ATLAS Pixel Detector Commissioning using Cosmic Rays

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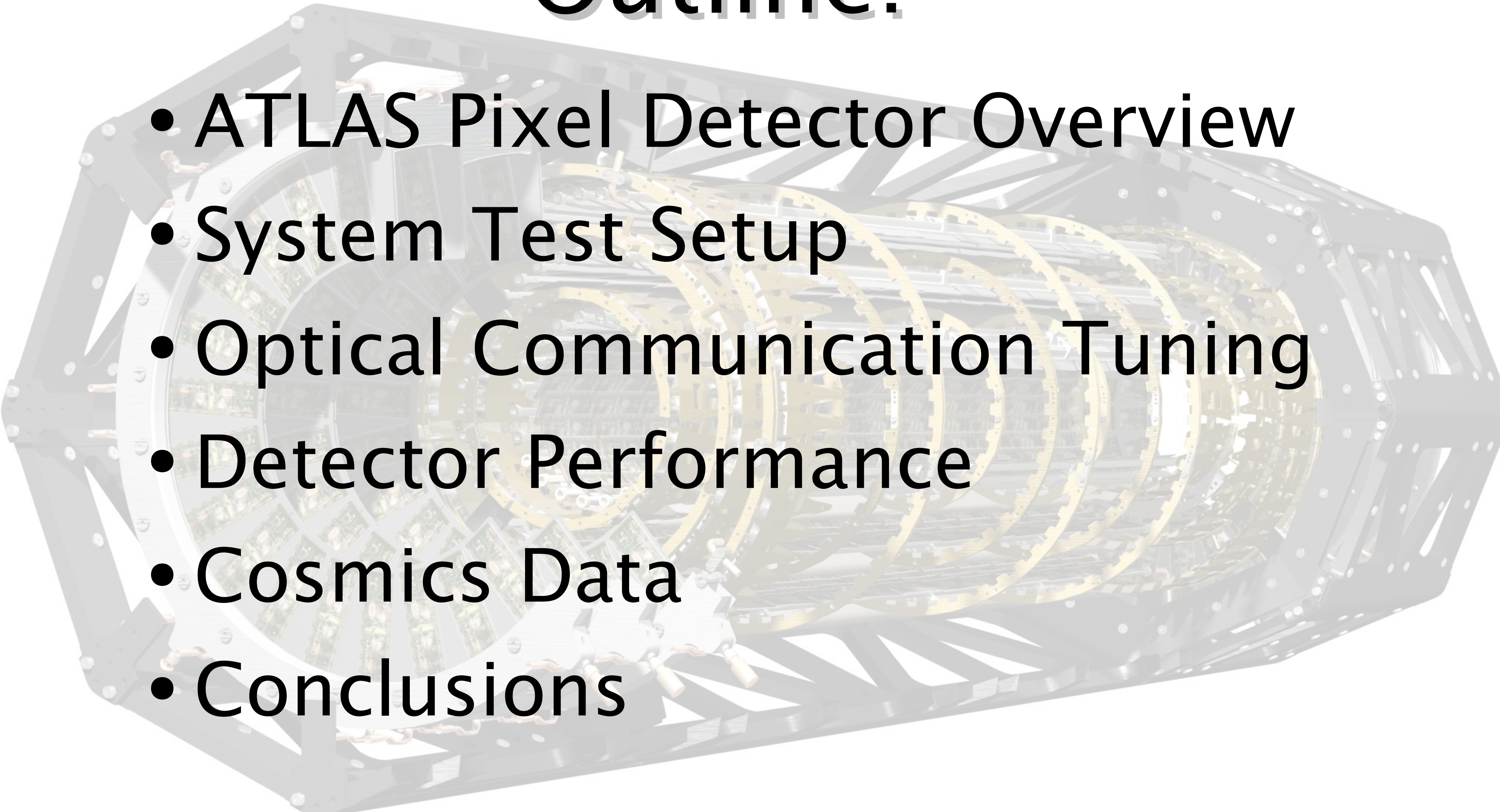
Vertex 2007 – Lake Placid, NY, USA – 23.-28. September 2007

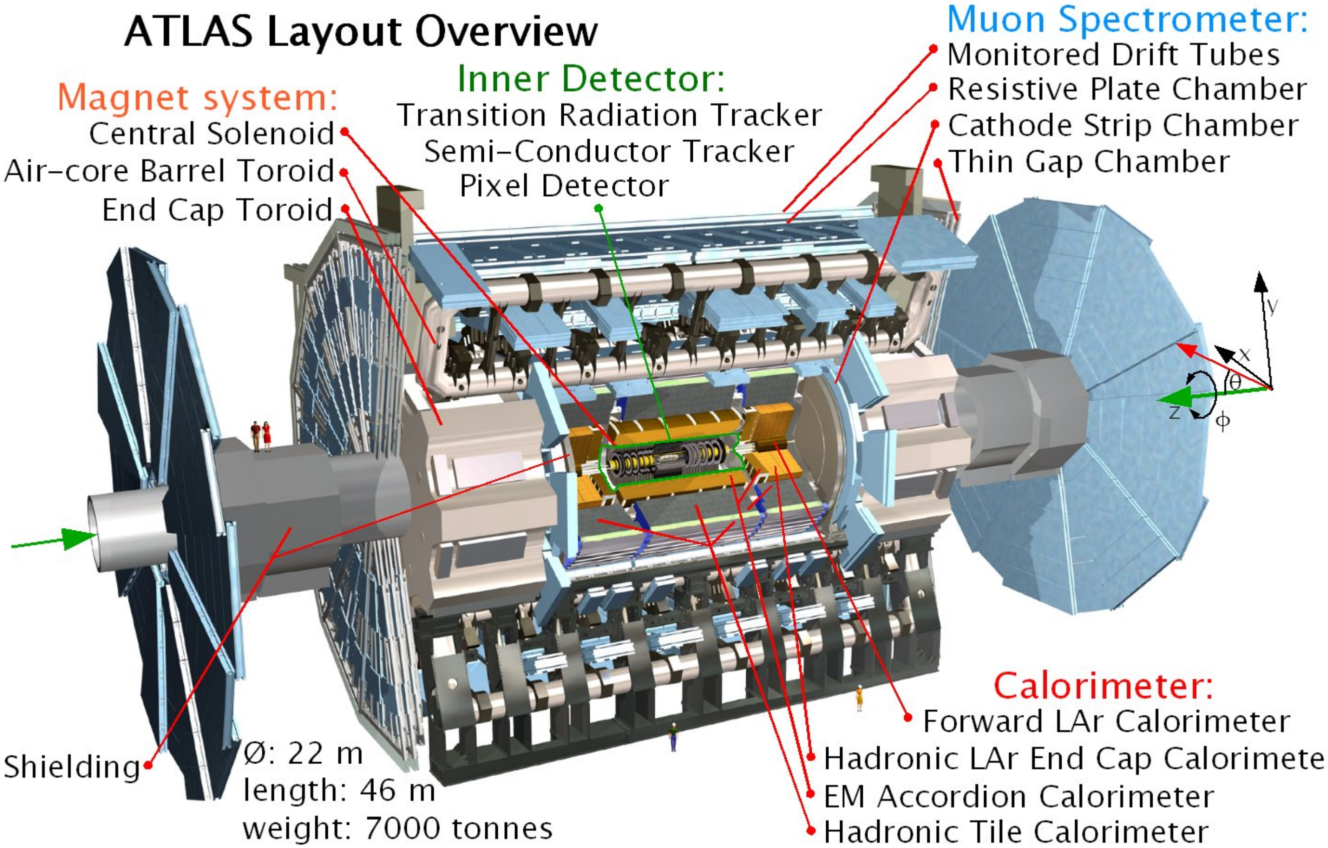
Outline:



- ATLAS Pixel Detector Overview
- System Test Setup
- Optical Communication Tuning
- Detector Performance
- Cosmics Data
- Conclusions

ATLAS Pixel Detector

- high multiplicity tracking detector; ~ 1200 tracks per bunch crossing
  ⇒ high granularity (80 million channels)
- high impact parameter resolution; ~ 12 µm vertex resolution
  ⇒ high granularity, low mass
- high radiation dose tolerance; $\sim 10^{15} n_{eq}/cm^2$ (NIEL) or 50 Mrad
  ⇒ low temp. & radiation-hard design tubes, ...)



- high time resolution; 40 MHz bunch crossing rate
  ⇒ fast preamplifier rise time
- high occupancy/long trigger decision; 2 µs Level1 trigger latency
  ⇒ buffering of hits on-detector
- low interaction length; ~10% X_0 (~0.7% per Module)
  ⇒ low mass (thinned readout electronics, carbon-carbon support structure, aluminum cables and cooling tubes, ...)

Pixel Detector Design Requirements

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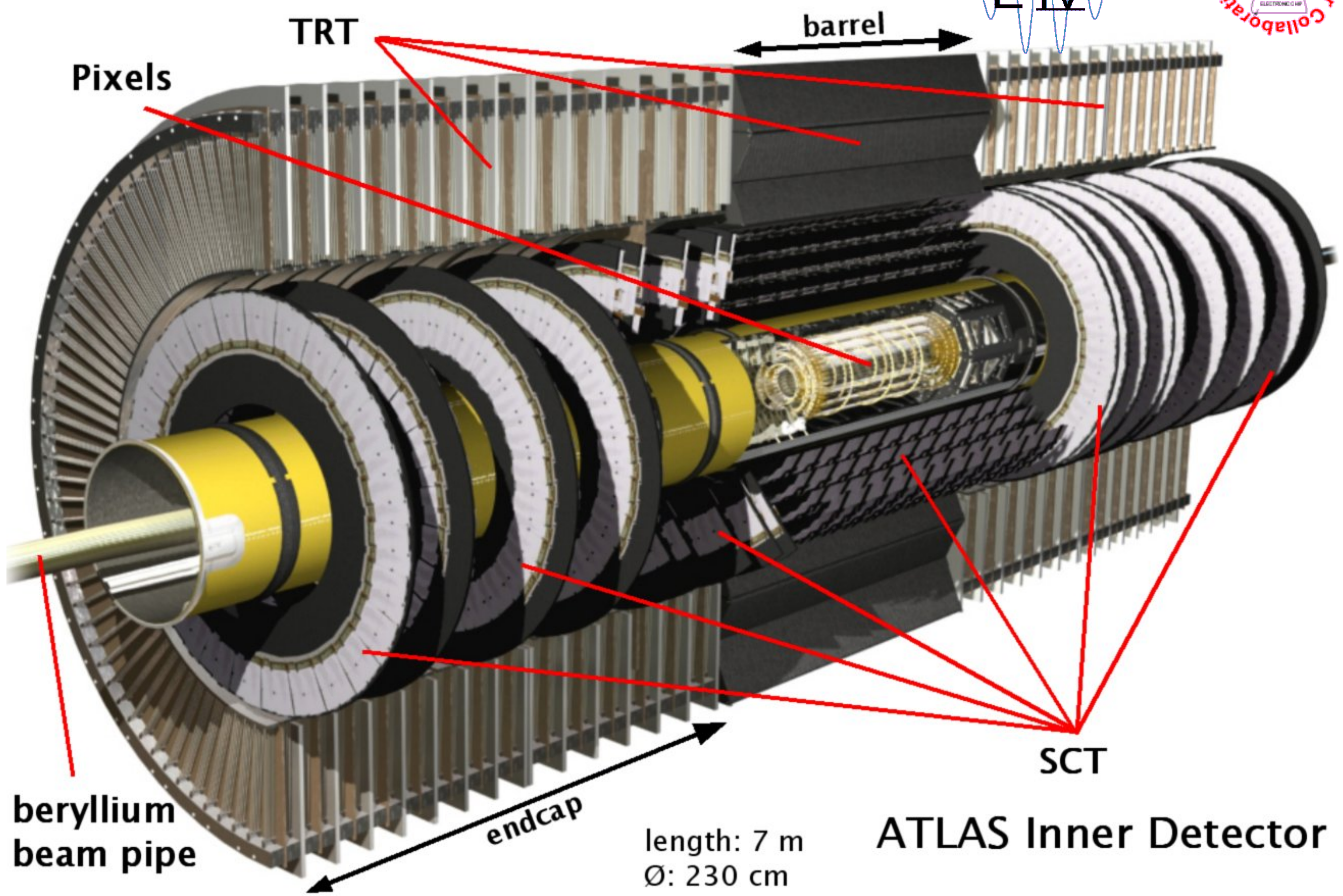

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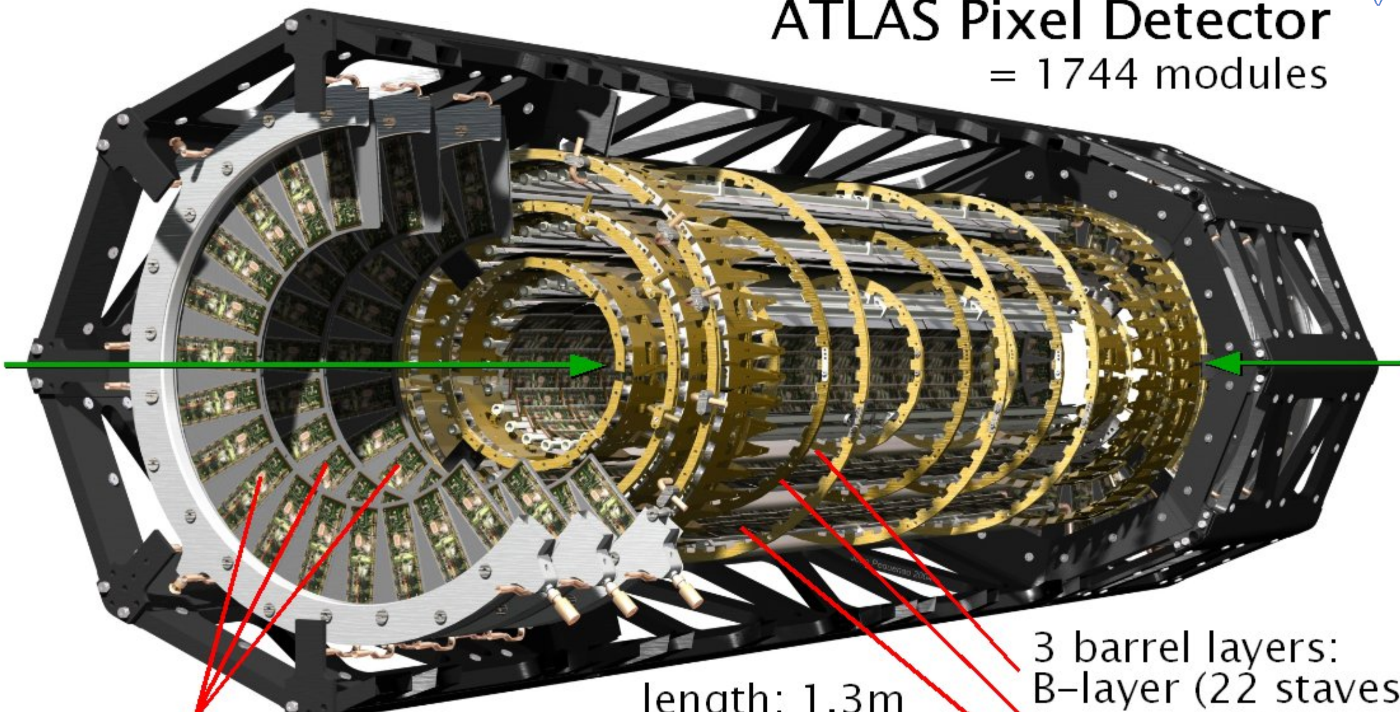
Pixel Detector Design

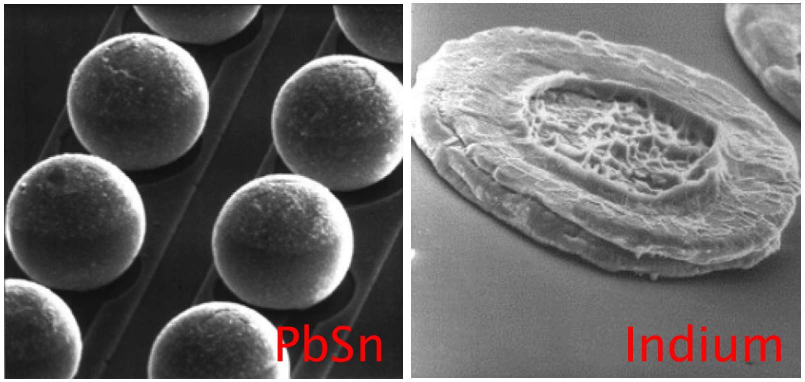


- 3 Barrel layers (r = 5, 9, 12 cm)
- 2 Endcaps with 3 Disks each
- 3 space points for pseudorapidity < 2.5
- 80 million channels in 1744 Pixel Modules
- 1.8 m^2 active sensor area
- ~ −10°C operating temperature with ~10 kW power load ⇒ evaporative C_3F_8 cooling integrated into carbon support structure

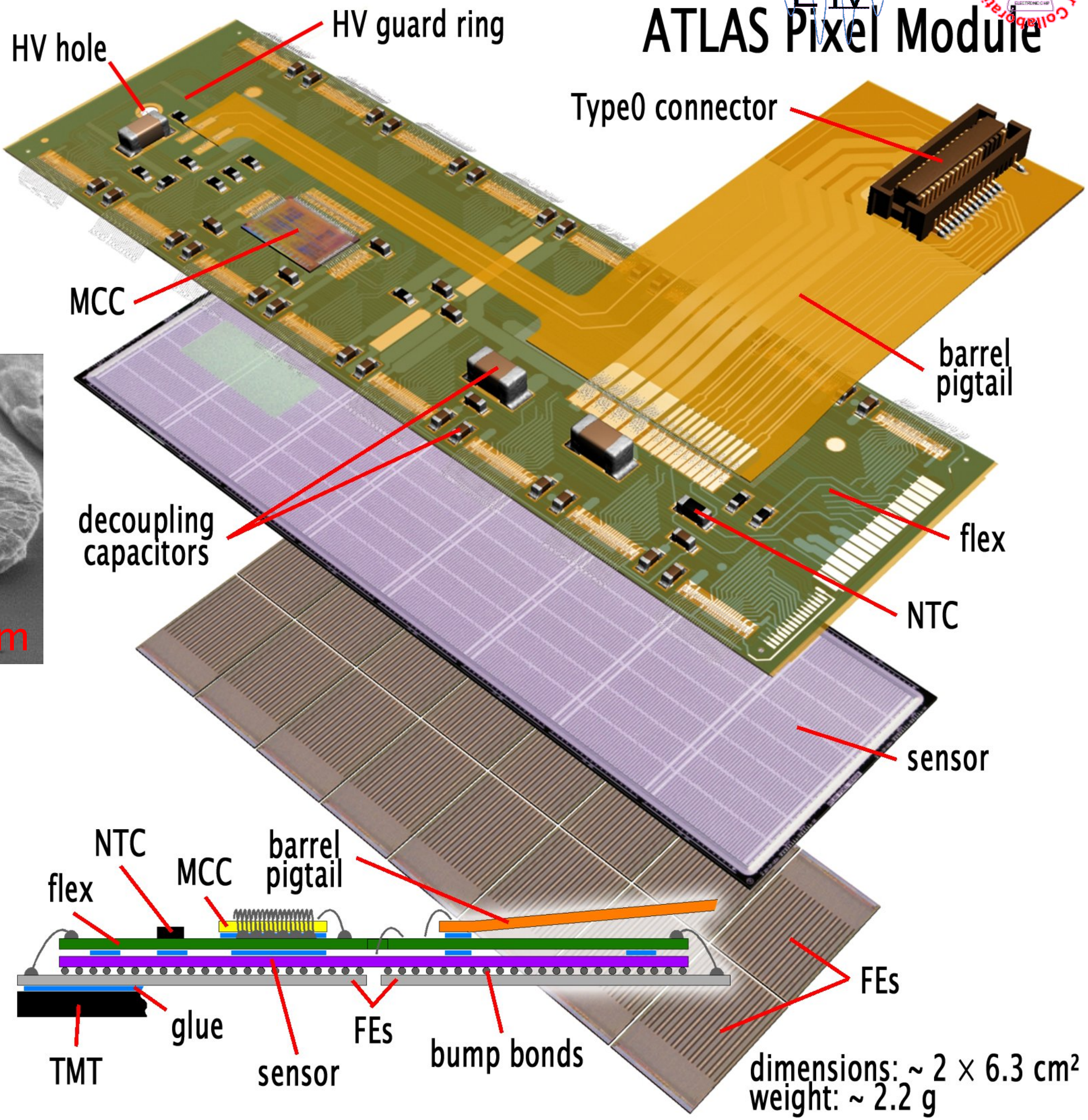
1st large scale active pixel detector (soon) in operation

ATLAS Pixel Module

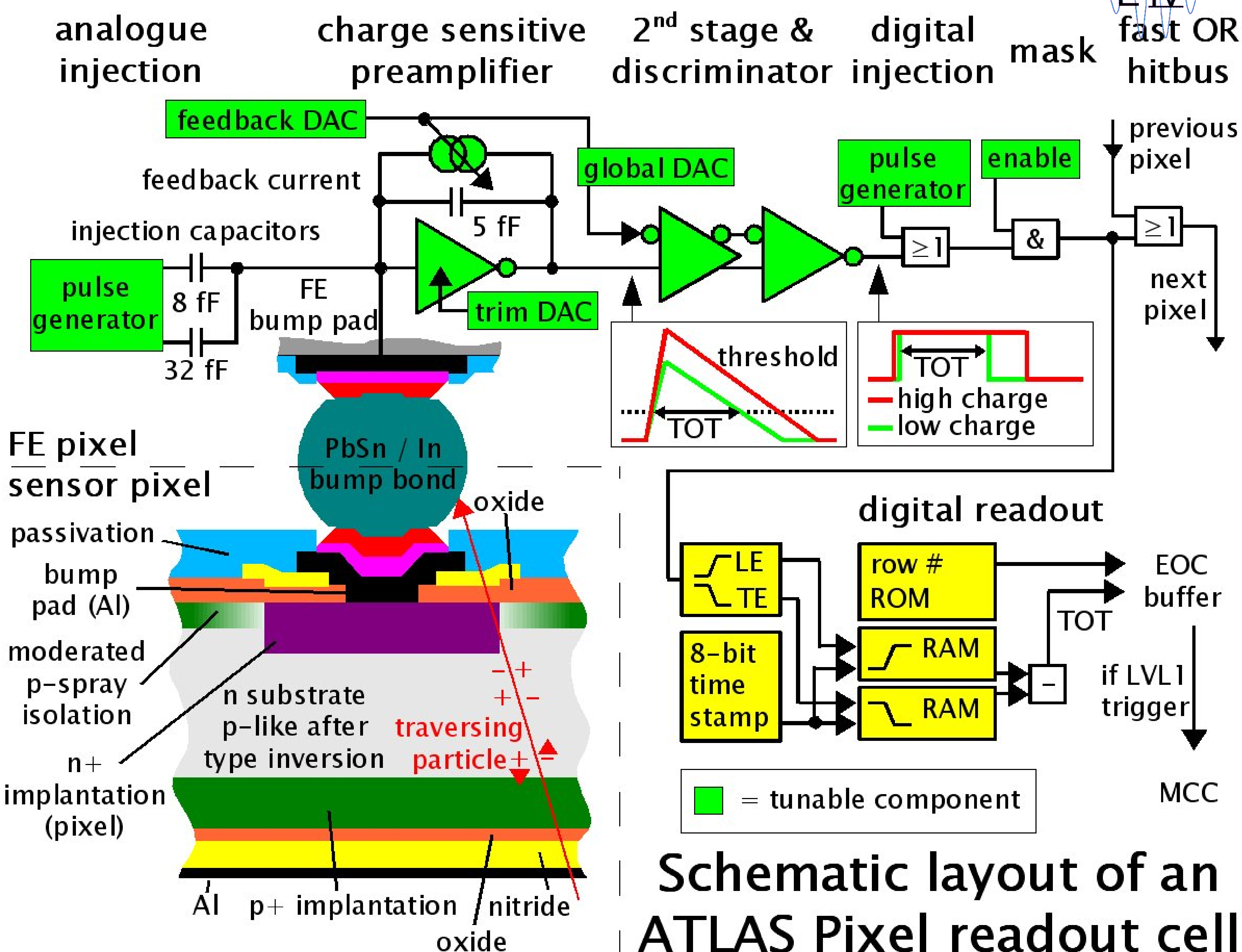
- ~ 47k pixels (50 × 400 μm) on $n^{+}np^{+}$ silicon sensor
- 16 Front-End (FE) chips connected with bump bonds (flip chipping) with the Pixel sensor



- FEs connected with wire bonds to a flexible circuit board (flex: routing and passive components)
- readout of the FEs by a Module Control Chip (MCC) ⇒ module based event building



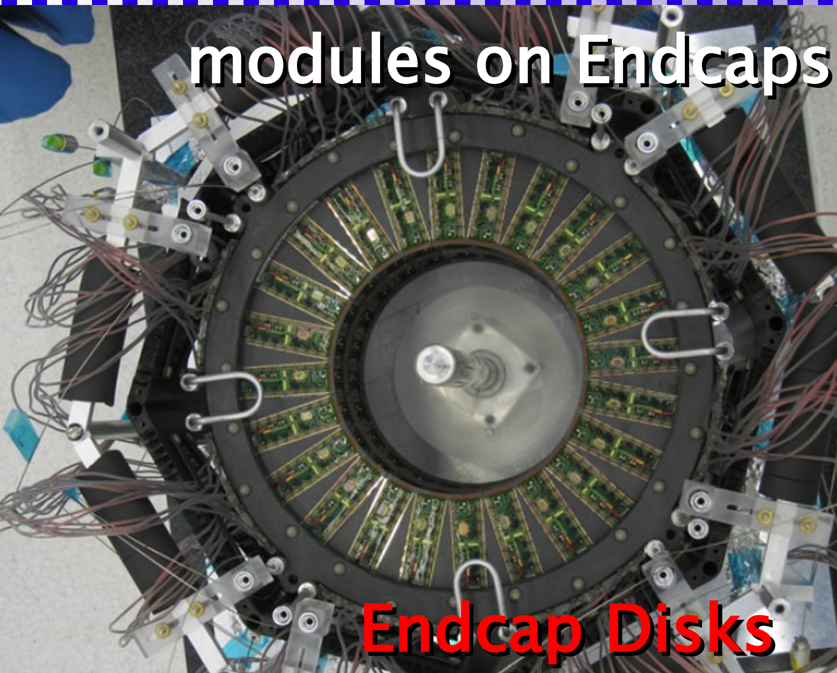
FE pixel schematic

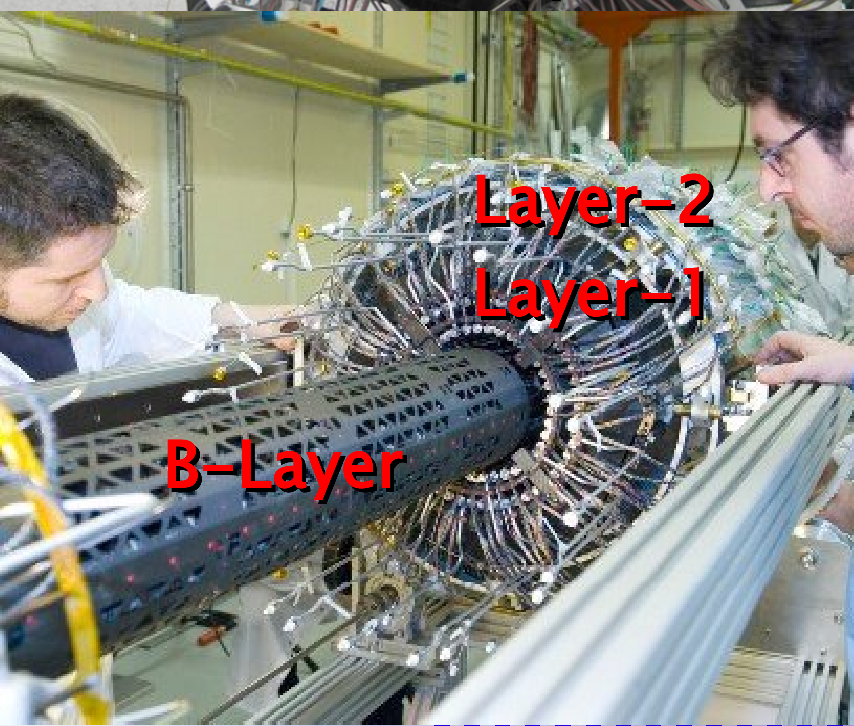


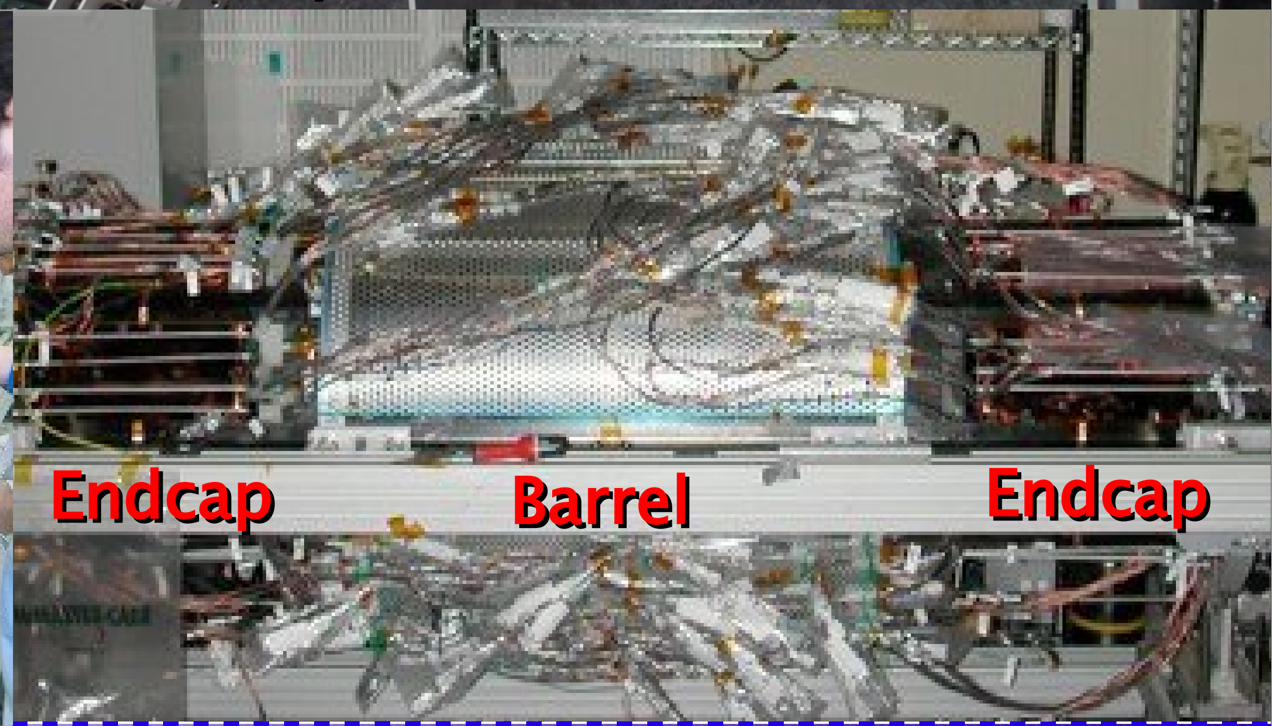
Schematic layout of an ATLAS Pixel readout cell

Pixel Detector Integration

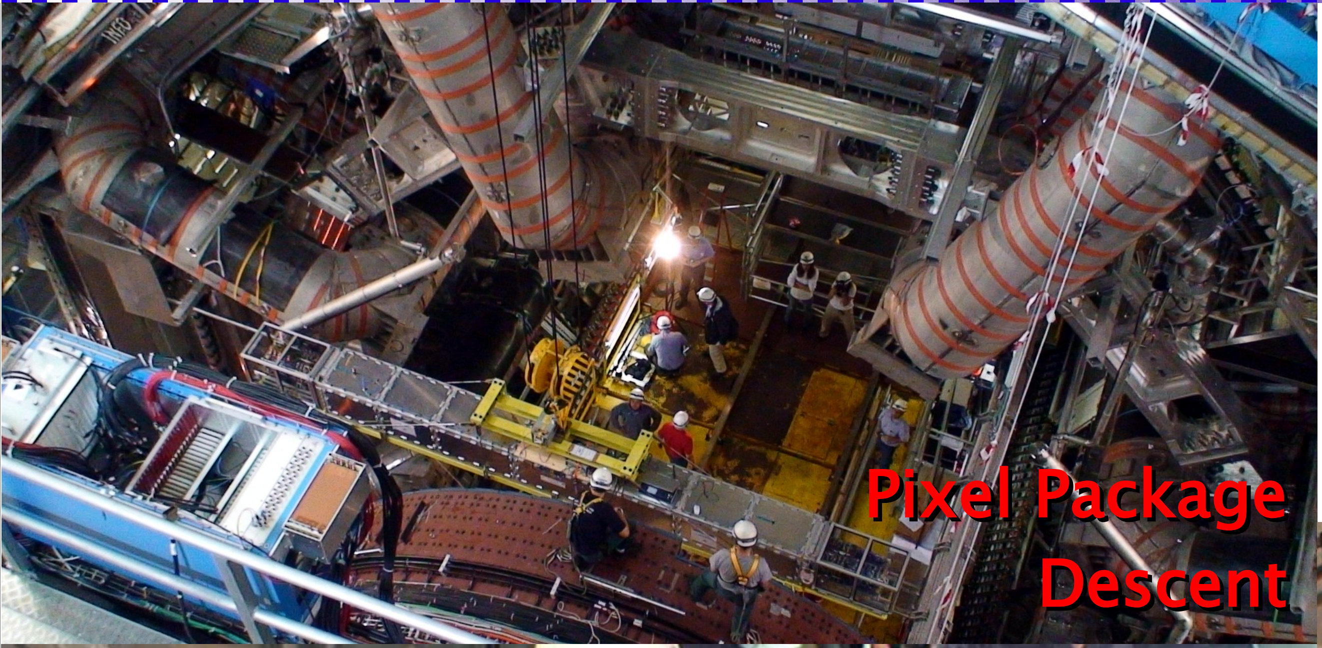
modules on Endcaps and Barrel are identical



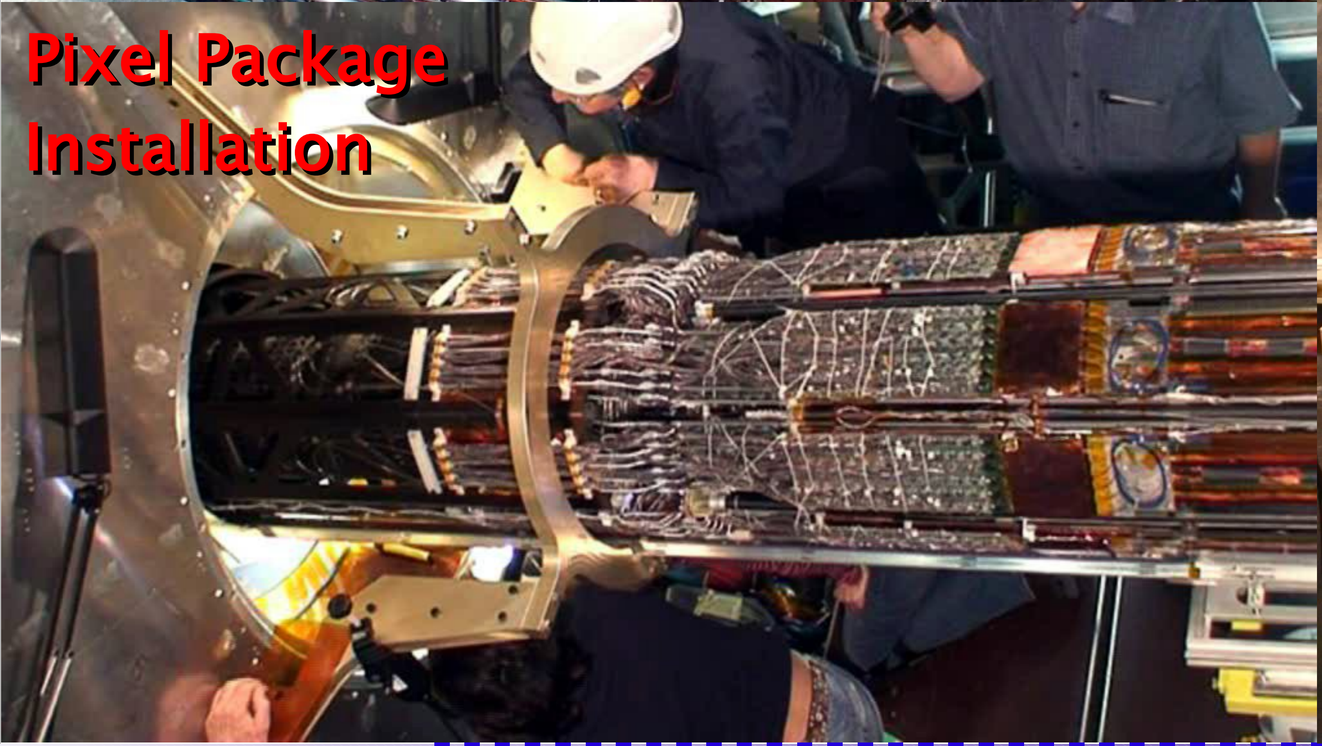


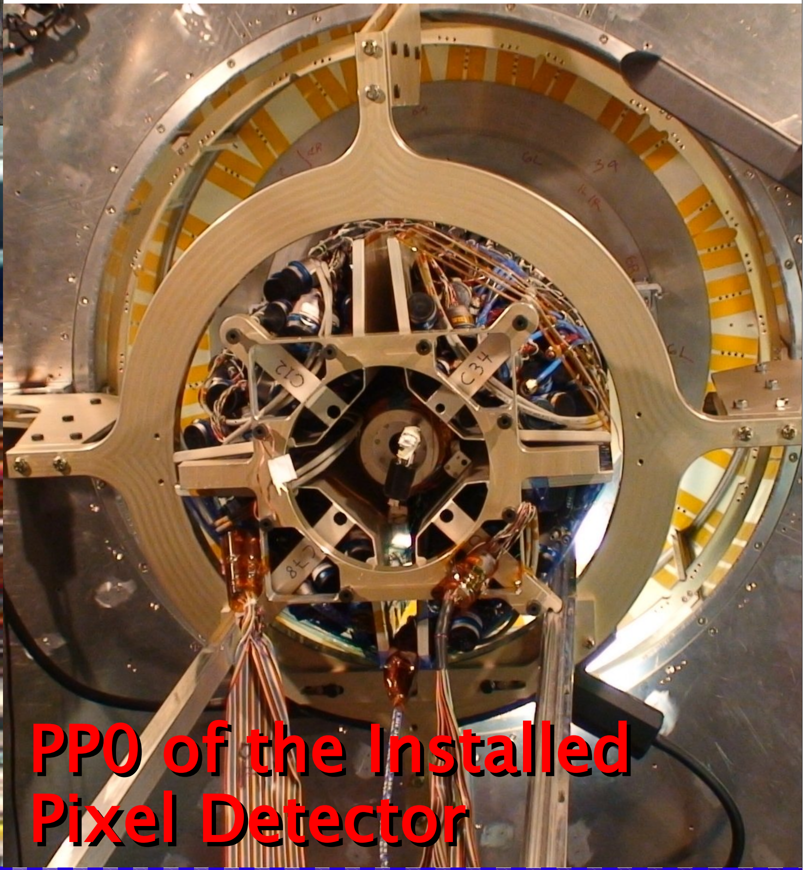


Pixel Detector Installation



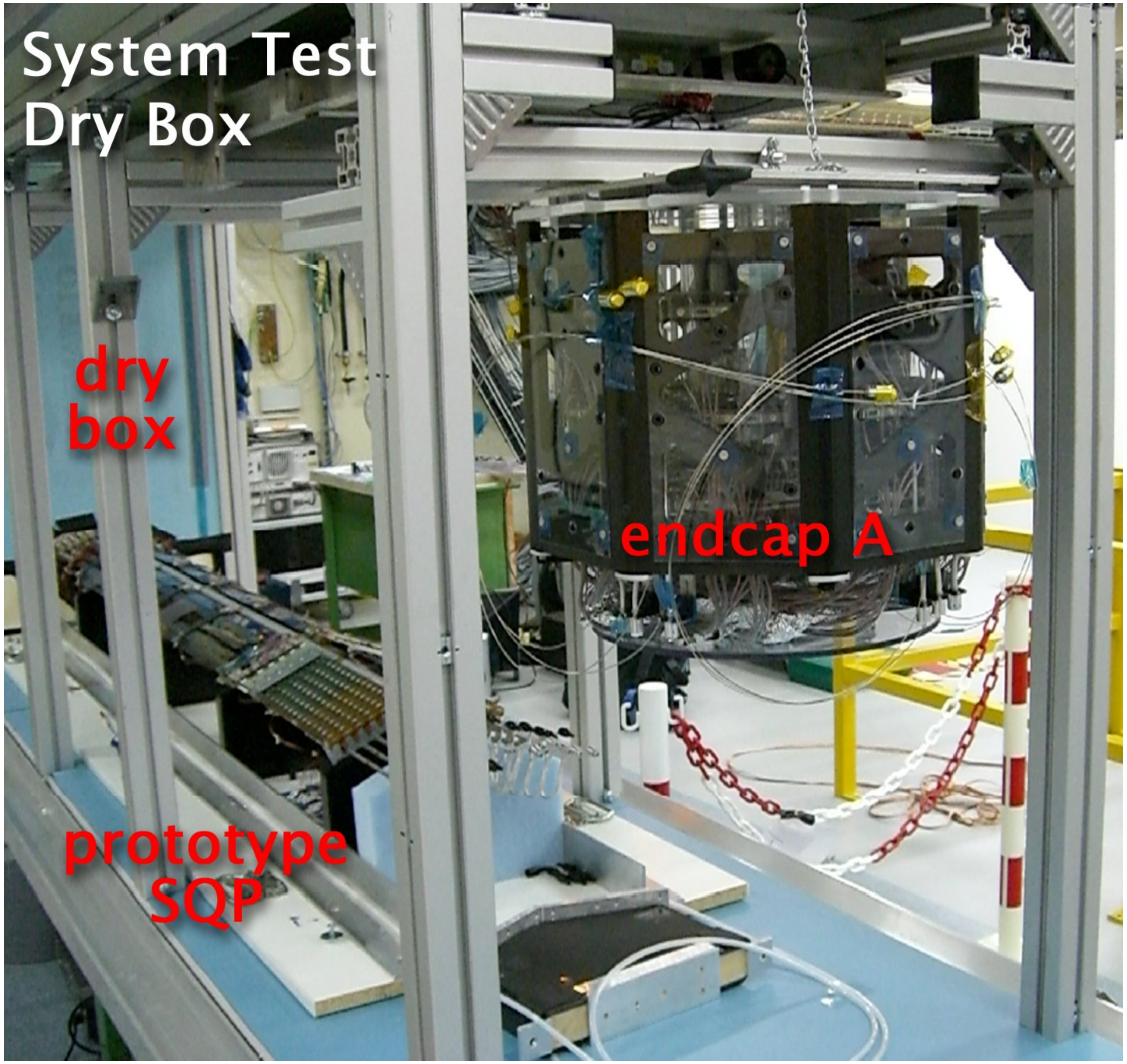
- Pixel Detector Package (detector with service quarter panels) lowered and installed in late June
- next step: cabling of service cables and fibers at PP0



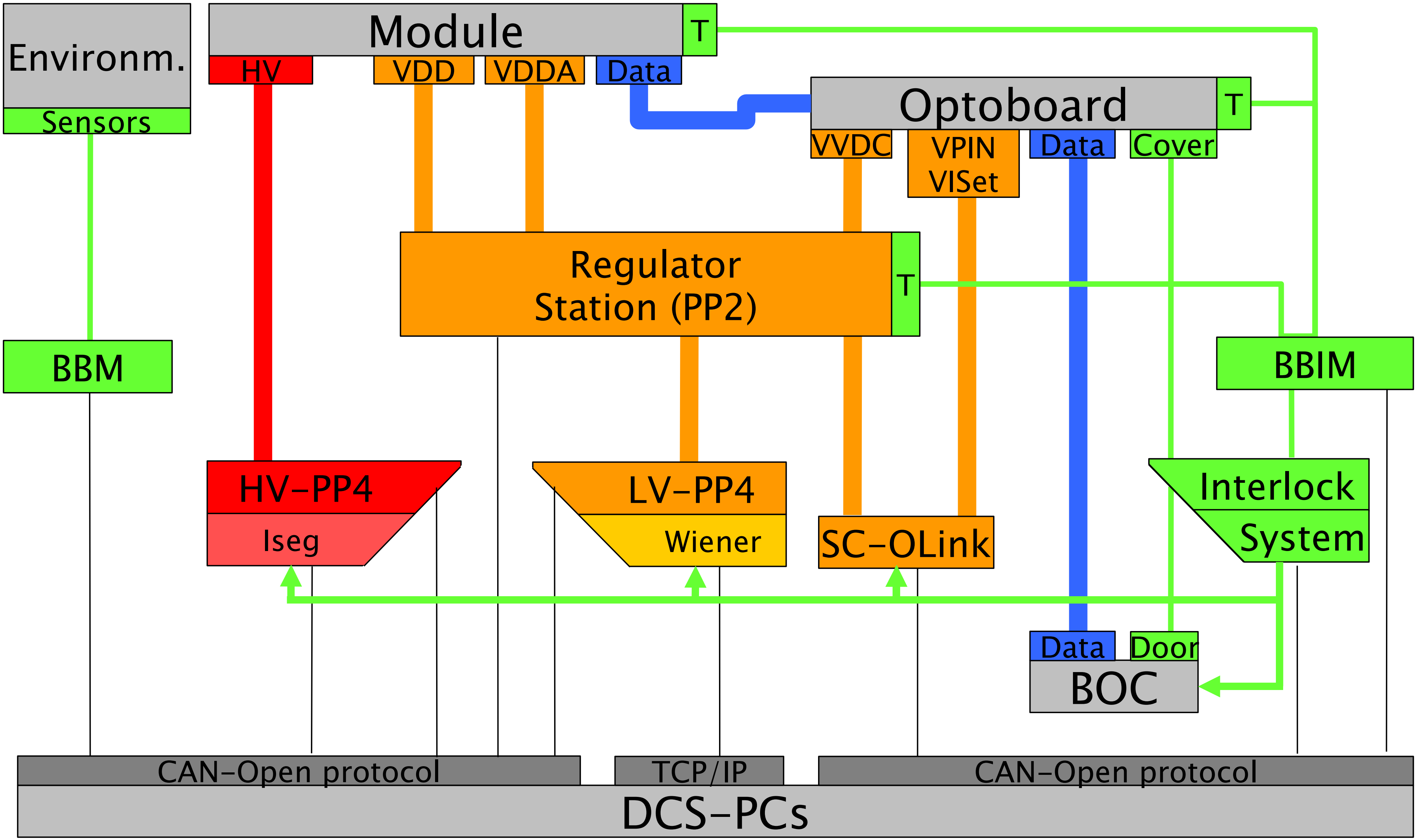


- verify the performance and interaction of production detector and service components (threshold, noise, cooling, ...)
- test complete infrastructure (HW, SW, procedures) on ~10% of the entire detector (Endcap A, 144 modules, 24 optoboards) ⇒ biggest operated Pixel system so far
- realistic long term operation (shifts, 24/7, experts on-call, ...) to learn for real operation
- 'playground' for procedure and software developments (optical communication tuning, module tuning, tuning analyzes, slow control, DAQ, online monitoring, ...)
- test trigger and DAQ chain with cosmics: (noise occupancy, readout performance, tracking, alignment, ...)

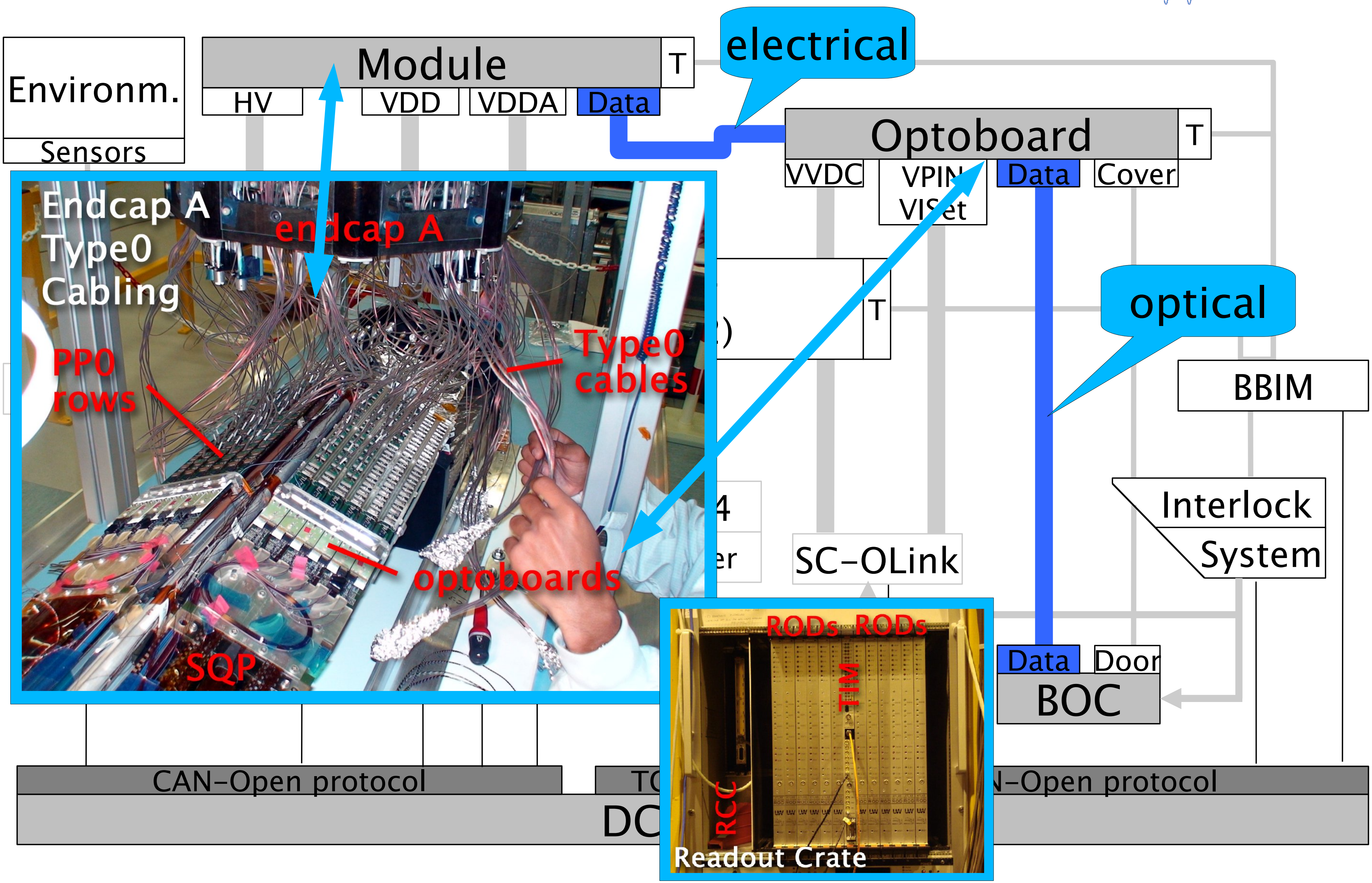
ATLAS Pixel System- and Cosmics-Test at CERN



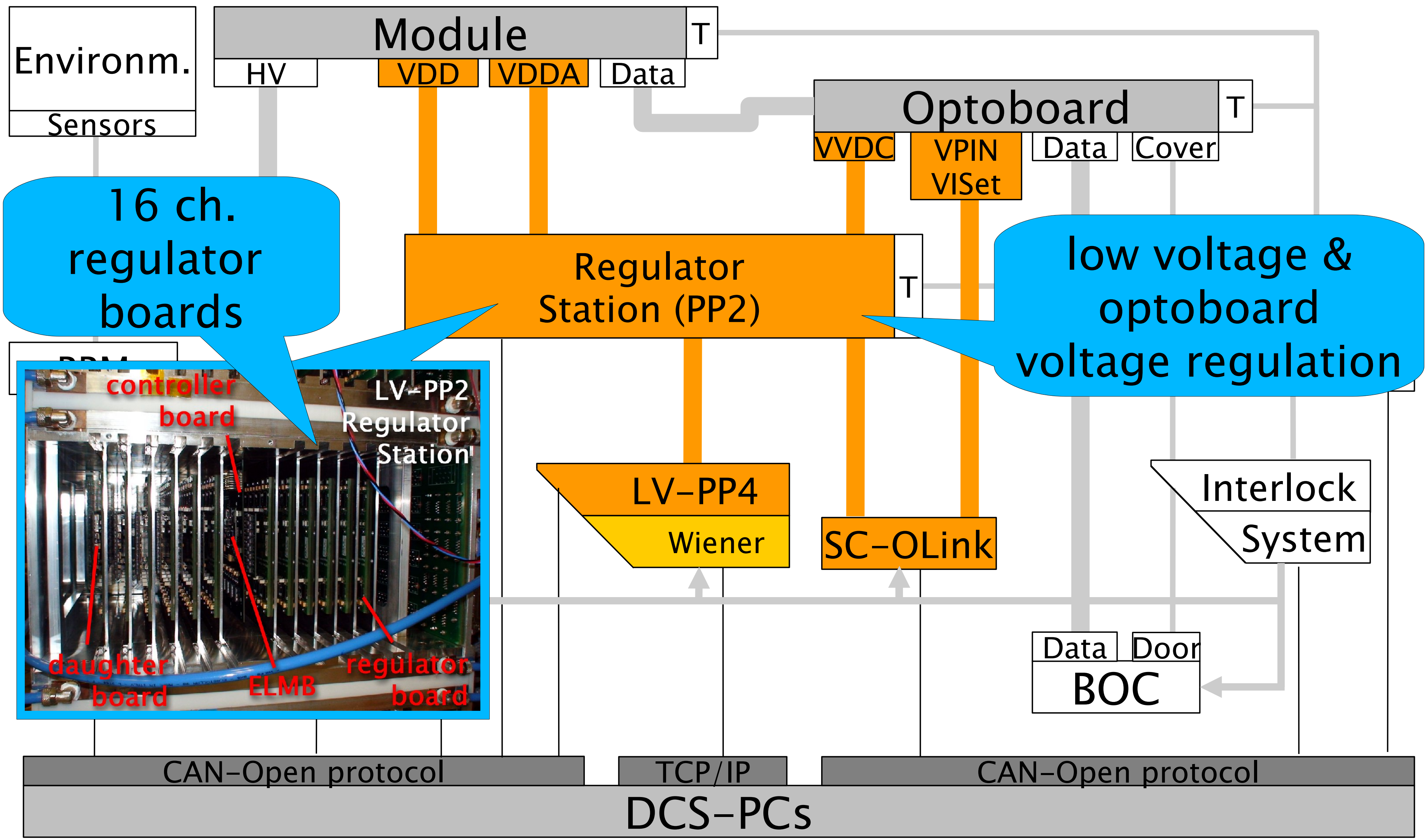
System Test Setup



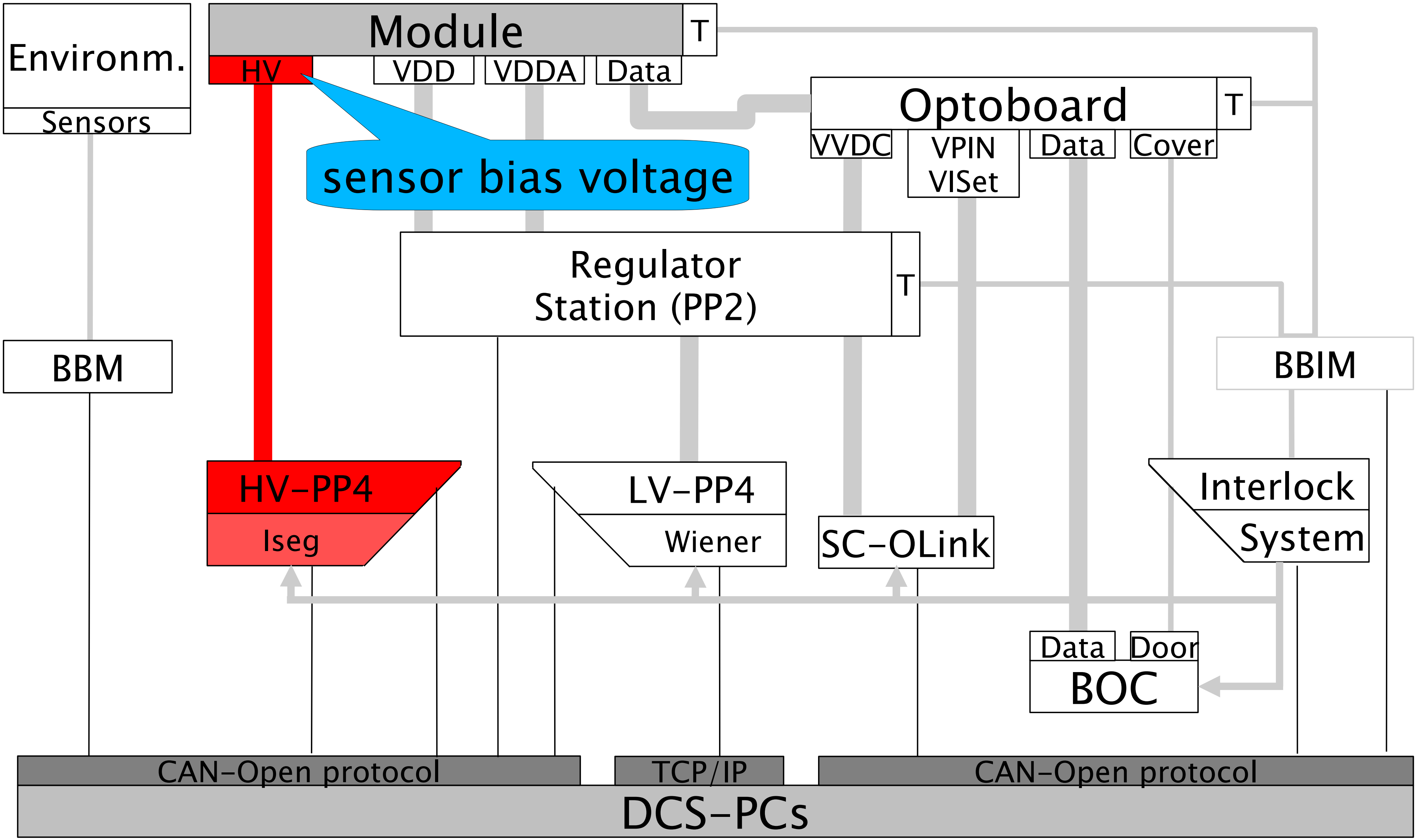
System Test Setup (Data)



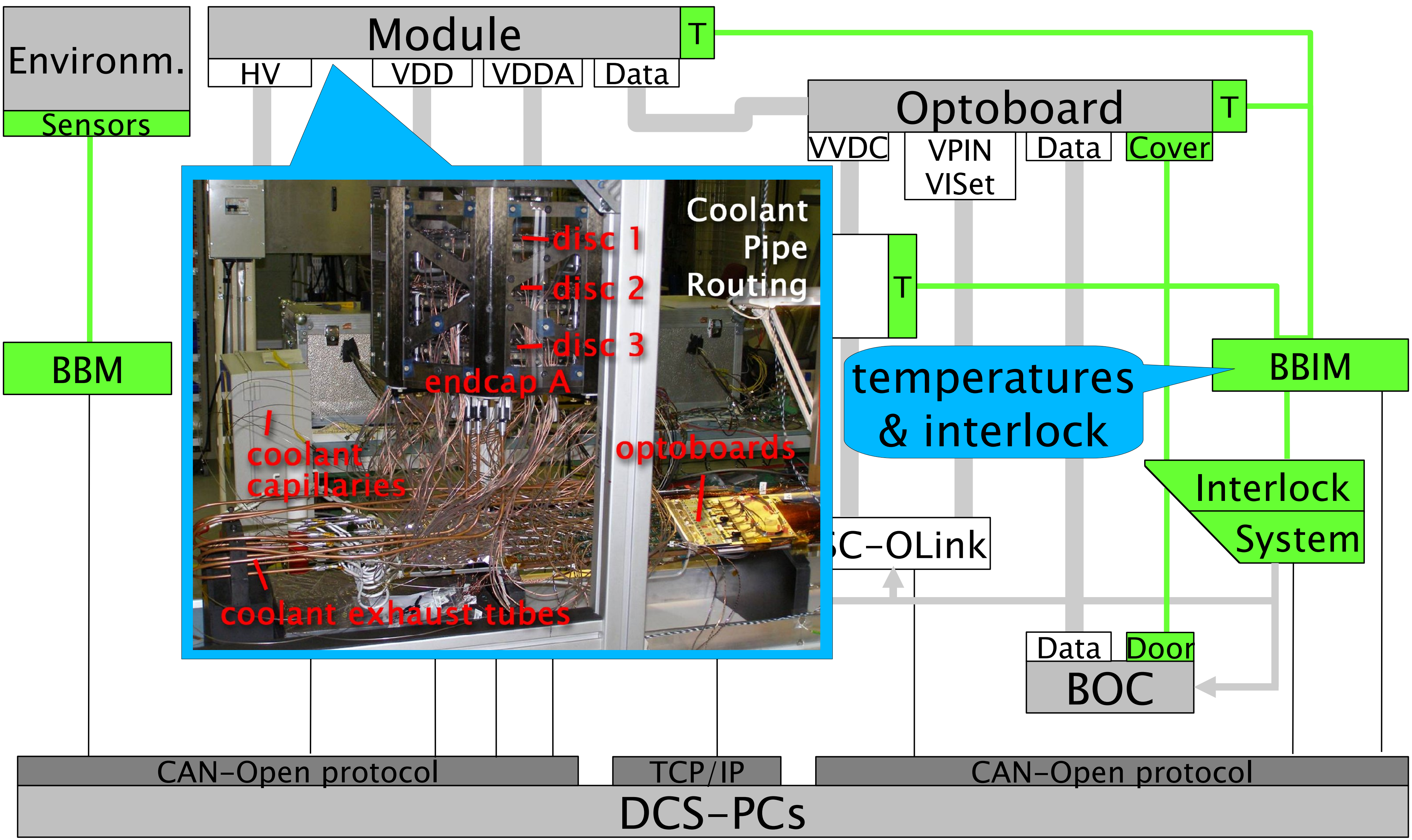
System Test Setup (Low Voltage)



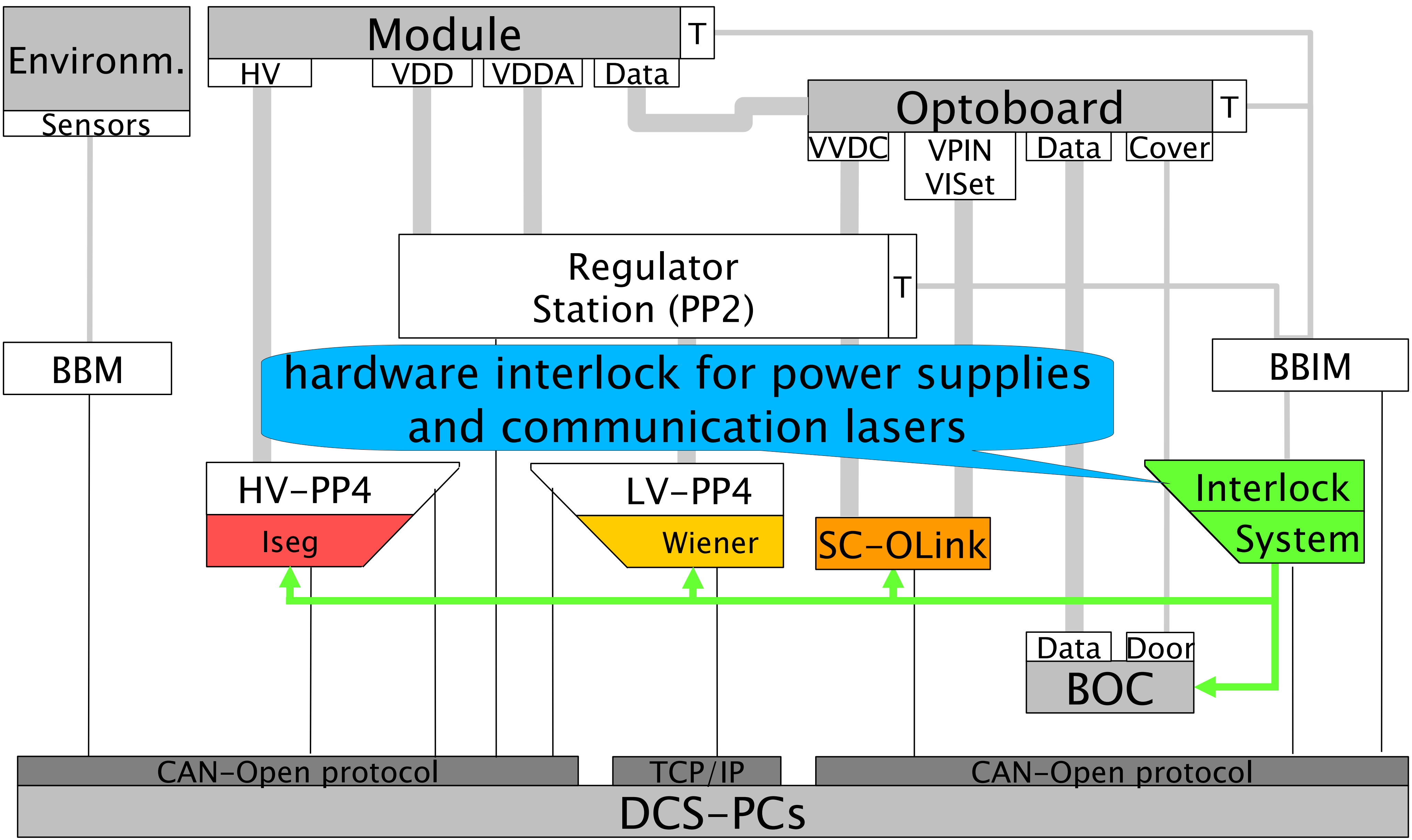
System Test Setup (High Voltage)



System Test Setup (Cooling & Monitoring)

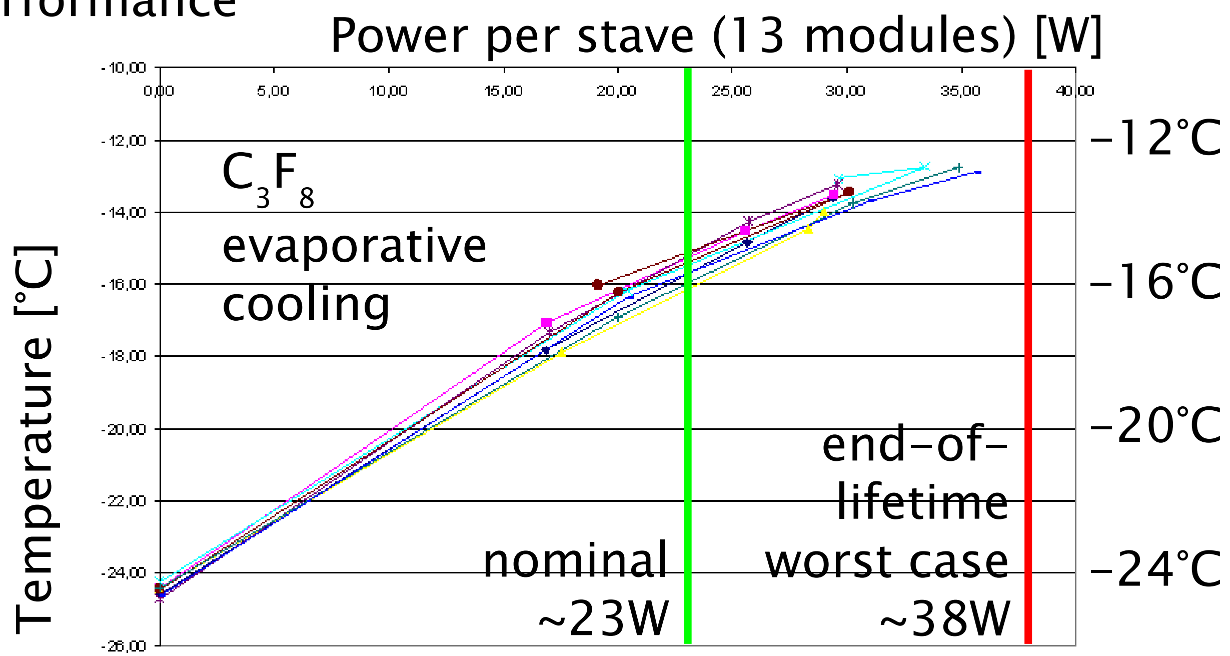


System Test Setup (Interlock)



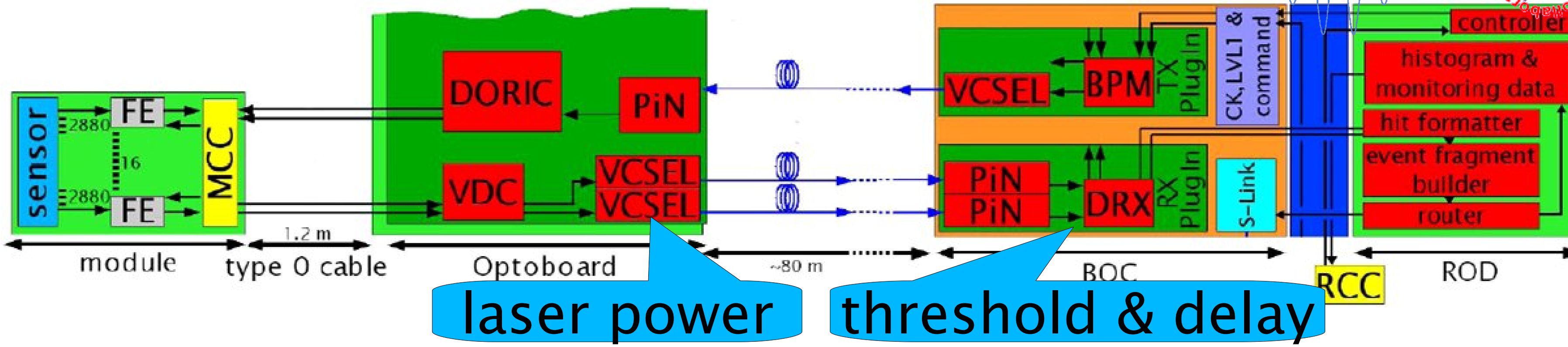
Services & Cooling

- automated service test system has been developed
- complete services chain tested including interlocks, connectivity information in the slow control software and calibration measurements
- service test system qualified for the test of the services before detector is installed in the pit
- intense development and tests in service communications and slow control software (PP2, finite state machine, detector monitoring)
- Endcap operated with evaporative C_3F_8 cooling, as will be used in the final detector with good performance



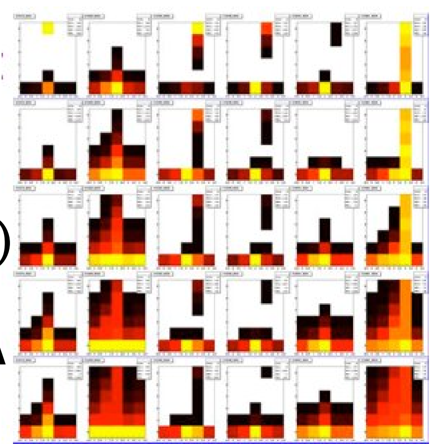
All services and cooling fulfill the requirements of the detector

Optical Communication Tuning

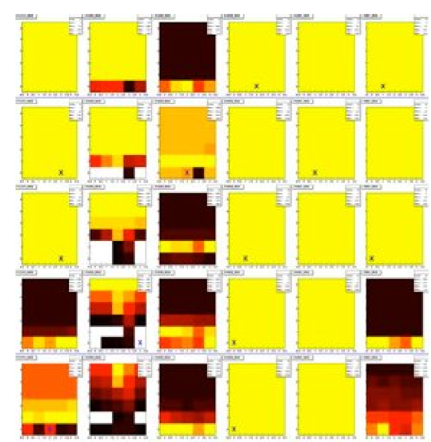


- several parameters need to be tuned for the optical data link between on-detector optoboards and off-detector BOC cards:
  - laser power for the optoboard (1 voltage for up to 14 channels)
  - threshold and delays at the BOC receiver side (channelwise)
- challenge: adjust optoboard laser power such that all 7 opto links have a working parameter space
- power and channel to channel light spread depends on optoboard temperature ⇒ untunable channels below 5°C

bit pattern errors (color scale) vs. threshold ↑ delay →



+10°C

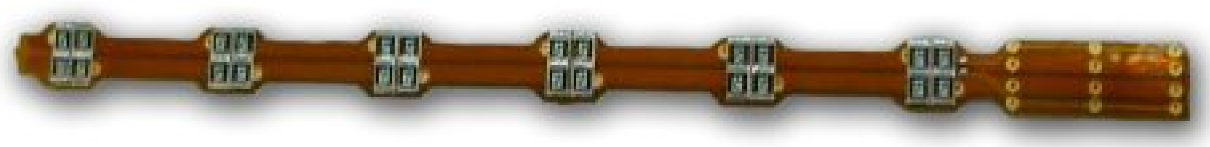


−10°C

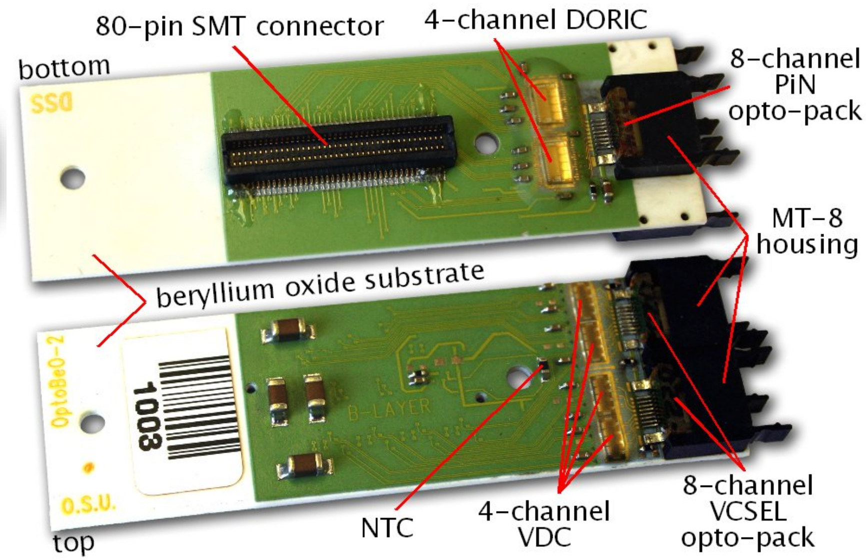
laser power ↓

Optical Communication Tuning

- heaters have been installed on the optoboards
  ⇒ all channels behave well at ~20°C

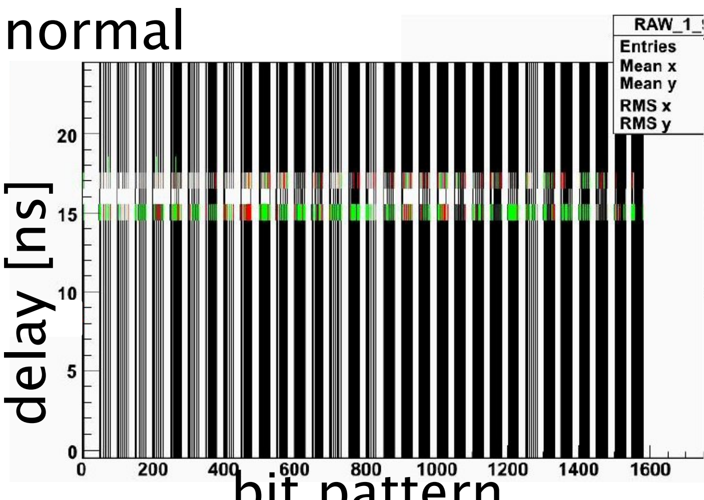


- slow turn-on of light power for few channels
  ⇒ has been addressed in the optoboard quality assurance procedure

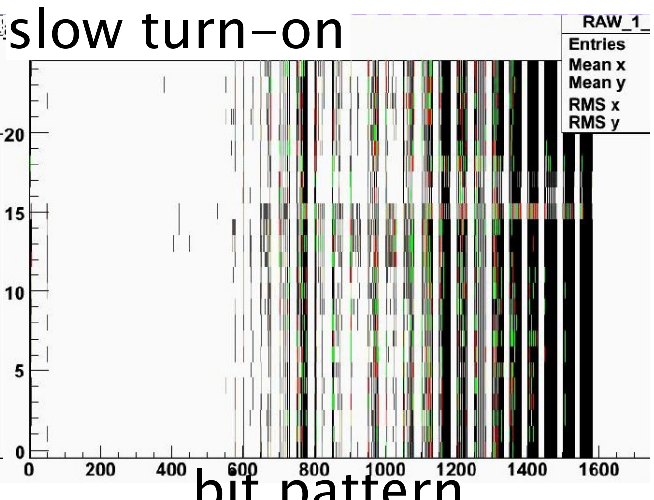


probably most of the problems can be explained by not first-choice quality optoboards in the System Test

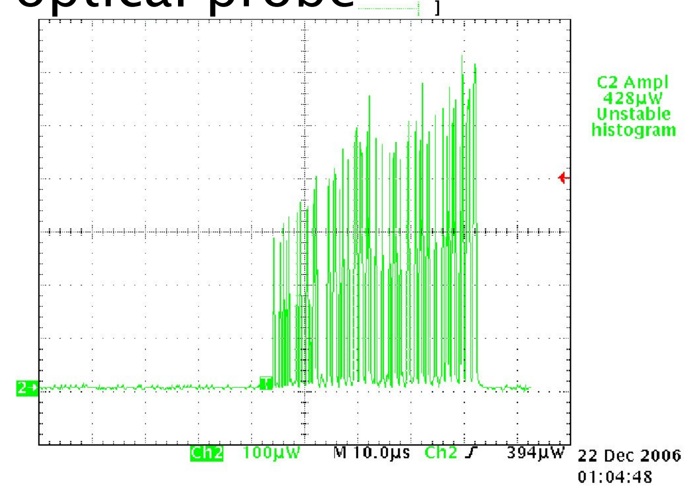
normal



slow turn-on

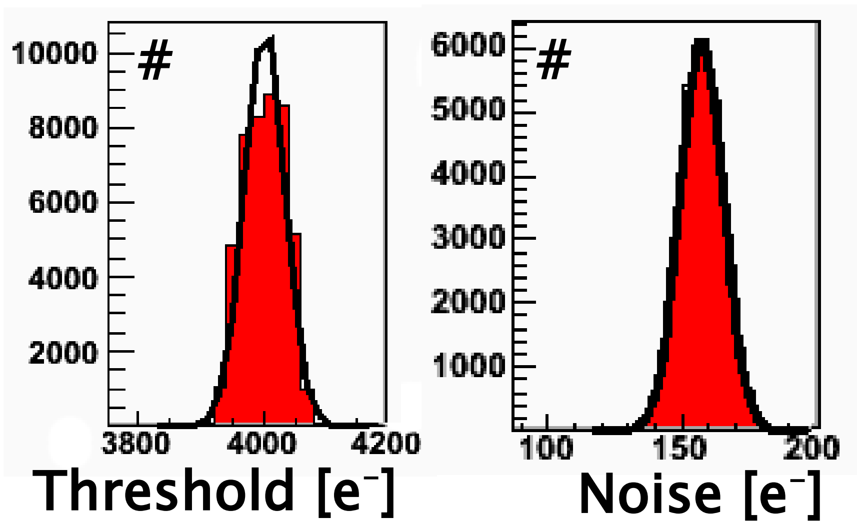


optical probe

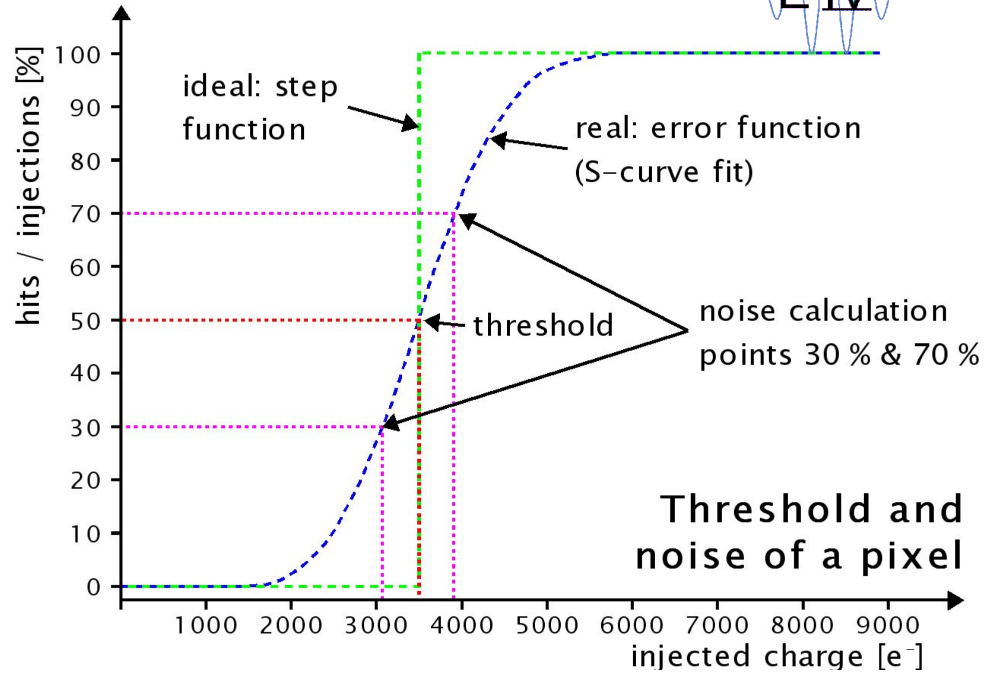


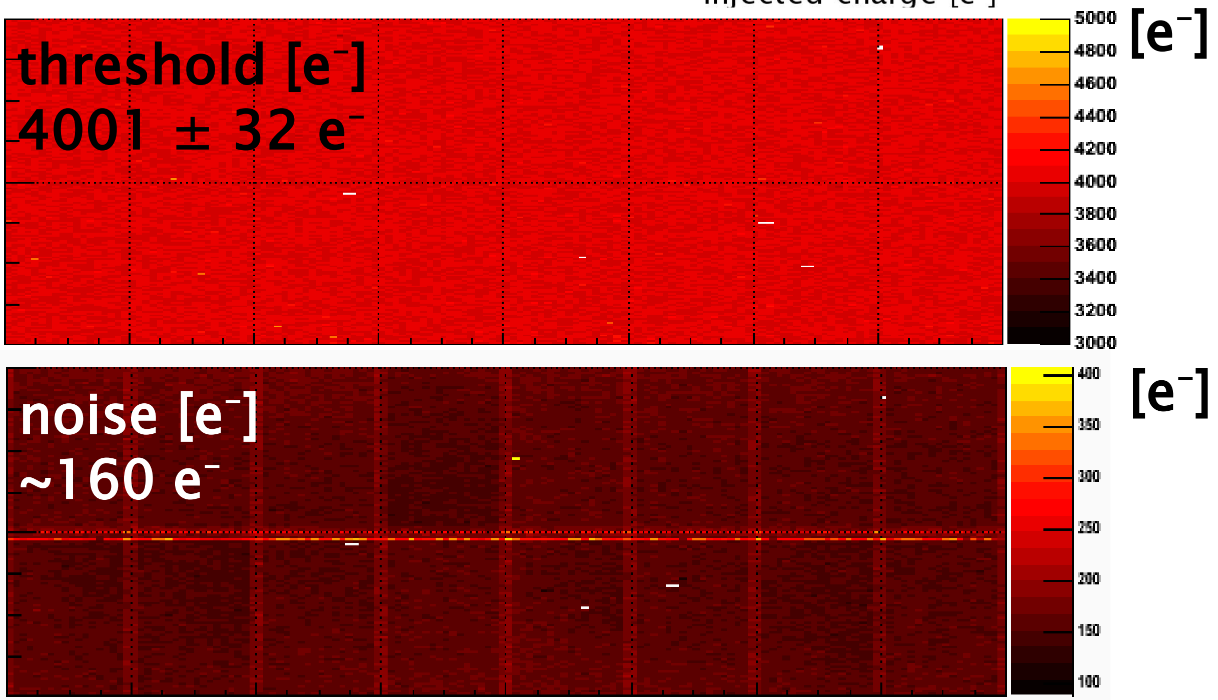
Module Tuning Performance: Thresholds & Noise

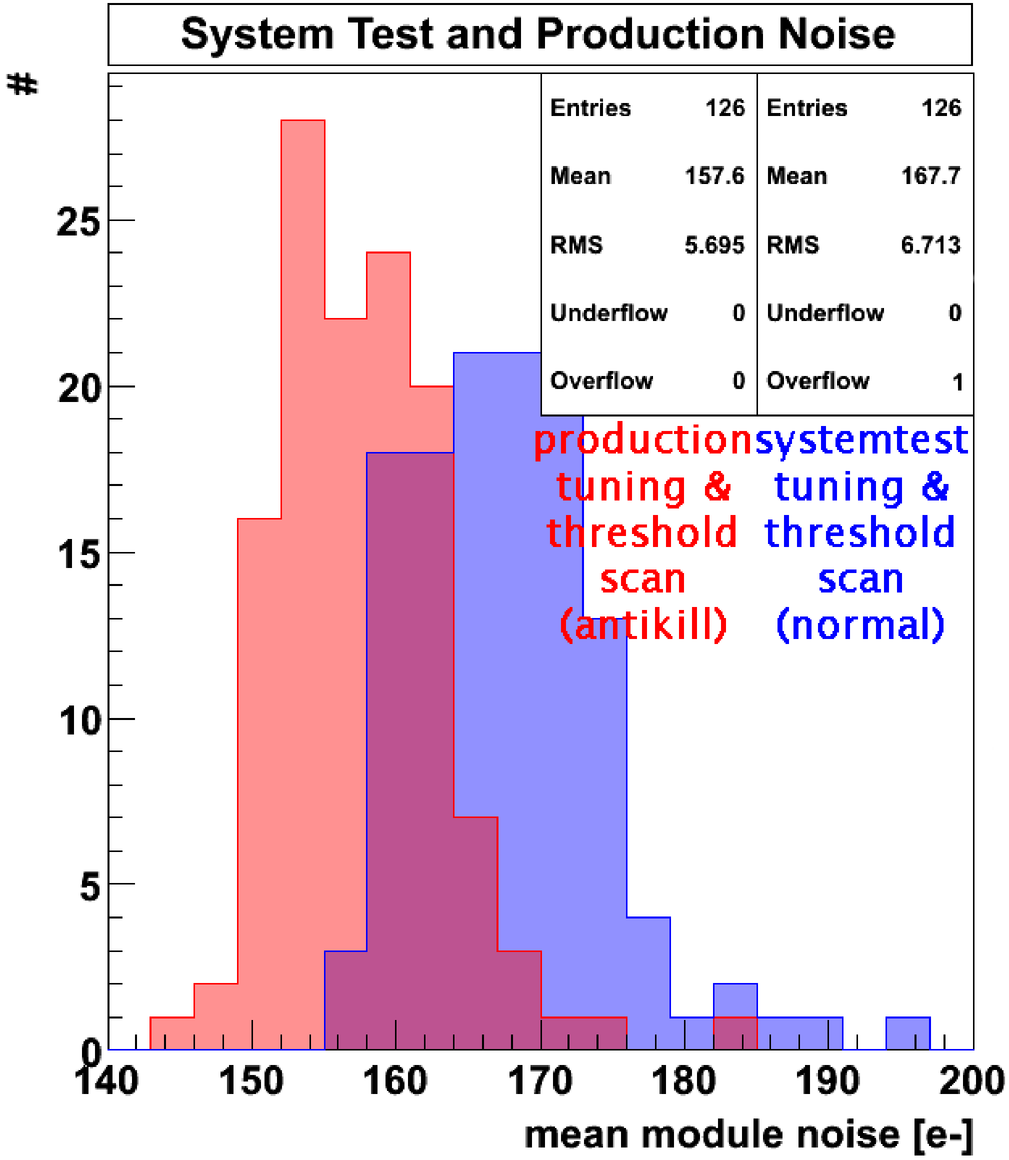
- charge injected into preamplifiers and response after discriminator measured
- nicely correlated with production data and only slightly higher (<10e$^-$)

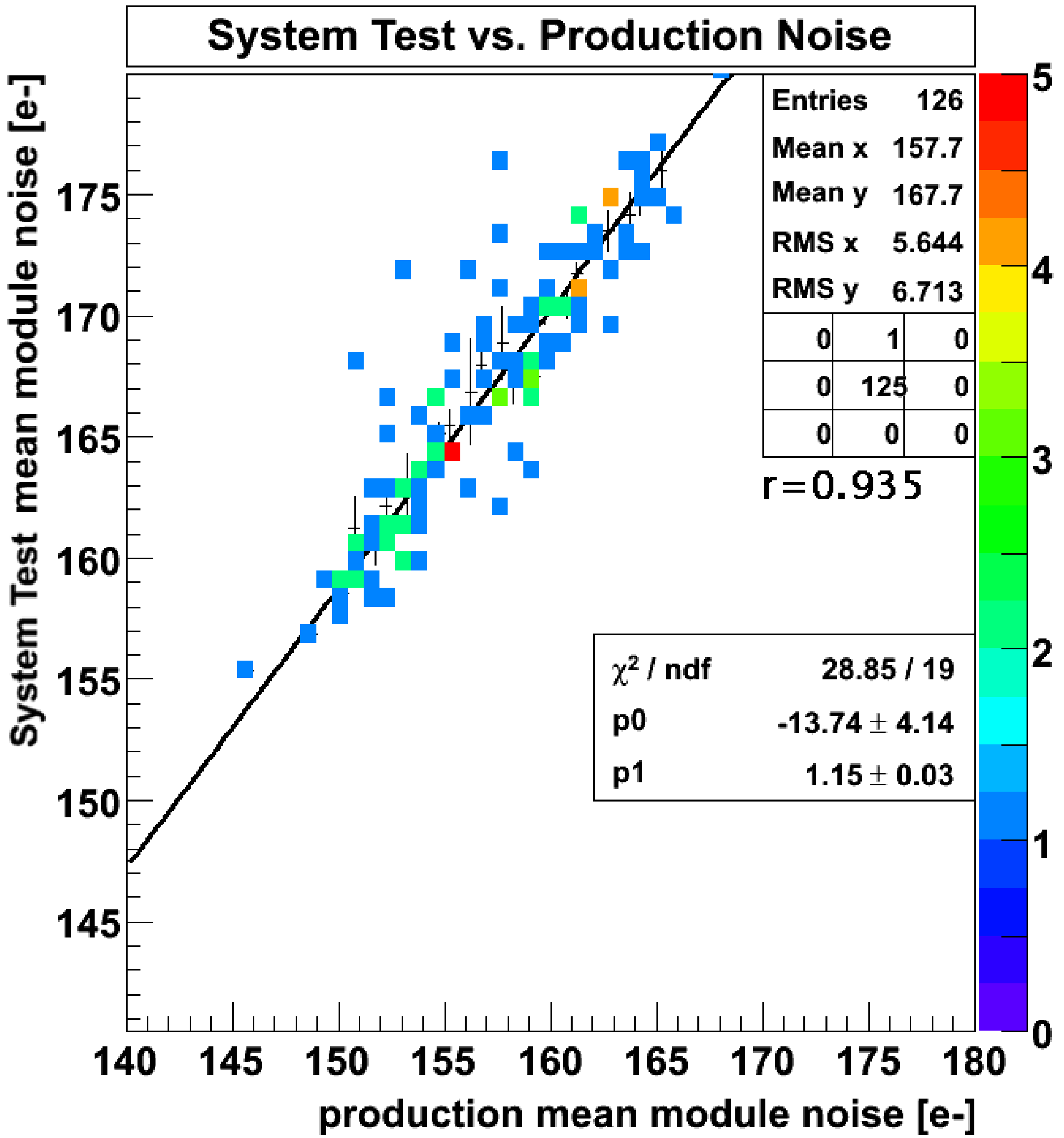


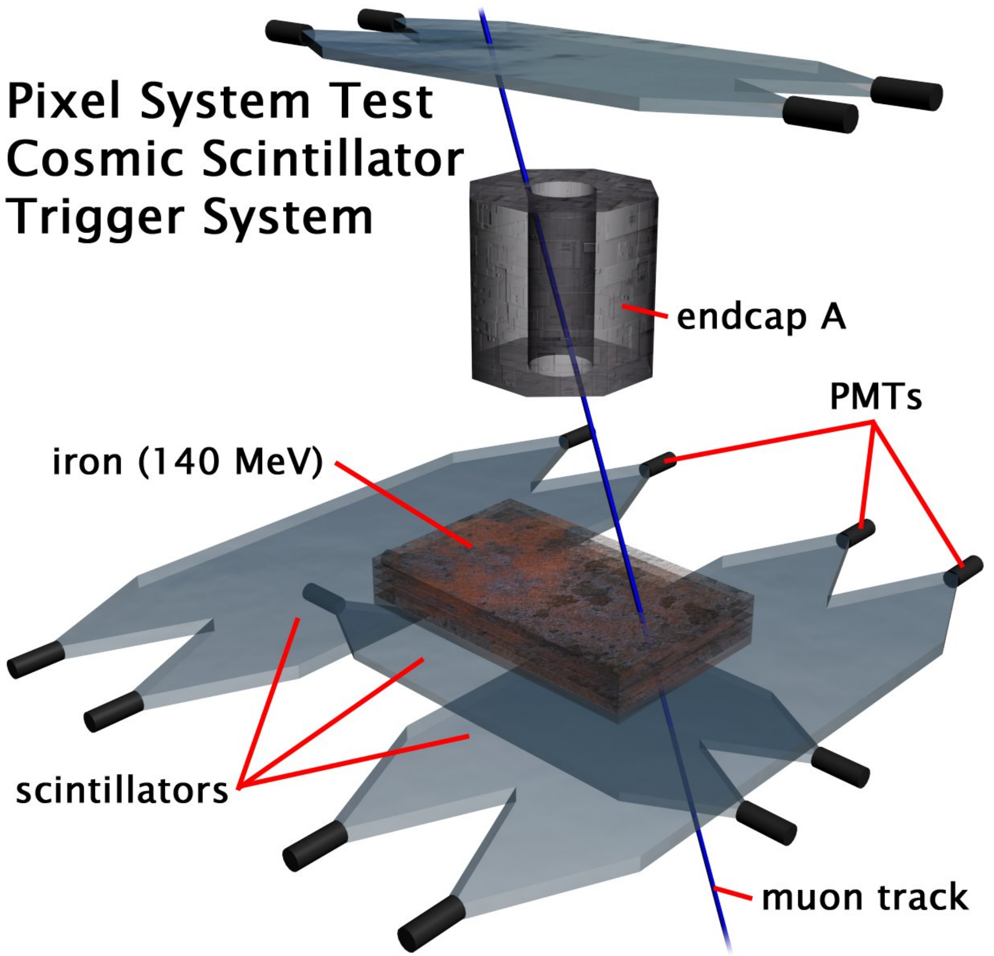
- MIP in 250 µm silicon sensor: mean energy loss 27 ke-
  ⇒ with charge sharing ~17 ke-
  ⇒ after life-time dose irradiation irradiation ~ 8 ke-

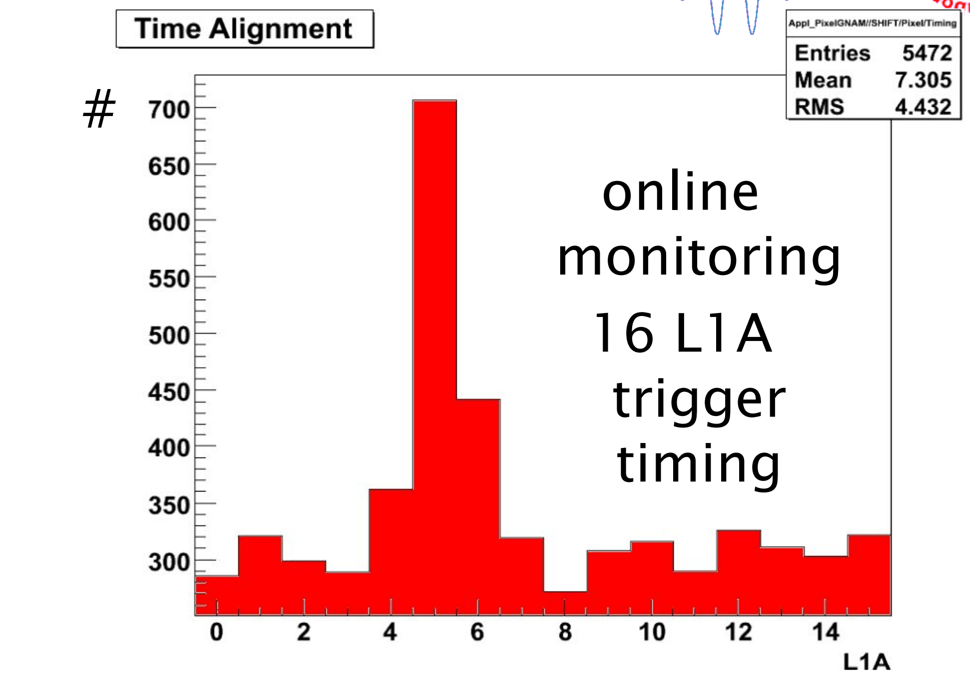


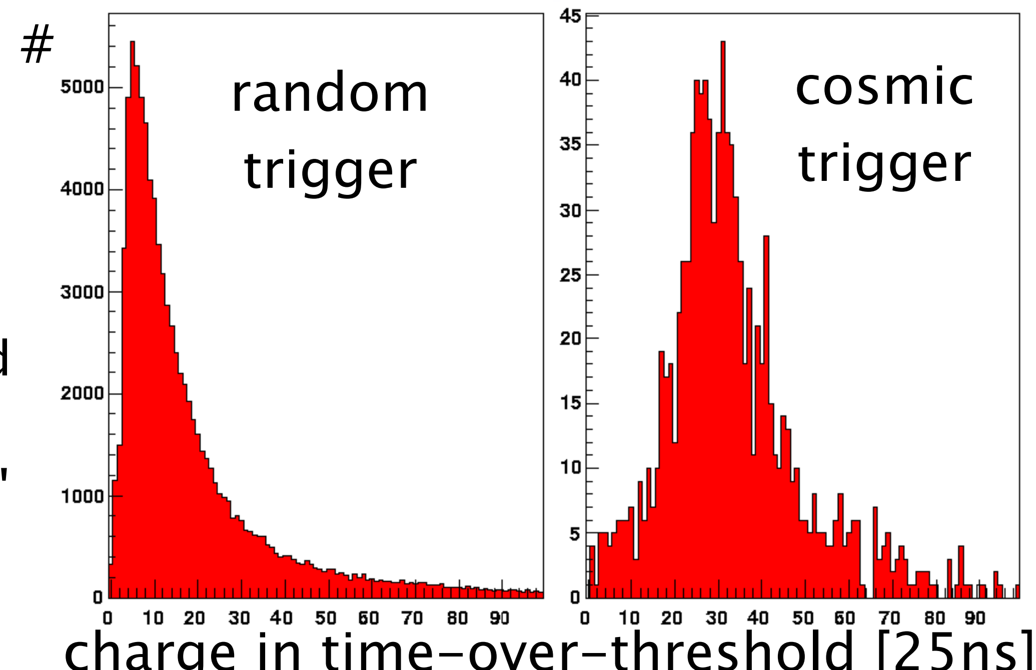



System Test and Production Noise
#
Entries 126
Mean 157.6
RMS 5.695
Underflow 0
Overflow 0
Entries 126
Mean 167.7
RMS 6.713
Underflow 0
Overflow 1
production tuning & threshold scan (antikill)
systemtest tuning & threshold scan (normal)
mean module noise [e-]


System Test vs. Production Noise
Entries 126
Mean x 157.7
Mean y 167.7
RMS x 5.644
RMS y 6.713
r=0.935
χ² / ndf 28.85 / 19
p0 -13.74 ± 4.14
p1 1.15 ± 0.03
System Test mean module noise [e-]
production mean module noise [e-]

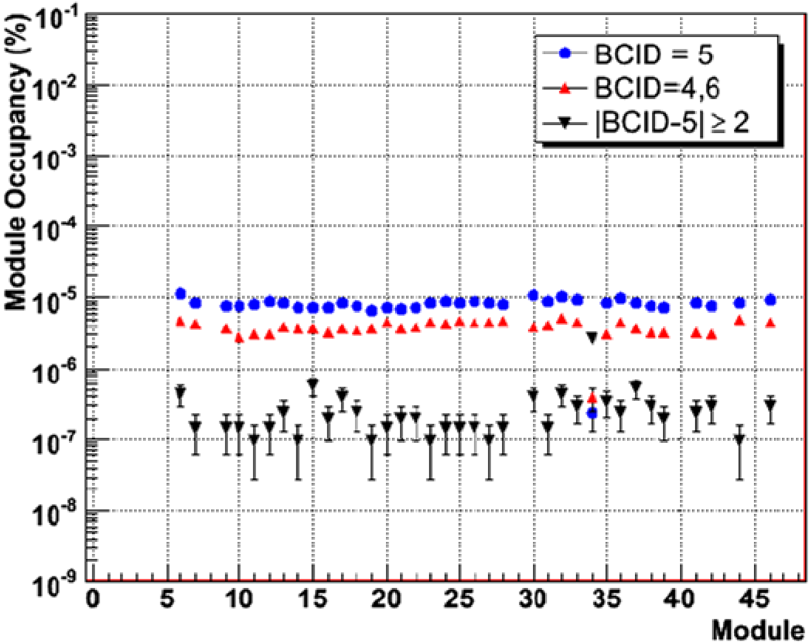




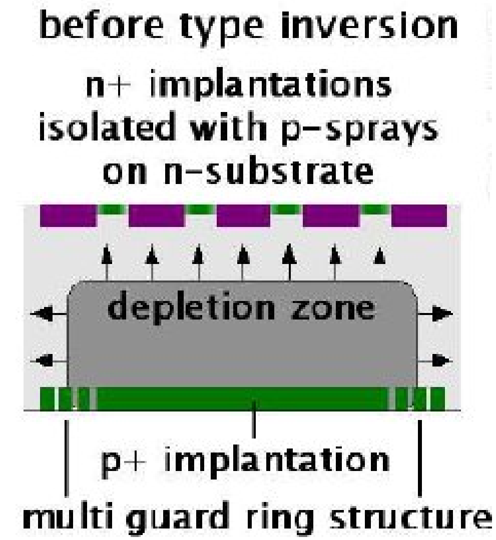


- trigger requests hit in top scintillator and any of the bottom scintillators
- hit position within 16 consecutive 'level1' triggers for cosmic triggers show clear cosmic peak above noise floor

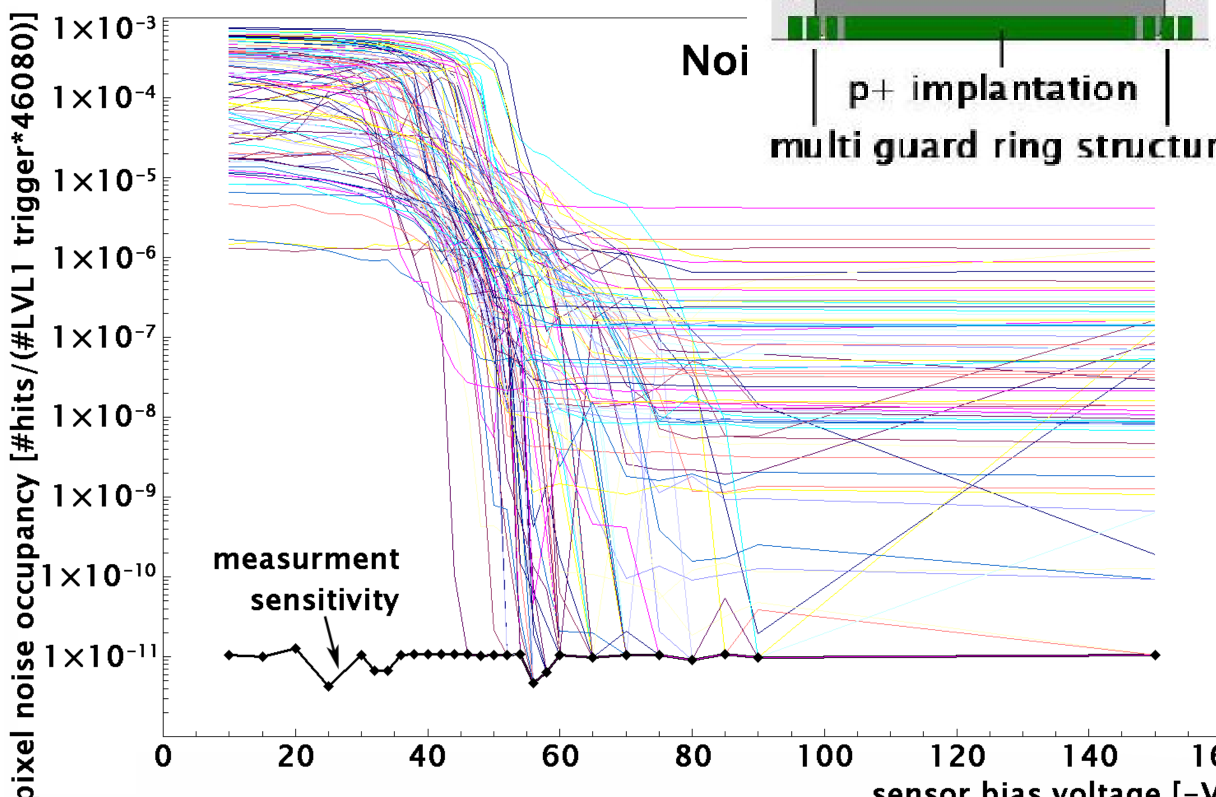
Noise Occupancy and Sensor Depletion Voltage



- noise occupancy measured with cosmic trigger
- after removal of noisy (10^{-4}) pixel noise occupancy as low as 10^{-7}
- 90% of noisy pixel identified from production measurements
- total fraction of affected pixels >1%

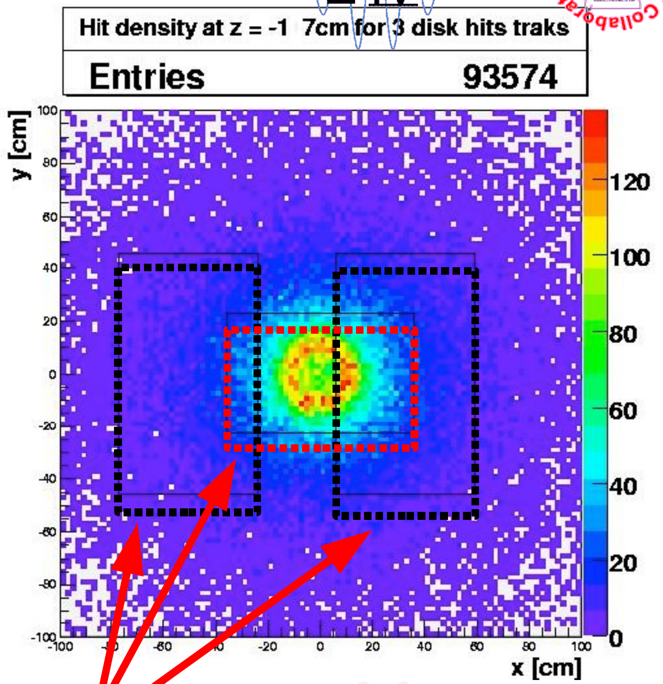


- noise occupancy with random trigger vs. sensor bias voltage measurement used to determine depletion voltage
- depletion zone grows towards pixel side ⇒ bias voltage below full depletion – pixel shorted ⇒ high capacitive load to preamplifiers ⇒ high noise ⇒ high noise occupancy

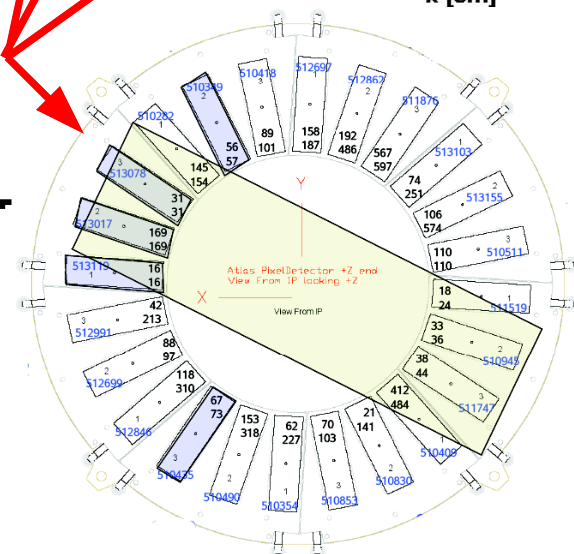


Monte Carlo vs. Data

- 29 out of 144 modules disabled
- measured trigger rate 15.7 Hz vs. ~ 18 Hz full simulation rate

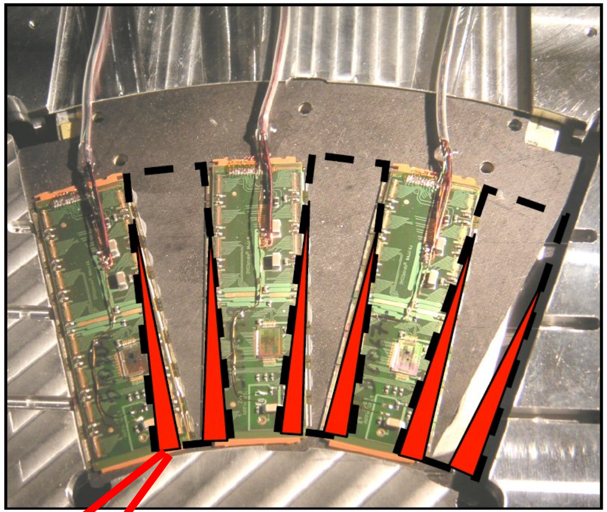


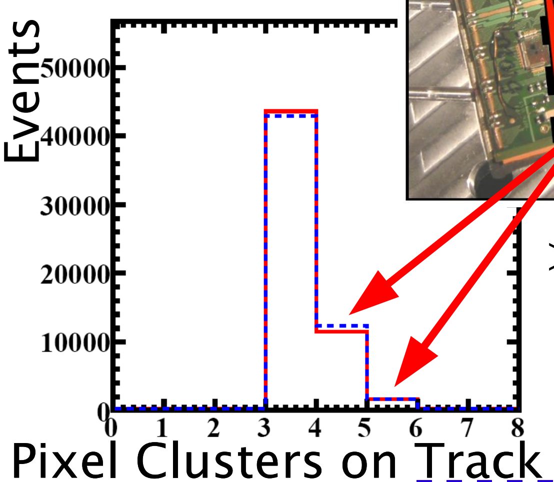
Scintillators



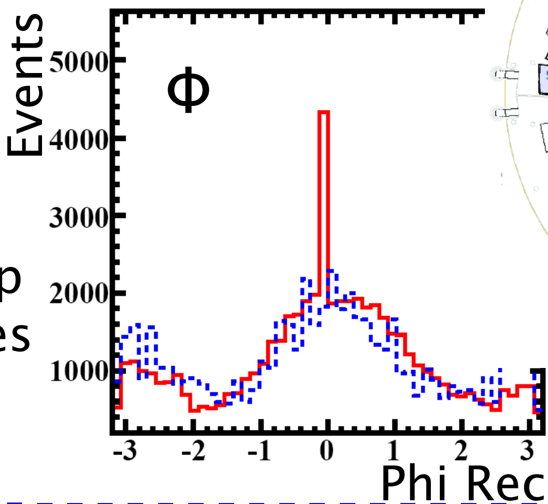
MC

Data

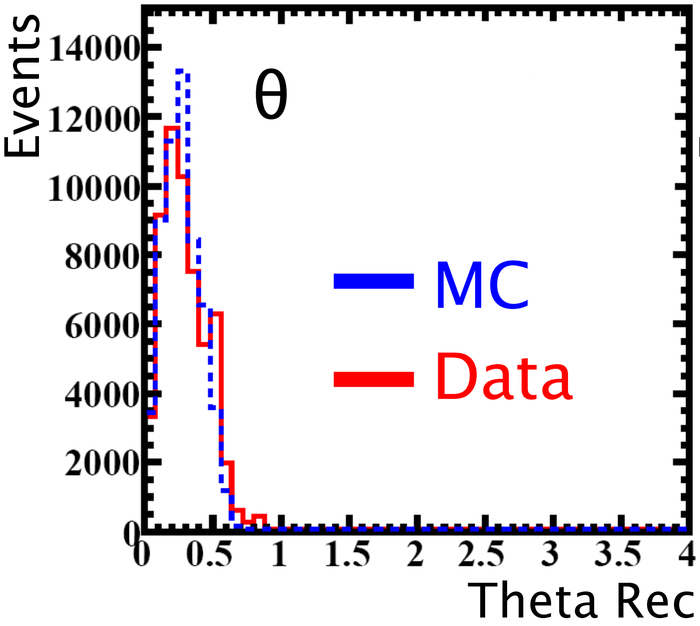


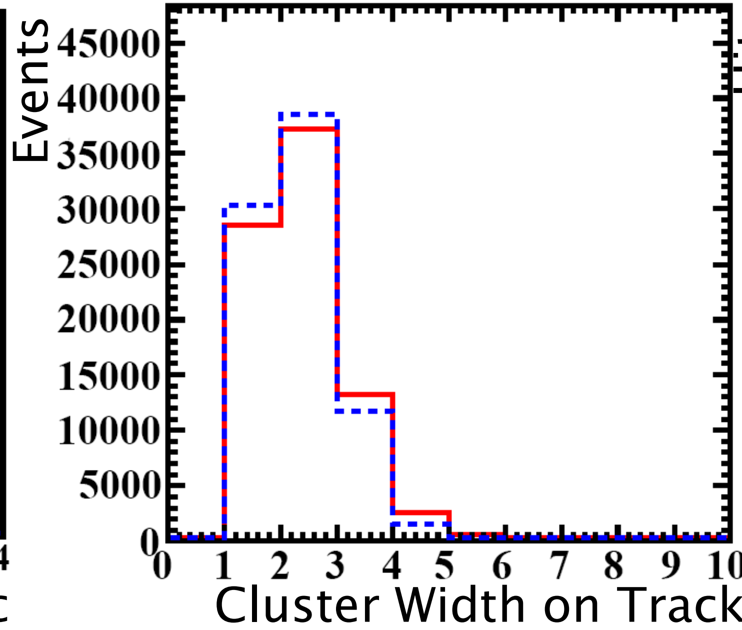


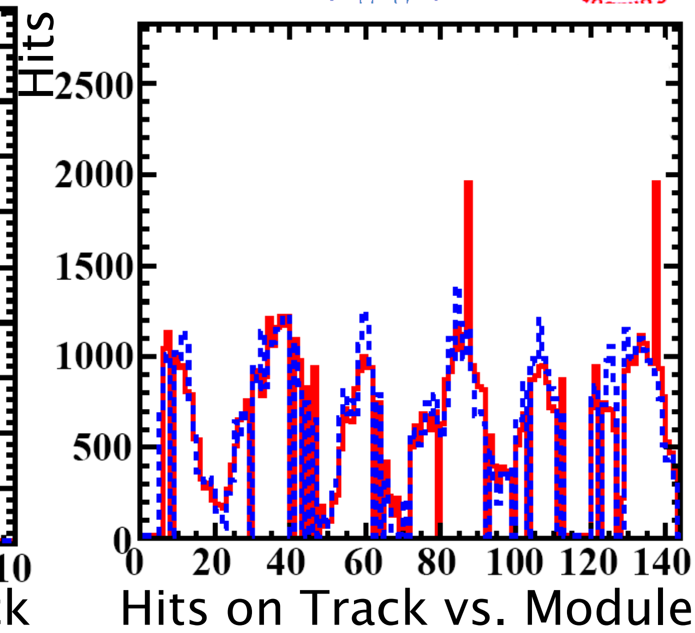
>10% of area overlap region with modules on other side $\Delta z = 4.2$ mm



Monte Carlo vs. Data (2)

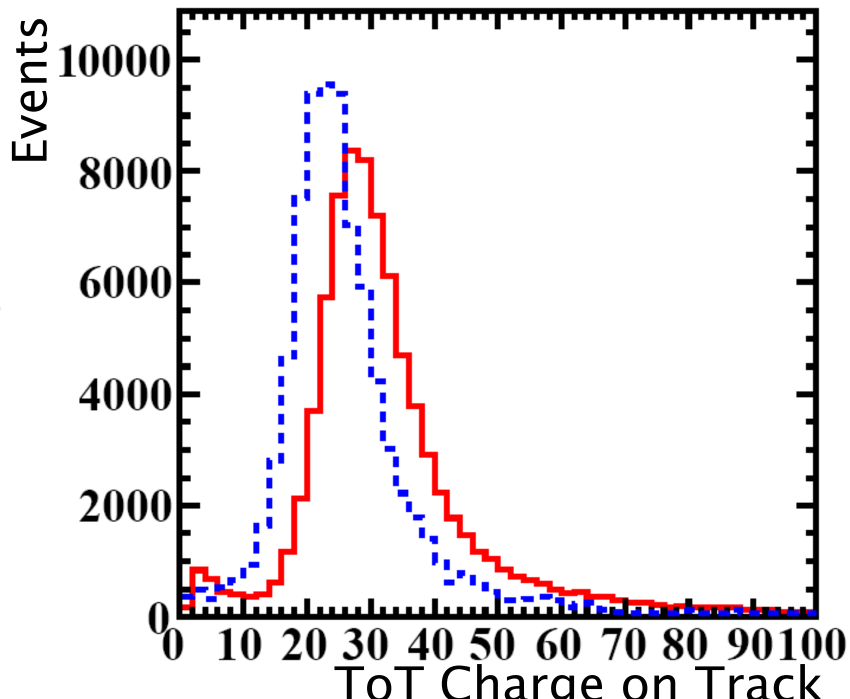


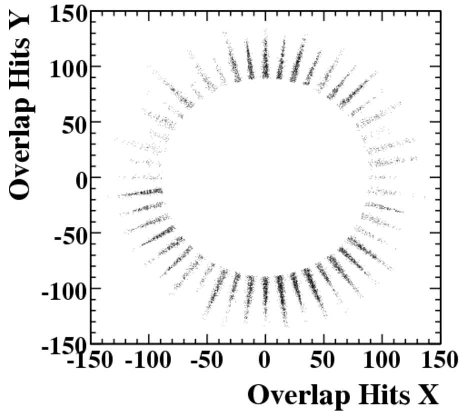


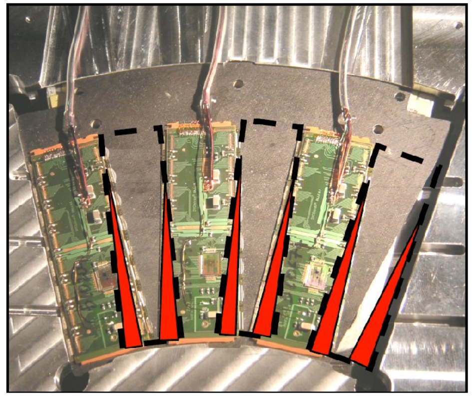


- MC tuned on cosmic data
- theta reconstruction, cluster width and hits on track vs. module agree with MC (hits on track inhomogeneous due to asymmetric scintillator, missing modules & 3 noisy pixels)
- TOT shape correct ⇒ TOT calibration (from production measurements) OK
  ⇒ shift due to wrong fit parameter C:

$$TOT = A + \frac{B}{(C+Q)}$$

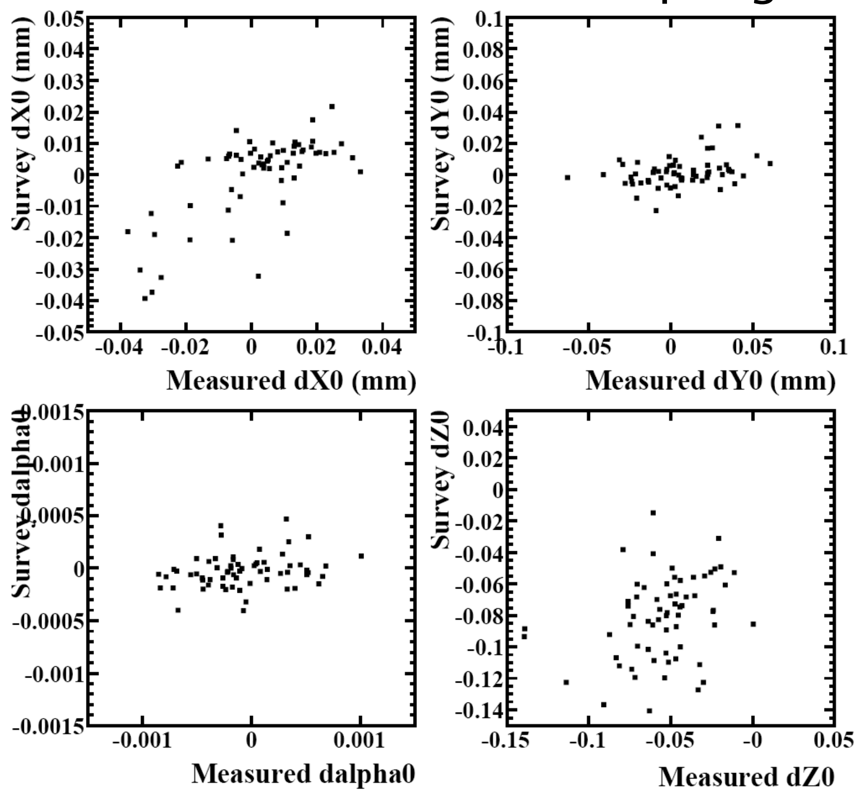


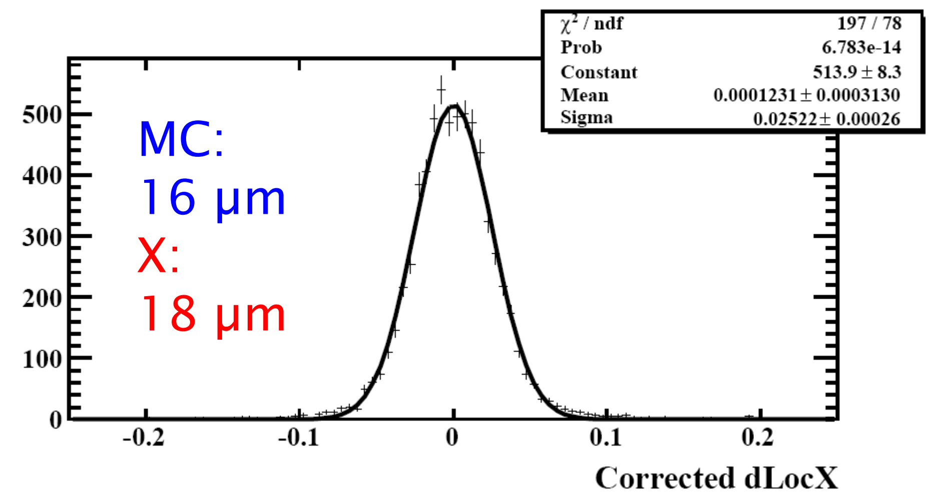


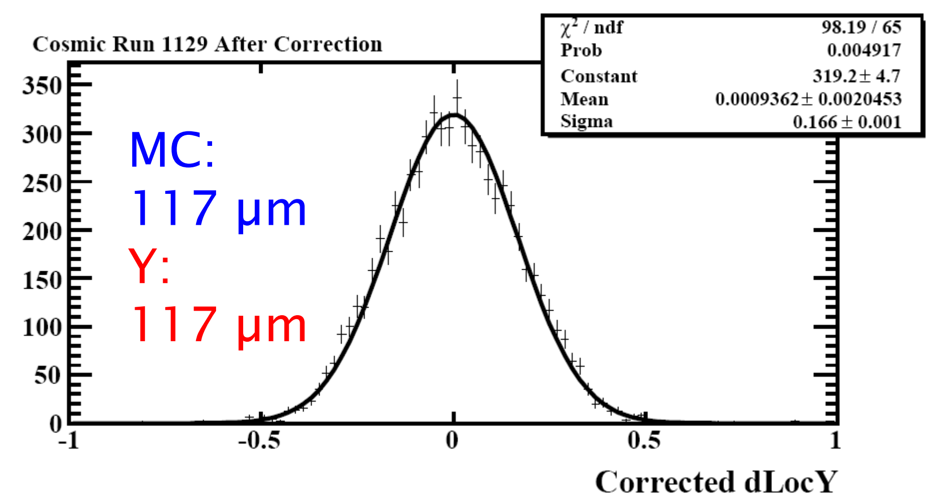


- use >10% overlap region between modules on different side of a disk Δz=4.2 mm to determine relative alignment between modules

Survey vs. cosmic alignment for modules with more than 50 hits in the overlap region

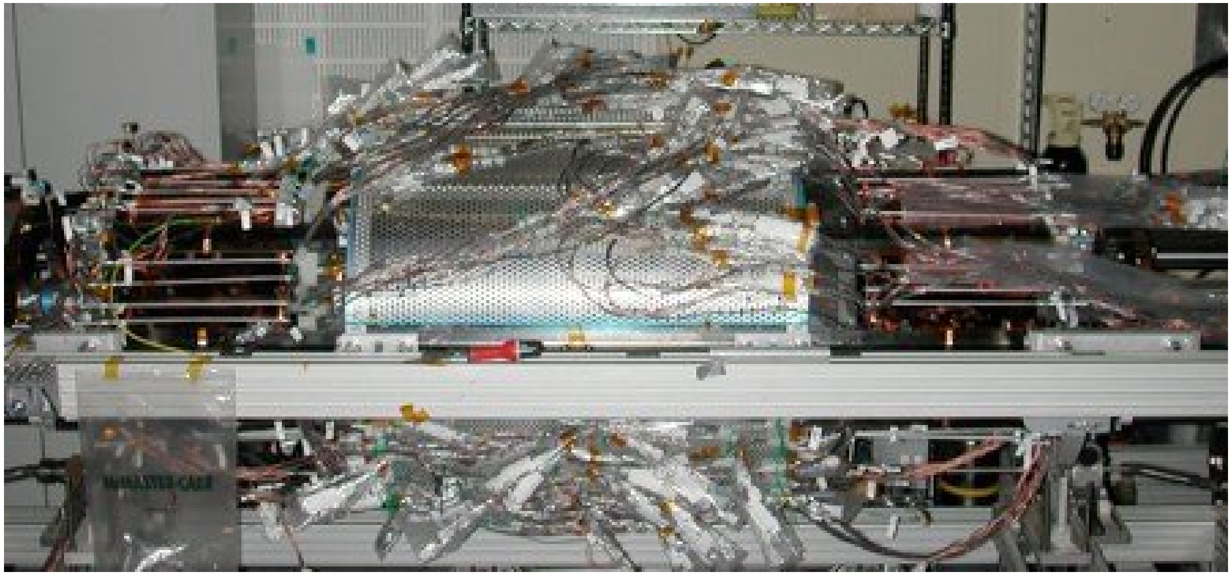


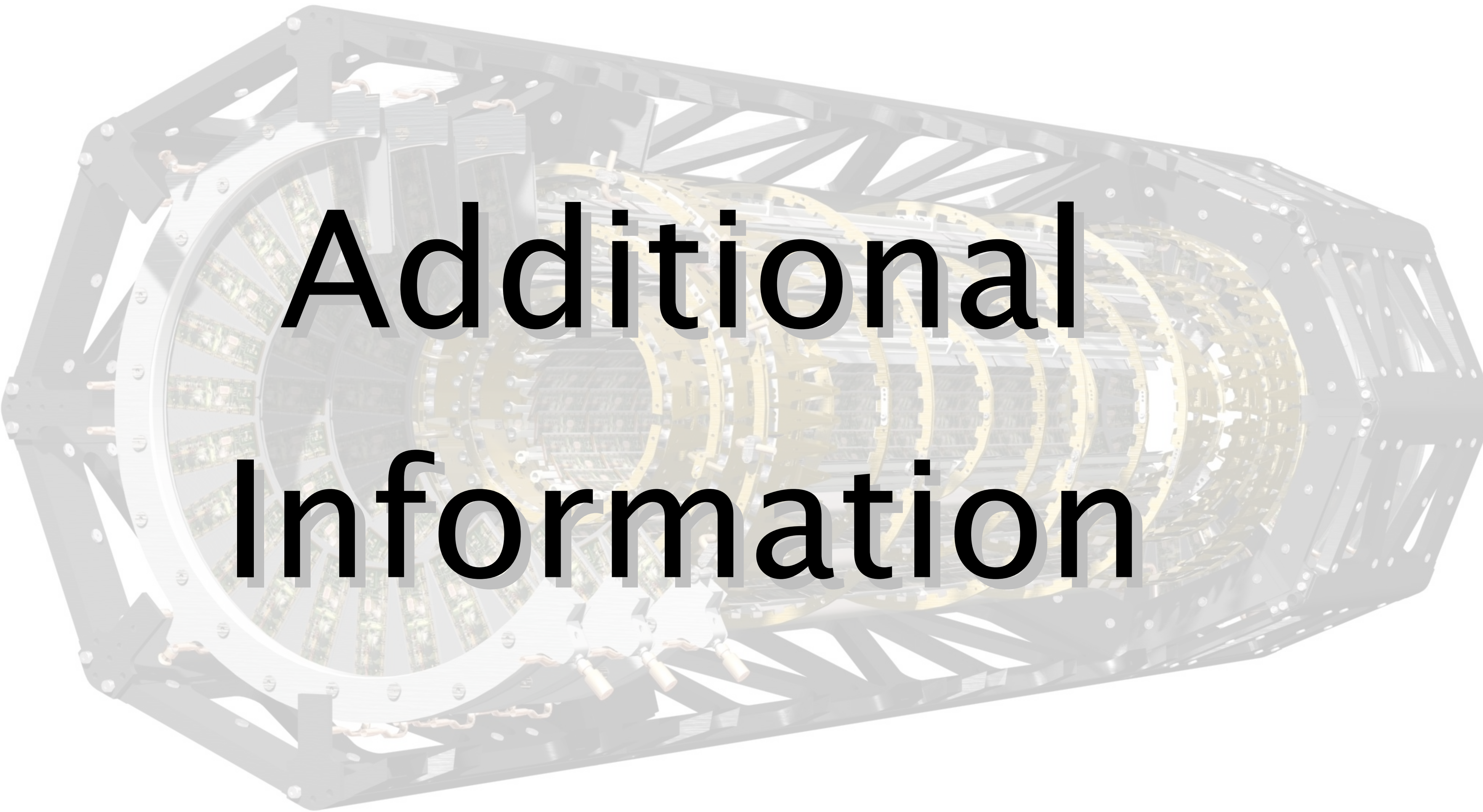




Conclusions

- the ~10% System Test was a success and we gained valuable experience for a successful commissioning and the operation of the detector
- various parts of the services have been validated (cooling, services, interlock system)
- huge development step was done in online and offline software driven by the System Test
- difficulties in optical communication tuning were identified in time to take necessary actions before commissioning
- expected good detector performance (threshold, noise, noise occupancy) could be verified and no system specific problems have been observed
- Monte Carlo expectations for cosmic data have been confirmed – recorded data allows us to test the entire reconstruction chain and exercise alignment and resolution studies

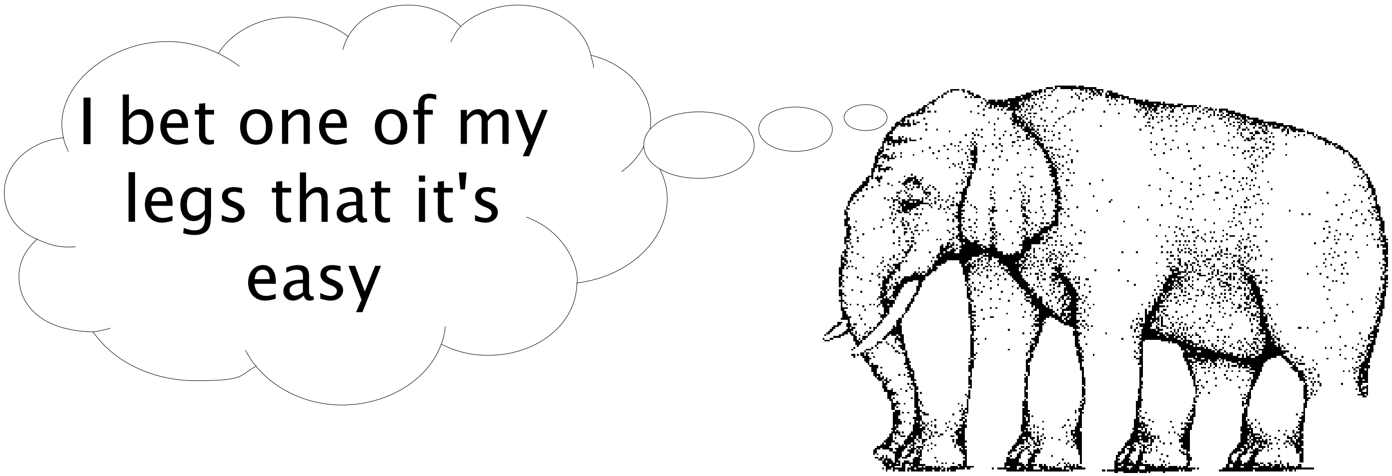


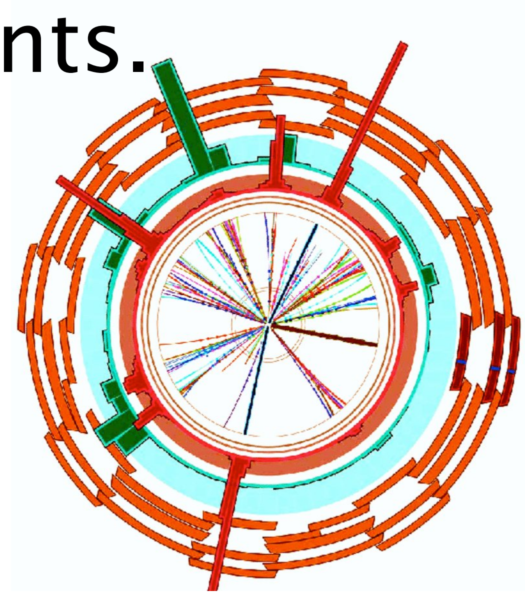


Additional Information

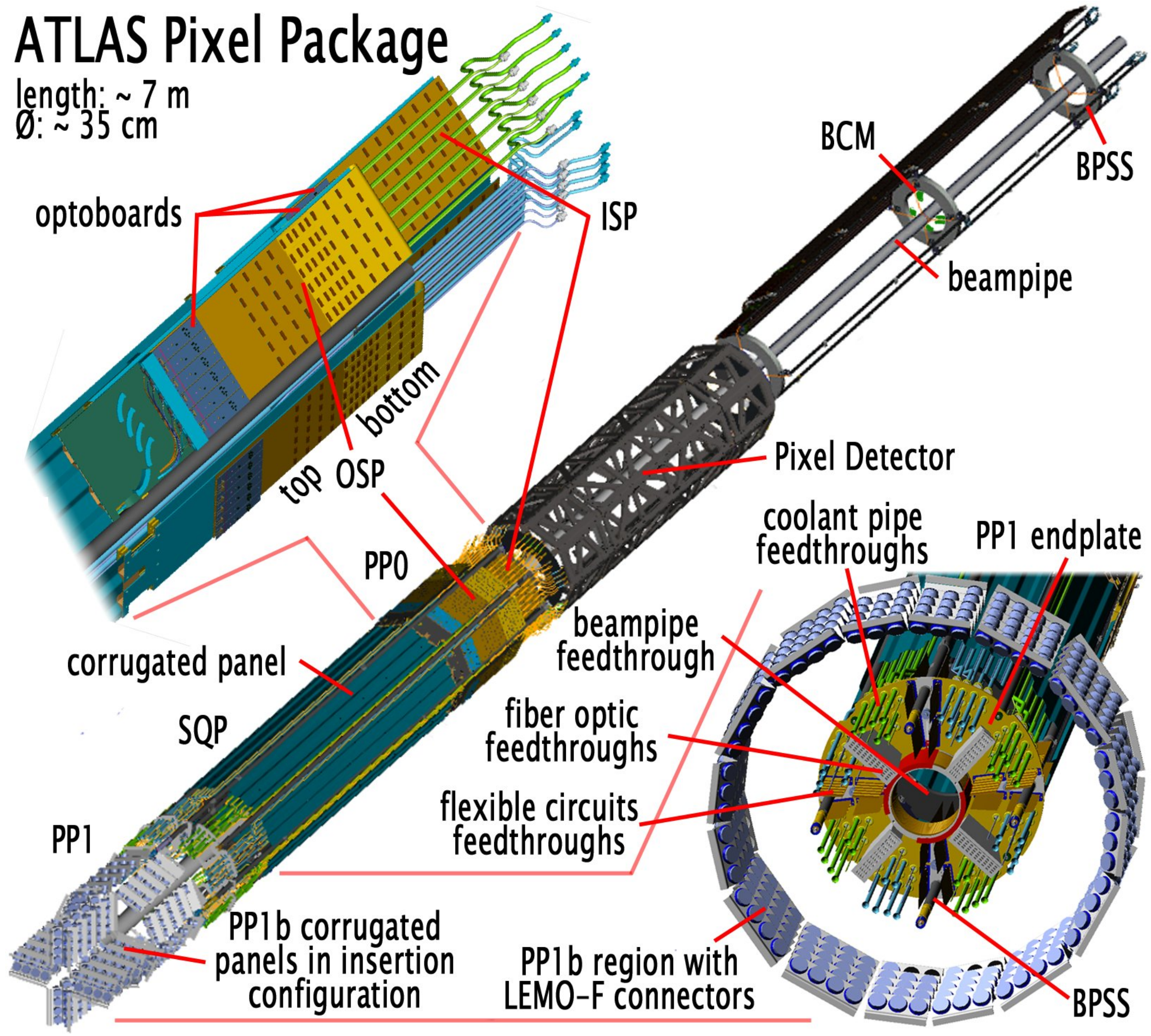
Tracking and Vertexing:

Measure sometimes (40 million times a second) many (three) ultimate precise (~12 μm) space-points at zero distance (r_{min}~5 cm) to the interaction point of few (1000) particle tracks with a perfect (>97% overall efficiency), radiation hard ($>1 \cdot 10^{15}\, n_{MeV\,eq}/cm^2$), massless ($X_0$<10%) and full coverage (pseudo rapidity < |2.5|) detector and readout some (75k/s) selected events.





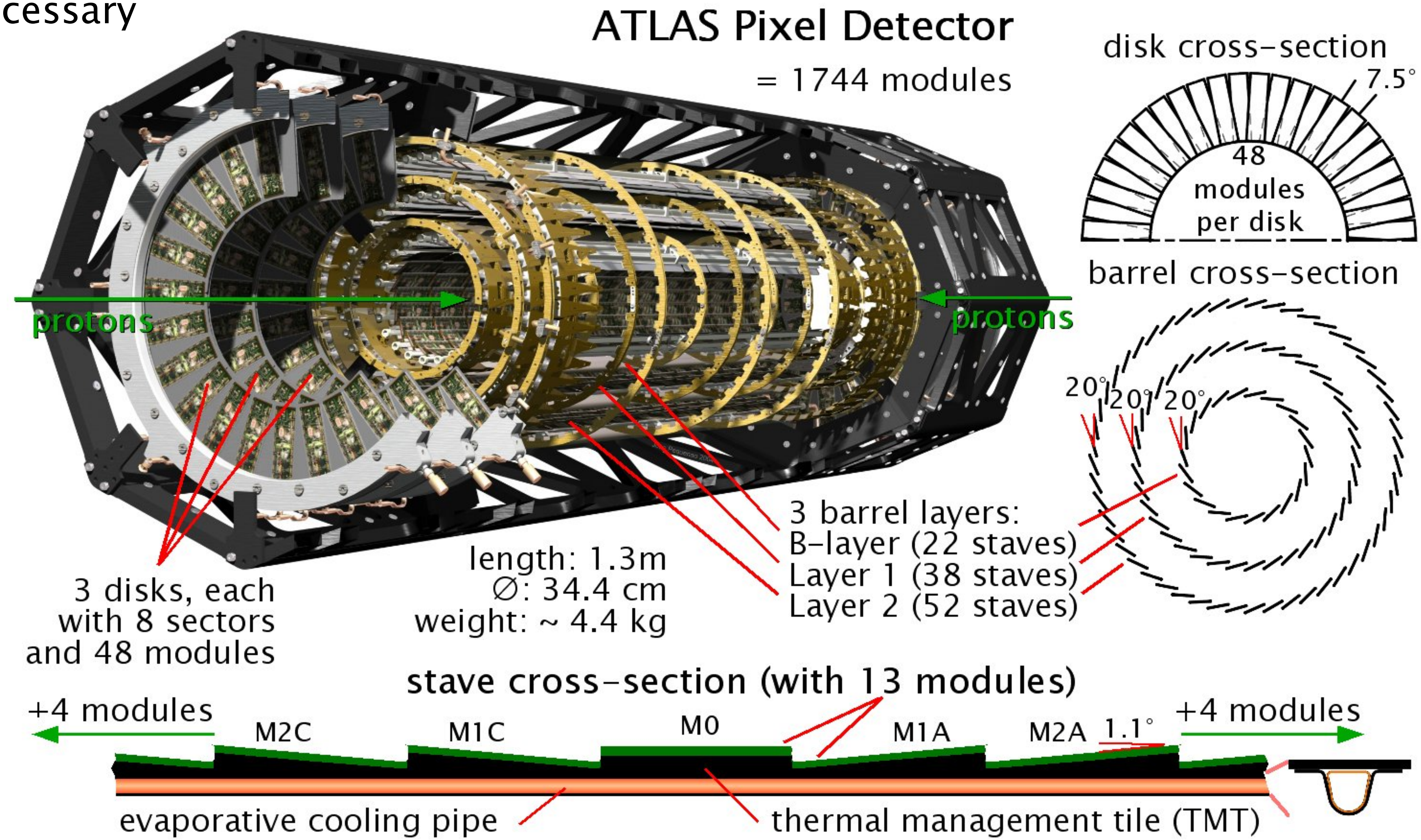
ATLAS Pixel Package



- beryllium beampipe integrated in the Pixel package
- active surface only in the 1.3 m long central detector section
- BeamPipe Support Structure (BPSS) connected at both ends position the beampipe in the middle of the detector and support Service Quarter Panels (SQP)
- in total eight SQPs provide all services to the detector
- cooling tubes and electrical module connections at PP0
- optoboard mounted at PP0 provide optical/ electrical conversion
- all services break at PP1

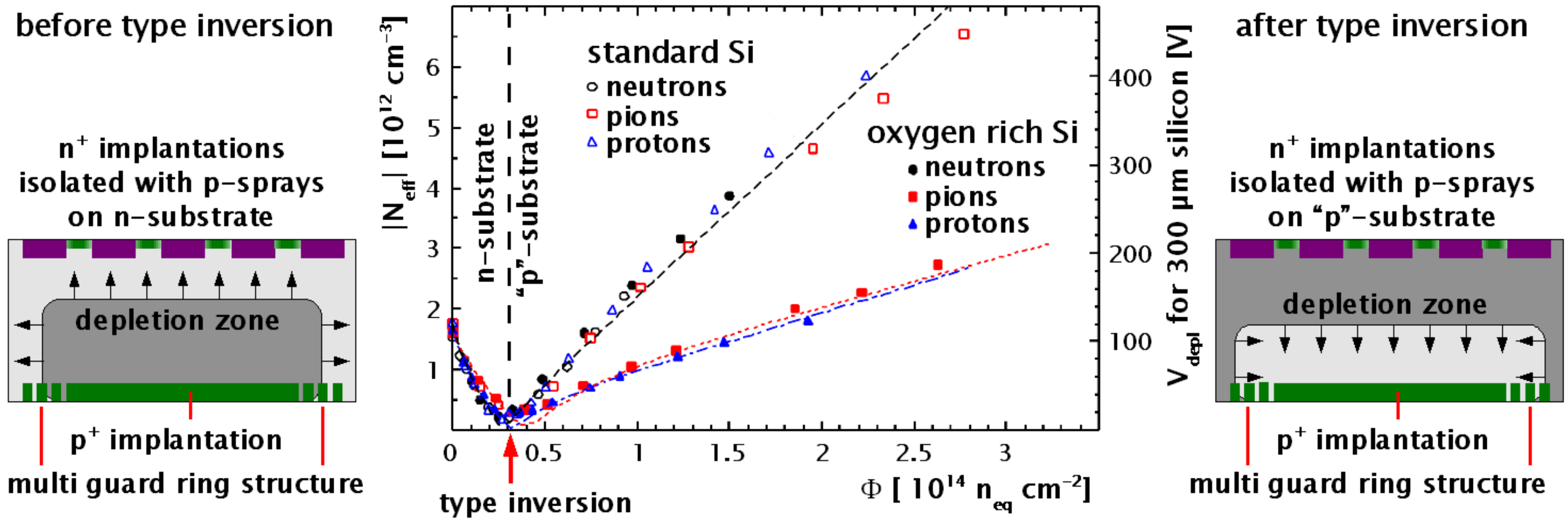
ATLAS Pixel Detector

- 3-hit (3 layers and 3 disks) semiconductor detector closest to the interaction point ⇒ track resolution of 12 μm in Rϕ and of 100 μm in z direction ⇒ 1744 modules
- ⇒ required radiation tolerance: up to $10^{15}\ n_{eq}\ cm^{-2}$ (B-layer)
- overall efficiency aim: > 97 % ⇒ good charge collection even after irradiation necessary

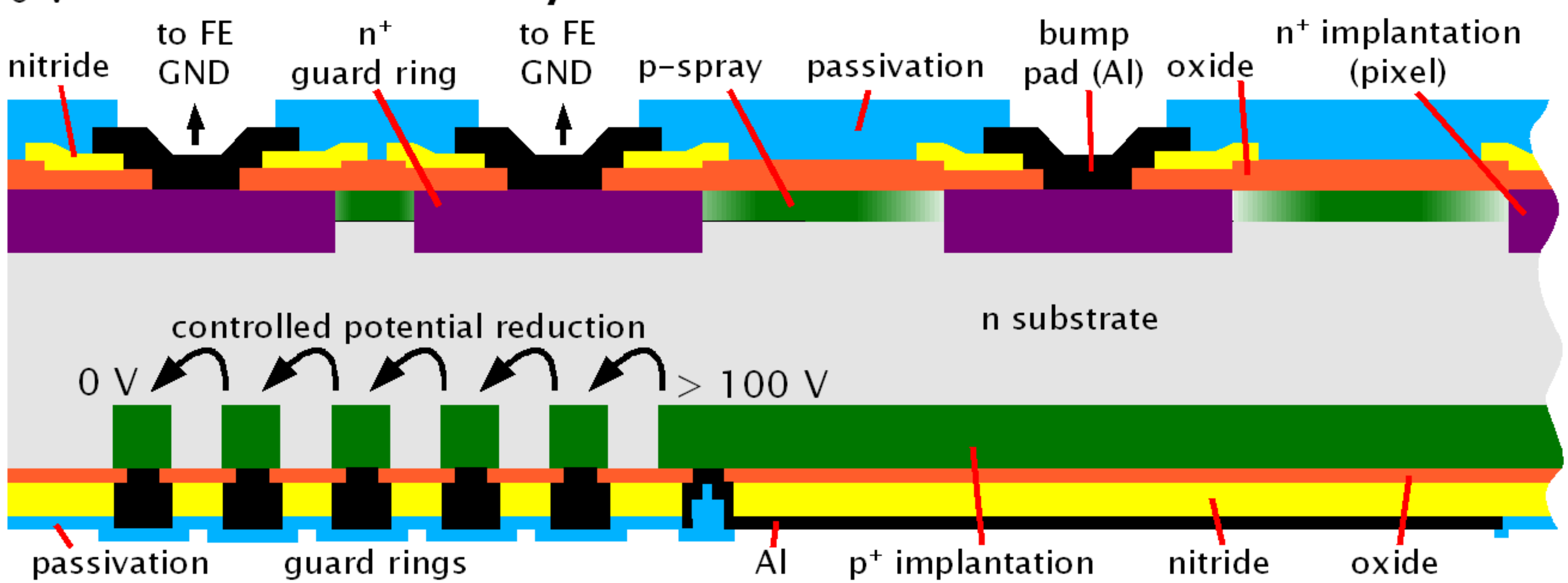


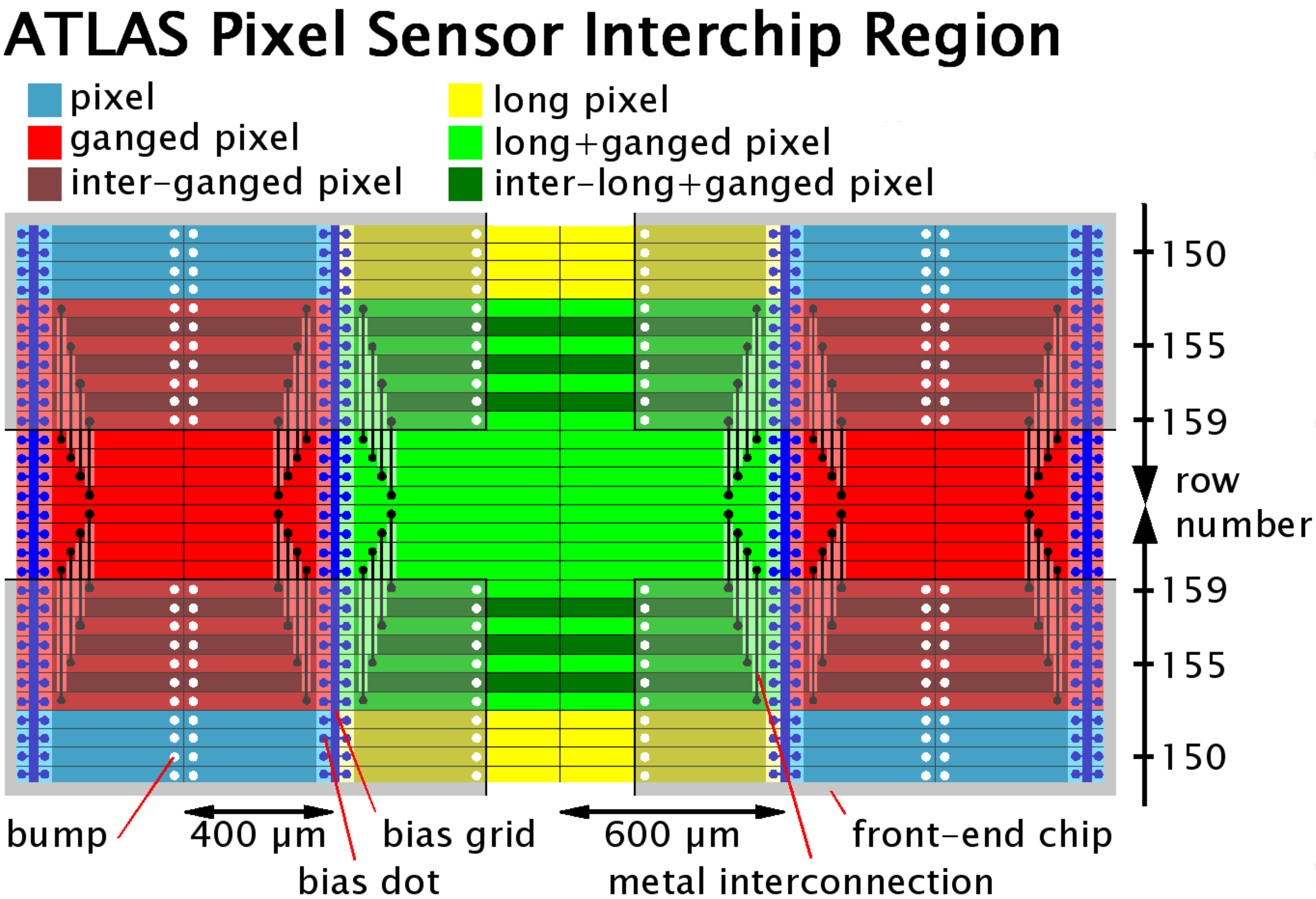
ATLAS Pixel Sensor

- type inversion during irradiation ⇒ oxygen rich Si improves radiation tolerance for pion and proton irradiation
- ⇒ depletion zone has to reach pixel implantations
  ⇒ n^+np^+ design
  ⇒ not fully depleted sensor still can detect particles
- p implantations necessary to isolate pixels
  ⇒ p-stop: alignment risk & high lateral maxima of electric field at bulk-oxide-p^+ junction
  ⇒ p-spray: high lateral maxima of electric field at bulk-p^+-n^+ junction
  ⇒ moderated p-spray



Schematic Layout of the ATLAS Pixel Sensor

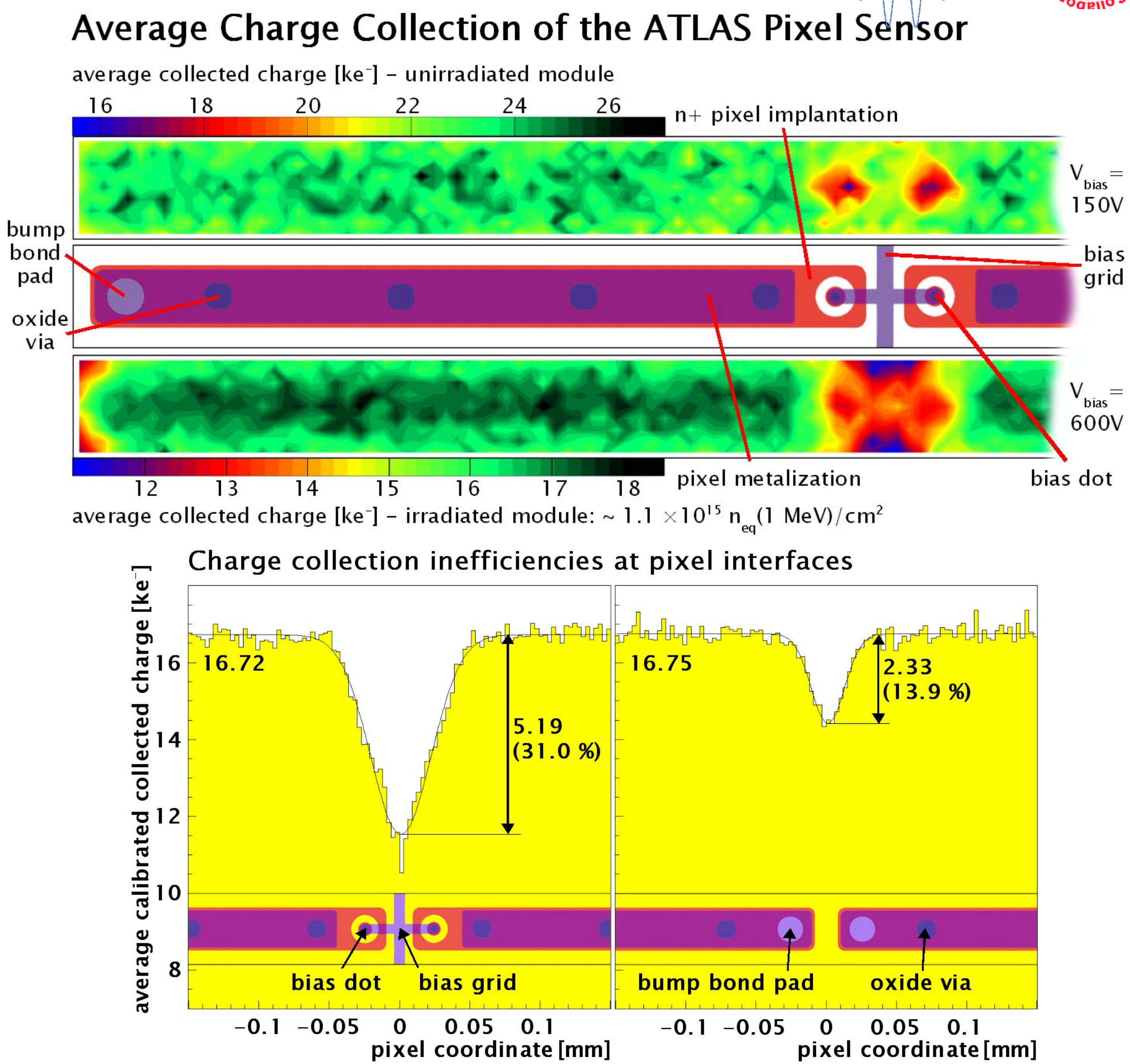




- standard pixel are 400 * 50 µm
- to avoid dead areas between FEs pixel are prolonged in the long direction ⇒ long pixel
- in the short pixel direction a pixel in the interchip region is connected by a metal layer to a pixel which has a connection to the FE ⇒ ganged pixel
- only every second pixel with FE connection close to the interchip region is ganged ⇒ allows to distinguish between interchip and FE hit for 2-pixel hits ⇒ higher capacitance due to metal layer for inter-ganged pixel
- ganged and inter-ganged pixel exist also for long pixel ⇒ in total 6 pixel types

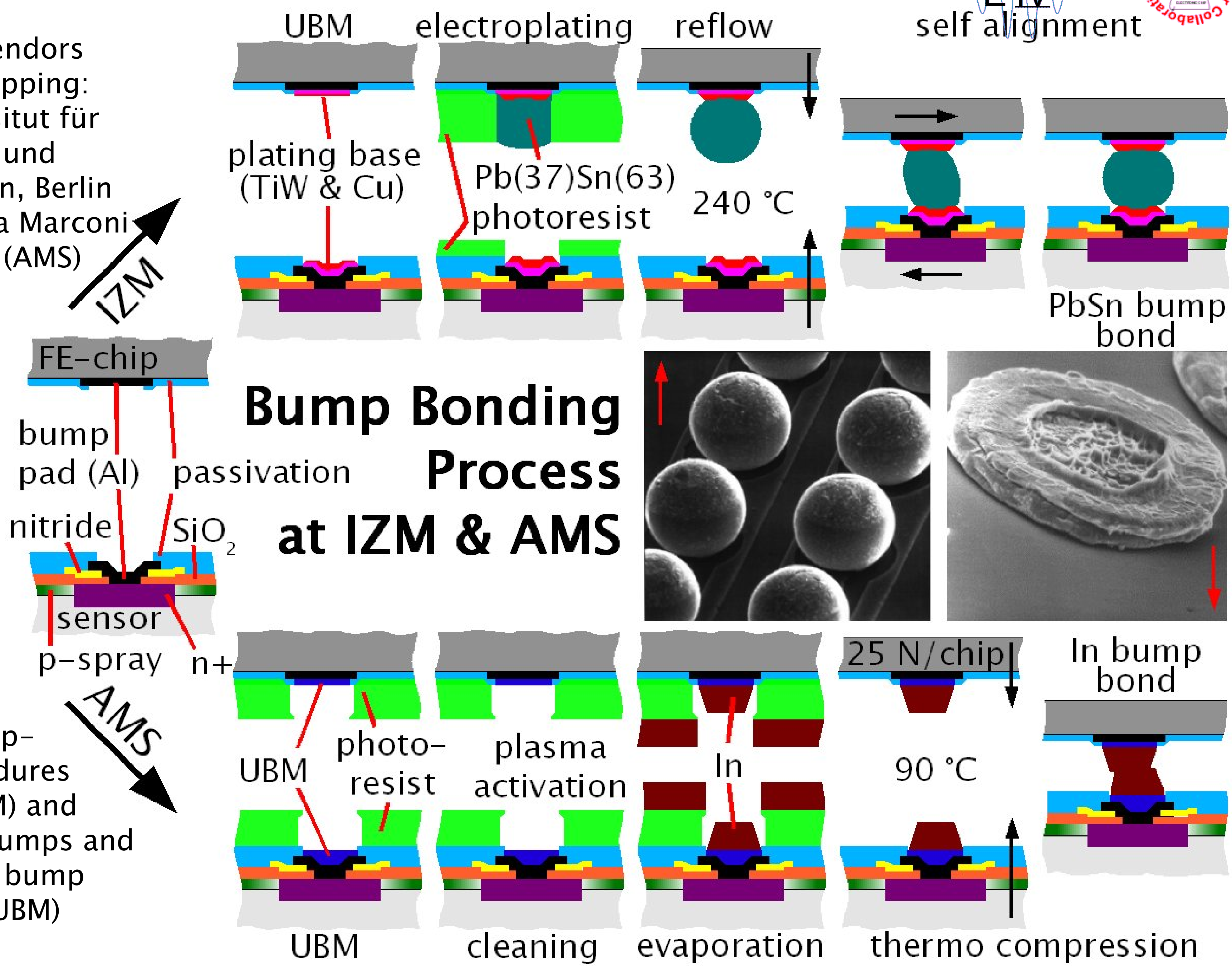
Sensor Charge Collection

- unirradiated: average collected charge homogeneous & no significant charge losses at the interfaces – but: ~ 33 % loss at bias dots caused by direct charge collection onto the bias dot and ~ 8 % between the bias dots due to indirect capacitive coupling through the p-spray to the bias grid metalization
- irradiated: not fully depleted & radiation induced trapping centers ⇒ 20 % lower average collected charge – increased trapping probability for charges following the bend streamlines of the electric field at the margins – high probability of charge sharing between up to 4 pixels in corners and increased indirect coupling ⇒ up to 33 % charge loss there

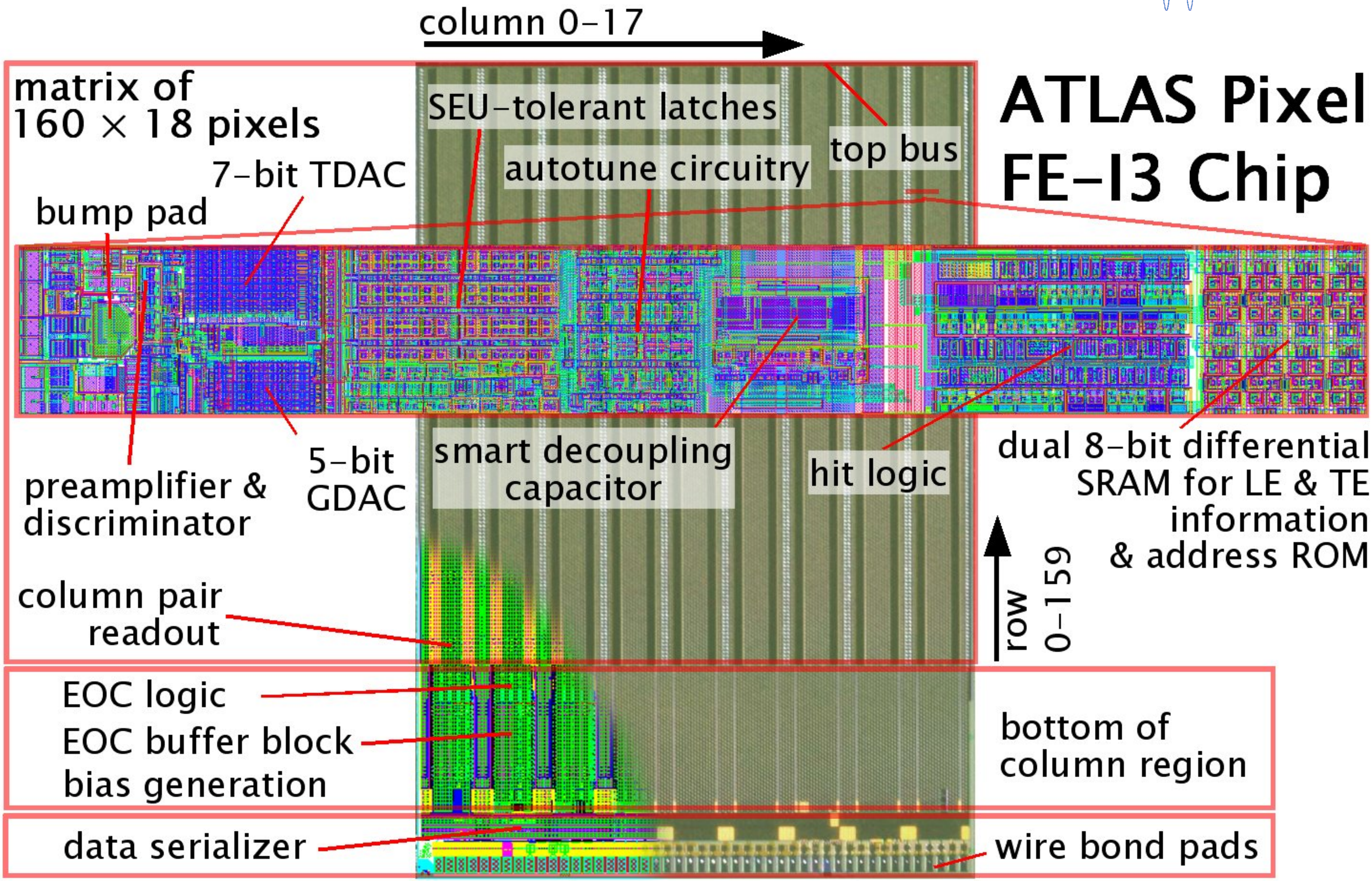


Flip-chipping at IZM and AMS

- two different vendors provide flip-chipping: Frauenhofer Insitut für Zuverlässigkeit und Mikrointegration, Berlin (IZM) and Alenia Marconi Systems, Roma (AMS)
- two different flip-chipping procedures with solder (IZM) and indium (AMS) bumps and different under bump metalizations (UBM)

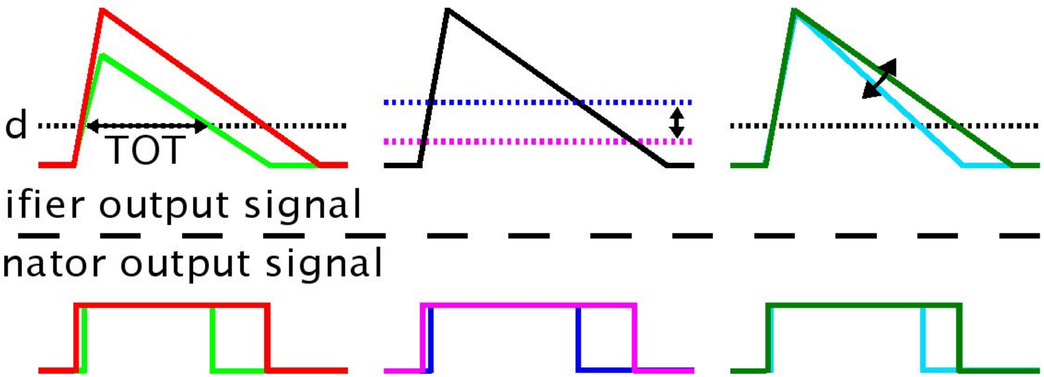


FE-I3 Readout Chip

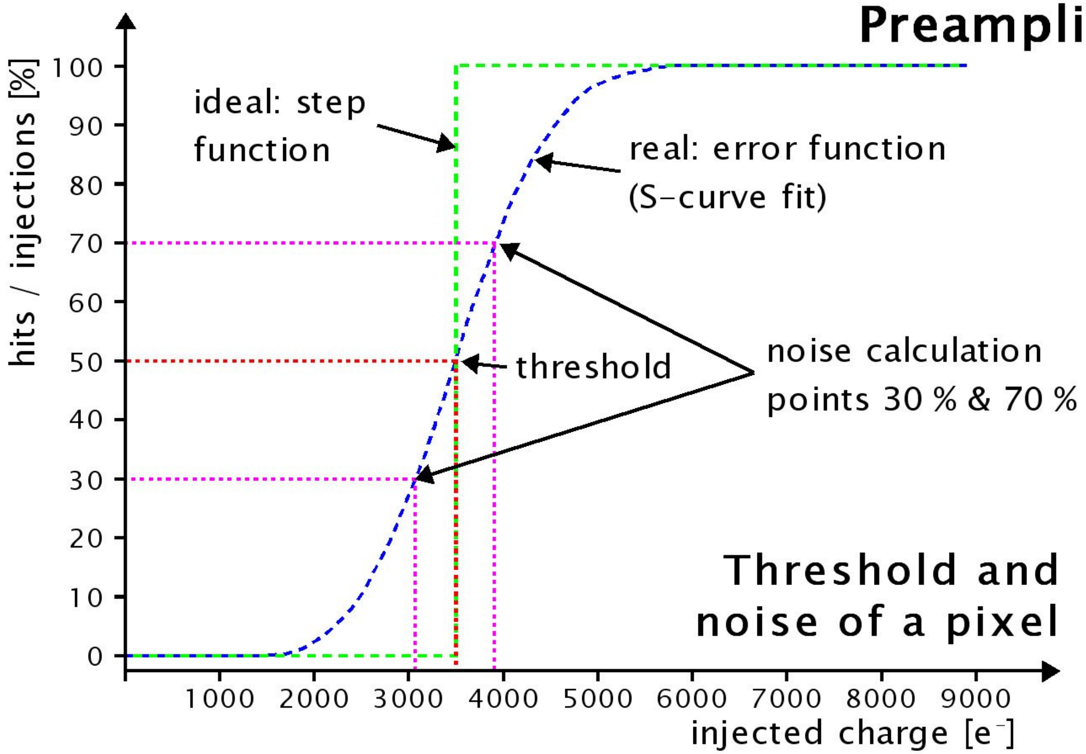


Preamplifier and discriminator signal shapes

- preamplifier output signal proportional to the collected charge; feedback current decreases signal lineary ⇒ discriminator used to digitalize signal ⇒ time over threshold (TOT) proportional to the collected charge
- each pixel can be tuned individually by changing the threshold and the feedback current

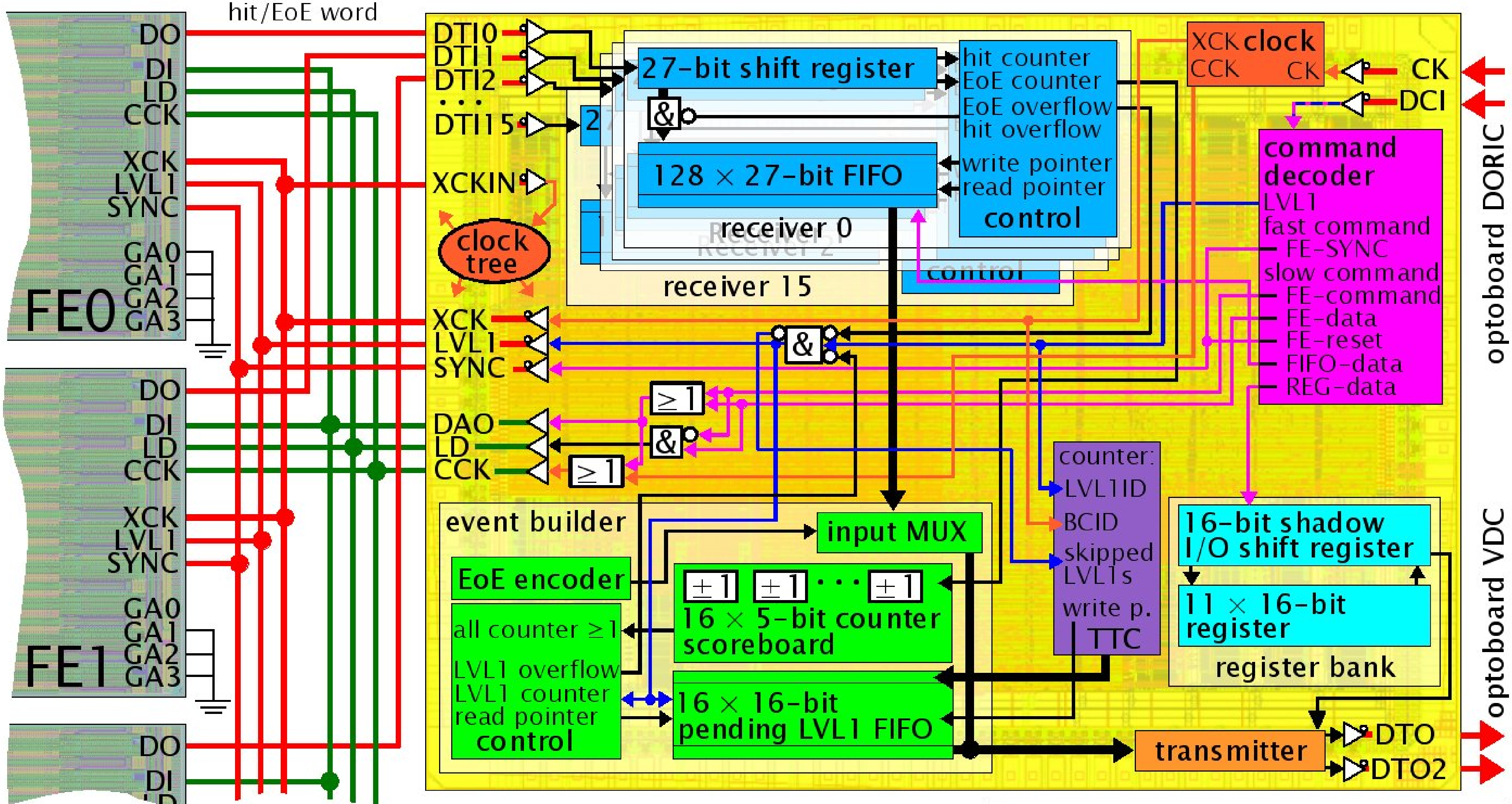


Preamplifier and discriminator signal shapes



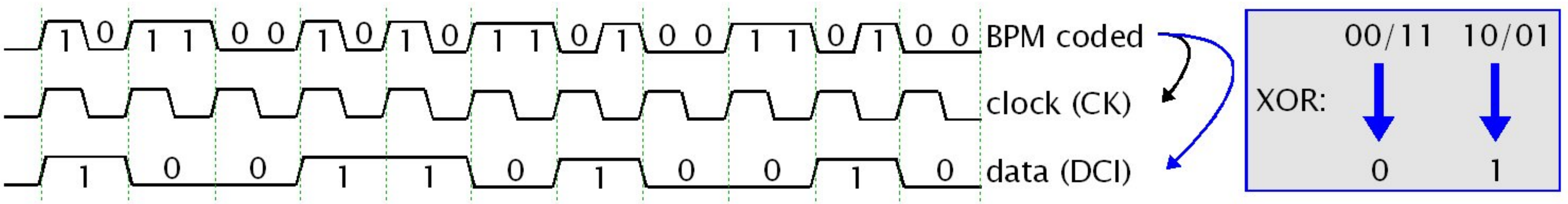
Threshold and noise of a pixel

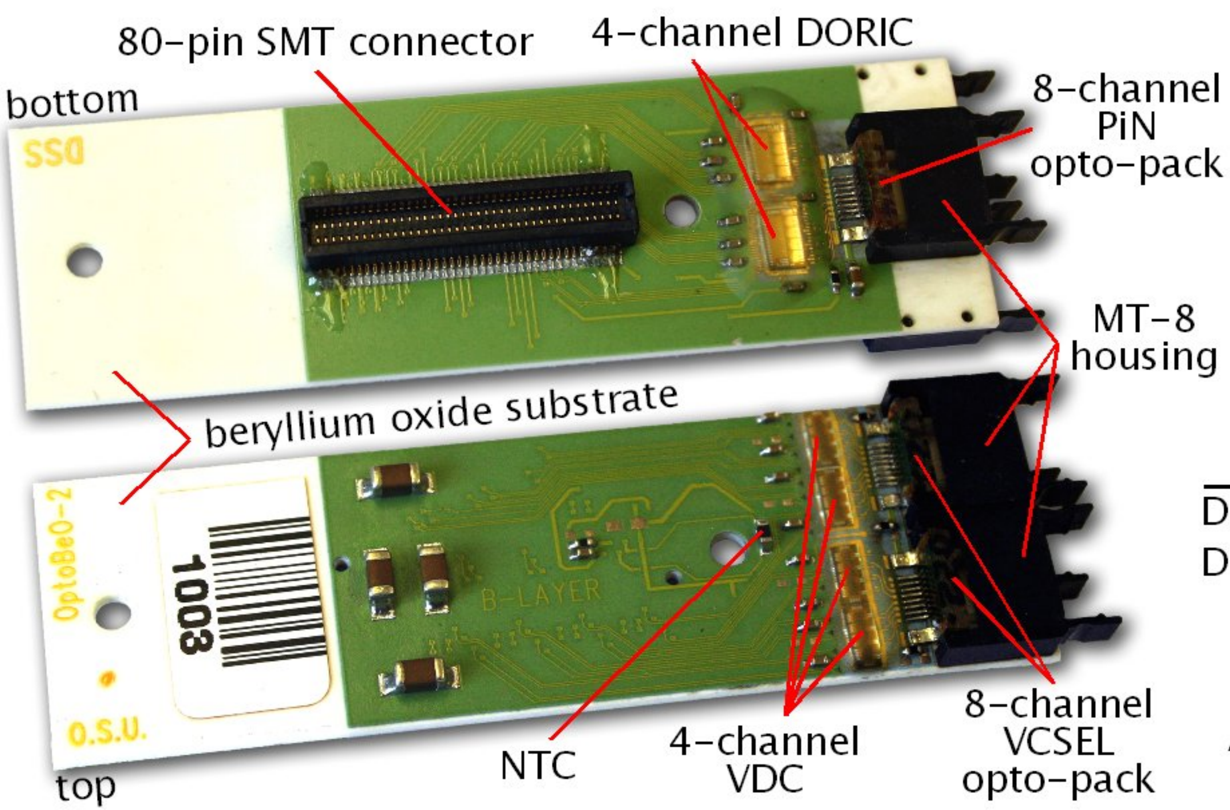
- without noise: step function expected ⇒ all collected charges above threshold visible and collected charges below threshold are not detectable
- pixel/preamplifier noise ⇒ convolution of the step function and the Gaussian pixel noise distribution ⇒ error function
- ⇒ 50% efficiency: threshold
- ⇒ noise inversely proportional to the stepness of the transition from no detected hits to full efficiency

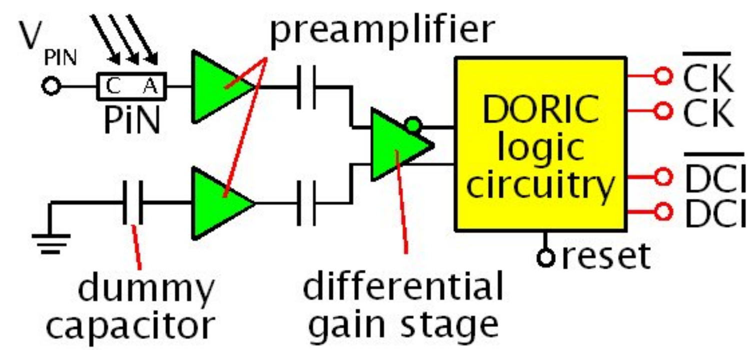


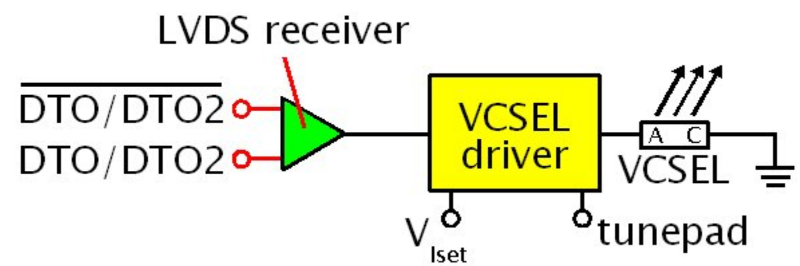
ATLAS Pixel MCC Schematic

clock
LVL1
command/data
LVDS line
CMOS line





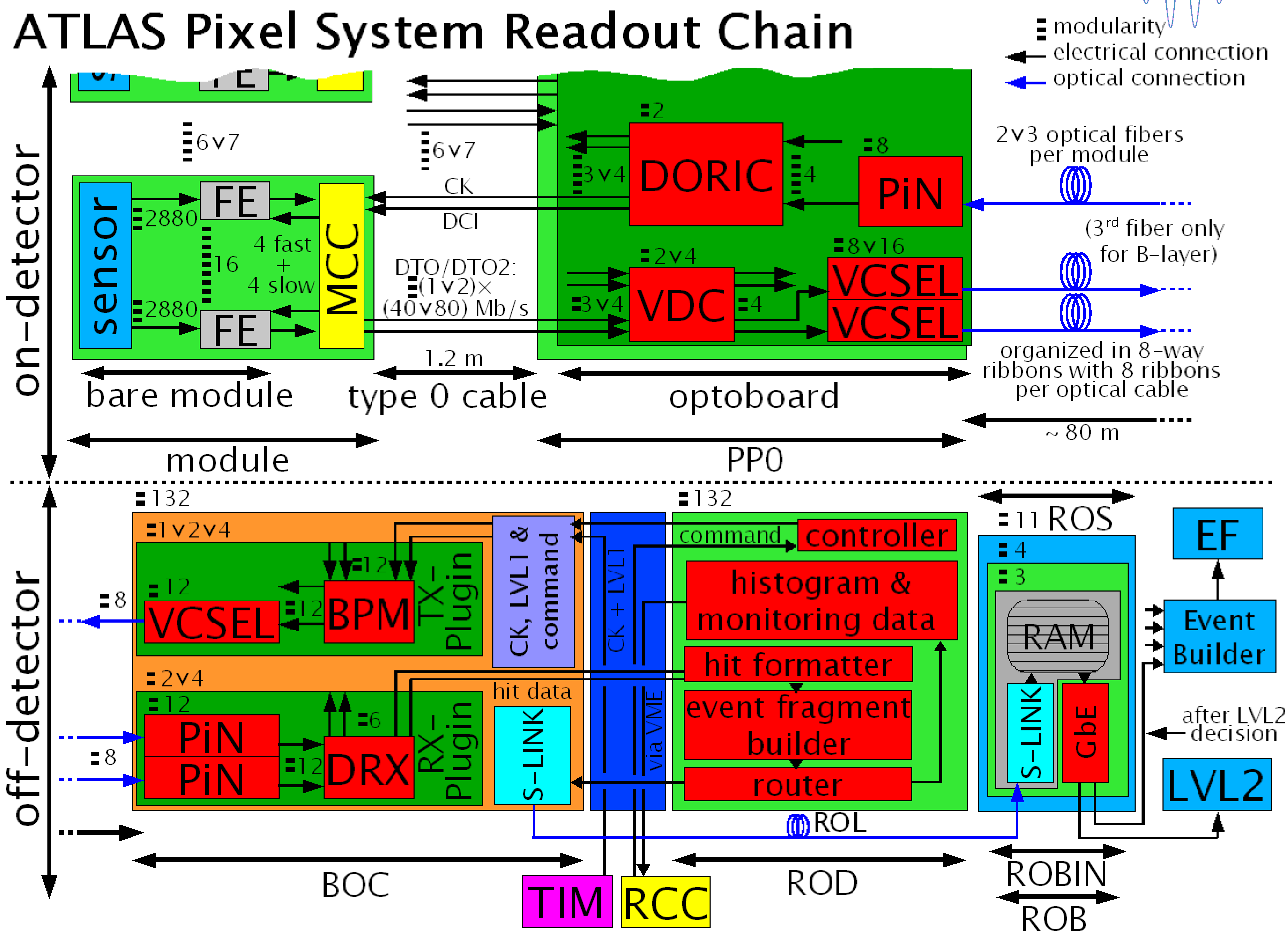




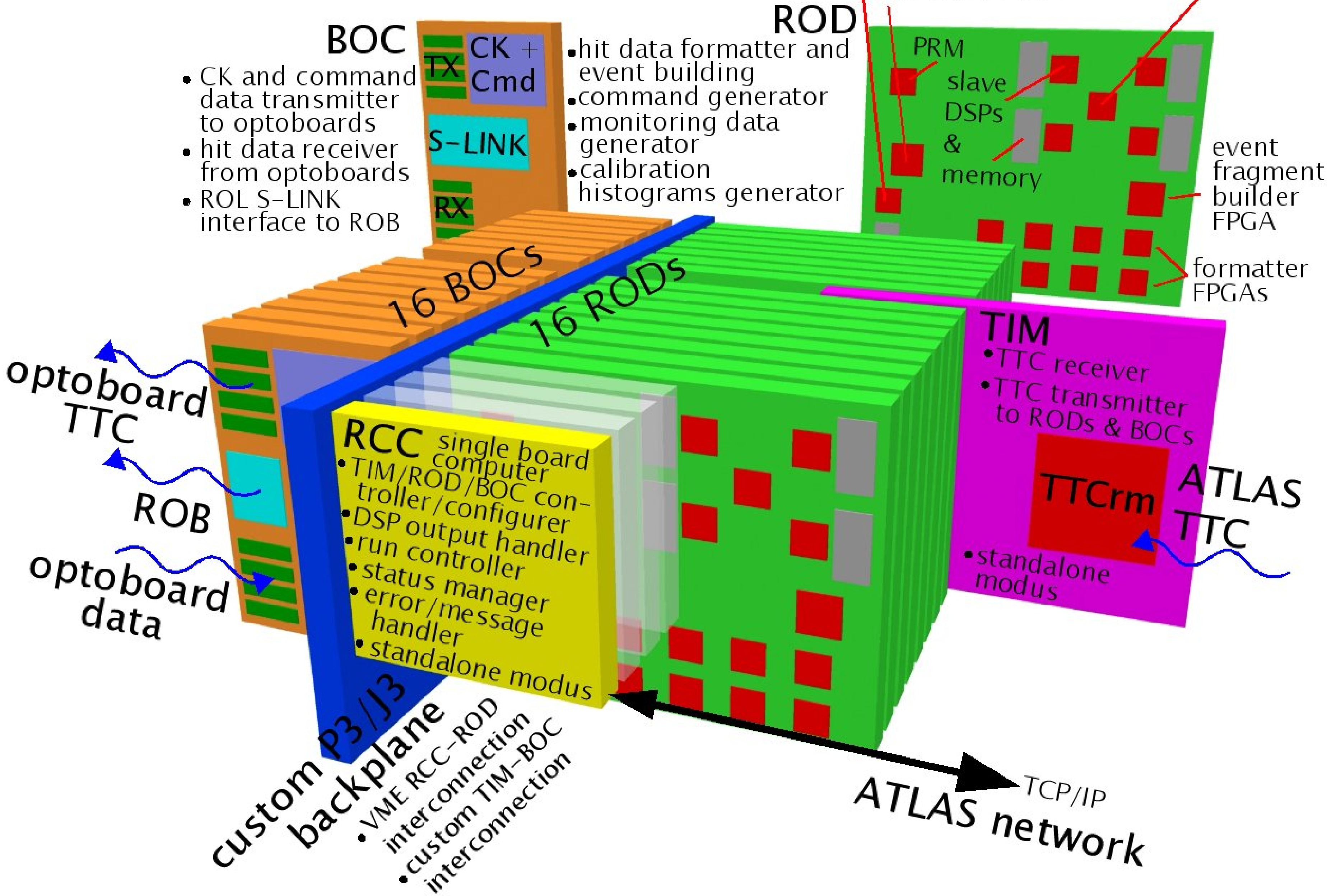
ATLAS Pixel Optoboard

dimensions: 2 × 6.5 cm^2

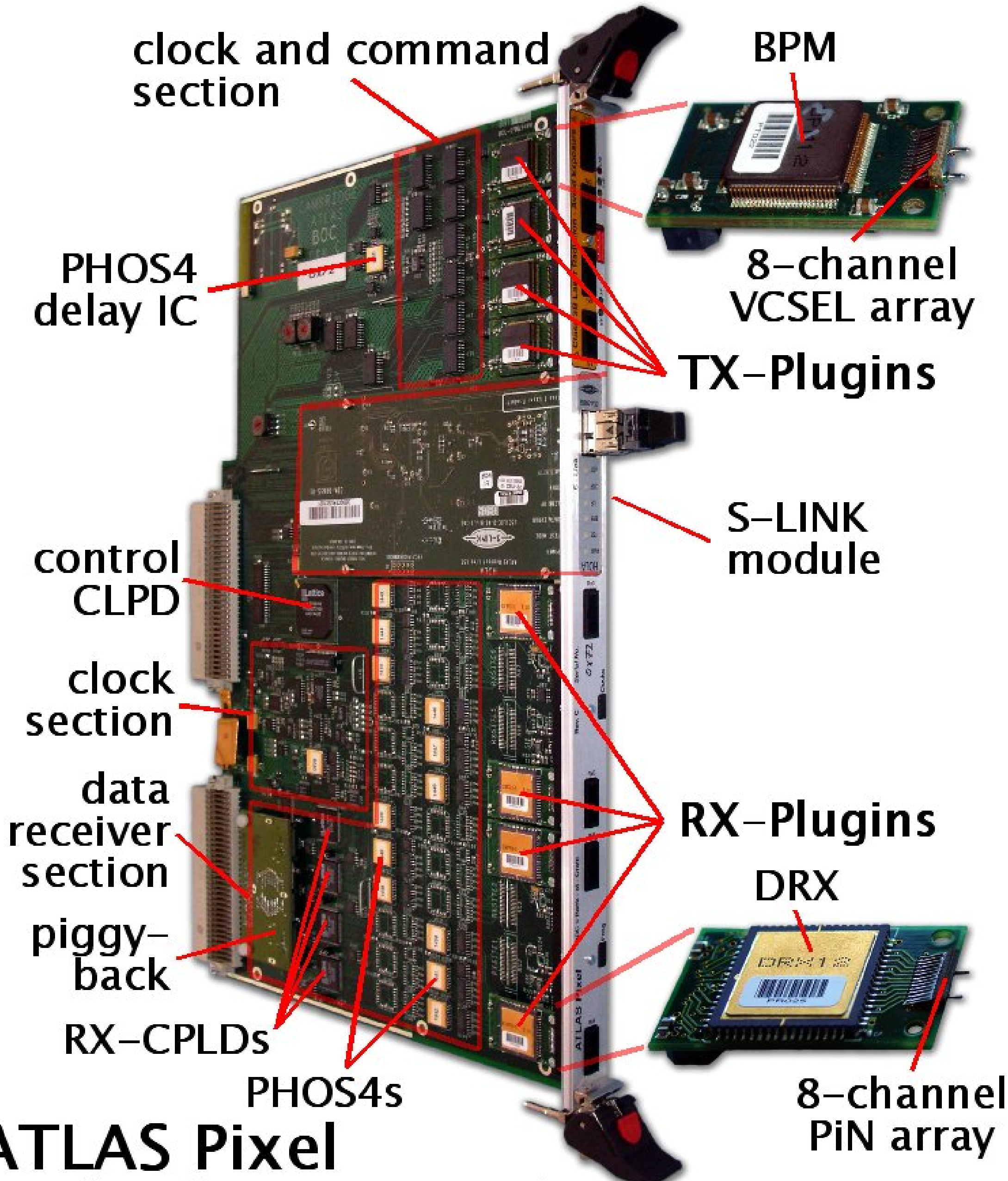
Readout Chain



ATLAS Pixel Readout Crate

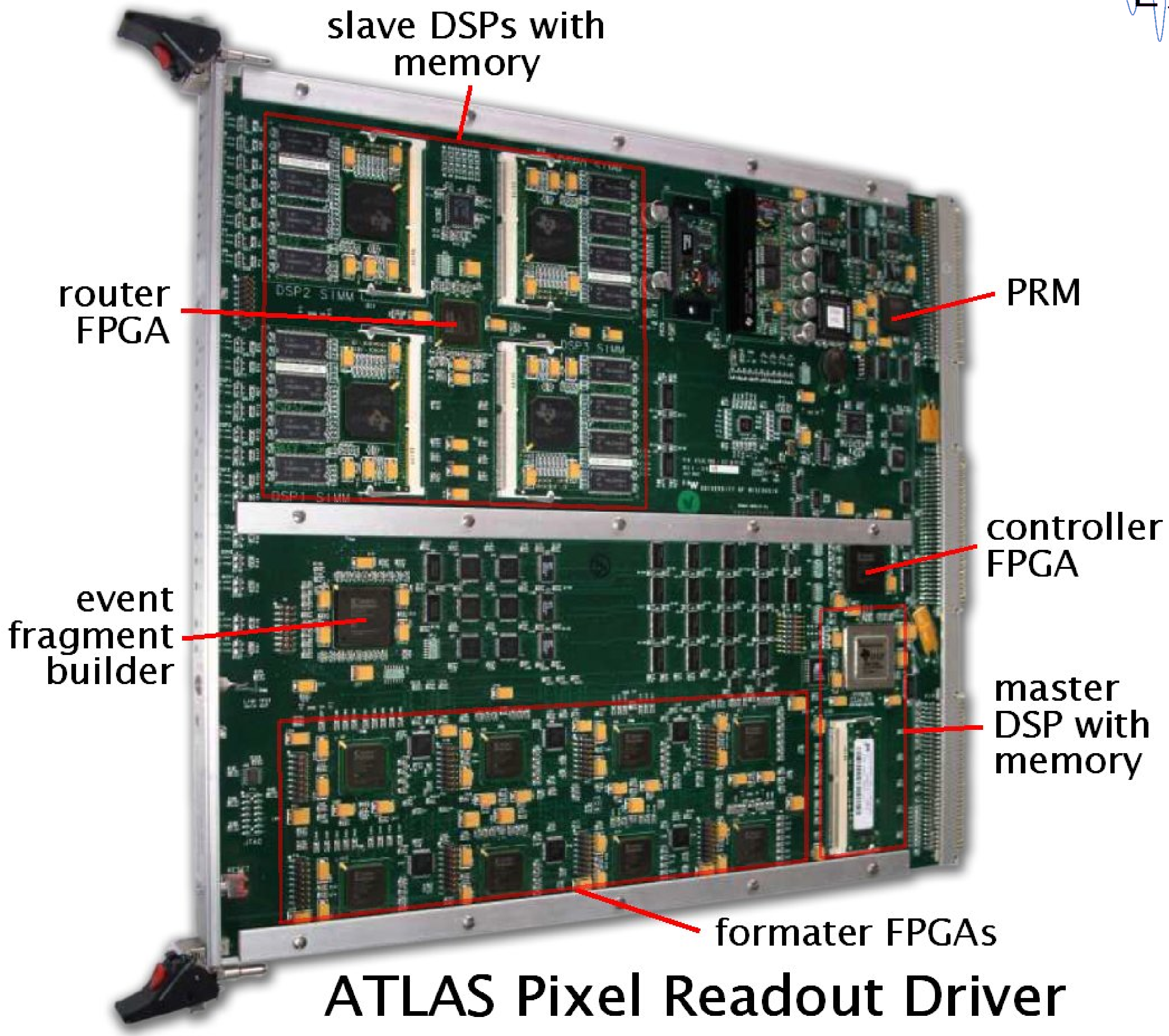


Readout Crate – BOC



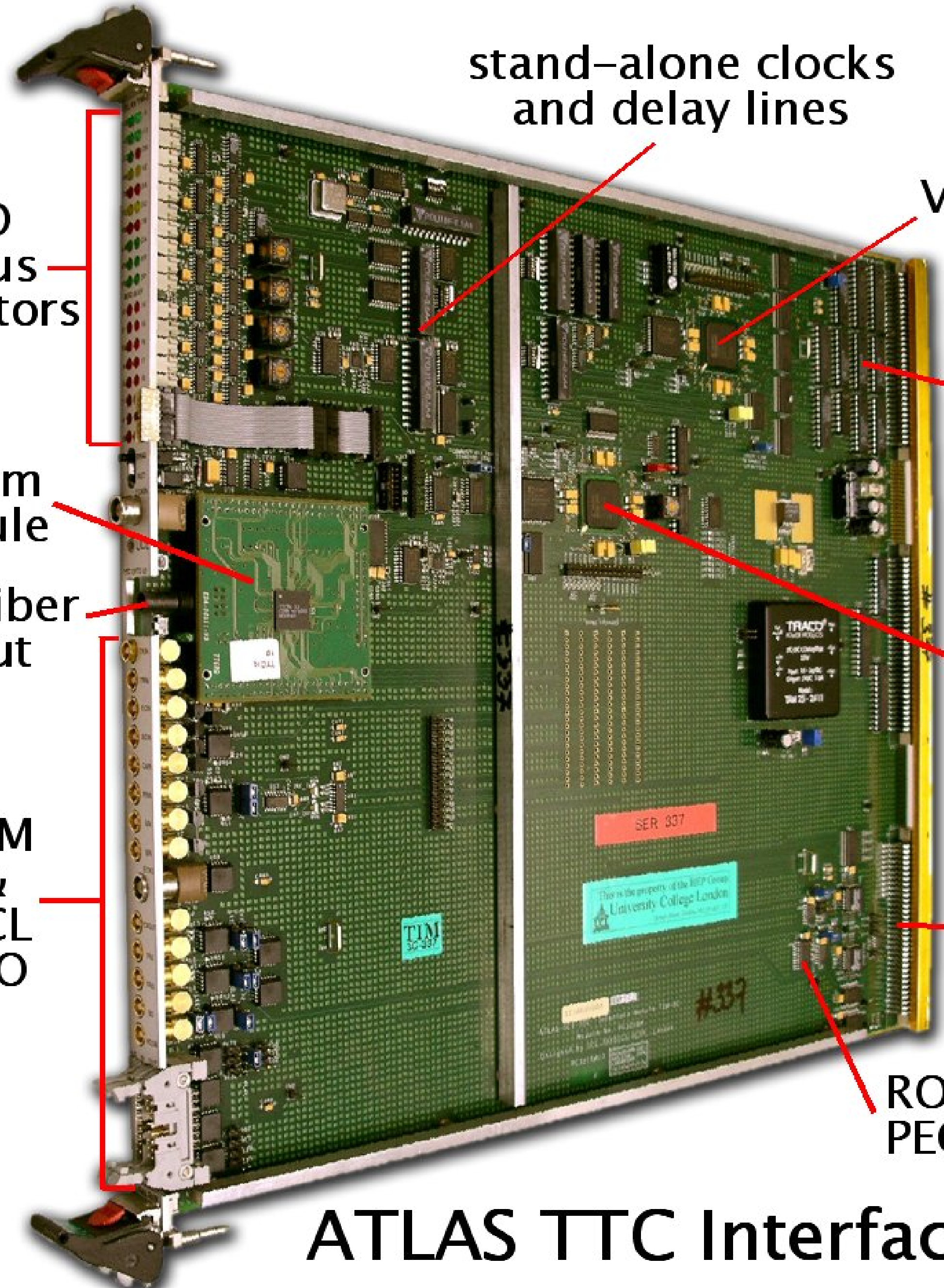
ATLAS Pixel
Back of Crate Card

Readout Crate - ROD



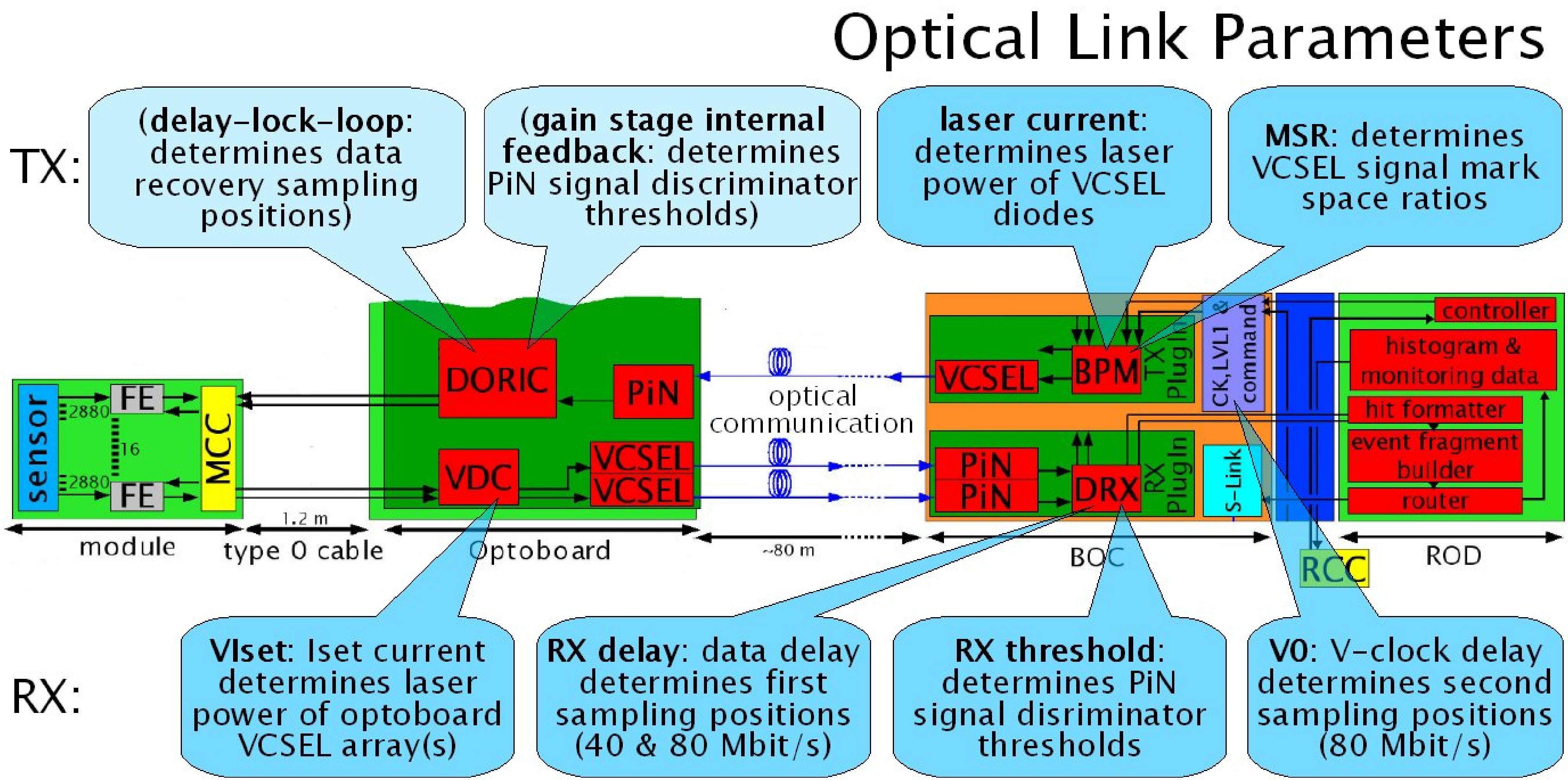
ATLAS Pixel Readout Driver

Readout Crate – TIM

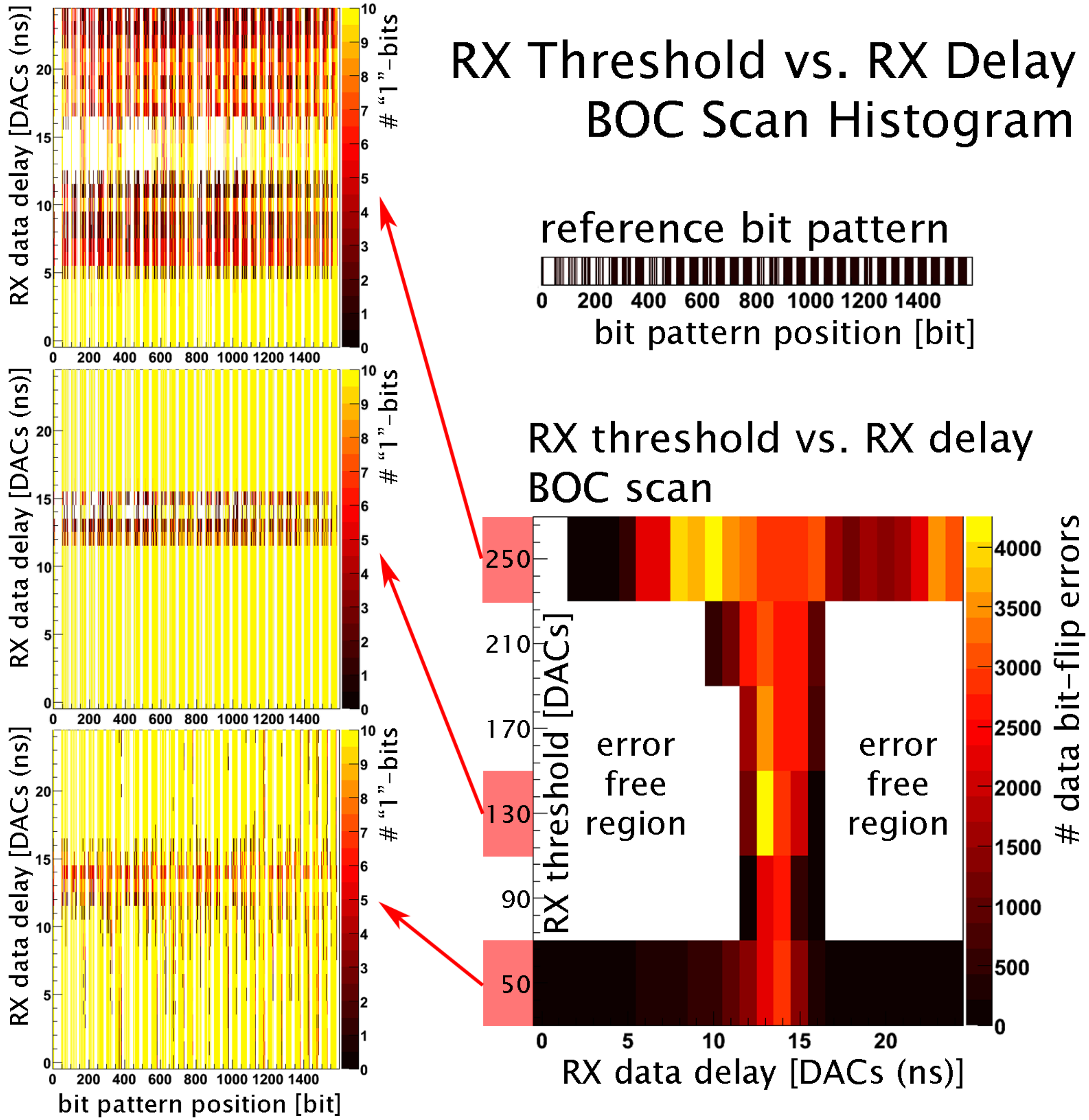


ATLAS TTC Interface Module

Optical Link Tuning Parameters

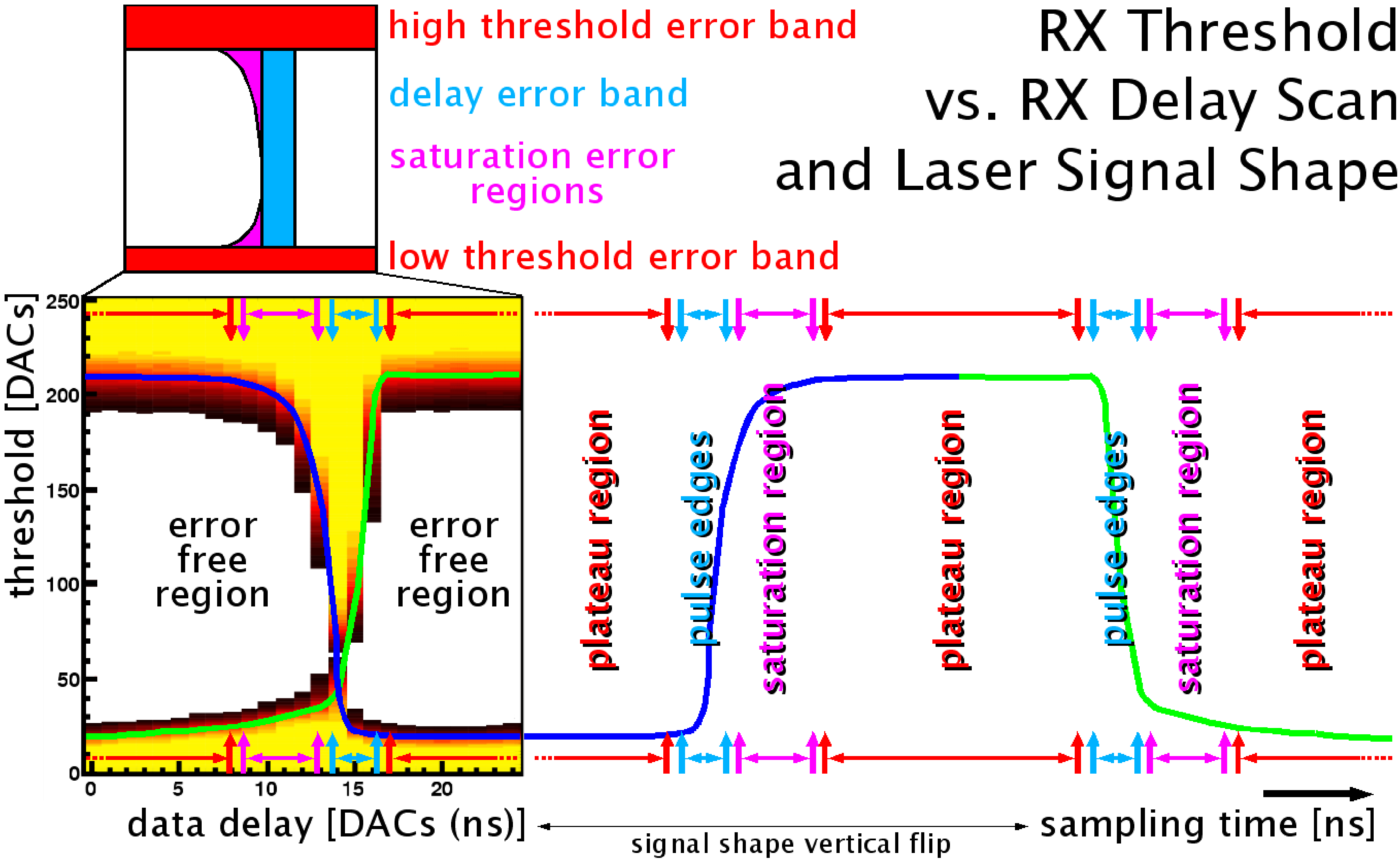


RX Threshold vs. RX Delay BOC Scan Histogram

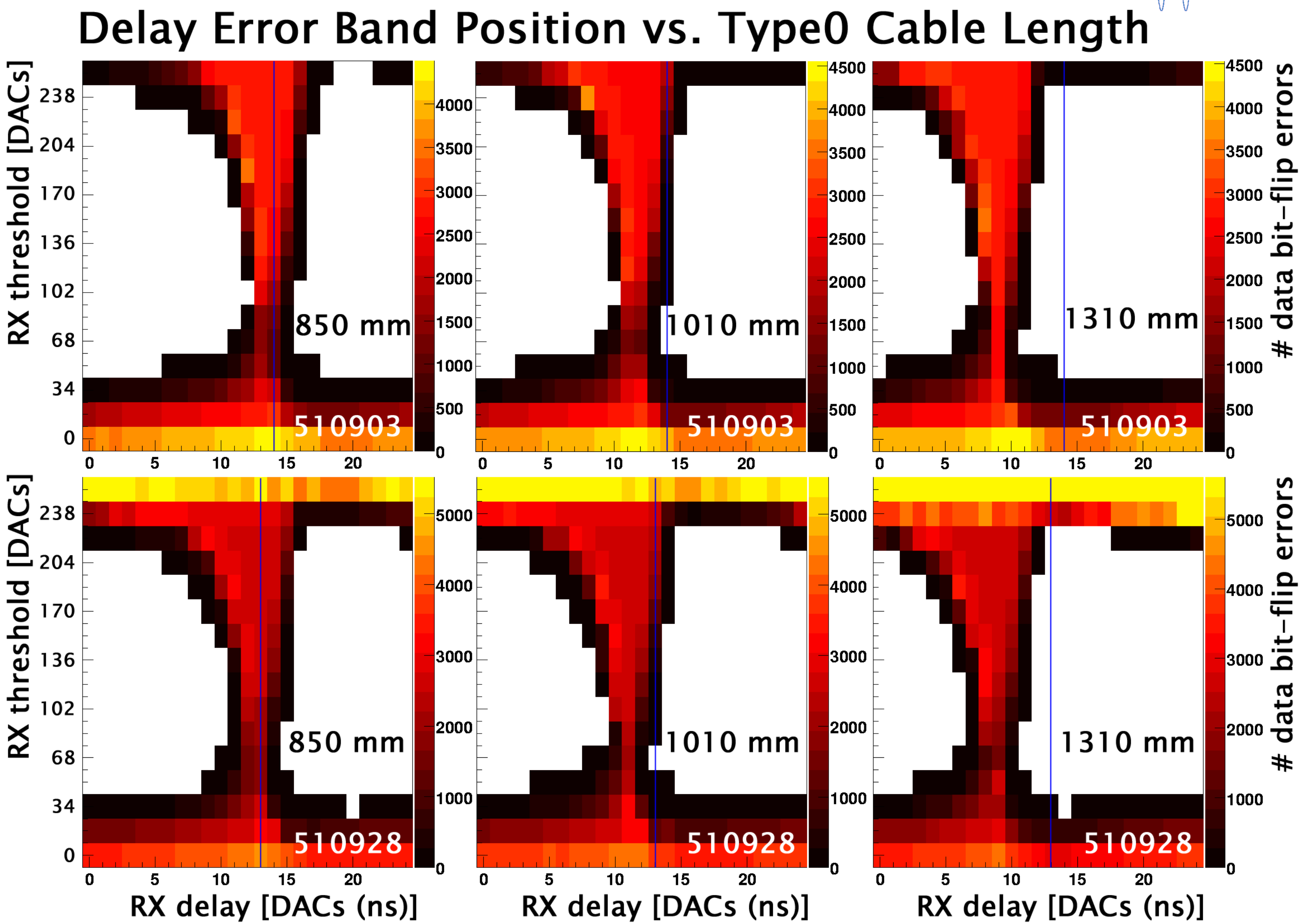


Optical Data Transmission Signal Shape

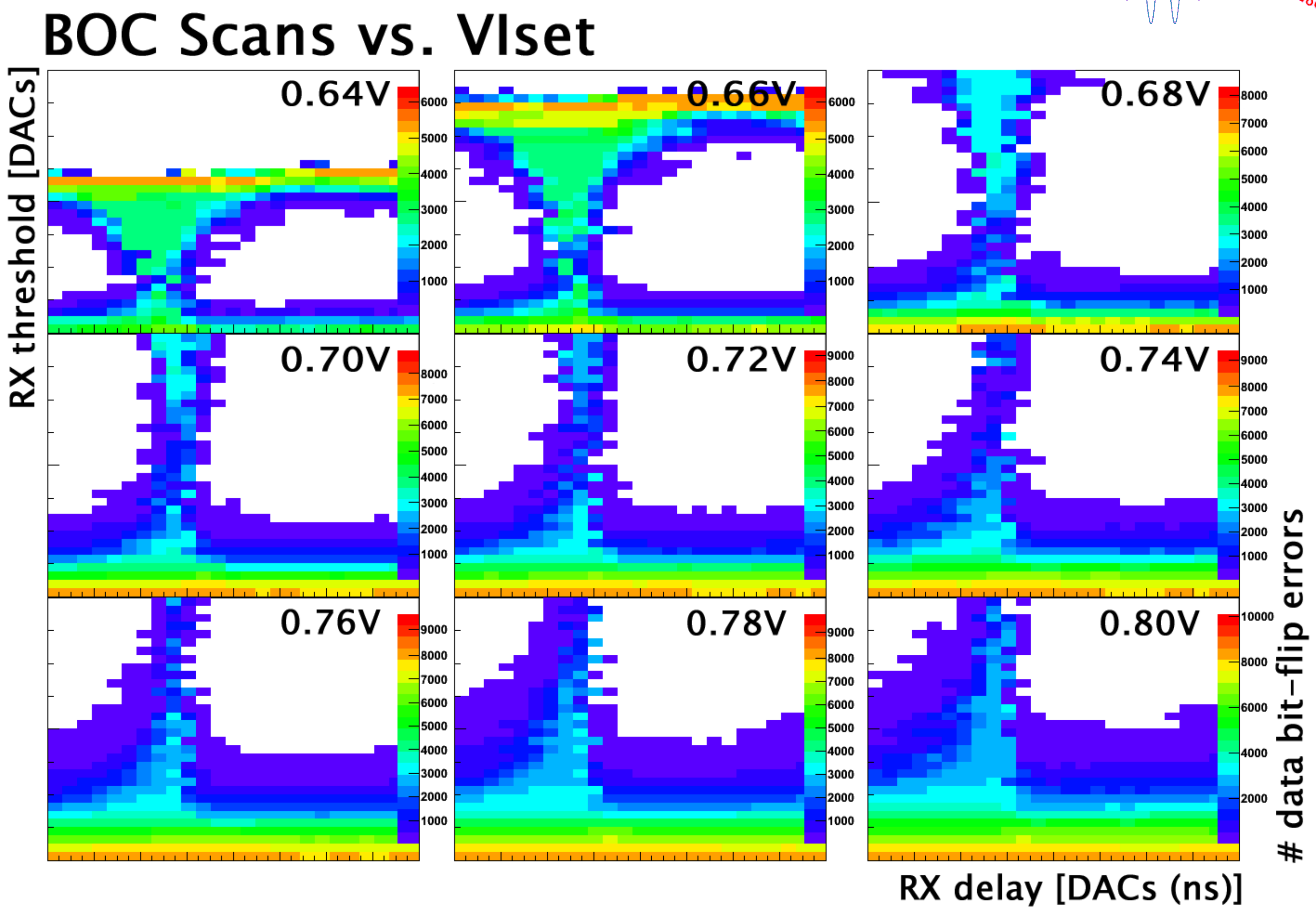
RX Threshold vs. RX Delay Scan and Laser Signal Shape



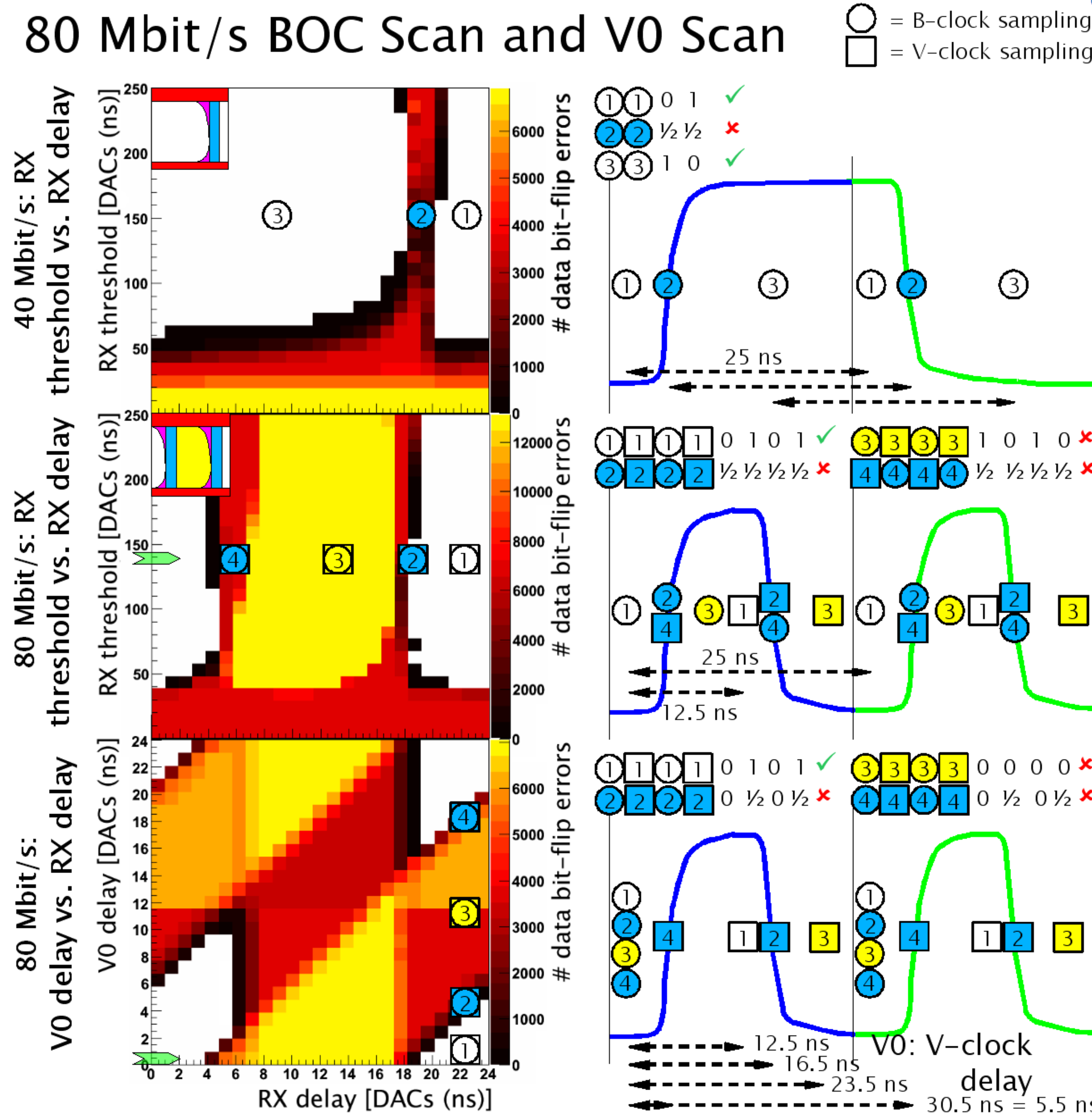
RX Delay Cable Length Dependency



BOC Scan VIset Dependency



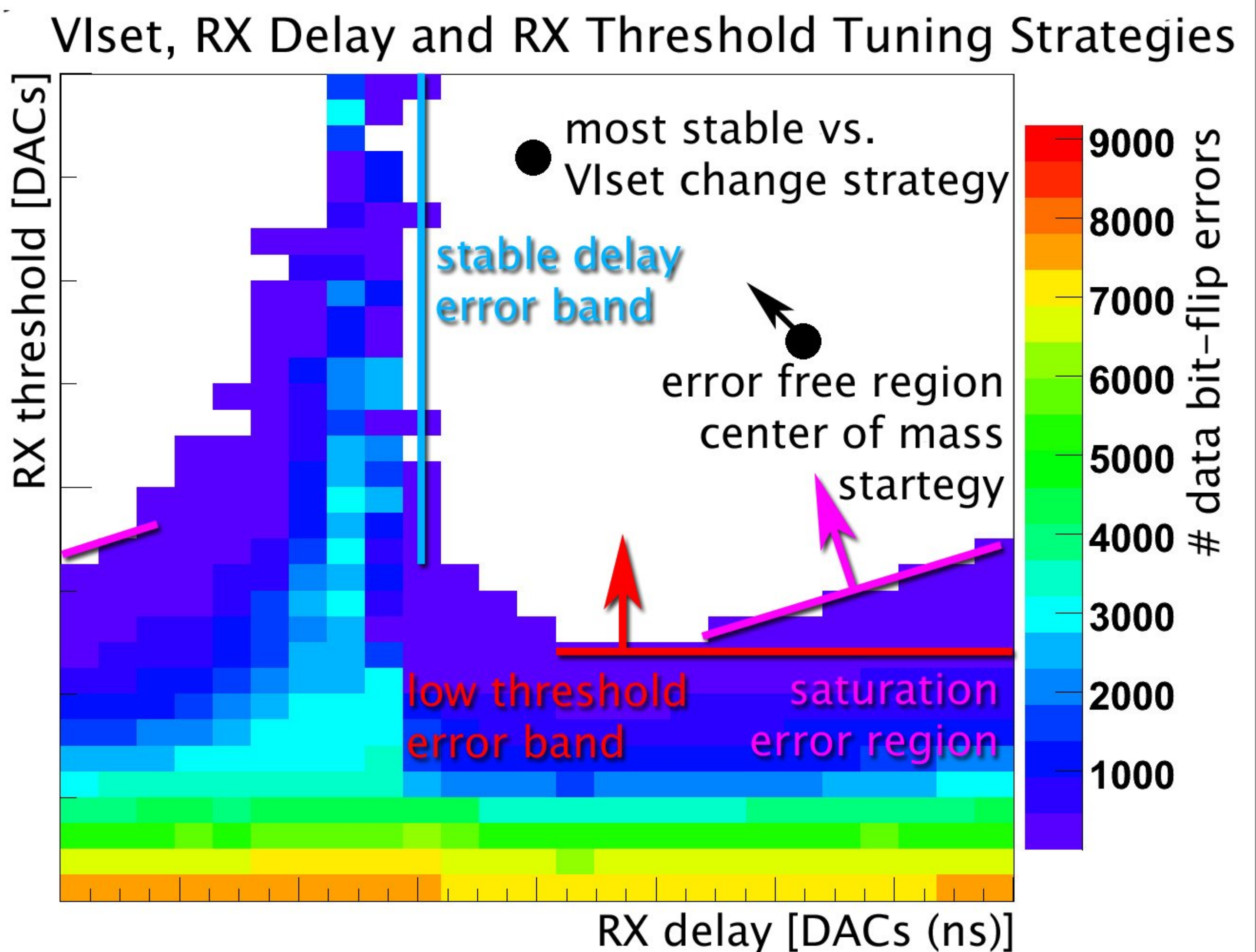
80 Mbit/s BOC Scans



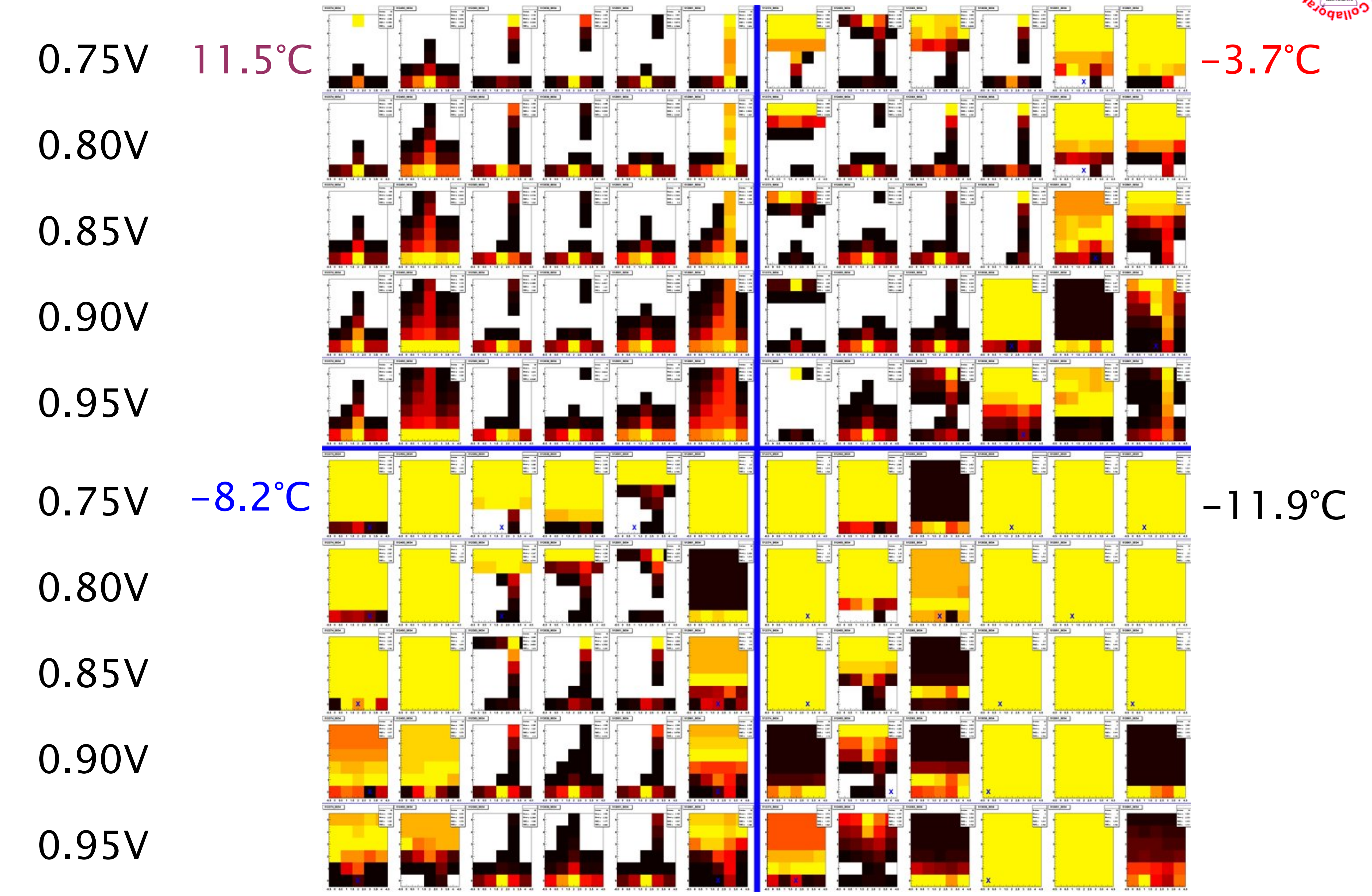
Phenomenology of the good-parameter-space

- optoboard channel dependent lower threshold band increases linearly with ViSet
- upper threshold band with much higher slope as well
- module (cable length) dependent delay-error band with threshold and ViSet stable upper and wide tailed lower edge

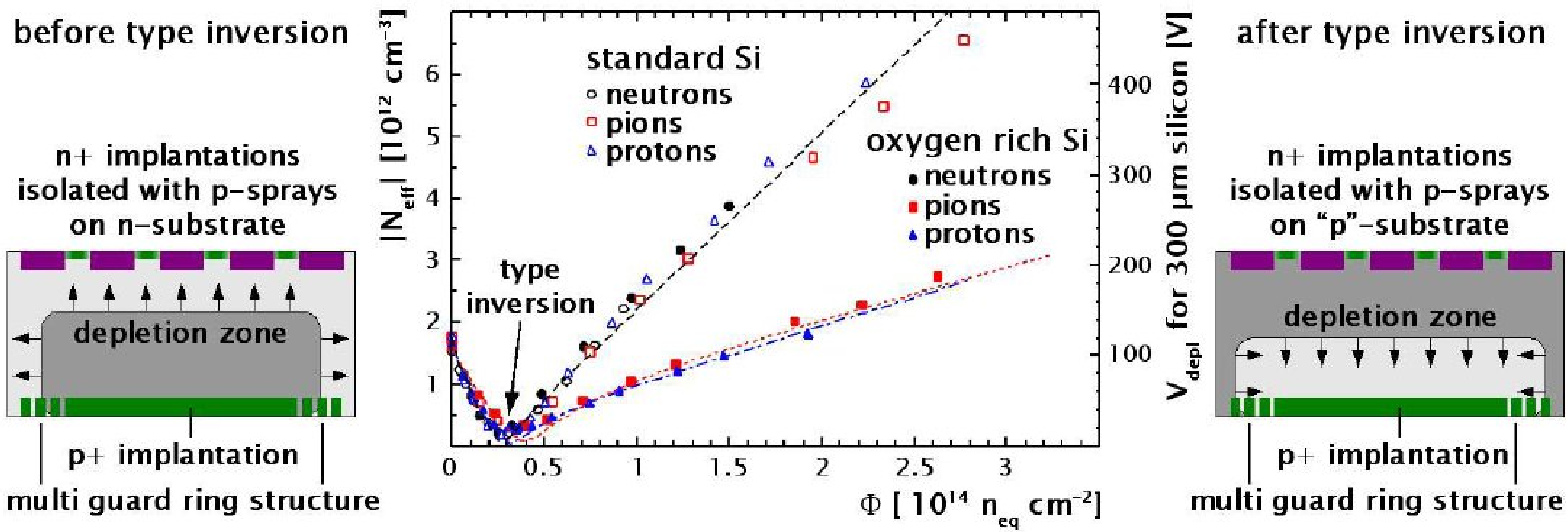
➔ good-parameter-space is reduced with increasing ViSet in upper-left direction



sector 9034 – optoboard 2029 – BAD

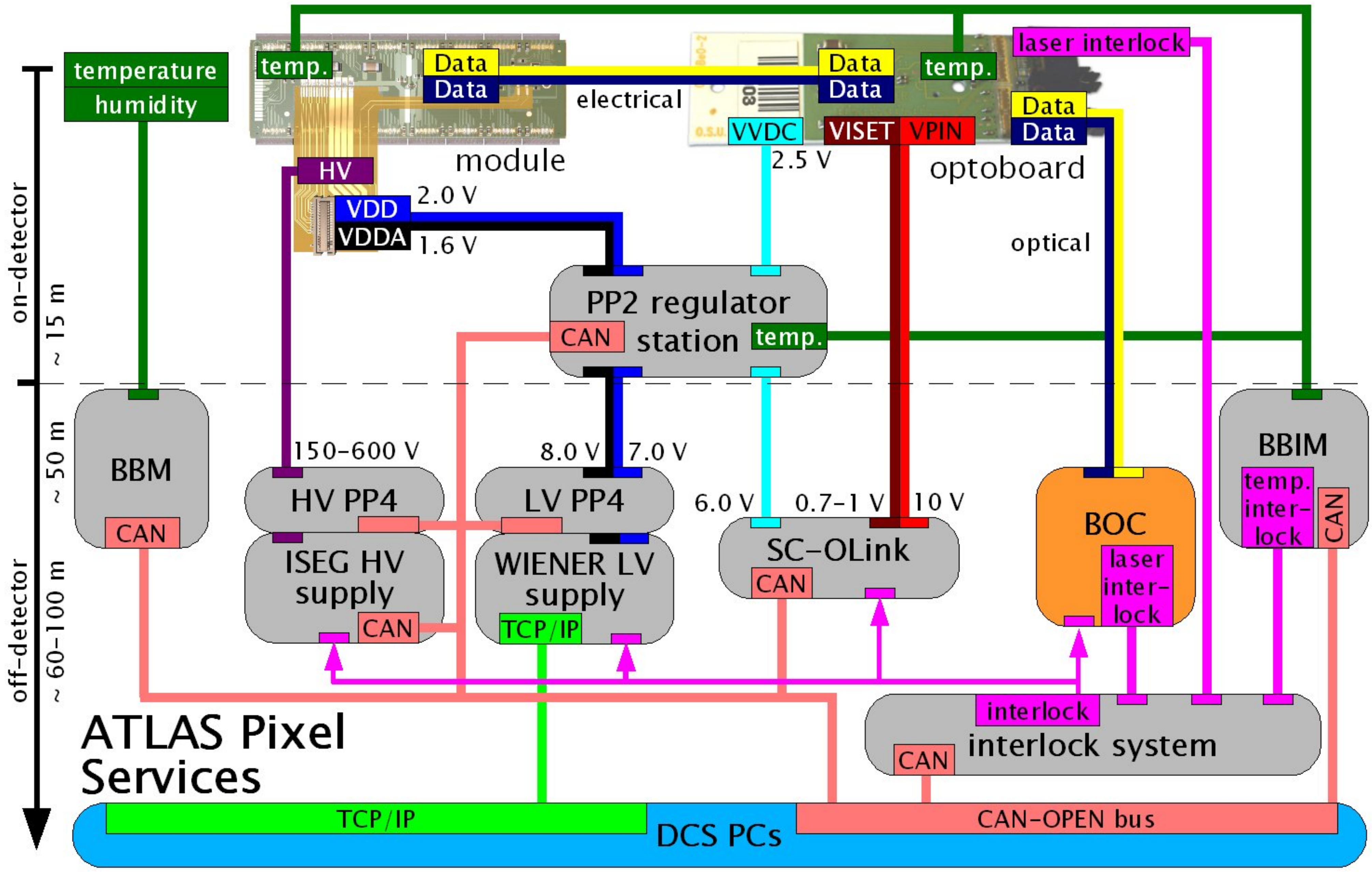


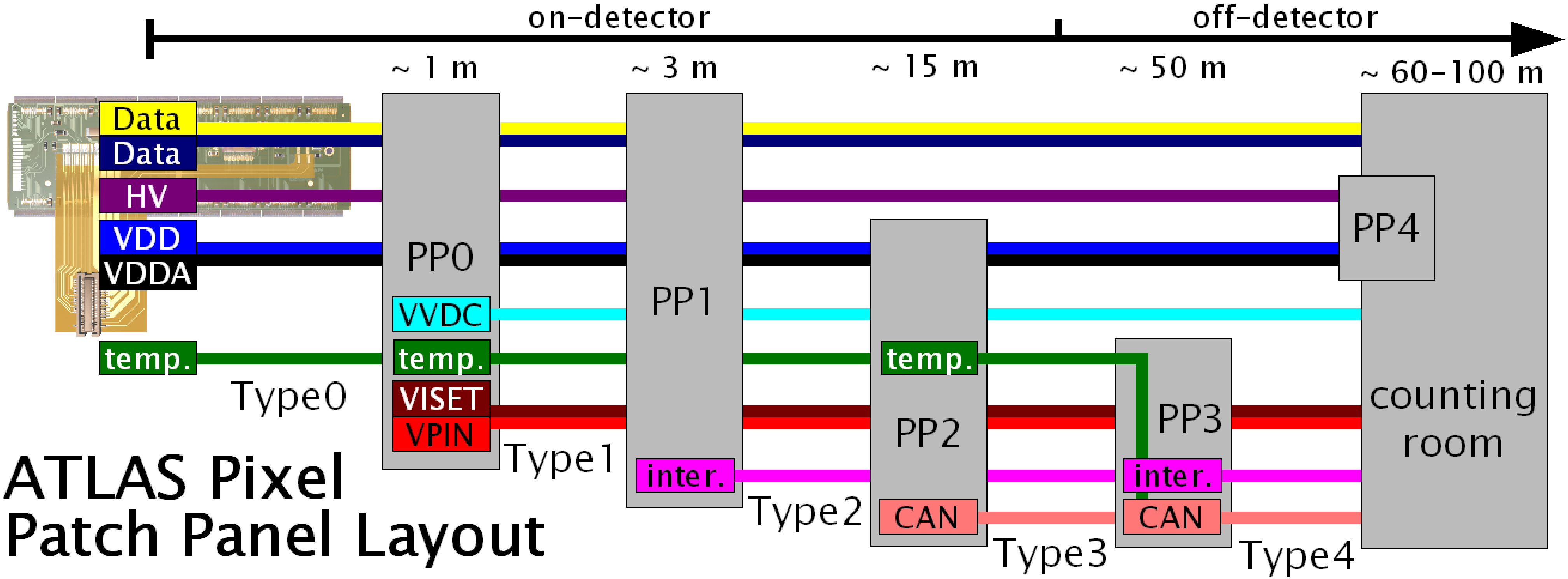
Noise Occupancy at the edge of the depletion voltage



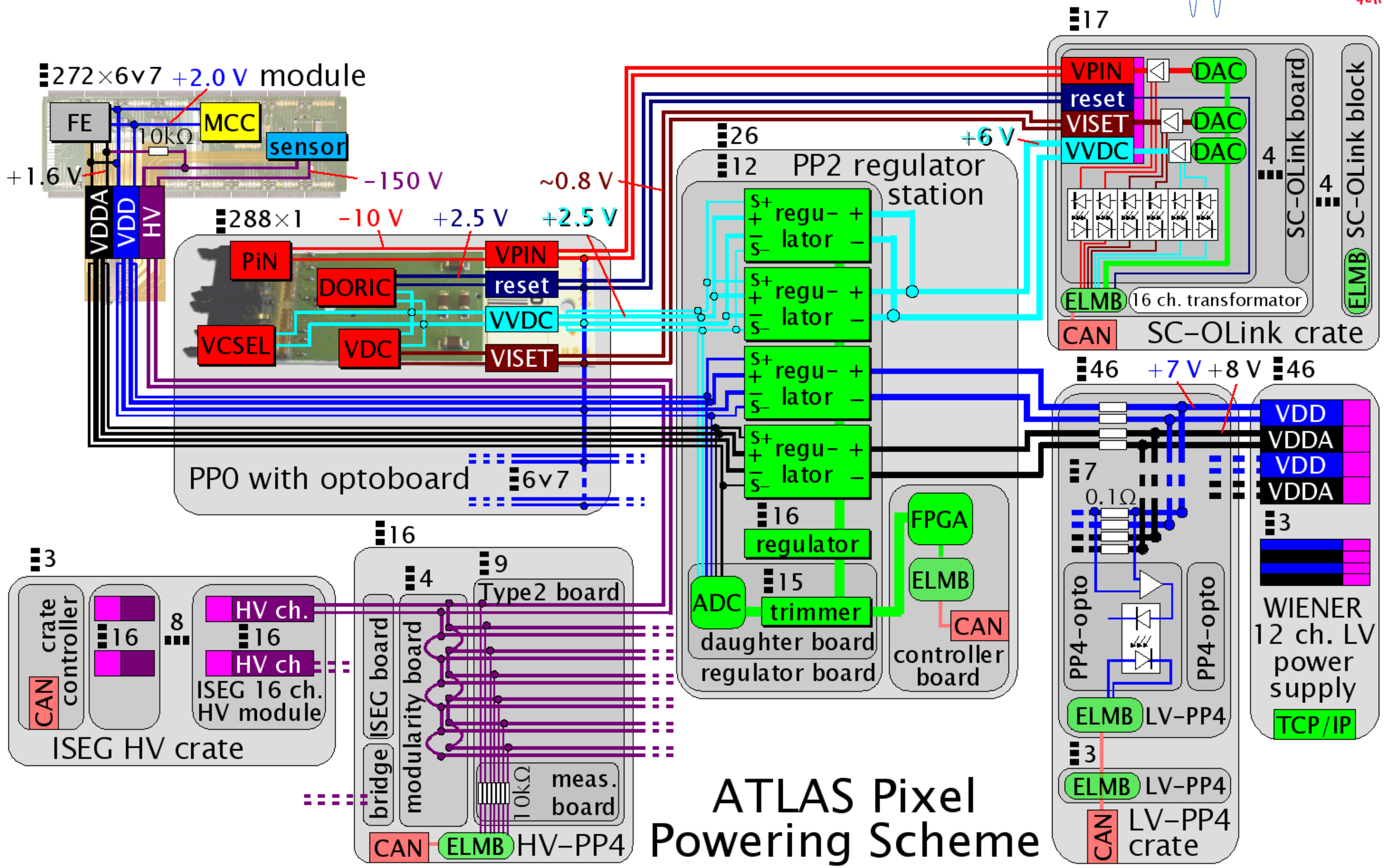
- after type inversion depletion zone grows from pixel (n+) to p+ side
- before type inversion depletion zone grows towards pixel implantations
- 'under depleted' => all pixel short-circuited => high capacitive load to FE preamplifiers => high noise => high noise occupancy

Pixel Services



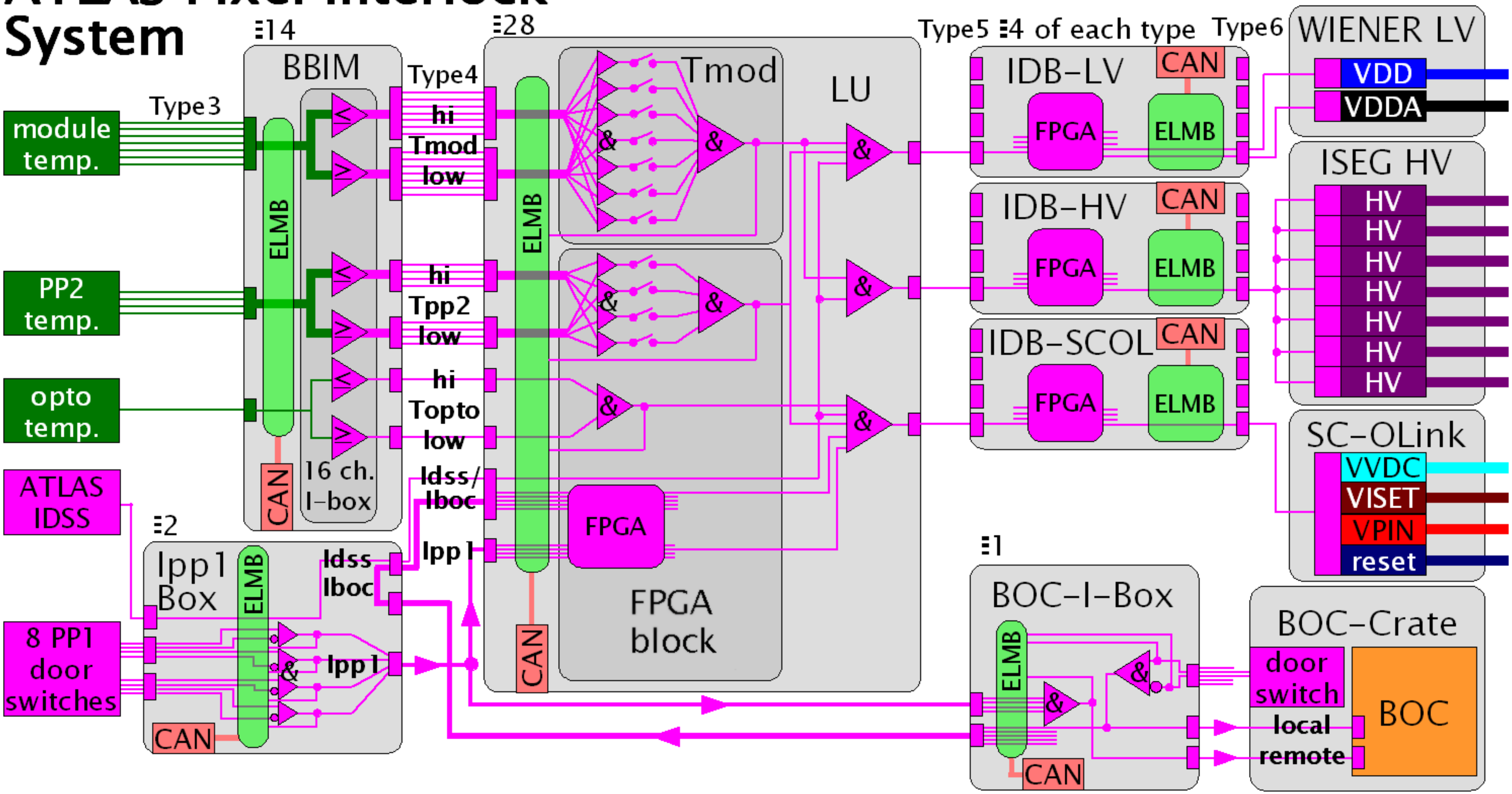


ATLAS Pixel Patch Panel Layout

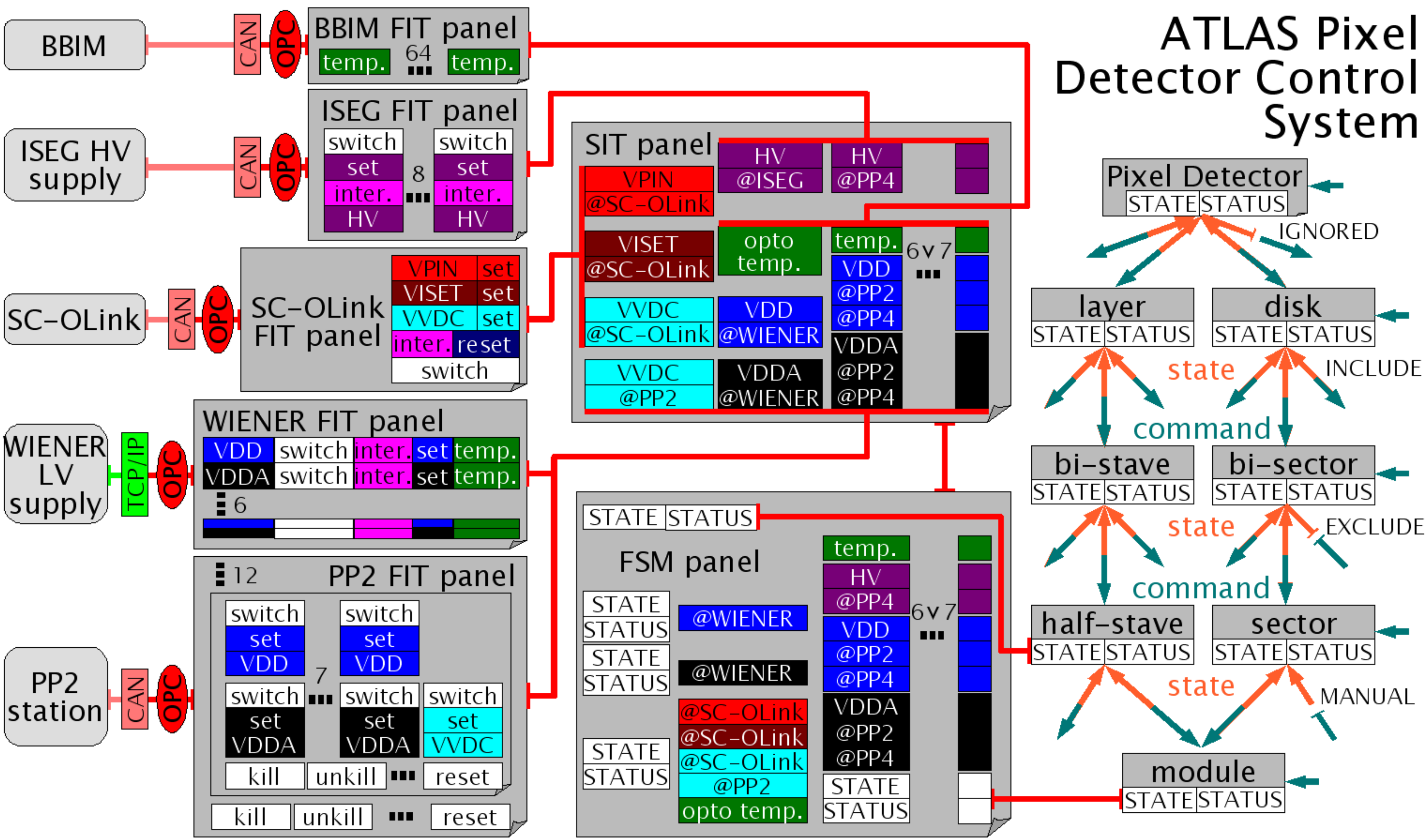


ATLAS Pixel Powering Scheme

ATLAS Pixel Interlock System

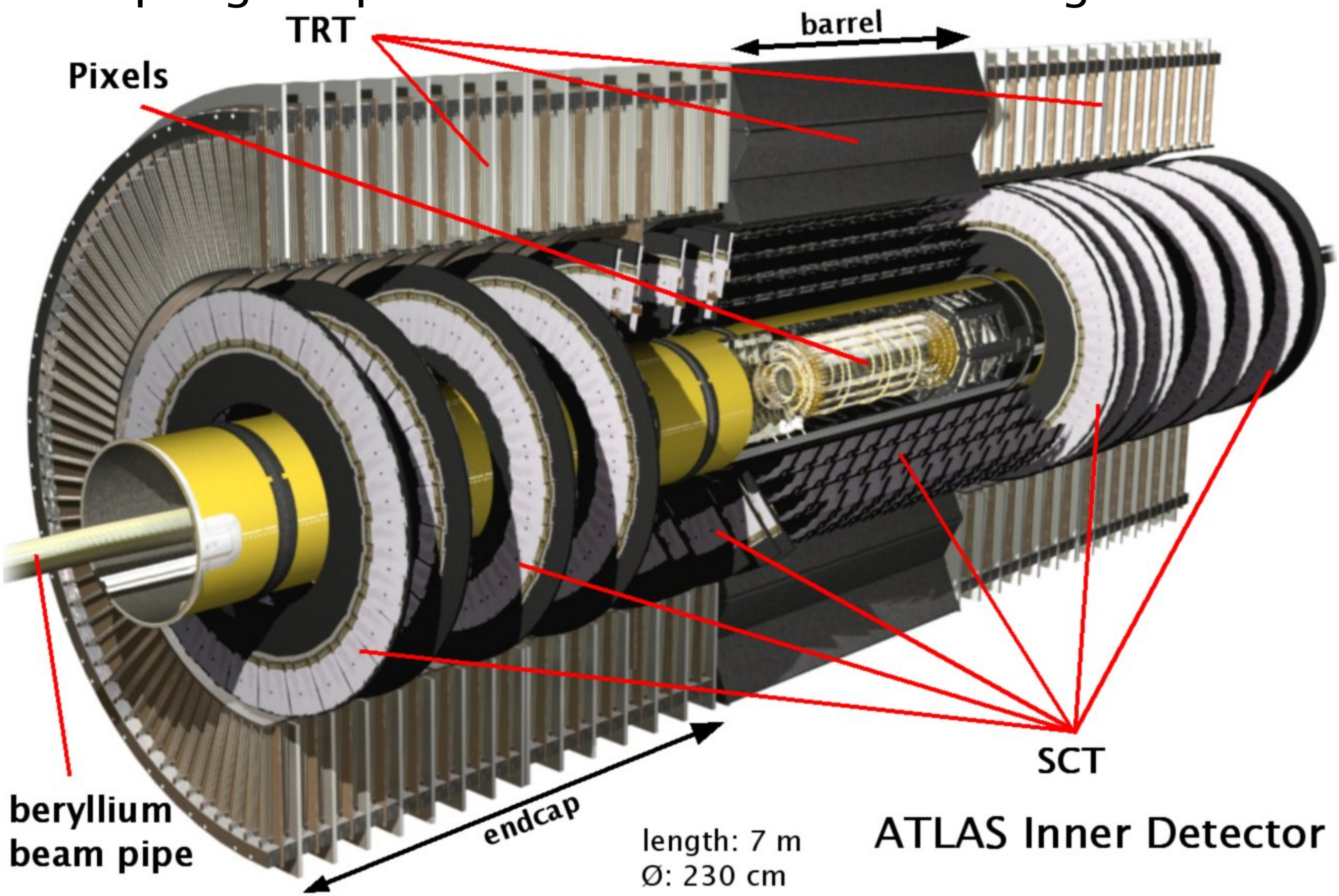


Detector Control System



ATLAS Inner Detector

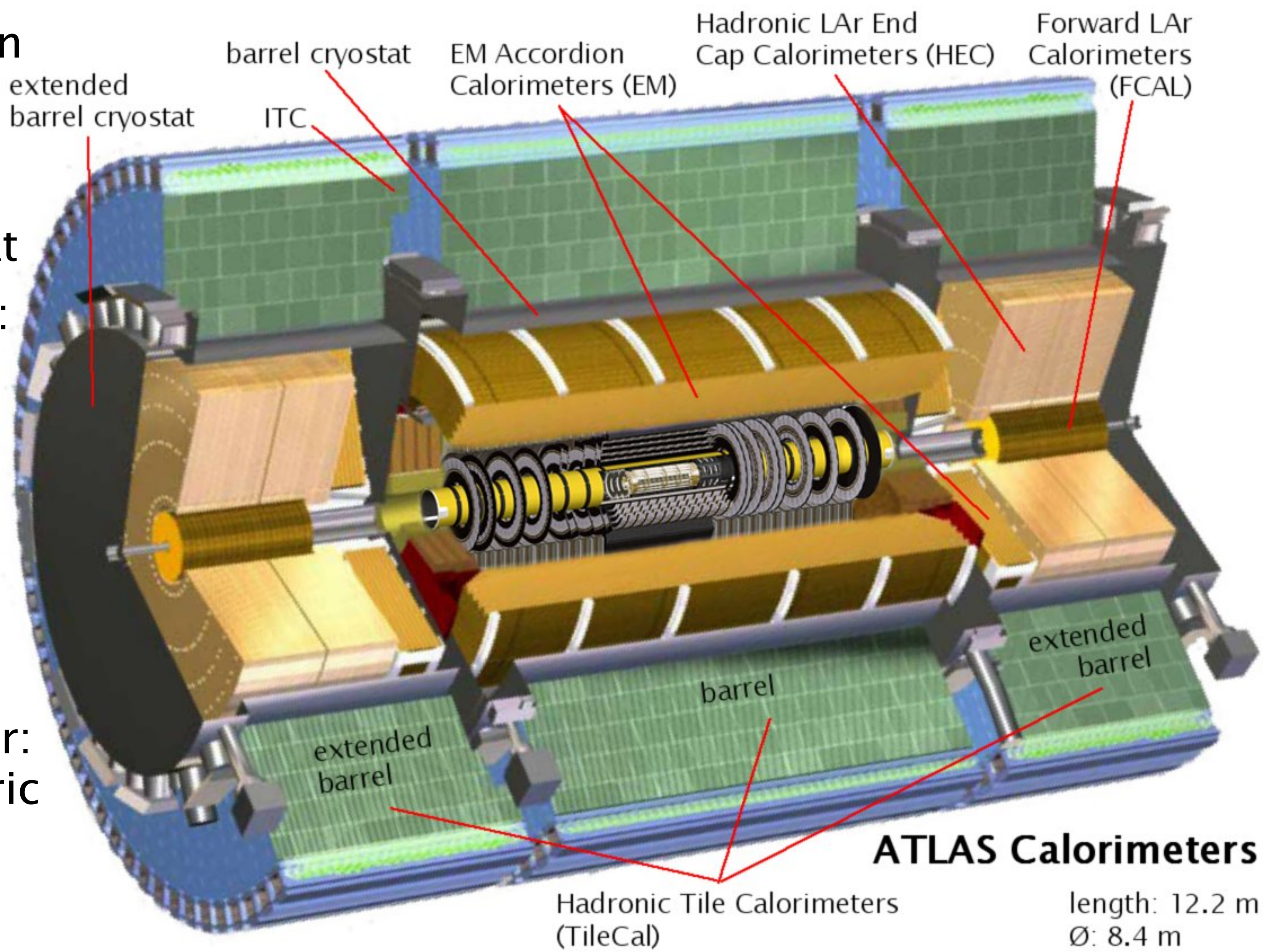
- high-resolution tracking sub-detectors closest to the interaction point & continuous tracking sub-detectors at the outer radii
- Transition Radiation Tracker: straw detectors can cope with high particle rates & occupancy; 36 space points; charged particle passing through dielectric constant boundary ⇒ mirror charge ⇒ electric dipole ⇒ time dependent dipole field ⇒ transition radiation; Xenon, CO_2, CF_4 gas mixture ⇒ detecting transition-radiation photons, created in a radiator between the straws, with Xenon ⇒ identification of e^-; 30 μm gold-plated W-Re wires ⇒ straw lengths < 144 cm; drift-time measurement ⇒ track resolution of 50 μm



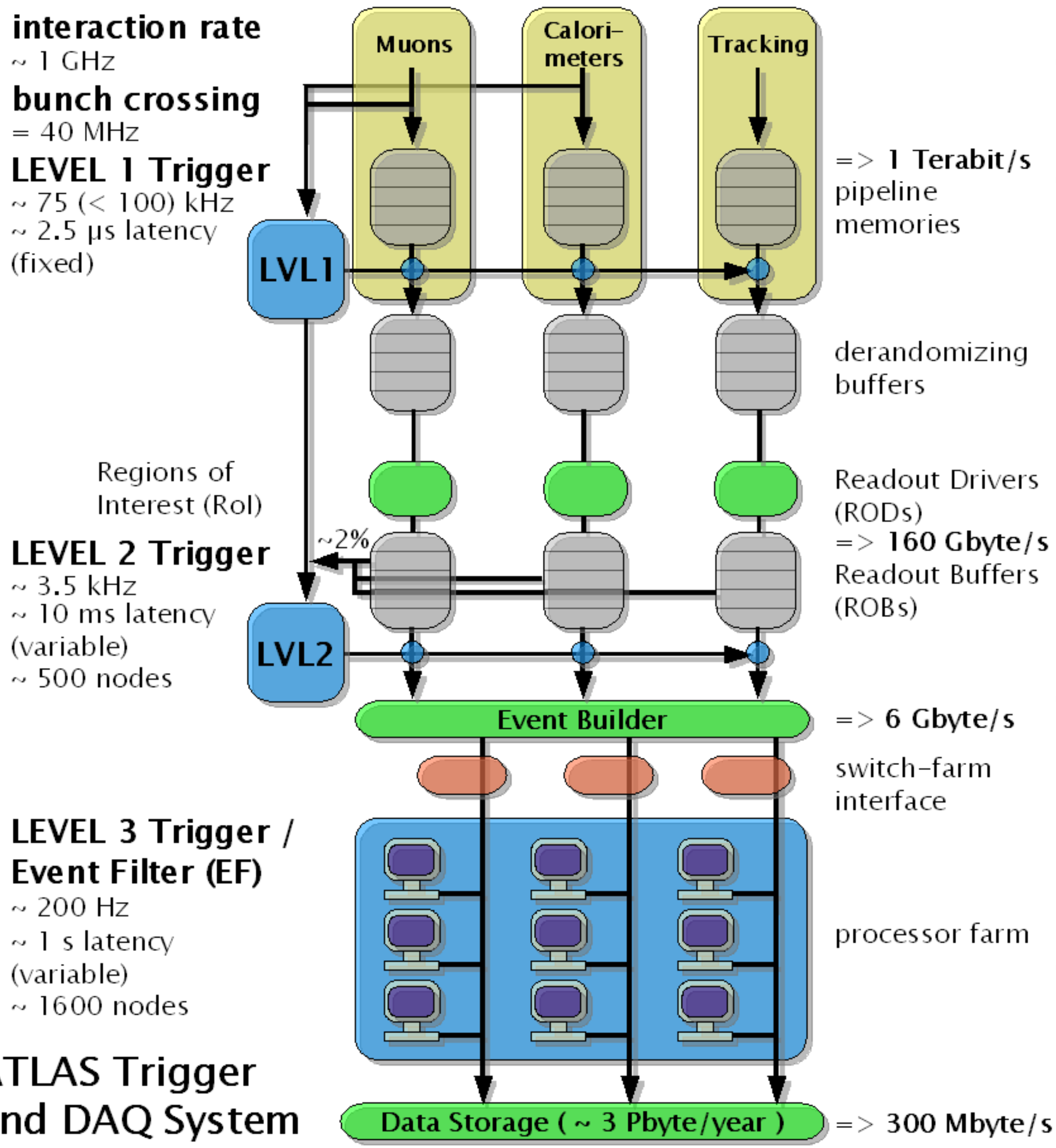
- Semiconductor Tracker: eight high-precision space points per track with Silicon microstrip detectors with 80 μm pitch and 40 mrad stereo angle ⇒ 6.2 million channels; front-end amplifier followed by discriminator; track resolution of 16 μm in Rϕ direction and 580 μm in z direction
- Pixel Detector ...

ATLAS Calorimeters

- sampling technique to measure particle- and jet-energies: alternating layers of passive absorber & active detector materials
- TileCal: absorber: Fe; detector: scintillating tiles ⇒ wavelength shifting fibres ⇒ PMT
- EM calorimeter: absorber: lead; detector: liquid Argon with accordion-shaped Kapton electrodes ⇒ preamplifier & bipolar shaper outside the cryostat
- HEC calorimeter: absorber: copper; detector: liquid Argon with 3 parallel electrodes: central one for readout - two carry 4 kV HV ⇒ preamplifier boards at wheel periphery
- FCAL: absorber: copper & sintered tungsten; detector: liquid Argon with concentric rods at a positive HV & grounded tube electrodes



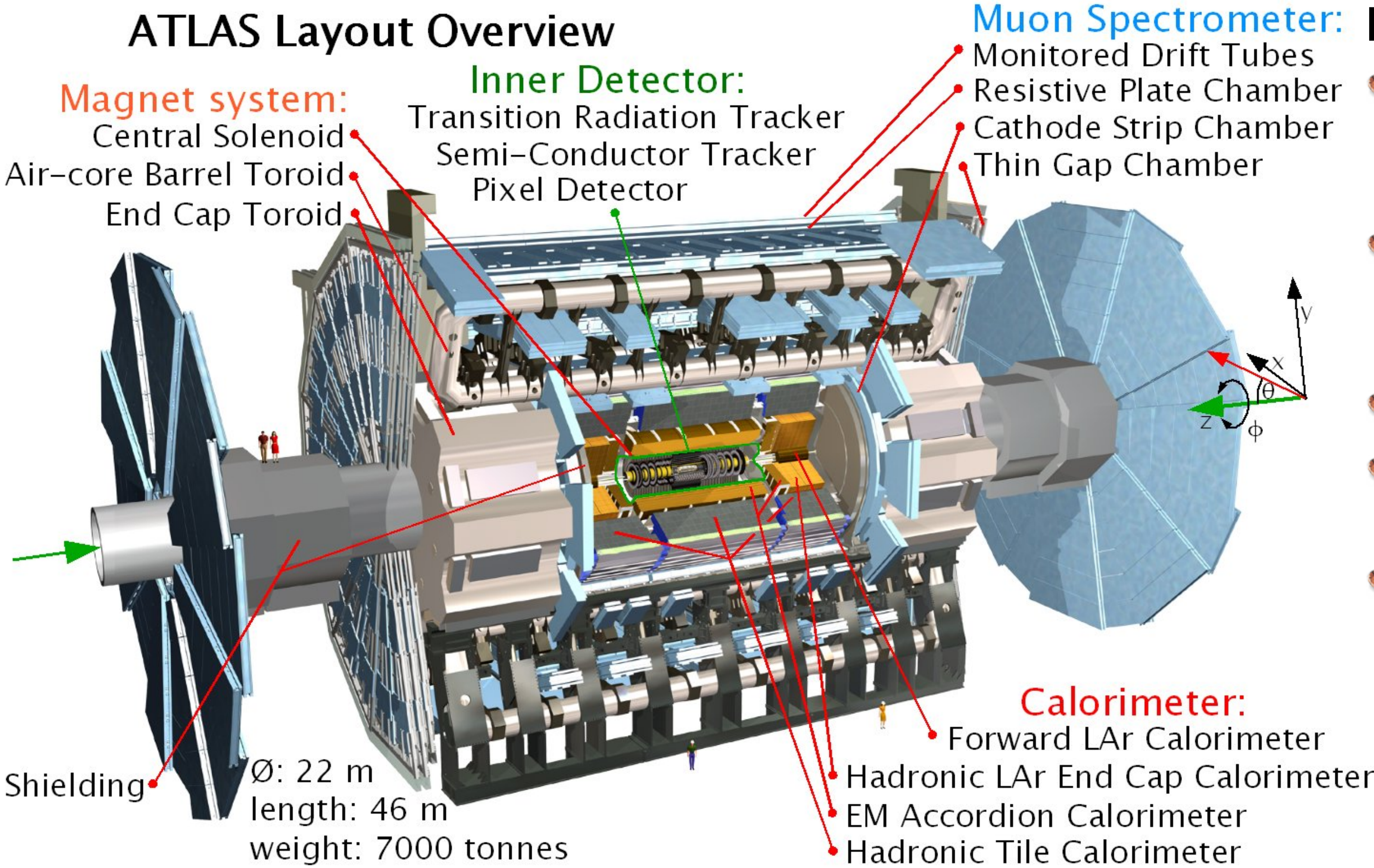
ATLAS Trigger



ATLAS Trigger and DAQ System

- 3 levels of online event selection
- rejection factor of 10^7 against 'minimum-bias' events
- LVL1: reduced-granularity muon spectrometer & calorimeters; summing over trigger towers
  ⇒ sum of jet transverse energies, missing and total transverse energies; flexible implemented
  ⇒ reprogrammable, non-trivial: size of muon spectrometer implies TOF values comparable to bunch crossing interval; fixed latency
- LVL2: Region-of-Interest information from LVL1 & full precision & granularity information of all sub-detectors if necessary; variable latency
- EF: offline algorithms & methods on a processor farm with most up to date calibration, alignment & magnet field map information; variable latency

- diameter: 22 m; length: 46 m; weight 7000 tons
- air-core (⇒ to avoid multiple scattering) barrel toroid magnetic field: 4 T
- central solenoid magnetic field for inner detector: 2 T

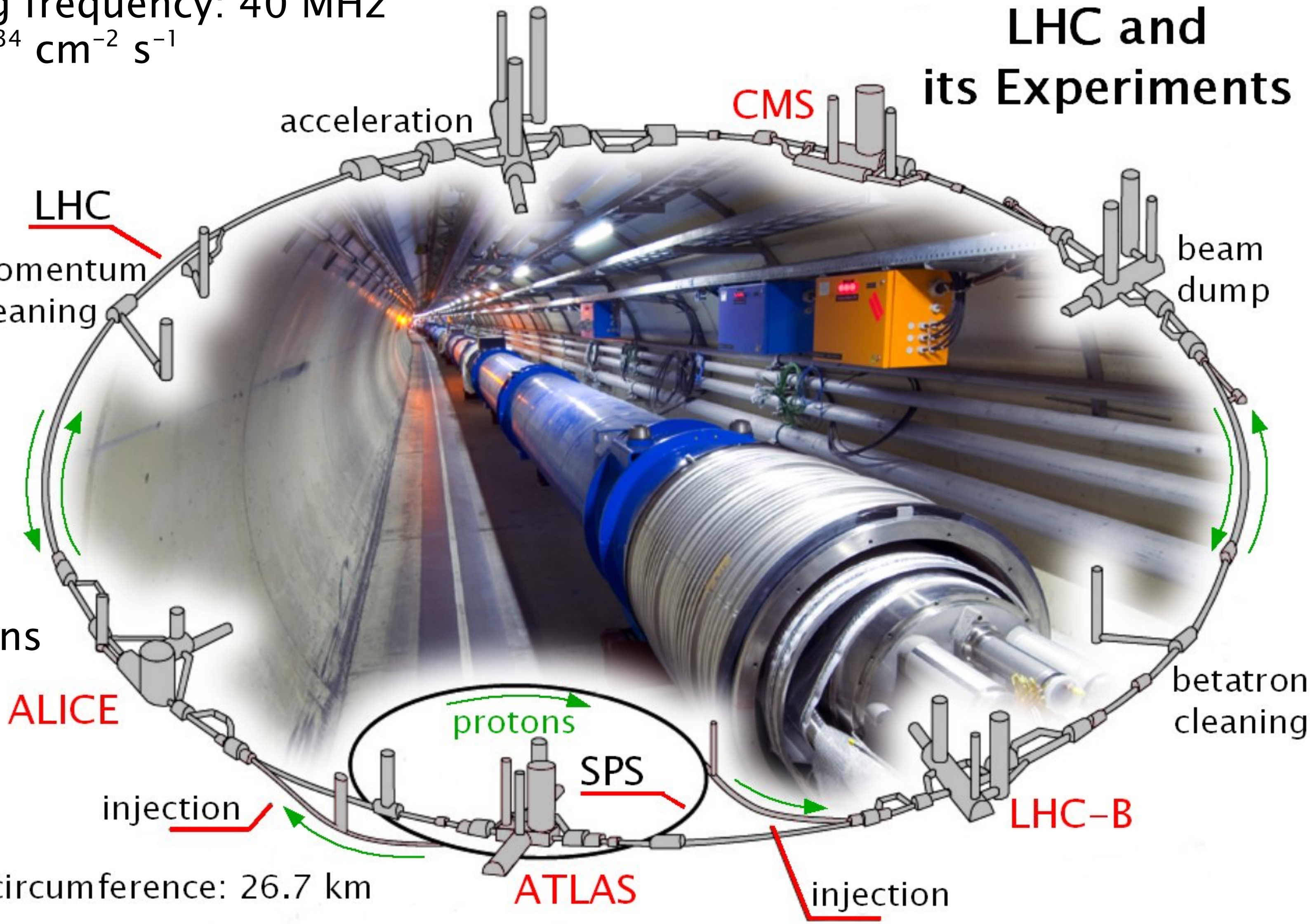


basic design criteria:

- very good electromagnetic calorimetry
- high-precision muon momentum measurement
- efficient tracking
- large acceptance in η
- triggering and measurement of particles with low transverse momentum thresholds

SPS, LHC and the LHC experiments

- SPS: 450 GeV
- LHC: 26.7 km circumference; 2·7 TeV; 2835 bunches with 10^{11} protons each
  ⇒ beam current: 0.53 A ⇒ beam energy: 668 MJ
  ⇒ bunch crossing frequency: 40 MHz
  ⇒ luminosity: 10^{34} cm^{-2} s^{-1}



- **ATLAS** & CMS:
  p-p collisions
- LHC-b:
  b-physics
- ALICE:
  heavy ion collisions