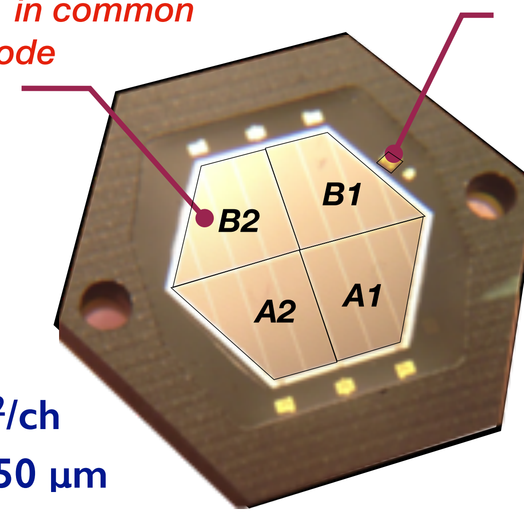


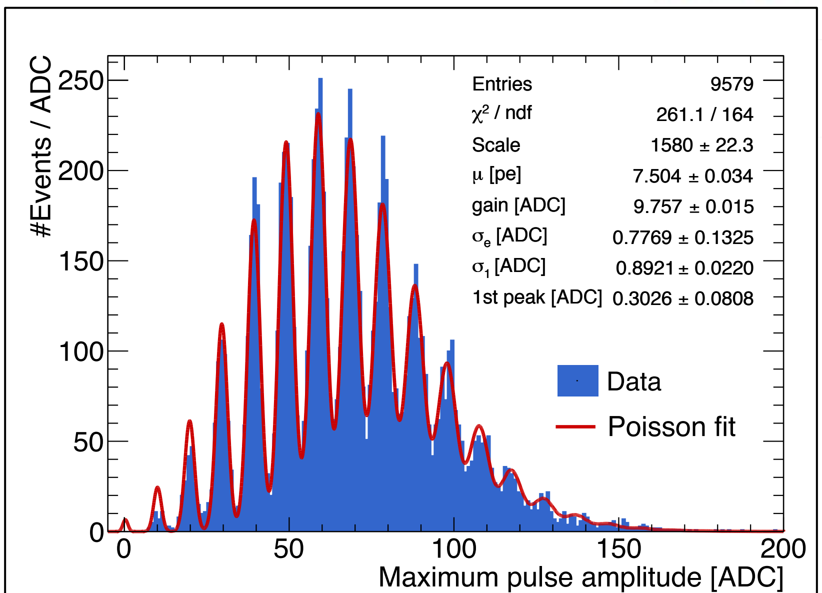
- Despite the use of the light concentrators, the pixel size remains large compared to common devices,
- Result of a collaboration between DPNC University of Geneva and Hamamatsu, the sensors are large hexagonal arrays of G-APD.

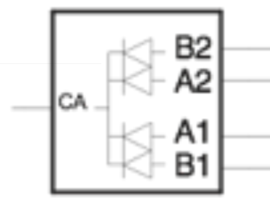


4 channels in common cathode mode

Thermistor





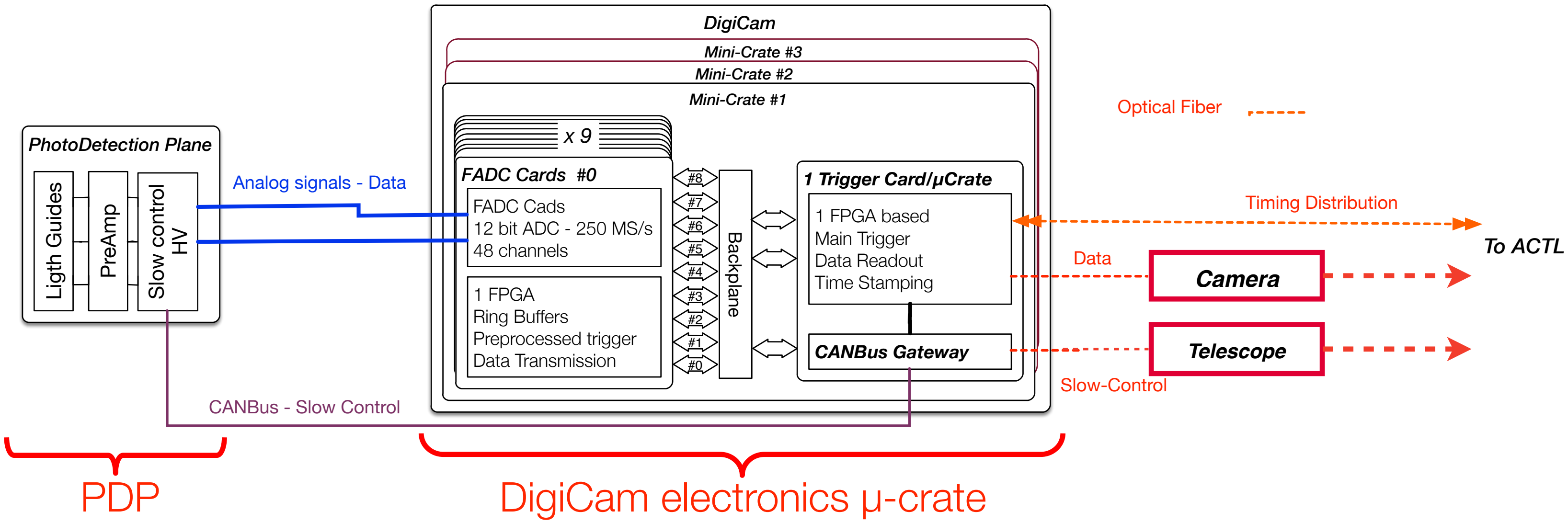


Channels:	**4**
Area:	**23.8 mm²/ch**
Cell size:	**50 µm x 50 µm**
Fill factor:	**68%**
N. pixels:	**9210 SPADs/**
Capacitance:	**840 pF/ch**
DC rate:	**2-3 MHz/ch**

➡ 93.6 mm² surface

➡ 10.4 mm flat-to-flat

The Camera concept



- Separation of PDP and Digital Readout
  - Separate mechanics and power supplies
  - Analogue signals over CAT6/RJ45
  - DC coupling for NSB monitoring
- Window and chassis sealed, IP65
- Water cooled - Heat pipes on Digital board
- Compact, robust, lightweight and self-contained

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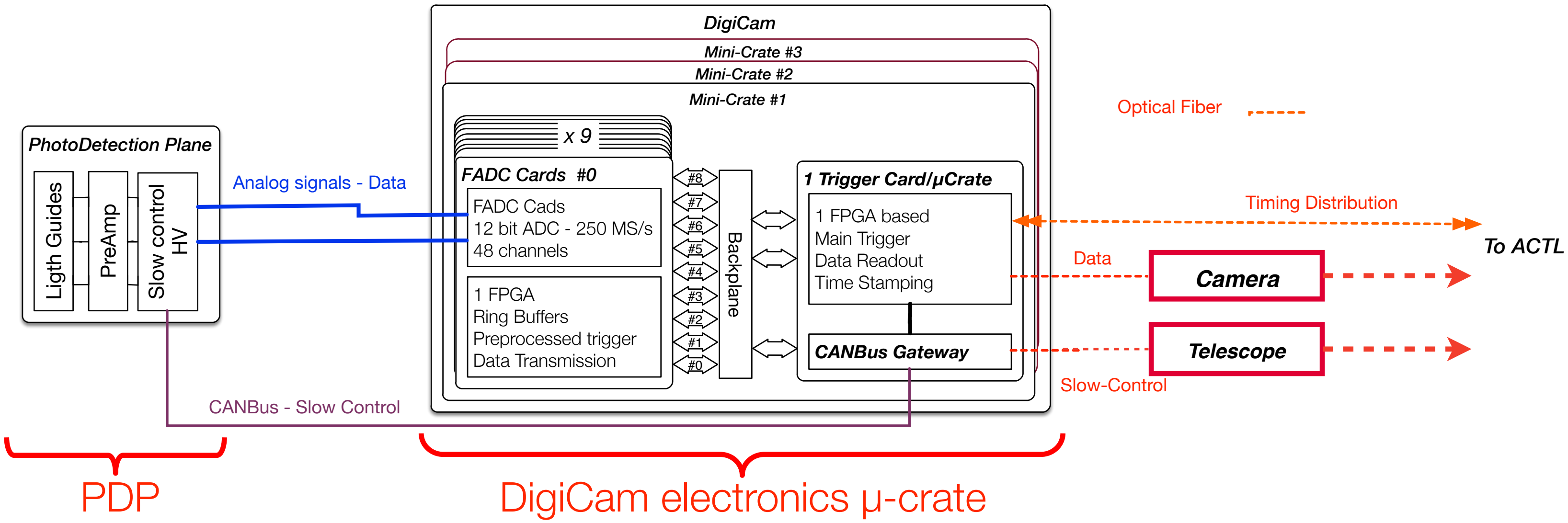

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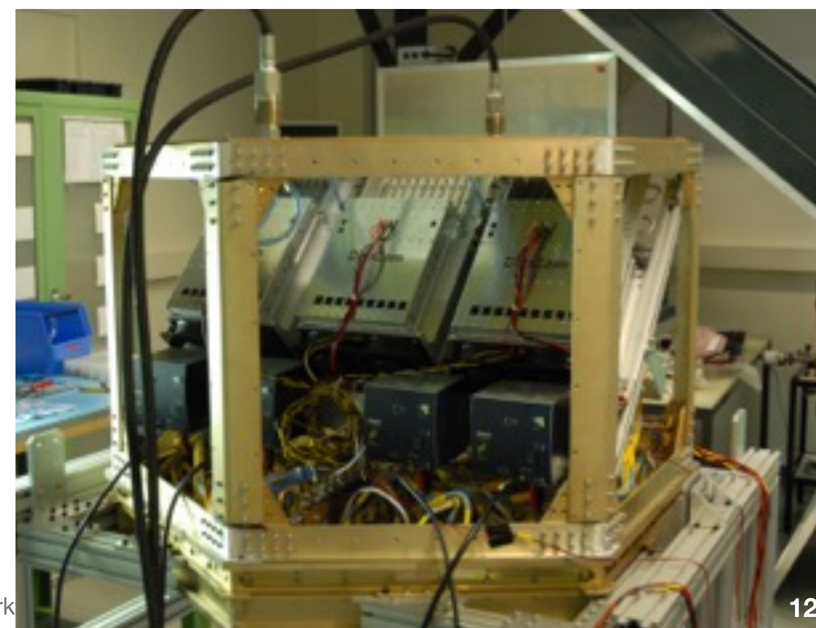
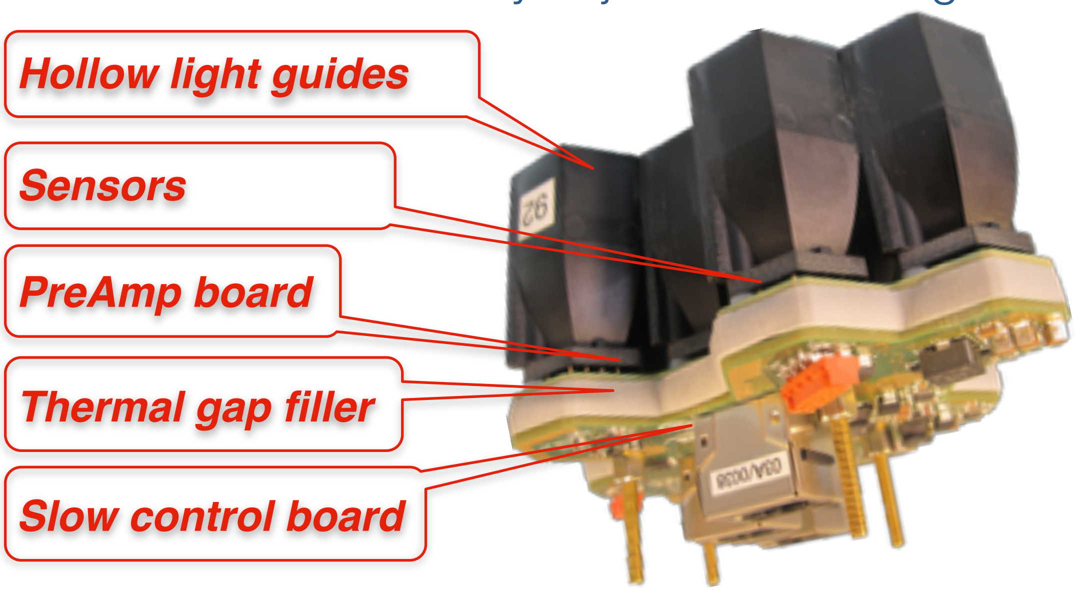
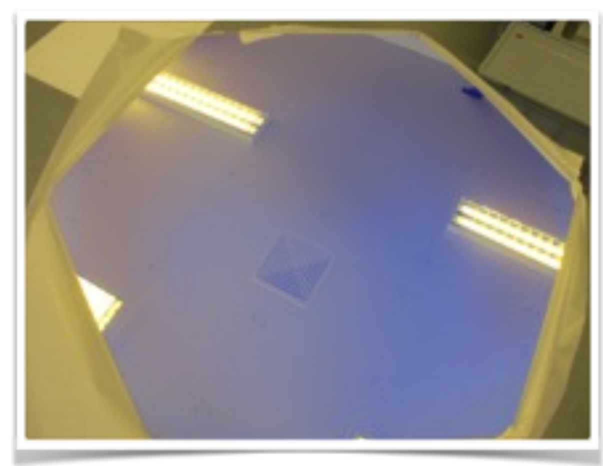


Photo Detection Plane

- 1296 pixels, 108 modules (12 pixels each)
- Power consumption ~ 500 W
- Total weight 35 kg
- Borofloat entrance window 3.3 mm coated with AR filter (Cut-off at 540 nm)
- Aluminum backplate (6 mm) as backbone and cold plate for Cooling
- Sensor bias automatically adjusted according to temperature (reso. of 0.17 deg)

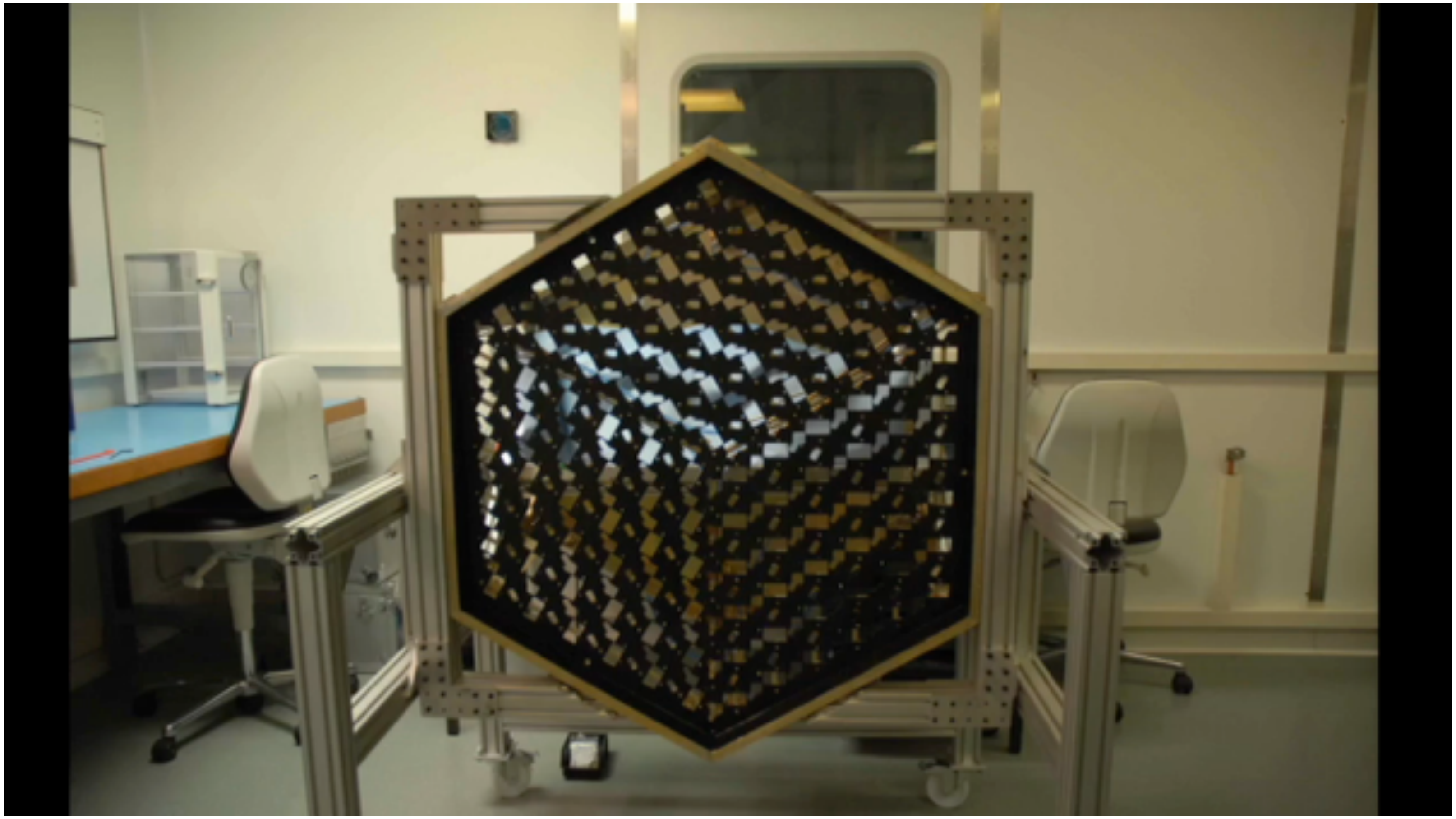




Borofloat window

Assembly - Photo Detection Plane

1 day of work to assemble full PDP



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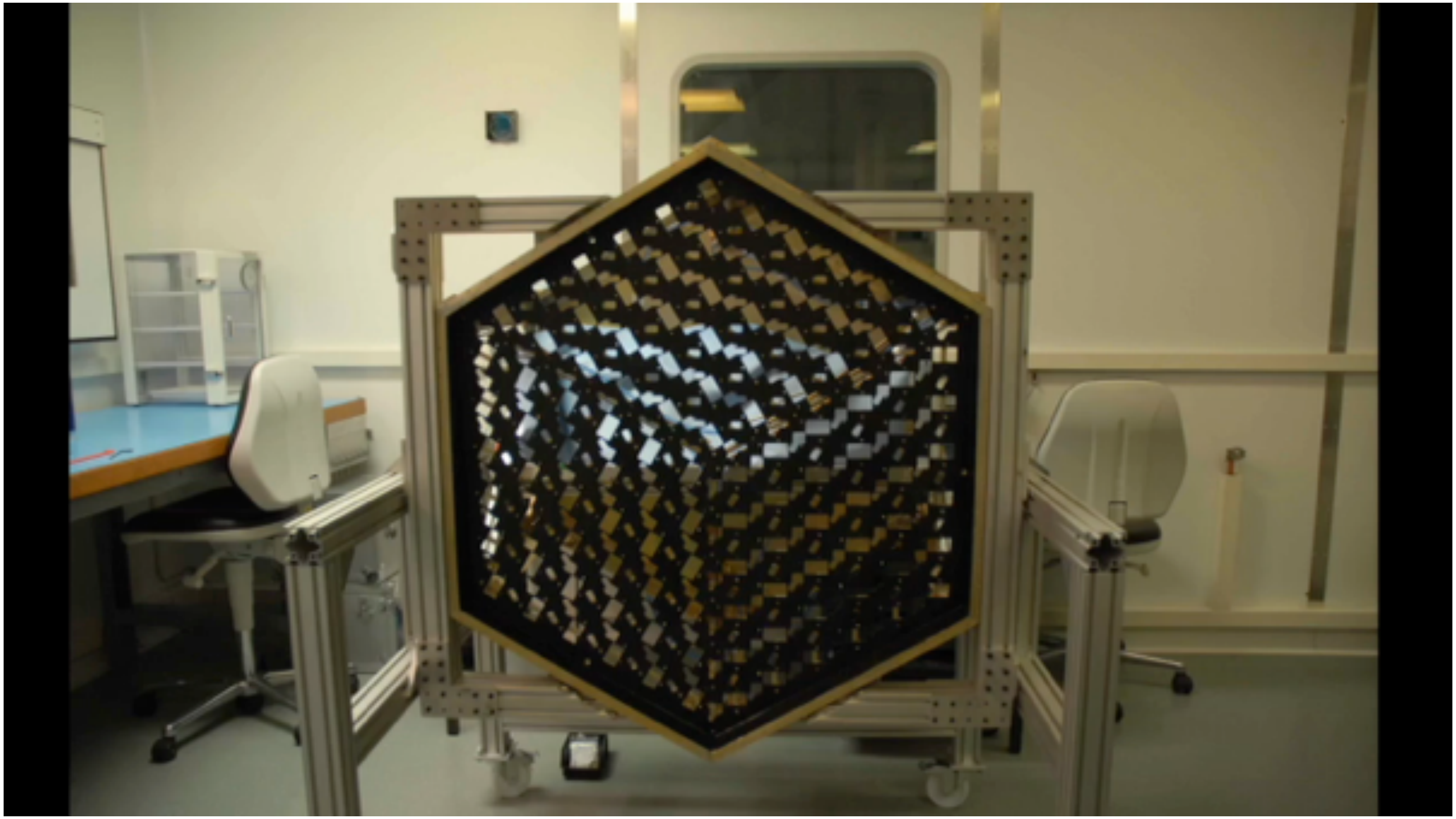
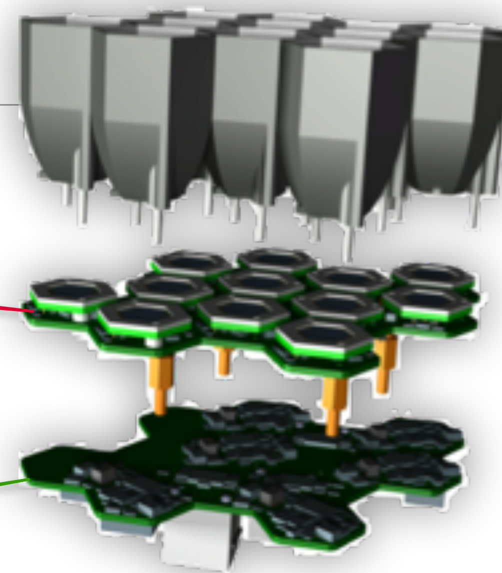
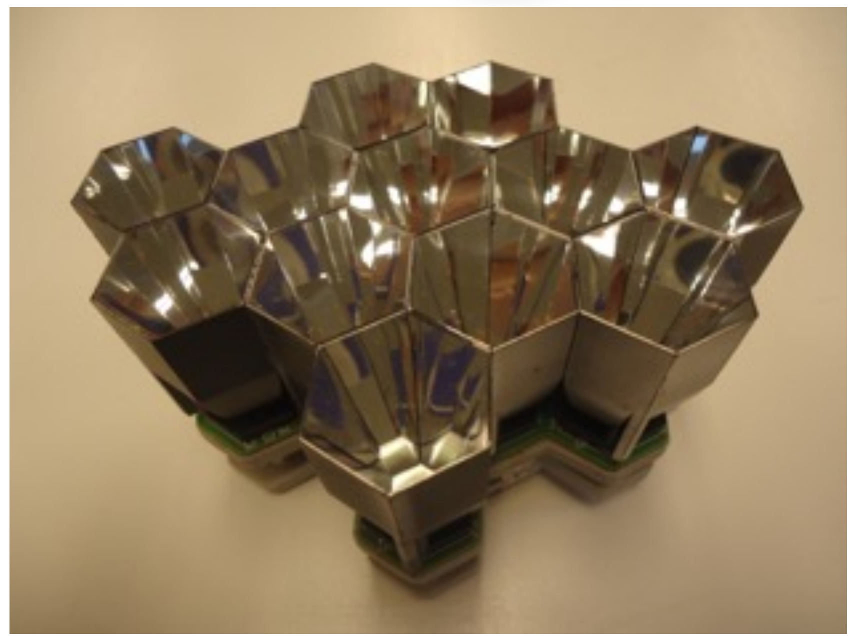


The Front-end electronics



- The pre-amp boards
    - read and pre-amplify the analog signals
    - routes out signals, the HV and the output of the NTC probe, present on the sensor package.
- SlowControl Board
    - route pixel signals to Digicam via the RJ45 connector
    - distributes the power and the HV
    - regulate HV for each pixel
    - Use a micro controller to change HV of each pixel to compensate temperature variations measured by the NTC probe in sensor package
    - Board accessed via CAN-bus



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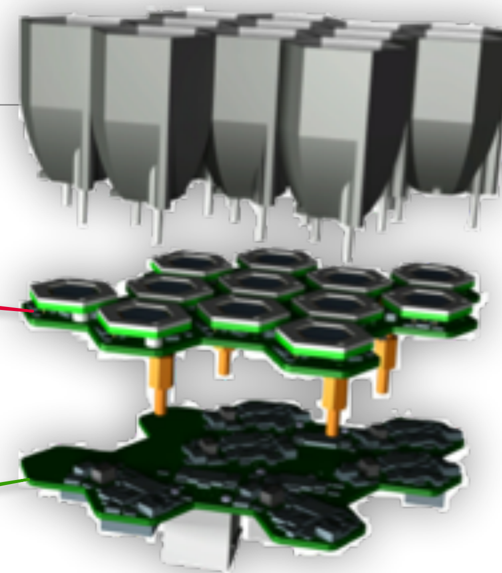

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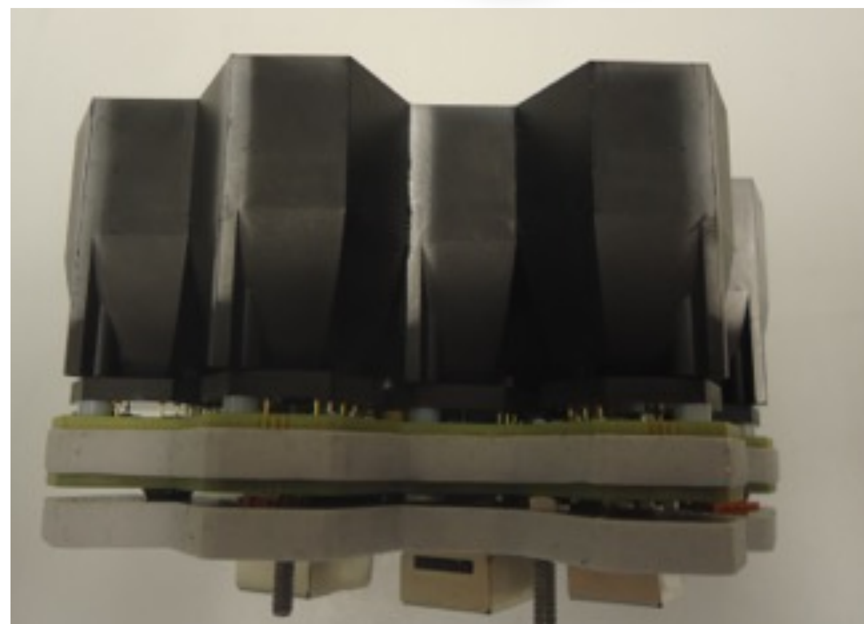
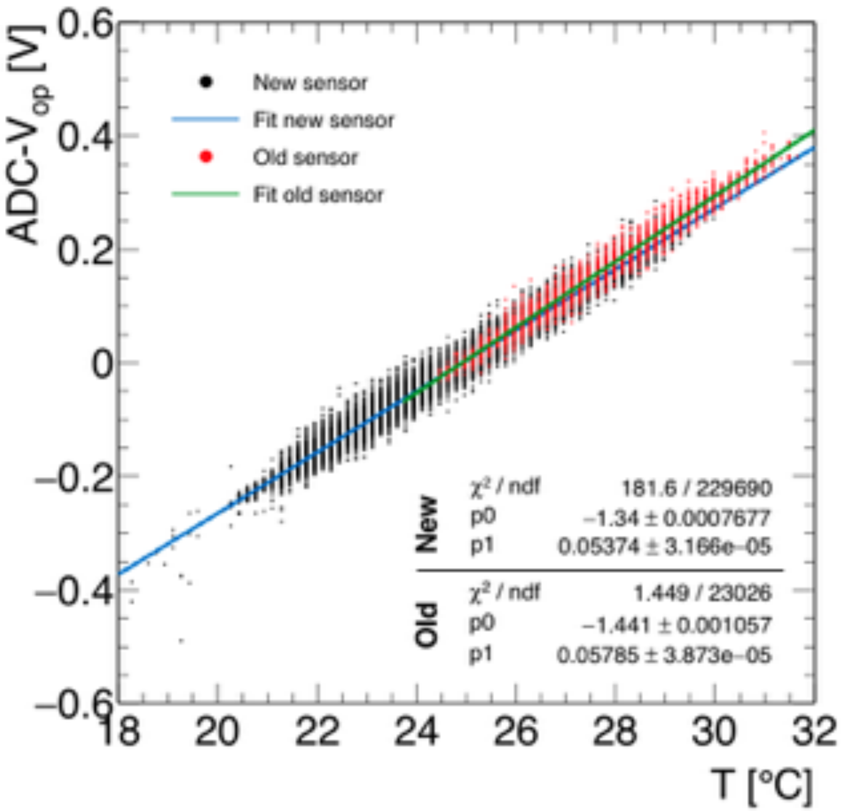
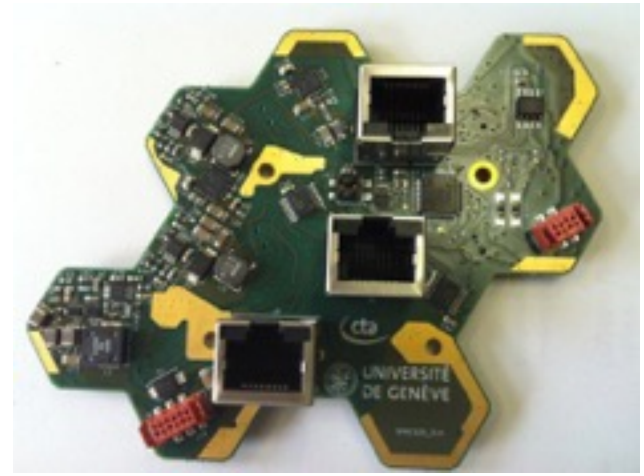


Slow control Board

- The slow control board has the following task
    - route pixel signals to Digicam via the RJ45 connector
    - provide the bias and
    - change the bias to compensate for temperature variations
- a micro controller supervises the temperature compensation
    - look-up table is loaded with correction
    - each pixel has its own correction
    - temperature reading
- Board accessed via CAN-bus

Commissioning - Design validation



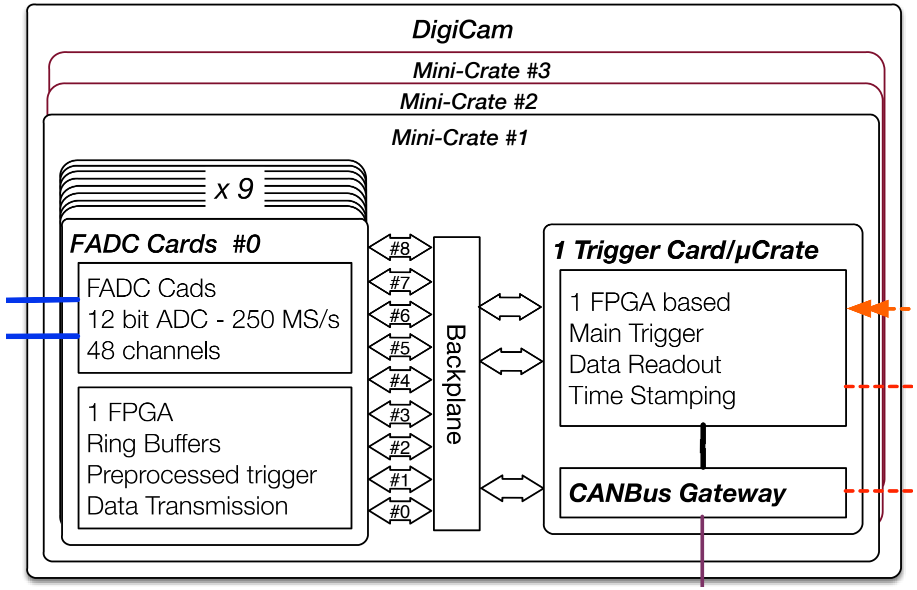


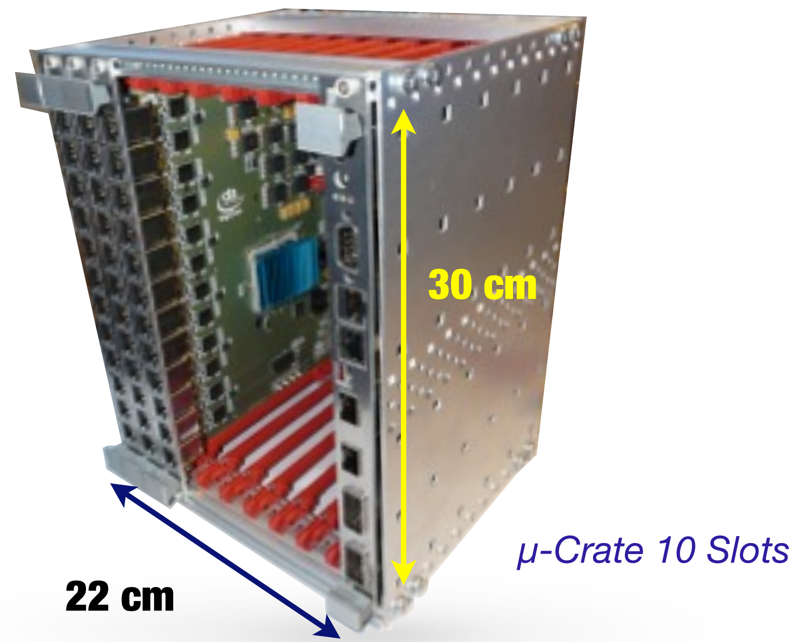
Control:
- ✓ Enable boost for bias
- ✓ Activate bias voltage
- ✓ Reference voltage and temperature setting
- ✓ Temperature variation factor

Monitoring of:
- ✓ Temperature and bias voltage
- ✓ Compensation loop

✓ Slow control and communication validated

Digital readout and trigger / DigiCam

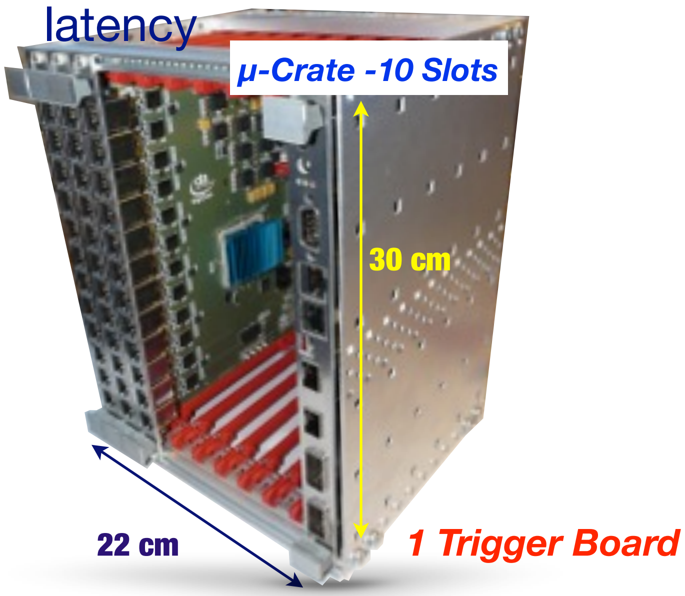


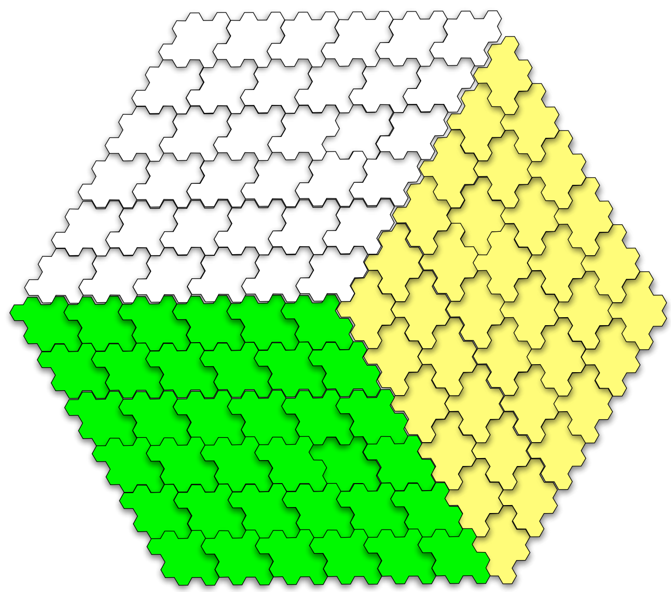


- Sampling rate 250 MHz
- Readout rate: 32 kHz @ 80 ns readout window, no dead-time
- Fully digital trigger and readout (High-speed/High-throughput)
- Serial architecture based on multi-Gigabit links (trigger and ADC readout)
- Trigger path with reconfigurable algorithms and signal preprocessing

DigiCam Electronics

- Based on last generation of High performance Xilinx FPGA ⇒ Flexibility, High Speed, Low power consumption
  - ➡ up to **56 GTX** transceivers, max 12.5Gbit/s
  - ➡ up to **96 GTH** transceivers, max 13.1Gbit/s
- Using DDR expandable RAM for data buffering ⇒ Upgradable, handle high latency





BackPlane with 54 differential pairs

- *36 - high speed 8Gbit/s for crate trigger data*
- *18 - low speed 1Gbit/s for readout and slow control*

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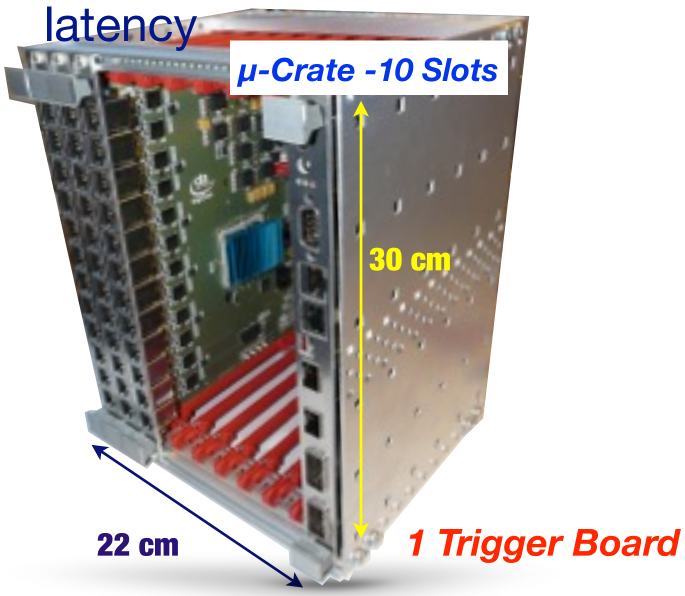

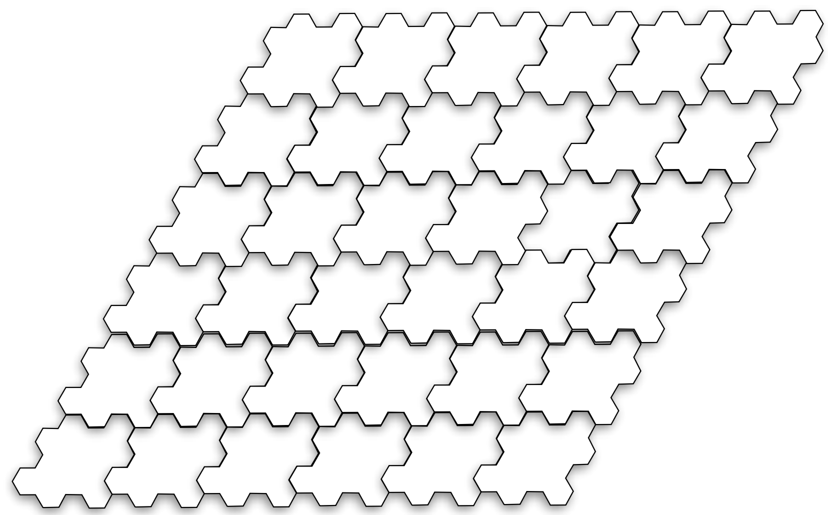

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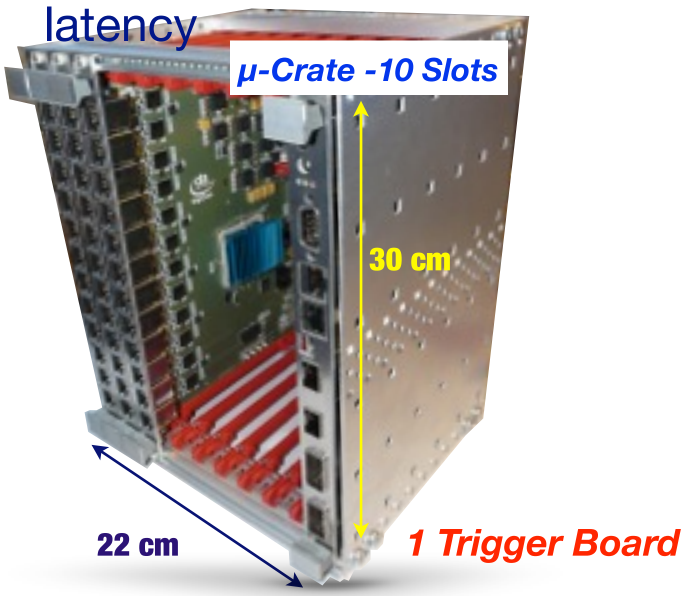

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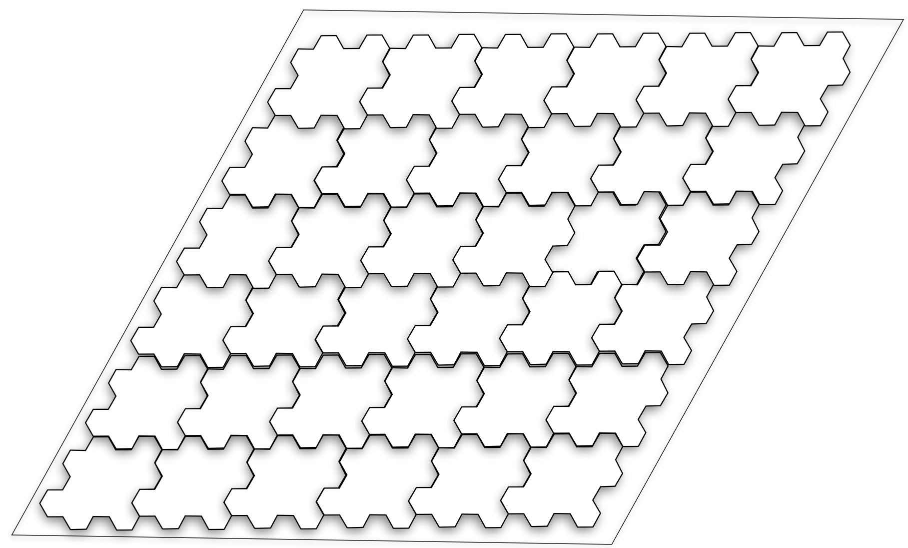

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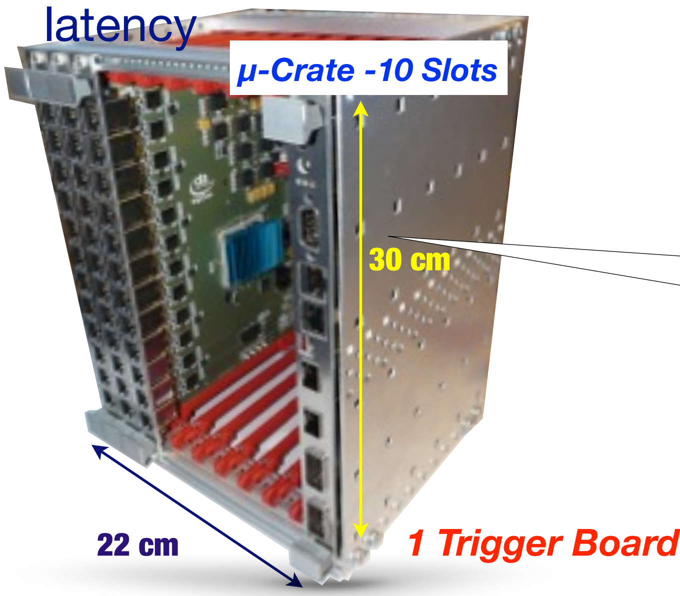

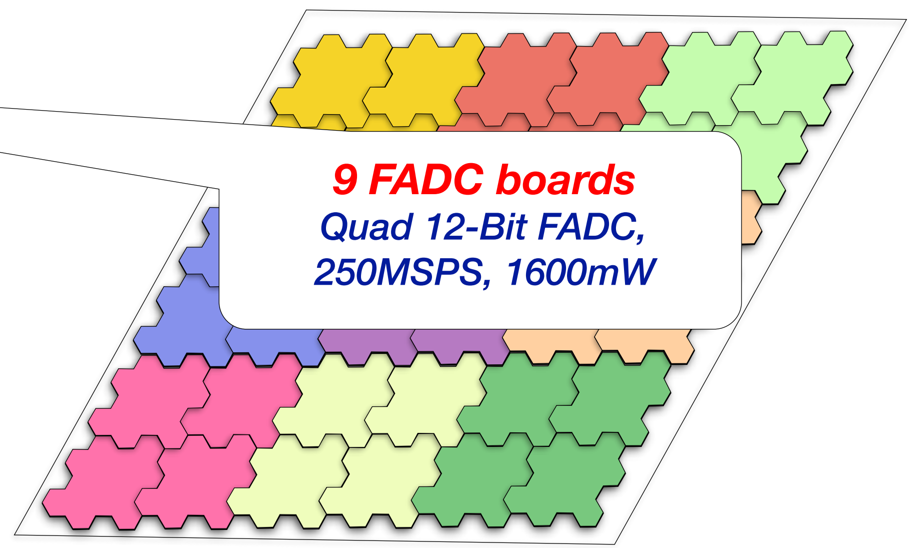

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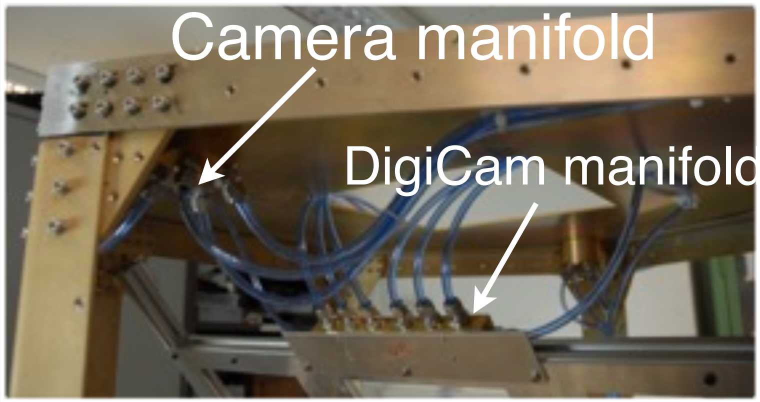
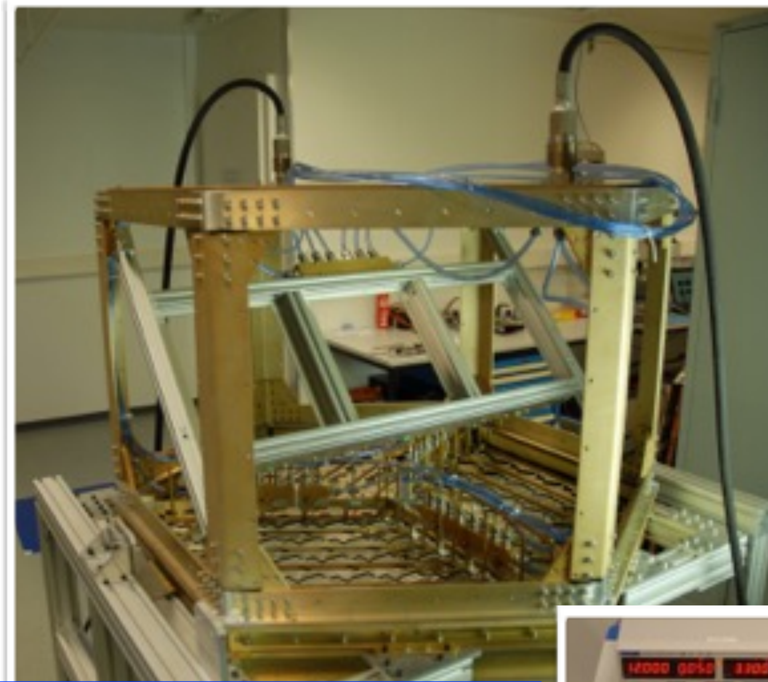
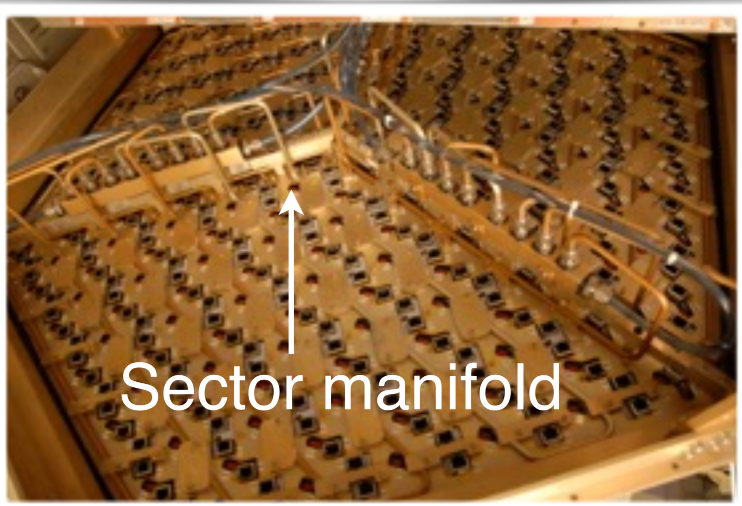
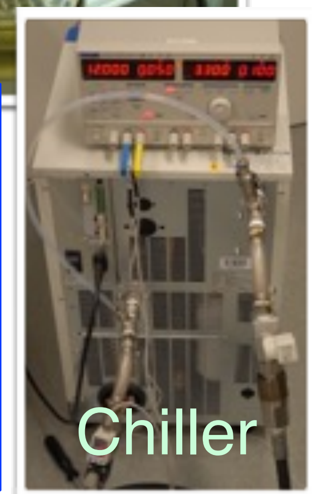
Assembly - Water Cooling system







- Cooling pipes installed prior to any electrical system
- Water tightness checked
- Epoxy resin applied on joints for safety



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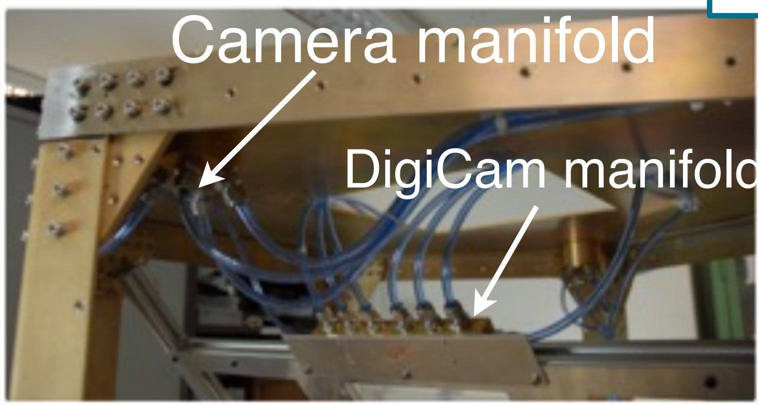
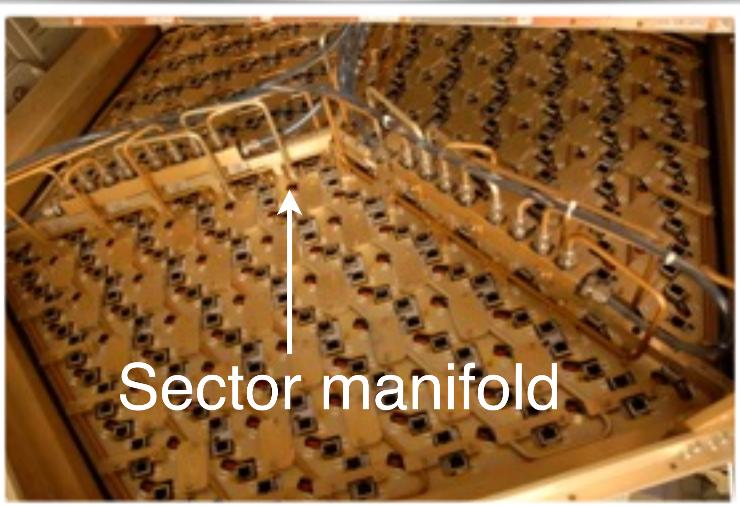
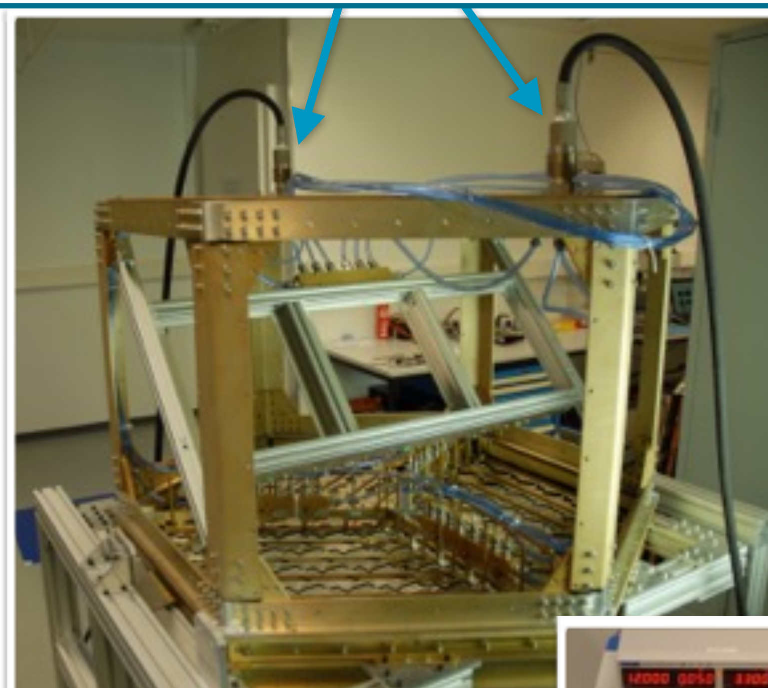
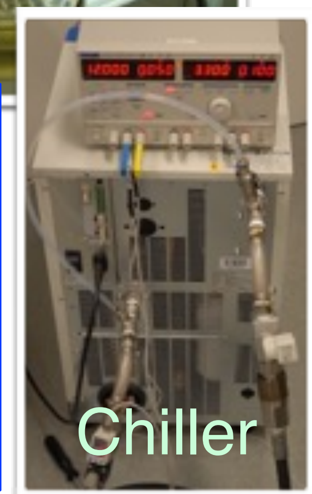




fast connectors for inlet/outlet camera



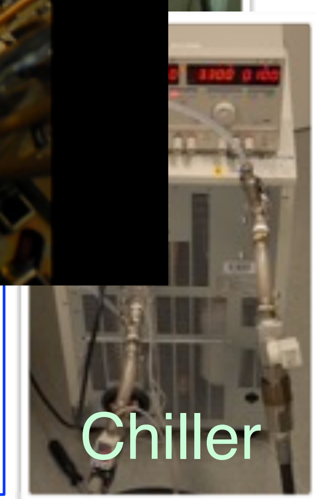
- Cooling pipes installed prior to any electrical system
- Water tightness checked
- Epoxy resin applied on joints for safety



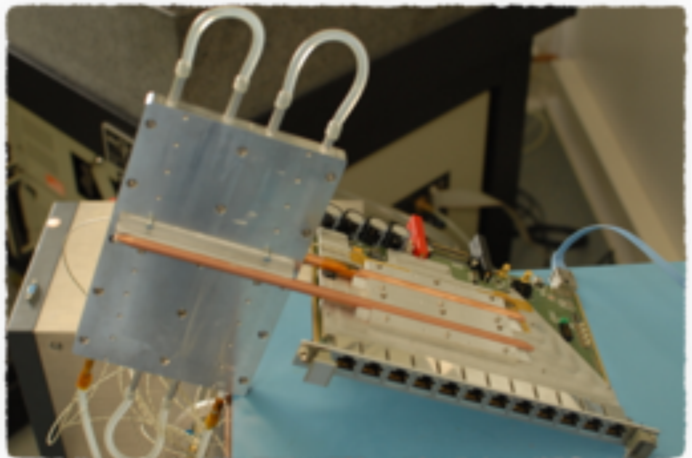
Assembly - Water Cooling system

fast connectors for inlet/outlet camera

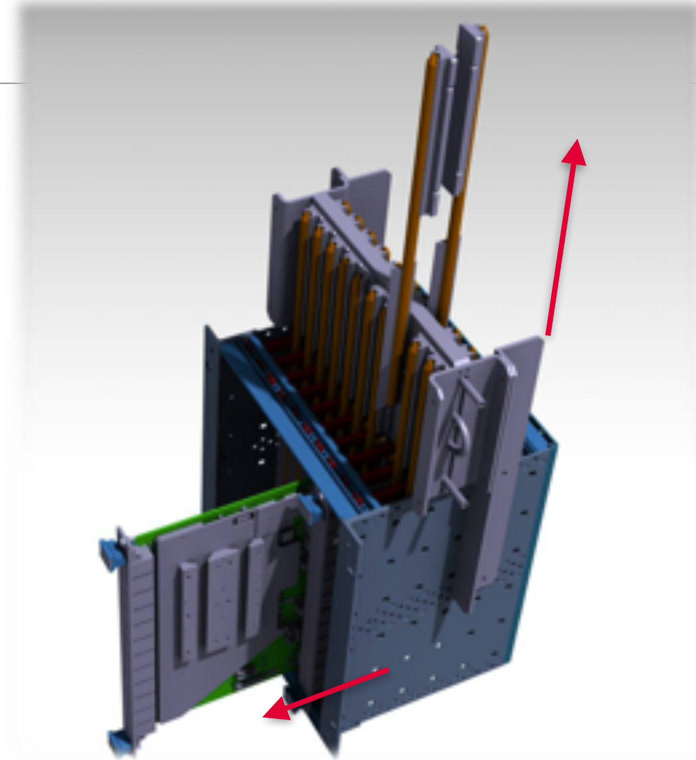
- Water tightness checked
- Epoxy resin applied on joints for safety

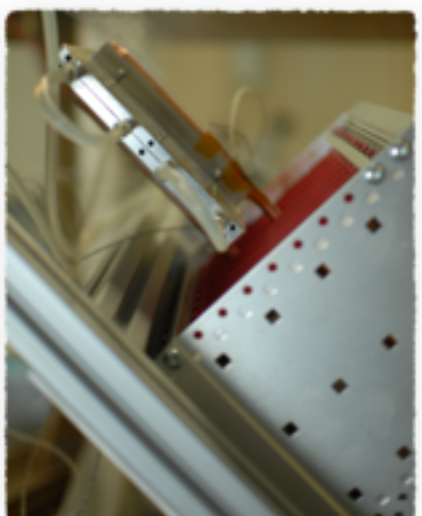


Digicam Cooling



2 Heat pipes (25W each) per board coupled to a water cooled plate

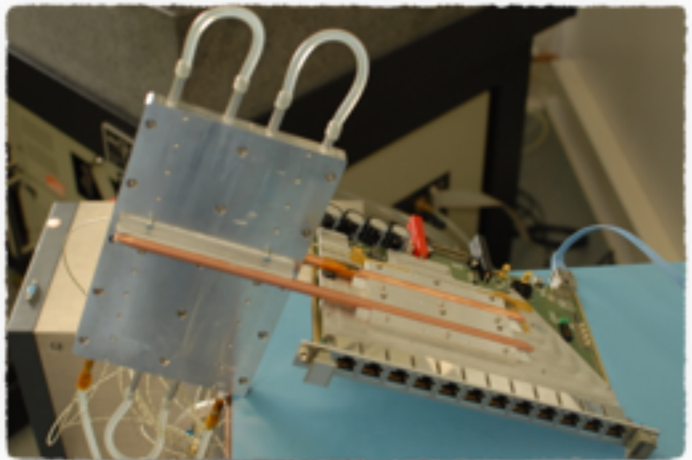




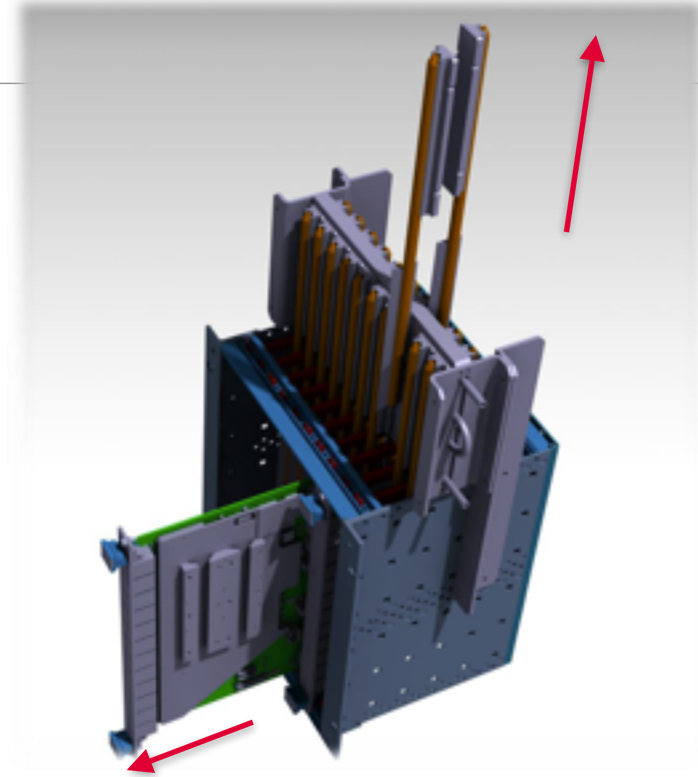
- Board can be removed from the crate with limited intervention on the cooling system

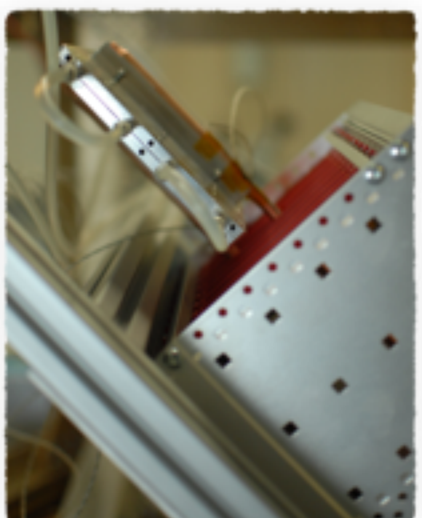
Micro-crate mounted at 45° to have always optimal heat-pipes efficiency

Digicam Cooling



2 Heat pipes (25W each) per board coupled to a water cooled plate

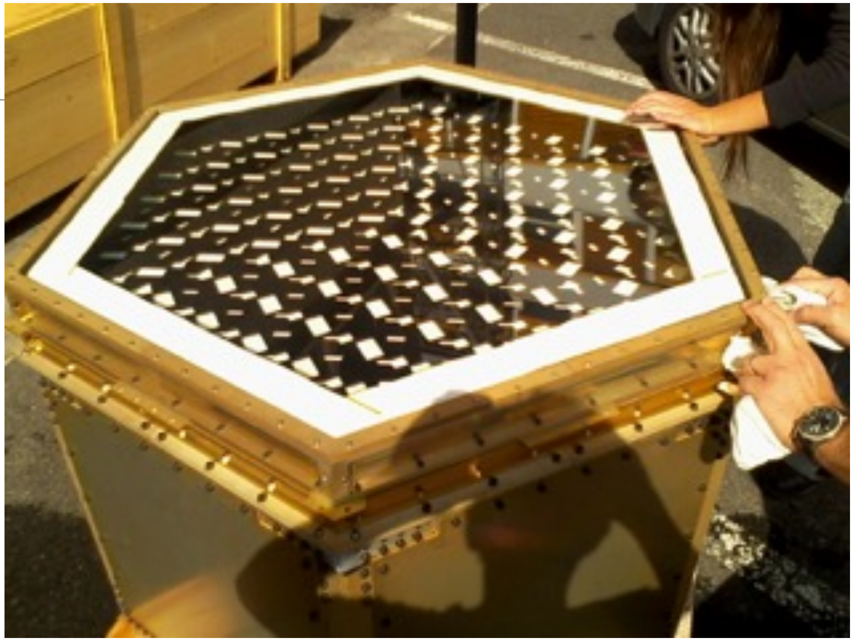




- Board can be removed from the crate with limited intervention on the cooling system

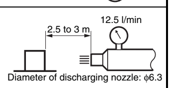
Micro-crate mounted at 45° to have always optimal heat-pipes efficiency

Camera Chassis IP65 Test



- Camera tested against IP65 Specs
  - to check even tiny leaks the internal surface of the camera was covered with a special paper which change color in case it comes in contact to water
- No water leak but on 2 points on the patch panel
  - Due to a wrong machining of the holes
  - cured with a small joint
- Another test is scheduled next week to qualify the new solution

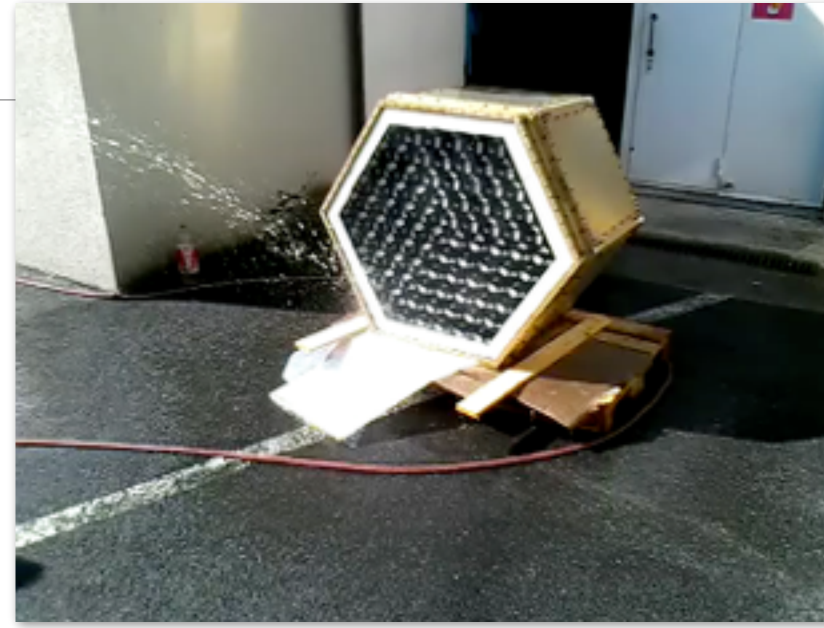
5	Protection from water jets	No harmful effect of water splash from all direction	By using tool as descripted in right picture, Jet the water from all direction to the object surface for 1 m^2/min, at least for 3 min in total.



Camera Chassis IP65 Test

- Camera tested against IP65 Specs
  - to check even tiny leaks the internal surface of the camera was covered with a special paper which change color in case it comes in contact to water
- No water leak but on 2 points on the patch panel
  - Due to a wrong machining of the holes
  - cured with a small joint
- Another test is scheduled next week to qualify the new solution

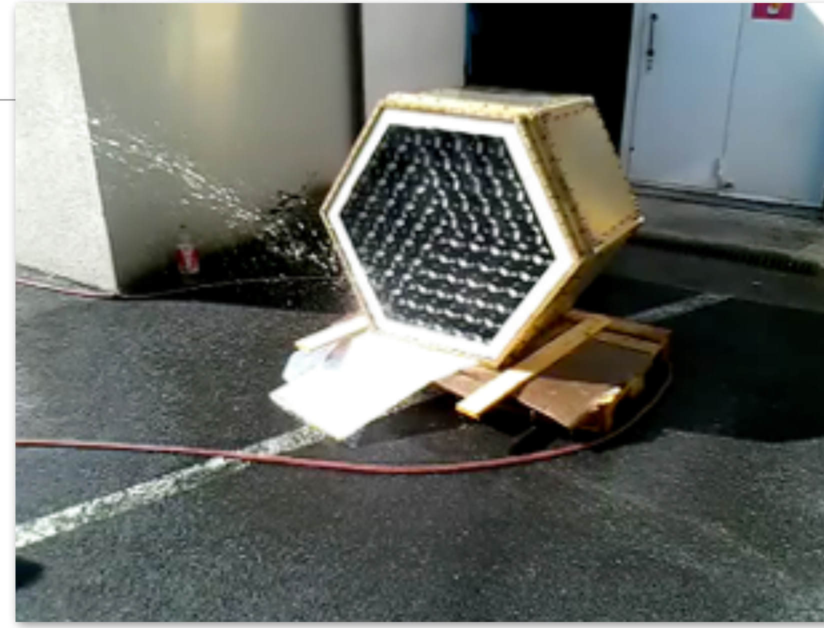
5	Protection from water jets	No harmful effect of water splash from all direction	By using tool as descripted in right picture, Jet the water from all direction to the object surface for 1 m^2/min, at least for 3 min in total. 12.5 l/min; 2.5 to 3 m; Diameter of discharging nozzle: ϕ6.3



Camera Chassis IPX5 Test

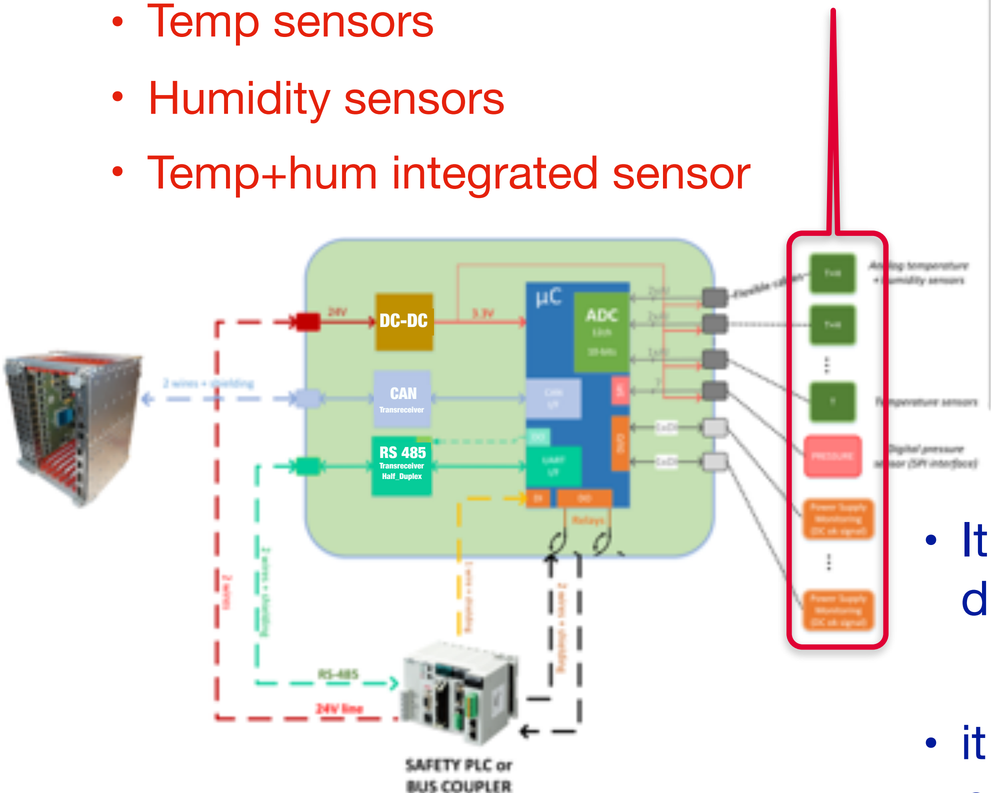
- Camera tested against IP65 Specs
  - to check even tiny leaks the internal surface of the camera was covered with a special paper which change color in case it comes in contact to water
- No water leak but on 2 points on the patch panel
  - Due to a wrong machining of the holes
  - cured with a small joint
- Another test is scheduled next week to qualify the new solution

5	Protection from water jets	No harmful effect of water splash from all direction	By using tool as descripted in right picture, Jet the water from all direction to the object surface for 1 m^2/min, at least for 3 min in total.	2.5 to 3 m; 12.5 l/min; Diameter of discharging nozzle: ϕ6.3



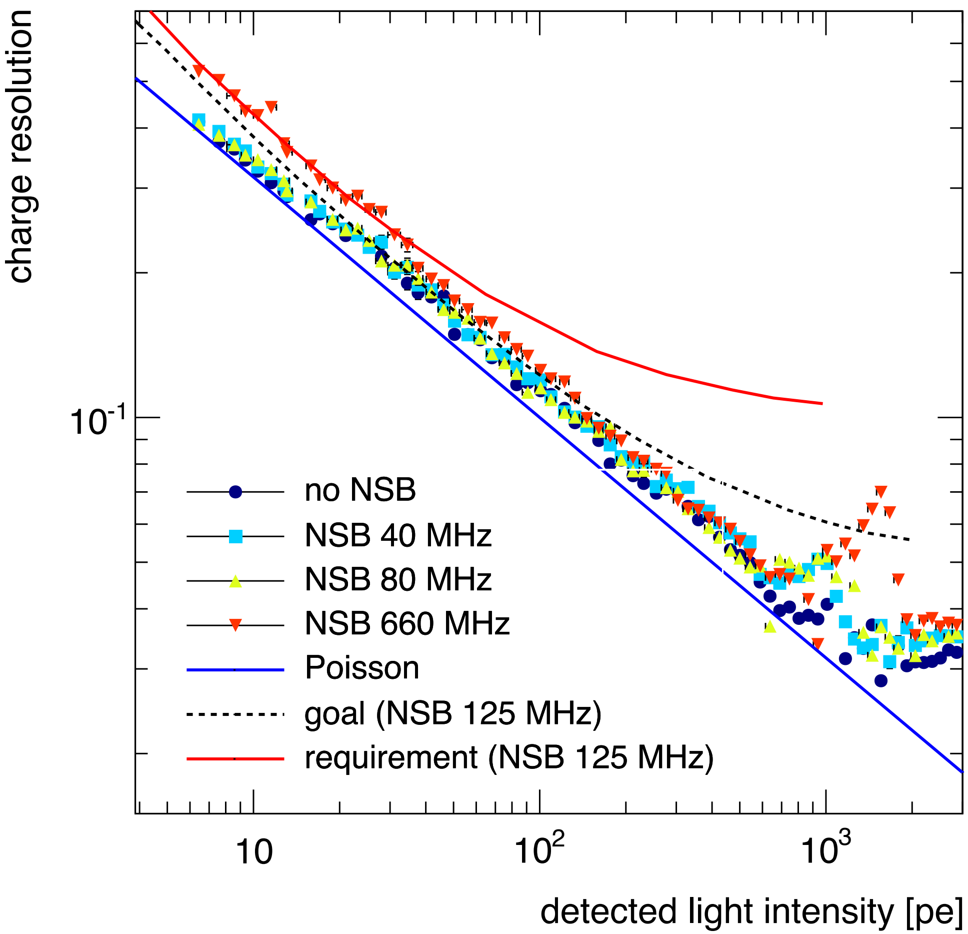
Camera Safety - Housekeeping Board

- to have as many possible probes but not having lots of cables from camera to the PLC we designed an Housekeeping board
- It can host 3 different type of sensors
    - Temp sensors
    - Humidity sensors
    - Temp+hum integrated sensor



- It can be connected to the PLC with 2 different protocols:
    - RS485 or CanBus
- it can trigger alarm to PLC in case of problems
- it will also monitor the power supply

Performance

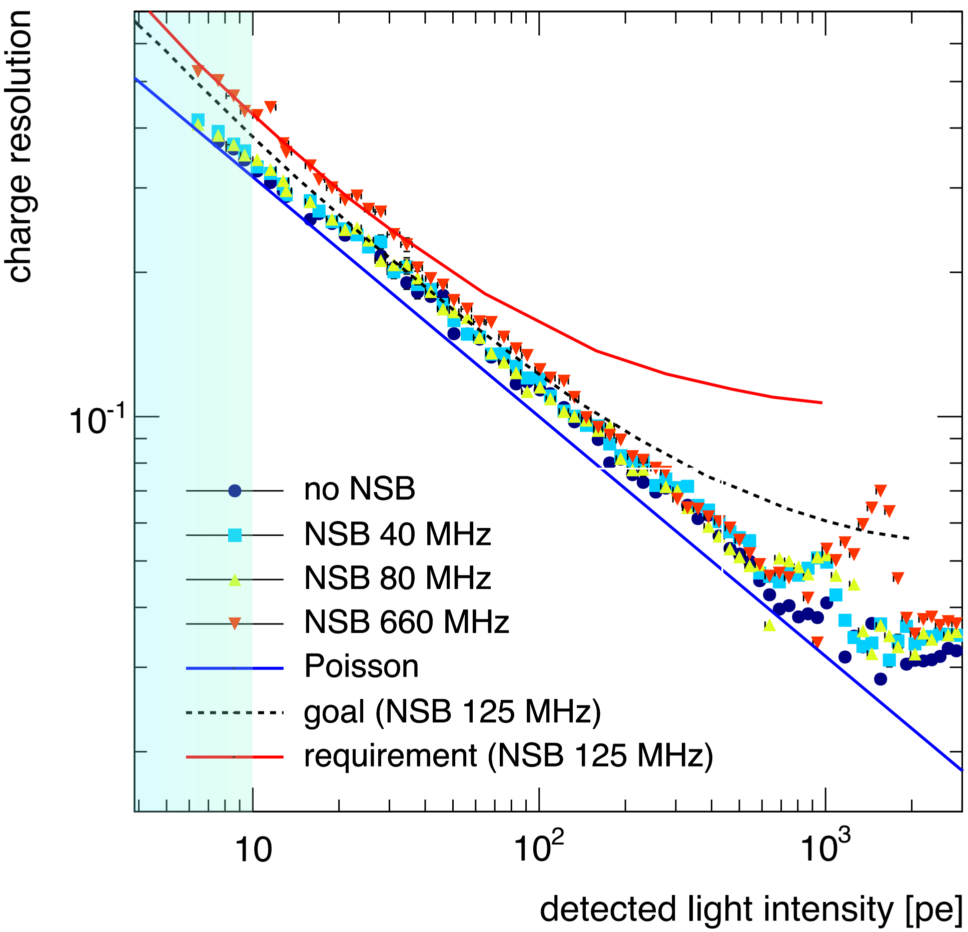


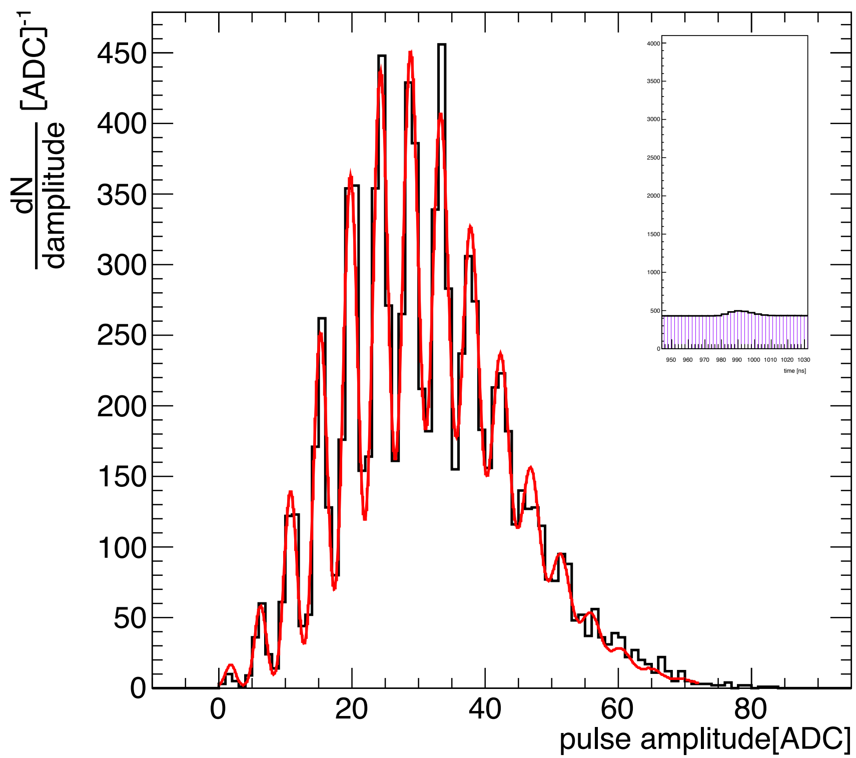
Charge resolution measurement:

- Key parameter to assess quality of image reconstruction (Hillas parameters)
- Measurement performed injecting both pulsed and continuous light
- Different NSB level from dark night to half-moon (45° off-axis)

Performance

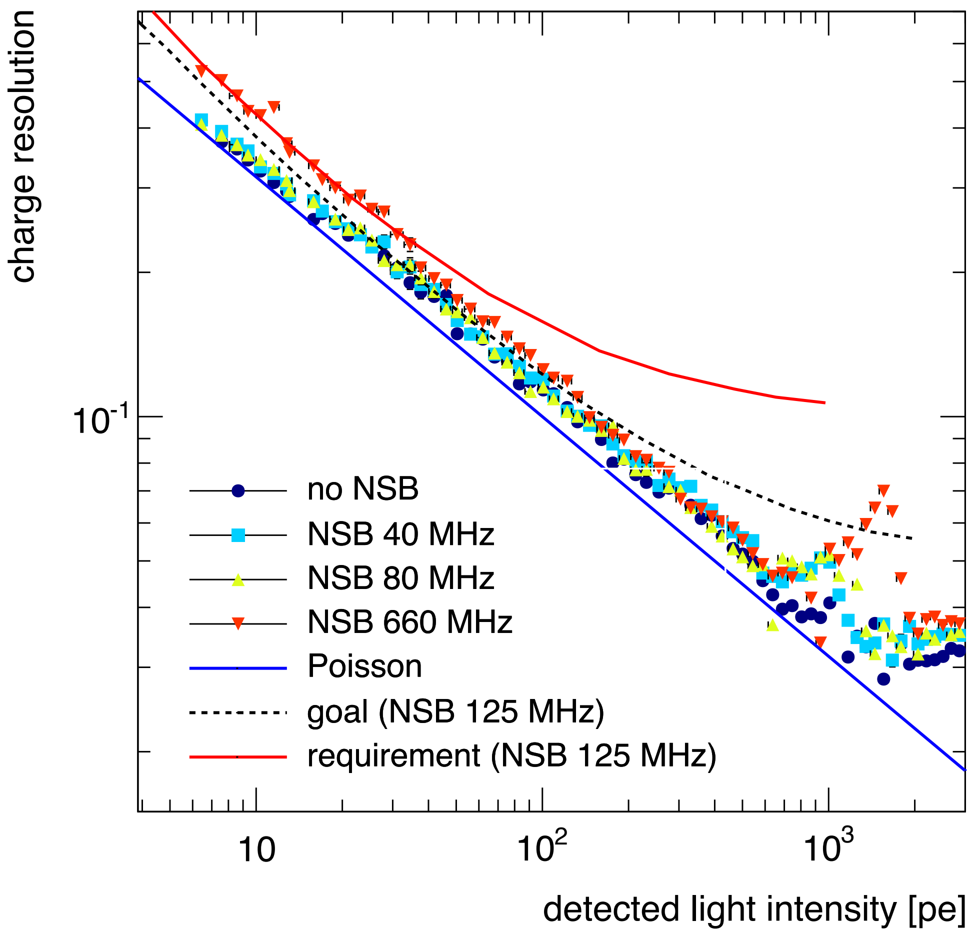
Linear
low light





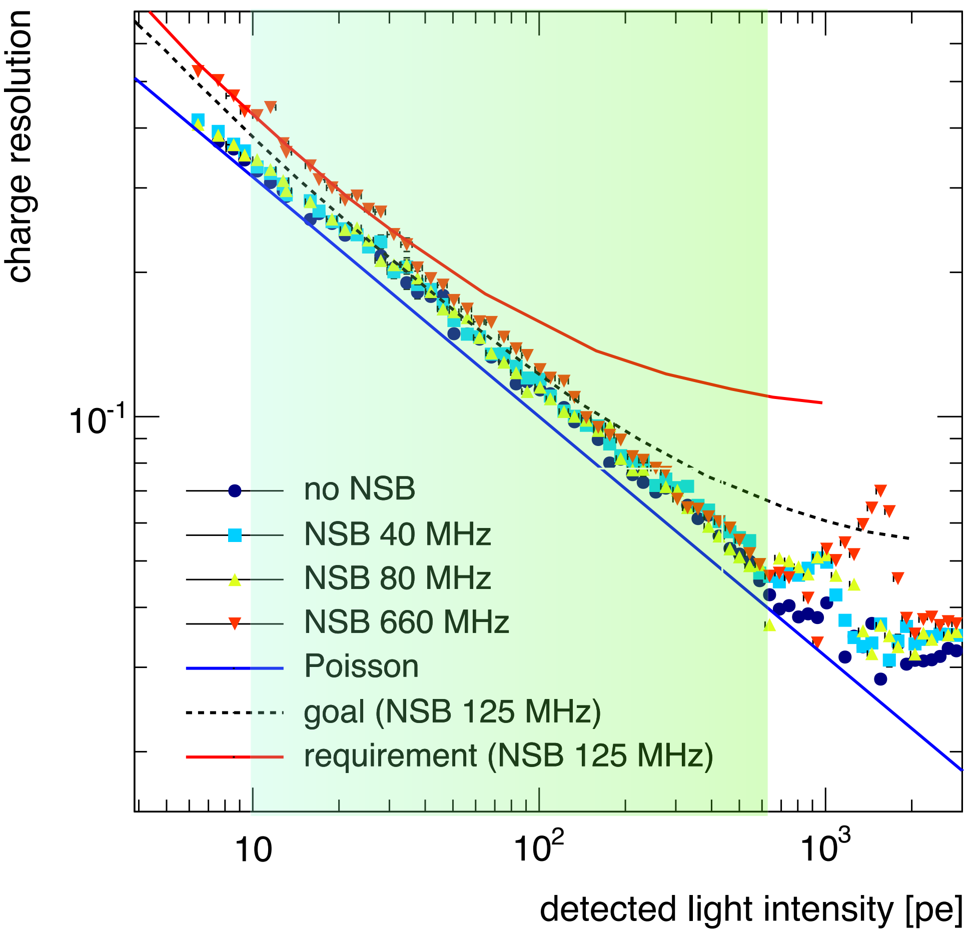
Performance

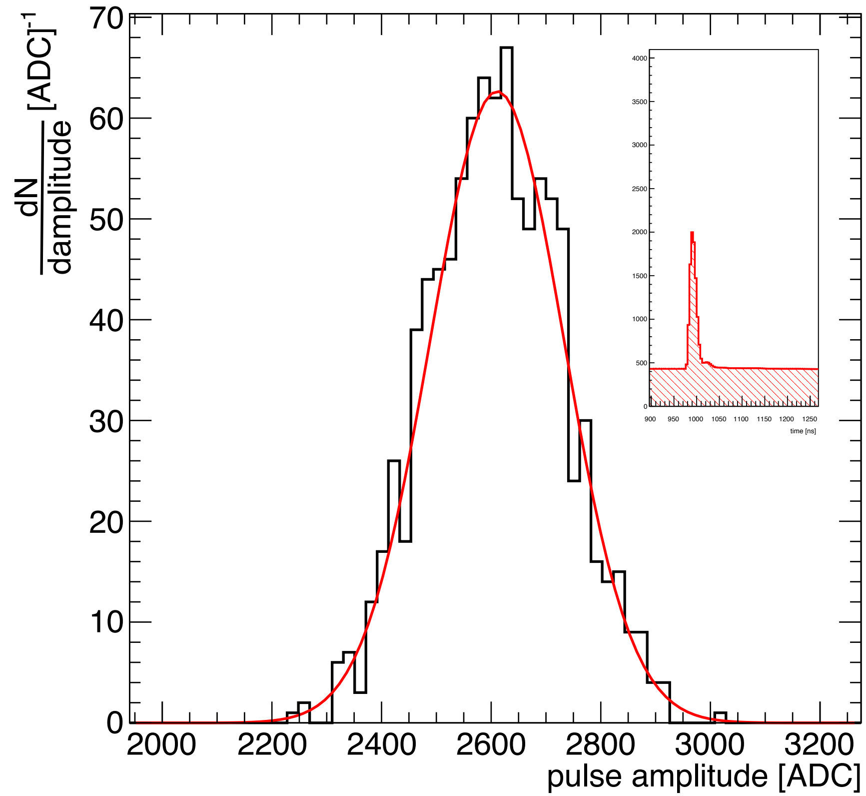
Linear
medium light



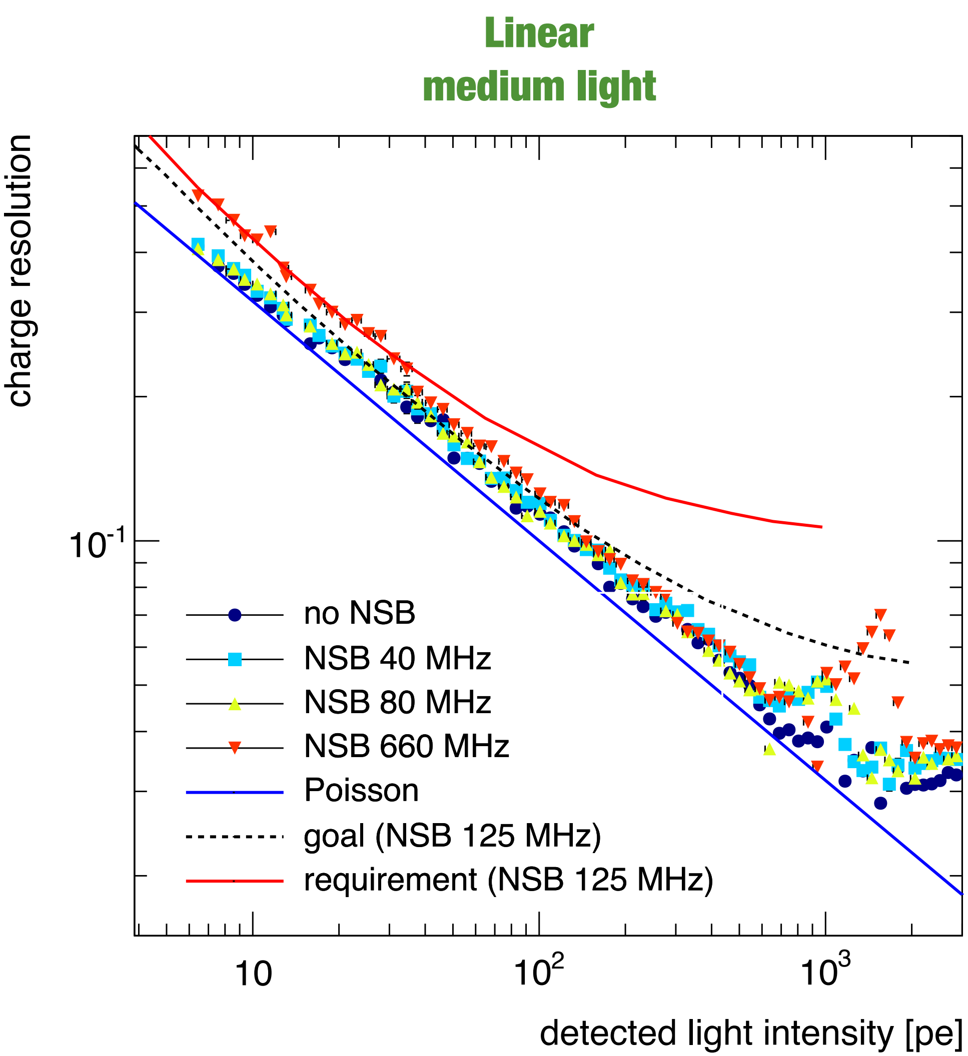
Performance

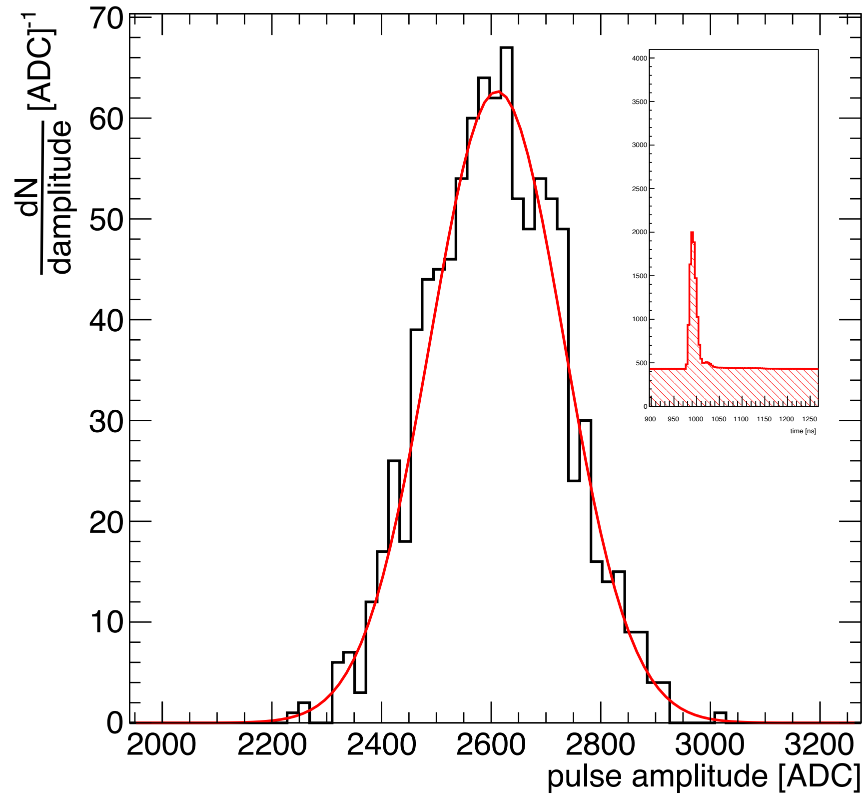
Linear
medium light



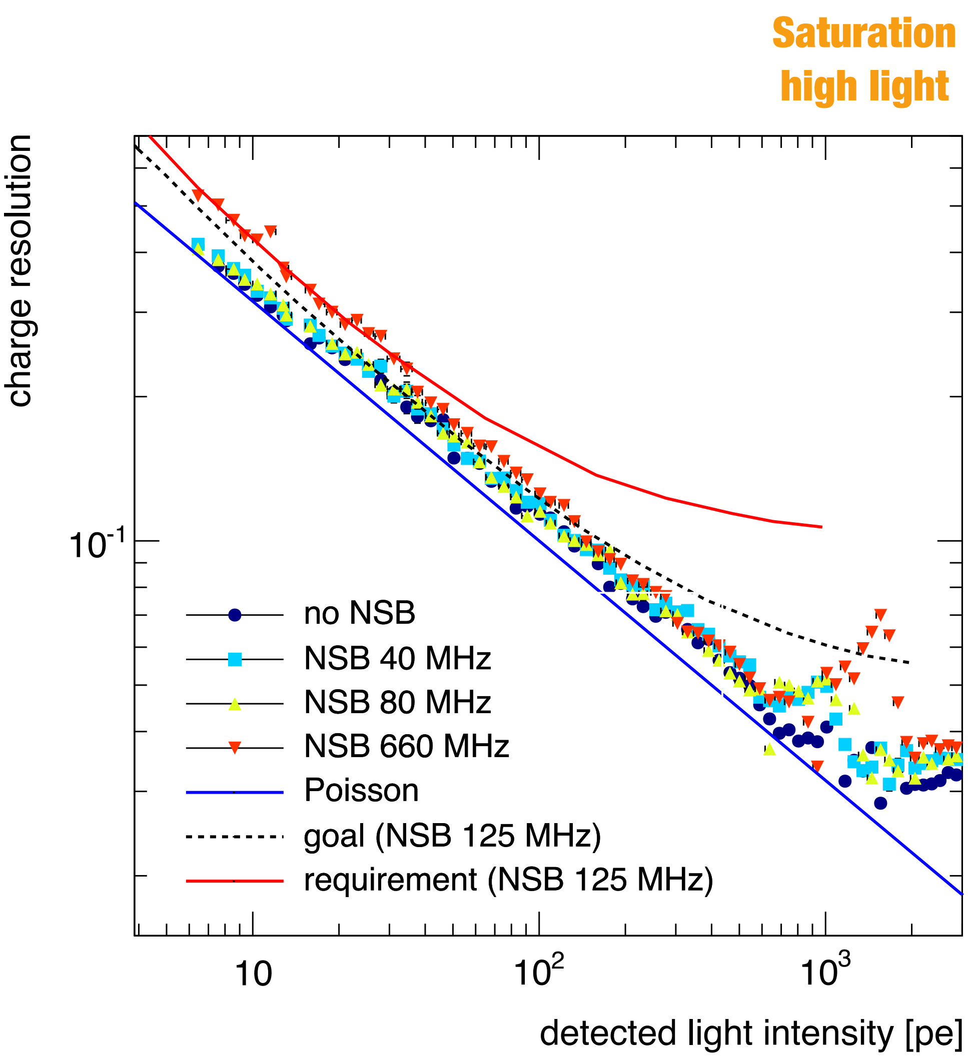


Performance

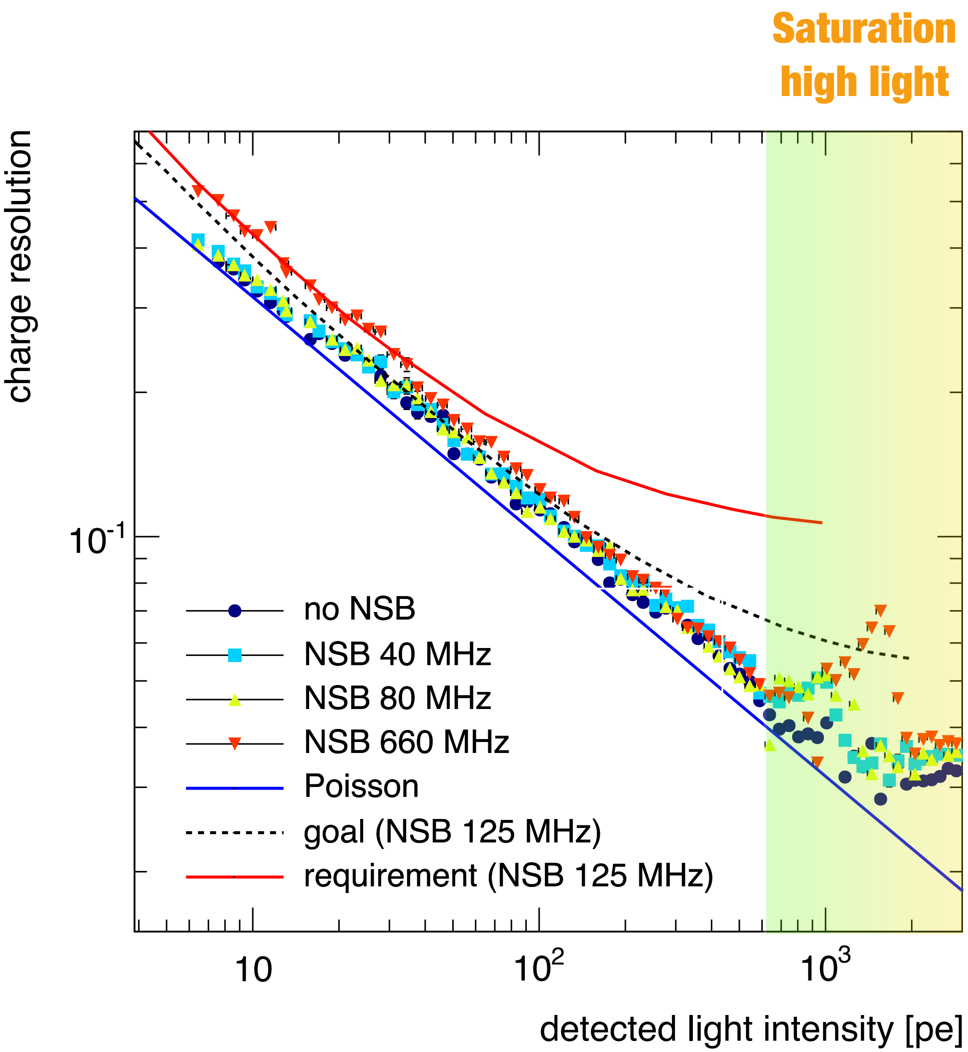


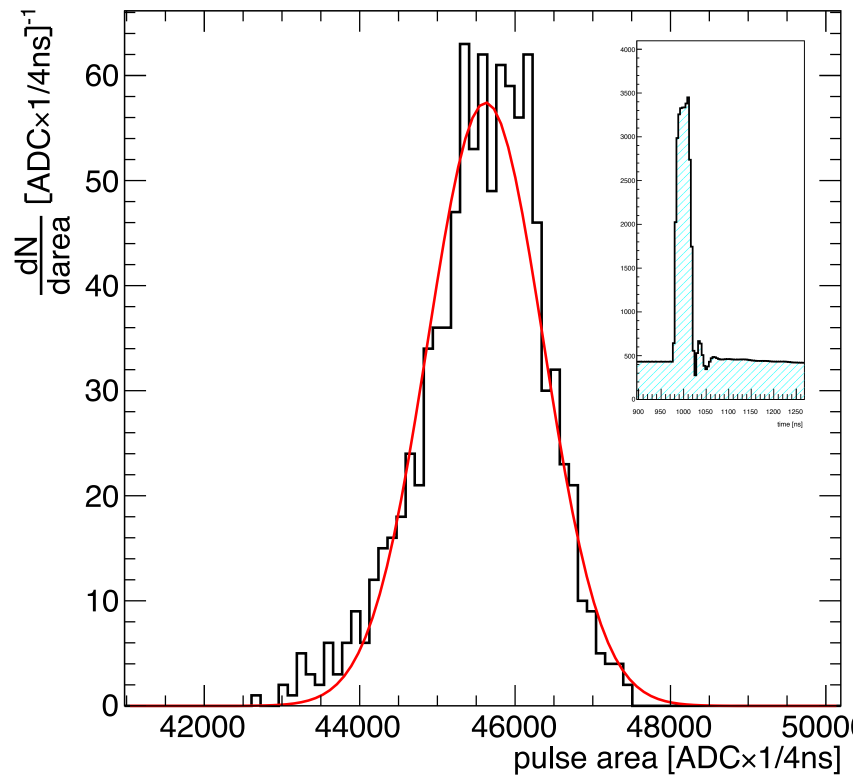


Performance



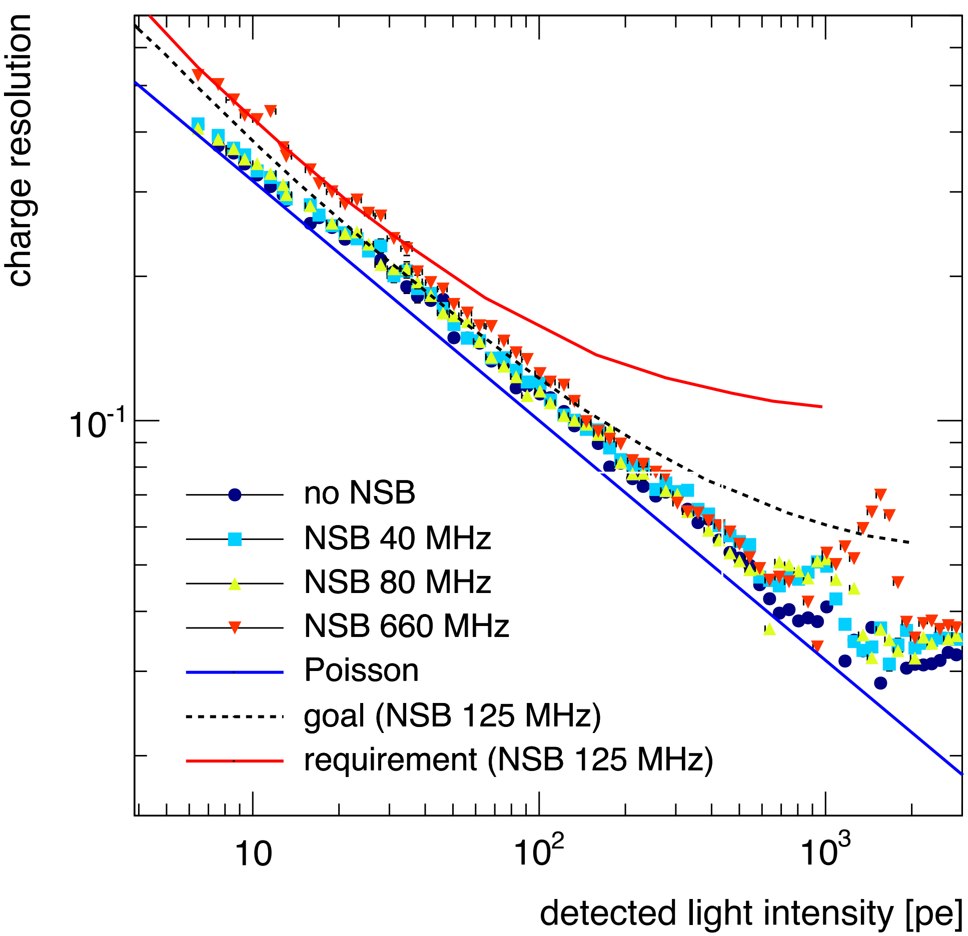
Performance

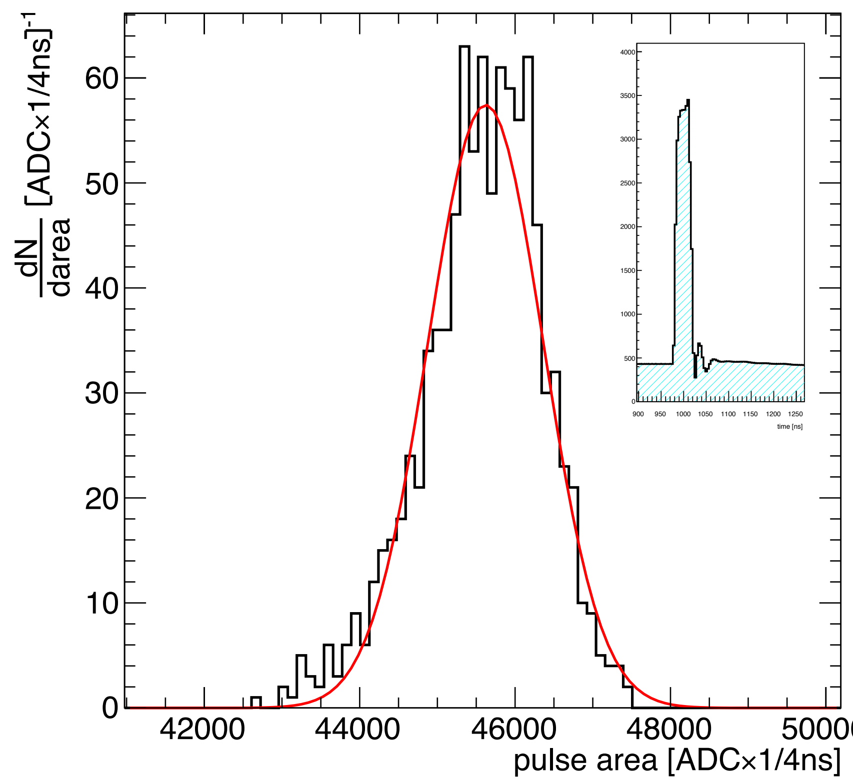




Performance

Saturation high light



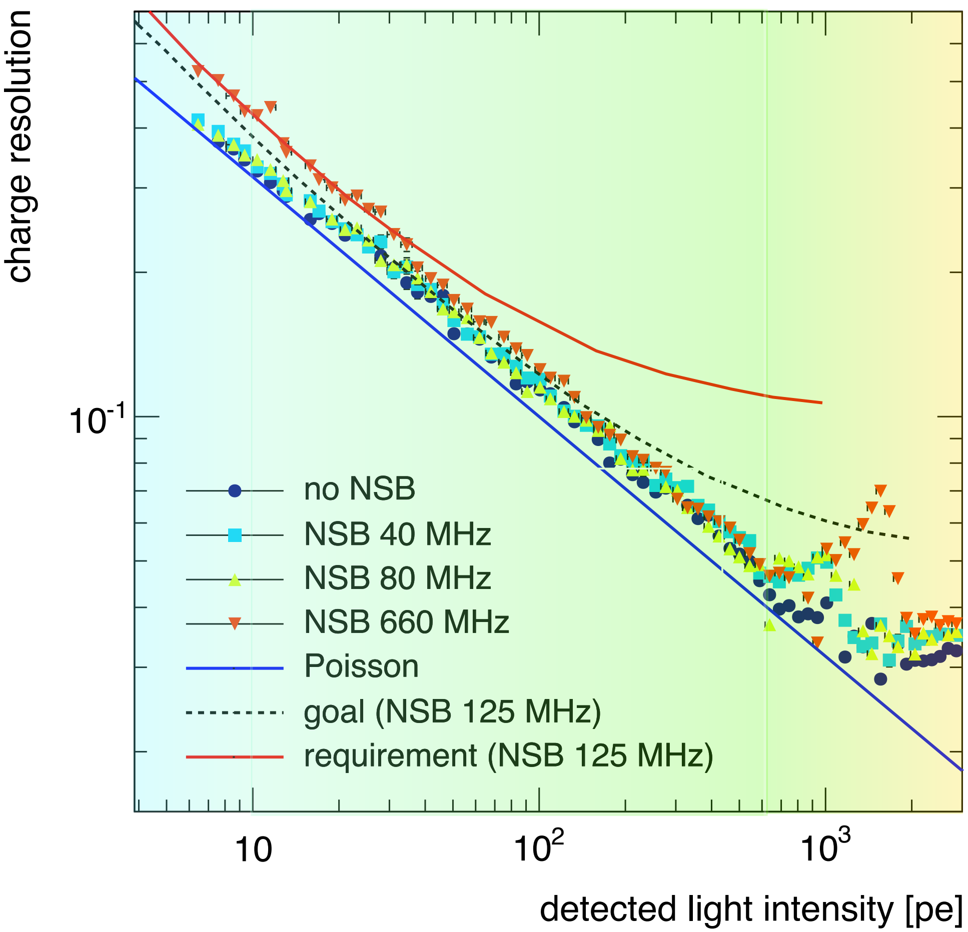


Performance

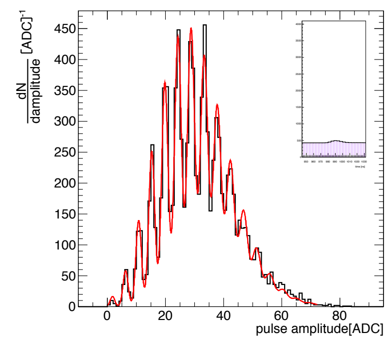
Linear
low light

Linear
medium light

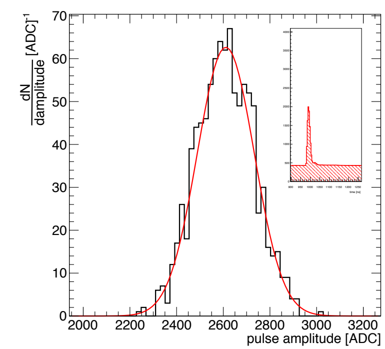
Saturation
high light



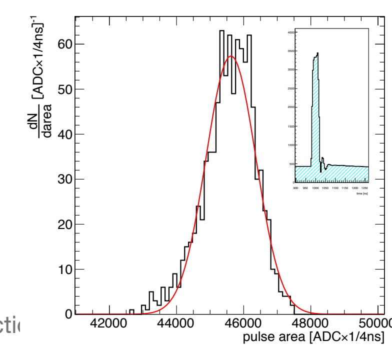
Linear
low light



Linear
medium light

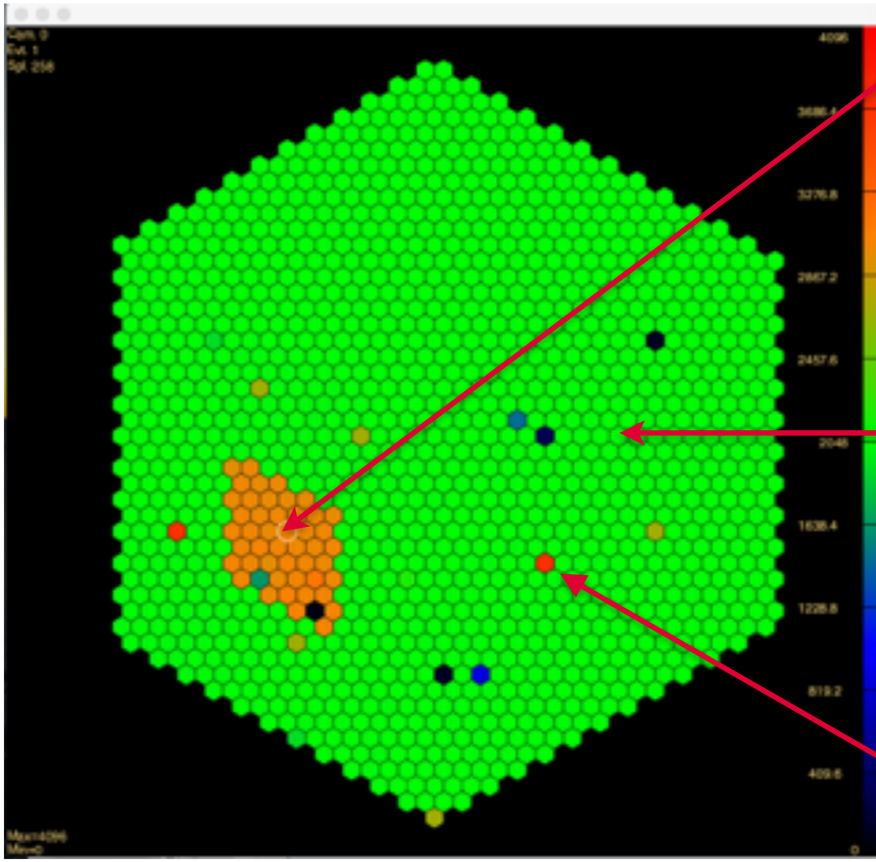


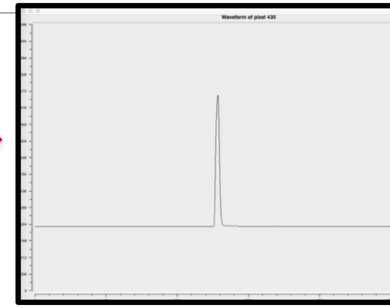
Saturation
high light



First operations of the camera

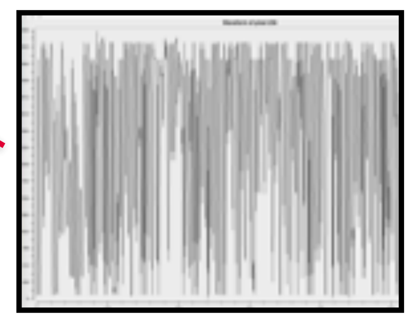
- Current Setup (See Vitalii's talk)





Normal pixel with injected signal

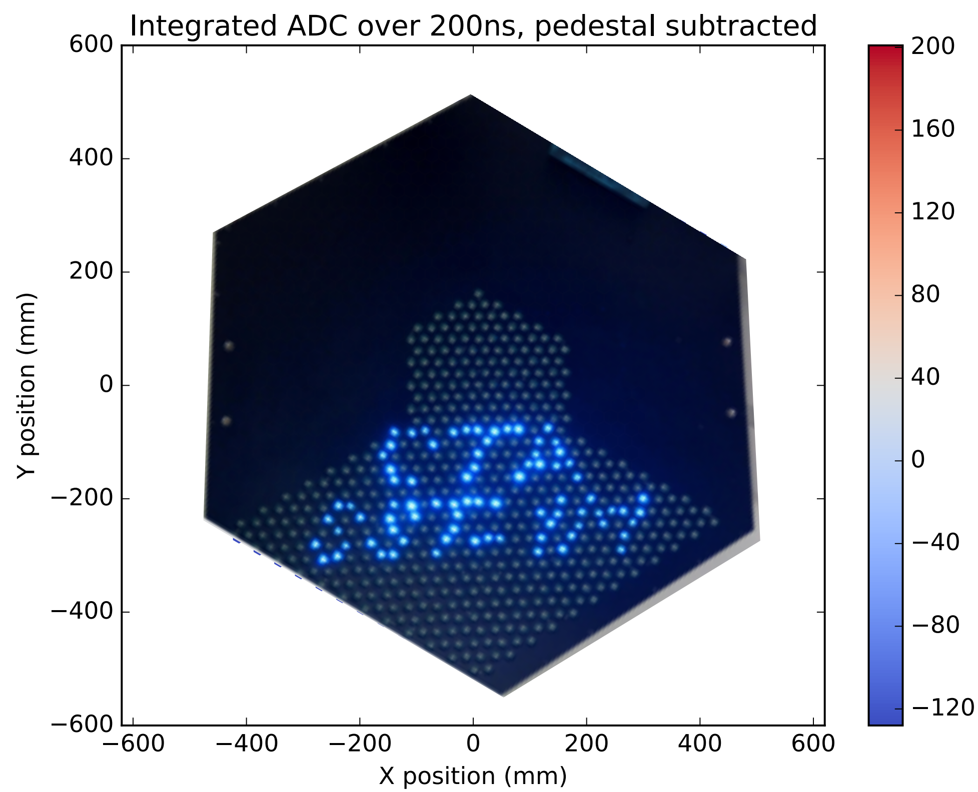
Normal pixel w/o signal



Unsynchronised pixel

First operations of the camera

- A camera test set-up has been realised.
- 1 sector (1/3 of the camera) + the centre of the camera can be tested at the same time
- For each pixel, 2 LEDs are present: one flashing (AC) to emulate Cherenkov flashes and one DC to emulate NSB.
- Cherenkov shower-like shapes can be produced to verify and validate trigger algs and efficiency
- The set-up is very flexible and allow to check the cabling/ mapping, the working pixels, the flat fielding, charge resolution for each individual pixel, calibrations, trigger algs



Pixels scan to check mapping and working pixels

First operations of the camera

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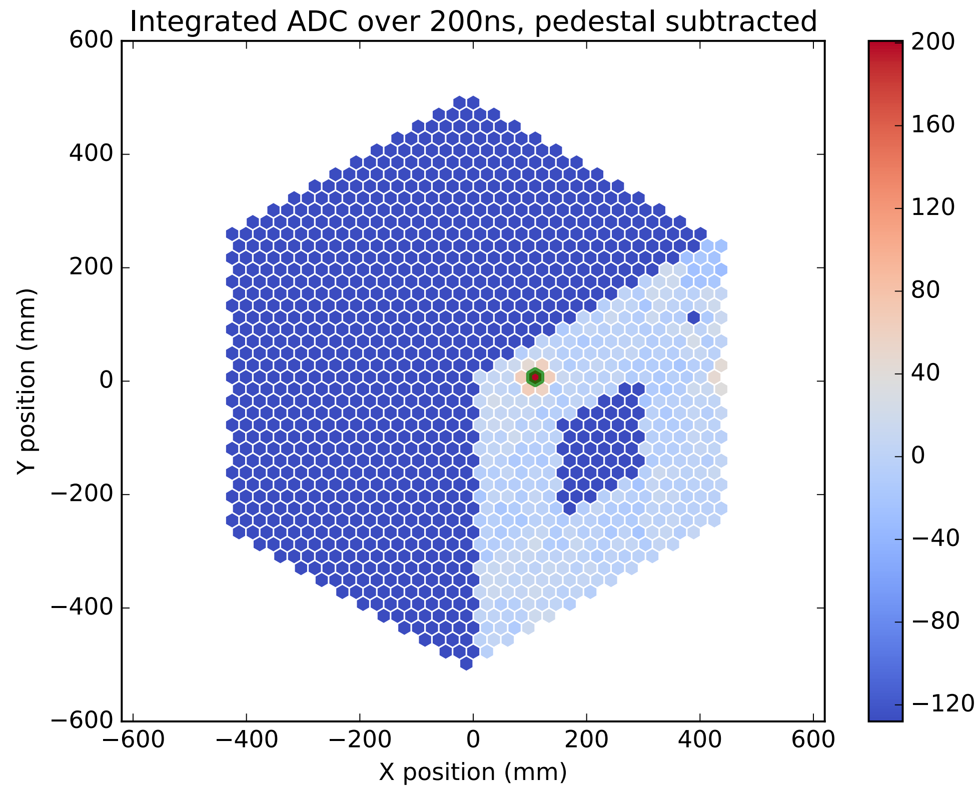
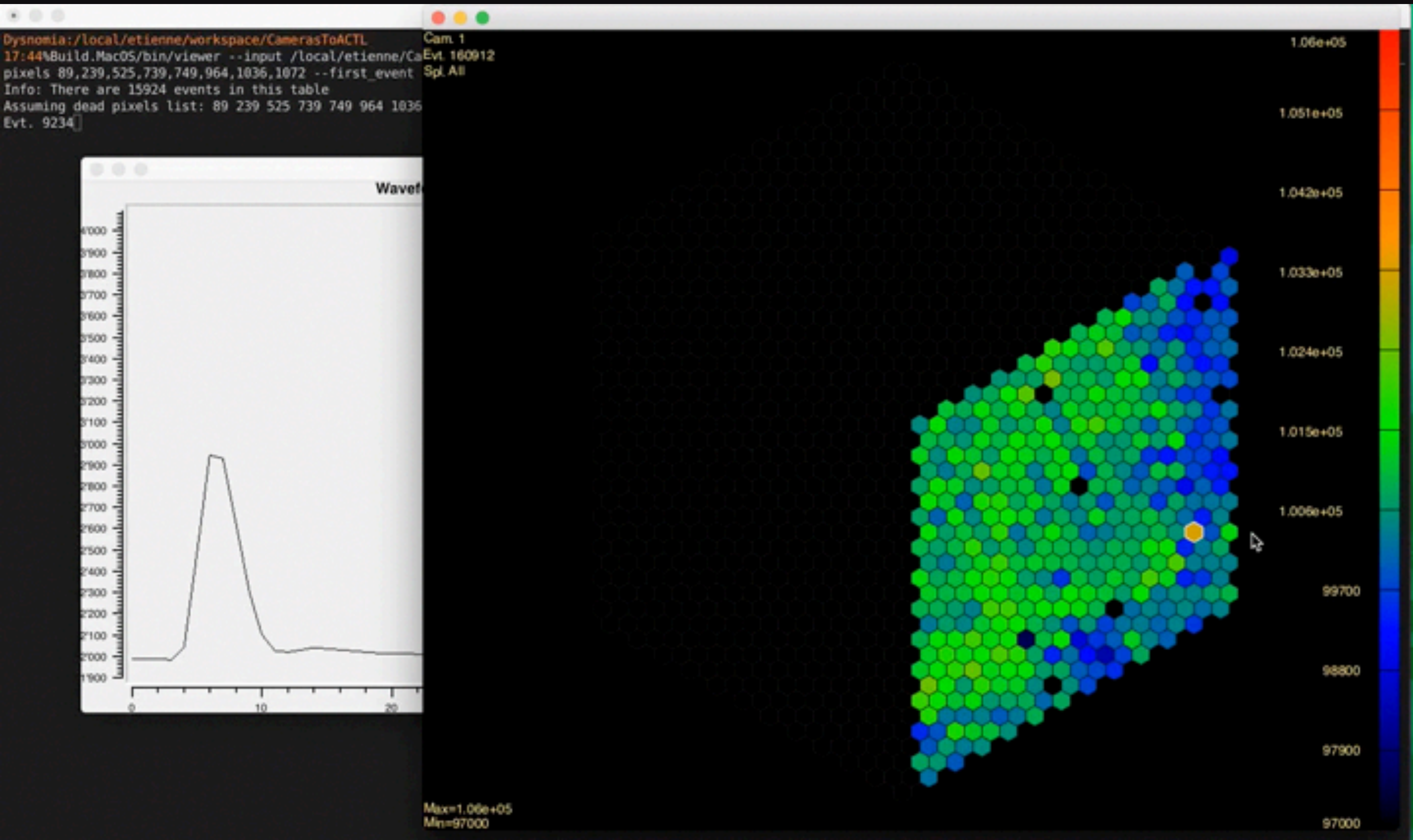


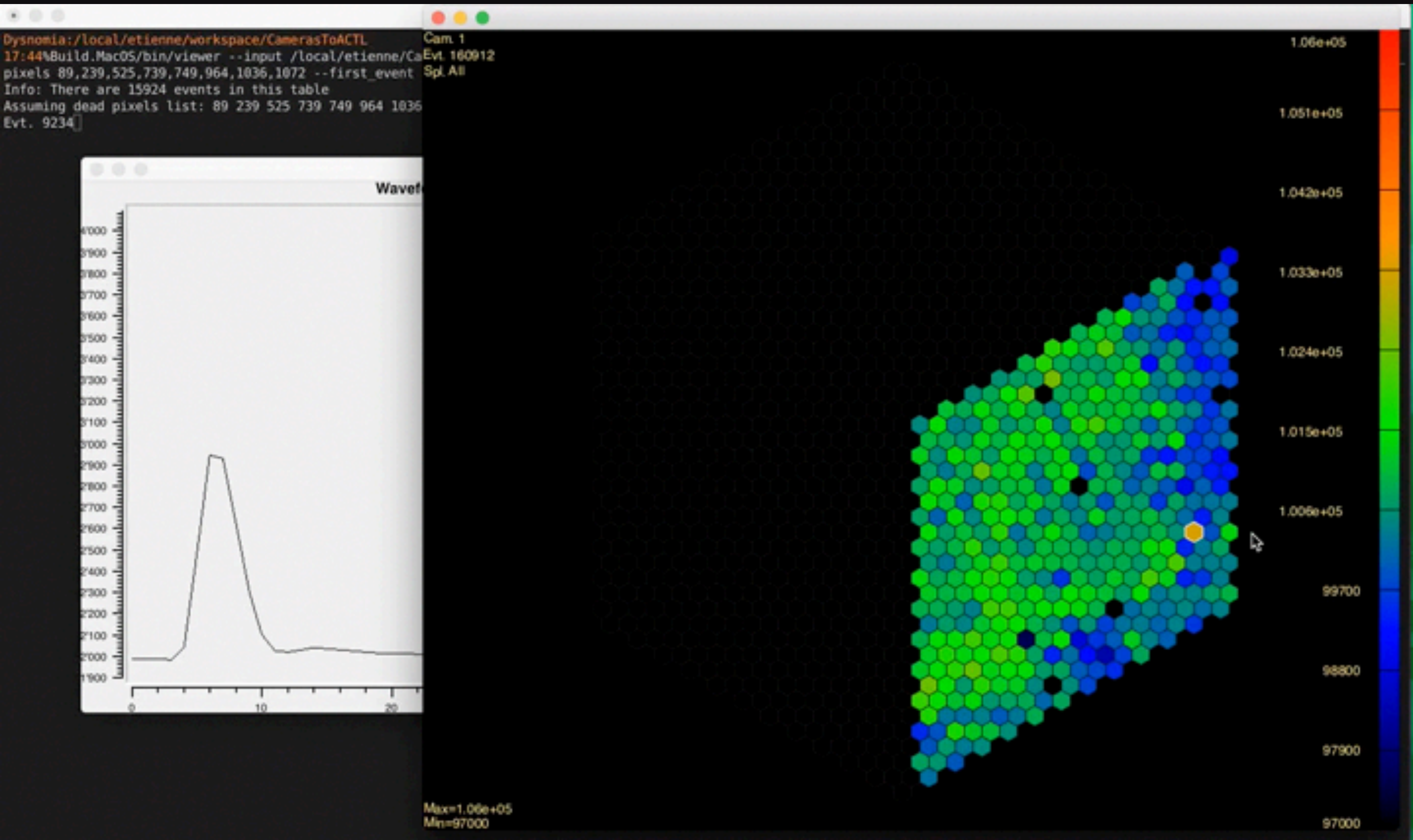
Pixels scan to check mapping and working pixels

Conclusions

- SiPM use is spreading in many fields given their advantages.
- SiPM are particularly fit for gamma-ray astronomy,
  - Operation during Moonlight ~ 30% larger duty cycle
  - No evidence of ageing
  - Lightweight and robust cameras
  - Excellent single PE sensitivity
  - High Photo-Detection Efficiency at ~ 40%
- SST-1M camera goes in this direction but tried to open a new road towards large area devices.
  - Custom designed hexagonal device in collaboration with Hamamatsu
  - Large Area devices are complicated to handle but can be done!
- Many Lessons learned
  - SiPM parameter spread verified and validated
  - Large capacitance can be mastered
- The camera is under test . Very soon result on the field with real data…. stay tuned
- The solution worked out for CTA can be exploit without major modification both in larger CTA telescope and LHAASO WFCTA.
- Now under evaluation last generation of FBK sensor to see if they can work in our approach at room temperature.



Looking for seeing real shower!!!



Looking for seeing real shower!!!