A vertex and tracking detector system for CLIC

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on behalf of the CLICdp collaboration

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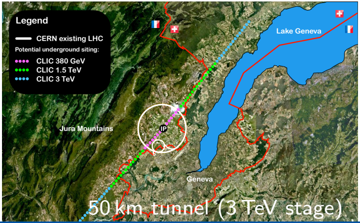
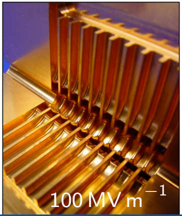
CLIC

- 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

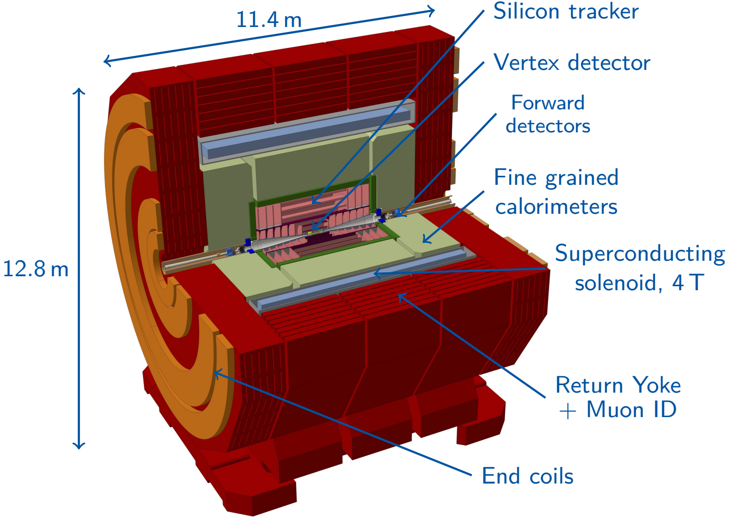
Possible layout near Geneva



CLIC accelerating structure



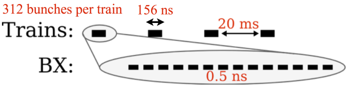
CLIC detector model



Detector requirements and experimental conditions

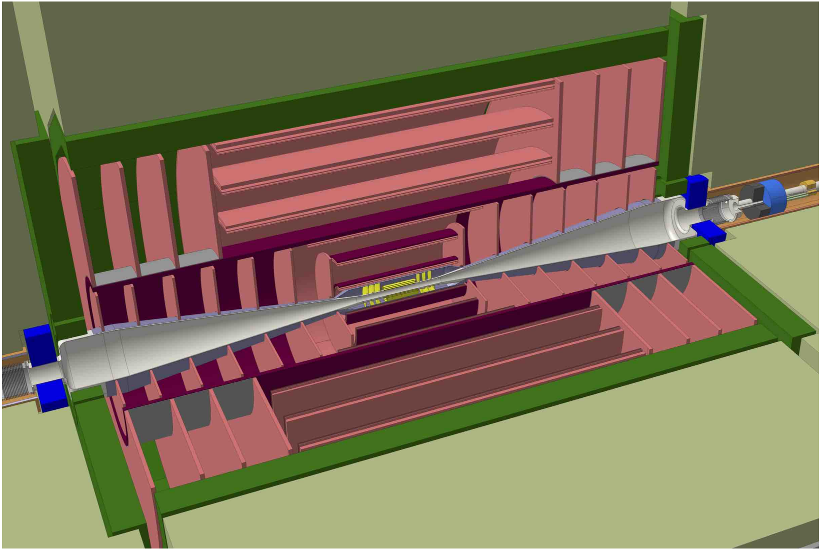
- Impact parameter resolution, $\sigma_{r\varphi} = 5 \oplus 15/(p[\mathrm{GeV}] \sin^{\frac{3}{2}} \theta)\mu\mathrm{m}$
- Momentum resolution, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$
- Jet-energy resolution $\frac{\sigma_E}{E} \sim 3.5\,\% - 5\,\%$
- No trigger, full readout of 156 ns bunch train
- Beam induced backgrounds:
  - High rate: 3 $\gamma\gamma \to$ hadron events per bunch crossing at 3 TeV
  - Requires high readout granularity
  - Requires precise timing ≤ 10 ns
- Moderate radiation environment:
  - 10^{-4} LHC levels

	3 TeV CLIC
Luminosity	$6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Bunch separation	0.5 ns
Buches / train	312
Train duration	156 ns
Repetition rate	50 Hz
Duty cycle	$\sim 10^{-5}$
Beam size σ_x / σ_y	45 nm $\times$ 1 nm
Beam size σ_z	44 μm



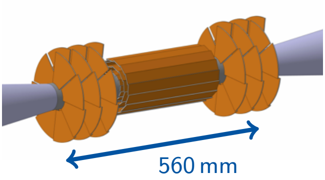
More information on experimental conditions and detector challenges → Talk by E. Sicking on Monday

Vertex and Tracking region



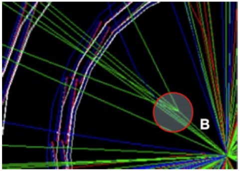
Vertex detector

Goal: efficient tagging of heavy quarks through a precise determination of displaced vertices



Multi-layer barrel and endcap pixel detectors

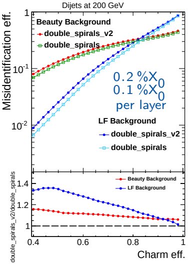
- 560 mm in length
- Barrel radius from 30 mm – 70 mm
- Spiral endcap geometry

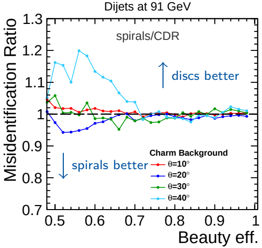


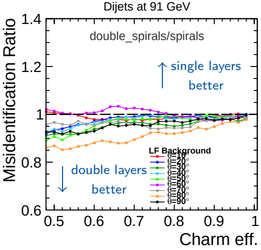
- 3 μm single point resolution
- Material budget $< 0.2\,\%X_0$ per layer (50 μm silicon sensor + 50 μm ROC)
- No liquid cooling, use forced air flow cooling
- Limit the power dissipation to $50\,\mathrm{mW\,cm^{-2}}$, pulsed power operation
- Hit time slicing of 10 ns

Vertex detector optimization - flavour tagging

- Use b- and c-tagging performance as benchmark for detector design
- Full simulation study (multivariate analysis), implementations following engineering studies:
  - Geometry with x2 in material budget → 5 %-35 % degradation
  - Spiral endcap geometry → Few regions with reduced coverage, otherwise similar performance
  - 3 double layers vs. 5 single layers → small improvement for low-energy jets (less material per layer)

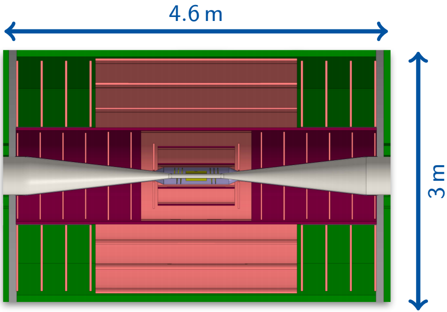


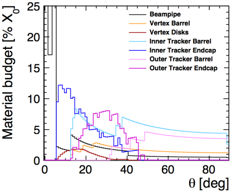


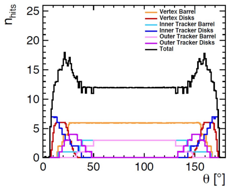


Silicon tracker

- Radius ~ 1.5 m, half-length ~ 2.3 m
- 6 barrel layers, 7 inner + 4 outer endcap discs
- Radius of beam-pipe support tube increased to maximize forward acceptance
- 7 µm single point resolution
- 10 ns timestamping
- Very light, $1\,\%X_0 - 1.5\,\%X_0$ per layer
- Liquid cooling foreseen
- Good coverage, at least 8 hits for tracks above $\theta = 8^\circ$

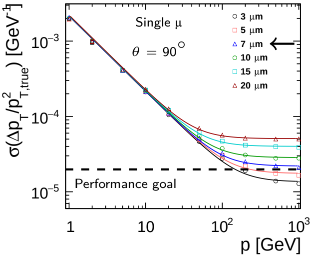


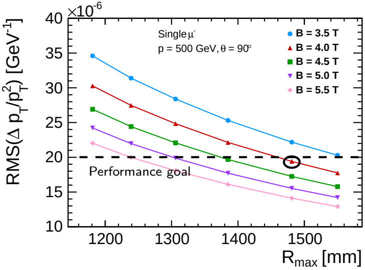


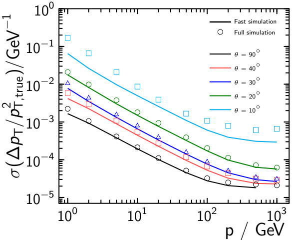


Tracker optimization

- Tracker design is outcome of optimization studies in fast and full detector simulations
- Requirement on momentum resolution for high momentum tracks lead to $B = 4\,\mathrm{T}$, $R = 1.5\,\mathrm{m}$ and single point resolution $\sigma_{r\varphi} = 7\,\mu\mathrm{m}$
- Good agreement between fast and full simulation



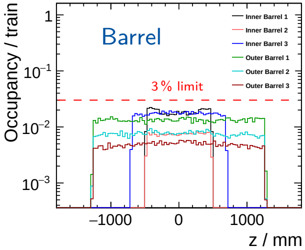


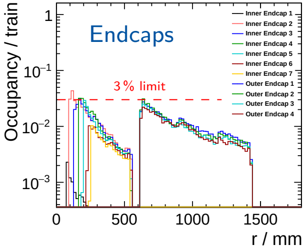


Beam induced backgrounds

- Granularity of the tracker driven by background occupancy
- Aim is to limit the occupancy to 3 % over the bunch train, need short strips/long pixels
- Full simulation study: strip length for 50 µm $r\varphi$-pitch is limited to 1 mm–10 mm
- Actual granularity will depend on the chosen technology

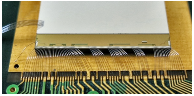
Detector layers	Strixel length / mm	Strixel width / mm
Inner barrel 1–2	1	0.05
Inner barrel 3	5	0.05
Outer barrel 1–3	10	0.05
Inner disc 1	0.025	0.025
Inner discs 2–7	1	0.05
Outer discs 1–4	10	0.05



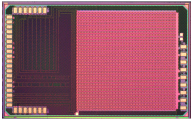


Technology R&D programme

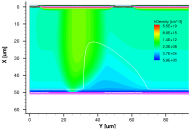
Sensors



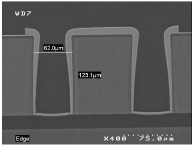
Readout ASICs



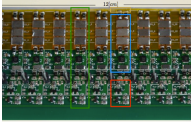
Simulations



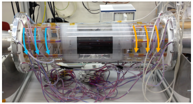
Interconnects/TSV



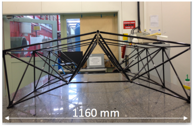
Powering



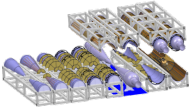
Cooling



Light-weight supports



Detector integration



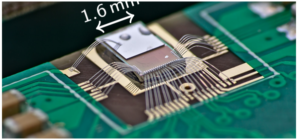
Beam tests

→ Integrated R&D effort addressing CLIC vertex and tracker detector

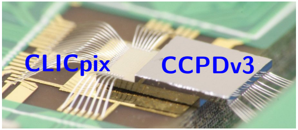
Silicon pixel detector R&D

- Different technology options to match the different detector requirements
- Characterization of prototypes in lab and testbeam studies
- 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 (→ Talk by M. Buckland on Thursday)
- Tracking detector, avoid costly bump bonding for large surface detector
  - Integrated high-resistivity CMOS (→ Talk by M. Münker on Thursday)
  - Silicon-on-insulator

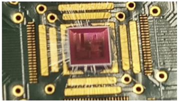
50 μm planar sensor on CLICpix ASIC



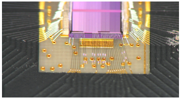
Capacitively coupled detector



SOI test chip



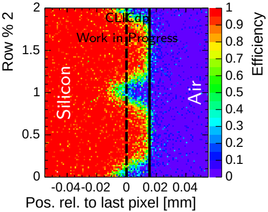
HR-CMOS test chip



Testbeam: active edge sensors

- To minimize material budget, minimize overlap of sensor tiles
- Active edge processing of planar sensor allows for seamless tiling without large impact on coverage
- Study feasibility of thin sensors with active edge using Timepix3 readout ASICs in testbeam
- In this example: grounded guard ring collects charge ⇒ lower efficiency understood using T-CAD simulations
- Other geometries, e.g. without guard ring are fully efficient to the edge

50 μm thick, GND guard ring



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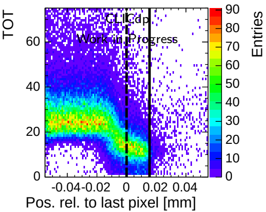
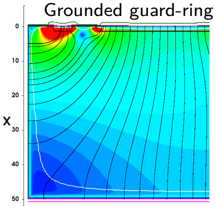


T-CAD simulation of electric field in the edge region



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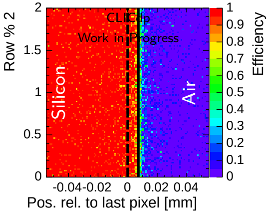

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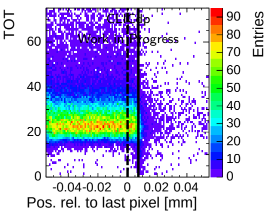

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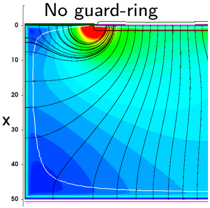
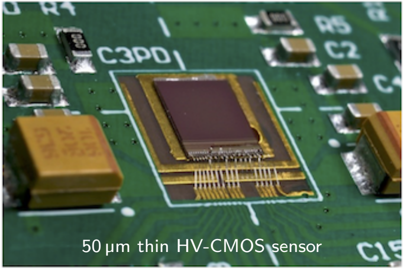
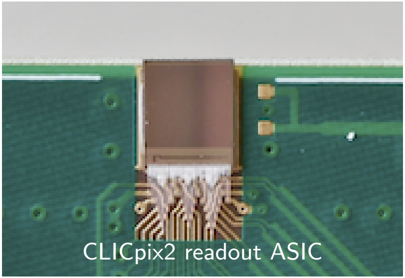


Next generation of readout chips (hybrid)

- Bigger and improved CLICpix2 readout ASIC (128 × 128 matrix) and matching HV-CMOS sensor for the CLIC vertex detector produced
- Keep 25 μm pixel size
- Standalone characterizations show expected performance
- Capacitively coupled detector assemblies to be tested in particle beam
- Generic CaRIBOu readout system under development → Talks by A. Fiergolski on Tuesday, H. Liu on Thursday

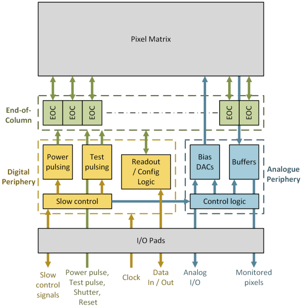


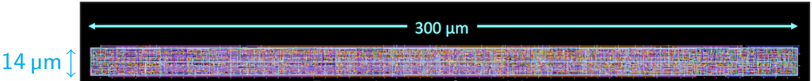
50 μm thin HV-CMOS sensor


CLICpix2 readout ASIC

Next generation of readout chips (monolithic)

- Design of fully integrated HR-CMOS chip with elongated pixels for the CLIC tracker started recently (CLICTD: CLIC Tracker Detector)
- 30 μm × 300 μm pixel
- To maintain high efficiency, fast timing and low capacitance, form pixel out of 30 μm × 30 μm sub-pixels
- To maintain energy information, current summing in analog front-end
- Testbeam studies of Investigator pixel test chip in the same technology → Talk by M. Münker on Thursday



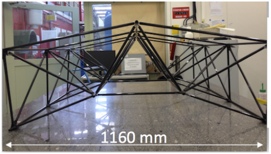


Digital part of pixel layout

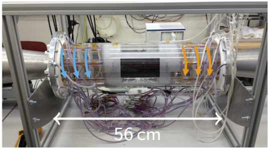
Mechanics and cooling

- Challenging layout and requirements for the vertex and tracker detectors:
  - Air cooling of the vertex detector (thermal gradients, vibrations,. . .)
  - Low material budget per layer
  - Large tracker outer barrel
- Work is focused on conceptual design and validation through FEA simulations and prototypes of critical components

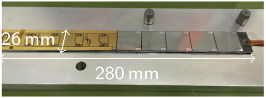
Full scale sector of outer tracker barrel stucture



Full scale vertex detector mockup for air-flow cooling tests



Vertex barrel stave (thermal dummy)



- FEA calculations and prototypes have shown that the proposed concepts are feasible

Summary

- Physics aims at the proposed future CLIC high energy linear e^+e^- collider pose challenging demands on the detector system
- New CLIC detector model CLICdet defined
- Low mass, high precision vertex and tracking detector system
- Integrated R&D program addressing the challenges is progressing in the areas of ultra-thin sensors and readout ASICs, interconnect technology, mechanical integration and cooling
- Ongoing studies on prototype silicon pixel detectors and thermo-mechanical demonstrators show the feasibility of the proposed vertex and tracker detector concept

Backup

CLIC detector and physics collaboration

- CLICdp collaboration addresses detector and physics issues for CLIC
- CERN acts as host laboratory
- Currently 29 institutes from 18 countries, $\sim$ 150 members

Timeline

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

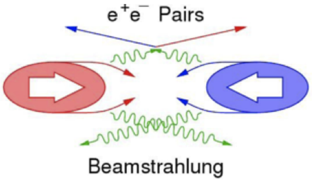
Ready for construction; start of excavations

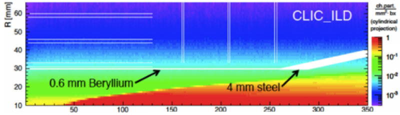
2035 First Beams

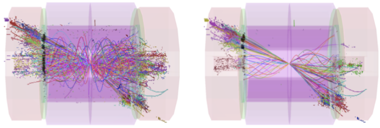
Getting ready for data taking by the time the LHC programme reaches completion

Beam induced backgrounds

- Dense bunches, high energy, small transverse size leads to very high E-field, resulting in beamstrahlung
- Consequences:
  - beam-induced backgrounds: incoherent pairs, $\gamma\gamma \rightarrow$ hadron events
  - high occupancies drive small pixel/strip size for tracking
  - also geometric requirements on vertex detector inner radius
  - background energy deposits drive small cell size for calorimetry
  - high precision timing

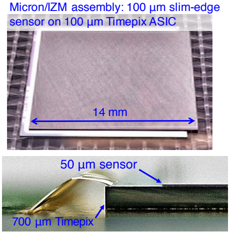




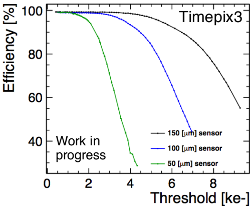


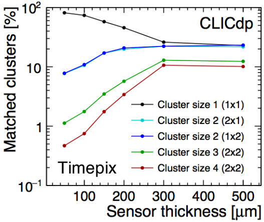
No bkg suppression After bkg suppression

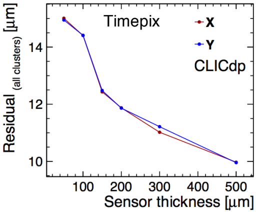
Thin sensor test beam results



- Test beam studies on sensor assemblies with different thickness (Micron, Advacam) using Timepix(3) readout ASICs, 55 µm pitch
- Thinnest assembly: 100 µm sensor on 100 µm Timepix ASIC
- Study performance of thin planar sensors
  - High detection efficiency even for 50 µm thin sensor under normal operating conditions
  - Resolution limited by cluster size in thin sensors

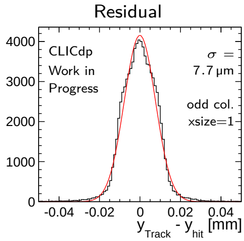


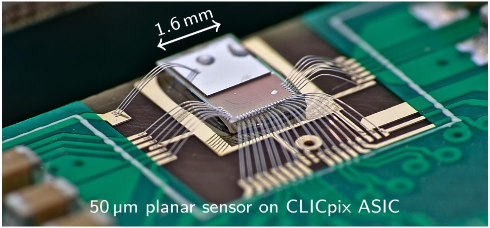


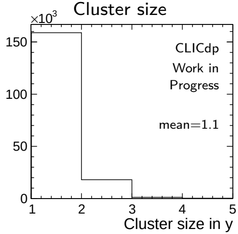


CLICpix hybrid sensor assemblies

- Demonstrator chip with 64x64 pixels
- 25 µm pixel size
- Single-chip Indium bump-bonding process for 25 µm pitch developed at SLAC
- Assemblies with 200 µm, 150 µm and 50 µm n-in-p sensors



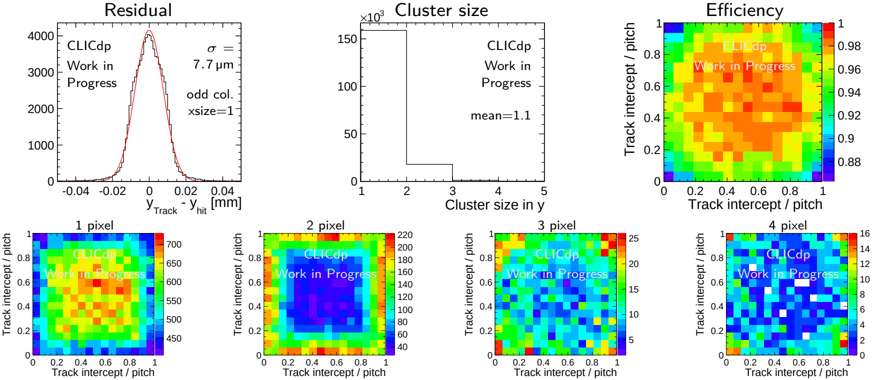




Resolution limited by single pixel clusters

CLICpix with thin planar sensor: Analysis results

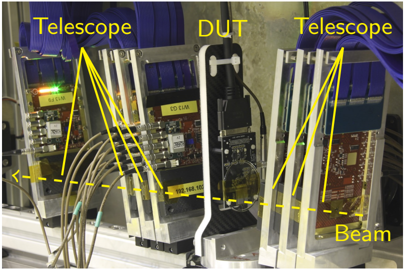
- 5V bias, $\sim 1300\,e^-$ (lowest possible threshold for this assembly)



- DUT performance as expected from 50 μm thin sensor at this threshold
- Telescope pointing resolution of ~ 2 μm allows for in-pixel studies even with 25 μm small pixels

Test beam

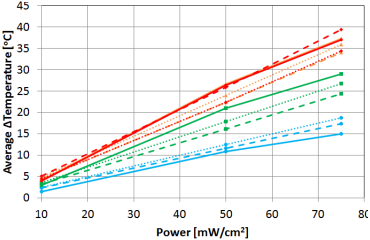
- 7 planes of Timepix3 assemblies (300 μm thick, 55 μm pitch, p-in-n sensors) for reference tracking
- Spatial resolution: $\sim 2\,\mu m$ on DUT
- Timing resolution: $\lesssim 1$ ns on DUT, each pixel hit is time tagged with 1.56 ns clock
- Rate: $\sim 1 \times 10^6$ Tracks/s



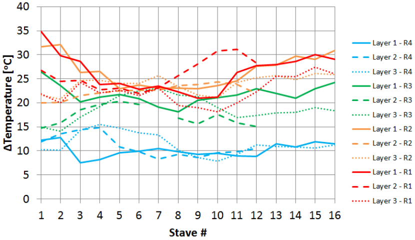
Thermal studies

1:1 scale mock-up

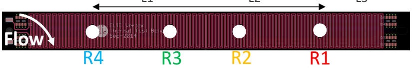
Temperature vs. Power (for 17 l/s)

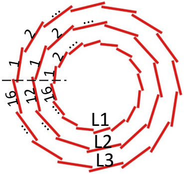


Temperature distribution along φ



@ 50 mW/cm^2: $\Delta T_{L1} \approx 15$ °C; $\Delta T_{L2} \approx 14$ °C; $\Delta T_{L3} \approx 10$ °C



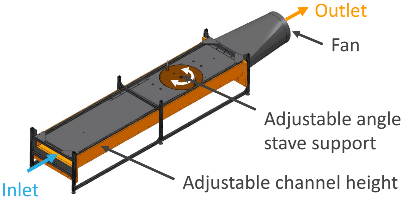


Layer 1

Layer 2

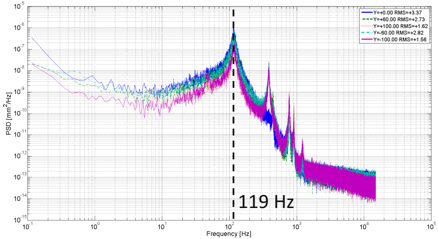
Layer 3

Vibration studies



At 5m/s, the out-of-plane vibrations are below 2.5 µm (3.5 µm @ 7.5 m/s)

PSD (simply-supported)



Amplitude (RMS)