Silicon Pixel R&D for CLIC

38th International Conference on High Energy Physics (ICHEP 2016)

August 3-10, 2016
Chicago

Dominik Dannheim (CERN)
on behalf of the CLIC detector and physics (CLICdp) collaboration
Outline

• CLIC vertex- and tracking detector requirements
• Hybrid pixel-detector assemblies with:
  • thin planar sensors
  • small-pitch planar sensors
  • small-pitch active sensors
  • Integrated CMOS pixel sensors
• Summary / Conclusions
CLIC

• **CLIC (Compact Linear Collider):** linear e^+e^- collider concept for post HL-LHC phase
• \( \sqrt{s} \) from few hundred GeV up to 3 TeV (two-beam acceleration with \( \sim 100 \text{ MV/m} \))
• 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 staged CLIC implementation near CERN

![CLIC accelerating structure](image)

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CLIC vertex-detector and tracker requirements

Vertex detector:
- **efficient tagging of heavy quarks** through precise determination of displaced vertices:
  - **good single point resolution**: $\sigma_{SP} \sim 3 \mu m$
  - small pixels $< \sim 25 \times 25 \mu m^2$, analog readout
  - **low material budget**: $X \lesssim 0.2\% X_0$ / layer
  - low-power ASICs ($\sim 50$ mW/cm$^2$) + gas-flow cooling

Tracker:
- Good momentum resolution: $\sigma(p_T) / p_T^2 \sim 2 \times 10^{-5}$ GeV$^{-1}$
  - $7 \mu m$ single-point resolution ($\lesssim 50 \mu m$ pitch)
  - many layers, large outer radius ($\sim 90 m^2$ surface)
  - $\sim 1$-2% $X_0$ per layer
  - low-mass supports + services

Both:
- **20 ms gaps** between bunch trains
  - trigger-less readout, pulsed powering
- **few % maximum occupancy** from beam backgrounds
  - sets inner radius and limits cell sizes
  - time stamping with $\sim 10$ ns accuracy
  - depleted sensors (high resistivity / high voltage)
- **moderate radiation exposure** ($\sim 10^4$ below LHC!):
  - NIEL: $< 10^{11} n_{eq}/cm^2/y$
  - TID: $< 1$ kGy / year

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Vertex and tracker technology R&D

- Sensors
- Readout ASICs
- Simulations
- Interconnects
- Powering
- Cooling
- Light-weight supports
- Detector integration + assembly

• Integrated R&D effort, simultaneously addressing CLIC vertex+tracking detector challenges
• Examples of recent developments on the following slides (focus on sensors & readout)

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Test-beam data taking

EUDET/AIDA telescopes:
- Used for initial test-beam studies at DESY II, CERN PS and CERN SPS
- Rolling-shutter r/o over $\sim230 \, \mu s$
  $\Rightarrow$ limited rate and timing capabilities
- Pointing resolution at DUT $\sim1.6$-$3 \, \mu m$

CERN-LCD Timepix3 telescope:
- Permanent installation at CERN SPS H6B
- Movement and rotation stages for automatic scans
- High rate: up to 10M particles / s
- Track timing with $<2 \, \text{ns}$ accuracy
- Track pointing resolution at DUT $\sim2 \, \mu m$

CERN-LCD Timepix3 telescope in SPS H6B
Thin sensor test-beam results

- Test-beam measurements of Timepix/Timepix3 assemblies (Micron, Advacam) with different sensor thicknesses, 55 μm pixel pitch
- Goal: test feasibility of ultra-thin sensors with minimized inactive regions
- High detection efficiency (>99%) under normal operating conditions, even for 50 μm sensors
- Resolution limited by single-pixel clusters → worse resolution for thinner sensors

**Detection Efficiency**

**Cluster size**

**Resolution**

CLICdp work in progress
Active edge sensors

- Deep Reactive Ion Etching (DRIE) process:
  - Implantation on the sensor sidewalls: extension of the backside electrode to the edge
  - Efficiency extends to the physical edge → allows for seamless tiling of sensors
- Comparing different edge layouts:
  w/o guard ring (GR), floating GR and grounded GR → signal loss to GR for very thin sensors, in agreement with TCAD simulations

TCAD simulation of E-field in n-in-p active-edge sensor

Edge efficiency (no GR)
work in progress
50 µm n-in-p active-edge, no GR

guard ring, gnd
active edge

Edge efficiency (GR gnd)
work in progress
50 µm n-in-p active-edge, grounded GR

Signal at edge (GR gnd)
work in progress
Hybrid r/o technology: CLICpix

- 65 nm CMOS hybrid r/o chip, targeted to CLIC vertex detectors
- based on Timepix/Medipix chip family,
- demonstrator chip: 64 x 64 pixel matrix
- 25 μm pixel pitch
- simultaneous 4-bit time (ToA) and energy (ToT) measurement per pixel
- front-end time slicing < 10 ns
- selectable compression logic: pixel, cluster + column-based
- full chip r/o in less than 800 μs (at 10% occup., 320 MHz r/o clock)
- power pulsing scheme
  → $P_{\text{avg}} < 50$ mW/cm$^2$
- lab measurements
  → performance in agreement with simulations
- test assemblies with planar and active HV-CMOS sensors

New version CLICpix2:
- 128x128 pixels
- 5 bit ToT, 8 bit ToA
- Improved I/O
- design currently under validation (UVM)
- to be submitted in coming weeks

CLICpix

CLICpix2
CLICpix planar sensor assemblies

- Single-chip bump-bonding process for 25 μm pitch developed at SLAC (C. Kenney, A. Tomada)
- Results for 3 test assemblies with 200 μm Micron sensors:
  - 0.2-3% unconnected channels
  - 1-2% shorted channels
  - Test-beam measurements:
    - Operation threshold ~1000 e⁻, $V_{dep}$~35 V
    - High detection efficiency (>99.5%)
    - ~20% single-pixel clusters at $V_{dep}$
    - ~4 μm single-point resolution
- Validation of assembly with 50 μm Advacam active-edge sensor ongoing

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HV-CMOS active sensor with capacitive coupling

**Capacitive Coupled Pixel Detector (CCPD)**
- Prototype for ATLAS (FEI4) and CLIC: **CCPDv3**
- Commercial 180 nm High-Voltage-CMOS process
- $V_{\text{bias}} \sim 30-90$ V $\rightarrow$ depletion layer $\sim 10-20$ μm
- 2-stage amplifier, capacitive coupling to readout ASIC through thin glue layer (few μm)
- Includes 64x64 matrix (25 μm pitch)
- glue assemblies with CLICpix readout chips $\rightarrow$ lab and test-beam results (next slide)
- new improved chip version **C3PD** matching CLICpix2 $\rightarrow$ chip functional, lab tests ongoing
CLICpix+CCPDv3 test-beam results

CERN SPS test beam with AIDA telescope:
• High detection efficiency, even without bias (diffusion)
• Measured mean charge (ToT) varies across matrix → non-uniformity of glue thickness, observed in early assemblies produced without control of planarity
• ~6 μm single-point resolution

Detection efficiency vs. bias

Detection efficiency vs. threshold

ToT uniformity

CLICdp-Pub-2015-003
August 4, 2016

Nucl. Instrum. Meth. A823 (2016) 1

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HV-CMOS TCAD simulation

- Implemented CCPDv3 pixel layout in TCAD
- 2-D and 3-D transient simulation for MIPs at different positions within pixel → input for ASIC simulation
- Measured leakage current breakdown of ~90 V well reproduced
- Fast rise of collected charge within ~ns (drift in depleted volume)
- Increasing pulse height over hundreds of ns (diffusion in bulk)

Leakage current simulation

<table>
<thead>
<tr>
<th>Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Ωcm</td>
</tr>
<tr>
<td>80 Ωcm</td>
</tr>
<tr>
<td>200 Ωcm</td>
</tr>
<tr>
<td>1000 Ωcm</td>
</tr>
</tbody>
</table>

Bias voltage [-V]

Collecting Charge [e-]

Time [μs]

MIP response in CCPDv3

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CLICdp

CLICdp

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Integrated CMOS technologies for tracker

TowerJazz 180 nm High-Resistivity CMOS:
• Quadruple well process with full CMOS: n-wells shielded by deep p-wells
• 15-40 μm / 1-8 kΩcm epitaxial layer, not fully depleted (Vbias ≲ 6 V)
• ALICE Investigator analog test chip
• Pixel sizes: 20x20 to 50x50 μm²
• Optimization of collection-diode geometry to minimize capacitance (∼2 fF)
• Readout with external sampling ADCs
• Integration in CLIC test-beam setup → good time resolution obtained (few ns)

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
• Test-chip from AGH Cracow:
  • Different pixel sizes (≥ 30 x 30 μm²)
  • Targeted towards CLIC requirements (position, amplitude and few ns timing)
  • Integration in CLIC test-beam setup → chip functional, data taking and analysis ongoing
Summary and Conclusions

• CLIC accelerator provides:
  • unique potential for discovery and precision physics at the TeV scale
  • challenging requirements for vertex and tracking detectors
• Ongoing integrated R&D program on CLIC vertex + tracking detectors:
  • Sensor and readout technologies for precision measurements:
    • Hybrid readout ASICs with planar sensors
    • Hybrid readout ASICs with active HV-CMOS sensors
    • Integrated CMOS sensors
  • Not shown today: powering, cooling and mechanical integration studies incorporating realistic constraints

Thanks to everyone who provided material for this talk!
CLIC detector & physics collaboration

CLICdp member institutes:

- Aarhus University
- ACAS Australia
- AGH-UST Cracow
- Argonne National Lab
- Bergen University
- Birmingham University
- Bristol University
- Cambridge University
- CERN
- DPNC Geneva
- Glasgow University
- IFJPAN Cracow
- IPASCR Czech Republic
- Institute of Space Science Bucharest
- JINR Dubna
- KIT IPE Karlsruhe
- LAPP Annecy
- Liverpool University
- Michigan University
- MPI Munich
- NC PHEP Belarus
- Oxford University
- Pontíficia Univ. Catolica de Chile
- Spanish Network for Future Linear Colliders
- Tel Aviv University
- Vinca Institute Belgrade
- University of Warsaw

- The CLICdp collaboration is addressing detector and physics issues for the future Compact Linear Collider (CLIC) http://clicdp.web.cern.ch/
- CERN acts as host laboratory
- Currently 27 institutes from 17 countries
- The CLIC accelerator R&D is being conducted in collaboration with ~48 institutes
CLIC physics program

- **CLIC (Compact Linear Collider):** linear $e^+e^-$ collider concept for post HL-LHC phase
- Staged construction: $\sqrt{s}$ from few hundred GeV up to 3 TeV
- 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

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CLIC physics reach: SM + SUSY example

**Minimal anomaly-free $Z'$ model**

$$Q_i = g_Y(Y_i) + g_{BL}(B-L)_i$$

**$Z'$ 5$\sigma$ mass discovery limit from $e^+e^- \rightarrow \mu^+\mu^-$**

*arXiv:1208.1148*

**Cross-section vs $\sqrt{s}$**

- Higgs
- $\tilde{\tau}, \tilde{\mu}, \tilde{\nu}$
- Charginos
- Squarks
- SM $t\bar{t}$
- $\tilde{\nu}_\tau, \tilde{\nu}_\mu, \tilde{\nu}_e$
- Neutralinos

*arXiv:1202.5940*
CLIC accelerator

- Linear e^+e^- collider
- 2-beam acceleration scheme, operated at room temperature
- Gradient: 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Luminosity: $6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (at 3 TeV)
- Physics + Detector studies for 350 GeV - 3 TeV

CLIC layout at 3 TeV
# Machine parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC at 14 TeV</th>
<th>CLIC at 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (cm(^{-2})s(^{-1}))</td>
<td>(1 \times 10^{34})</td>
<td>(6 \times 10^{34})</td>
</tr>
<tr>
<td>BX separation</td>
<td>25 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>#BX / train</td>
<td>N/A</td>
<td>312</td>
</tr>
<tr>
<td>Train duration</td>
<td>N/A</td>
<td>156 ns</td>
</tr>
<tr>
<td>Train repetition</td>
<td>N/A</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>(~1)</td>
<td>0.00078%</td>
</tr>
<tr>
<td>(\sigma_x / \sigma_y) [nm]</td>
<td>15000 / 15000</td>
<td>(\approx 45 / 1)</td>
</tr>
<tr>
<td>(\sigma_z) [(\mu)m]</td>
<td>(~50000)</td>
<td>44</td>
</tr>
</tbody>
</table>

Very small beam sizes at interaction point

Beams separation drives timing requirements for detectors

CLIC Not to scale!
CLIC detector concept

- low-mass **vertex detector** with ~25x25 μm² pixels
- **silicon tracker**
- fine-grained PFA calorimetry, $1 + 7.5 \Lambda_i$
  - W-ECAL + Fe-HCAL
- **4 T solenoid**
- **return yoke** with muon ID
- Complex instrumented forward region
Flavor tagging: impact on physics performance

- $e^+e^- \rightarrow H_{\nu\nu}$: dominating Higgs production process at $\sqrt{s}=3$ TeV
- $\sigma \times BR$ measurement for the decays to $bb$ and $cc$
- flavor tagging crucial for achievable precision

- $H \rightarrow bb$ and $H \rightarrow cc$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Stat. unc. on $\sigma \times BR$</th>
<th>Change for $\pm 20%$ fake r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>0.23%</td>
<td>0.24% / 0.21%</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>3.1%</td>
<td>3.6% / 2.6%</td>
</tr>
</tbody>
</table>

$\sqrt{s}=3$ TeV
$L_{\text{int}}=2$ ab$^{-1}$
$p_{T,\text{jet}} \sim 70$ GeV
$E_{\text{jet}} \sim 130$ GeV

- consider $\pm 20\%$ change in fake rates
- sizeable effect, in particular for $H \rightarrow cc$: 30% more integ. luminosity required for same precision when increasing fake rate by 20% ($>1$ year of additional running!)
## Medipix/Timepix hybrid r/o chip family

<table>
<thead>
<tr>
<th>Chip</th>
<th>Year</th>
<th>CMOS Process</th>
<th>Pitch [μm²]</th>
<th>Pixel operation modes</th>
<th>r/o mode</th>
<th>Main applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timepix</td>
<td>2006</td>
<td>250 nm</td>
<td>55x55</td>
<td>∫ToT or ToA or γ counting</td>
<td>Sequential (full frame)</td>
<td>HEP, Medical</td>
</tr>
<tr>
<td>Medipix3RX</td>
<td>2012</td>
<td>130 nm</td>
<td>55x55</td>
<td>γ counting</td>
<td>Sequential (full frame)</td>
<td>Medical</td>
</tr>
<tr>
<td>Timepix3</td>
<td>2013</td>
<td>130 nm</td>
<td>55x55</td>
<td>ToT + ToA, γ counting + ∫TOT</td>
<td>Data driven</td>
<td>HEP, Medical</td>
</tr>
<tr>
<td>CLICpix/CLICpix2</td>
<td>2013/2016</td>
<td>65 nm</td>
<td>25x25</td>
<td>ToT + ToA</td>
<td>Sequential (data compr.)</td>
<td>Test chips targeting CLIC requirements</td>
</tr>
<tr>
<td>Velopix</td>
<td>2016</td>
<td>130 nm</td>
<td>55x55</td>
<td>ToT + ToA, γ counting + ∫TOT</td>
<td>Data driven</td>
<td>LHCb (10x Timepix3 rate)</td>
</tr>
<tr>
<td>Medipix4/Timepix4</td>
<td>tbd</td>
<td>65 nm</td>
<td>~35x35</td>
<td>ToT + ToA, γ counting + ∫TOT</td>
<td>Data driven</td>
<td>HEP, Medical 4-side buttable</td>
</tr>
</tbody>
</table>

ToT: Time-over-Threshold
→ Energy
ToA: Time-of-Arrival
→ Time

- Taking advantage of smaller feature sizes:
  - Increased functionality and/or
  - Reduced pixel size
  - Improved noise performance
DATURA telescope

1-6 GeV e⁻

TLU

HV source

Temp. r/o

Timepix DAQ

Telescope planes

1-6 GeV e⁻

DATURA telescope DUT prediction resolution

- June 2013, Al box, transl. stage
- August 2013, Al box, fixed DUT
- August 2013, with rotation stage
- October 2013, with rotation stage
- January 2014, with rotation stage
Timepix calibration

- Calibration of non-linear Timepix energy response with radioactive sources + fluorescence
- Parameterization with 4 parameters; global and per-pixel
  → Improves accuracy of position determination with charge-weighting methods

\[ f(x) = ax + b - \frac{c}{x-t} \]

\[ \chi^2 / \text{ndf} = 4.585 / 13 \]
\[ p0 = 423.1 \pm 153.2 \]
\[ p1 = 11.87 \pm 2.841 \]
\[ p2 = 2533 \pm 2361 \]
\[ p3 = -2.596 \pm 4.035 \]

A06-W0110
100 μm sensor
global calibration

CERN
Target/Source | $^{55}$Fe | Brass | $^{99}$Cd | Indium | $^{241}$Am | $^{241}$Am
---|---|---|---|---|---|---
E (kα) in keV | 5.8 | 8.1 | 22.9 | 24 | 26.2 | 60

LNLS
Target | Co | Cr | Cu | Fe | Mn | Ni | Ti | V | Zn
---|---|---|---|---|---|---|---|---|---
E (kα) in keV | 4.51 | 4.95 | 5.414 | 5.89 | 6.4 | 6.93 | 7.47 | 8.04 | 8.63

M. Benoit, S. Arfaoui, D. Celeste

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# Characteristics of Medipix chips

<table>
<thead>
<tr>
<th></th>
<th>Medipix2</th>
<th>Timepix</th>
<th>Medipix3</th>
<th>Timepix3</th>
<th>Medipix4</th>
<th>Timepix4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel side (µm)</td>
<td>55</td>
<td>55</td>
<td>55/110</td>
<td>55</td>
<td>x/2x/3x</td>
<td>y</td>
</tr>
<tr>
<td>Technology (nm)</td>
<td>250</td>
<td>250</td>
<td>130</td>
<td>130</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td># pixels in x and y</td>
<td>256</td>
<td>256</td>
<td>256/128</td>
<td>256</td>
<td>512/512/128</td>
<td>512</td>
</tr>
<tr>
<td>Readout architecture</td>
<td>Frame based Sequential RW</td>
<td>Frame based Sequential RW</td>
<td>Frame based Continuous RW</td>
<td>Data driven/ frame based</td>
<td>Frame based Continuous RW</td>
<td>Data driven/ frame based</td>
</tr>
<tr>
<td>Charge summing and allocation mode (CSM)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td># thresholds</td>
<td>2 (window discriminator)</td>
<td>1</td>
<td>2/4/8 Seq RW</td>
<td>1/4 Cont RW</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>ToT/ToA</td>
<td>No</td>
<td>ToT (14 bit) OR ToA (14 bit, 10ns precision)</td>
<td>No</td>
<td>ToT (10 bit) AND ToA (14 bit, 1.56ns precision)</td>
<td>No</td>
<td>ToT AND ToA</td>
</tr>
<tr>
<td>Front end noise (e⁻ rms)</td>
<td>110</td>
<td>100</td>
<td>80(SPM) 174(CSM)</td>
<td>62</td>
<td>≤ 80 (SPM) ≤ 174 (CSM)</td>
<td>≤ 62</td>
</tr>
<tr>
<td>Peaking time (ns)</td>
<td>150</td>
<td>100</td>
<td>120</td>
<td>30</td>
<td>≤ 120</td>
<td>≤ 30</td>
</tr>
<tr>
<td>Max count rate (Mc/mm²/s)*</td>
<td>826</td>
<td>-</td>
<td>826 (SPM 55µm) 164 (CSM 55µm) 376 (SPM 110µm) 28 (CSM 110µm)</td>
<td>0.43 (data driven)</td>
<td>x5 Medipix3</td>
<td>x10 Timepix3</td>
</tr>
<tr>
<td>Number of sides available for tiling</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

*Depends strongly on exact conditions of threshold, sensor material and energy of illumination
Brown indicates parameters which are still to be defined

M. Campbell
October 15, 2015
• The analog front-end shapes photocurrent pulses and compares them to a fixed (configurable) threshold
• Selectable polarity (positive / negative signals)
• Digital circuits simultaneously measure Time-over-Threshold and Time-of-Arrival of events and allow for zero-compressed readout
CLICpix analog frontend

Krummenacher network

CSA preamplifier

Calibration DAC

Digital part

Discriminator
Pixel logic block diagram

End of column block diagram
CLICpix: time and energy measurement

**Time Measurement:**
- **Baseline:** The baseline is the initial voltage level before any signal.
- **Time of Arrival (TOA):** The time it takes for a particle to reach the detector, measured from the moment the shutter is closed.

**Energy Measurement:**
- **Threshold:** The voltage level above which an event is considered to have occurred.
- **Time Over Threshold (TOT):** The time duration for which the voltage exceeds the threshold level.

Configuration data:
- Threshold
- \( V_{test\_pulse} \)
- Clock
- \( V_{test\_pulse} \)
- \( V_{test\_pulse} \)
- \( V_{test\_pulse} \)

**Diagram Notes:**
- The diagram illustrates the process of measuring time and energy with a focus on the relationship between voltage (V) and time.
- The use of a CSA (Current-Sensitive Amplifier) and a 4-bit Th.Adj DAC for amplifying and adjusting the threshold voltage.
- A feedback network is used to maintain stability in the measurement process.

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CLICpix: energy measurement

- Measure charge released in each pixel
  → Improve position resolution through interpolation

- Time-Over-Threshold (TOT) measurement (4-bit precision)

- Calibration measurement using external test pulser:
Calibrated spread across the whole matrix is 0.89 mV RMS (~22 e⁻)
For comparison: MIP signal in 50 μm silicon ~3700 e⁻
CLICpix: uniformity of gain and noise

- Uniform gain across the matrix
- Gain variation \( \sim 4.2\% \) r.m.s.
  (for nominal feedback current)

- Uniform ENC across the matrix
- Mean ENC: 55 e\(^-\), SD: 5.7 e\(^-\)
  (without sensor)

S. Kulis, P. Valerio

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CLICpix: radiation qualification

- Moderate radiation-tolerance requirements at CLIC: <100 kRad TID
- However: building blocks can be re-used for RD53 (~1 GRad required)
- Results of radiation testing useful for gaining deeper understanding of the chip
→ performed radiation test up to 1 GRad (up to 150 kRad/minute) in calibrated X-ray setup

### Power consumption

![Power consumption graph](image)

- No significant changes observed in sub-MRad range relevant for CLIC
- For >250 MRad: PMOS switches in current mirror fail
→ Break-down of analog power (note: band gap foreseen for final chip, instead of current mirror)
- digital components kept working normally

S. Kulis, P. Valerio

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### CLICpix: summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Simulation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time</td>
<td>[ns]</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>TOA accuracy</td>
<td>[ns]</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Gain</td>
<td>[mV/ke⁻]</td>
<td>44</td>
<td>40 (*)</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>[ke⁻]</td>
<td>44 (configurable)</td>
<td>40 (*) (configur.)</td>
</tr>
<tr>
<td>Integr. nonlinearity (TOT)</td>
<td>[LSB]</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>ENC (w/o sensor)</td>
<td>[e⁻]</td>
<td>~60</td>
<td>~55 (*)</td>
</tr>
<tr>
<td>DC spread σ (uncalibrated)</td>
<td>[e⁻]</td>
<td>160</td>
<td>128 (*)</td>
</tr>
<tr>
<td>DC spread σ (calibrated)</td>
<td>[e⁻]</td>
<td>24</td>
<td>22 (*)</td>
</tr>
<tr>
<td>Power consumption</td>
<td>[μW/pixel]</td>
<td>6.5</td>
<td>7</td>
</tr>
</tbody>
</table>

* results obtained with electrical test pulses

- good agreement between simulations and measurements
- power pulsing works according to specifications (~100x reduction of average power)
- programmable power on/off times, front-end wake up within ~15 μs
- Radiation test: chip functional up to ~250 MRad

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August 4, 2016

Silicon Pixel R&D for CLIC
CLICpix+HV-CMOS glue assemblies

- Study of **glue parameters**:
  - Viscosity
  - Bonding force
  - Alignment
  - Glue-layer uniformity

- Cross sections of glue assemblies
  - **alignment** precision $\sim 1 \ \mu m$
  - glue-layer **thickness** $\sim 0.5 \ \mu m$ (+2 $\mu m$ polyimide passivation)

- Laboratory and test-beam measurements
  - **correlate** performance with glue parameters (coupling strength, uniformity)

**SEM picture CCPDv3-CLICpix assembly**

- **viscosity**: 450 Pas, $F=5 \ N$, $T=100 \ ^\circ C$, $t=10 \ min$
- **pad alignment**: centered alignment, $\frac{1}{2}$ pixel offset
Simulation of capacitive coupling

- COMSOL multi-physics simulation of capacitance between sensor and r/o ASIC
- Detailed model of the major metal and passivation layers and the glue in 3x3 matrix
- Obtain coupling capacitance (~3 fF) and cross capacitances
- Significant cross coupling (~4%) to neighboring pads for current CCPDv3 version
- Cross coupling largely reduced for newly designed C3PD active sensor with guard ring
CLICpix+HV-CMOS calibration

• Dedicated test pixels: direct access to CCPDv3 output signal
• Used to calibrate CLICpix ToT response
• Simulation of CLICpix ToT response for different values of coupling capacitance → estimate coupling capacitance by comparison of measured and simulated response: \( \sim 10 \text{ fF} \)

![Simulated CCPDv3+CLICpix response](image1.png)

![Measured CCPDv3+CLICpix response](image2.png)

\[ \text{Capacitance} \quad [10^{-15} \text{ F}] \]

CLICdp work in progress

August 4, 2016 Silicon Pixel R&D for CLIC
New HV-CMOS active sensor

- New HV-CMOS chip C3PD produced in same process:
  - Increased matrix size to $128 \times 128$ pixels
  - Major redesign of the full chip:
    - On-pixel amplification scheme significantly changed
      → reduced peaking time to some $\sim 10$ ns
    - Guard ring around coupling pads
      → reduced cross capacitance
    - Power pulsing circuitry introduced
    - Testpulsing of the matrix
  - 10 $\Omega$ cm substrate
  - Possible future submissions with substrate resistivities of 100, 200, 1k $\Omega$ cm
  - Lab measurements for first chips ongoing

![C3PD simulation](image)

![Response to simulated pulse](image)
First results from ALICE Investigator

• First test-beam performance results:
  • Good time resolution \( \sim 5 \text{ ns} \)
  • Cluster size distributions and spatial resolution in agreement with expectations

• Caveats:
  • Results based on full waveform analysis of signals from external sampling ADC
  • Unknown absolute efficiency (r/o deadtime not recorded)

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**Example waveform**

- CLICdp work in progress

**Time residuals**

- Gauss fit \( \sigma = 5.9 \text{ ns} \)
  - CLICdp work in progress

**Cluster size**

- Mean cluster size in \( x \)

**Track residuals**

- 5 \( \mu \text{m} \) track res.
  - Not unfolded

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August 4, 2016

Silicon Pixel R&D for CLIC