http://clicdp.cern.ch

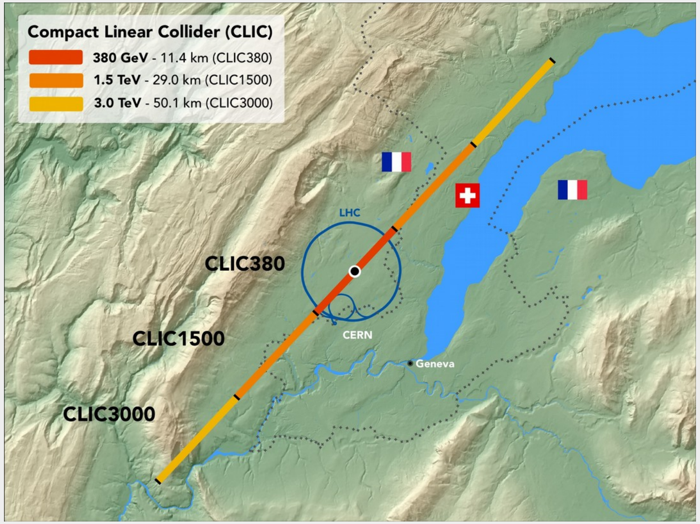
Technologies for Future Vertex and Tracking Detectors
at the Compact Linear Collider (CLIC)

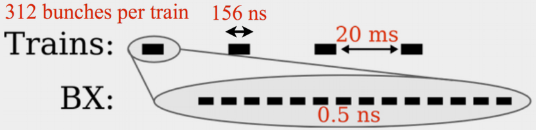
Simon Spannagel, CERN
on behalf of the CLICdp Collaboration

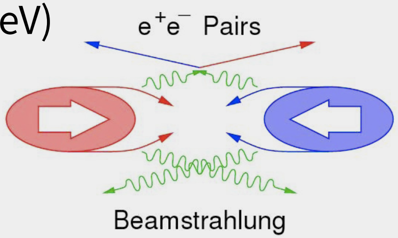
14th Pisa Meeting on Advanced Detectors
Elba, 29 May 2018

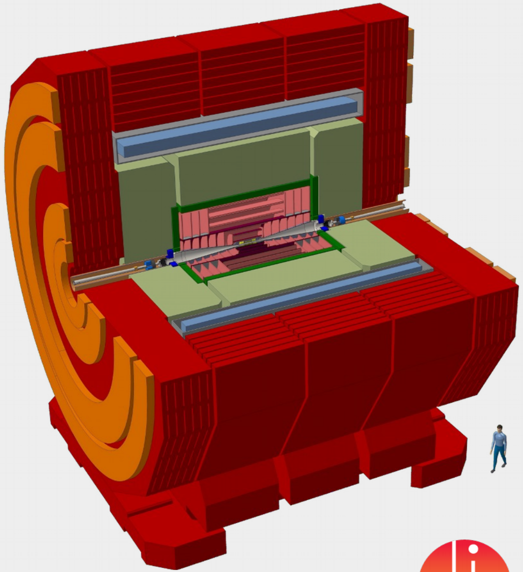
The Compact Linear Collider

- Proposed linear collider with two-beam acceleration: Achieves field gradients of ~100 MV/m
- Construction in 3 stages: 380 GeV → 3 TeV
- Physics goals: **precision SM Higgs, Top and BSM physics**
- Vertex & Tracker design driven by beam structure
  - Trains of 312 bunches, 50Hz repetition rate
  - Spacing between bunches: 0.5ns
- High bunch density leads to interactions between bunches
  - Large background from γ γ → hadrons / e+e- (beamstrahlung):
  - ~100 particles/BX within acceptance (at 3TeV)
  - Mostly in forward direction
  - Timing cuts can reduce impact



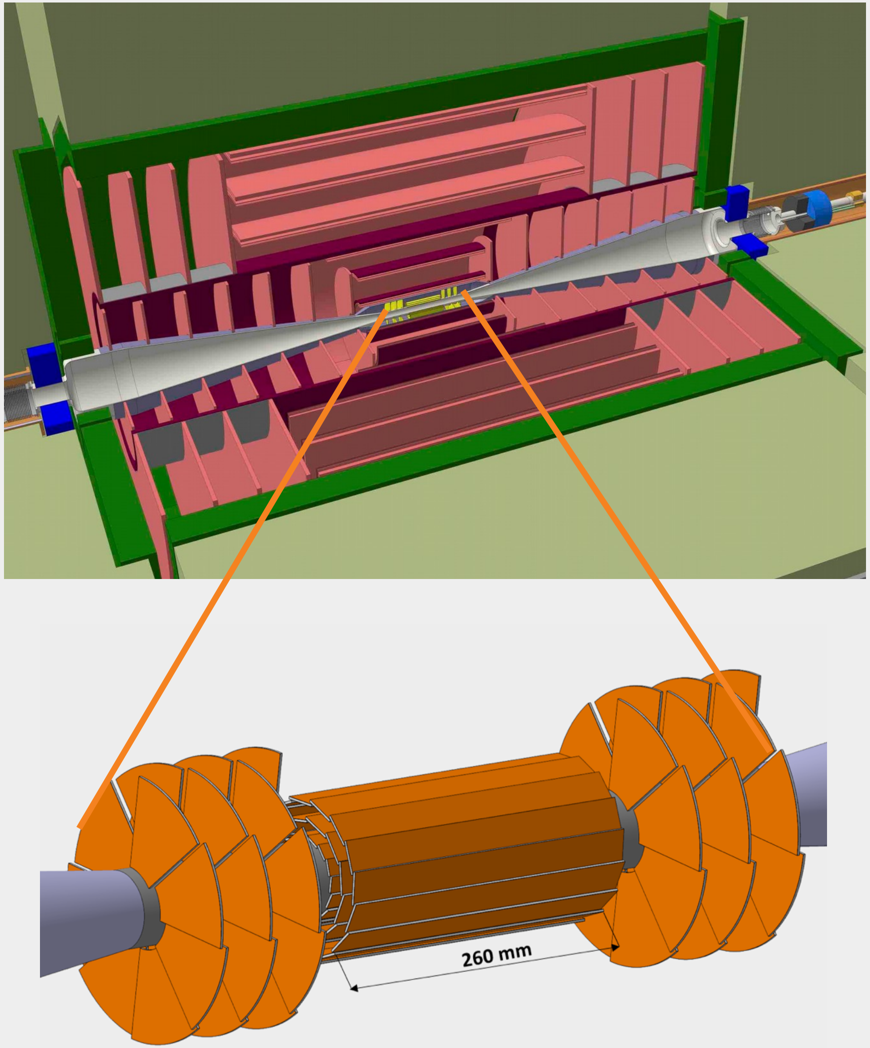




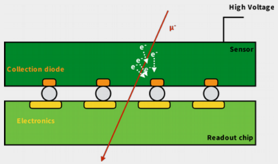


CLIC Vertex & Tracking Detectors

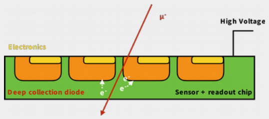
- All-silicon vertex & tracking detectors
- Requirements:
  - **Low mass** – 0.2% X_0 per vertex layer
  - **Low power consumption** – 50mW/cm^{-2} in the vertex, air-flow cooling
  - **High single-point resolution**
    - Vertex: σ_{SP}~3µm
    - Tracker: σ_{SP}~7µm
  - **Precise time stamping** ~5ns
- Large area tracker (140m^2) with high granularity, elongated pixels (1 – 10mm)



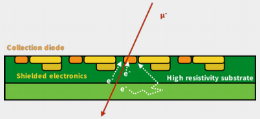
Silicon Technologies



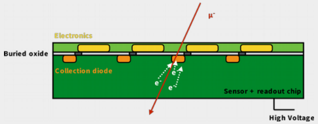
Hybrid



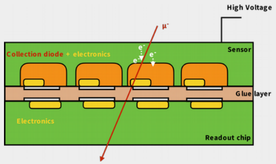
HV-CMOS



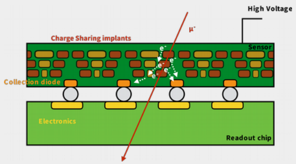
HR-CMOS



SOI

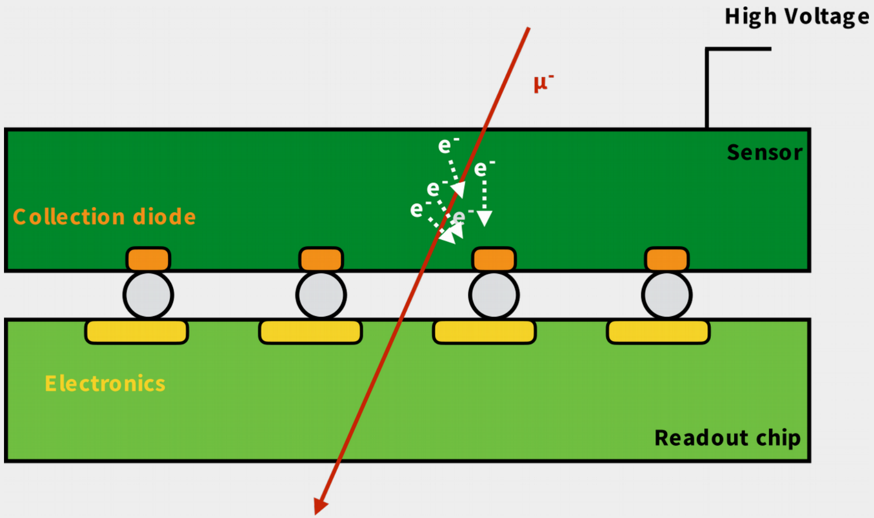


Capacitive



ELAD

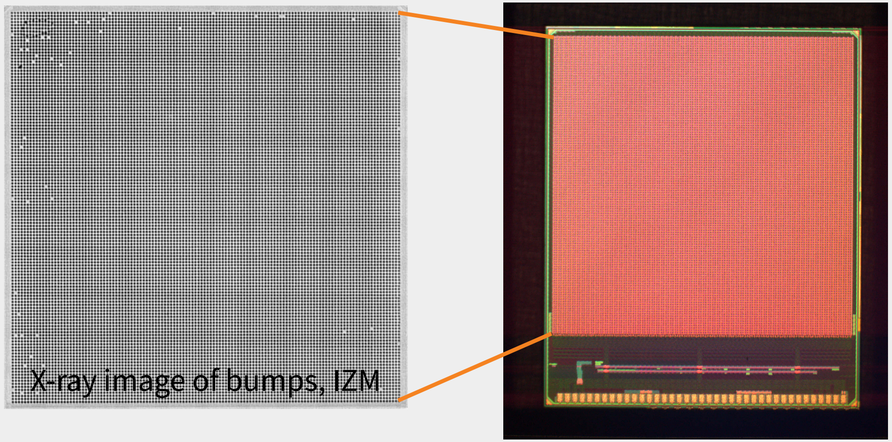
Hybrid Pixel Detectors

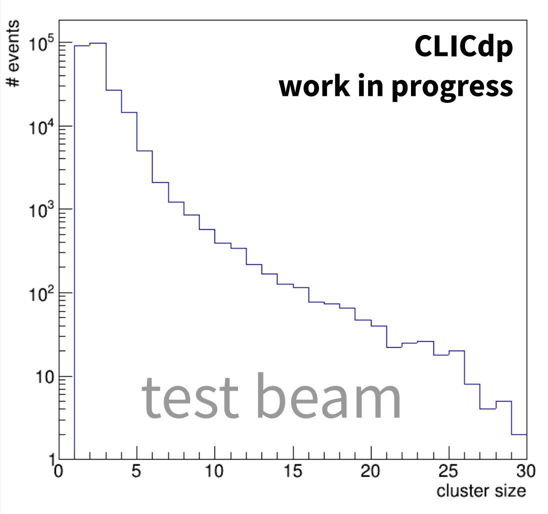


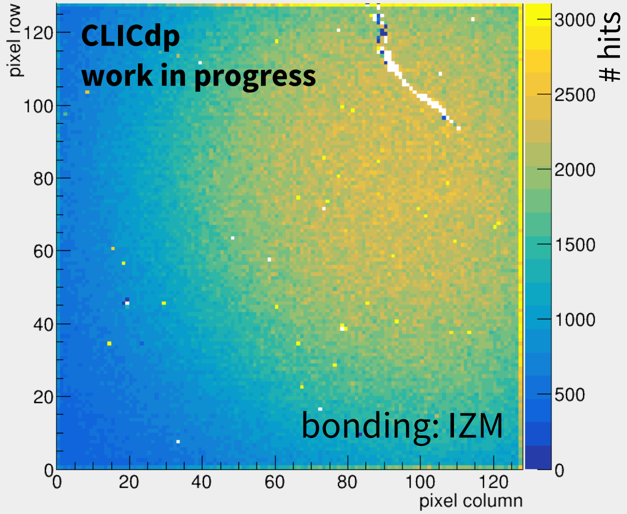
- Traditional design of HEP silicon pixel detectors with independent parts:
  - Sensor (high-resistivity silicon with pn-junction)
  - CMOS readout chip with small feature size
  - Solder bumps as interconnect
- Allows extensive functionality on-pixel using mixed-mode CMOS circuits
- Small pixel cell sizes achievable, 25µm – 250µm
- Bump bonding
  - Cost-driving factor on detector production
  - Limiting factor for the pixel pitch
  - Limiting factor for device thickness: stability

The CLICpix2 Prototype

- Readout ASIC to meet CLIC vertex requirements
- Timepix/Medipix chip family
  - 128 x 128 pixels (3.2 x 3.2 mm² active area)
  - 65nm CMOS, 25µm x 25µm pitch
  - Per-pixel charge and arrival time measurement
- Shutter-based acquisition
- Power pulsing of the pixel matrix
- Challenge: bump bonding of sensors with 25µm pitch

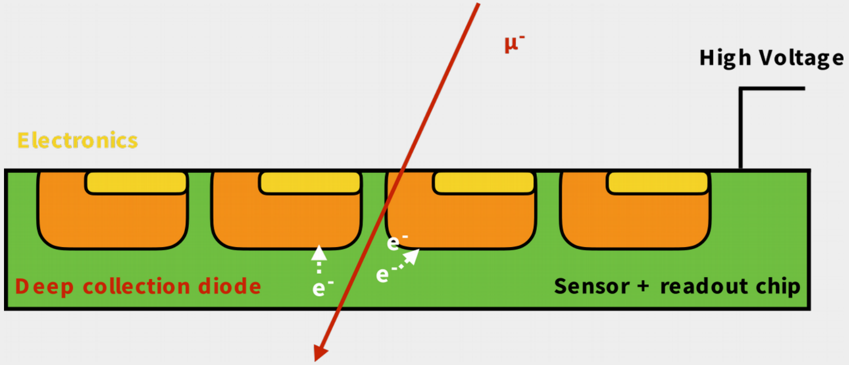






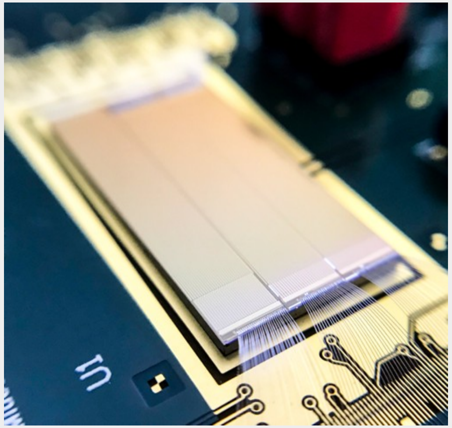
- Successfully tested in lab & test beam measurements, characterization ongoing

Monolithic High-Voltage CMOS Sensors

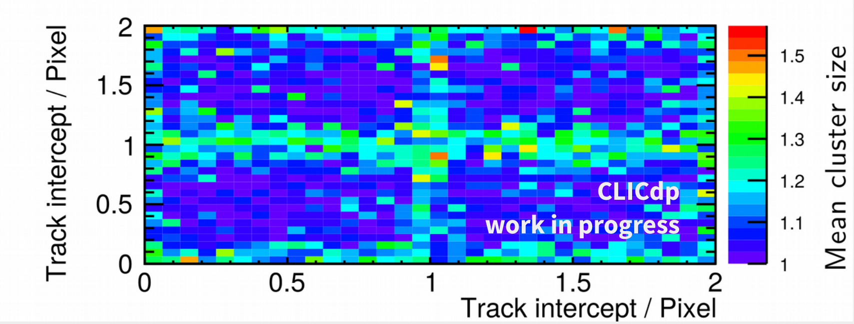


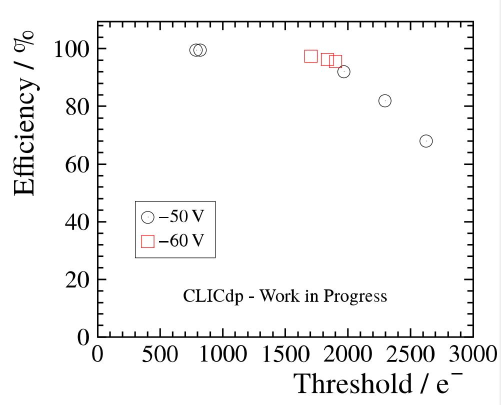
- Evolution of Monolithic Active Pixel Sensors (MAPS)
  - Electronics and sensor on same wafer
  - Lower mass than hybrids, no bump-bonding
  - Fully integrated: amplification & readout
- Goal: Charge collection through drift instead of diffusion
  - Fast charge collection
  - Larger depleted volume, more charge collected
- Shield electronics via deep collection diode surrounding electronics
  - Allows high voltage to be applied to substrate
- Challenges:
  - Large collection diode means large input capacitance (& increased power consumption, reduced SNR)
  - Full depletion has yet to be achieved (high resistivity substrates and backside bias)

The ATLASpix Prototype (ATLAS)

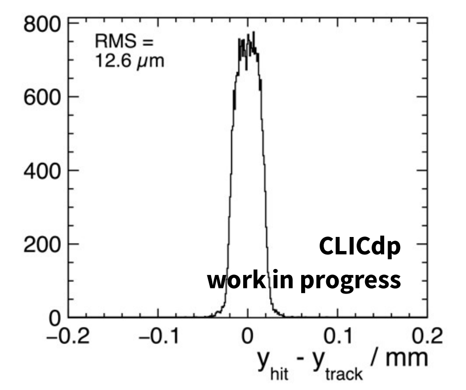


- Fully integrated chip designed for ATLAS ITk upgrade
  - Under investigation in view of CLIC tracker requirements
  - AMS 180 nm HV-CMOS process, substrates with 20-1000Ωcm
  - 25 x 400 pixels, 130µm x 40µm pixel pitch
  - Charge amplifier, discriminator in pixel, charge and arrival time measurement in periphery
- Promising results from first beam tests
- Ongoing: beam tests with improved readout system to characterize timing performance



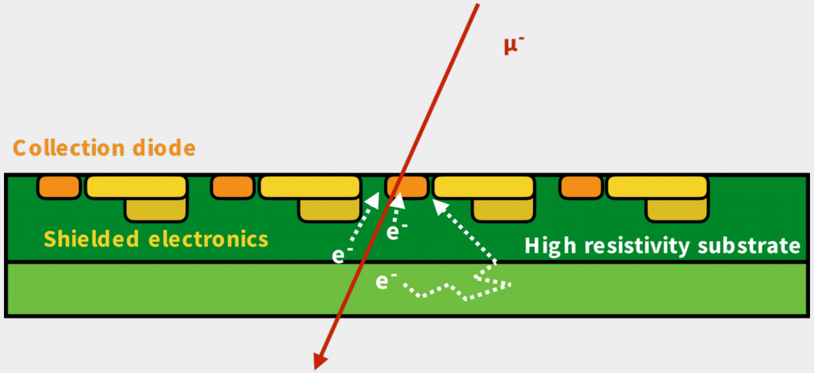


Efficiency ~99.5%



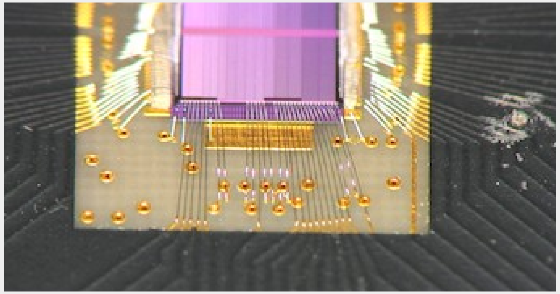
Resolution σ_{SP}~13µm

Monolithic High-Resistivity CMOS Sensors

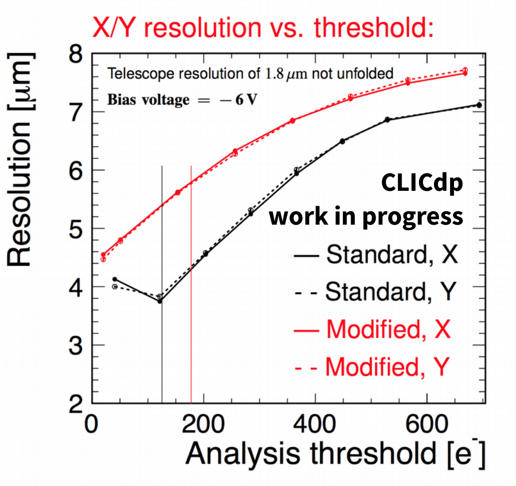


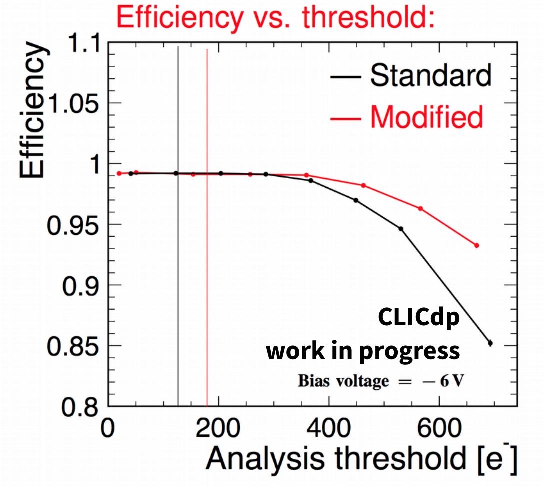
- Alternative to HV-CMOS
- Electronics outside charge-collection well
  - Small collection diode reduces input capacitance
  - Form depleted region by using high-resistivity substrate
- No special HV design rules for electronics necessary
- Lower bias voltage than HV-CMOS
  - Avoid electronics shielding to compete with collection diode
- Process modifications allow full lateral depletion
  - Higher backside bias possible due to isolation of electronics by depleted region

The Investigator Prototype Chip (ALICE)



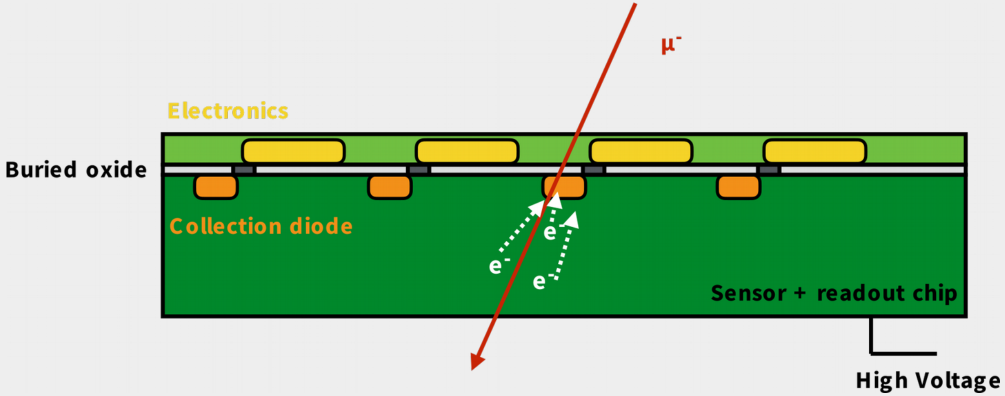
- Analog prototype – digitization off-chip
- Two different TowerJazz 180nm processes
  - Different doping profiles/depletion approaches
- For 28 x 28µm^2 pitch: 99.3% efficiency, $\sigma_t < 5$ns, $\sigma_{SP} \sim 4$µm
- Good spatial and time resolution at very low threshold
- Future plans:
  - Design of fully integrated chip for CLIC tracker: CLICTD
  - Low resolution interesting for CLIC vertex?



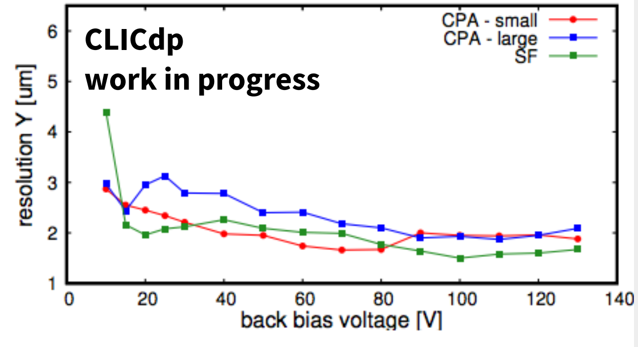


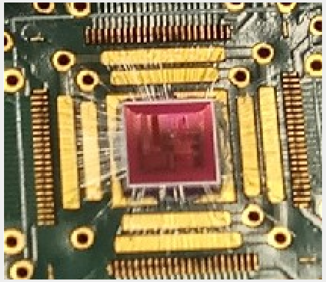
Monolithic Silicon-on-Insulator Sensors

- Monolithic sensor on single wafer with high-resistivity substrate
- Separate sensor/electronics by insulation oxide layer

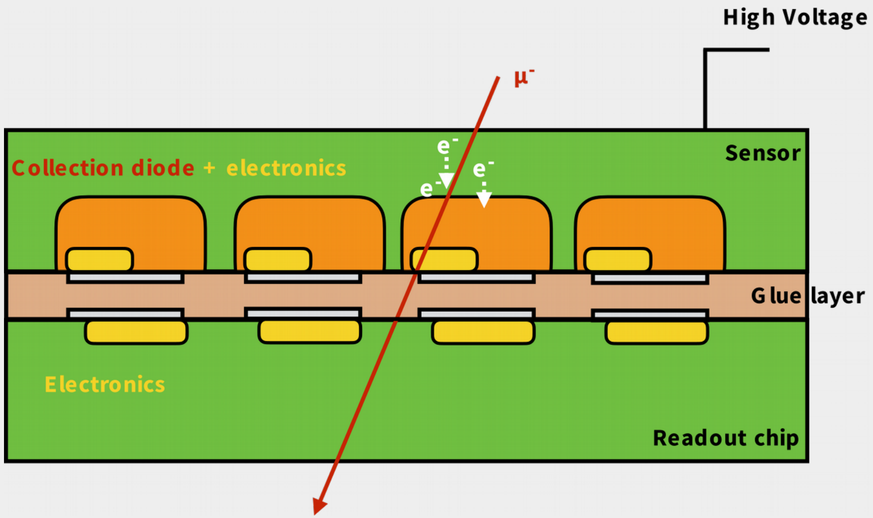


- Cracow SOI test chip in 200nm LAPIS SOI process, different parameters: >= 30µm x 30µm pitch, single-SOI & double-SOI, different r/o schemes
- First test beam results for 500 µm thickness, 30x30 µm^2 pitch: Efficiency > 99%, σ_{SP}~ 2µm
- Ongoing work:
  - Analysis of prototype test-beam data
  - Production of vertex test chip CLIPS



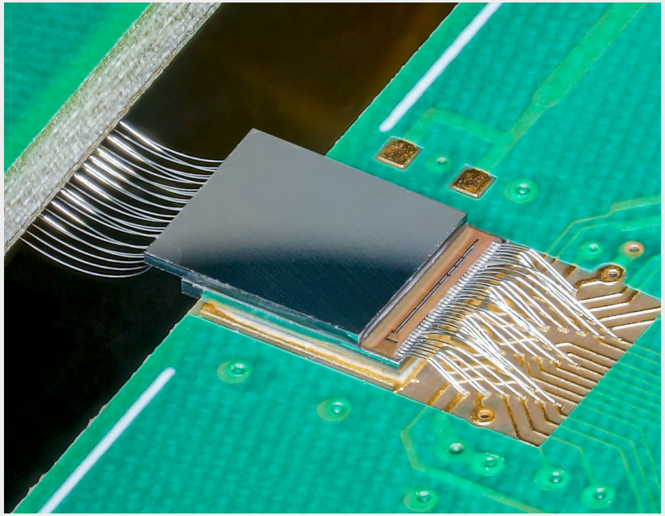


Capacitively Coupled Detectors

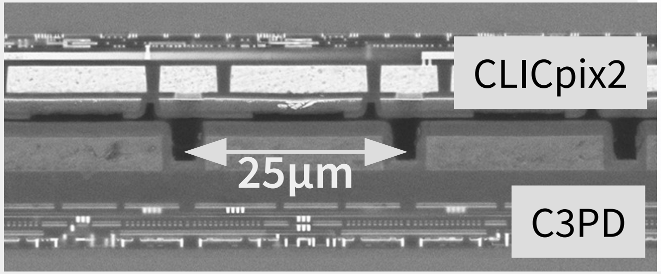


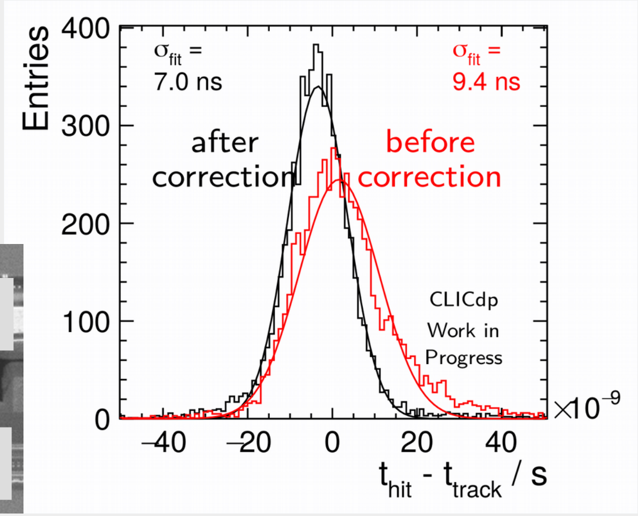
- Combination of "traditional" readout chip and HV-CMOS active sensor
- Only analog part (amplification) in sensor
- Advantages:
  - Large signal from amplifier while rather simple circuitry in HV-CMOS
  - Can use full feature set of readout chip CMOS process
  - Chips can be glued, avoids bump-bonding
- Challenges:
  - Gluing requires precise alignment
  - Main influence: distance – good uniformity required

CLICpix2 + C3PD



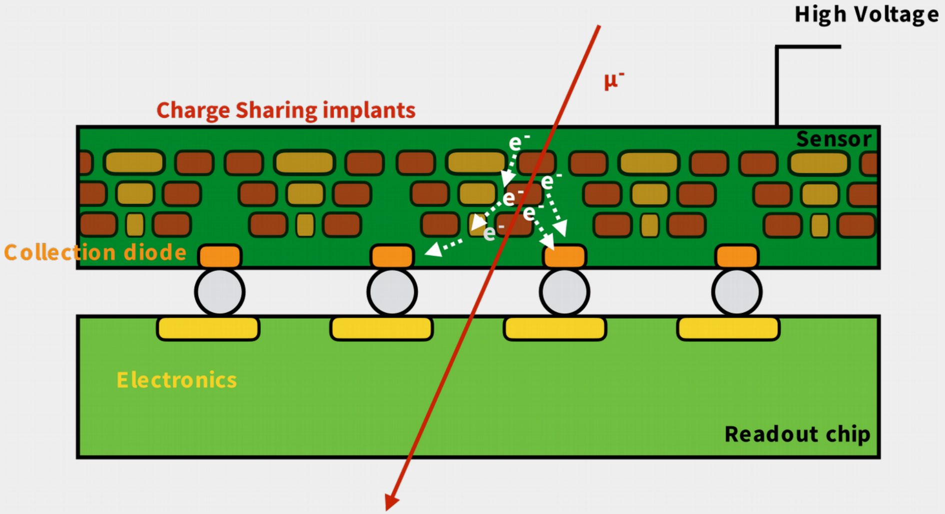
- Two generations of active sensors (CCPDv3, C3PD) in AMS 180 nm HV-CMOS process,
    - 10-1000Ωcm substrates, 25 x 25µm² pitch
- First test beam measurements performed
    - Efficiency > 90% , σ_t ~7ns, σ_{SP} ~8µm
- Finite-element simulation of capacitive coupling
- Ongoing work:
    - Evaluation of high-resistivity sensors for larger depletion zone
    - Glue-process optimization

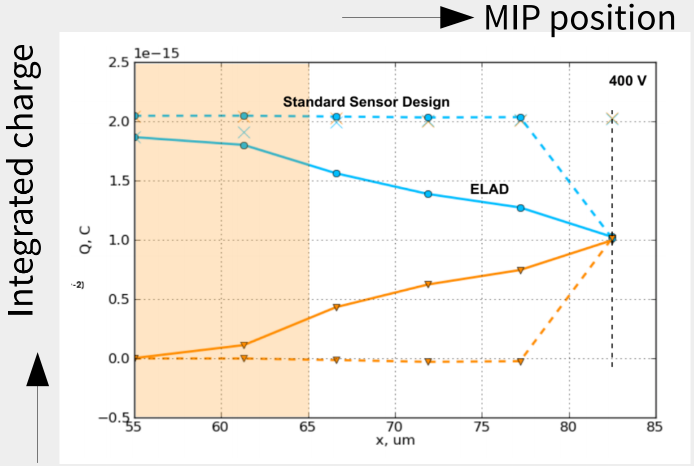




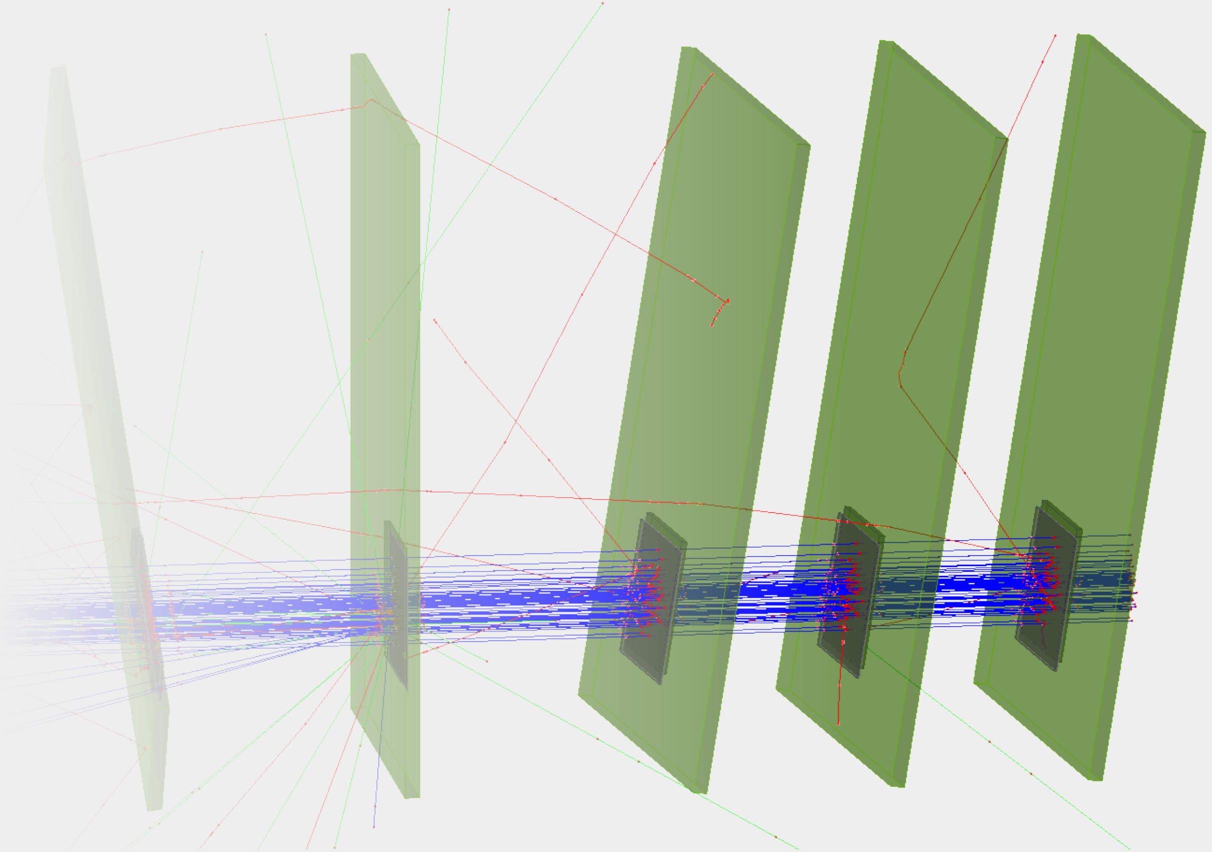
Enhanced Lateral Drift Detectors

- Position resolution in thin sensors limited to pitch / √12 (almost no charge sharing)
- New sensor concept: **enhance charge sharing** Enhanced LAteral Drift sensors (ELAD)
  - Close to theoretical optimum: linear charge sharing
- Deep implantations to alter the electric field
  - Lateral spread of charges during drift, cluster size ~2
  - Improved resolution for same pitch
- Challenges:
  - Complex production process, adds cost
  - Have to avoid low-field regions (recombination)
- Simulations ongoing: implantation process, sensor performance
- First production in 2018: test structures, strips and test sensors with Timepix3 footprint (55µm pitch)



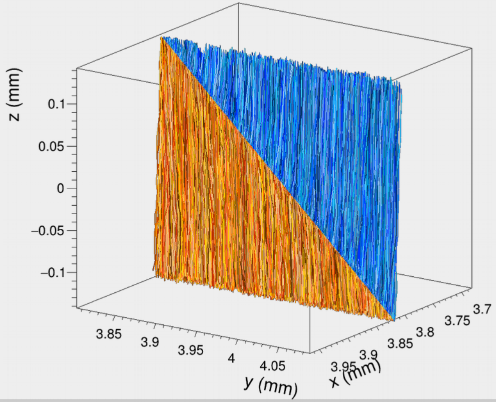


Prototype Simulation

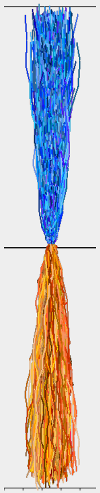


Simulation of Detector Prototypes: **Allpix Squared**

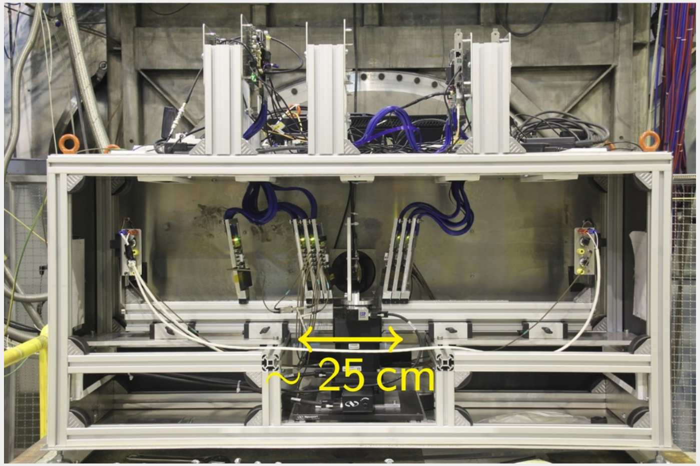
- Powerful simulation tools required to understand prototypes and optimize designs
- Monte Carlo simulation complementary to device modeling like TC
  - Account for stochastic nature of processes: high statistics samples
  - Simulate full setup (potentially multiple detectors)
- Combine tools: **Geant4** + **TCAD fields** + **Front-end simulation**
- Provides access to main detector characteristics (resolution, efficiency…)
- Implements drift-diffusion model to model charge flow in sensor:
- Simulation of transient effects for timing under development



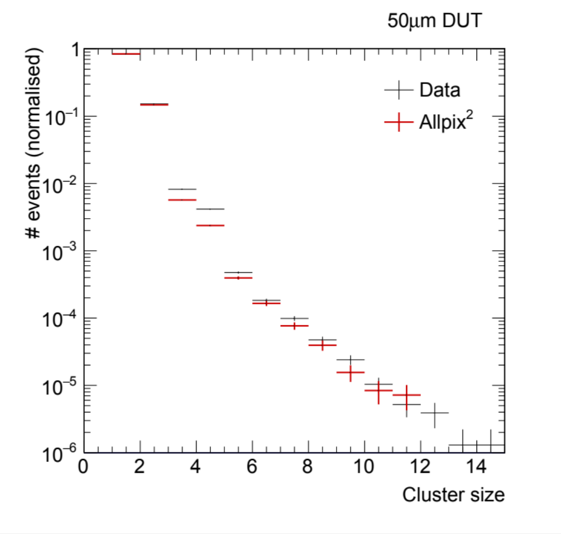
drift animations of electrons/holes through a planar silicon sensor

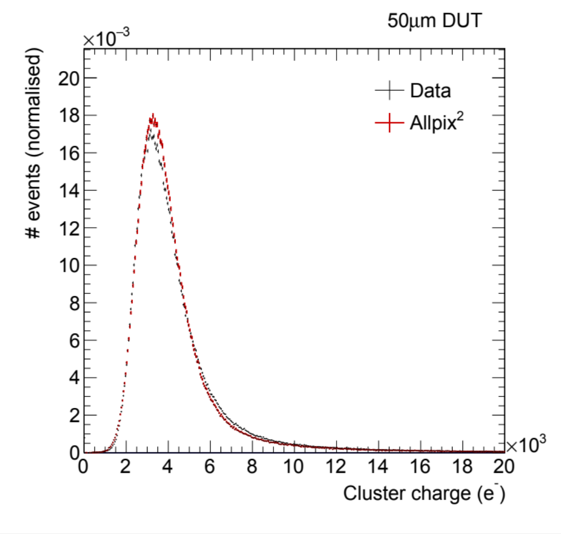


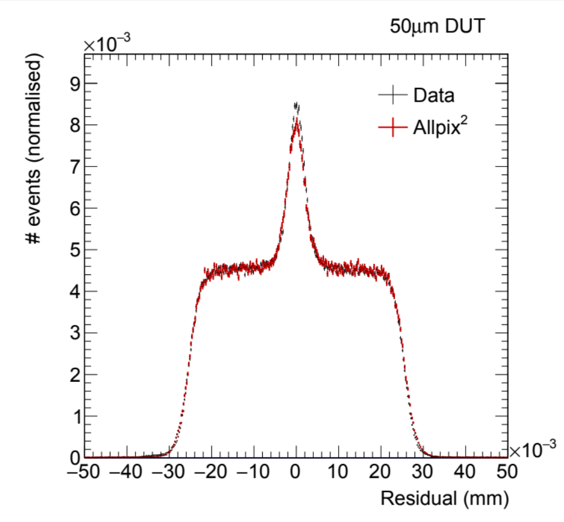
Verification With Test Beam Data



- **CLICdp** Timepix3 Telescope + DUT: **50μm planar sensor**
- Simulate device only with few parameters taken from data
  - Dimensions, bias/depletion voltages, temperature, threshold
  - Reconstruction with same cuts & corrections
- Very good agreement between data and simulation







In a nutshell…

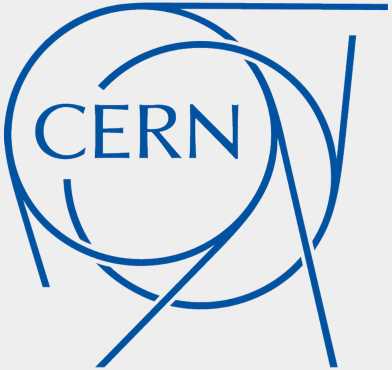
Summary & Outlook

- Proposed CLIC linear e+e- collider poses challenges to silicon detectors

  … excellent spatial and temporal resolution, minimum material

  … ambitious detector design concept

- Comprehensive R&D program for CLIC silicon detectors
  - Many technologies and concepts under investigation
  - Most initial requirements shown to be achievable, 3µm resolution still to be reached
- New and validated simulation tools help R&D and prototyping
- Ongoing developments:
  - New HR-CMOS chip for tracker: CLICTD
  - New SOI chip for vertex: CLIPS
  - Production and testing of a first ELAD silicon sensor


CERN

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

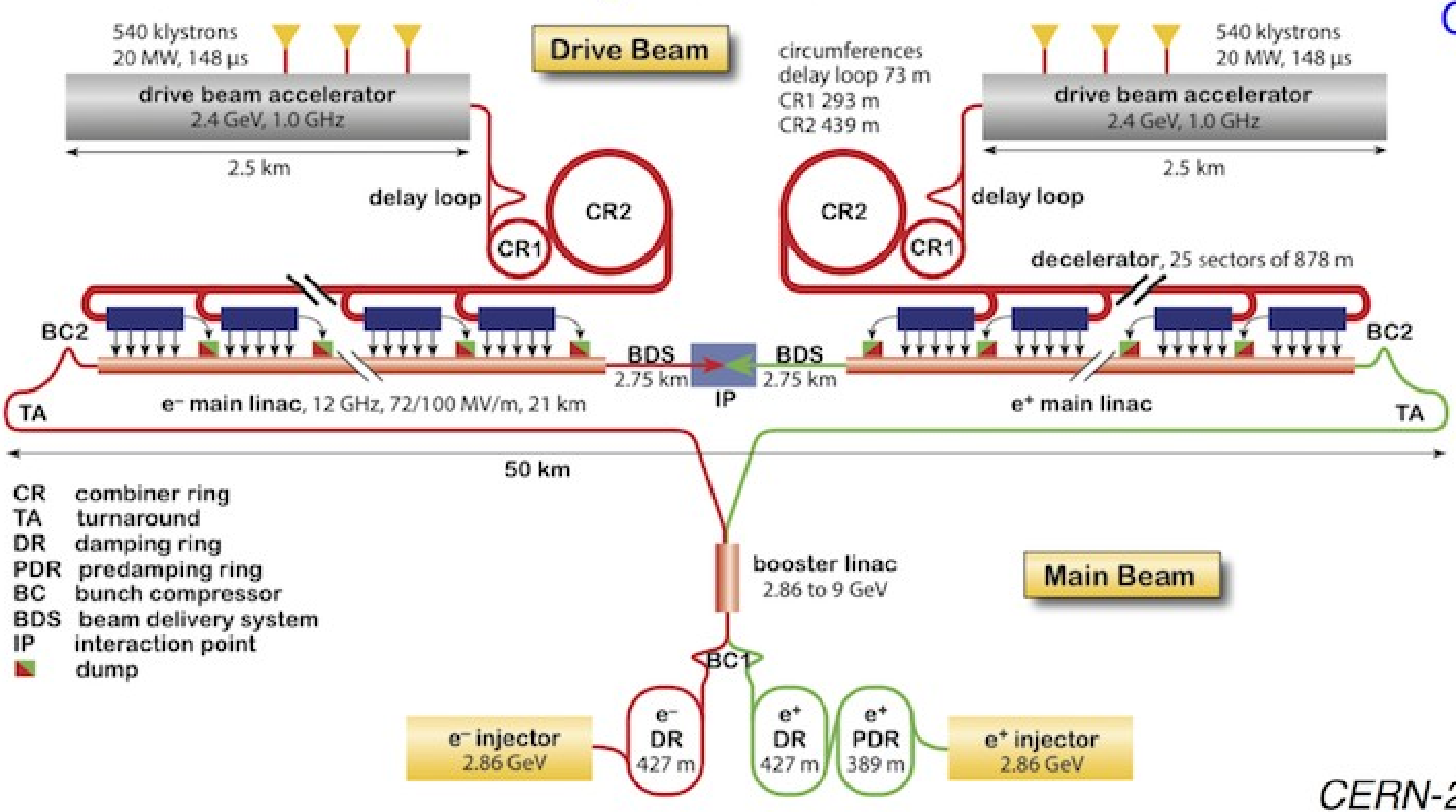
Ready for construction; start of excavations

2035 First Beams

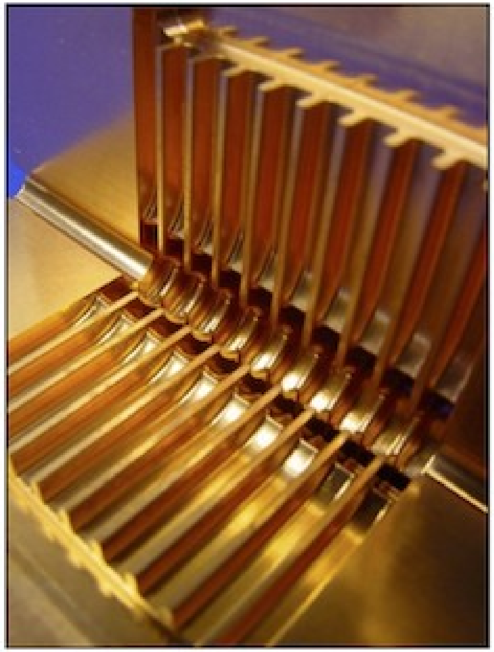
Getting ready for data taking by the time the LHC programme reaches completion

CLIC Accelerator Complex

CLIC layout at 3 TeV



CLIC accelerating structure



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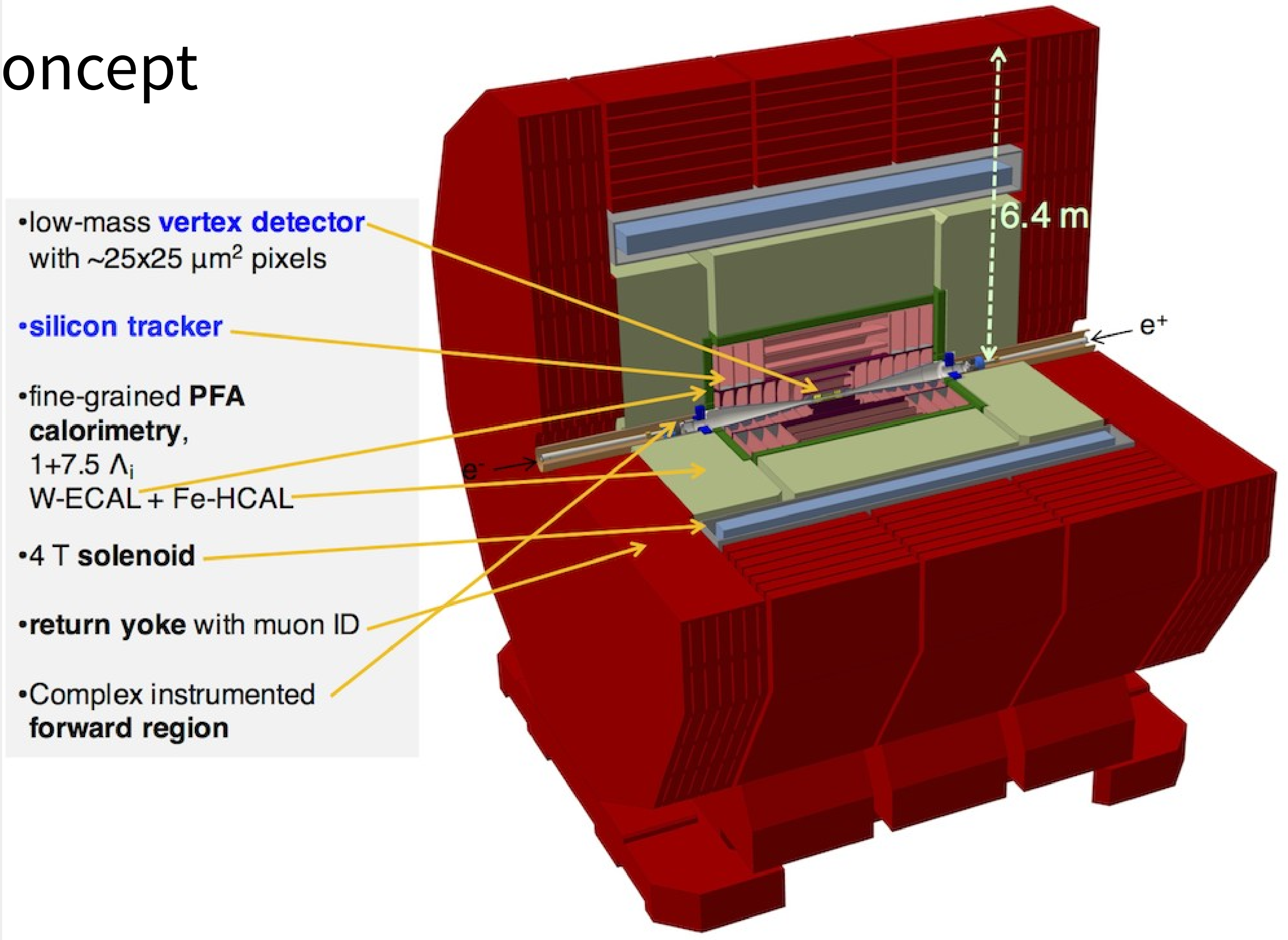
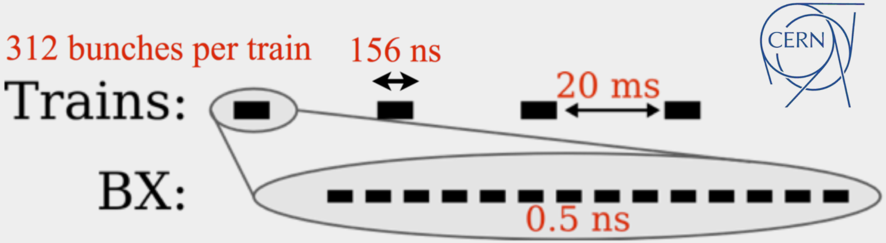
CLIC Detector Concept

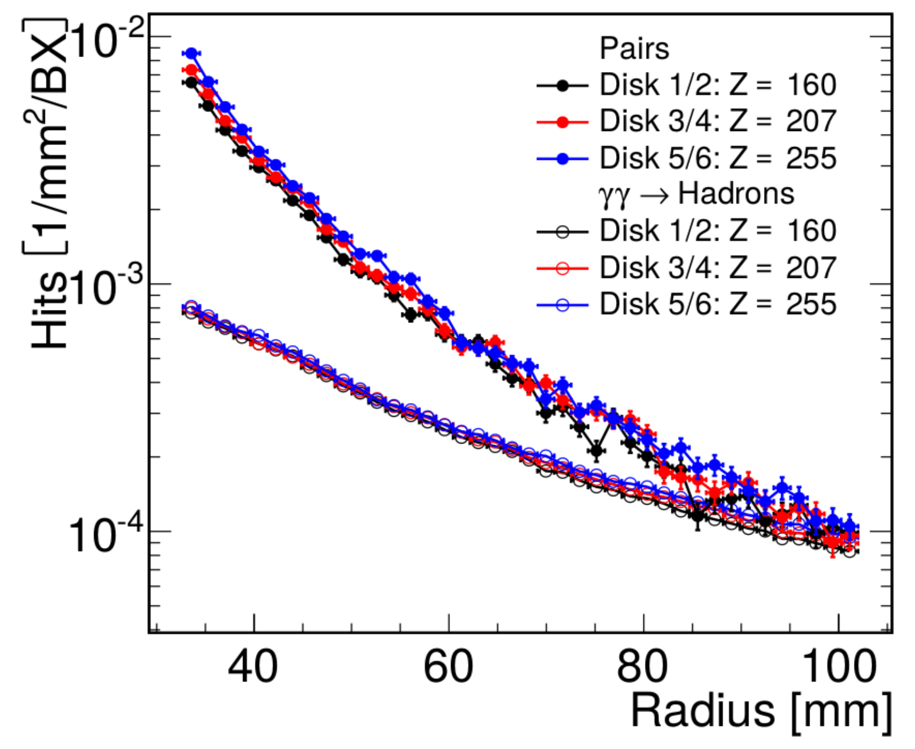


- low-mass **vertex detector** with ~25x25 μm^2 pixels
- **silicon tracker**
- fine-grained **PFA calorimetry**, 1+7.5 Λ_i W-ECAL + Fe-HCAL
- 4 T **solenoid**
- **return yoke** with muon ID
- Complex instrumented **forward region**

Experimental Conditions at CLIC

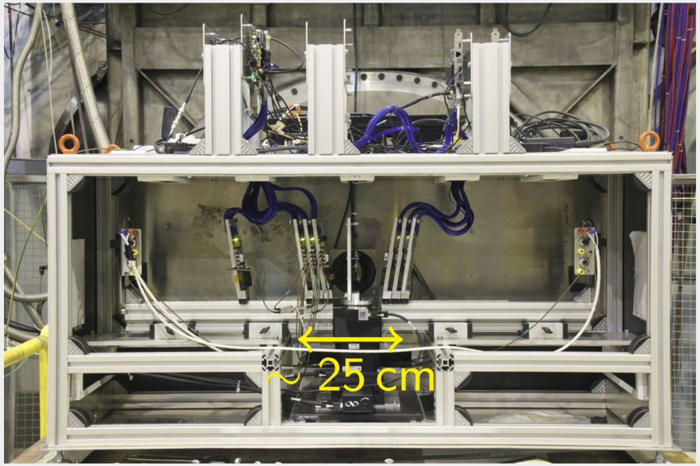
- CLIC beam structure drives design
  - Spacing between bunches: 0.5 ns
  - Trains of 312 bunches, 50 Hz repetition rate
  - Transverse beam size ~nm
- Interactions between bunches
  - Large experimental background:
    γ γ → hadrons / e+e- (beamstrahlung):
    ~100 particles/BX within acceptance @ 3TeV
  - Mostly in forward direction
- **Low radiation** environment
  - Factor 10^4 lower than at LHC

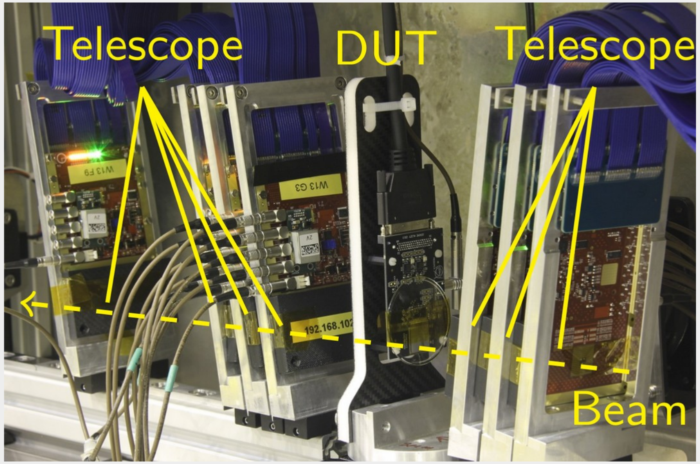




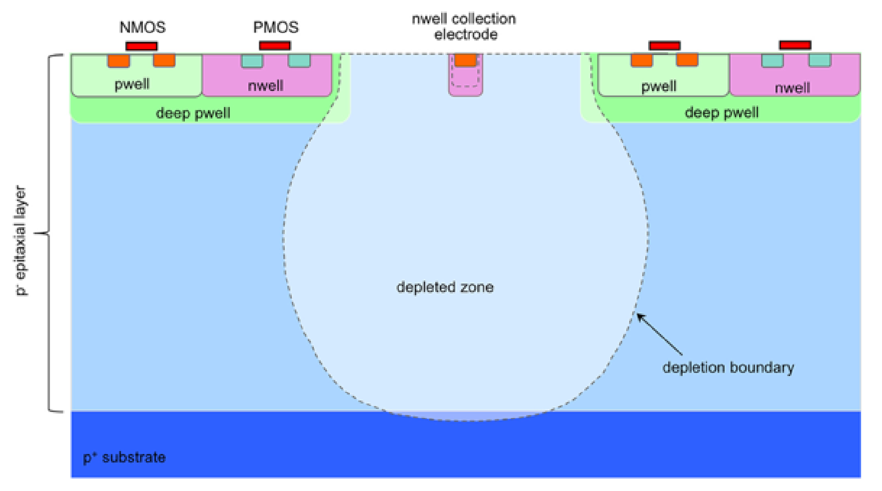
The CLICdp Timepix3 Telescope

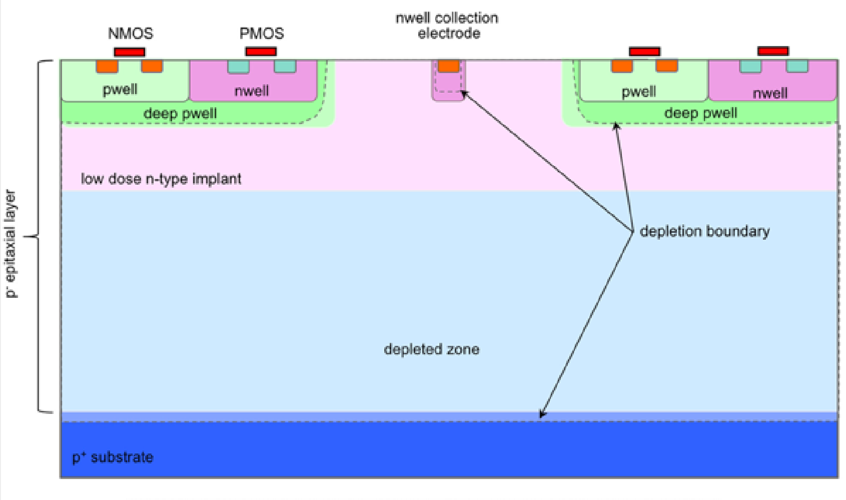
- Beam telescope with 7 Timepix3 planes
    - Operated in SPS H6, typically 120 GeV pions
    - Timepix3 assemblies : 300 µm thick, 55 µm pitch
    - Resolution on DUT: spatial ~2µm, timing ~1 ns
    - High rate, capable of > 1 × 10^6 Tracks/spill
    - x/y linear movement + rotation stage for the DUT
- 3 scintillator triggers in coincidence (for DUT)
- Motion stage for the full telescope, allows to operate parasitically to other users in the same beam line



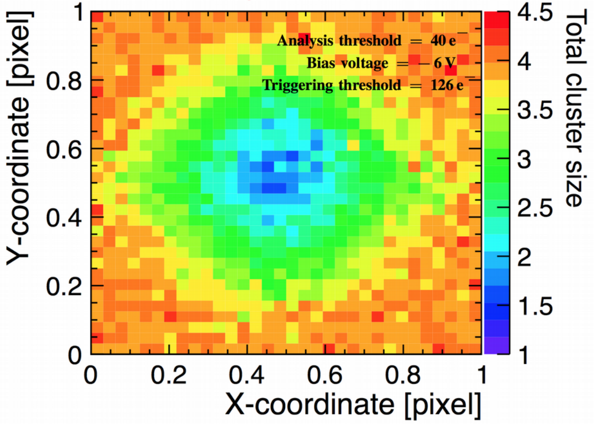


HR-CMOS: Standard/Modified Process

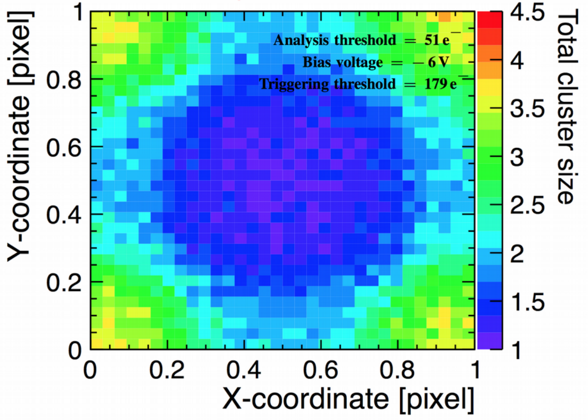




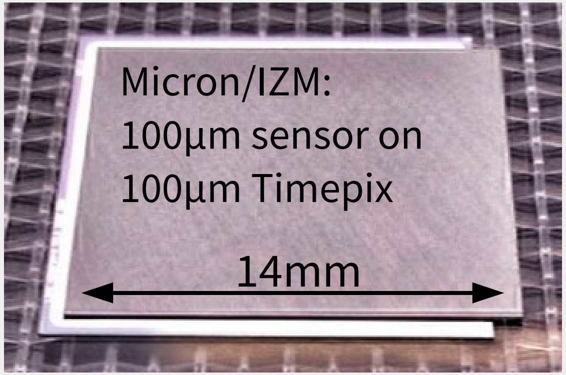
Standard, in-pixel total cluster size:



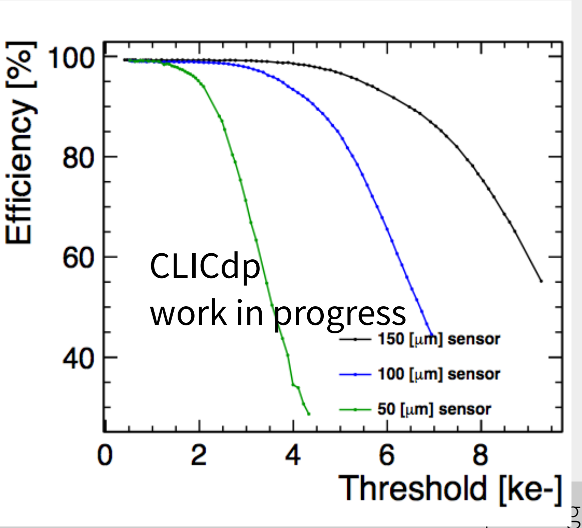
Modified, in-pixel total cluster size:

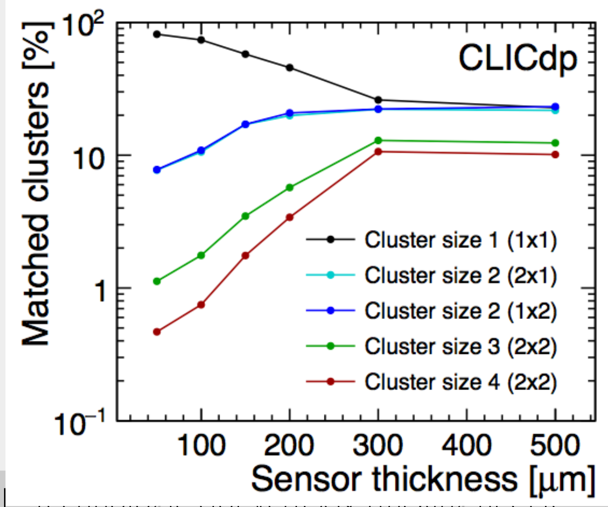


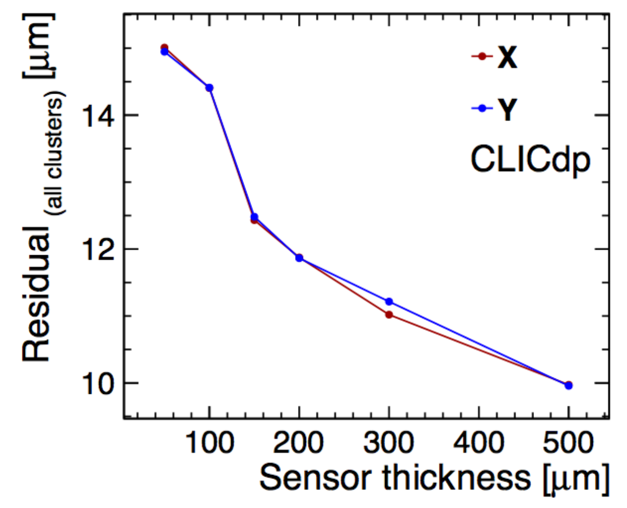
Performance of Thin Planar Sensors


Micron/IZM:
100µm sensor on
100µm Timepix

- Test beam studies: performance of thin sensors
    - CLIC Timepix3 telescope for reference, 2 µm resolution
    - **Timepix/Timepix3 ASICs**, 55 µm pitch
- High detection efficiency even for 50 µm sensor @ normal operating conditions
- Resolution limited by charge sharing / cluster size







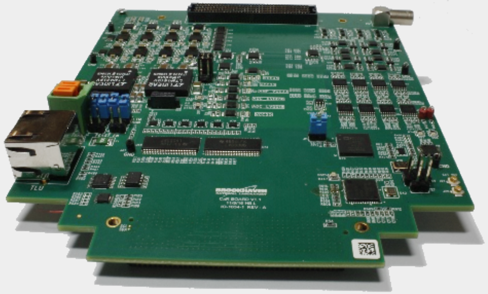
Caribou – Multi-chip modular DAQ system

- Variety of DAQ systems for pixel detector prototypes
  - Requirements very similar
  - Not very innovative from functional point of view
  - Repeated integration effort into (test beam) DAQ

- Solution: versatile, modular readout system
  - Collective effort for maintenance and extension
  - Support for wide range of current & future prototypes
  - Suited for laboratory and test beam measurements

Caribou – Multi-chip modular DAQ system



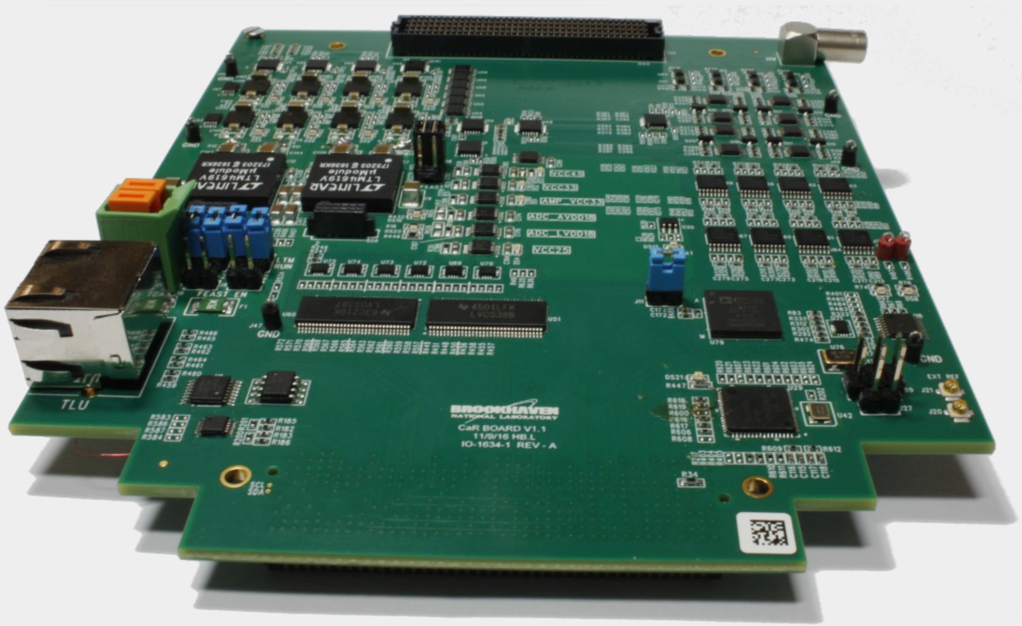



Xilinx ZC-706 + (optional) FMC + interface board + chip board

- Zynq System-on-Chip platform: FPGA + ARM Cortex A9 + …
  - Run Linux OS + DAQ software directly on the board
  - Access through network (1/10 Gbit ETH/SFP+)
  - SoC also contains (hardware) periphery: I2C, SPI modules, ...
- FMC cable allows to place main board in safe distance to beam

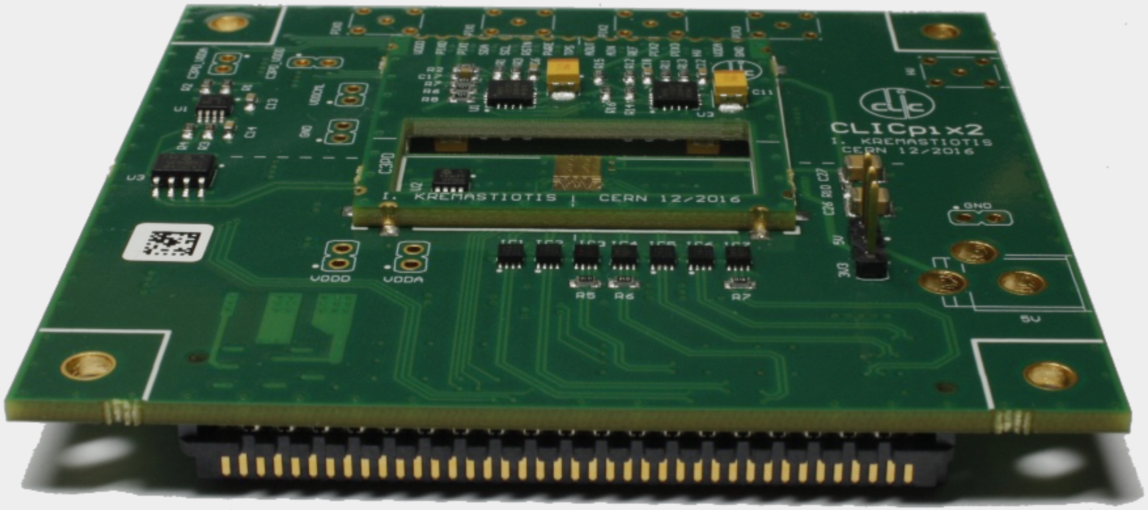
Caribou – The CaR interface board

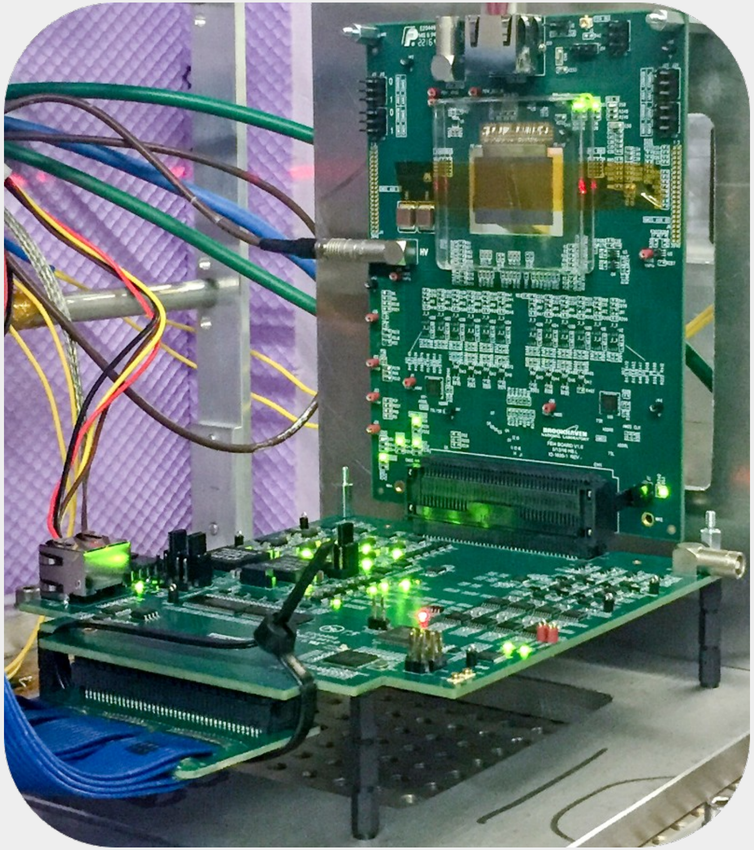
- FMC mezzanine board
- Hosts:
  power supplies, ADCs, current/voltage regulators, clock generator, pulse injectors, SERDES links
- RJ45 connector to interface TLU
- SEAF connector to chip board
- Designed for re-usability:
  contains all functionality & all expensive components



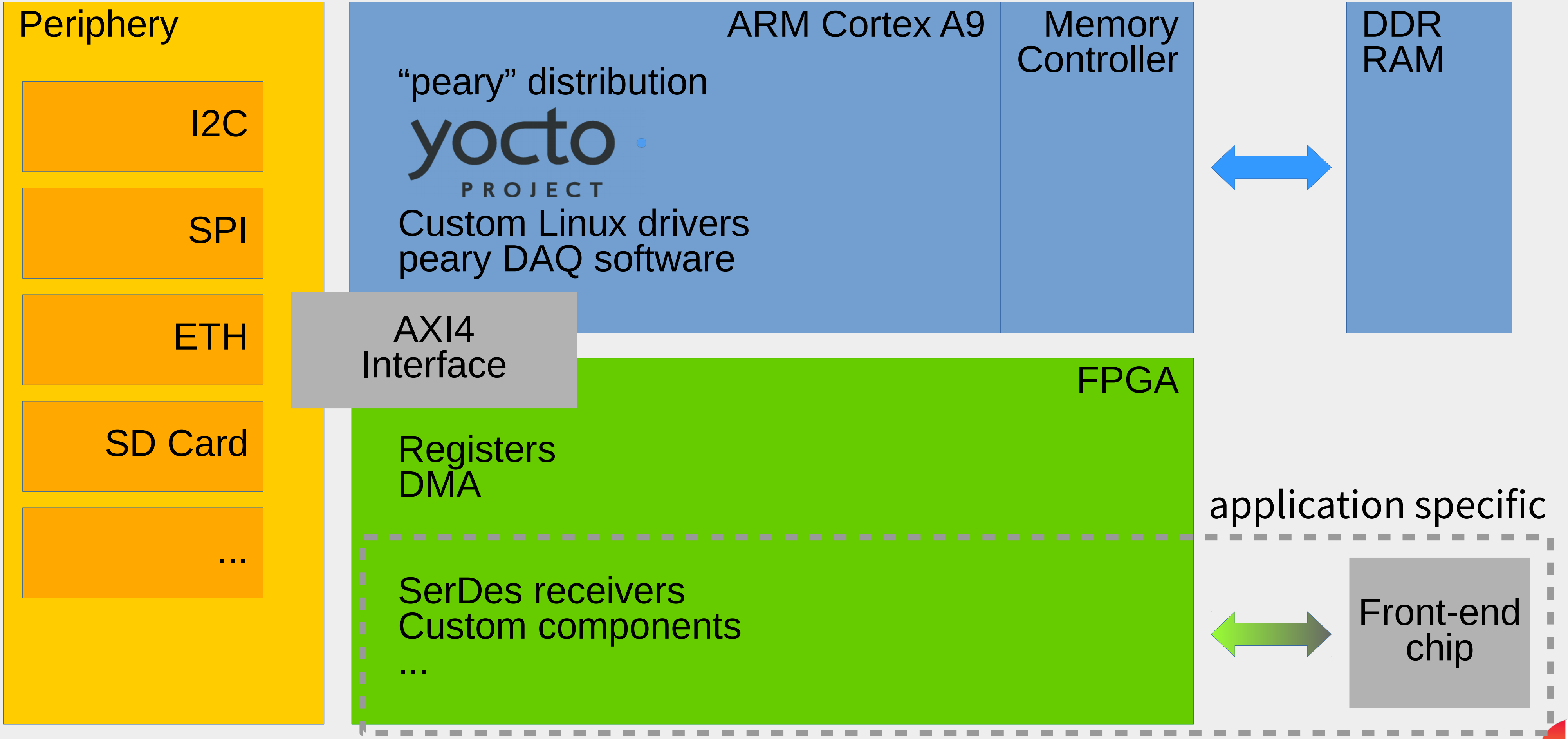
Caribou – Application-specific chip board

- Board with minimum functionality
  - Routing between SEAF connector and front-end
  - Special buffers (LVDS-CML …)
- Low production cost, simple design





Caribou – System-on-chip layout



Periphery

- I2C
- SPI
- ETH
- SD Card
- ...

AXI4 Interface

ARM Cortex A9

“peary” distribution

yocto PROJECT

Custom Linux drivers
peary DAQ software

Memory Controller

DDR RAM

FPGA

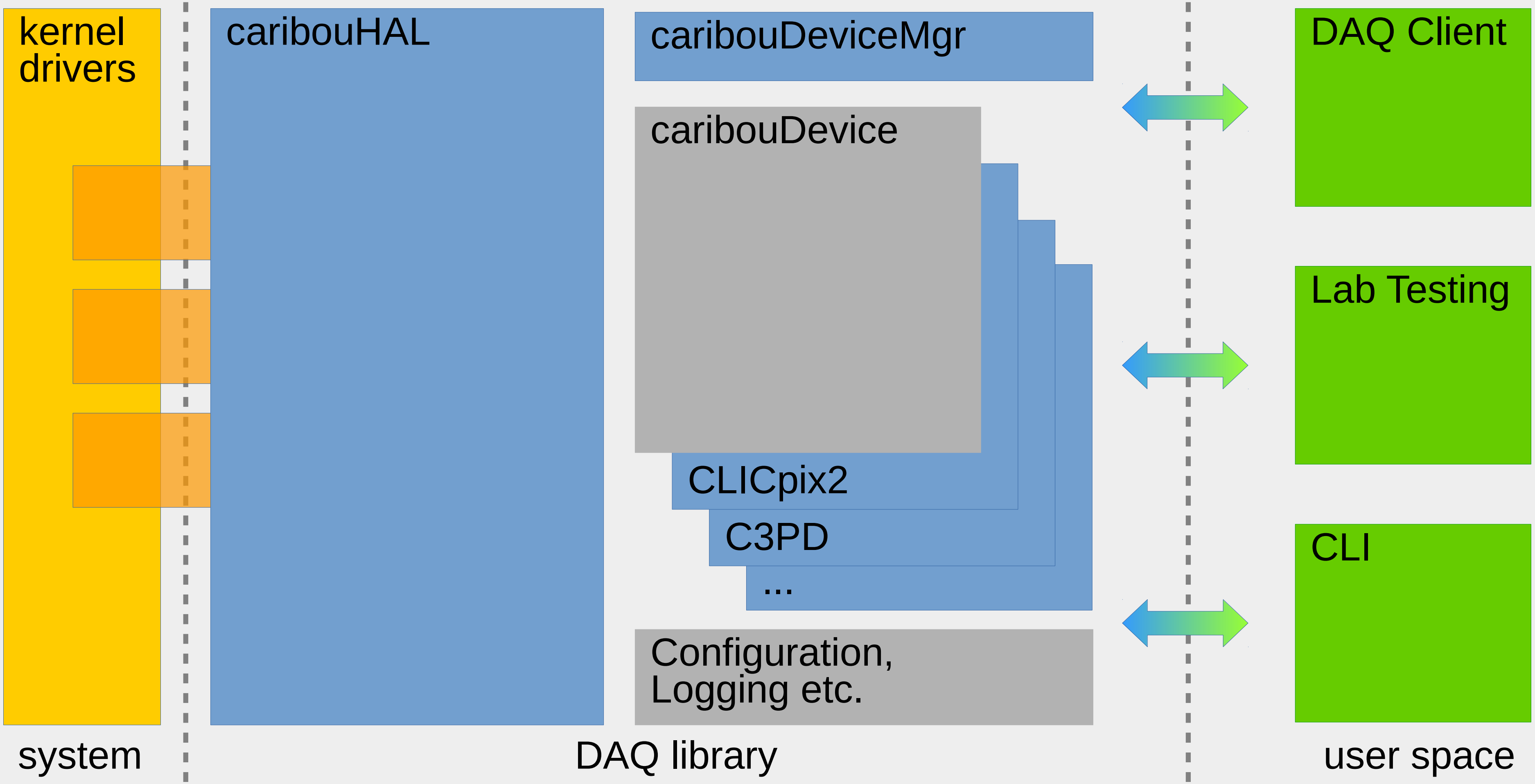
Registers
DMA

SerDes receivers
Custom components
...

application specific

Front-end chip

Caribou – Software architecture



kernel drivers

caribouHAL

caribouDeviceMgr

caribouDevice

CLICpix2

C3PD

...

Configuration, Logging etc.

DAQ Client

Lab Testing

CLI

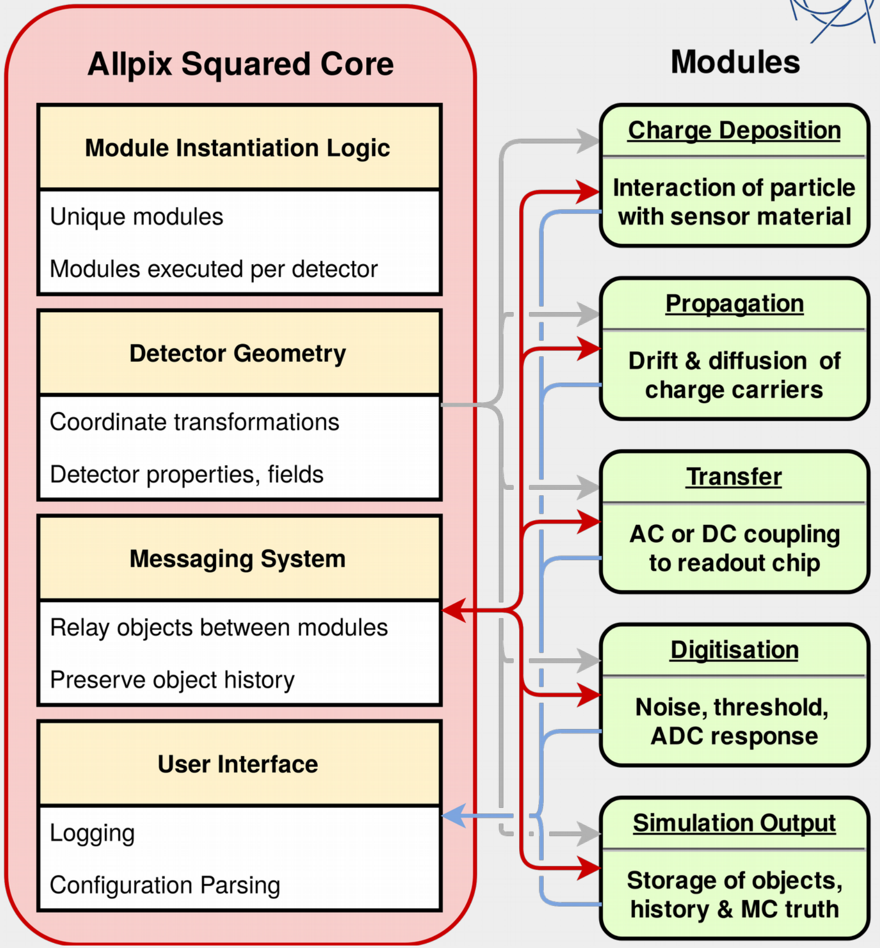
system

DAQ library

user space

The Allpix Squared Framework

- Written in modern C++
- Prov. central components
    - Convenient user interface
    - Logging, configuration
    - Geometry and transformations
- Implement physics in independent modules
    - Plug & play concept
    - IO using ROOT TTrees
- Loading lib, parallelization…

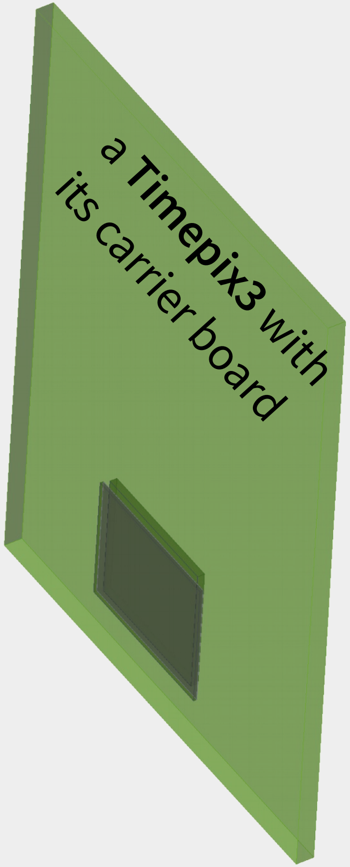


Detector Models

- Different detector types available
  - Monolithic detectors
  - Hybrid detectors w/ bump bonds
- Easy configuration through model files
  - Give it a name, decide on the type
  - Set detector parameters
- Some model files already shipped with the framework, at the moment:

  ATLAS FE-I3, FE-I4, CMS PSI46/dig, Medipix3, Timepix3, CLICpix, CLICpix2, Mimosa23, Mimosa26

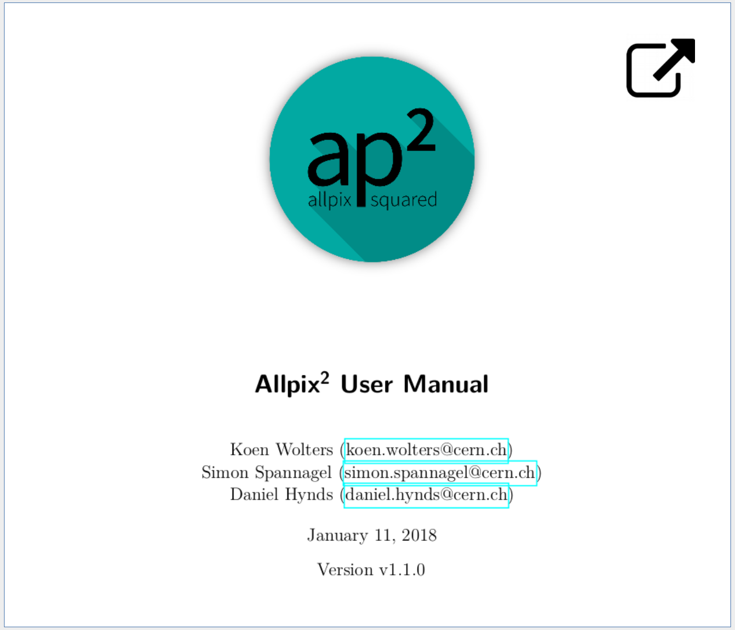
```
type = "hybrid"

number_of_pixels = 256 256
pixel_size = 55um 55um

sensor_thickness = 300um
chip_thickness = 700um

# ...

[support]
thickness = 1.76mm
```



a **Timepix3** with its carrier board

Documentation & Manuals

- Extensive User Manual ~115 pages **(PDF/TeX)**



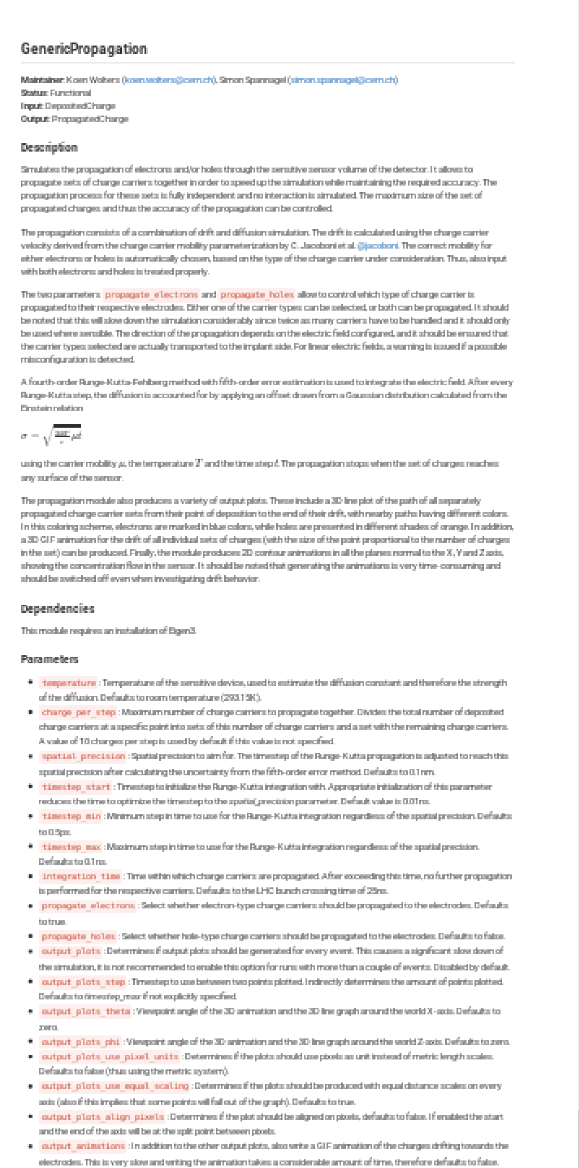
Allpix^2 User Manual

Koen Wolters (koen.wolters@cern.ch)
Simon Spannagel (simon.spannagel@cern.ch)
Daniel Hynds (daniel.hynds@cern.ch)

January 11, 2018

Version v1.1.0

- Well-documented code **(Doxygen)**
- Module documentation **(Markdown)**



GenericPropagation

Maintainer: Koen Wolters (koen.wolters@cern.ch), Simon Spannagel (simon.spannagel@cern.ch)
Status: Functional
Input: DepositedCharge
Output: PropagatedCharge

Description

Simulates the propagation of electrons and/or holes through the sensitive sensor volume of the detector. It allows to propagate sets of charge carriers together in order to speed up the simulation while maintaining the required accuracy. The propagation process for these sets is fully independent and no interaction is simulated. The maximum size of the set of propagated charges and thus the accuracy of the propagation can be controlled.

The propagation consists of a combination of drift and diffusion simulation. The drift is calculated using the charge carrier velocity derived from the charge carrier mobility parameterization by C. Jacoboni et al. @jacoboni. The correct mobility for either electrons or holes is automatically chosen, based on the type of the charge carrier under consideration. Thus, also input with both electrons and holes is treated properly.

The two parameters `propagate_electrons` and `propagate_holes` allow to control which type of charge carrier is propagated to their respective electrodes. Either one of the carrier types can be selected, or both can be propagated. It should be noted that this will slow down the simulation considerably since twice as many carriers have to be handled and it should only be used where sensible. The direction of the propagation depends on the electric field configured, and it should be ensured that the carrier types selected are actually transported to the implant side. For linear electric fields, a warning is issued if a possible misconfiguration is detected.

A fourth-order Runge-Kutta-Fehlberg method with fifth-order error estimation is used to integrate the electric field. After every Runge-Kutta step, the diffusion is accounted for by applying an offset drawn from a Gaussian distribution calculated from the Einstein relation

$$\sigma = \sqrt{\frac{2kT}{e}\mu t}$$

using the carrier mobility μ, the temperature T and the time step t. The propagation stops when the set of charges reaches any surface of the sensor.

The propagation module also produces a variety of output plots. These include a 3D line plot of the path of all separately propagated charge carrier sets from their point of deposition to the end of their drift, with nearby paths having different colors. In this coloring scheme, electrons are marked in blue colors, while holes are presented in different shades of orange. In addition, a 3D GIF animation for the drift of all individual sets of charges (with the size of the point proportional to the number of charges in the set) can be produced. Finally, the module produces 2D contour animations in all the planes normal to the X, Y and Z axis, showing the concentration flow in the sensor. It should be noted that generating the animations is very time-consuming and should be switched off even when investigating drift behavior.

Dependencies

This module requires an installation of Eigen3.

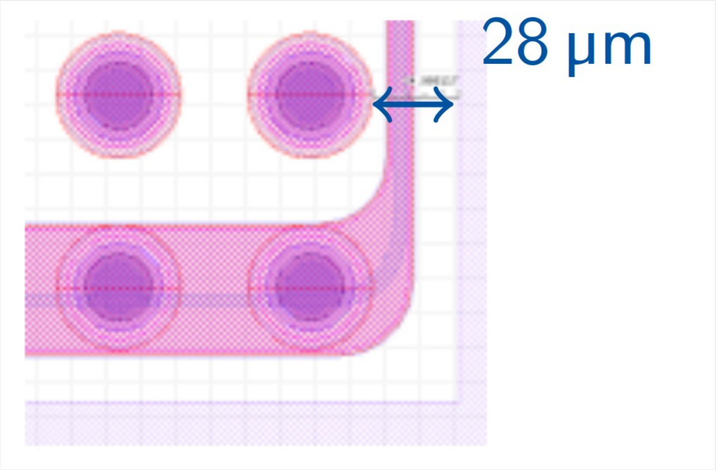
Parameters

- `temperature` : Temperature of the sensitive device, used to estimate the diffusion constant and therefore the strength of the diffusion. Defaults to room temperature (293.15K).
- `charge_per_step` : Maximum number of charge carriers to propagate together. Divides the total number of deposited charge carriers at a specific point into sets of this number of charge carriers and a set with the remaining charge carriers. A value of 10 charges per step is used by default if this value is not specified.
- `spatial_precision` : Spatial precision to aim for. The timestep of the Runge-Kutta propagation is adjusted to reach this spatial precision after calculating the uncertainty from the fifth-order error method. Defaults to 0.1nm.
- `timestep_start` : Timestep to initialize the Runge-Kutta integration with. Appropriate initialization of this parameter reduces the time to optimize the timestep to the *spatial_precision* parameter. Default value is 0.01ns.
- `timestep_min` : Minimum step in time to use for the Runge-Kutta integration regardless of the spatial precision. Defaults to 0.5ps.
- `timestep_max` : Maximum step in time to use for the Runge-Kutta integration regardless of the spatial precision. Defaults to 0.1ns.
- `integration_time` : Time within which charge carriers are propagated. After exceeding this time, no further propagation is performed for the respective carriers. Defaults to the LHC bunch crossing time of 25ns.
- `propagate_electrons` : Select whether electron-type charge carriers should be propagated to the electrodes. Defaults to true.
- `propagate_holes` : Select whether hole-type charge carriers should be propagated to the electrodes. Defaults to false.
- `output_plots` : Determines if output plots should be generated for every event. This causes a significant slow down of the simulation, it is not recommended to enable this option for runs with more than a couple of events. Disabled by default.
- `output_plots_step` : Timestep to use between two points plotted. Indirectly determines the amount of points plotted. Defaults to *timestep_max* if not explicitly specified.
- `output_plots_theta` : Viewpoint angle of the 3D animation and the 3D line graph around the world X-axis. Defaults to zero.
- `output_plots_phi` : Viewpoint angle of the 3D animation and the 3D line graph around the world Z-axis. Defaults to zero.
- `output_plots_use_pixel_units` : Determines if the plots should use pixels as unit instead of metric length scales. Defaults to false (thus using the metric system).
- `output_plots_use_equal_scaling` : Determines if the plots should be produced with equal distance scales on every axis (also if this implies that some points will fall out of the graph). Defaults to true.
- `output_plots_align_pixels` : Determines if the plot should be aligned on pixels, defaults to false. If enabled the start and the end of the axis will be at the split point between pixels.
- `output_animations` : In addition to the other output plots, also write a GIF animation of the charges drifting towards the electrodes. This is very slow and writing the animation takes a considerable amount of time, therefore defaults to false.

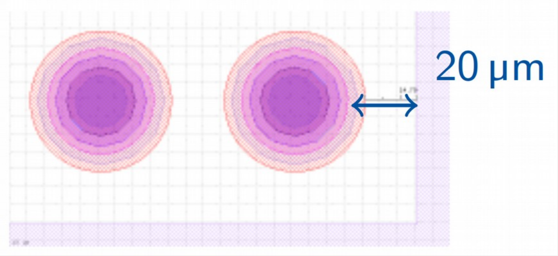
Active-Edge Sensors: Guard Ring Layouts

- Different guard ring layouts implemented
  - No guard rings, floating guard rings
  - Grounded guard rings, via additional row of bump bonds
- Edge distance: distance between last n-implant and cut edge

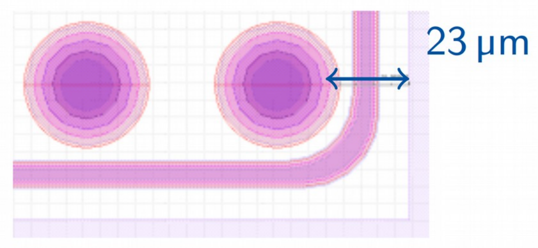
Grounded Guard Ring



No Guard Rings



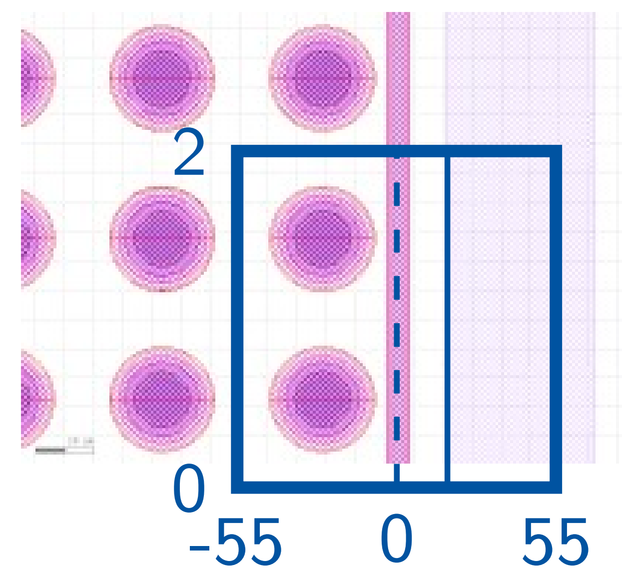
Floating Guard Ring



Edge Performance

- Test beam studies of sensor performance at the edge
  - CLIC Timepix3 telescope for reference, 2µm track resol
  - Timepix3 with active-edge sensors as DUT

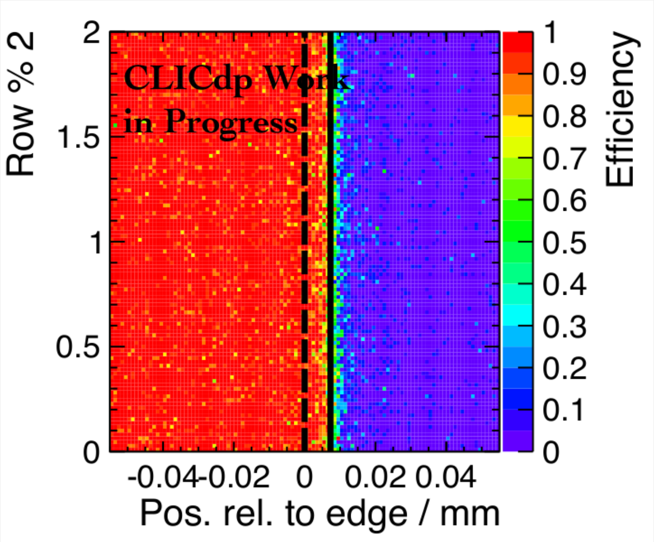
- Tracks from edge folded into 2x2 pixel matrix
  - Increase statistics
  - End of pixel matrix: dashed line
  - Physical cutting edge of sensor: solid line

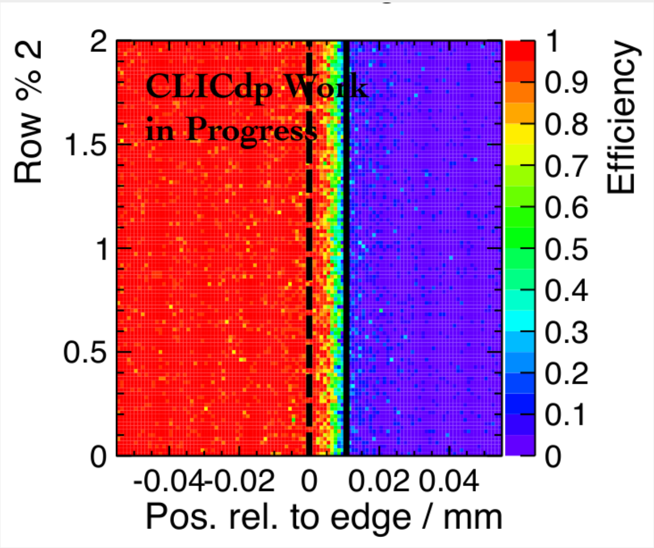


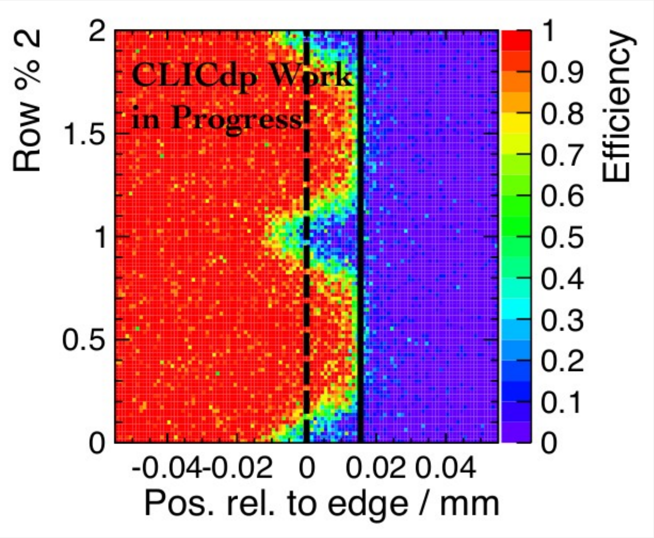
Active-Edge Sensor, 50µm thickness

- Without GR and with floating GR:
  fully efficient up to the physical sensor edge

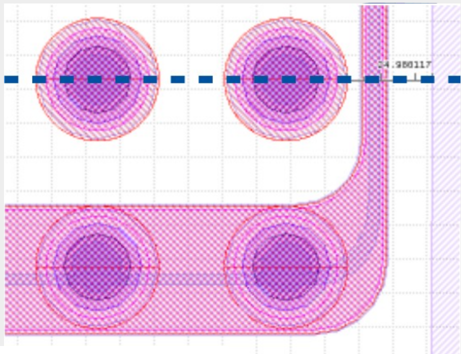
- With grounded GR:
  signal/efficiency loss



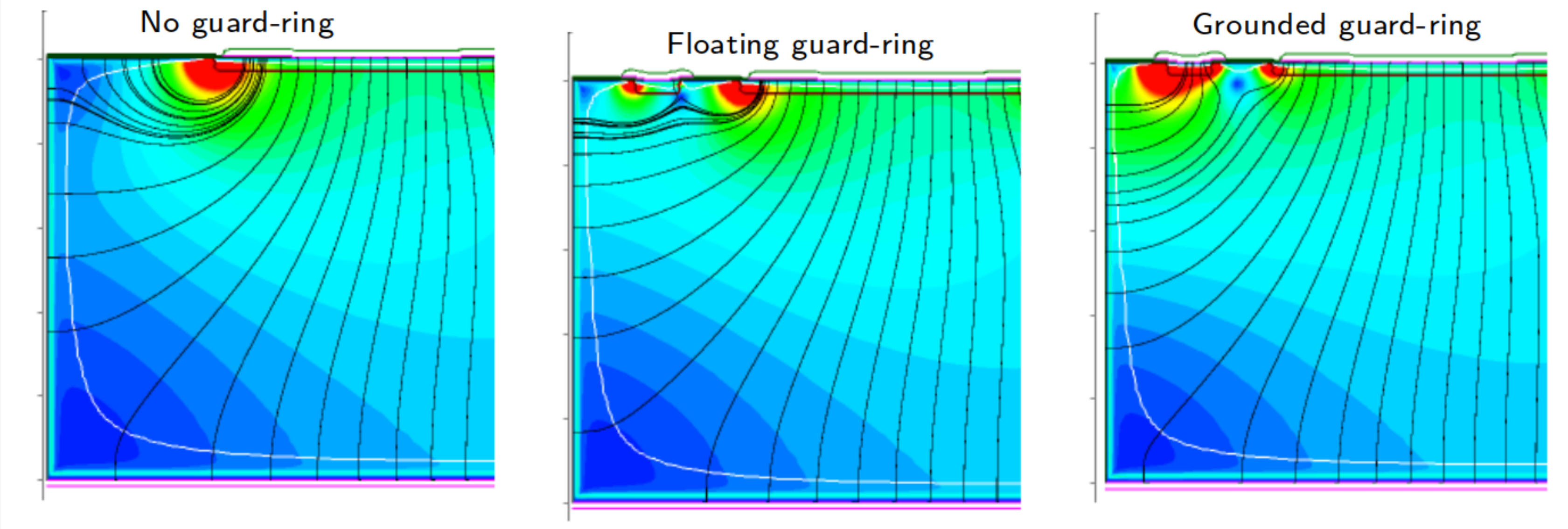




Active-Edge Sensors: TCAD Simulations



- Different guard ring layouts in Synopsys Sentaurus
- 2D simulation at implant center, 50µm thick, edge distance 20µm



- Field lines end at pixel
- No charge loss expected

- Most field lines at pixel
- Small charge loss

- Some lines end on ground ring
- Significant charge loss