ATLAS Pixel Detector Commissioning using Cosmic Rays

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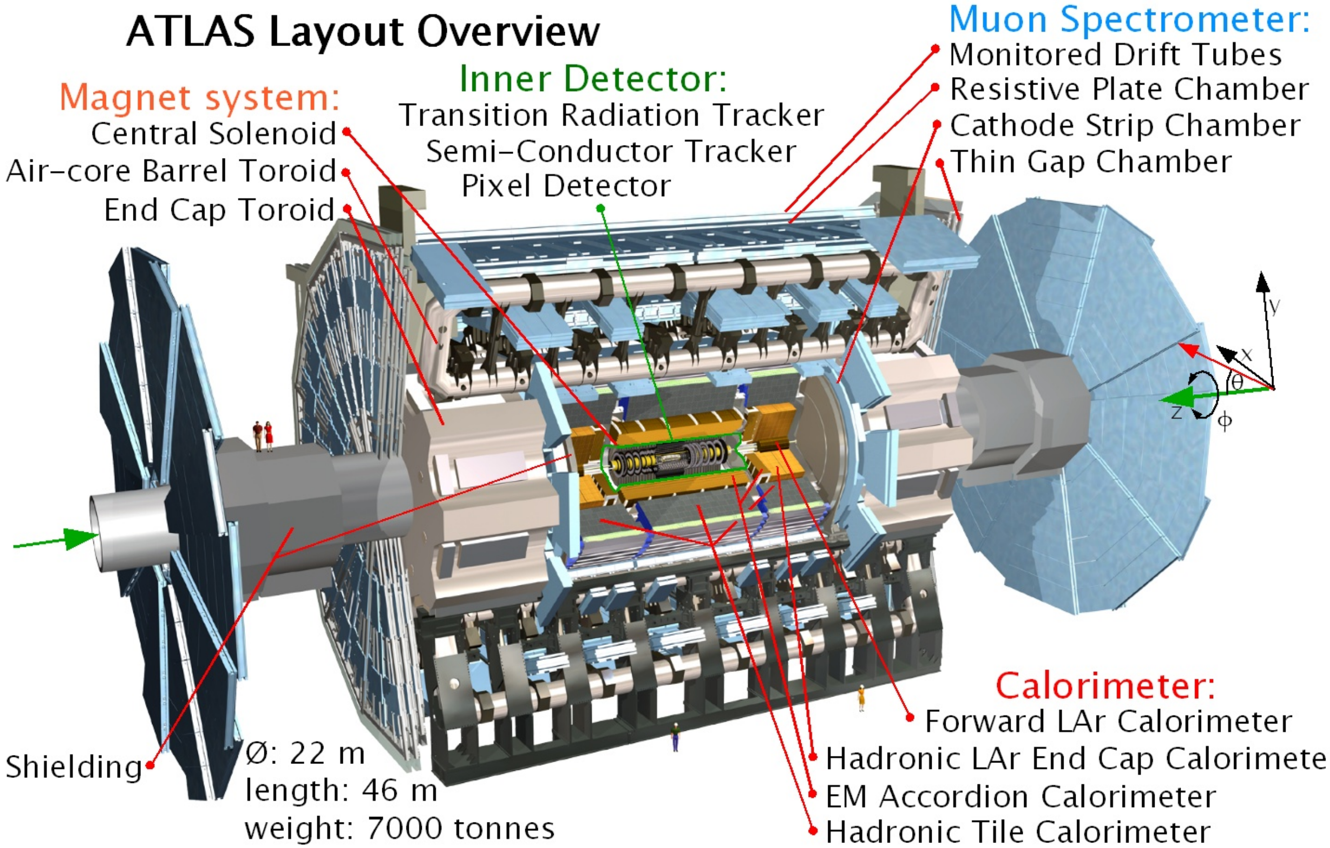
Outline:

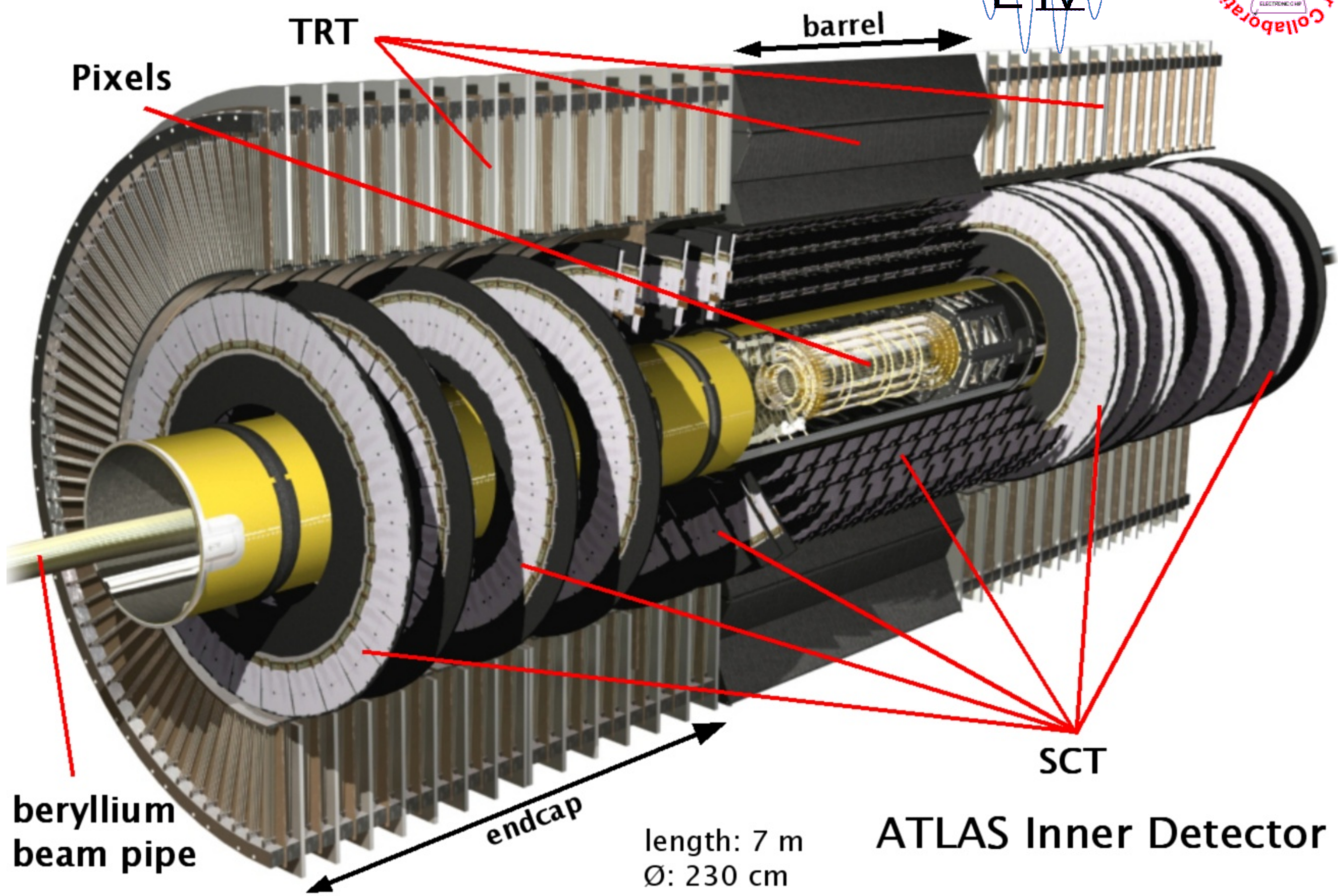
- ATLAS Pixel Detector Overview
- System Test Setup
- Optical Communication Tuning
- Detector Performance
- Cosmics Data
- Conclusions

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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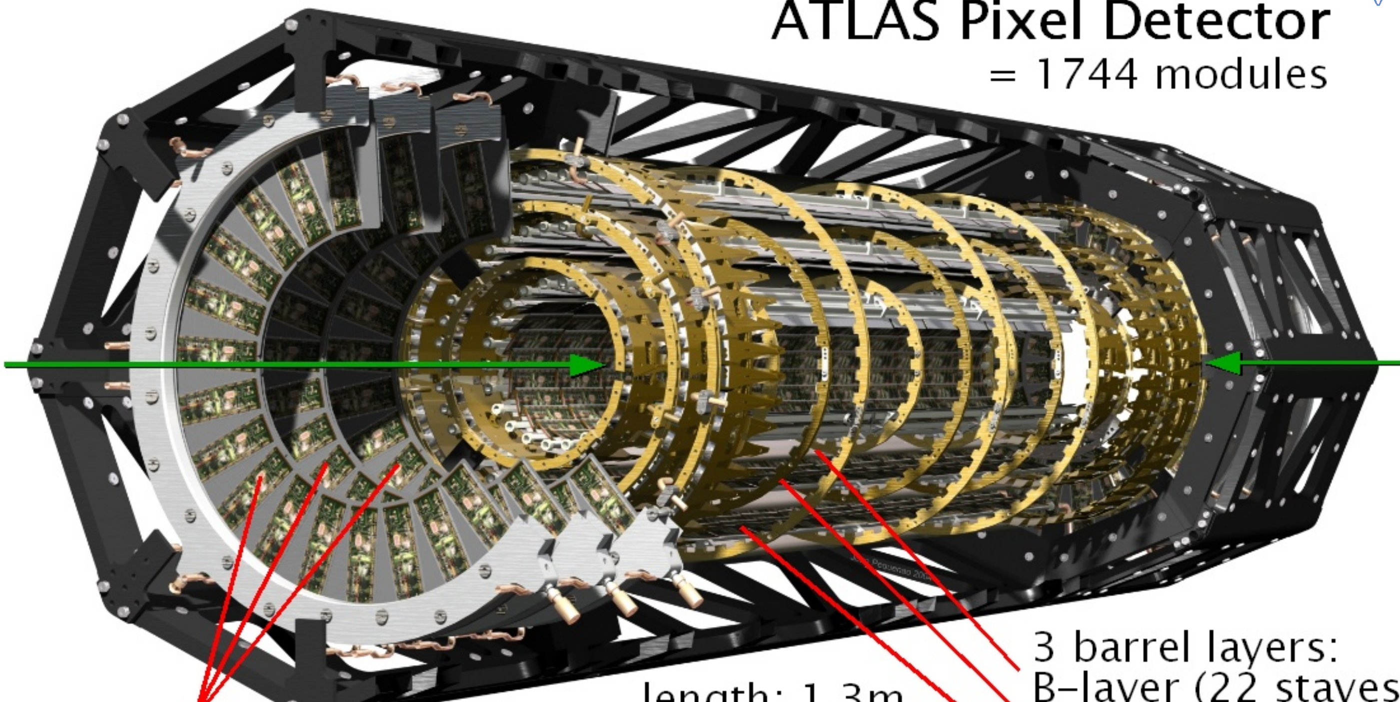
Pixel Detector Design

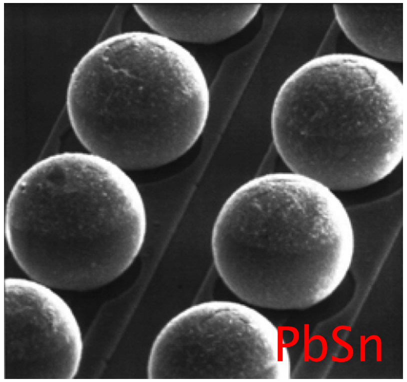


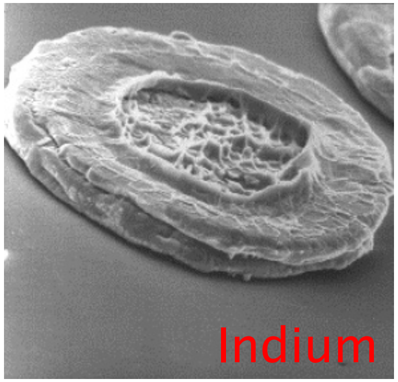
- 3 Barrel layers (r = 5, 9, 12 cm)
- 2 Endcaps with 3 Disks each
- 3 space points for pseudorapidity < 2.5
- 80 million channels in 1744 Pixel Modules
- 1.8 m^2 active sensor area
- ~ –10°C operating temperature with ~10 kW power load ⇒ evaporative C_3F_8 cooling integrated into carbon support structure

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

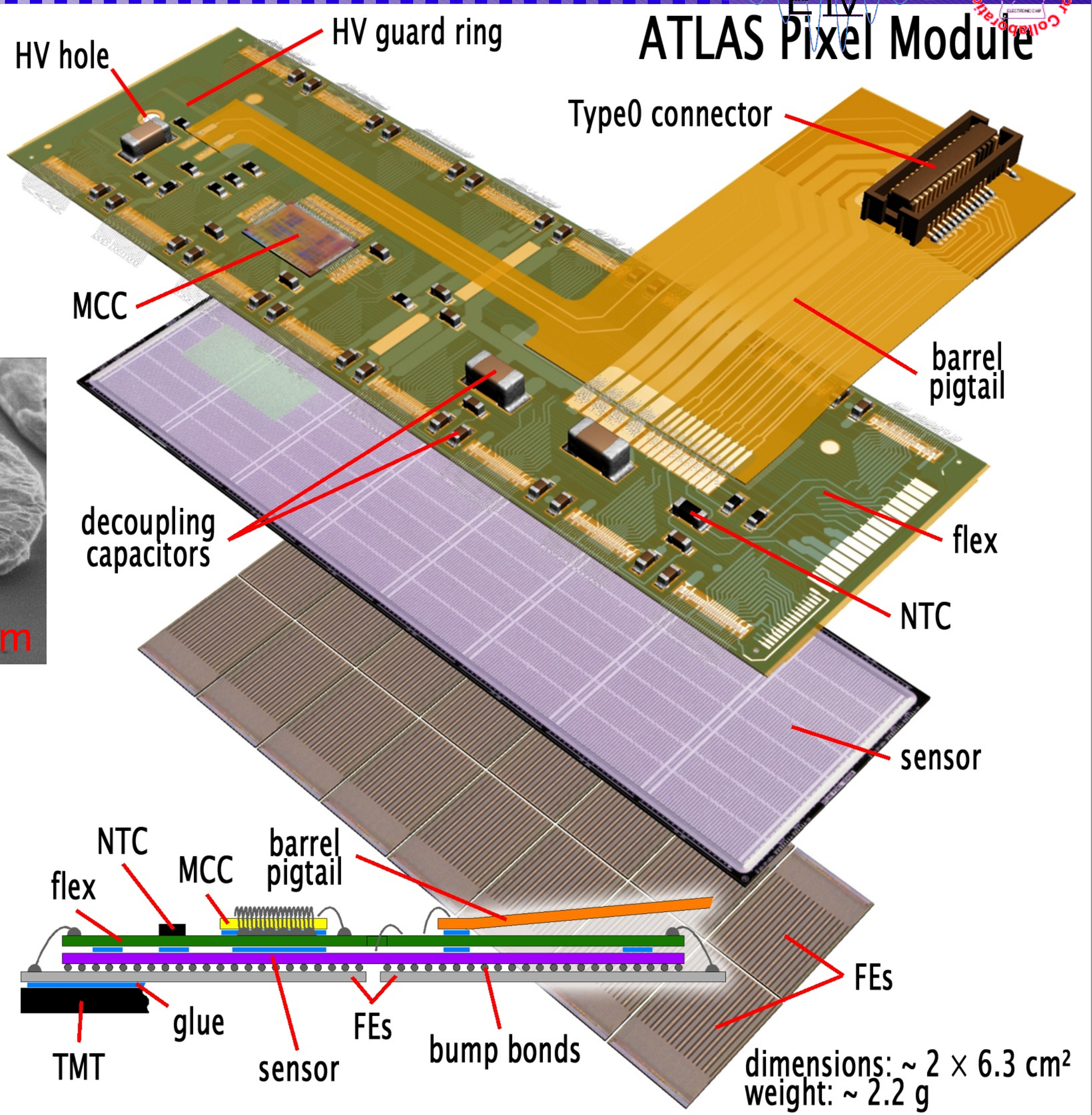
ATLAS Pixel Module

- ~ 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



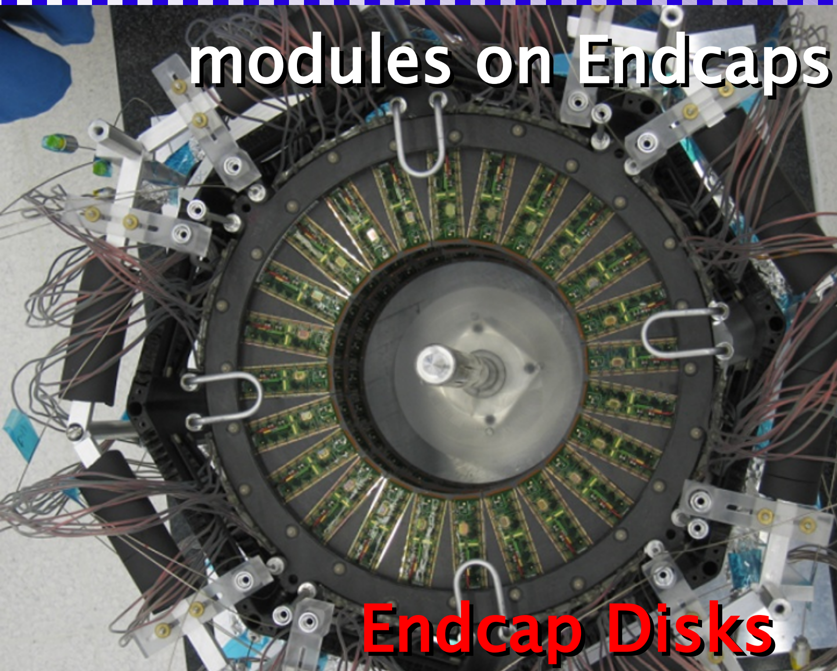


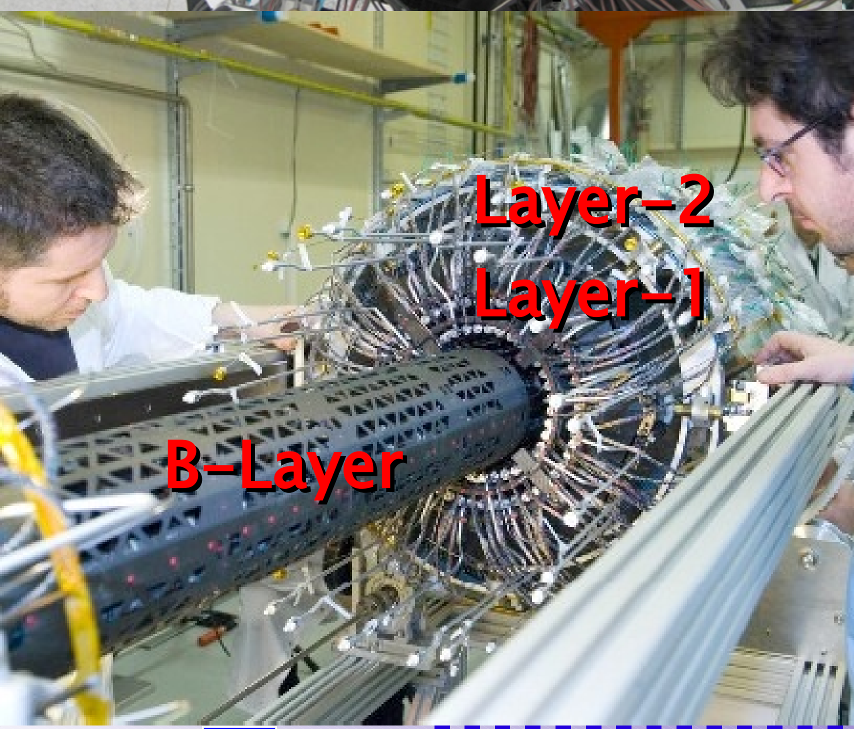
- FEs connected with wire bonds to a flexible circuit board (flex: routing and passive components)
- readout of the FEs by a Module Control Chip (MCC) ⇒ module based event building

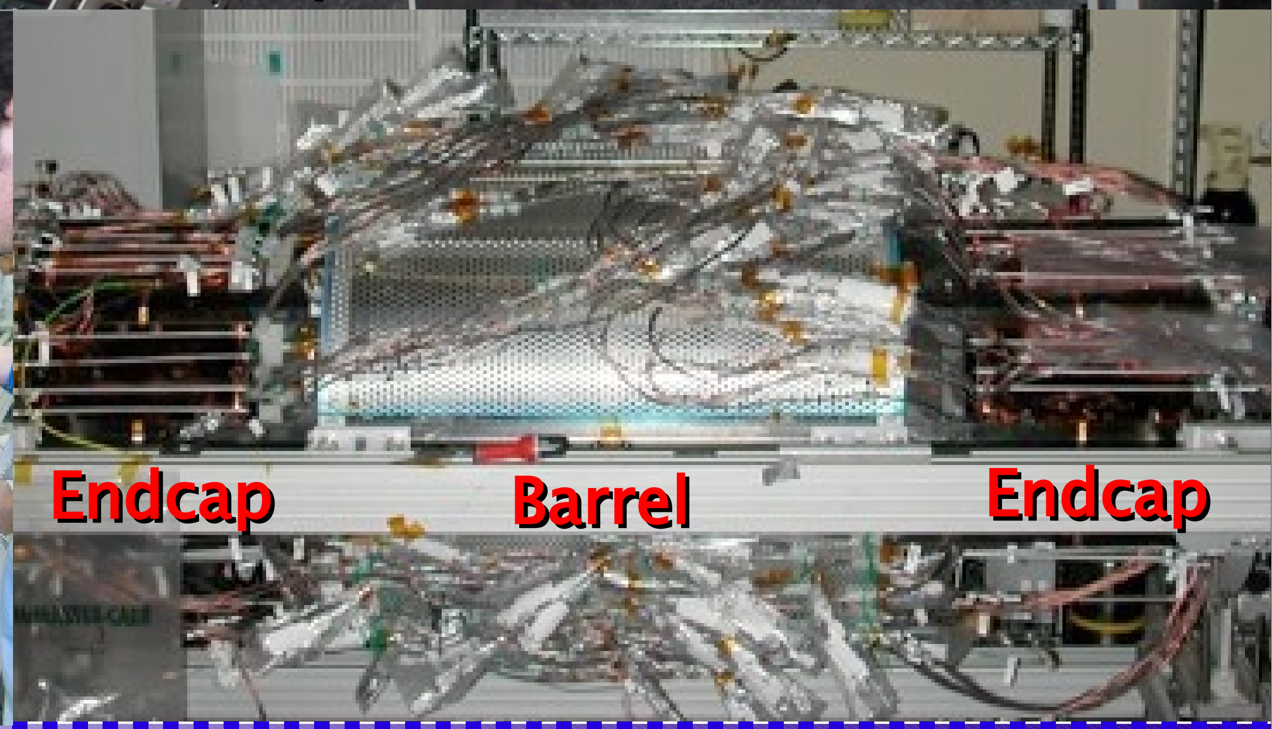


Pixel Detector Integration

modules on Endcaps and Barrel are identical

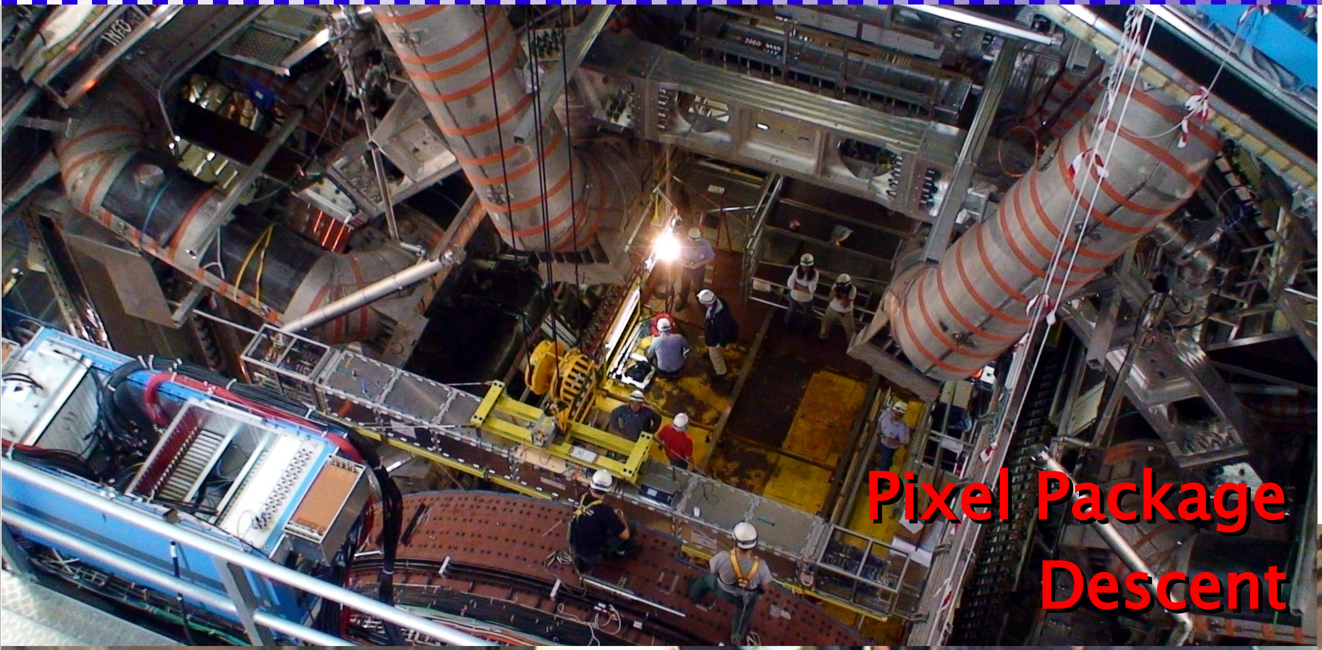


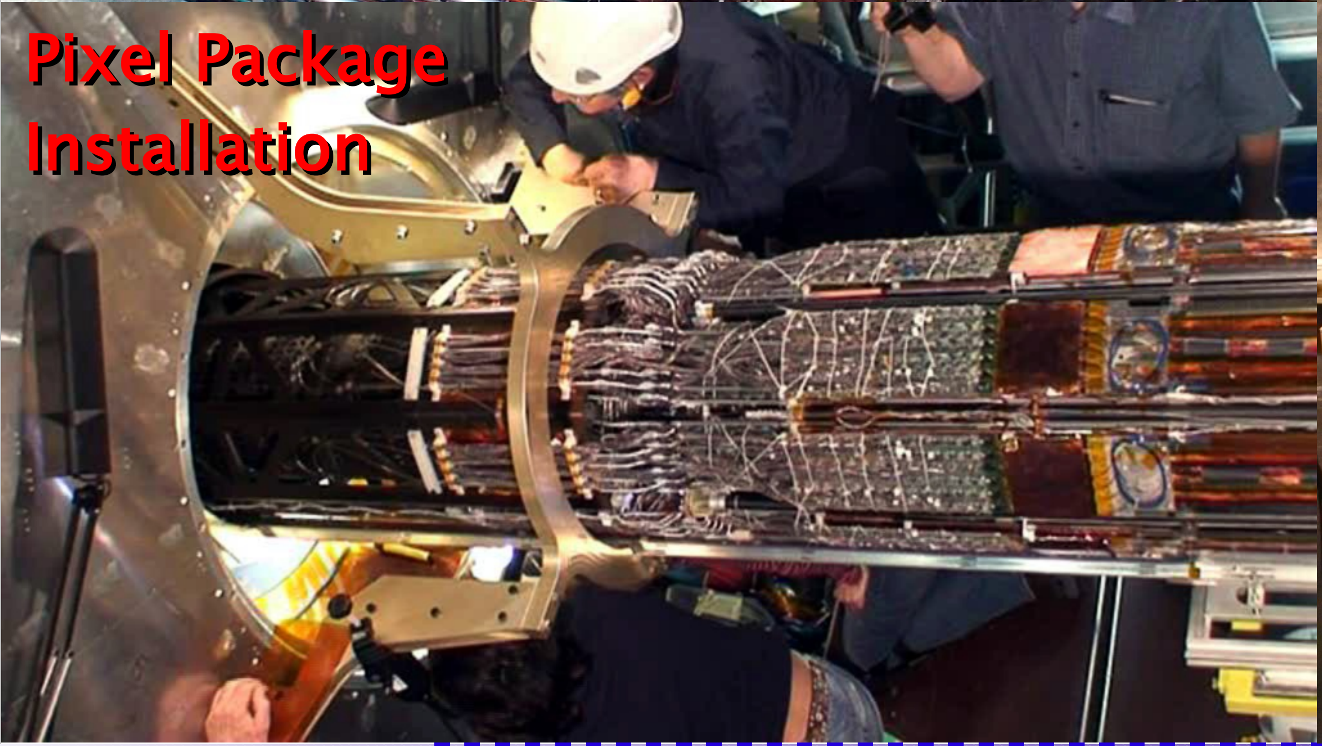


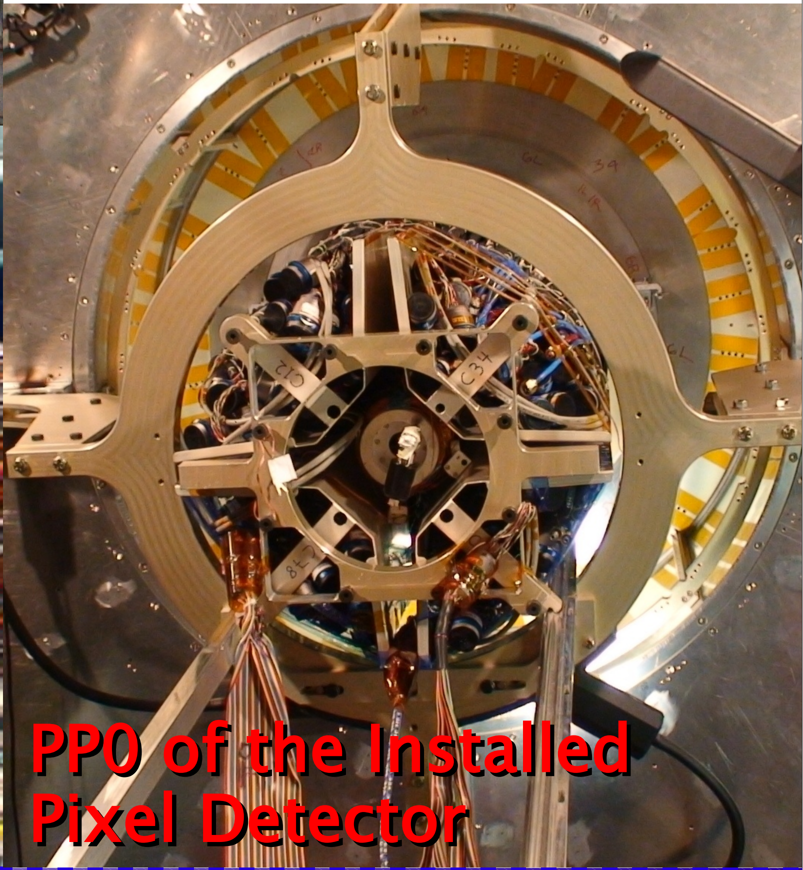


Pixel Detector Installation

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



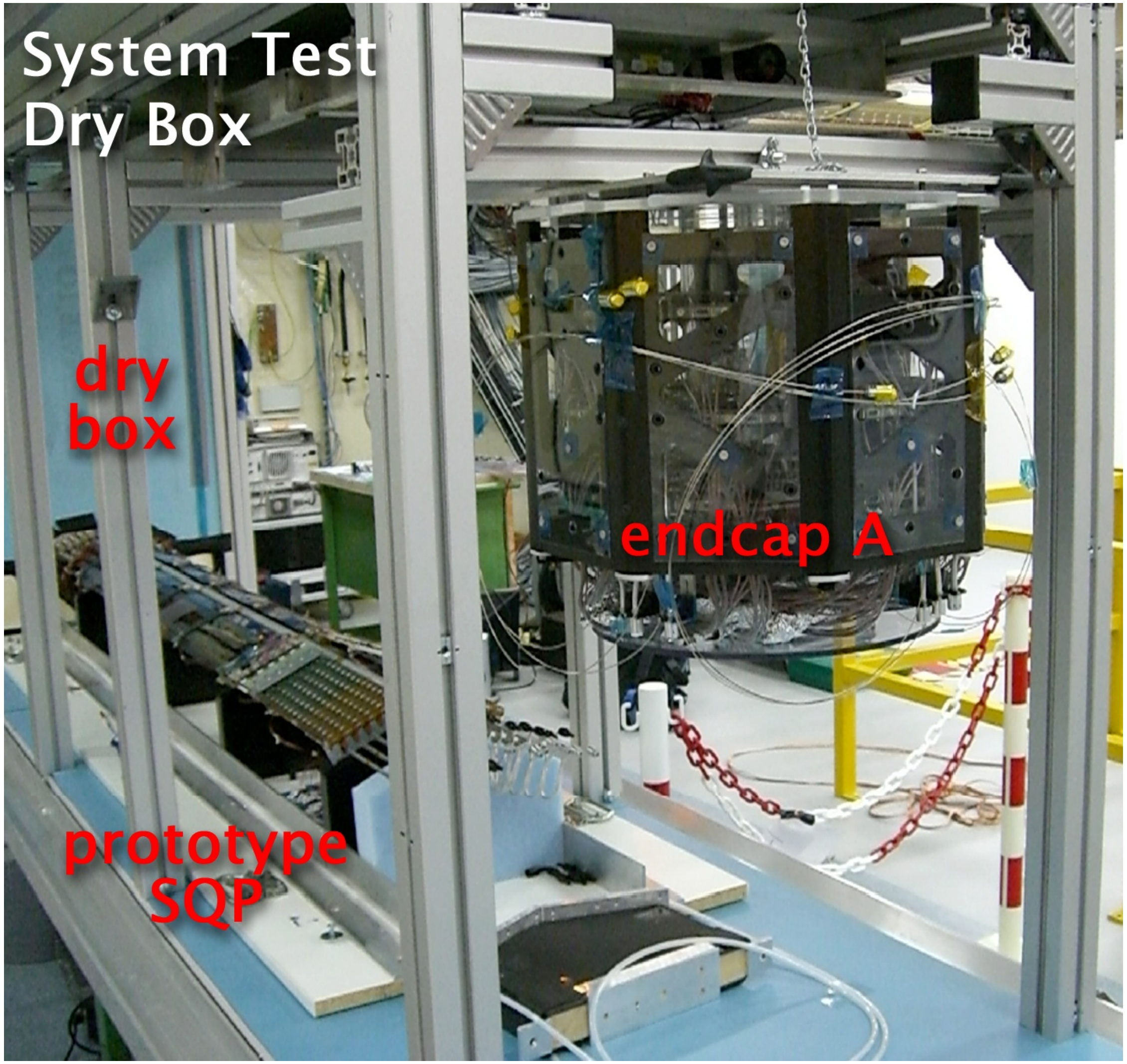




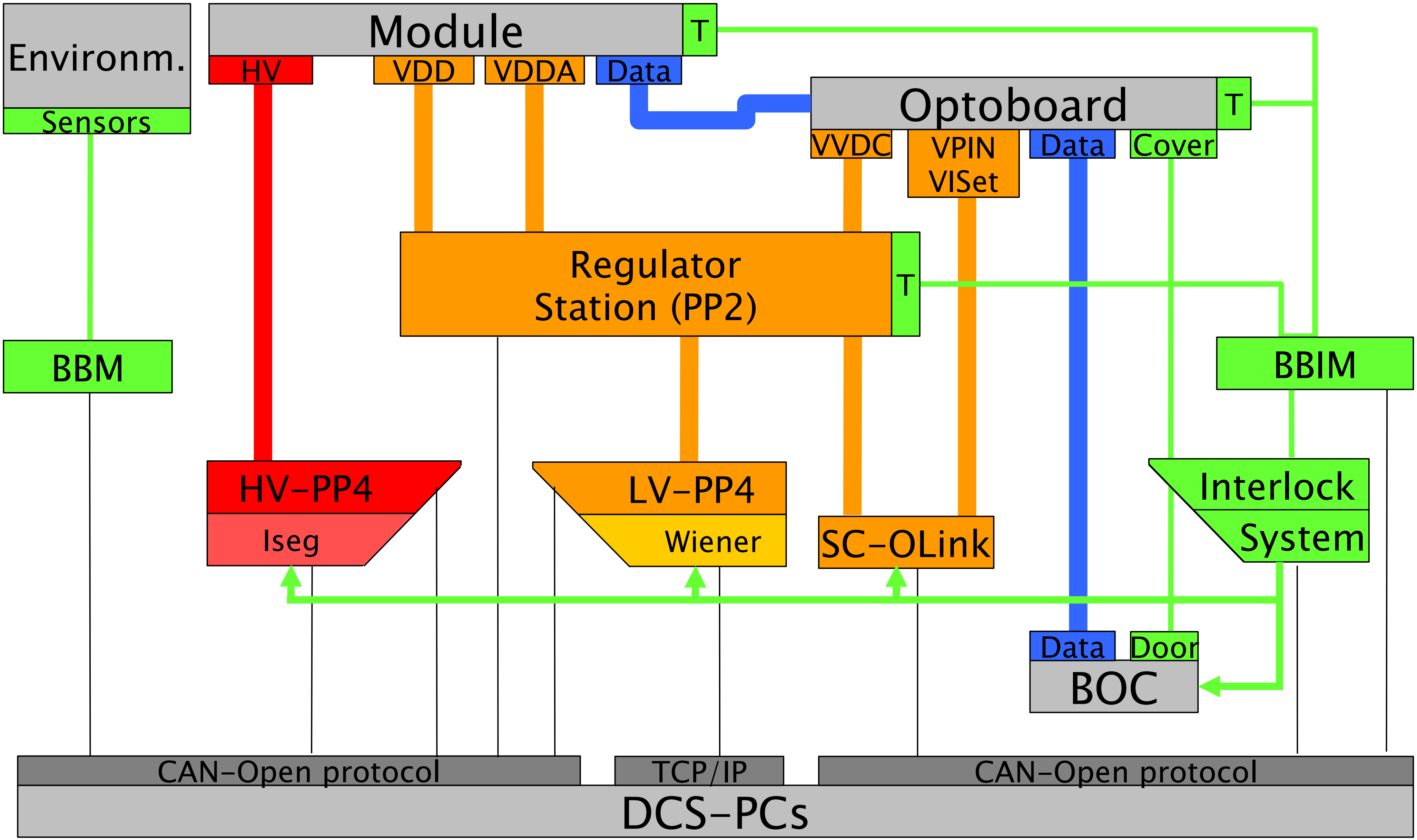
Aim & Operation Mode of the System Test

- 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, ...)

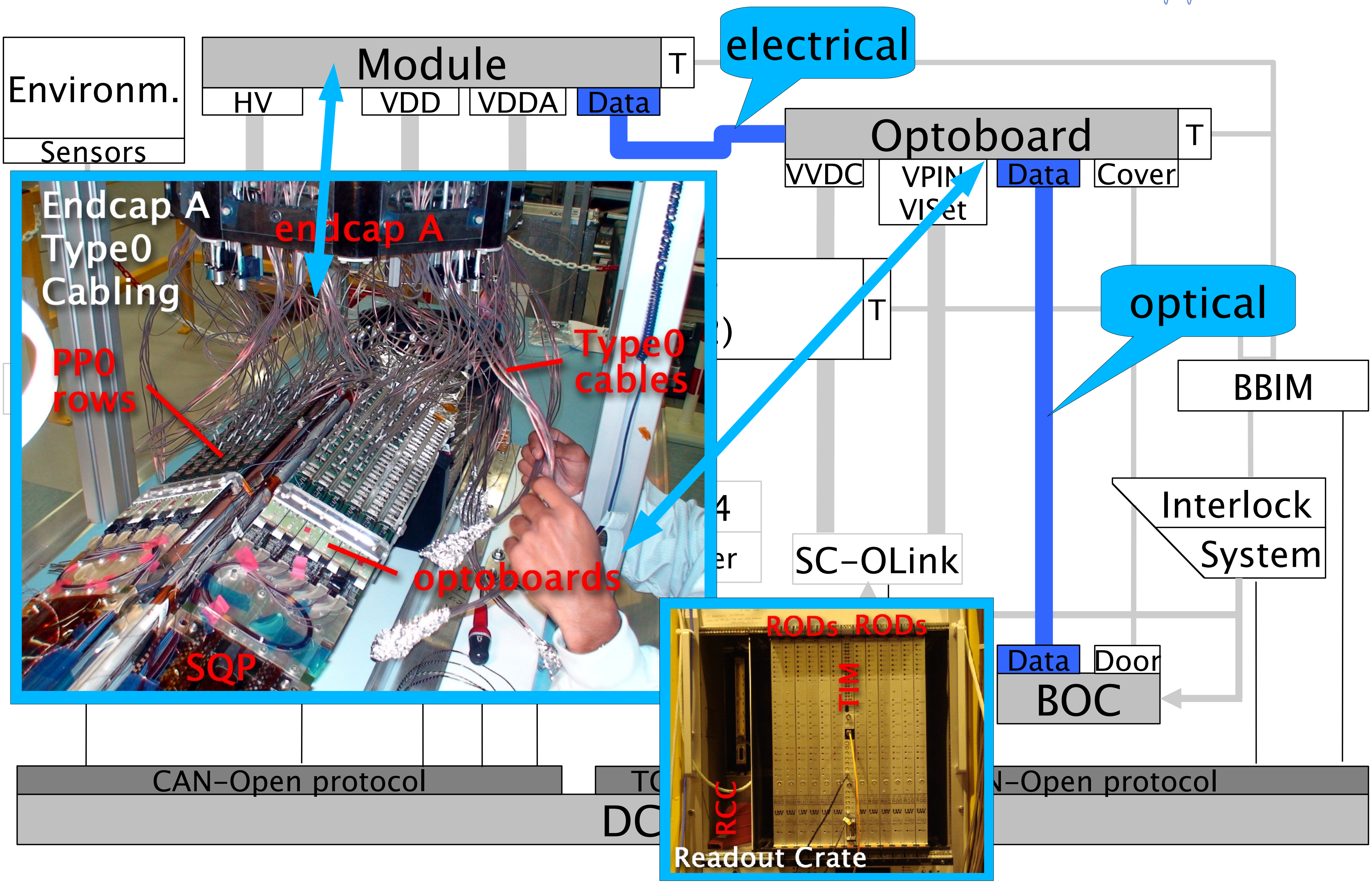
ATLAS Pixel System- and Cosmics-Test at CERN



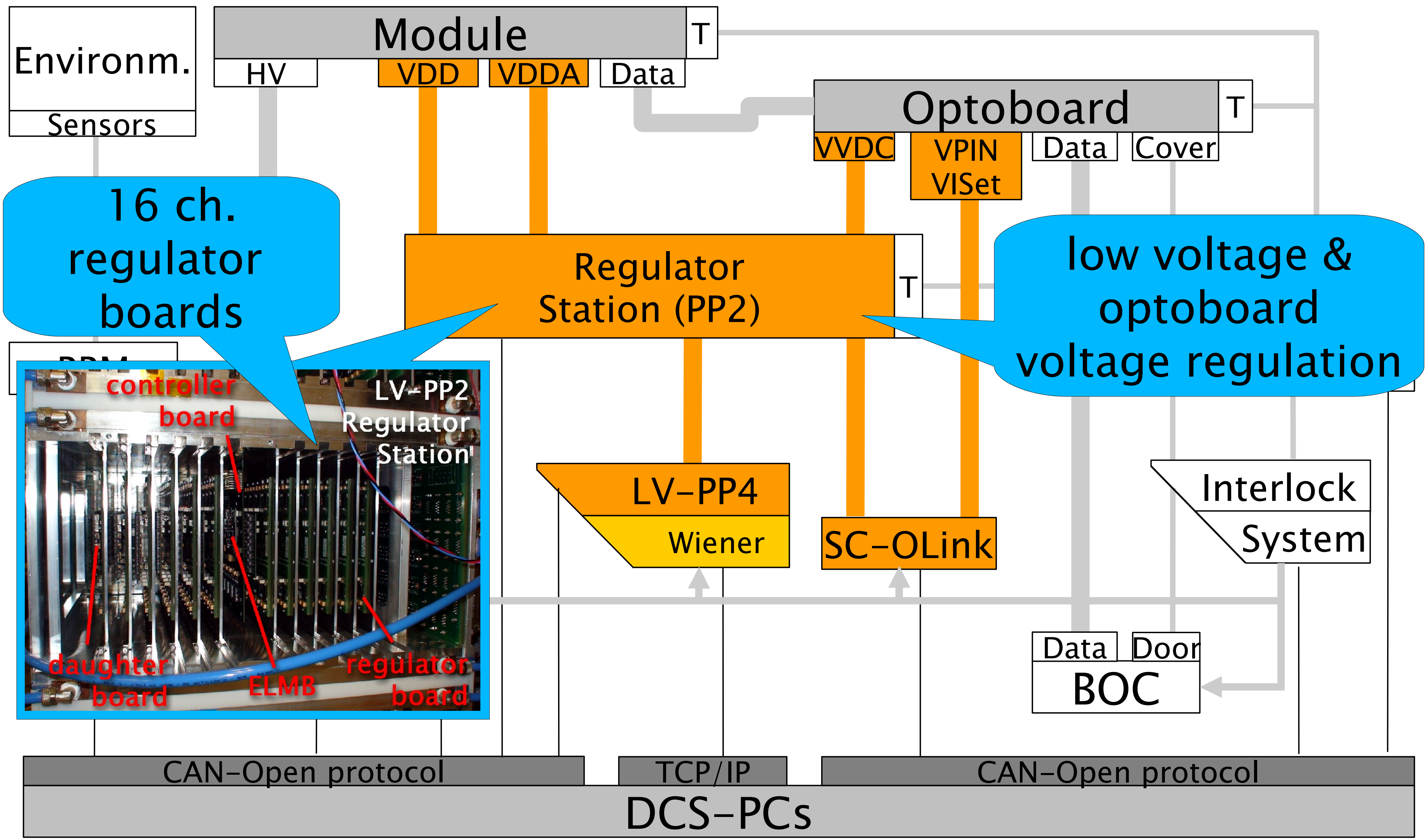
System Test Setup



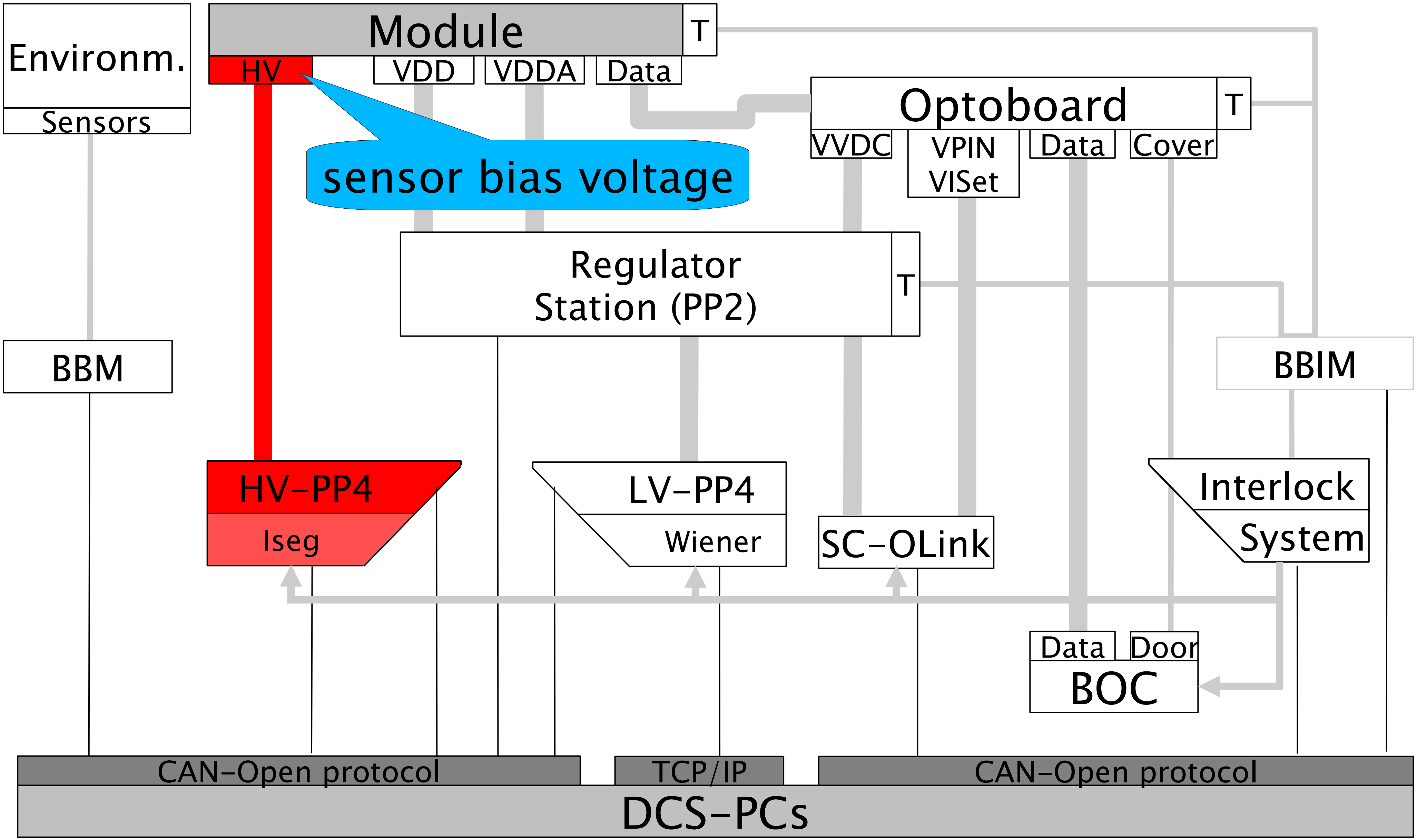
System Test Setup (Data)



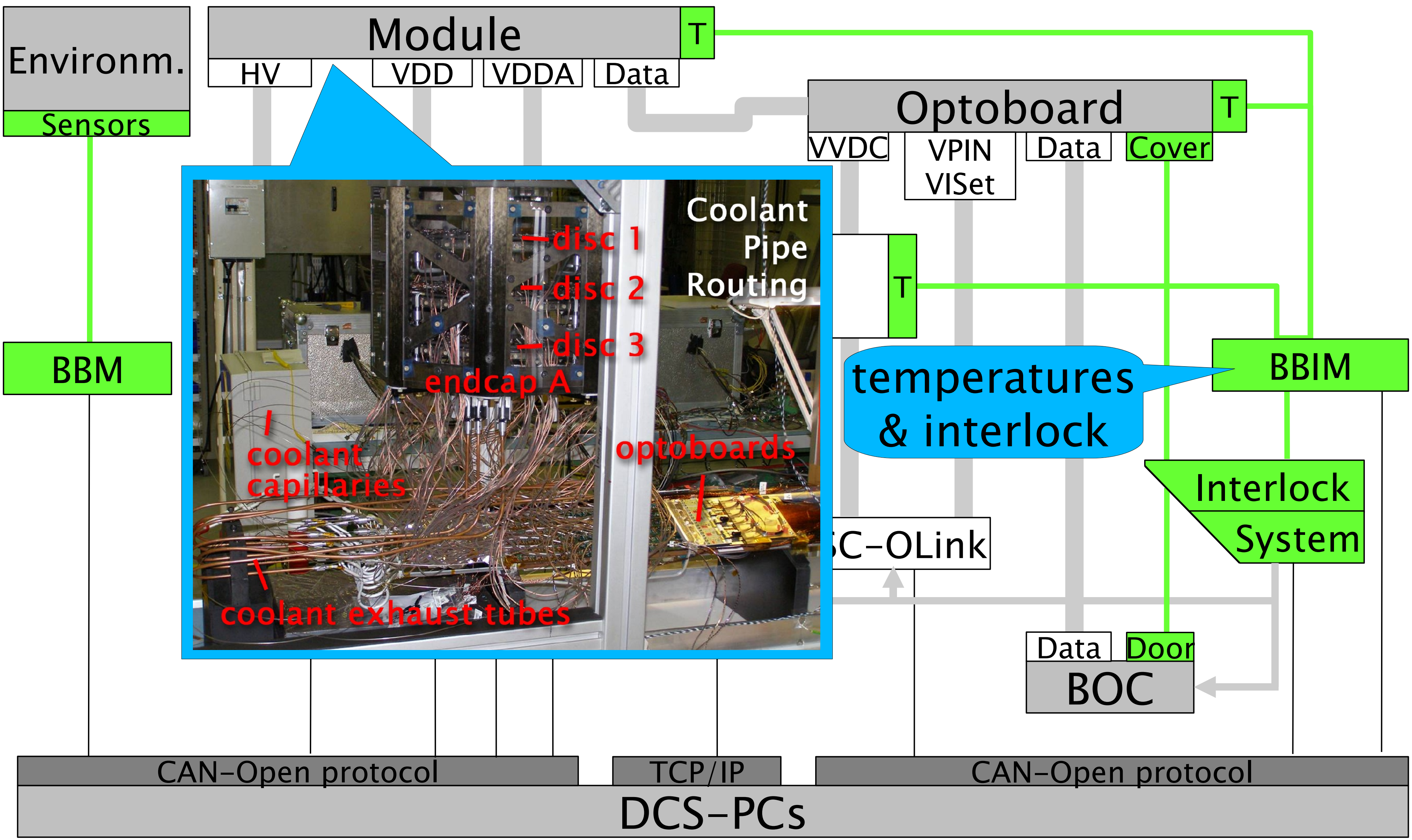
System Test Setup (Low Voltage)



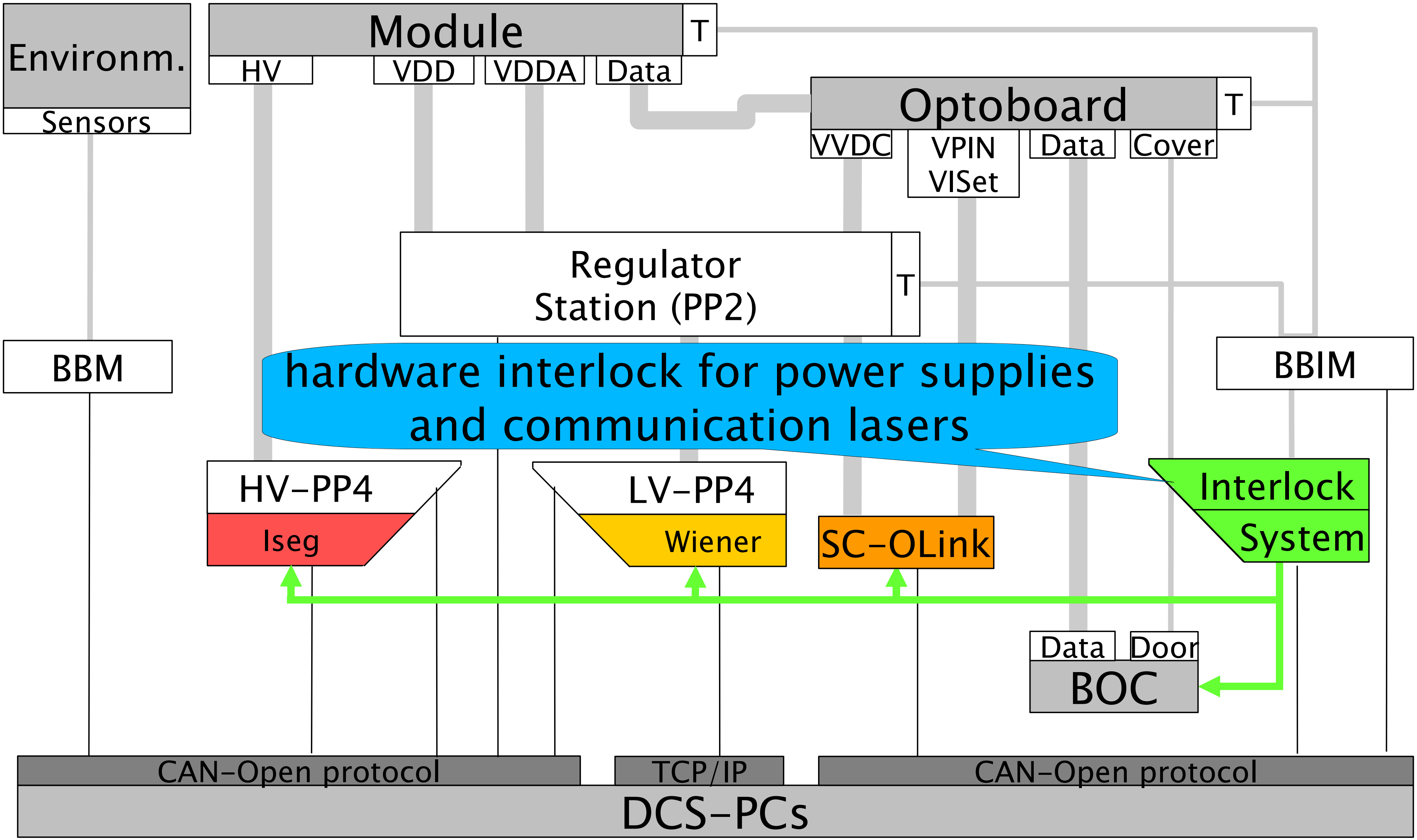
System Test Setup (High Voltage)



System Test Setup (Cooling & Monitoring)

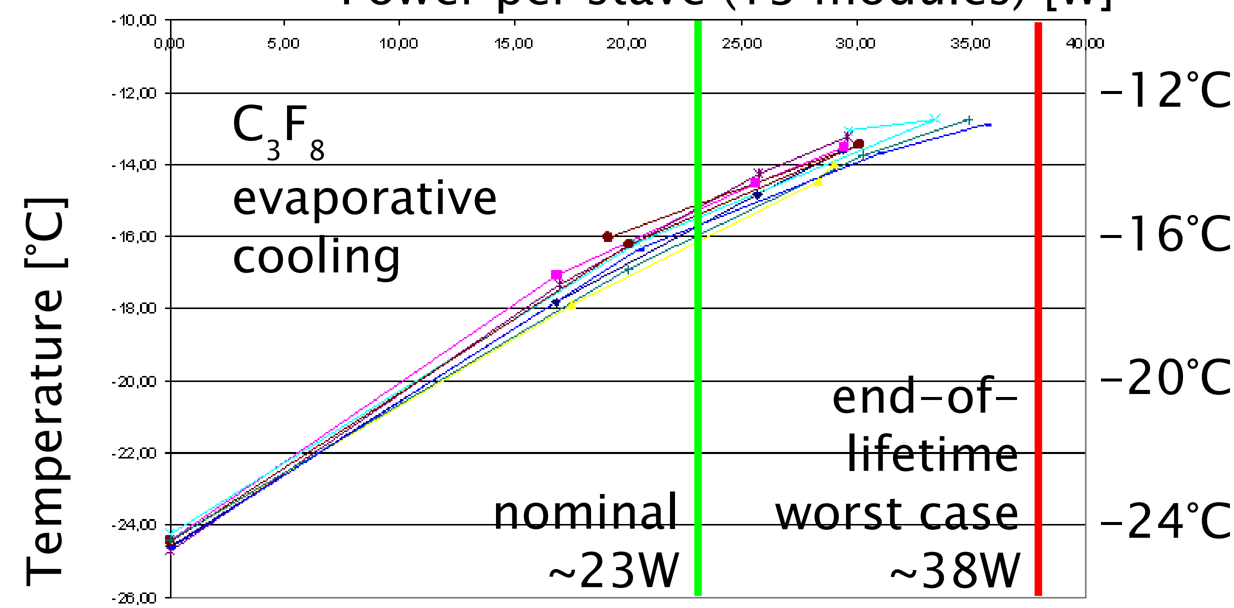


System Test Setup (Interlock)



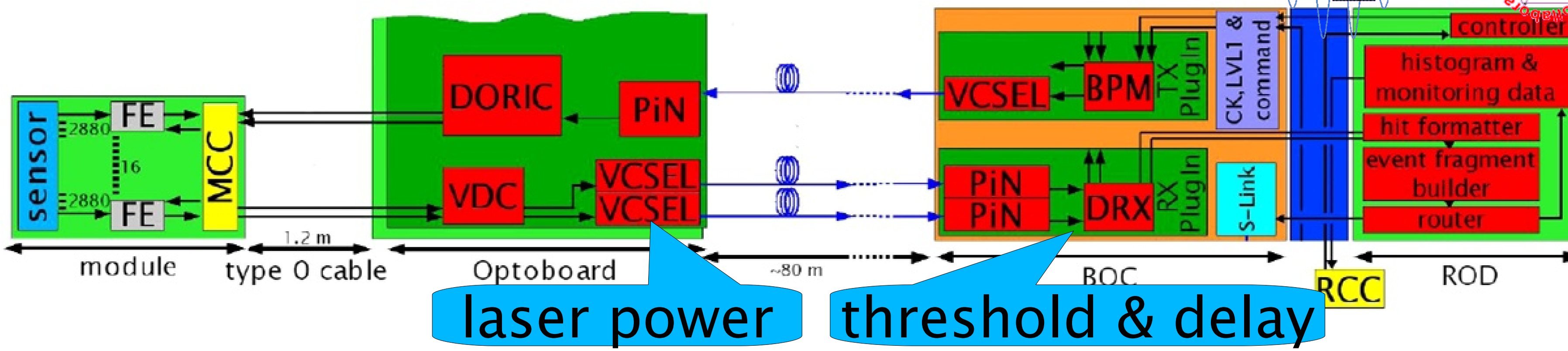
Services & Cooling

- 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



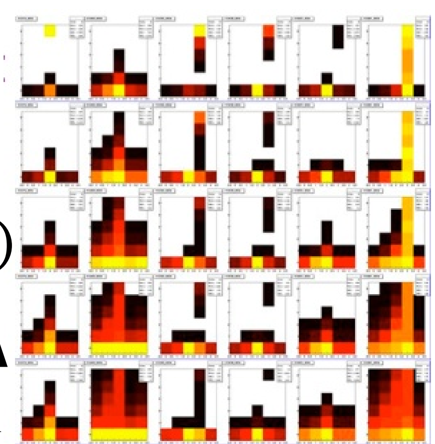
All services and cooling fulfill the requirements of the detector

Optical Communication Tuning

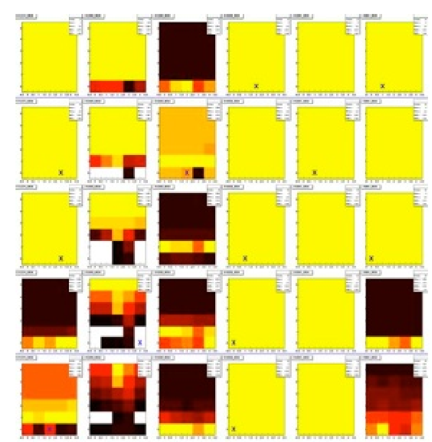


- several parameters need to be tuned for the optical data link between on-detector optoboards and off-detector BOC cards:
  - laser power for the optoboard (1 voltage for up to 14 channels)
  - threshold and delays at the BOC receiver side (channelwise)
- challenge: adjust optoboard laser power such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

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



+10°C

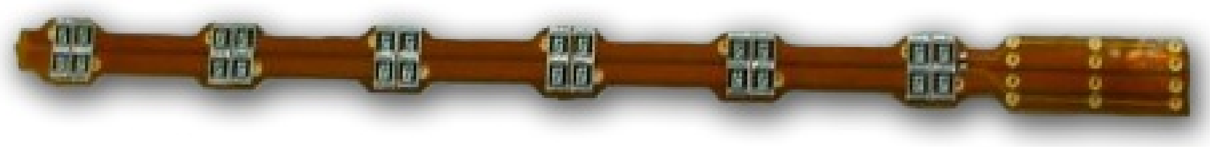


laser power ↓

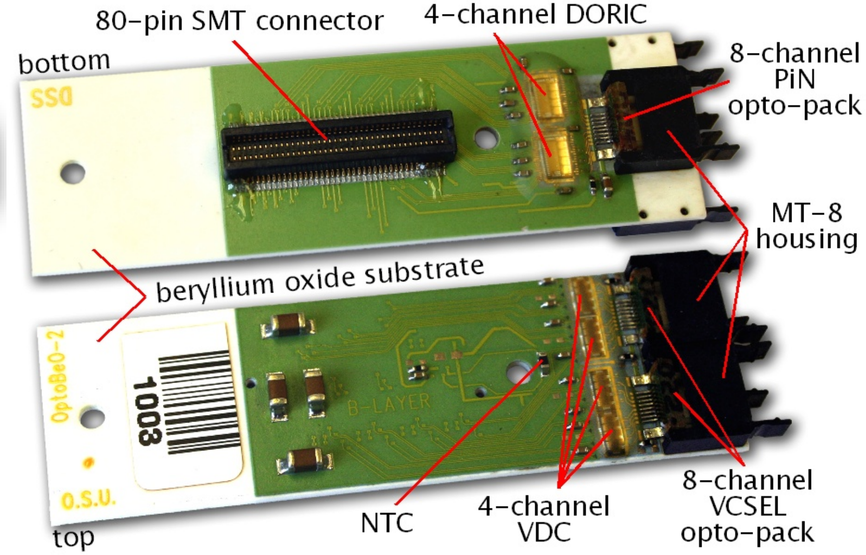
−10°C

Optical Communication Tuning

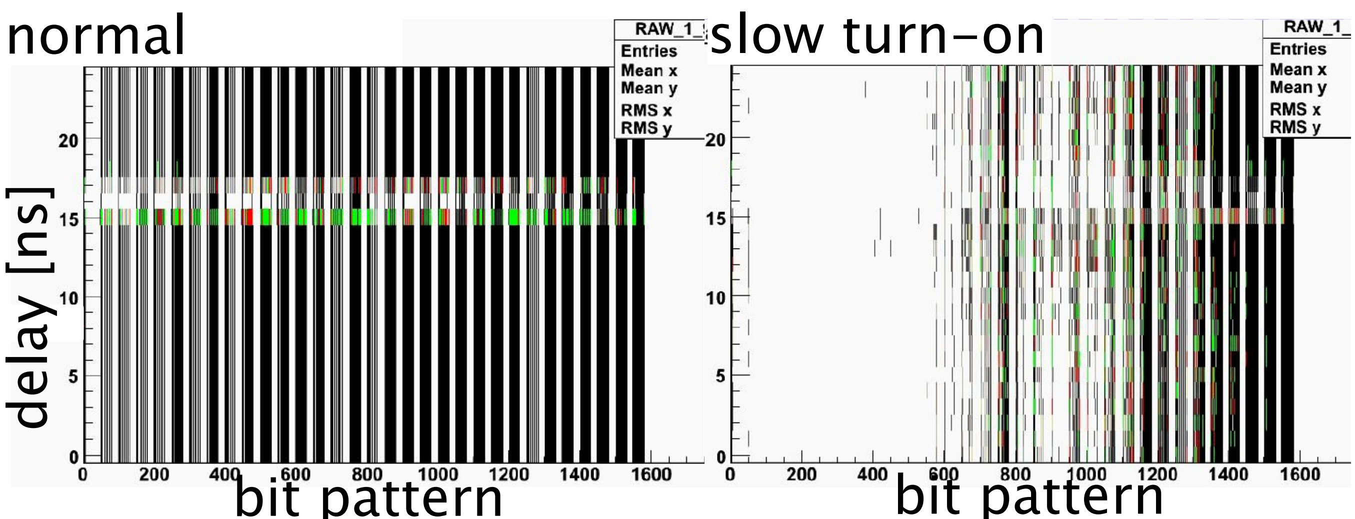
- heaters have been installed on the optoboards
  ⇒ all channels behave well at ~20°C

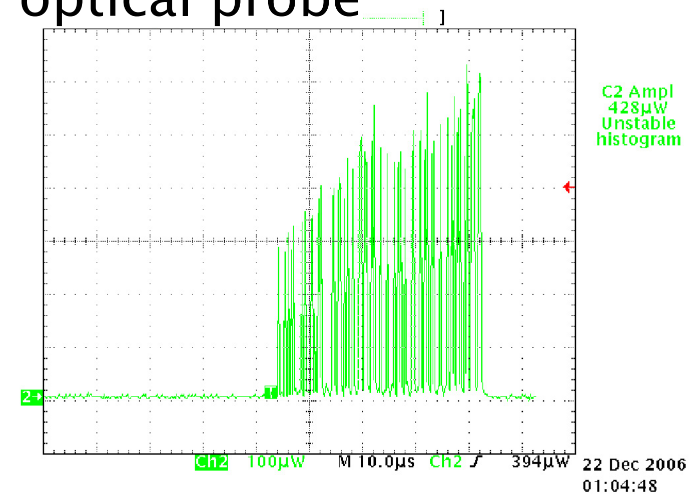


- slow turn-on of light power for few channels
  ⇒ has been addressed in the optoboard quality assurance procedure



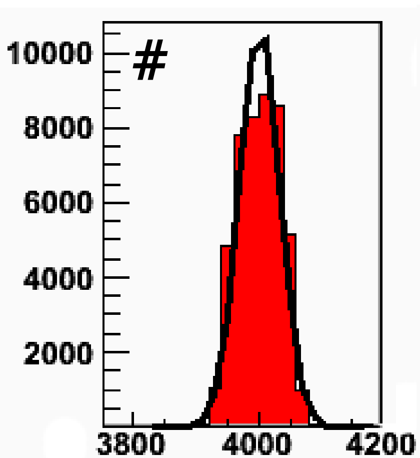
probably most of the problems can be explained by not first-choice quality optoboards in the System Test



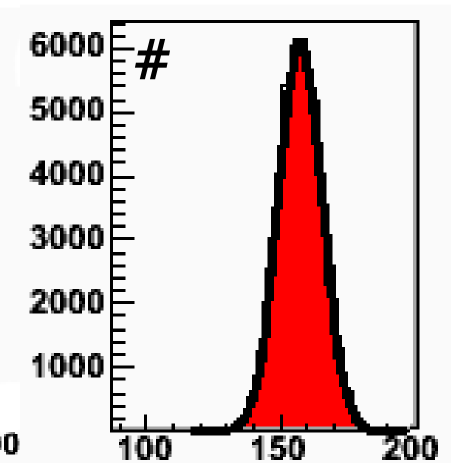


Module Tuning Performance: Thresholds & Noise

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

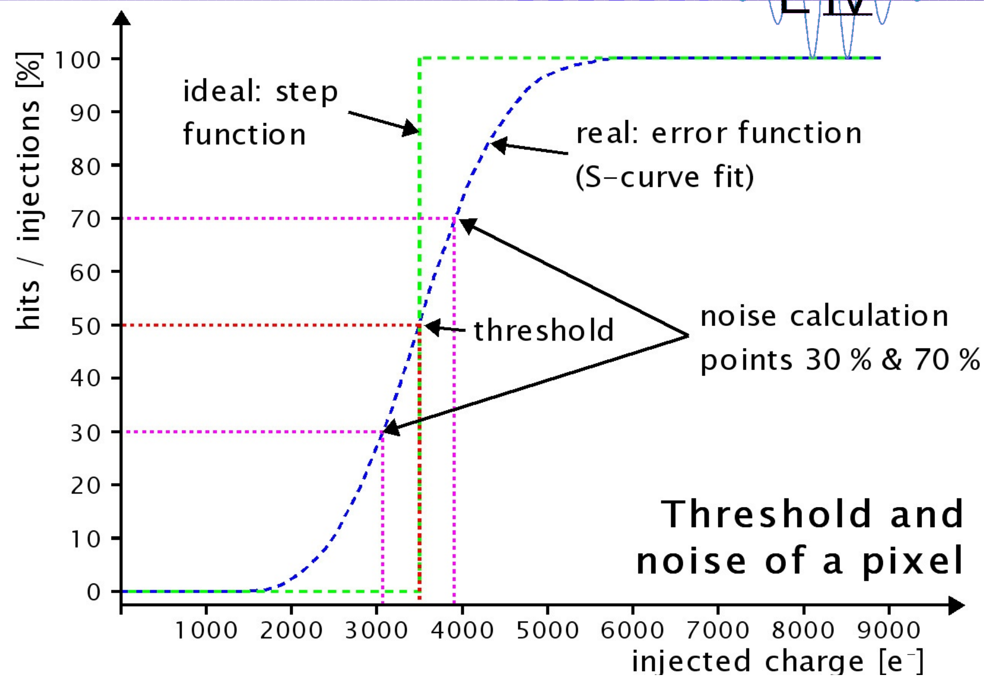


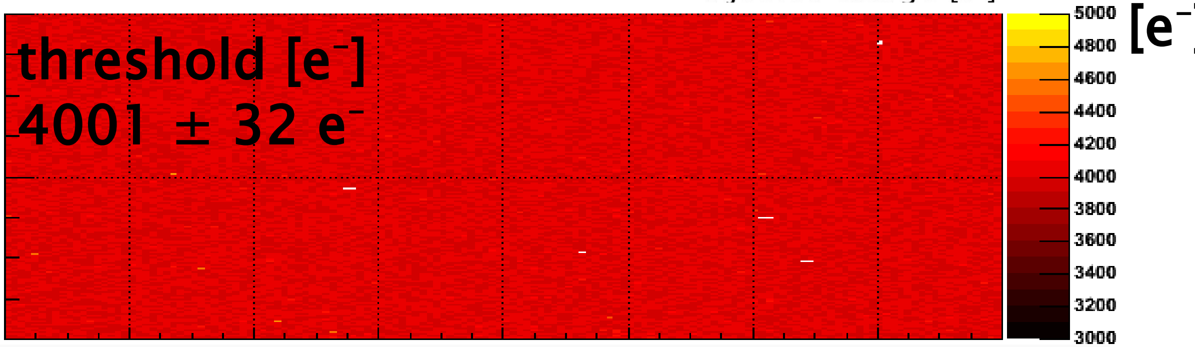
Threshold [e^-]

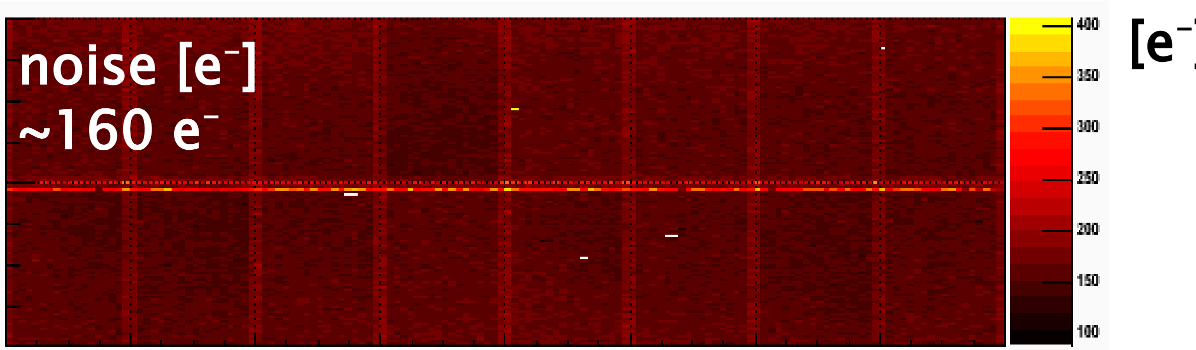


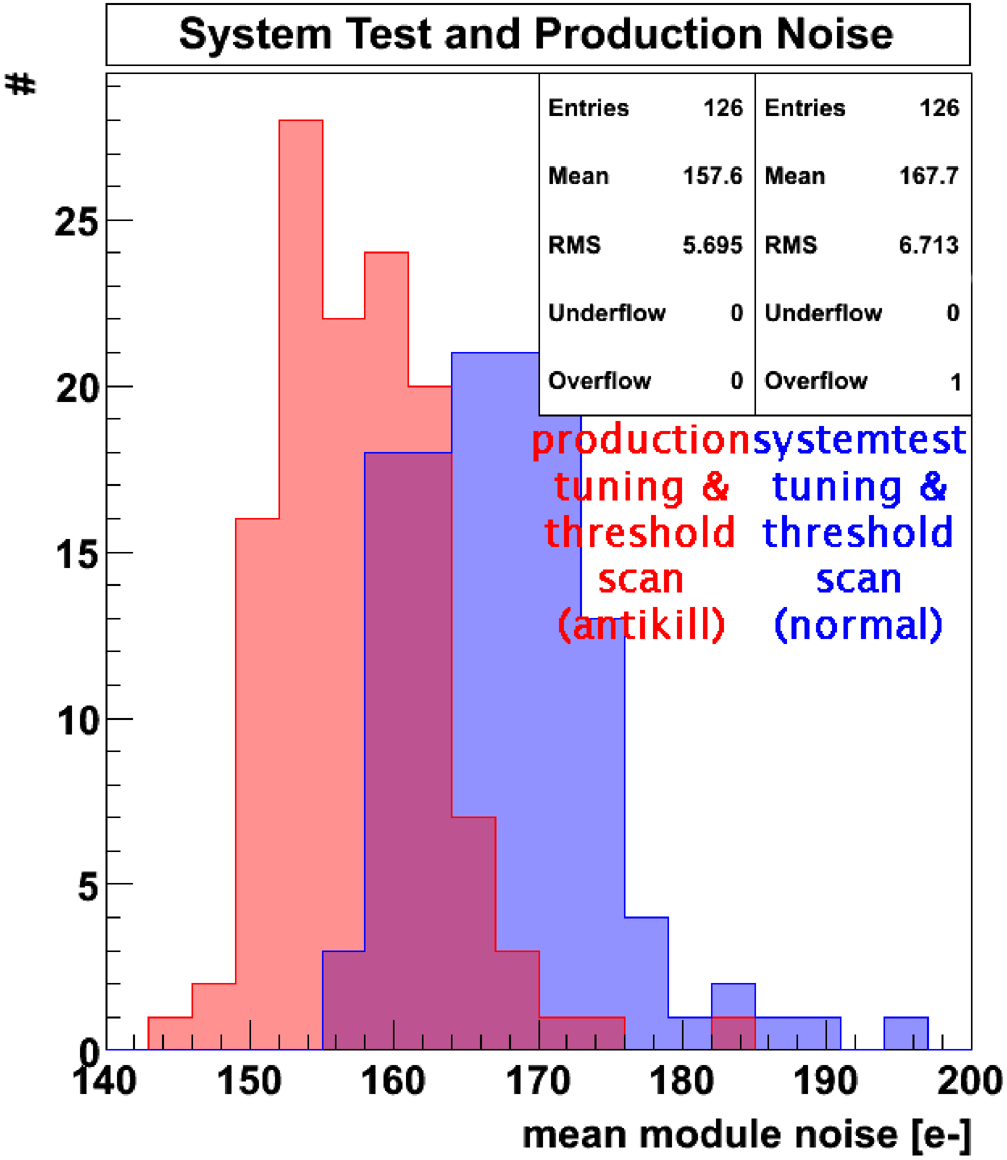
Noise [e^-]

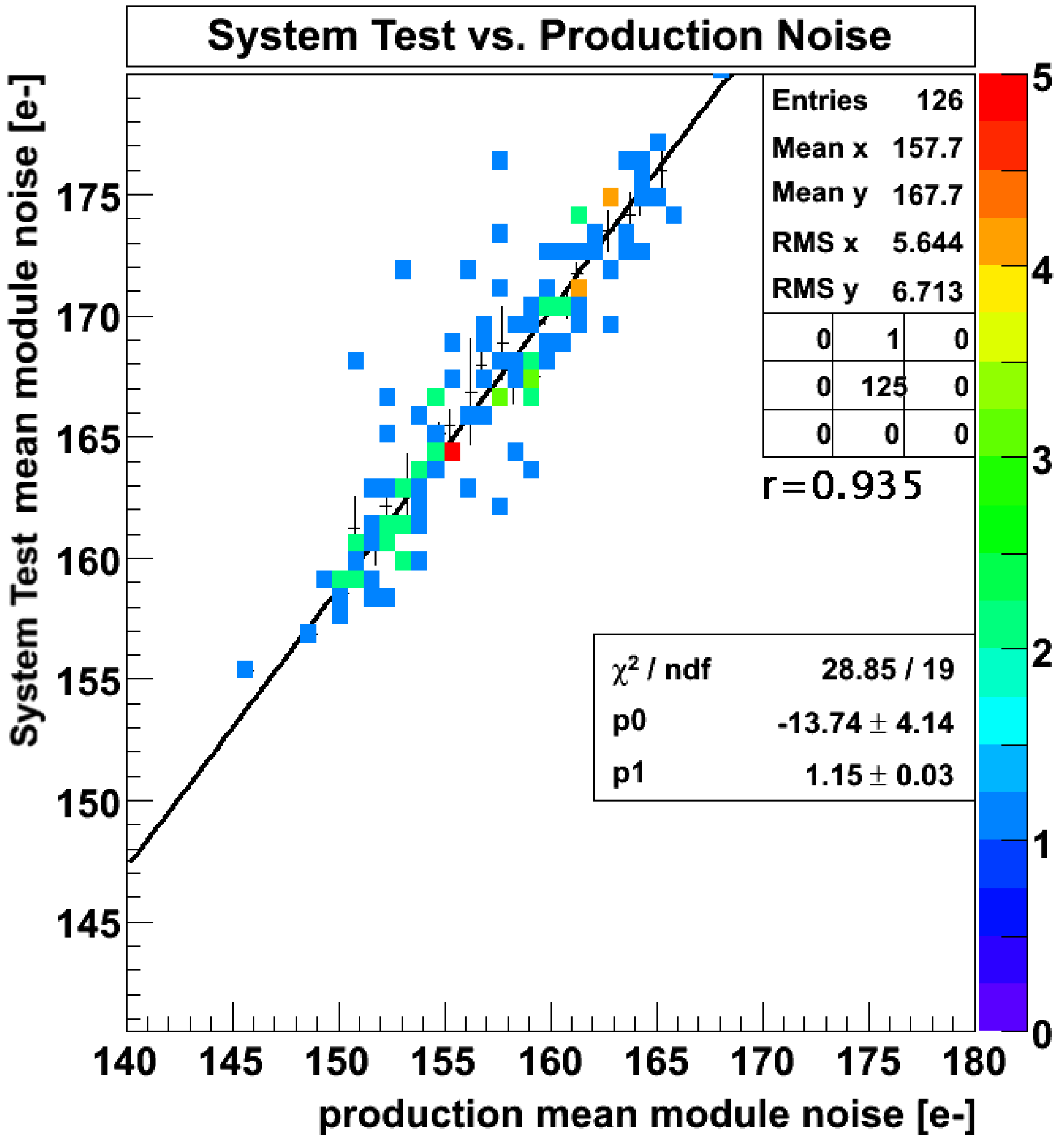
- MIP in 250 µm silicon sensor: mean energy loss 27 ke-
  ⇒ with charge sharing ~17 ke-
  ⇒ after life-time dose irradiation irradiation ~ 8 ke-



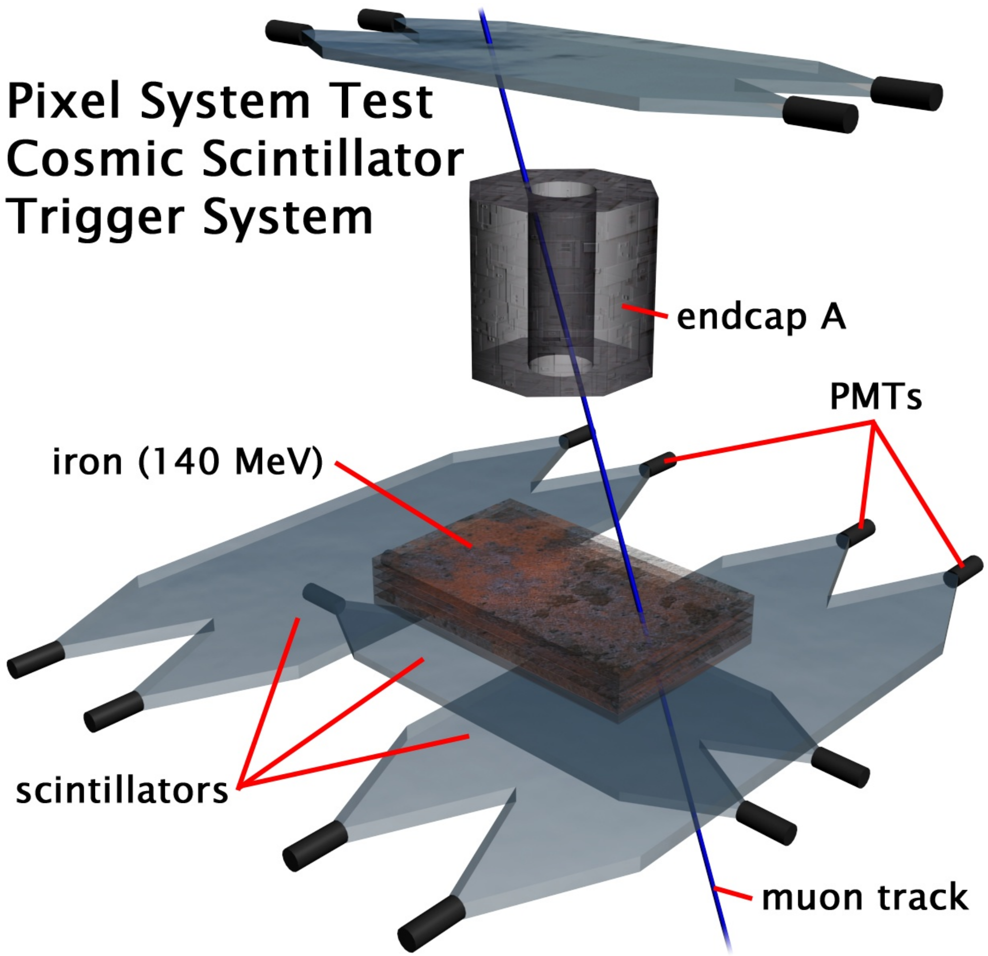


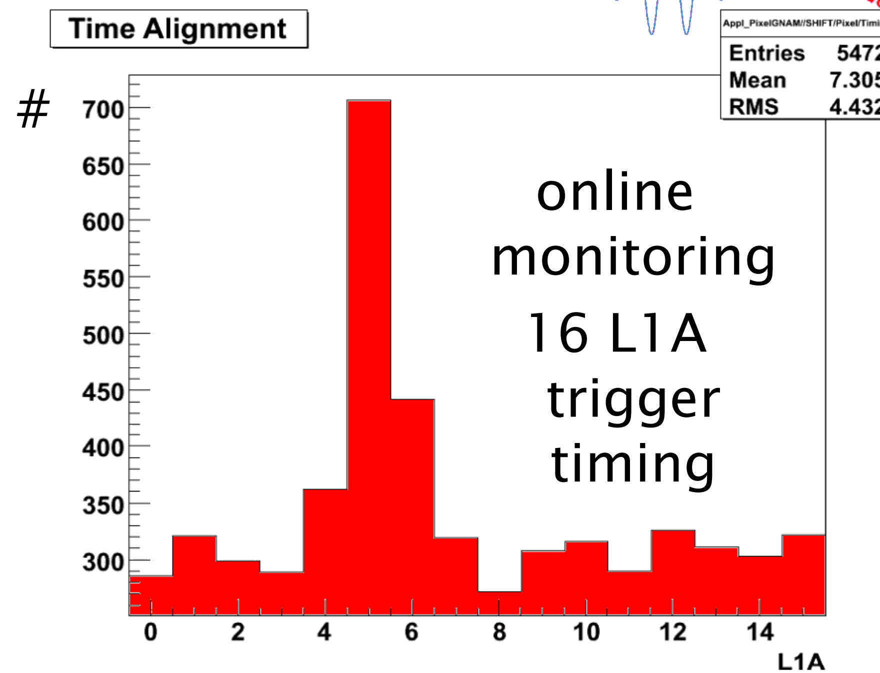


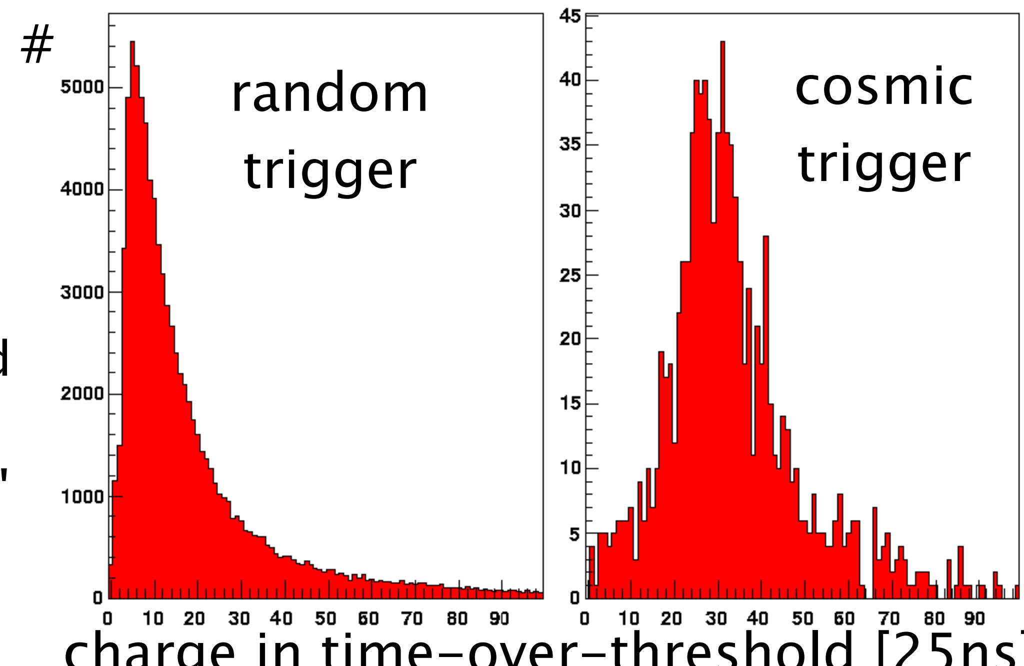

System Test and Production Noise
#
Entries 126
Mean 157.6
RMS 5.695
Underflow 0
Overflow 0
Entries 126
Mean 167.7
RMS 6.713
Underflow 0
Overflow 1
production tuning & threshold scan (antikill)
systemtest tuning & threshold scan (normal)
mean module noise [e-]


System Test vs. Production Noise
System Test mean module noise [e-]
production mean module noise [e-]
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

Pixel System Test Cosmic Scintillator Trigger System

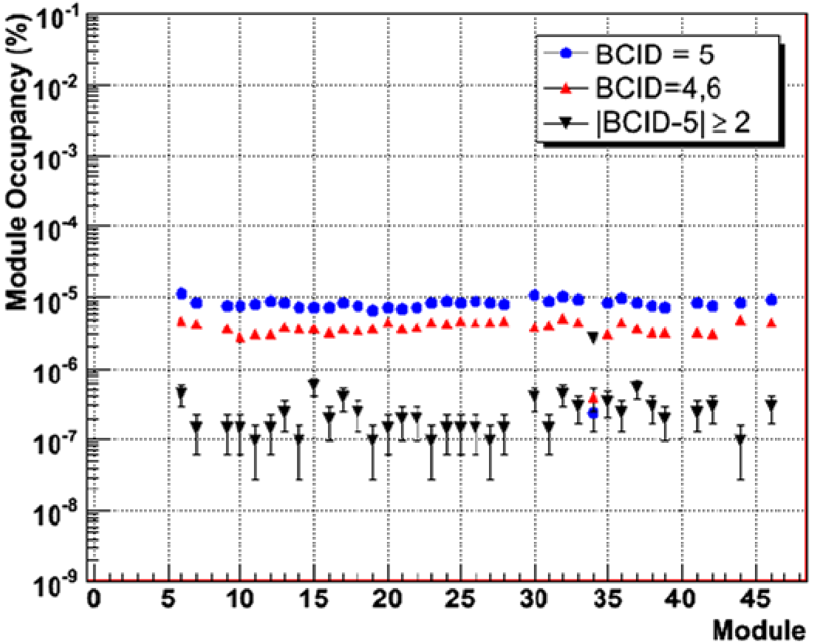




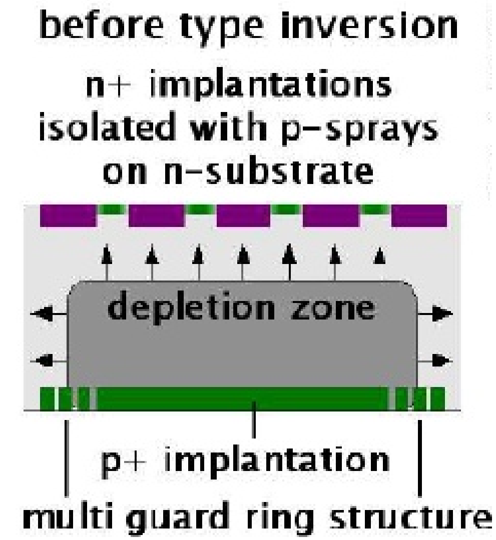


- trigger requests hit in top scintillator and any of the bottom scintillators
- hit position within 16 consecutive 'level1' triggers for cosmic triggers show clear cosmic peak above noise floor

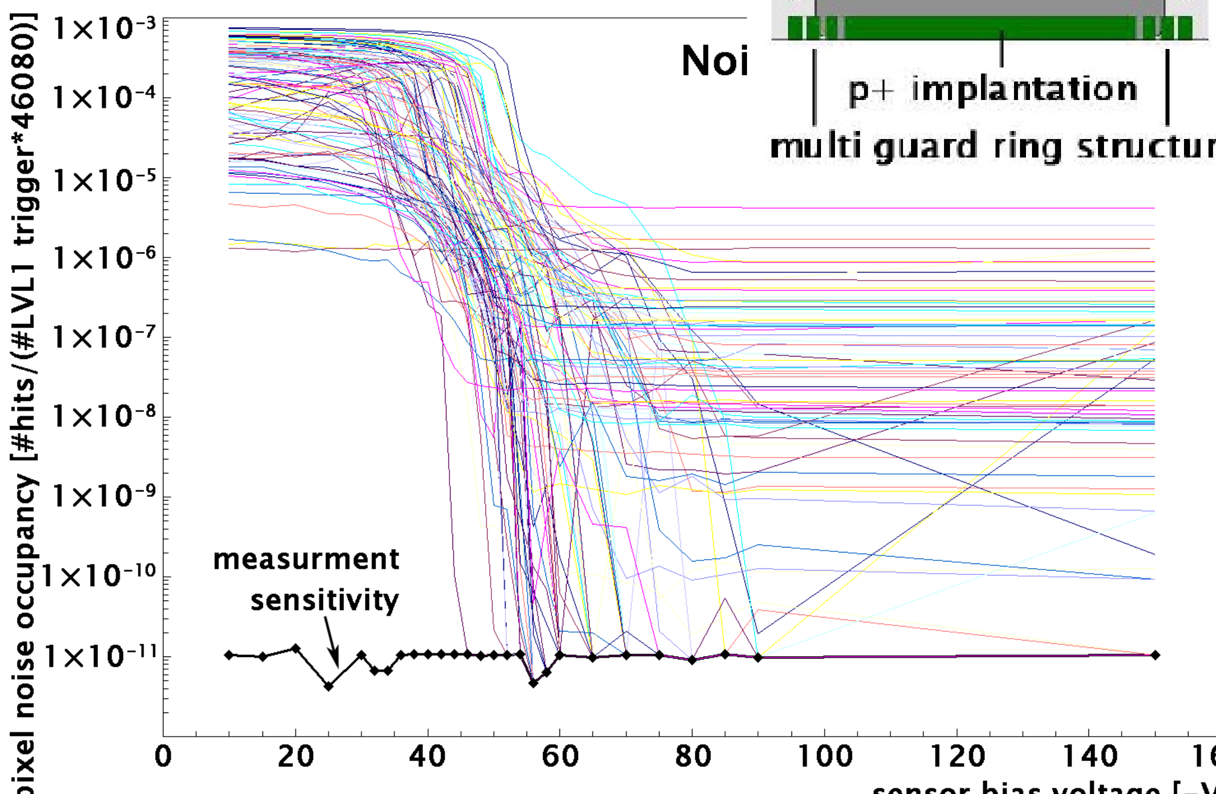
Noise Occupancy and Sensor Depletion Voltage



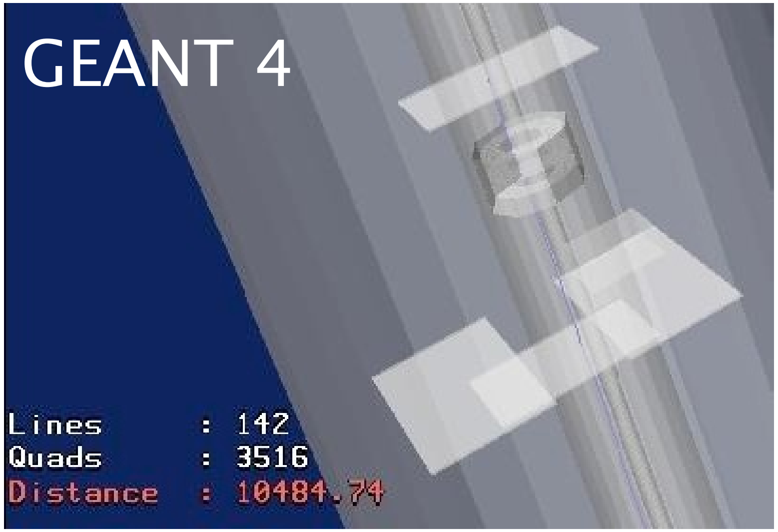
- noise occupancy measured with cosmic trigger
- after removal of noisy (10^{-4}) pixel noise occupancy as low as 10^{-7}
- 90% of noisy pixel identified from production measurements
- total fraction of affected pixels >1%



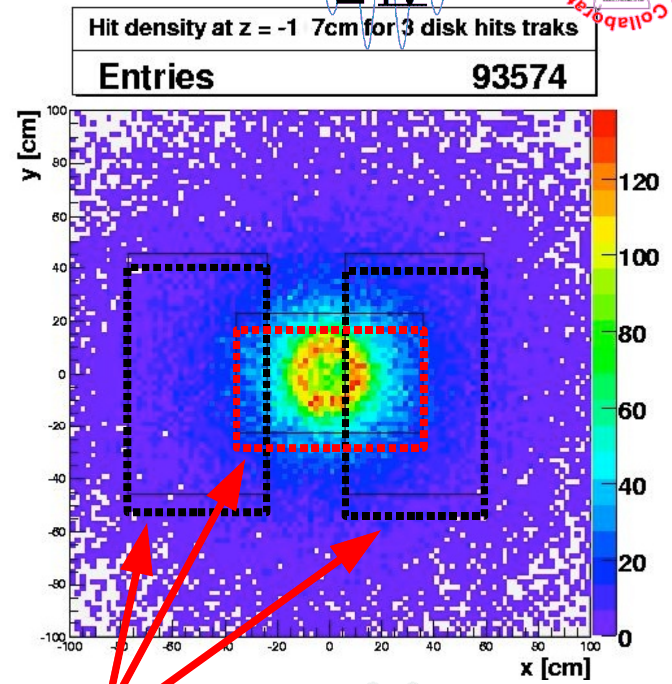
- noise occupancy with random trigger vs. sensor bias voltage measurement used to determine depletion voltage
- depletion zone grows towards pixel side ⇒ bias voltage below full depletion – pixel shorted ⇒ high capacitive load to preamplifiers ⇒ high noise ⇒ high noise occupancy



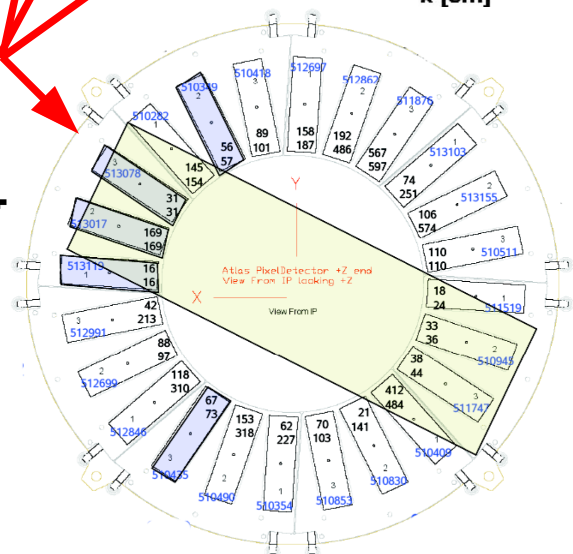
Monte Carlo vs. Data



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

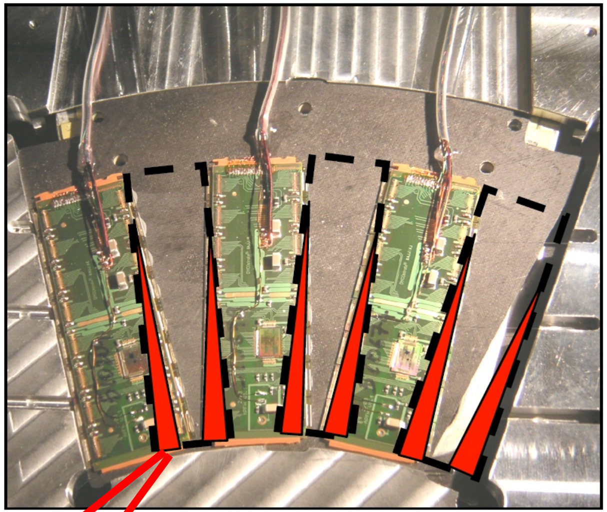


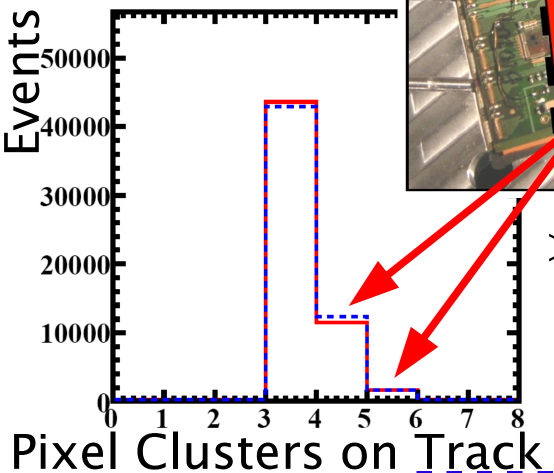
Scintillators



— MC

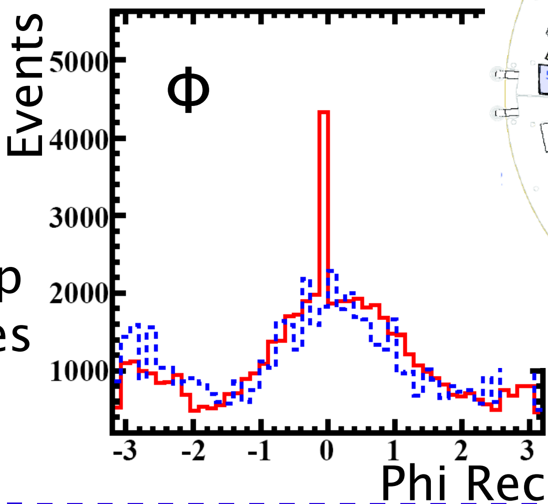
— Data



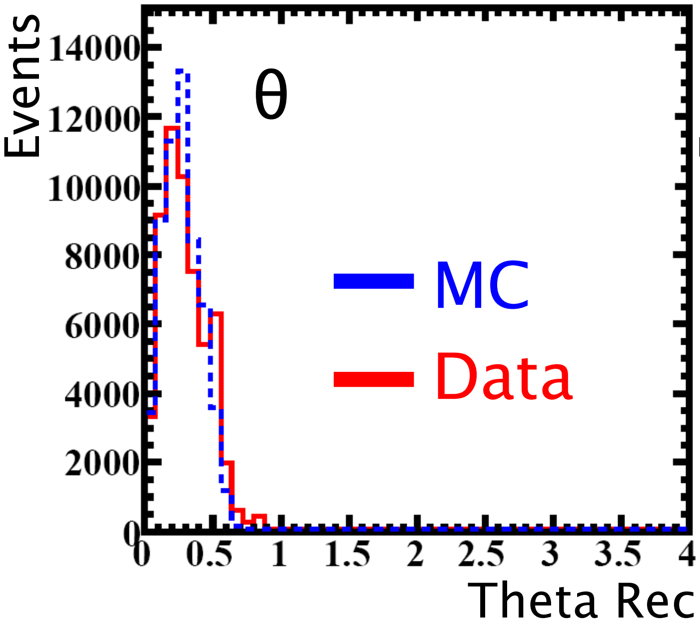


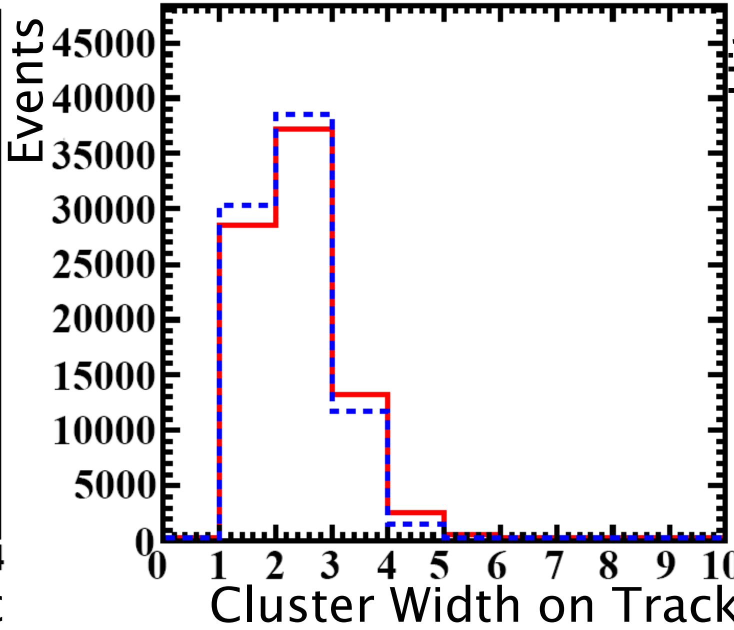
>10% of area overlap region with modules on other side

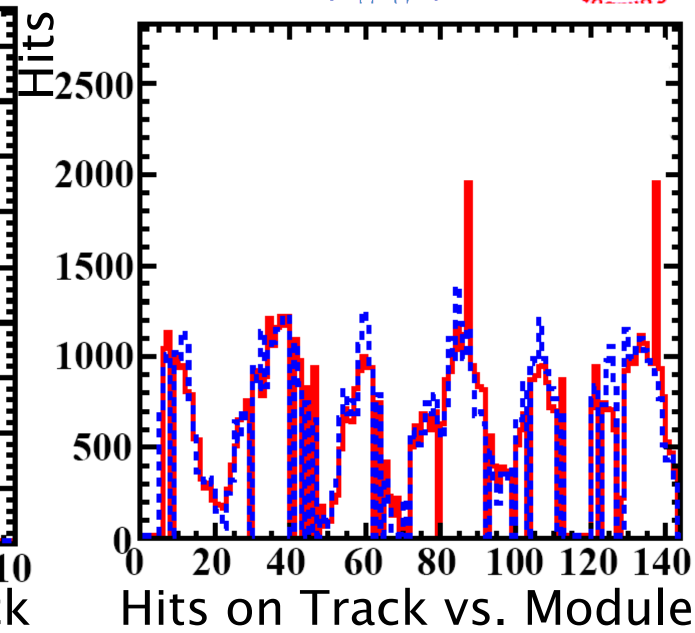
Δz=4.2 mm



Monte Carlo vs. Data (2)

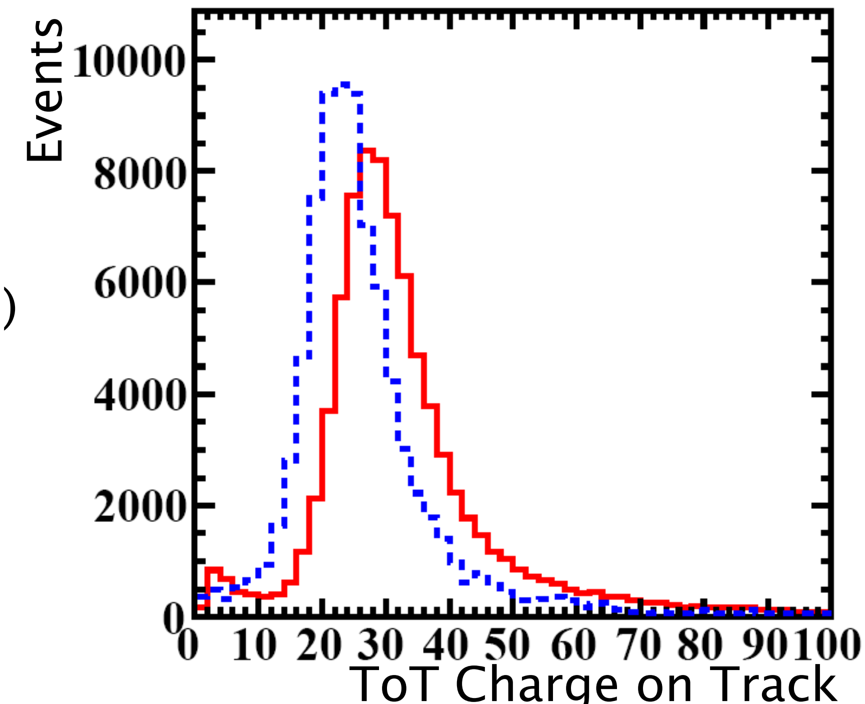




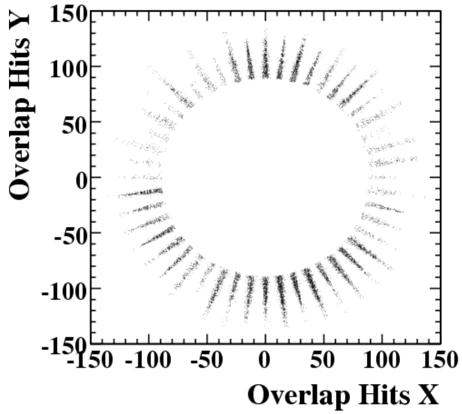


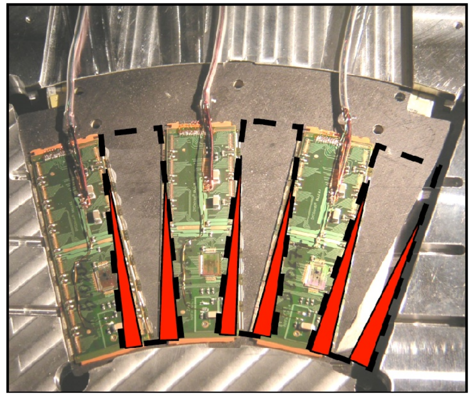
- MC tuned on cosmic data
- theta reconstruction, cluster width and hits on track vs. module agree with MC (hits on track inhomogeneous due to asymmetric scintillator, missing modules & 3 noisy pixels)
- TOT shape correct ⇒ TOT calibration (from production measurements) OK
  ⇒ shift due to wrong fit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

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



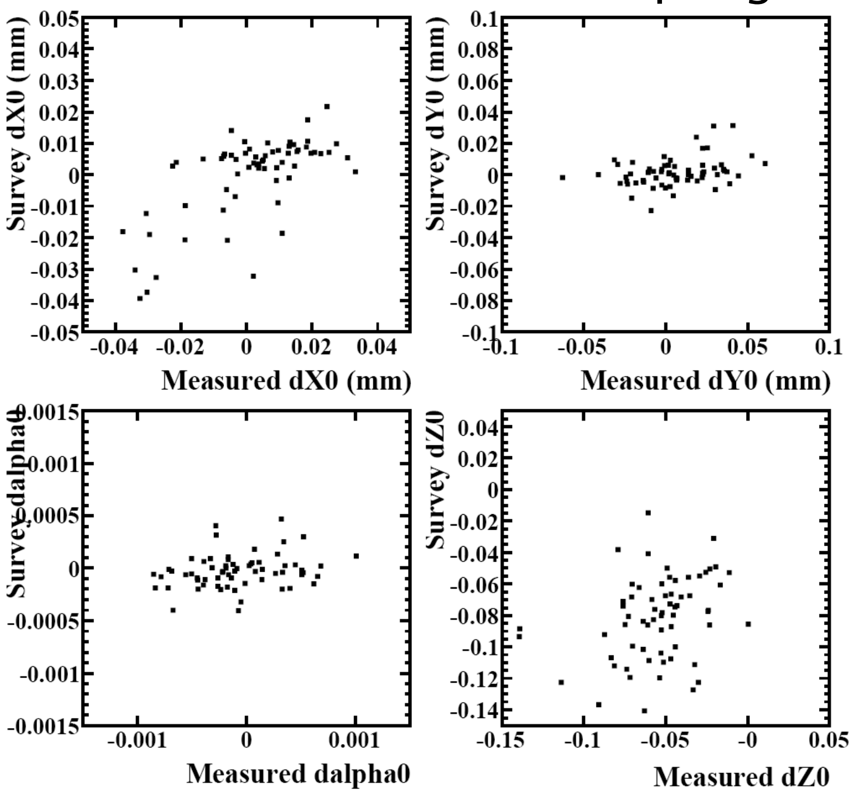
Alignment

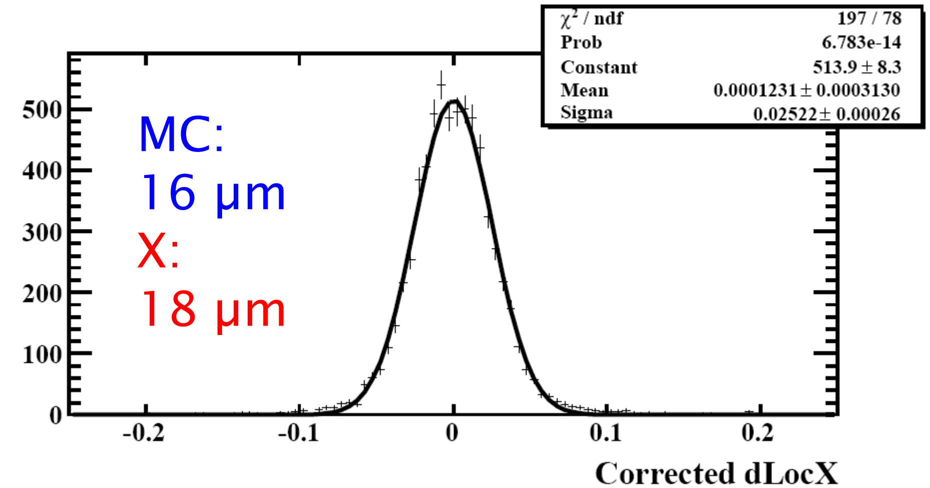


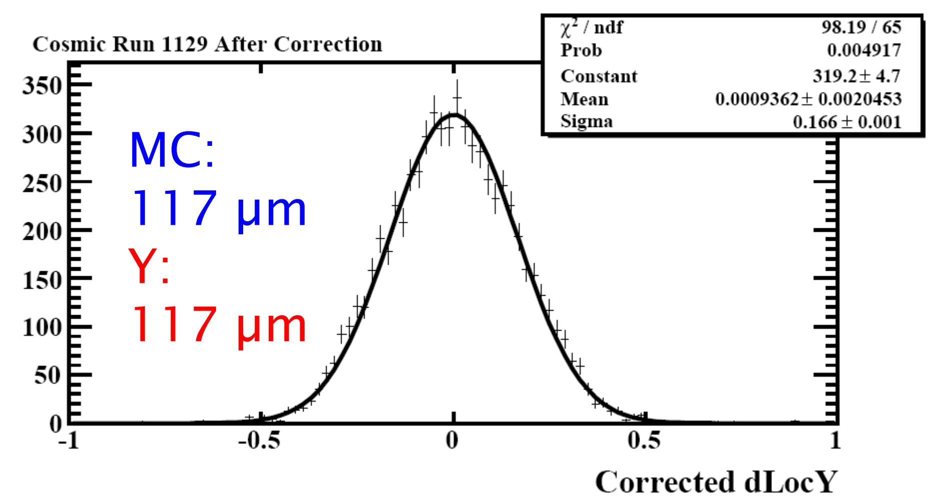


- use >10% overlap region between modules on different side of a disk Δz=4.2 mm to determine relative alignment between modules

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

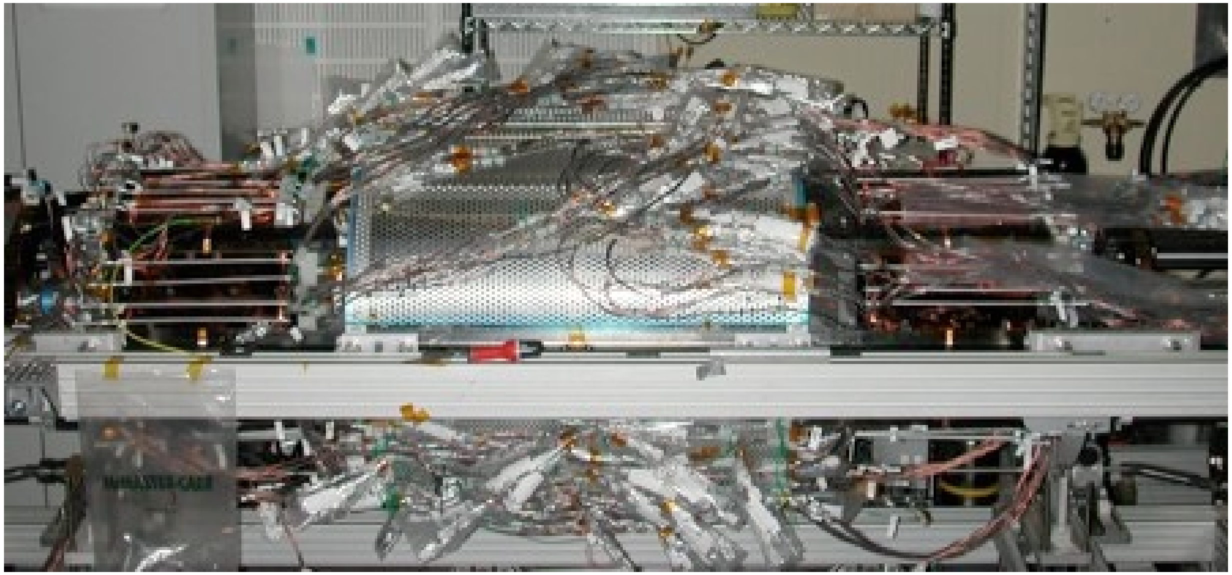


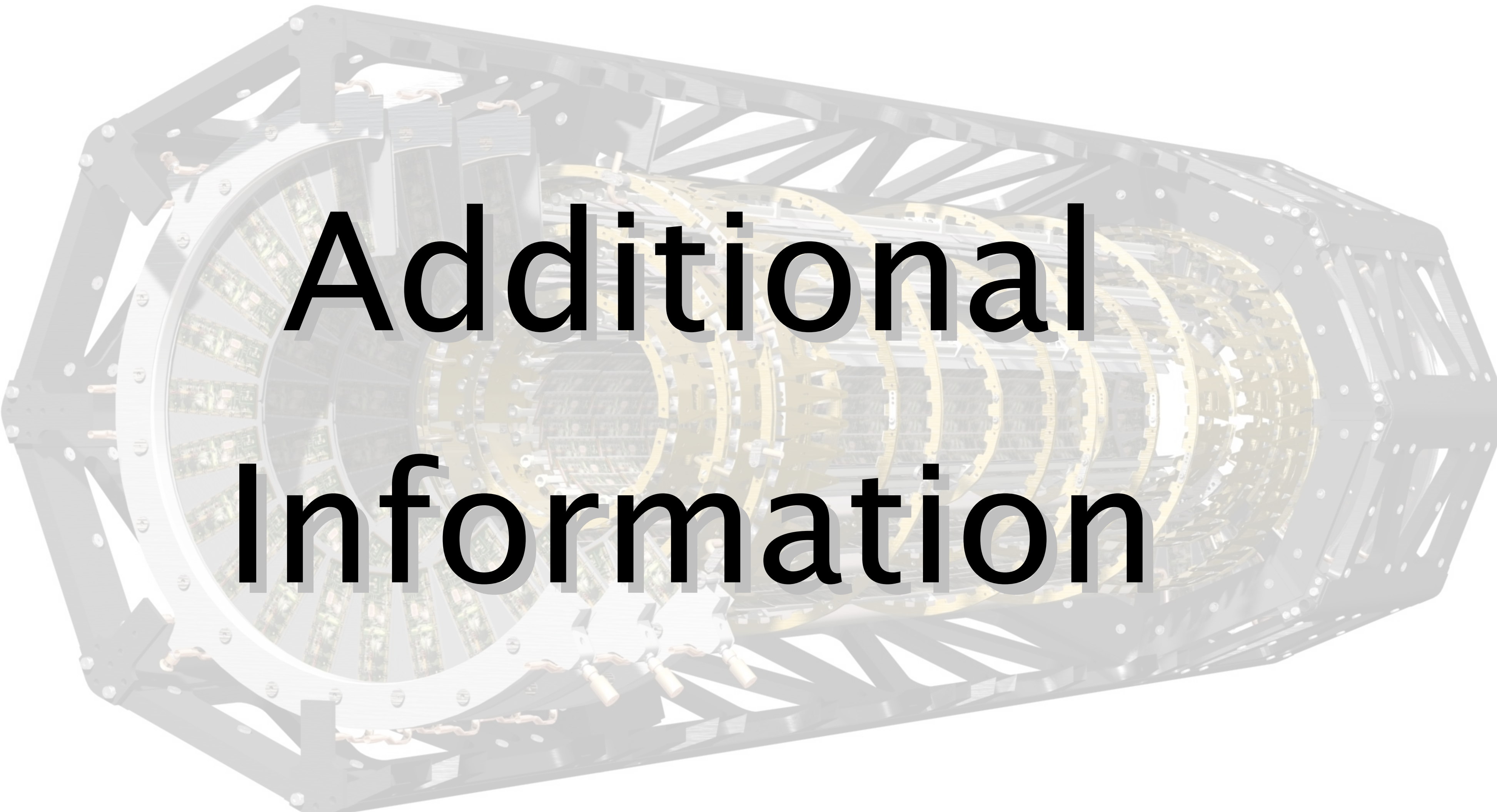




Conclusions

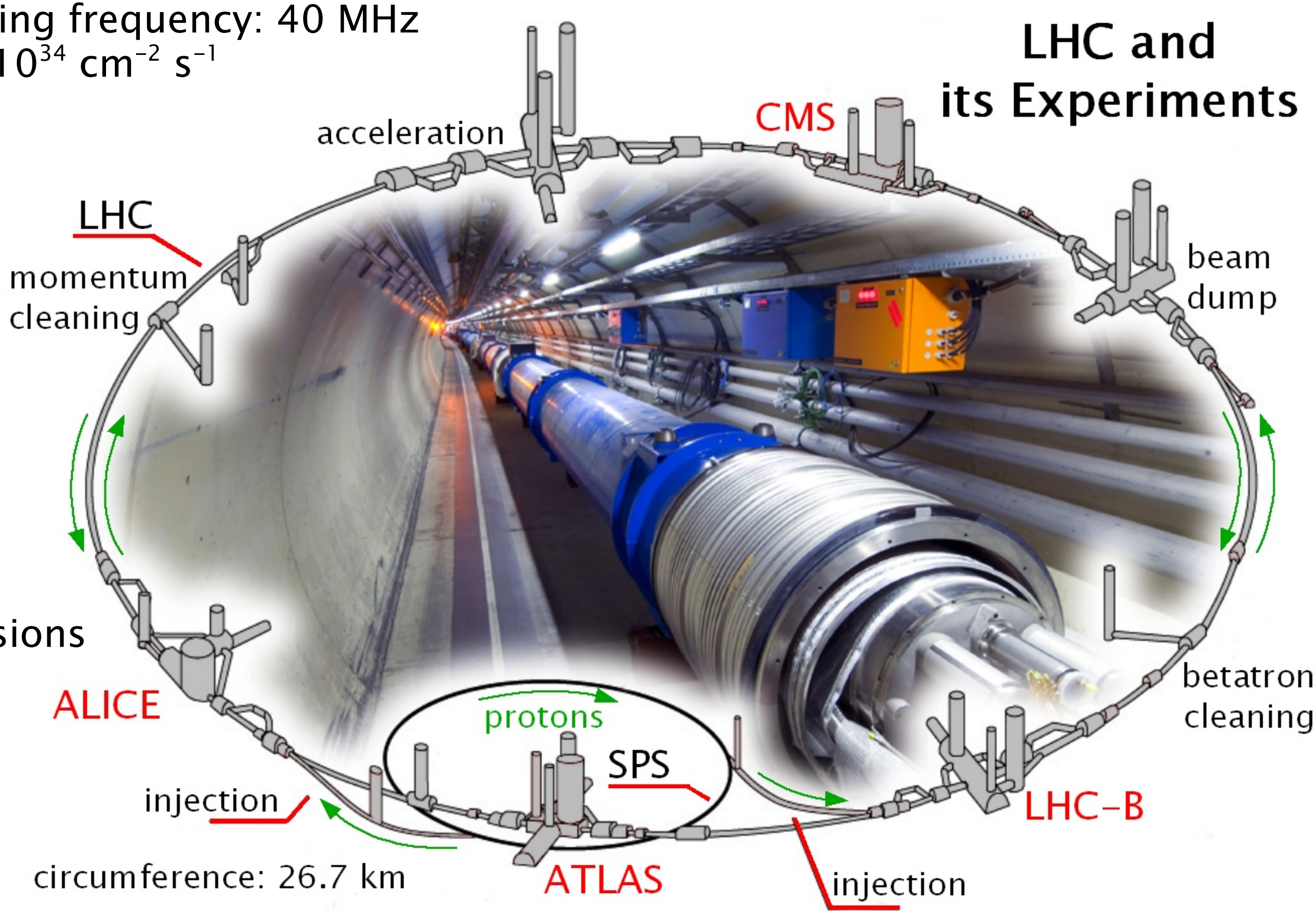
- the ~10% System Test was a success and we gained valuable experience for a successful commissioning and the operation of the detector
- various parts of the services have been validated (cooling, services, interlock system)
- huge development step was done in online and offline software driven by the 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





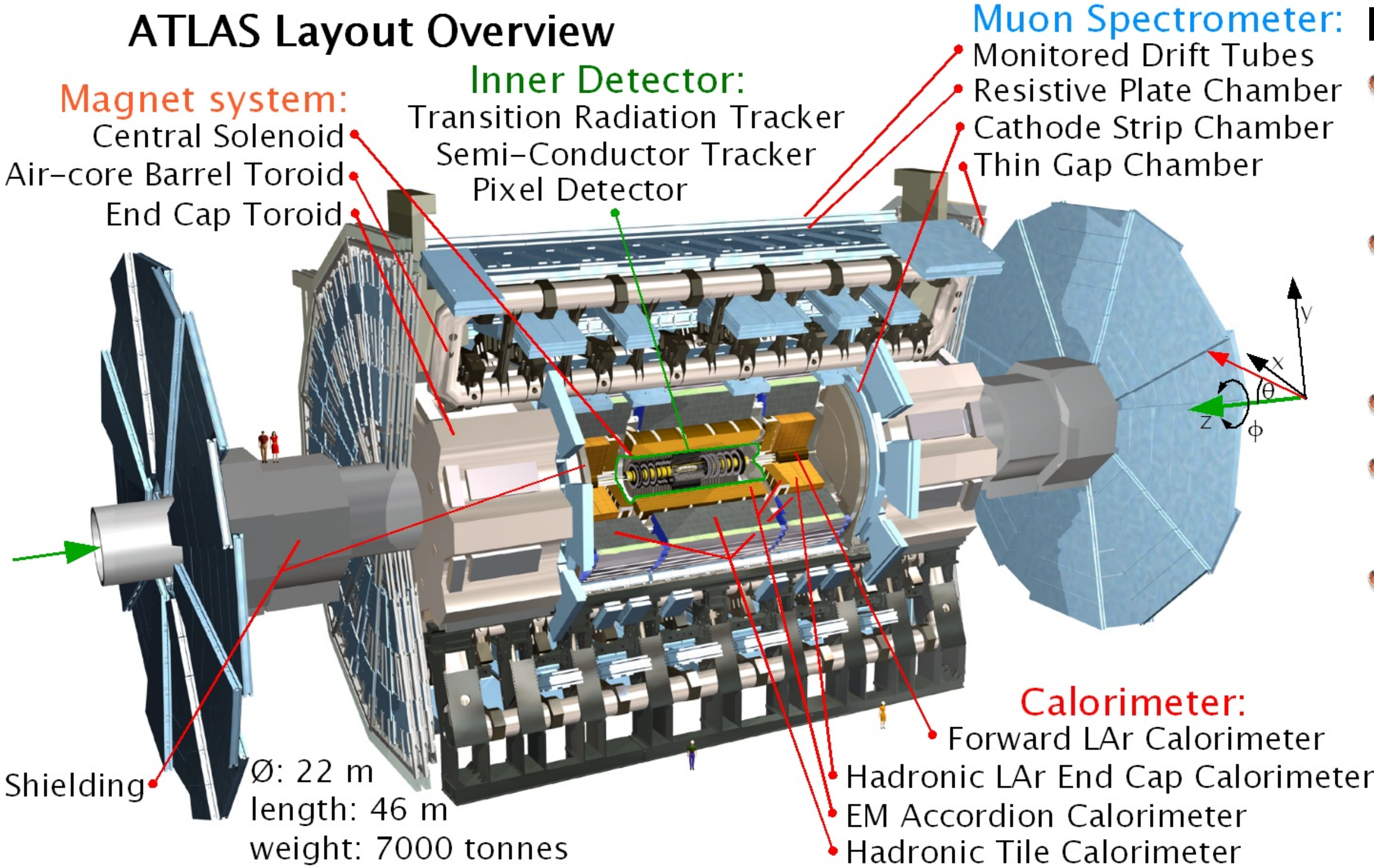
Additional Information

- 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

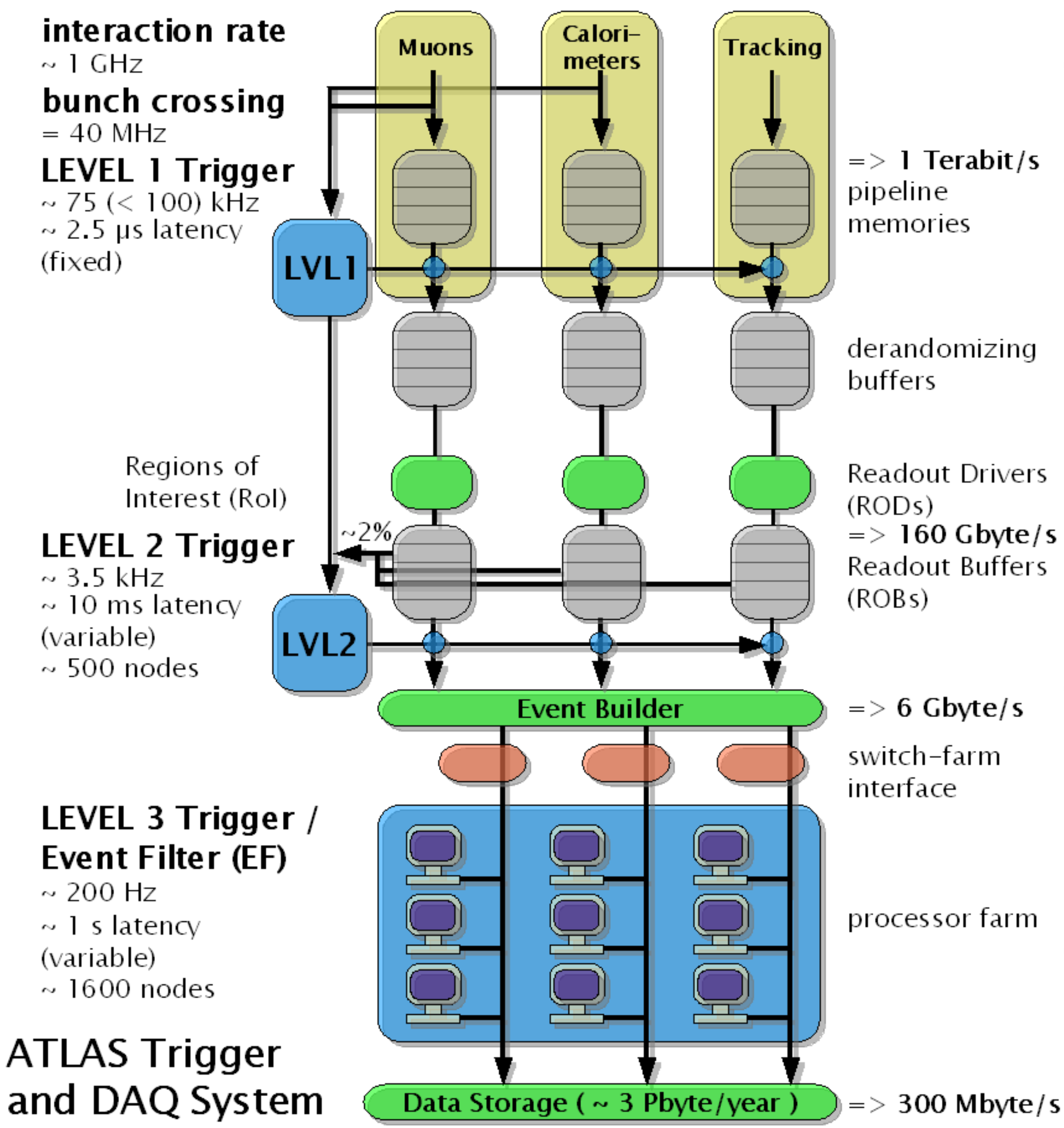
- diameter: 22 m; length: 46 m; weight 7000 tons
- air-core (⇒ to avoid multiple scattering) barrel toroid magnetic field: 4 T
- central solenoid magnetic field for inner detector: 2 T



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

ATLAS Trigger

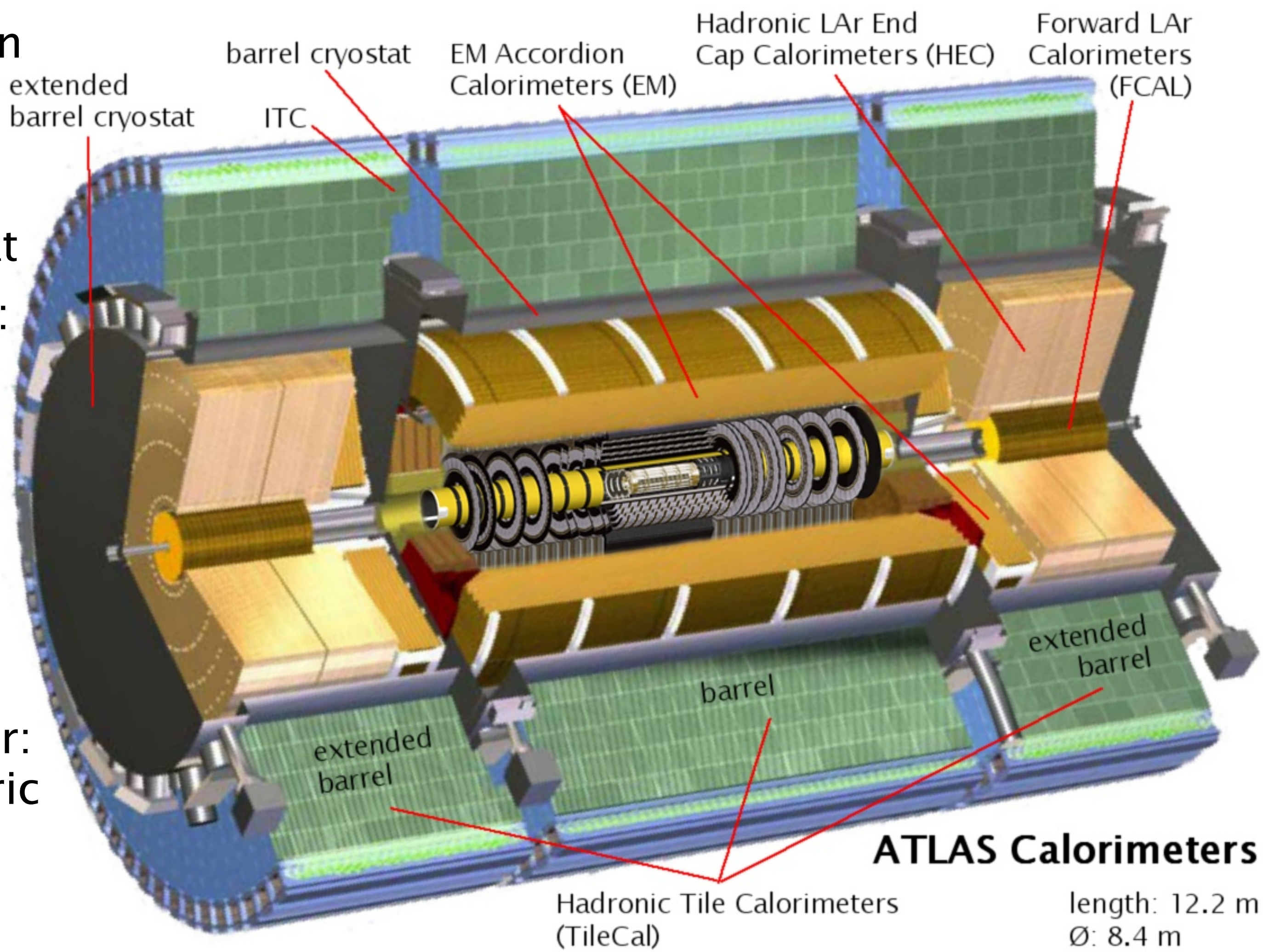


ATLAS Trigger and DAQ System

- 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

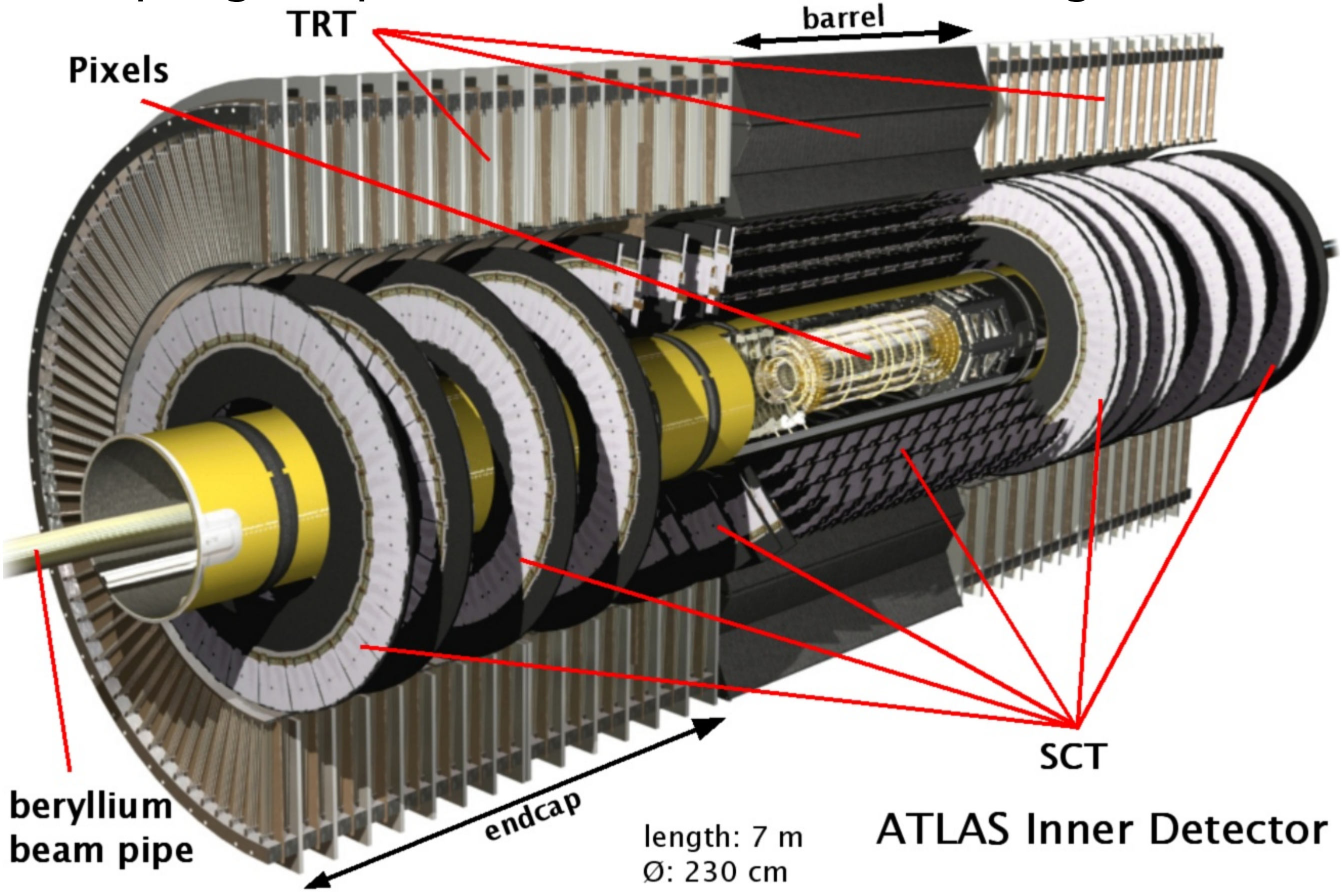
ATLAS Calorimeters

- 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 Inner Detector

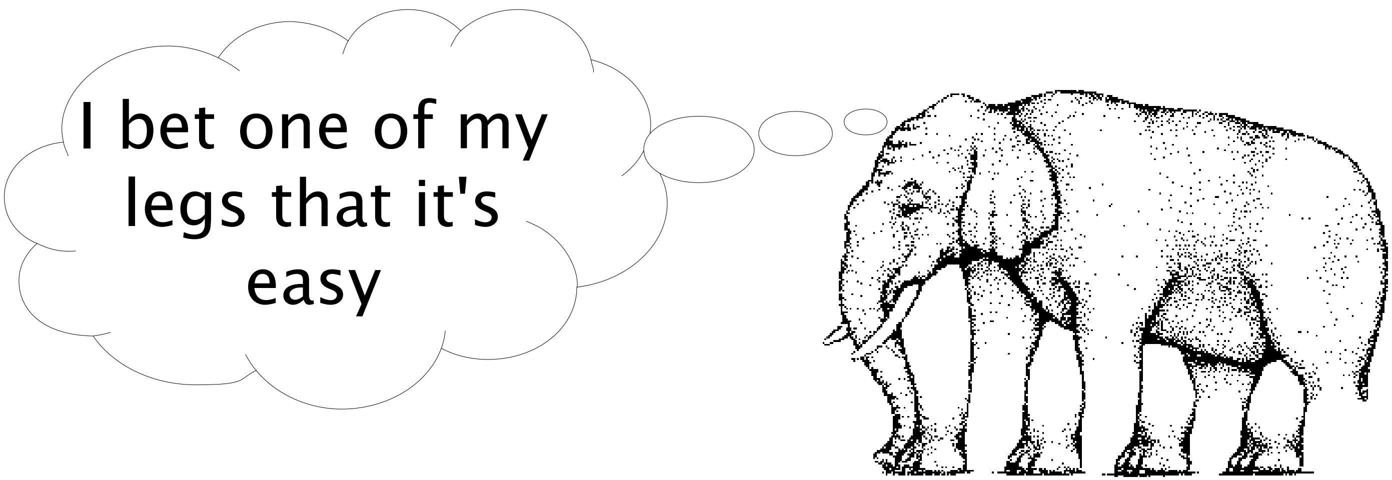
- high-resolution tracking sub-detectors closest to the interaction point & continuous tracking sub-detectors at the outer radii
- Transition Radiation Tracker: straw detectors can cope with high particle rates & occupancy; 36 space points; charged particle passing through dielectric constant boundary ⇒ 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

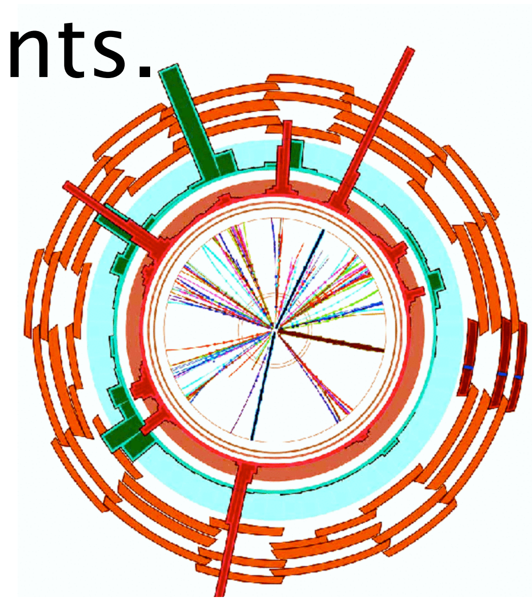


- Semiconductor Tracker: eight high-precision space points per track with Silicon microstrip detectors with 80 μm pitch and 40 mrad stereo angle ⇒ 6.2 million channels; front-end amplifier followed by discriminator; track resolution of 16 μm in Rϕ direction and 580 μm in z direction
- Pixel Detector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

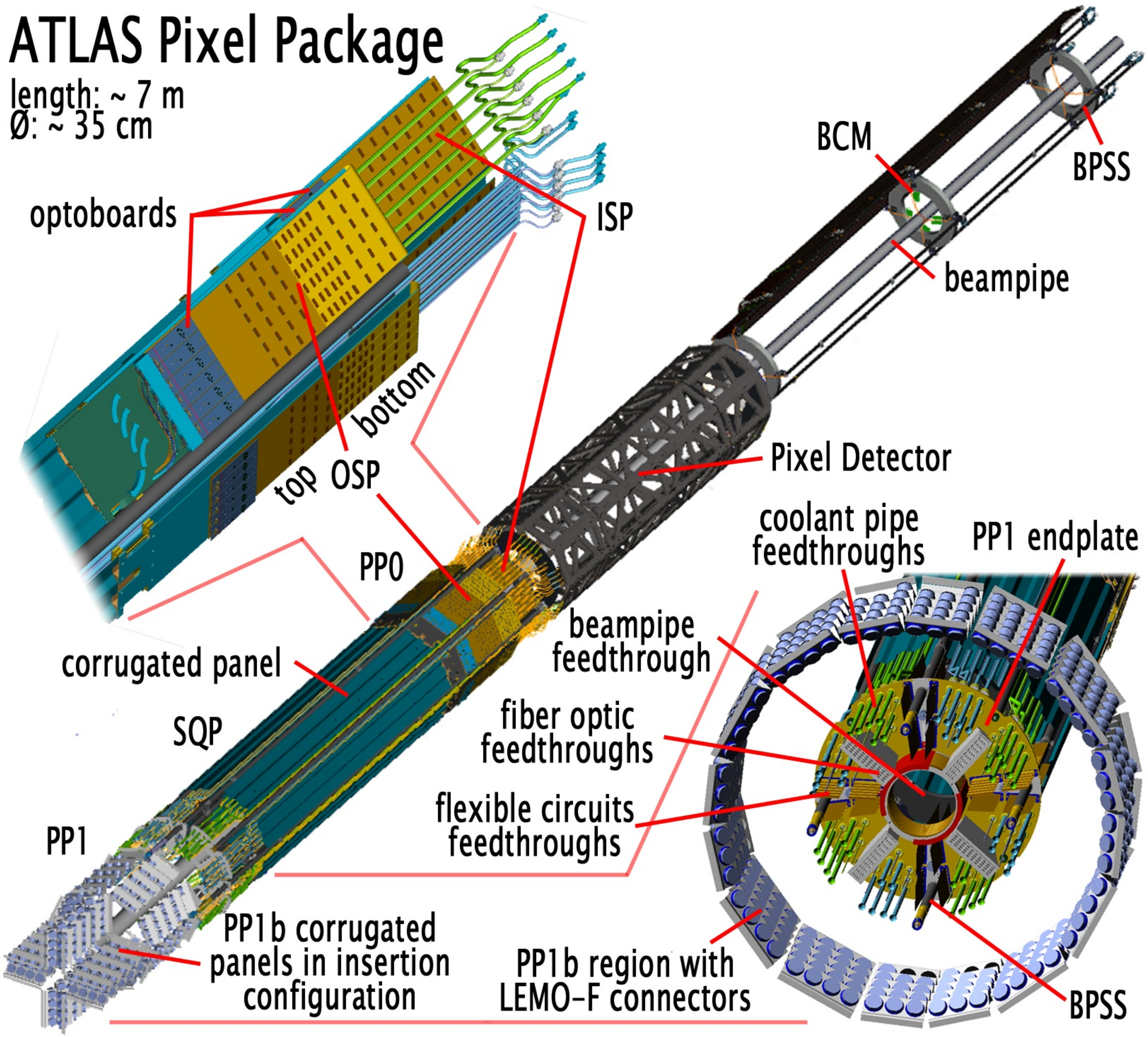
Tracking and Vertexing:

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.



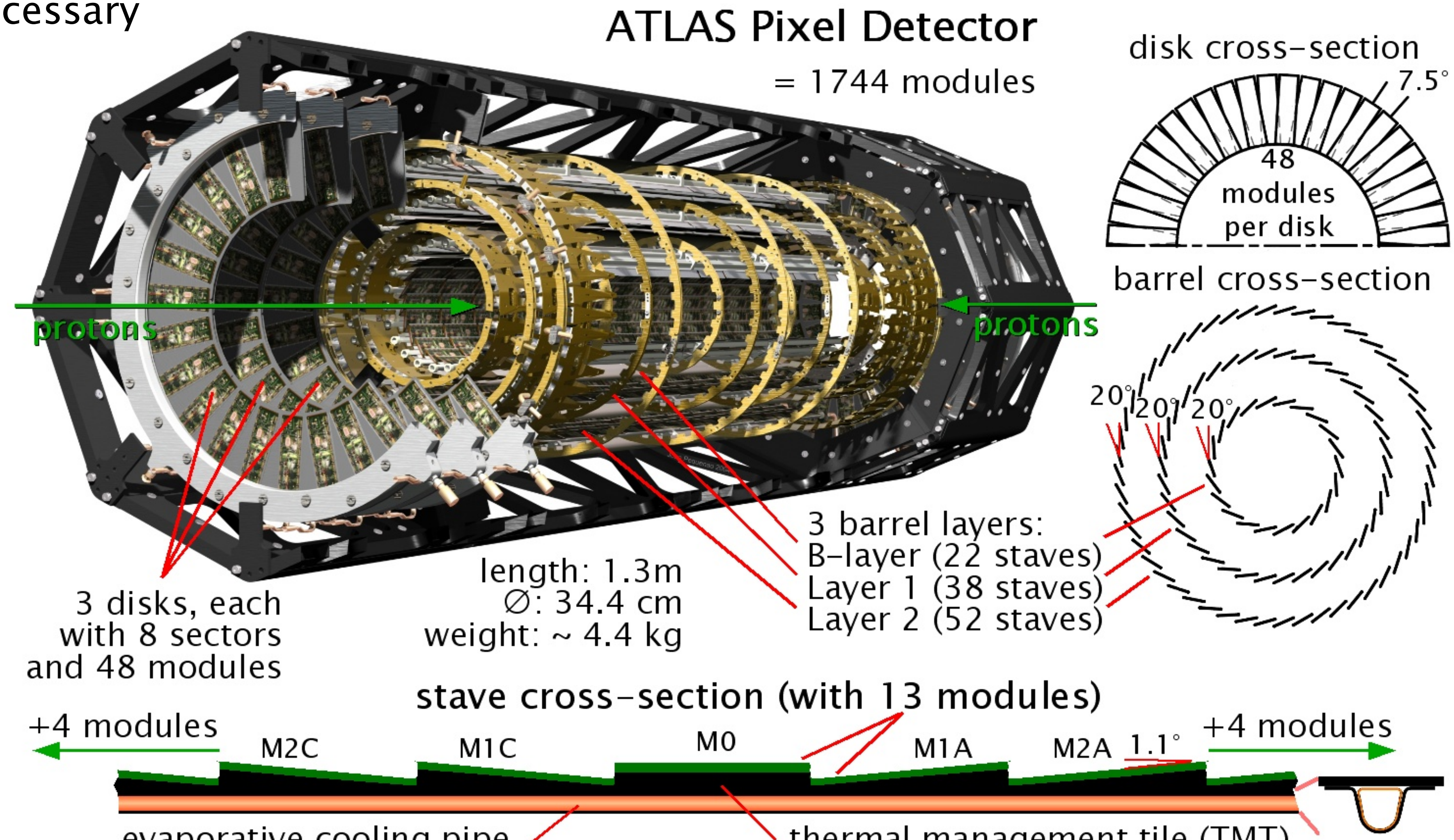


ATLAS Pixel Package

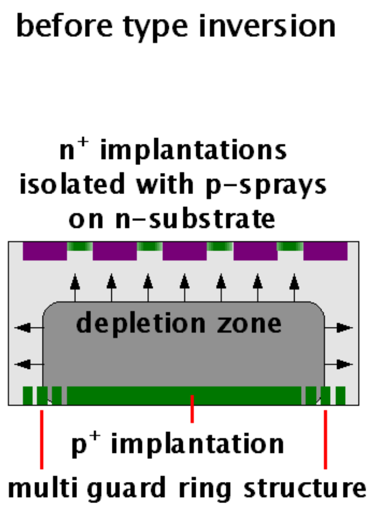


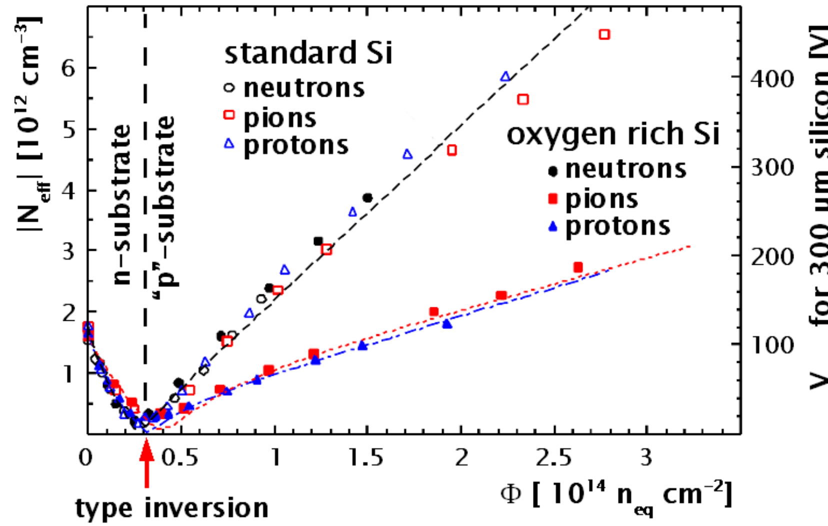
- beryllium beampipe integrated in the Pixel package
- active surface only in the 1.3 m long central detector section
- BeamPipe Support Structure (BPSS) connected at both ends position the beampipe in the middle of the detector and support Service Quarter Panels (SQP)
- in total eight SQPs provide all 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

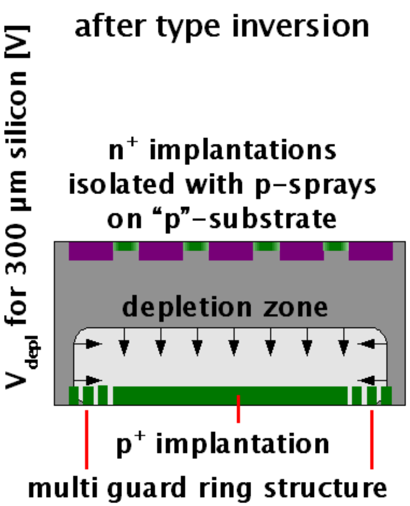
- 3-hit (3 layers and 3 disks) semiconductor detector closest to the interaction point ⇒ track resolution of 12 μm in Rϕ and of 100 μm in z direction ⇒ 1744 modules
- ⇒ required radiation tolerance: up to 10^{15} n_{eq} cm^{-2} (B-layer)
- overall efficiency aim: > 97 % ⇒ good charge collection even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



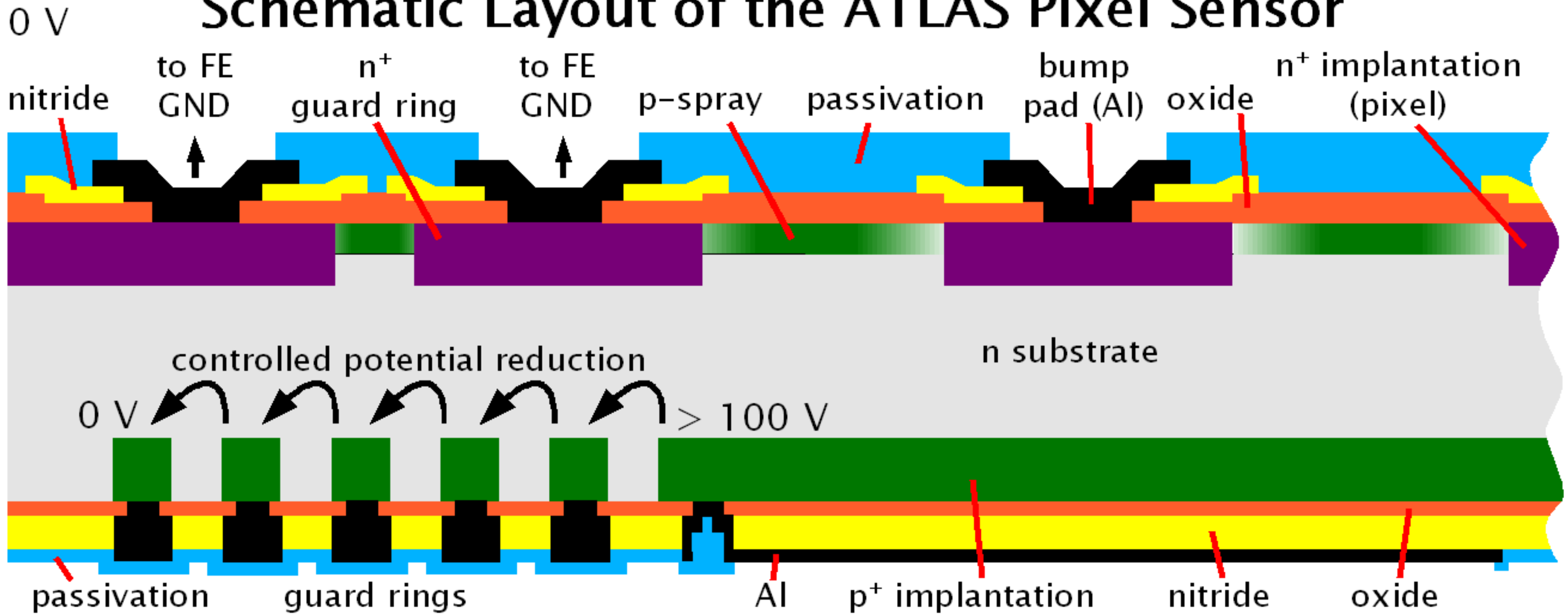
- type inversion during irradiation ⇒ oxygen rich Si improves radiation tolerance for pion and proton irradiation
- ⇒ depletion zone has to reach pixel implantations
  ⇒ n^+np^+ design
  ⇒ not fully depleted sensor still can detect particles
- p implantations necessary to isolate pixels
  ⇒ p-stop: alignment 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



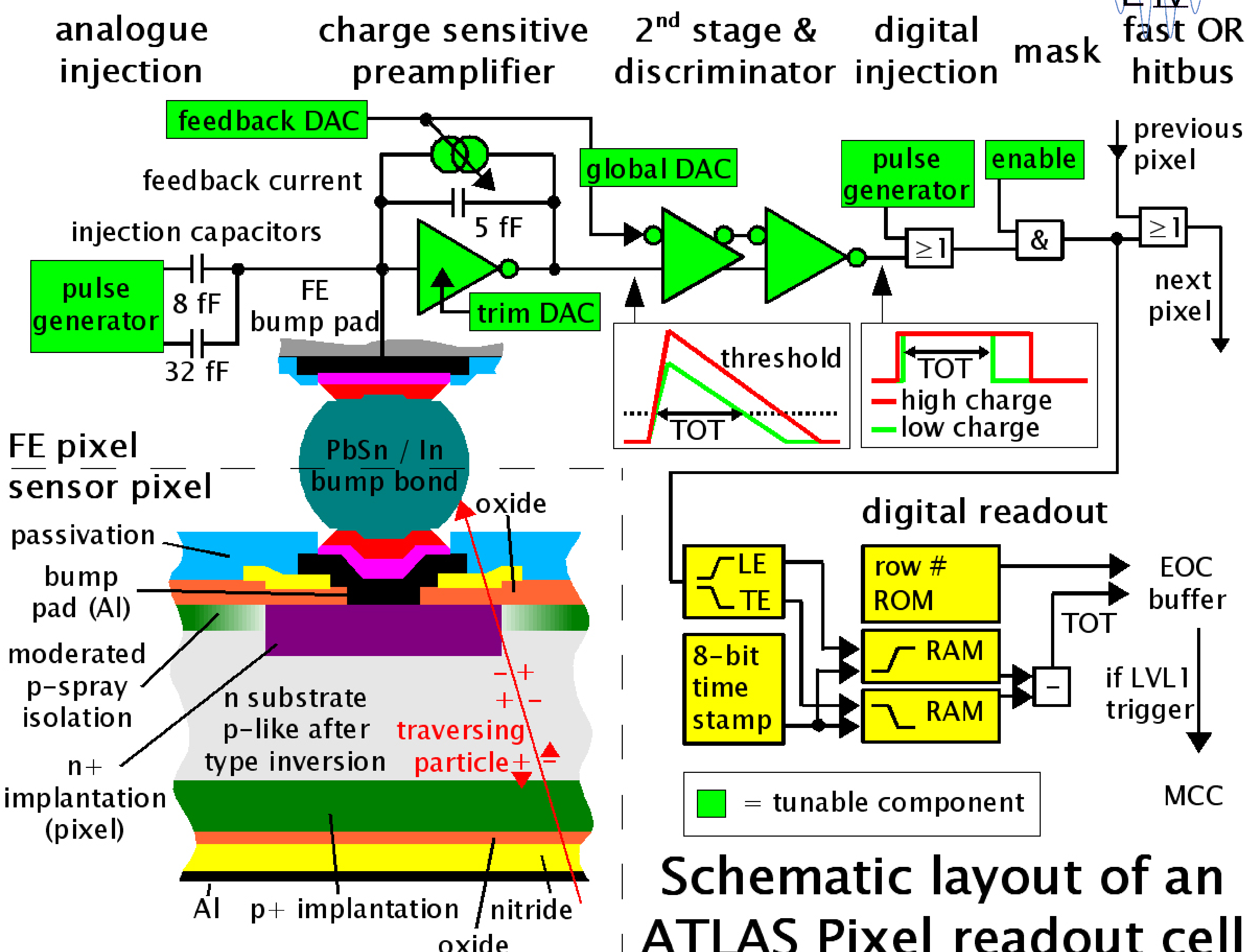




Schematic Layout of the ATLAS Pixel Sensor



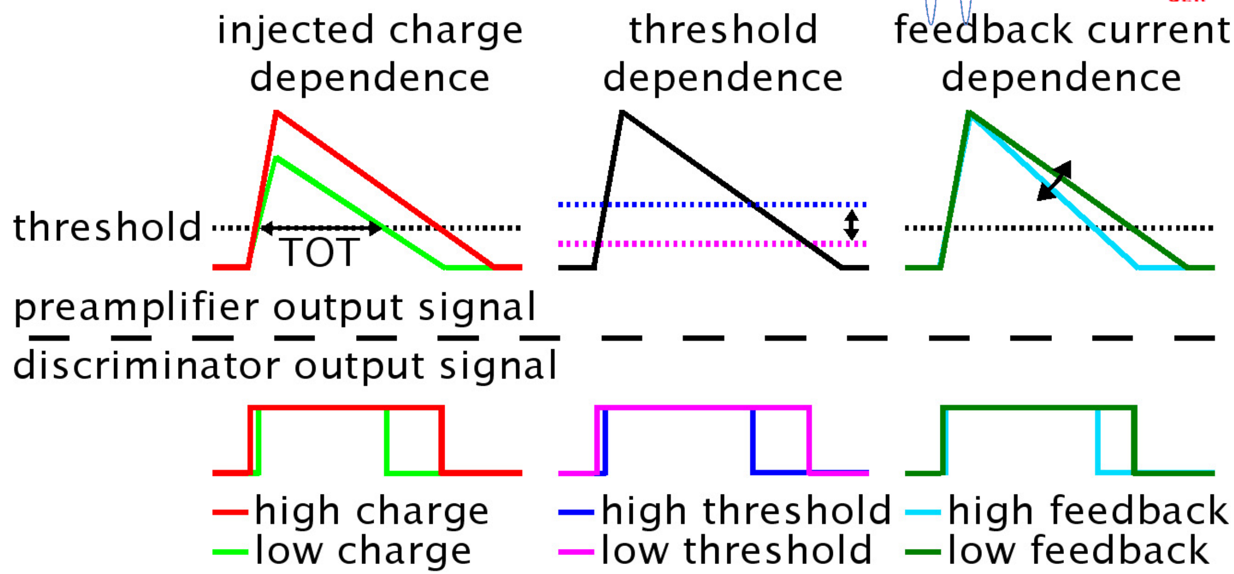
FE pixel schematic



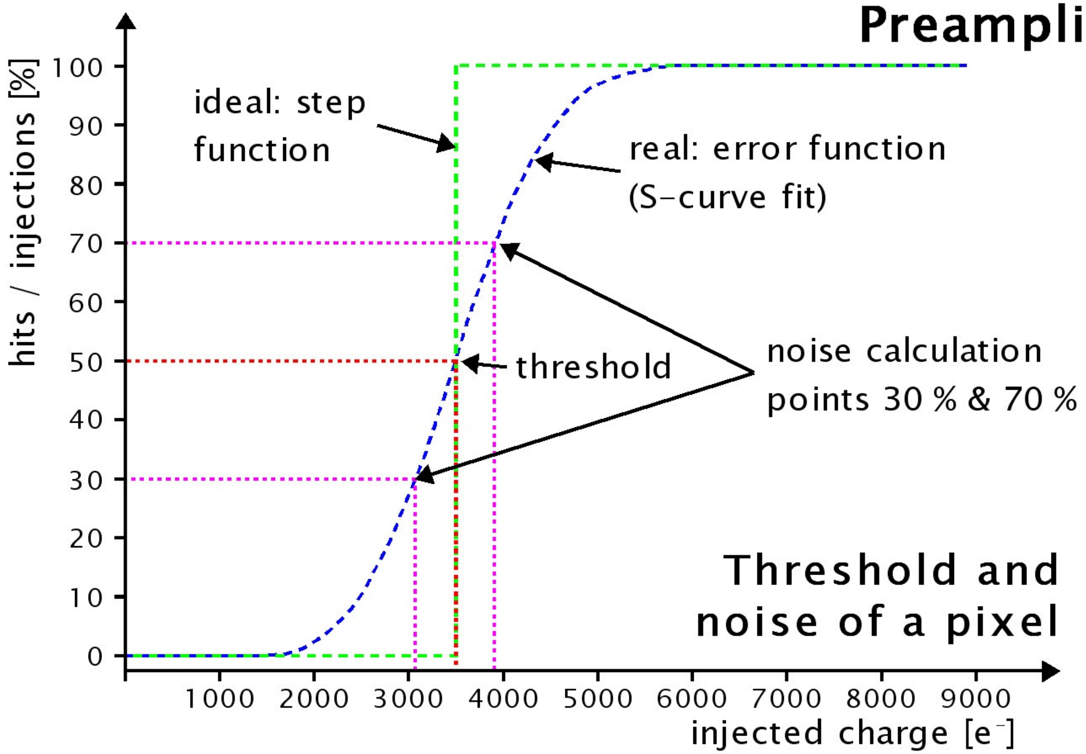
Schematic layout of an ATLAS Pixel readout cell

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



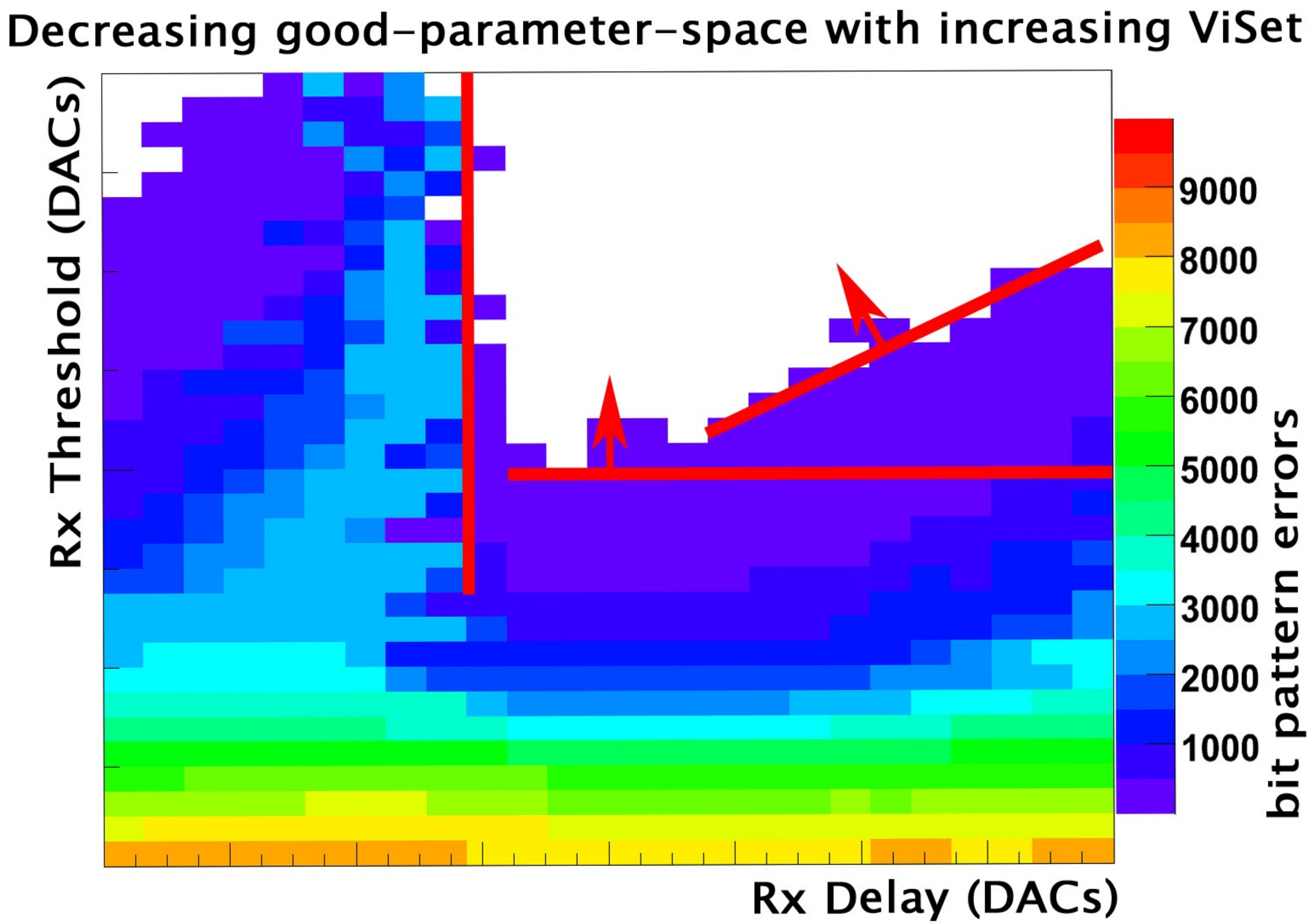
Threshold and noise of a pixel

- 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

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

0.75V 11.5°C

0.80V

0.85V

0.90V

0.95V

−3.7°C

0.75V −8.2°C

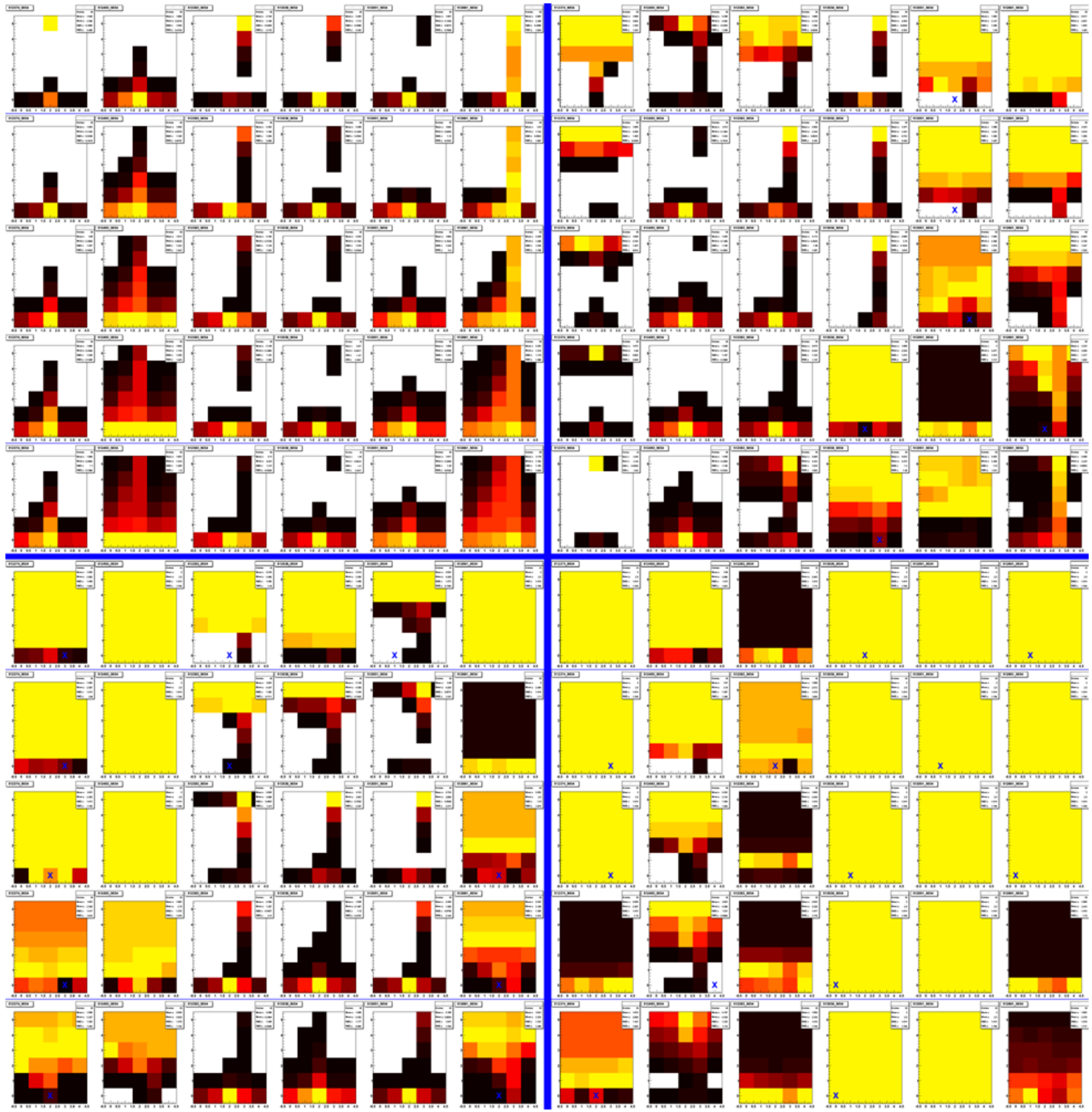
0.80V

0.85V

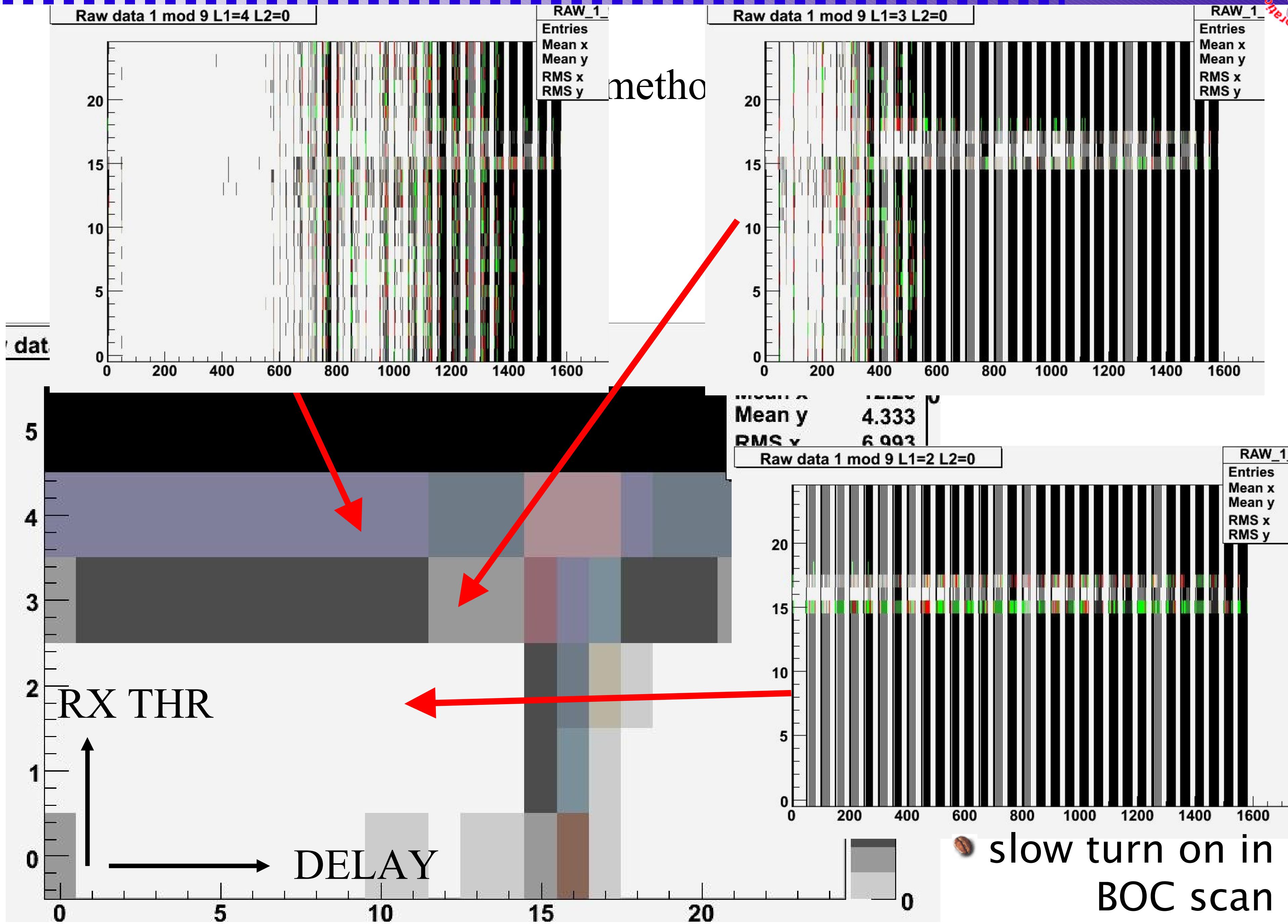
0.90V

0.95V

−11.9°C

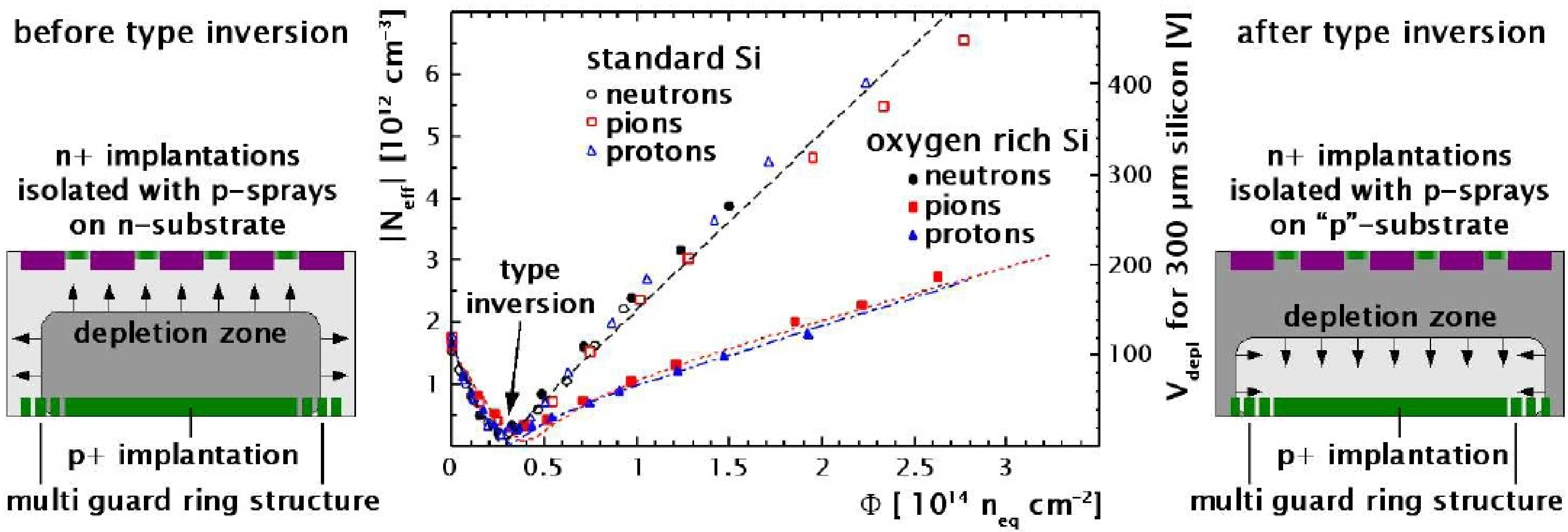


Slow turn on behaviour (BOC scan)



- slow turn on in BOC scan

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