IF03: Solid State Detectors and Tracking

Key Points

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on behalf of IF03 working group

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What is IF03?

• Past meetings/presentations available at:
  – [https://indico.fnal.gov/category/1183/](https://indico.fnal.gov/category/1183/)

• Focus on detectors and technologies needed for charged particle tracking:
  – Technologies for colliders, fixed target, or precision measurement experiments

• Trackers discussed in the context of future experimental challenges
  – Identify technological challenges and opportunities with different future accelerators
  – Moreover “blue sky” R&D is important => opportunities for future transformative breakthroughs’
Simulations of Silicon Radiation Detectors for High Energy Physics Experiments

N. Bachmann, W. B. Petritis, P. P. Parentis, A. Brandt, S. A. Wilkins, J. Zalewski

Strategies for Beam-Induced Background Reduction at Muon Counters

D. A. Y. Carpenter, T. Housman, L. L. S. P. V. W. J. A. Van Alphen

ICL-TAB: a block-based, tensor-aware, light-weight and highly thermally conductive wireless sensor

Light-weight and highly thermally conductive sensor architectures for future tunneling detectors

Executive summary

In the past years, high-energy physics experiments have been moving away from high density and complexity to more efficient and compact solutions. The move towards smaller and more efficient detector technologies has been driven by the need to reduce the cost and complexity of large-scale detector systems. This trend is heavily influenced by the desire to minimize the footprint of detector systems and to make them more cost-effective. In this context, the development of light-weight and highly thermally conductive sensor architectures has become increasingly important for future tunneling detector technologies.
4D trackers and precision timing

- Contact persons: R. Heller and A. Schwartzman
- Timing detectors critically important for designs of most future experiments:
  - Future hadron colliders, e^+e^- colliders (ILC, CLIC, C3), muon colliders, EiC, phase 4 LHC upgrades
- Requirement can be greatly different for each machine type, use case in each machine (PU, PID, BIB, etc)
  - Segmentation, timing and position resolutions
  - O(10 ps) and O(<10 μm)
4D trackers and precision timing

• Sensor technologies:
  – LGADs, AC-LGADs, LGAD optimizations (buried layer, double-sided, thin, etc), 3D sensors, MAPS (~100 ps-ns), Induced Current sensors
• Fast timing detectors require new specialized readout electronics.
  – Need R&D to achieve low power techniques and novel timing extraction architectures
• Layout optimizations
  – Examples: excellent time-and-position in all layers, vs excellent time in some and excellent position in others

<table>
<thead>
<tr>
<th>ASIC</th>
<th>Technology</th>
<th>Pitch</th>
<th>Total size</th>
<th>Power consumption</th>
<th>TID tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTIROC</td>
<td>130 nm</td>
<td>1.3 mm</td>
<td>$19.5 \times 19.5 \text{ mm}^2$</td>
<td>5 mW/chan</td>
<td>2 MGy</td>
</tr>
<tr>
<td>ETROC</td>
<td>65 nm</td>
<td>1.3 mm</td>
<td>$20.8 \times 20.8 \text{ mm}^2$</td>
<td>3 mW/chan</td>
<td>1 MGy</td>
</tr>
<tr>
<td>RD53A/HL-LHC pixels</td>
<td>65 nm</td>
<td>50 µm</td>
<td>$20 \times 11.6 \text{ mm}^2$</td>
<td>&lt; 10 µW/chan</td>
<td>5–15 MGy</td>
</tr>
</tbody>
</table>
Integration and Packaging

- Contact persons: S. Mazza, R. Lipton, R. Patti
- Current bump bonding technology is reliable but reaching its limits
  - 20-50 µm pitch, has yield, cost, material and performance limitations
- Advanced electronics and sensors packaging may provide solutions for future experiments.
  - Collaboration between research groups and industry is crucial
  - Technologies available can extend the reach/effectiveness of future detectors
    - Lower mass, finer pitch, lower noise
    - Optimize each layer: sensor, digital, analogue
- Commercial availability
  - Variants of 3D integration technology have been adopted by several foundries available to HEP
- Blue sky development required now to have the technologies ready when needed in the future
Monolithic integrated silicon detectors, CMOS (MAPs)

- Contact persons: C. Vernieri
- Challenges of the future trackers and calorimeters may be address by utilizing CMOS Monolithic Active Pixels (MAPs)
  - Si diodes and their readout are combined in the same pixels, and fabricated in a standard CMOS process
  - Integrating sensors and front-end electronics removes the need of interconnections, reducing complexity, mass, cost
- Different technologies are being investigated world-wide (HR/HV-CMOS)
  - Performance for EIC & e-e/muon-muon colliders are nearing readiness
    - Segmentation, radiation-tolerance, mass
    - R&D required for wafer-scale devices, low powering + improved timing performance
  - Hadron colliders more difficult and requires much more R&D
    - Occupancy, radiation damage
- Low power makes MAPs excellent technology choice for space-based missions

Measured timing resolution with CACTUS prototype: 88 ps
Novel Sensors for Particle Tracking

- Contact persons: S. Seidel
- Five contemporary technologies with potential application to particle tracking in future high energy physics experiments are discussed.
- Silicon and Diamond Sensors in 3D Technology
  - Sensors with improved uniformity, timing resolution, and radiation resistance.
  - Present research aims for operation with adequate signal-to-noise ratio at fluences approaching $10^{18}$ $n_{eq}/cm^2$, with timing resolution on the order of 10 ps.
- Submicron Pixels with a Quantum Well for Vertexing
  - Targeting submicron position resolution for vertex detector
  - Quantum well gate is made with a Ge layer deposited on a silicon substrate.
Novel Sensors for Particle Tracking

- **Thin Film Detectors**
  - May be fabricated in combination of thin film detection material with layers of electronics.
  - Potential of high optical transparency, mechanical flexibility, high spatial resolution, large area coverage, and low-cost relative

- **Scintillating Quantum Dots in GaAs for Charged Particle Detection**
  - Novel ultra-fast scintillating material utilizing semiconductor stopping media with embedded quantum dots
    - Optimized for timing and high granularity
  - First prototype detectors have been produced, and initial studies published
Simulation tools

• Contact persons: B. Nachman
• Models for single quantities
  – Annealing (e.g. Hamburg Models), Straggling (e.g. Bichsel Model)
• TCAD simulations for detector properties
  – Capable of full simulations of device fabrication, including epitaxy, implantation, annealing, deposition and oxygenation.
  – Invaluable in the development of new sensor technologies or in understanding the behavior of existing devices.
• Challenges and Needs
  – Unified radiation damage (TCAD) and annealing model
  – How to deal with proprietary software and device properties?
  – Feedback between full detector systems and per-sensor models
  – Extreme fluences of future colliders
  – Adding new effects/device types
  – Retention of institutional memory
Cooling and Mechanics

- Contact Person: A. Jung
- Increased segmentation leads naturally to larger power densities
  - Solutions with integrated services and cooling are necessary.
  - A holistic approach to design, simulation and manufacturing
  - Novel materials, new cooling and composite manufacturing techniques

- Personal opinion: Cooling developments currently is driven by European colleagues.
  - It is necessary for the US community to engage more in order for our tracking systems to be successful
Key Points

- Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments
- Adapt new materials and fabrication/integration techniques for particle tracking in harsh environments
- Realize scalable, irreducible-mass trackers in extreme conditions
- Advance model and provide training for simulation tools, developing required extensions for new devices, to drive device design
- Nurture collaborative networks, provide technology benchmarks & roadmaps and funding in order to develop required technologies on necessary time scales, costs and scale.