Highlights from the 2017 beam tests with the CLICdp Timepix3 telescope

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on behalf of the CLICdp collaboration

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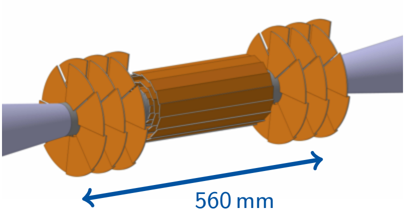
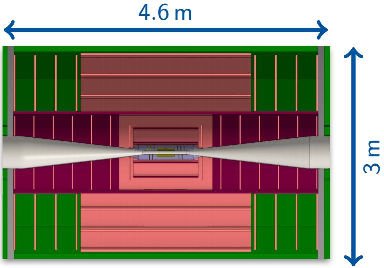
Introduction

- R&D for a detector at the Compact Linear Collider CLIC, post HL-LHC proposal
- Silicon vertex and tracking detector foreseen
- Low mass (0.2 %X_0 per vertex layer)
- Low power (50 mW cm^{-2} in the vertex det., air-flow cooling)
- High resolution (3 µm in the vertex, 7 µm in the tracker)
- Large area tracker (100 m^2), high granularity (1 mm to 10 mm strips)
- Fast timestamping (10 ns)

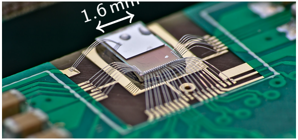




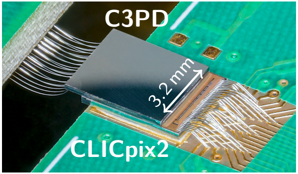
Silicon pixel detector R&D for CLIC

- Different detector requirements call for different technology options
- Vertex detector, difficult to achieve very good single-point resolution with very thin detection layers
  - Planar hybrid pixel detectors
  - Capacitively coupled pixel detector with active HV-CMOS sensor
- Tracking detector, avoid costly bump bonding for large surface detector
  - Integrated high-resistivity CMOS
  - Silicon-On-Insulator
  - Integrated HV-CMOS
- Mostly small test chips, challenging to test in beams

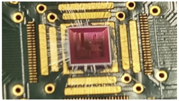
50 µm planar sensor on CLICpix ASIC



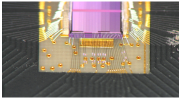
Capacitively coupled detector



SOI test chip

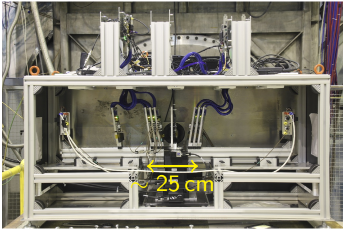


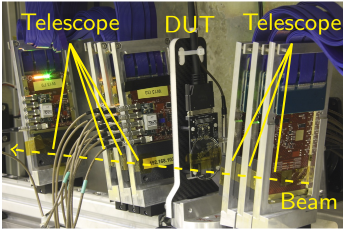
HR-CMOS test chip



Timepix3 Telescope

- Operated in SPS H6 beamline, typically 120 GeV pions
- 7 planes of Timepix3 assemblies (300 μm thick, 55 μm pitch, p-in-n sensors) for reference tracking, design inspired by the LHCb telescope
- Spatial resolution: $\lesssim 2\,\mu m$ on DUT, Timing resolution: $\lesssim 1$ ns on DUT
- High rate: $\gtrsim 1 \times 10^6$ Tracks/spill
- x/y linear movement + rotation stage for the DUT
- 3 scintillator triggers in coincidence (for DUT, not used for tel.)
- Motion stage for the full telescope installed last year. Improved possibility to operate parasitically to other users in the same beam line





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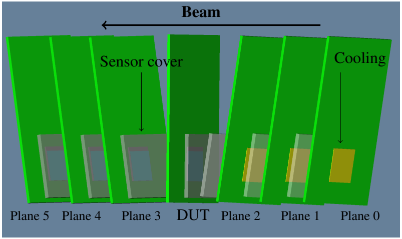
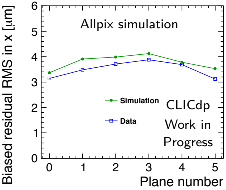
- Motion stage for the full telescope installed last year. Improved possibility to operate parasitically to other users in the same beam line
- SPIDR DAQ, LHCb/Bristol TLU
- Reconstruction using EUTelescope framework:
  - Event/frame-based $\Rightarrow$ re-definition of an event is needed
  - Build events with fixed duration

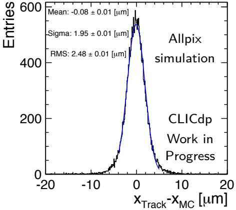
Telescope performance - Simulation

- Allpix simulation of Timepix3 telescope setup
- Realistic material budget
- Drift + Diffusion digitizer
- Track reconstruction with EUTelescope framework, similar to test beam data



- Biased residual distribution on telescope planes agree within 10 % to data
- Use MC information to estimate tracking resolution on DUT: <2 μm (central 95 %)





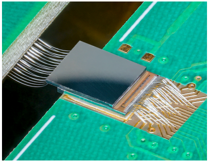
Allpix[2] validation ongoing → S. Spannagel on Thursday

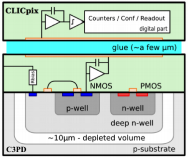
DUT integration

- No common DAQ (data collector) for telescope and DUTs
  - exception: Timepix3 DUTs (not covered here → M. Williams on Friday)
- Each DUT writes own data stream, time tagged using a global clock
- Data to be synchronized during analysis
- Timepix3 DAQ system provides:
  - 40 MHz clock
  - T0 signal
  - Busy input
  - TDC input
- Some examples on the following slides, showing different readout architectures:
  - Frame based: CLICpix2
  - Data driven: ATLASPix_Simple
  - Rolling shutter: Cracow SOI detector

New generation of prototype chips: CLICpix2/C3PD

- CLICpix2
  - Advancement of CLICpix design, 65 nm process
  - Increased matrix size to 128 × 128 pixels
  - Larger dynamic range: 5bit ToT, 8bit ToA
  - Improved noise isolation and removal of cross-talk issue observed in first CLICpix
- C3PD
  - Active HV-CMOS sensor to be capacitively coupled to the CLICpix2 readout chip
  - 180 nm HV-CMOS process, transistors placed in deep n-well
  - 128 × 128 square pixels with 25 μm pitch matching CLICpix2 footprint
  - Improved configuration and testing features
- Capacitively coupled detector assemblies produced and tested in beam

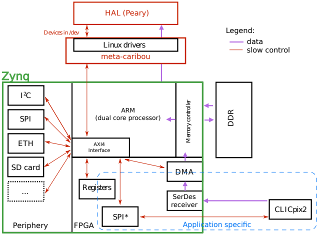




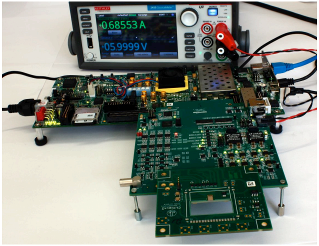
Caribou multi-chip modular r/o system

- Caribou universal r/o system (BNL, UniGE, CERN)
- Target: laboratory and high-rate test-beam measurements
- Generic DAQ Software Peary
- Modular concept:
  - Xilinx FPGA evaluation board ZC706 with ARM Cortex A9 processor
  - Generic periphery board (CaR)
  - Project specific chip boards: currently supporting CLICpix2, C3PD, FEI4, H35Demo, ATLASPix. Cheap, minimum functionality: routing, chip-specific buffers
- Open hardware / firmware / software: `https://gitlab.cern.ch/Caribou/`

CaRIBOu DAQ System schematics

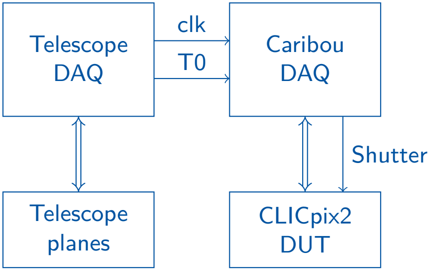


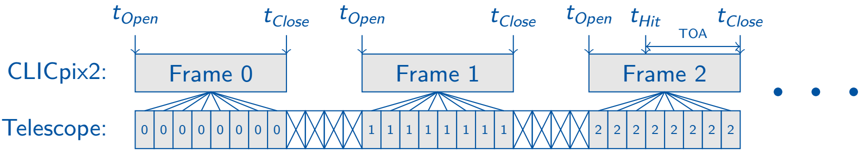
CaRIBOu with CLICpix2 r/o ASIC



CLICpix2: Telescope integration

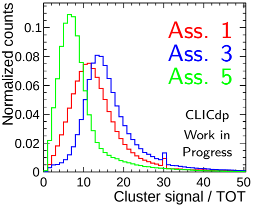
- Frame-based readout, fixed shutter length
- Caribou DAQ records timestamp of shutter open and close
- CLICpix2 TOA relative to falling shutter ⇒ 10 ns hit time binning
- Analysis builds telescope events, attach the corresponding CLICpix2 frame ⇒ Each frame is used in several telescope events

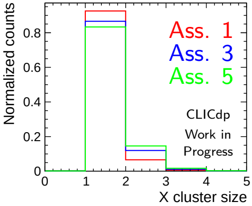


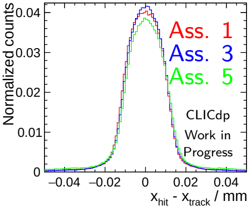


CLICpix2/C3PD: Signal, Cluster size and Resolution

- Preliminary results show difference in cluster signals and sizes, as expected from varying glue assembly quality
- CLICpix2 threshold set to $\sim 850\,e-$
- Most dominantly single-pixel hits, limiting factor for spatial resolution
- $8.5\,\mu m$ to $9\,\mu m$ residual RMS

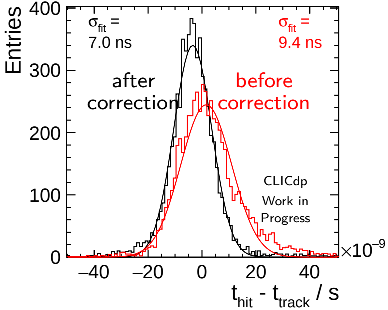


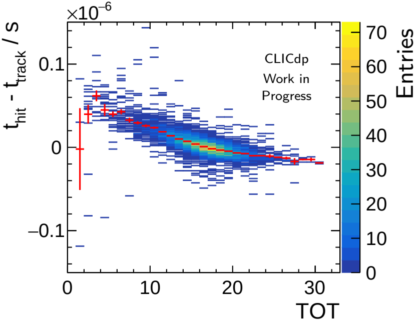




CLICpix2/C3PD: Timing measurement

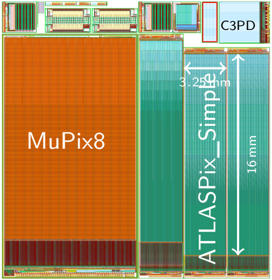
- 5bit TOA counter, 10 ns steps ⇒ shutter limited to 2.5 μs
- Plot time difference between reconstructed hit and track
- TOT information can be used to correct for time walk effect
- Gauss-Fit: σ =7 ns after time walk correction

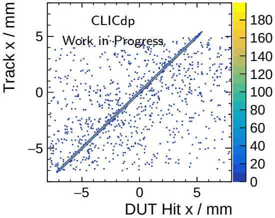




ATLASPix_simple - monolithic HV-CMOS

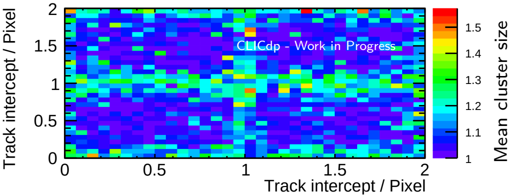
- Common MuPix8/ATLASPix submission
- Monolithic chips, 180 nm HV-CMOS process, 80 Ω cm
- 25 × 400 pixels, 130 µm × 40 µm pixel size
- ATLASPix_Simple pixel geometry close to the CLIC tracker requirements
- We tested one chip in Timepix3 based telescope in collaboration with Atlas
- Data driven, zero suppressed measurement of hit energy and arrival time
- DUT readout system counts 40 MHz clock and gets T_0 reset signal from telescope
  $\Rightarrow$ Telescope and DUT DAQ assign hit timestamps wrt. to the same clock
  $\Rightarrow$ synchronization

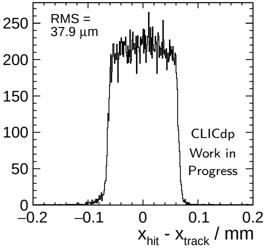


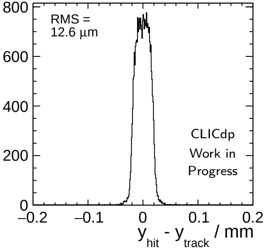


ATLASPix_simple - results

- Almost no charge sharing, residual plots resemble the pixel size
- Spatial resolution independent of threshold, dominated by single pixel clusters and pixel geometry
- Chip fully efficient at low threshold $\leq 1000\,e^{-}$, efficiency reduced for higher thresholds







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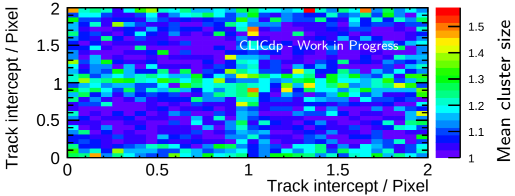
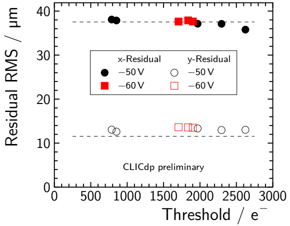
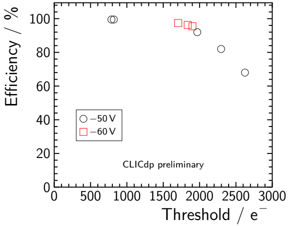
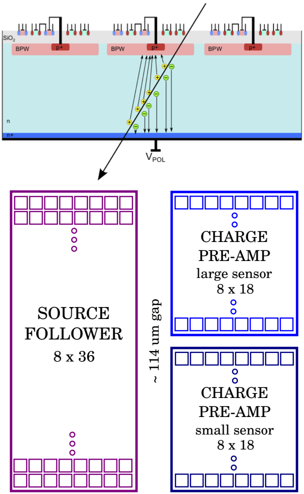






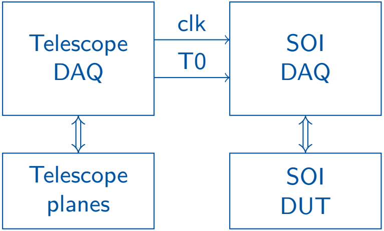
Silicon-On-Insulator chip in Lapis 200 nm SOI

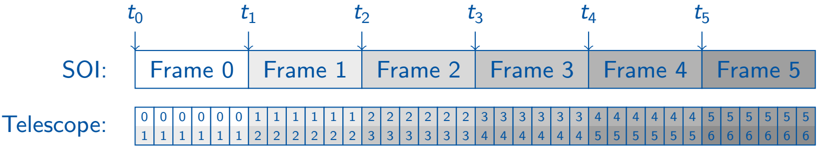
- CMOS sensor on Silicon-On-Insulator (SOI) wafers
- Electronics on low resistivity wafer, separated by buried oxide from fully depleted high-resistivity sensing layer
- Technology allows to fabricate thin sensors - down to 50 µm
- Double-SOI structure to mitigate charge-up effects under study, as well
- Different readout techniques (source follower, charge preamp., . . .) under study, 30 x 30 µm^2 pixels



SOI chip: Telescope integration

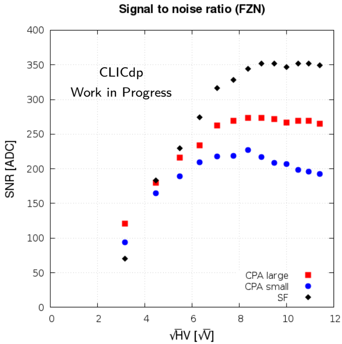
- Source follower matrix investigated in testbeam, rolling shutter readout, 150 μs integration time
- SOI DAQ takes clock and T0, marks begin of readout frame
- Hit can end up in the current or the next frame, depending on its position relative to the rolling shutter
- Analysis copies two frames overlaid into each telescope event

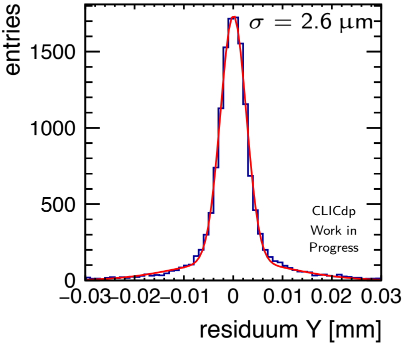




SOI - results

- FZ-n sensor
- 500 µm thick, high signal to noise ratio
- < 3 µm resolution on source-follower matrix with 500 µm thick FZ-n sensor achieved in test beam
- Fitted function is a sum of two gaussians, quote central part as resolution



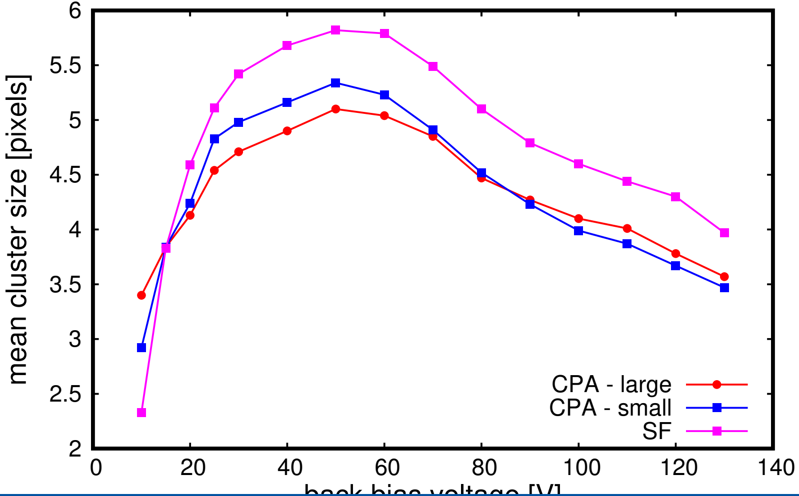


Summary

- Very successful beam tests in the SPS H6 beam line, stable and smooth operation of Timepix3 telescope.
- Performance validation using Geant4 based Monte-Carlo simulations (Allpix, Allpix-squared).
- Tested several new prototype pixel chips with different readout schemes:
  - CLICpix2 + C3PD capacitively coupled detector
  - Improved SOI prototype
  - ALICE investigator, HR-CMOS analog test chip
  - ATLASPix_Simple, fully integrated HV-CMOS
- Collaborative development together with Atlas towards new Caribou readout system. Has been used for CLICpix2 readout in the Timepix3 telescope, integration of ATLASPix progressing.
- Dense program for coming year
  - CLICpix2 bump bonded to planar sensors
  - New SOI prototype with snapshot readout
  - Monolithic CLICTD prototype for the CLIC tracker
  - Enhanced lateral drift (ELAD) sensors
  - ...

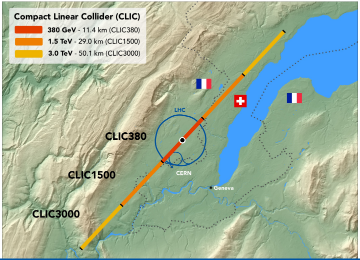
Backup

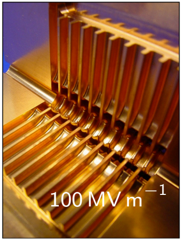
SOI: Cluster size



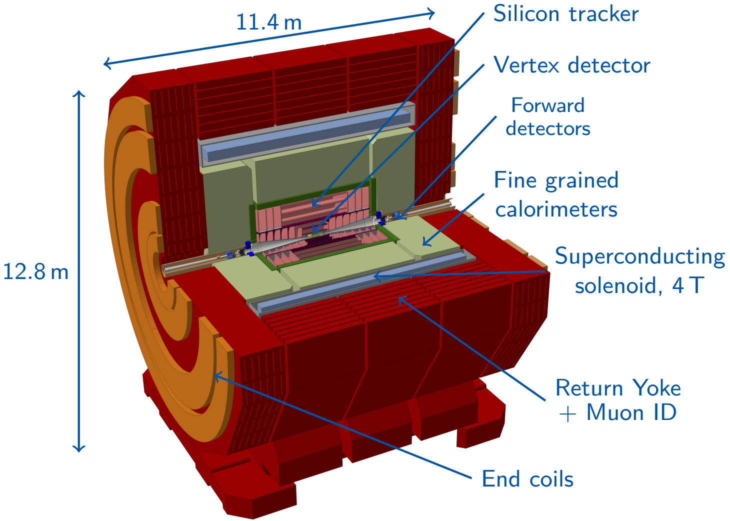
CLIC

- CLIC (Compact Linear Collider): linear e^+e^- collider proposed for the post HL-LHC phase
- Energy range from a few hundred GeV up to 3 TeV, staged construction
- Physics goals:
  - Precision measurements of SM processes (Higgs, top)
  - Precision measurements of new physics potentially discovered at 14 TeV LHC
  - Search for new physics: unique sensitivity to particles with electroweak charge

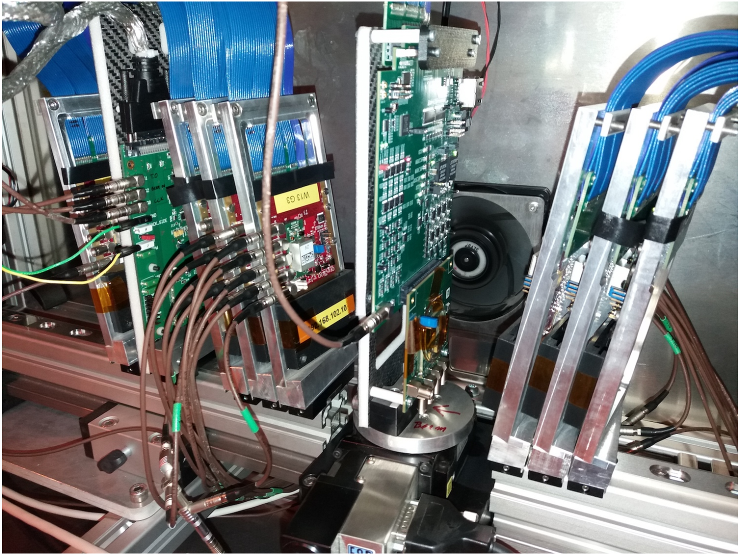




CLIC detector model



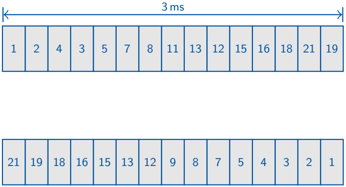
2 DUTs in parallel to maximize beam usage



Event building

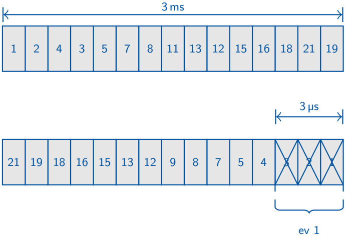
- Read 3 ms of hits from raw-file, no strict time ordering, fill vector

Event building



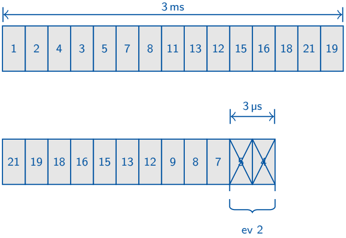
- Read 3 ms of hits from raw-file, no strict time ordering, fill vector
- Sort hits according to timestamp, descending

Event building



- Read 3 ms of hits from raw-file, no strict time ordering, fill vector
- Sort hits according to timestamp, descending
- Create 1st event, fixed size in time (3 μs), iterate from end of vector

Event building



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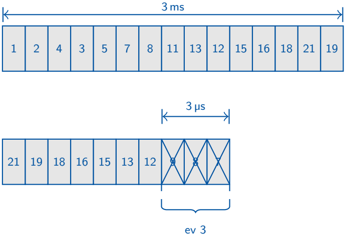
- Create 1st event, fixed size in time (3 μs), iterate from end of vector
- Create 2nd event

Event building



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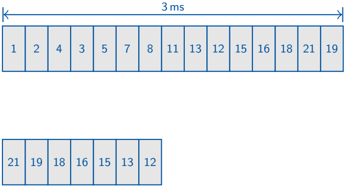
- Create 3rd event

Event building



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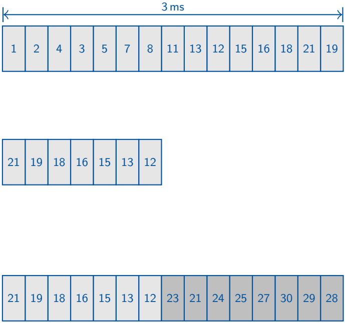
- Sort hits according to timestamp, descending
- Create 1st event, fixed size in time (3 μs), iterate from end of vector
- Create 2nd event
- Create 3rd event
- Buffer is almost empty

Event building



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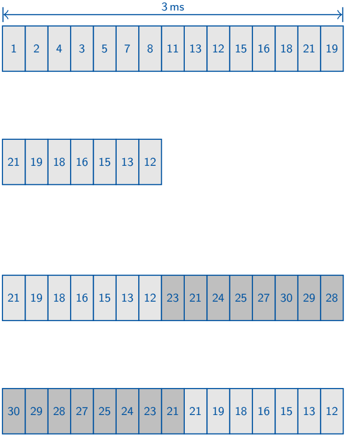
- Sort hits according to timestamp, descending
- Create 1st event, fixed size in time (3 μs), iterate from end of vector
- Create 2nd event
- Create 3rd event
- Buffer is almost empty
- Refill with next hits from raw-file, until buffer holds 3 ms of data

Event building



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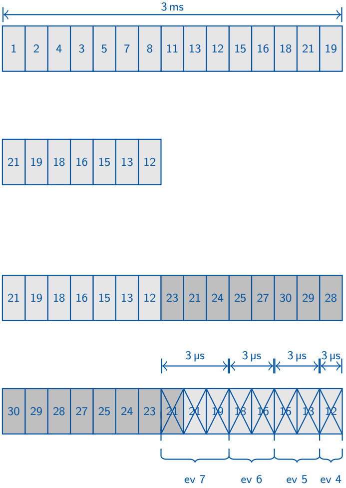
- Sort in time

Event building



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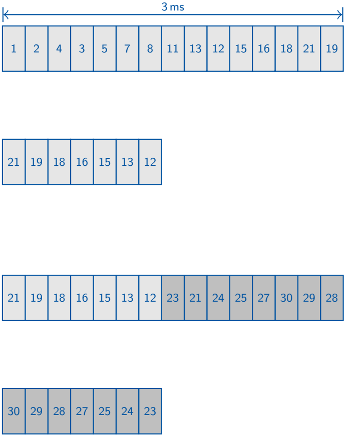
- Sort hits according to timestamp, descending
- Create 1st event, fixed size in time (3 µs), iterate from end of vector
- Create 2nd event
- Create 3rd event
- Buffer is almost empty
- Refill with next hits from raw-file, until buffer holds 3 ms of data
- Sort in time
- Build next events

Event building



- Read 3 ms of hits from raw-file, no strict time ordering, fill vector
- Sort hits according to timestamp, descending
- Create 1st event, fixed size in time (3 μs), iterate from end of vector
- Create 2nd event
- Create 3rd event
- Buffer is almost empty
- Refill with next hits from raw-file, until buffer holds 3 ms of data
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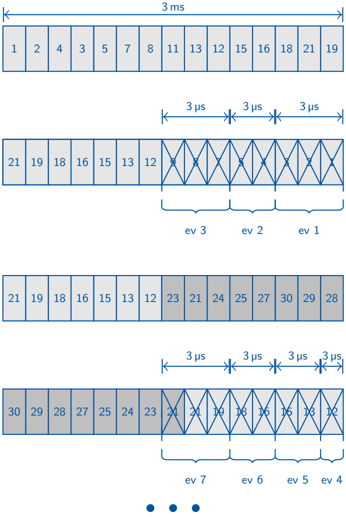
Event building



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- Sort in time
- Build next events
- Continue until end of file