CHROMIE: a new High-rate telescope. Detector simulation and commissioning

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On behalf of the CMS Collaboration

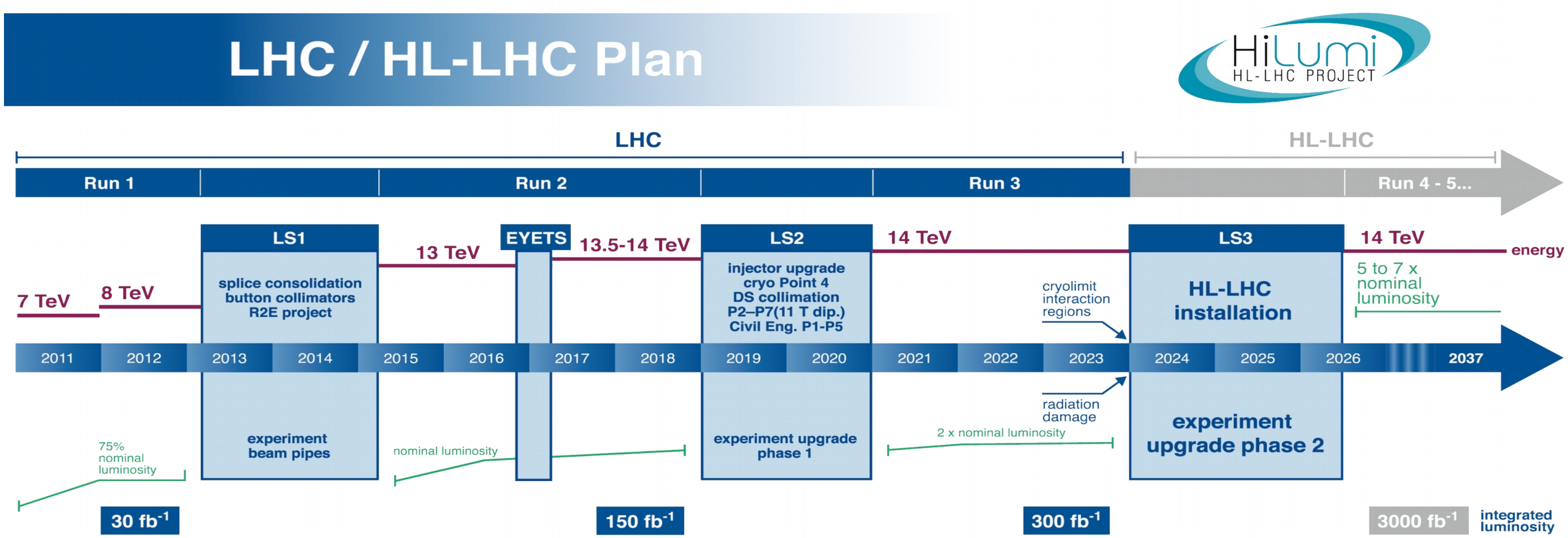
This work is supported by the Hellenic Foundation for Research and Innovation (HFRI) and IN2P3/CNRS.

High Luminosity upgrade for the LHC: HL-LHC

- Probing of new physics requires the increase of the luminosity: from 300 fb^{-1} (2011-2023) to 3000 fb^{-1} (2026-2037)

- The goal for HL-LHC [1]: Peak Luminosity: 5.0 (7.5) x 10^{34} cm^{-2} s^{1}; Integrated Luminosity over 10 years: 3000 (4000) fb^{-1}; PU: 150-200 at 25 ns bunch crossing

- Silicon sensors for the CMS Tracker [2]:
  - Need for radiation-hard silicon sensors (fluence: ~2.5 x 10^{16} n_{eq}/cm^2 in the center of CMS; Total Ionization Dose: ~10 MGy)
  - Need for higher granularity to reduce occupancy
  - Need for pattern recognition to improve the triggering of CMS



New pixel telescopes

- Right now we are in the prototyping phase of the new Tracker modules, so extensive beam tests of the silicon sensors and their readout electronics are necessary to examine the behavior of the sensors in realistic conditions.

- A new detector under development (usually named Detector Under Test, DUT) can be tested for channel efficiency, cluster size, cross talk between adjacent channels etc.

- In these beam tests the DUT is placed inside a system of well known highly segmented tracking modules in order to reconstruct with high accuracy particle tracks and measure the tracking efficiency of the DUT. Such systems are called telescopes.

- Comparison: Existing telescopes used by CMS (AIDA [3]) use a Monolithic Active Pixel Sensor chip with an integration time of 115.2 μs or 8.68 kHz readout frequency

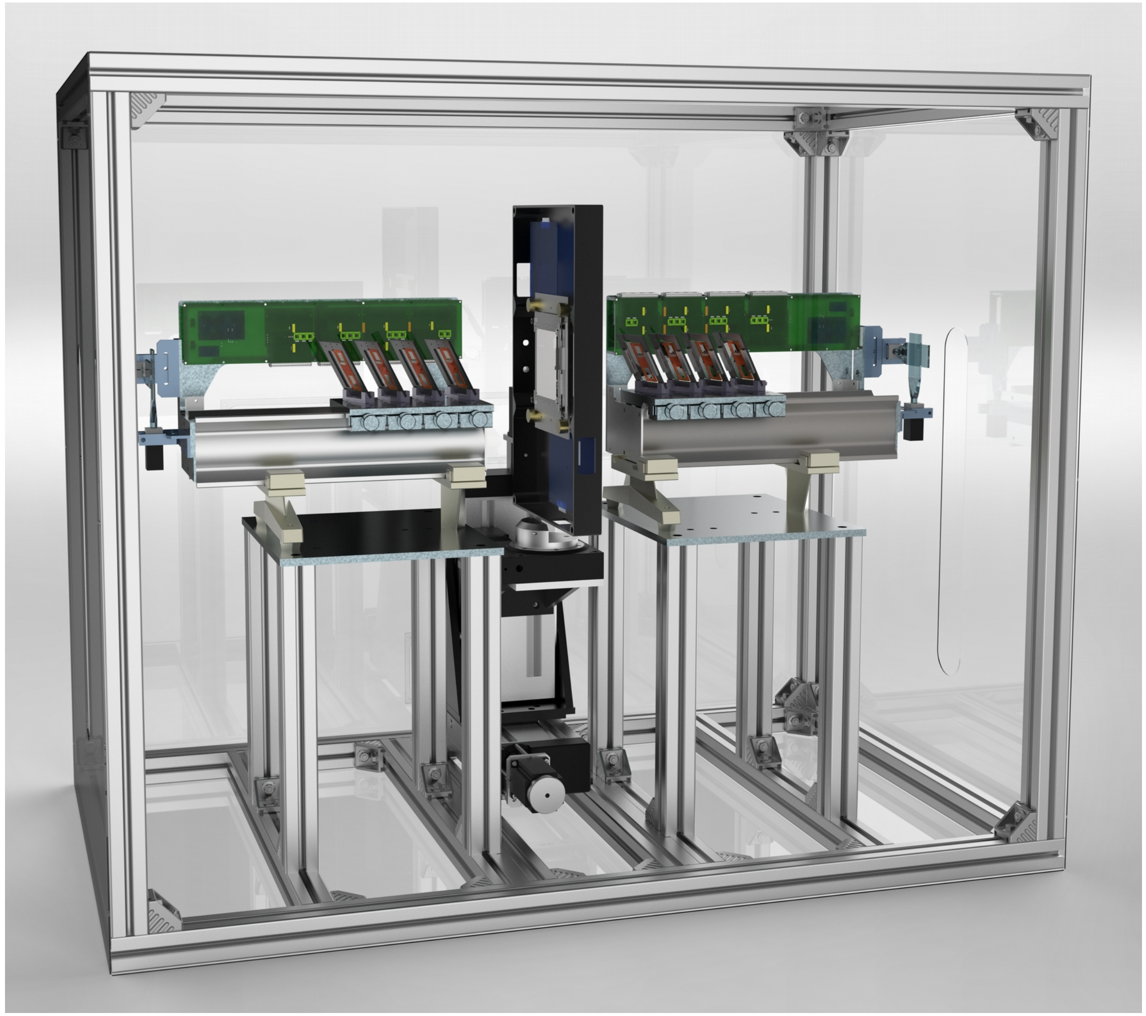
- Integration time in Phase-2 Tracker modules (and other HL-LHC sensors) is 25 ns → 40 MHz (x4600 the today's CMS telescopes readout frequency)

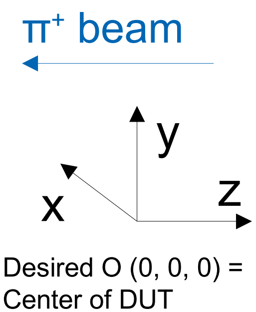
- We cannot test Phase-2 modules at nominal rates with the old telescopes used by CMS → That's why new telescopes are being developed, e.g. CHROMIE – CMS High Rate telescOpe MachInE at CERN [4], CHROMini at CYRCé, IPHC-Strasbourg [5], [6]

The design of CHROMIE

- Particle rates up to 200 MHz/cm^2 (the highest rate of a Phase-2 Outer Tracker DUT: 50 MHz/cm^2); resolution of the order of ~10-20 μm; pixel size: 100 x 150 μm^2
- Eight layers with some dead areas, each containing two CMS Phase-1 BPIX modules (Grade C, active area of 2 x 16.2 x 64.8 mm^2) in a frame, four layers in front of the DUT, and four layers behind it
- 20° tilt angle about x-axis; 30° skew angle about y-axis for all layers → to allow charge sharing between pixels
- Design for a large DUT (box size = 550 x 350 x 40 mm^3; cooling under investigation)
- A block mounted on a carriage that can slide over rails holds each layer
- Auxiliary electronics mounted close to the modules, on the rails
- Four scintillators for triggering mounted on the rails; two in front of the layers, two behind it
- Actuators for DUT, translation in X/Y, rotation about X
- CMS-standard readout system

Mechanics

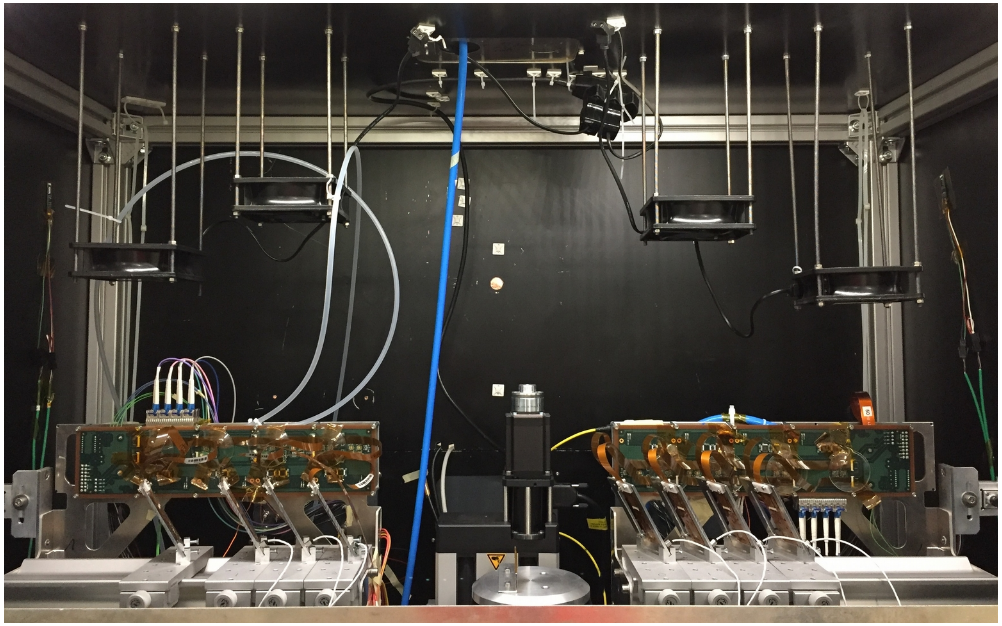




The mechanical design of the CHROMIE telescope, with a full-size 2S module in the center as the device under test (DUT).
Drawings by Nicolas Siegrist, rendering with KeyShot.

Towards the operation of the telescope

- Pre-calibration of each pixel module (before being mounted on telescope) →
- Calibration of each module after installation in the telescope →
- Commissioning in the beam (when we make the modules run synchronously) →
- Commissioning completed: all telescope modules run synchronously and there is a strong correlation between hits in different telescope layers → Particle tracks



Software

- Readout software: POS [7] + XDAQ [8]. This is CMS-standard.

- Data unpacking/analysis software: CMSSW [9] (this is also CMS-standard) + a tracking program developed by our team based on CMSSW.

- Simulation software: Geant4 [10]. We have developed a standalone program for the prediction of residuals, cluster charge, cluster size etc. before the beam tests.

Preliminary tracking and alignment method for data analysis in CMSSW (1)

- Tracking strategy:
  - Removing noisy channels
  - Applying a coarse alignment (demanding that all tracks should be // to beam axis). An iterative alignment hasn't been implemented in CMSSW yet (in progress).
  - Seeding
  - Pattern recognition

- Seeding: a search (conducted using global coordinates) for 2 points, one in Seeding Layer 1 and one in Seeding Layer 2, with $\Delta x < 0.1$ cm and $\Delta y < 0.1$ cm (corrected for misalignment: translation on x-axis + 50 cm → a new (0, 0, 0) point); loop on the clusters of the seeding modules.
  - First check L1-L2, then L2-L3, then L3-L4, until a seed is found. (The layers on the arm of CHROMIE behind the DUT, on the way of the beam, weren't used because two dead and one noisy modules are located there.)

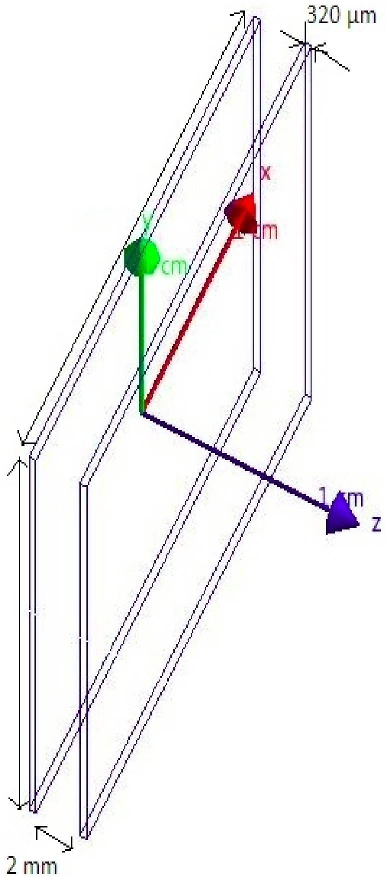
Preliminary tracking and alignment method for data analysis in CMSSW (2)

- Pattern recognition: look for the cluster with the smallest 2D distance from the track within the telescope layer → fit the track including the new cluster in the list, minimizing the 2D distance in the telescope layer

- Short tracks (that not hit at least 4 modules) are not considered valid tracks.

- Seeding efficiency: 78.7%. Note: In our run analysis:
  - (Number of events with at least 4 layers with at least one cluster and 0 seeds)/(Number of events with at least 4 layers with at least one cluster) = 6082/28551 = 21.3%.
  - Number of events with 0 layers with at least 1 cluster = 1015 → 1015/32536 = 3.12% of the total events → upper limit for efficiency 96.88%.

Geant4 simulation characteristics

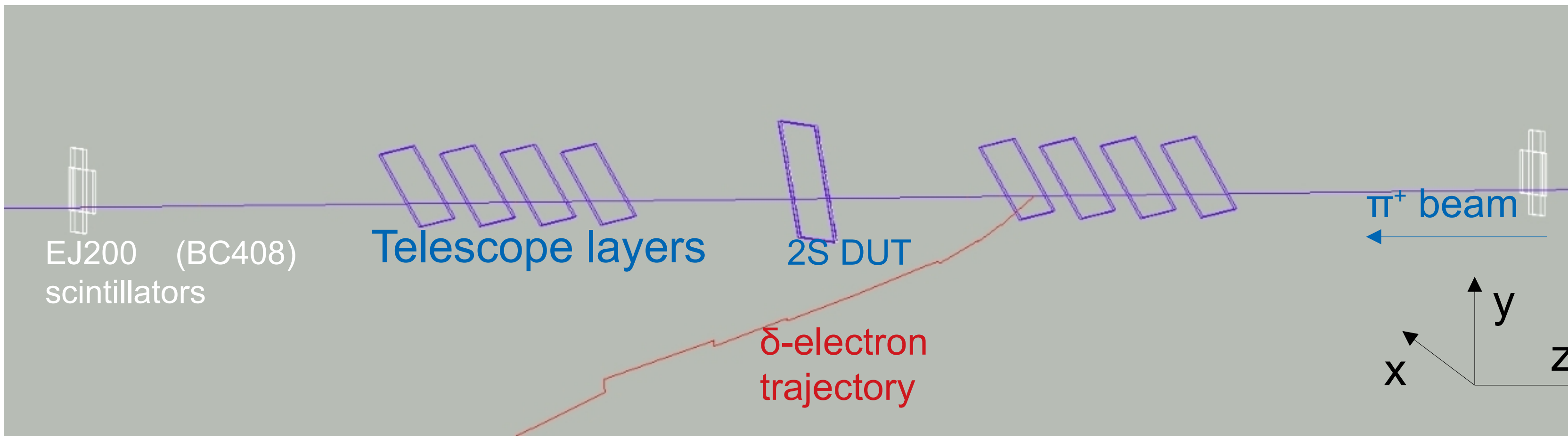


- Physics processes:
  - Ionizations
  - Bremsstrahlung
  - Pair production
  - Annihilation
  - Photoelectric effect
  - γ production
  - Compton scattering
  - Rayleigh scattering
  - Klein-Nishina model for the differential cross section

- General particle source for 120 GeV π^+:
  - sigma = 100 keV
  - Position = (-0.3, -0.65, 200) cm
  - type: beam
  - shape: ellipsoid
  - halfx = halfy = 7.5 mm

- In this talk results from a 2018 beam test with 120 GeV π^+ at SPS (CERN) are presented and compared with the output of the standalone Geant4 simulation. We have selected to analyze a run of 32536 events, with a 15 mm beam diameter (estimated from the simulation), where the left modules of each layer (as seen on the way of the beam) are hit.

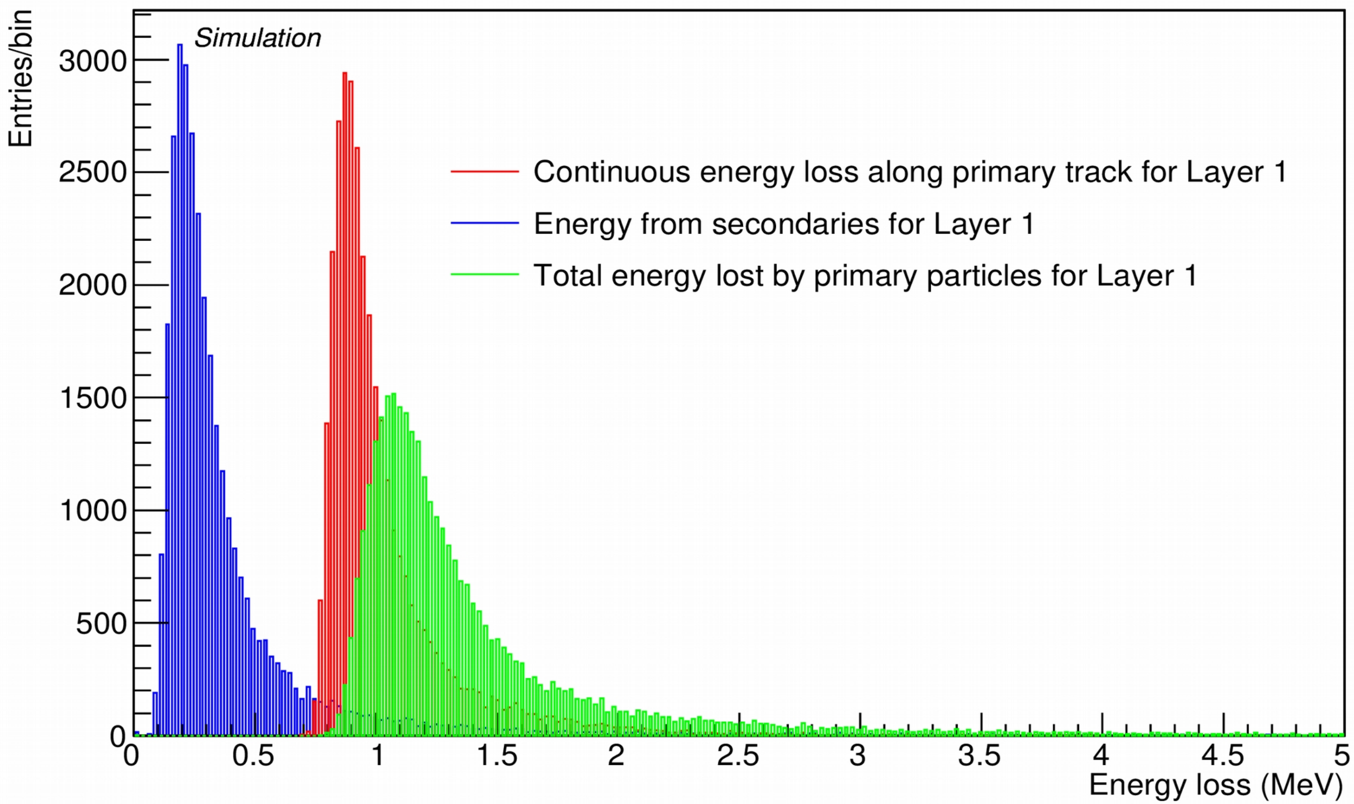
Visualization of the Geant4-simulated geometry of CHROMIE under beam



The DUT is a 2S module: 2 Si sensors (102700 μm X 94108 μm X 320 μm), with spacing between the sensors: 2 mm; strip pitch: 90 μm; active depth: 240 μm.

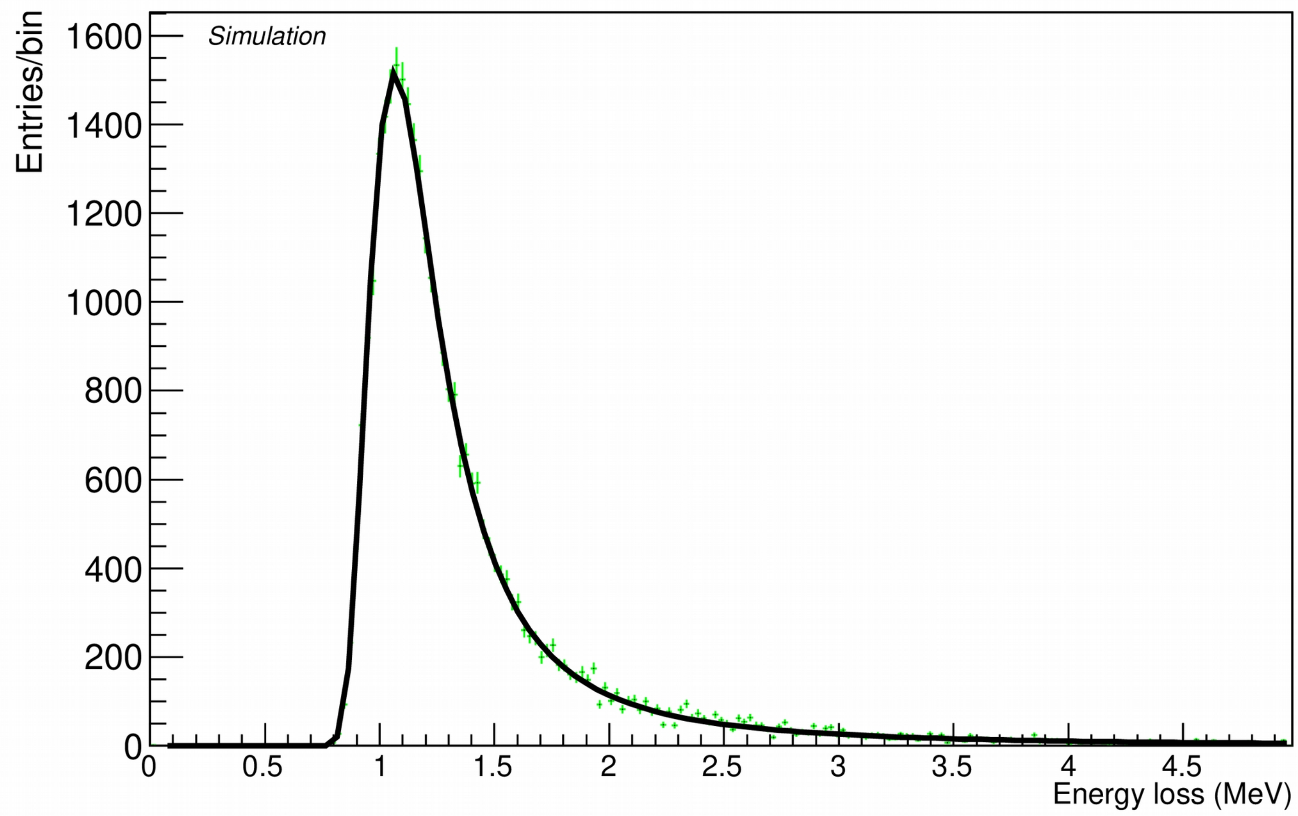
Angular straggling estimated: ~50-60 μrad on average

Energy loss by primary particles



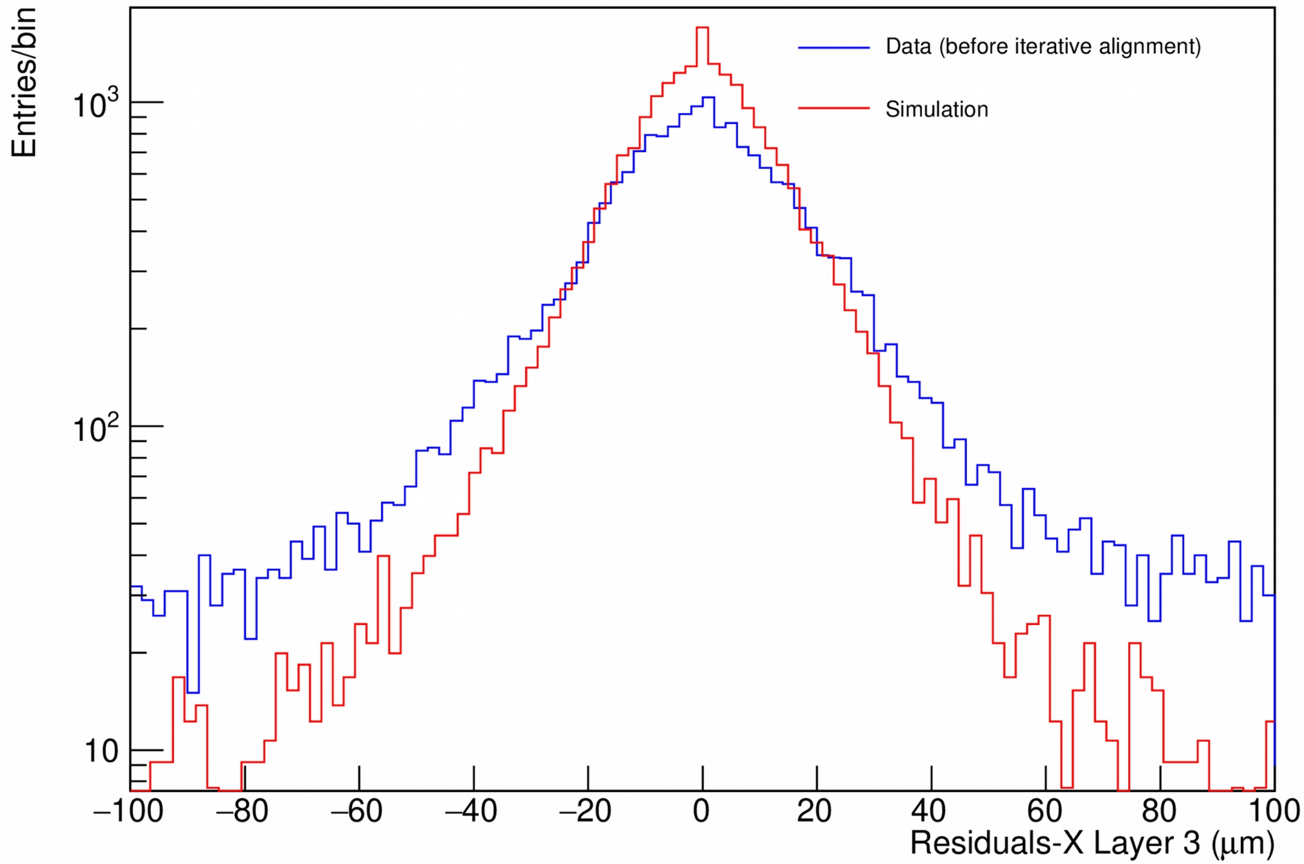
Energy lost by primary particles (120 GeV π^+) in CHROMIE layer 1 (simulation).

Total energy lost in a CHROMIE layer: a Landau fit



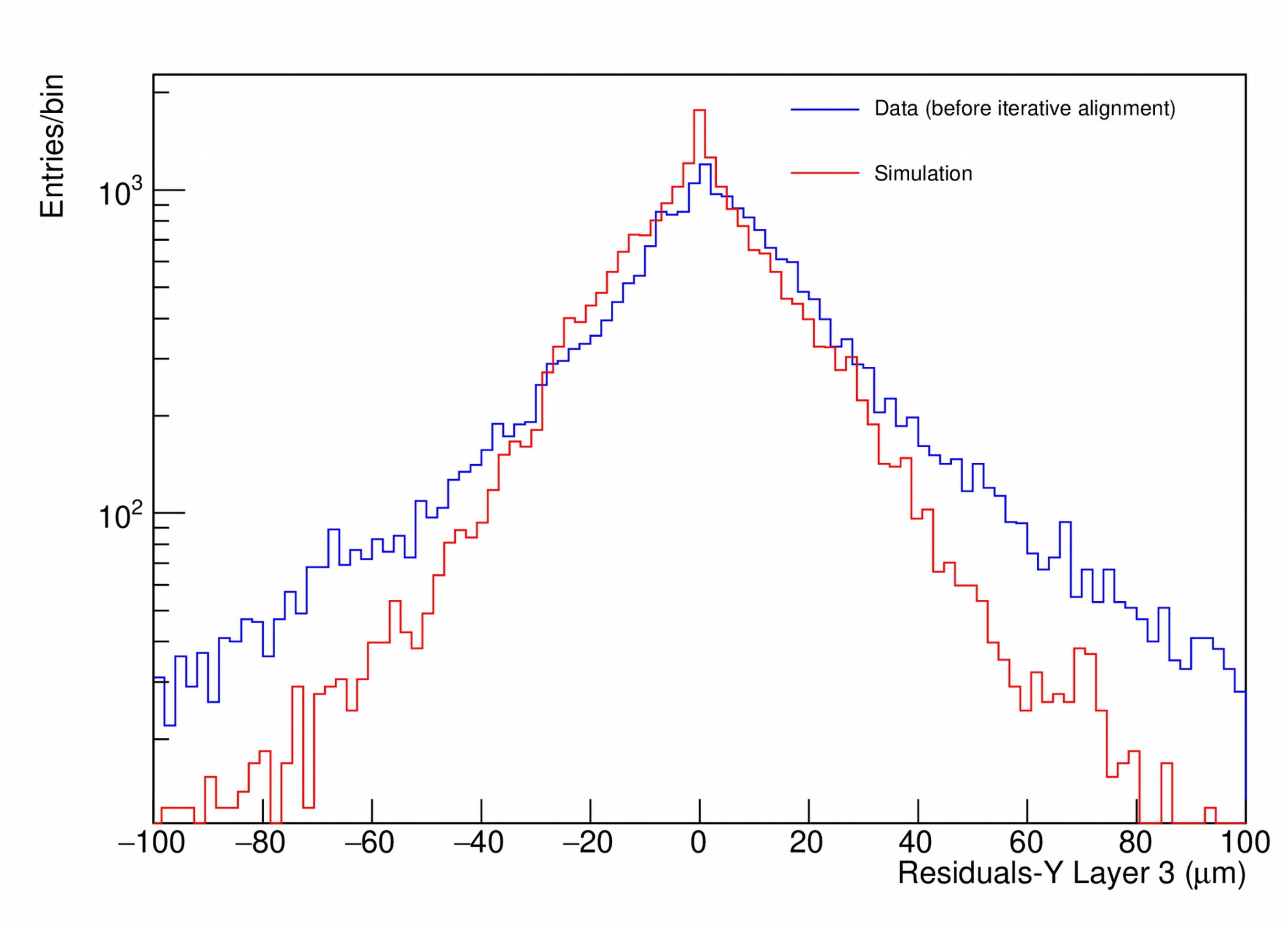
Total energy lost by primary particles (120 GeV π^+) in CHROMIE layer 1 after a Landau fit (simulation).
Most probable value (MPV): 1.086 MeV.
Sigma: 0.098 MeV.

X-residuals



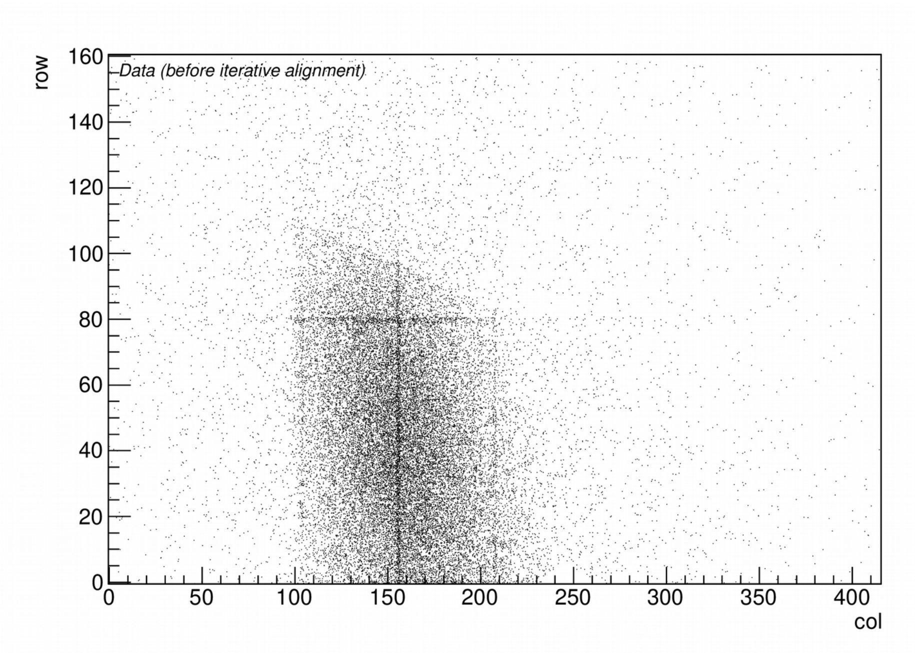
X-residuals for the left module of Layer 3 for a 120 GeV π^+ beam (comparison between beam test data before iterative alignment and simulation). Simulation residuals scaled for 26814 valid tracks from the beam test run out of 32536 total events.
Standard deviation (beam test): 29.1 μm. Standard deviation (simulation): 19.8 μm.

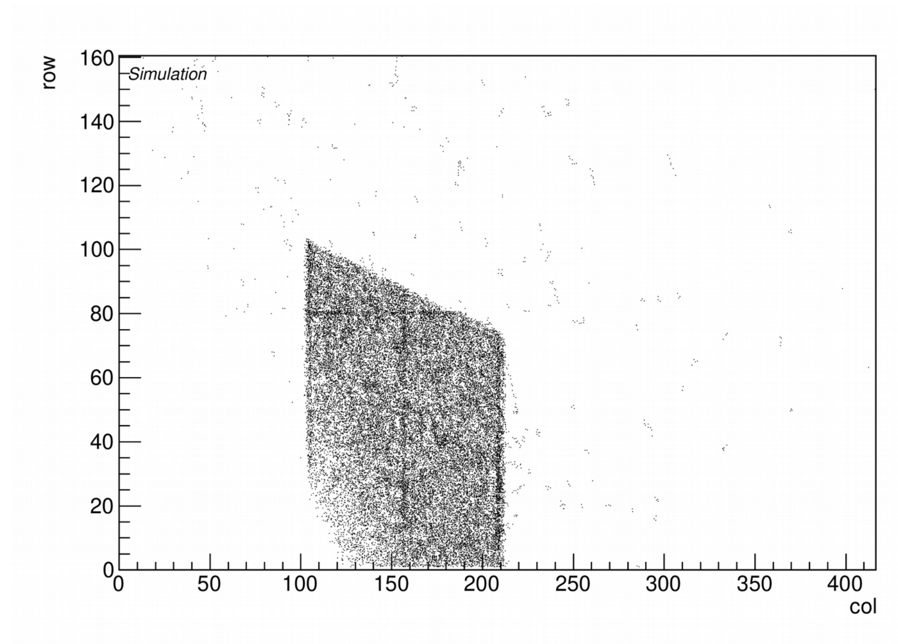
Y-residuals



Y-residuals for the left module of Layer 3 for a 120 GeV π^+ beam (comparison between beam test data before iterative alignment and simulation). Simulation residuals caled for 26814 valid tracks from the beam test run out of 32536 total events.
Standard deviation (beam test): 31.4 μm. Standard deviation (simulation): 23.3 μm.

Cluster occupancy (beam test data)





Cluster occupancy per column per row for the left module of Layer 2 for a 120 GeV π^+ beam (left: beam test, right: simulation simulation with beam diameter = 15 mm and σ_E = 100 keV); the beam size was measured from the beam spot on the cluster occupancy map for the same module, obtained from the analysis of the real run, and thus the above parameters were selected for the simulation run).

Conclusions

- A new high-rate telescope has been commissioned mostly based on technology developed for CMS, thus compatible with all other CMS hardware and software
- It can be used for tests of front-end electronics (FE) under high particle rate and high occupancy, to study the performance and saturation effects vs. track rate, and to monitor effects of radiation damage e.g. on silicon sensors
- A standalone simulation program → a potential base for future simulation of any particle telescopes; it could be used for giving an indication of unknown beam parameters through comparison of its output with plots from real data where some magnitudes are unknown
- A good comparison in resolution and cluster occupancy between beam test data and simulation → we are awaiting to improve it even further after iterative alignment

References

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[8] XDAQ CMS Online Software project page, https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOS

[9] CMS Offline Software, http://cms-sw.github.io/

[10] S. Agostinelli et. al., Geant4: A simulation toolkit, Nucl. Instrum. Meth. A, vol. 506, no. 3, pp. 250-303, 2003.

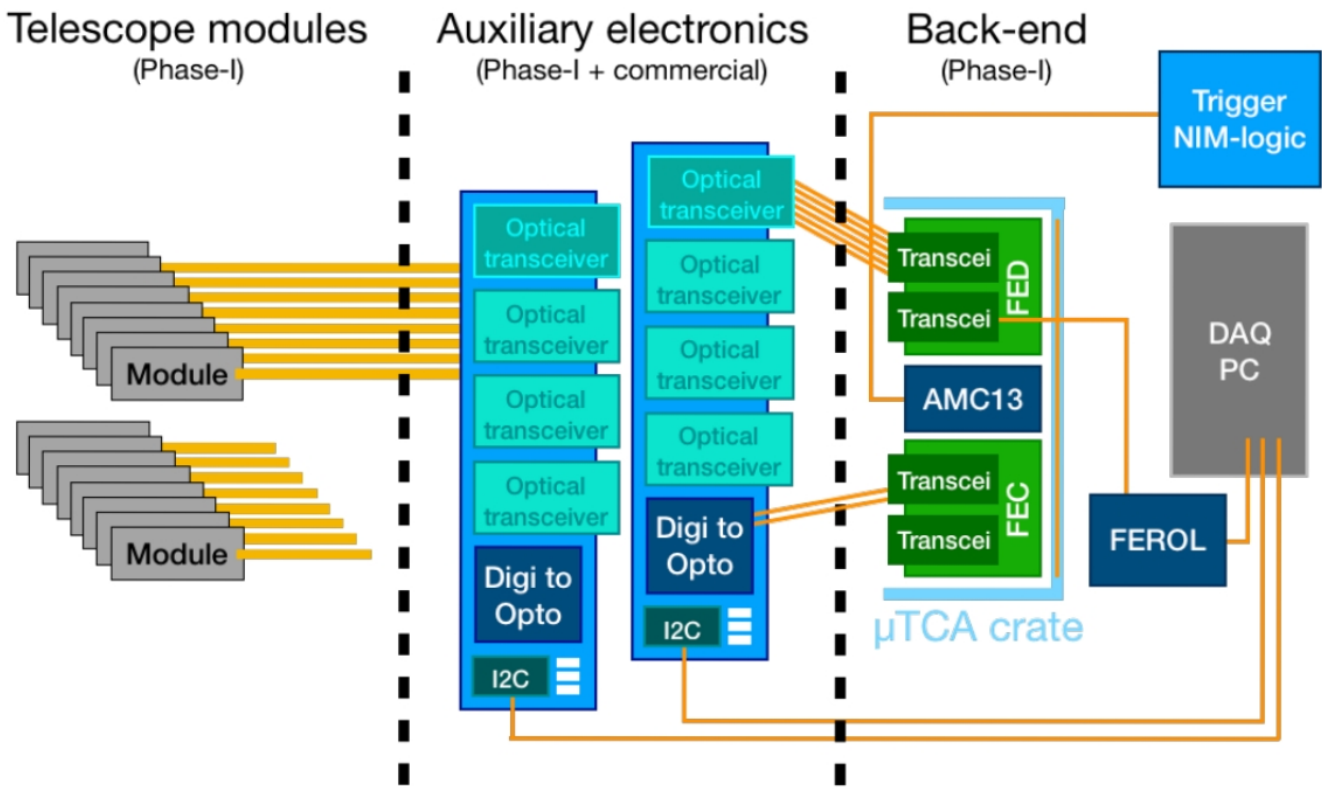
Backup

The CHROMIE team

- Bora Akgün, Jérémy Andrea, Patrick Asenov, Caroline Collard, Nikkie Deelen, Sandro Di Mattia, Gabrielle Hugo, Tivadar Kiss, Aristoteles Kyriakis, Dimitrios Loukas, Stefano Mersi, Nicolas Siegrist, Tamás Tölyhi, Andromachi Tsirou, Viktor Veszprémi

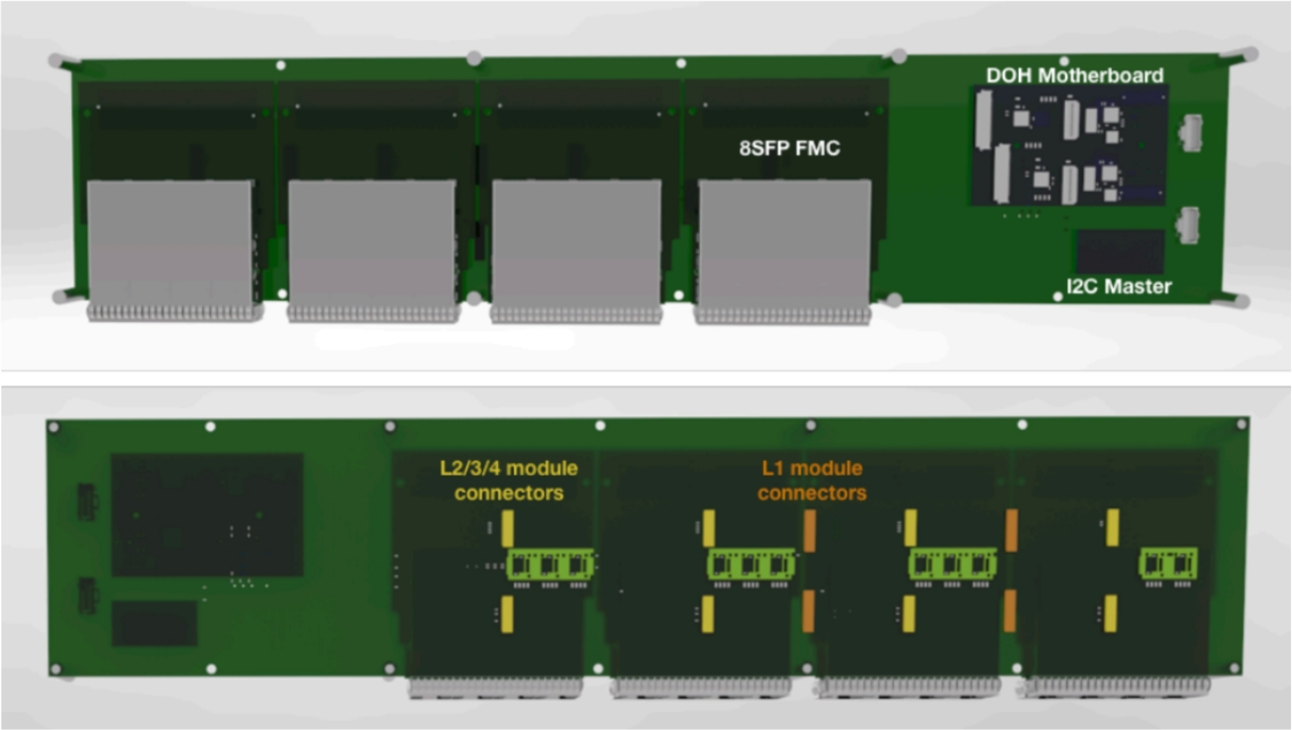
- Thanks to Imtiaz Ahmed, Eric Albert, Jonathan Fulcher, Dominik Gigi, Jean-François Pernot, Hans Postema and Piero Giorgio Verdini for their support!

Readout



The, mostly CMS standard, readout and DAQ of the CHROMIE Telescope. It is analogous to the readout of the CMS Phase-1 Inner Tracker readout. The yellow ribbons and black arrows represent electrical links. The orange arrows represent optical links.

Motherboards



The motherboards of the CHROMIE telescope. The top image is the front of the board with the 8SFP FMCs, DOH motherboard, I²C master, and power and bias connectors. The bottom image shows the back of the board with the module connectors. Design by Cerntech Ltd., rendering with KeyShot.

Tests

- Pre-calibration: IV test (for leakage current measurement), pixel functionality test, soldering (bump bond) test, pulse height optimization test, response to radioactive source test.

- Calibration: timing calibration (Delay25), trigger latency of the calibration pulse calibration, threshold calibration with calibration pulse, gain calibration of individual pixels.

Seeding

- Strategy used in Seeding algorithm:

i. Two detid iterators

ii. Check that the first detid corresponds to one of the modules of the first seed layer, and that the second detid corresponds to one of the modules of the second seed layer

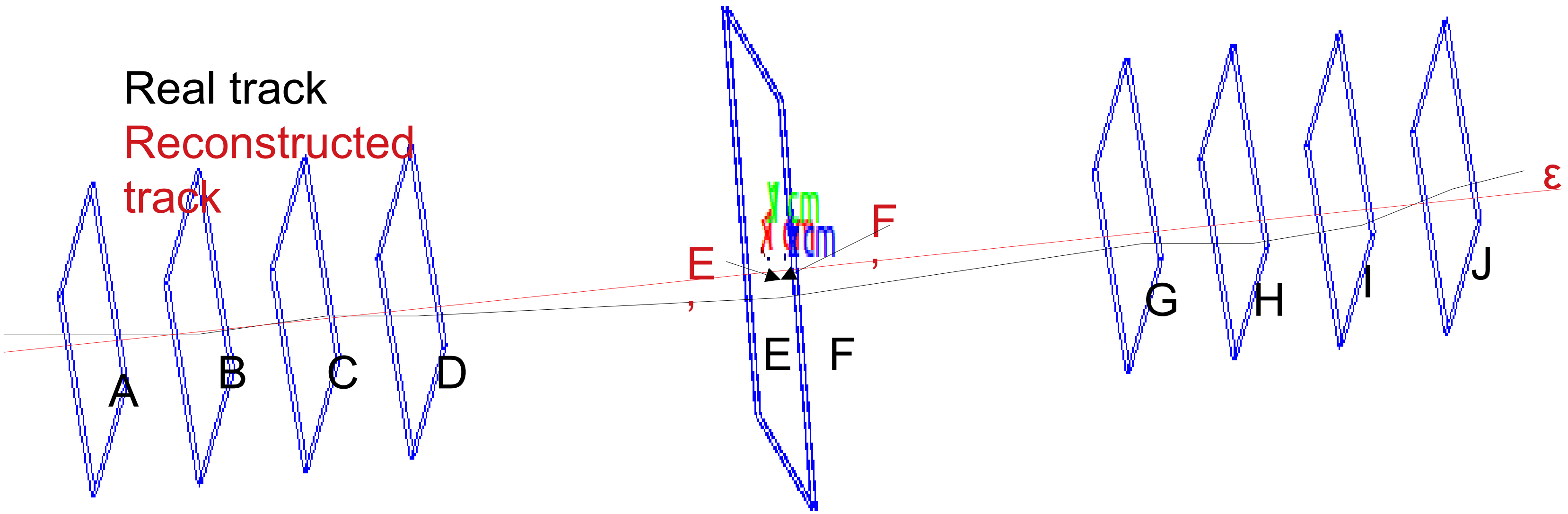
iii. Loops on the clusters of the modules

iv. Check noisy clusters

v. Apply alignment

vi. Conditions for Δx, Δy

Interaction points between particle beam and modules

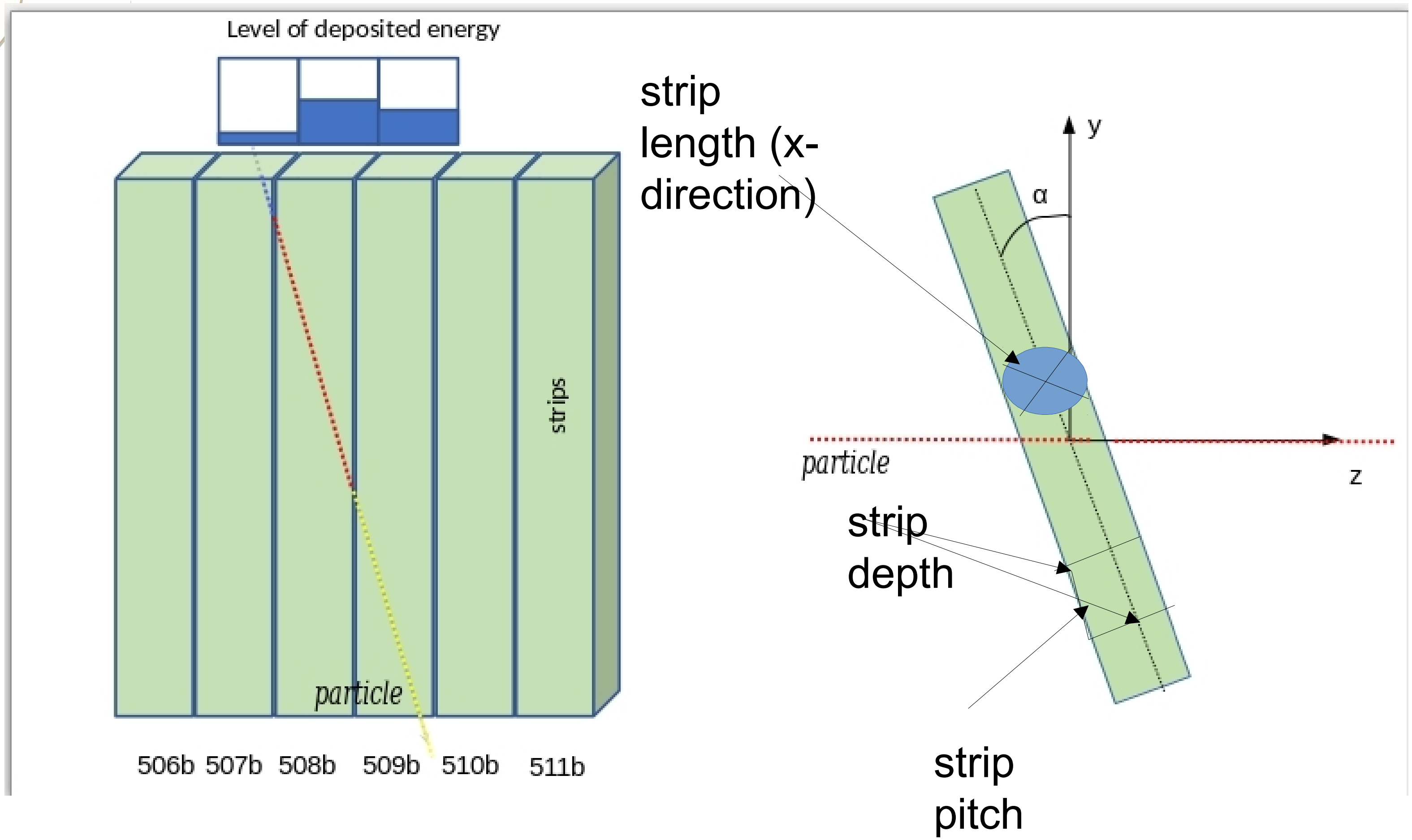


Goal: Fit A, B, C, D, G, H, I, J to line ε

Calculate residuals $(E'E)_x$, $(E'E)_y$, $(F'F)_x$, $(F'F)_y$

Sensitive 2S sensors

Level of deposited energy

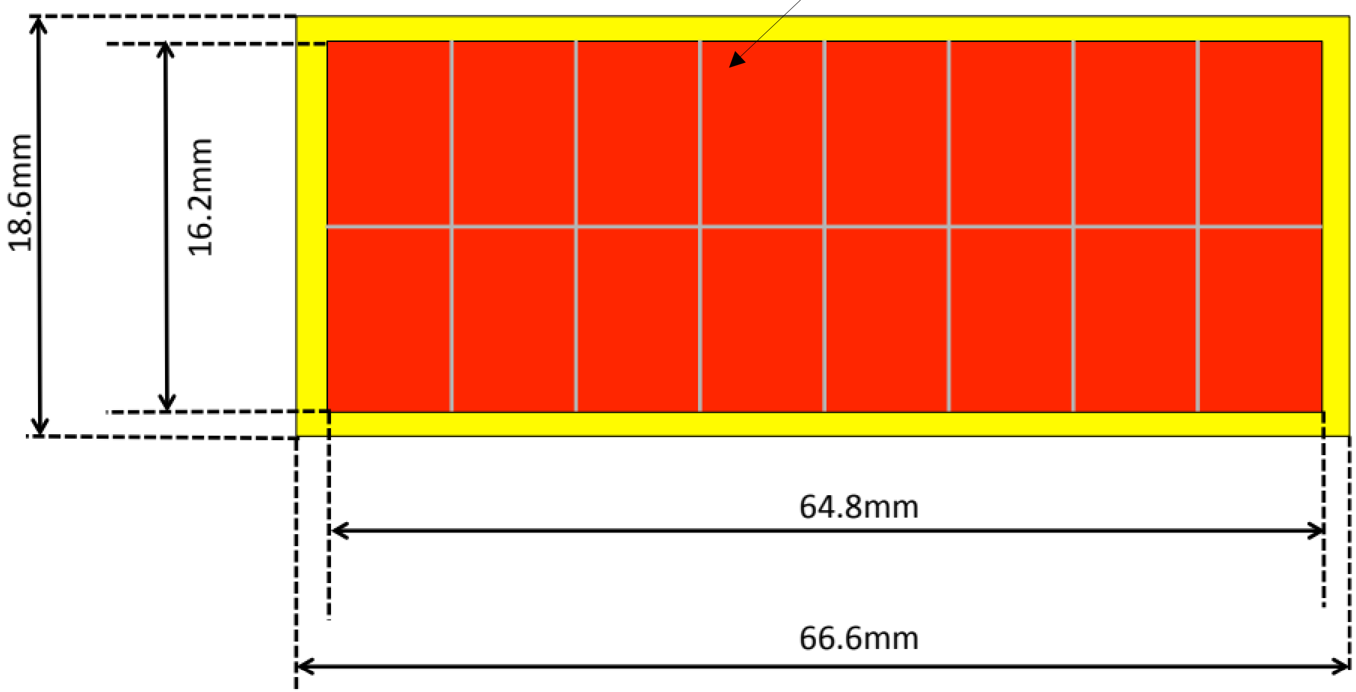


- 2 X 1016 strips in the active region (with active depth = 240 μm). Each strip is associated with an active volume below it with y-width = pitch = 90 μm.

BPIX (barrel pixel) modules

Sensor silicon area 18.6x66.6mm^2
Number of ROCs=2x8
Pixel size 100x150um^2 (size twice as wide at chip boarders)
Number of pixels 80x52
Sensor active area 16.2x64.8mm^2 since
2*(80*0.1mm+0.1mm)=16.2mm
8*(52*0.15mm+2*0.15mm)=64.8mm

Deposited energy calculated for each pixel



Definition of hits in strips and pixels

- 2S → strips: 5σ noise threshold → set at 5000 electrons
- BPIX → pixels: threshold → set at 1700 electrons
- For each event our program calculates the stored energy in each strip/pixel, respectively, and when dividing this energy by the energy required for a single electron-hole production in silicon (= 3.67 eV) one can get the charge collected in each pixel/strip in electrons. If this charge exceeds the threshold of 5000/1700 electrons, respectively, we consider that we have got a hit in the examined pixel/strip in the current event.