IF03: Solid State Detectors and Tracking White Paper Status

T. Affolder, A. Apresyan, S. Worm

on behalf of IF03 working group

February 18, 2022

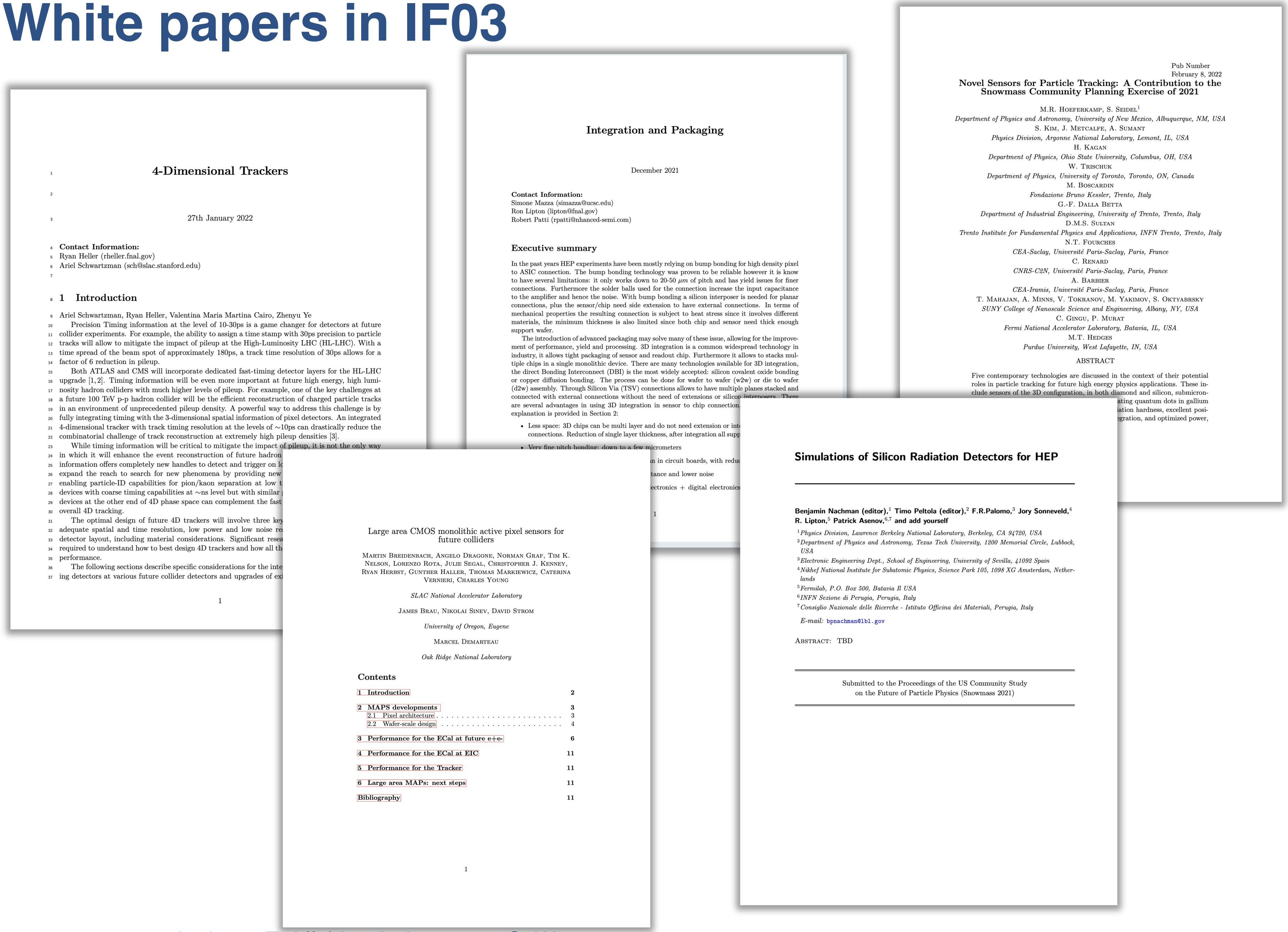
Status

- Restarted IF03 meetings in November 2021
  - Work continued from pre-Pause state to organize into white papers
  - Identified contact persons for each area
- Intention for the white papers to address
  - Briefly summarize the physics motivation,
  - Challenges that are being tackled
  - Recent results and a roadmap for near- to middle-term R&D.
- Suggested length of 10-15 pages
  - Include a one-page executive summary
- Will briefly overview the status of the WP as of now

White papers in IF03

1. 4D trackers and precision timing
2. Integration and Packaging
3. Novel Sensors for Particle Tracking
4. Simulation tools
5. Monolithic integrated silicon detectors, CMOS (MAPs)
6. *Mechanics, lightweight materials, cooling:* ***draft coming soon***
7. *Non-silicon trackers:* ***seems like this will not converge on time***

White papers in IF03



4-Dimensional Trackers

27th January 2022

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1 Introduction

Ariel Schwartzman, Ryan Heller, Valentina Maria Martina Cairo, Zhenyu Ye

Precision Timing information at the level of 10-30ps is a game changer for detectors at future collider experiments. For example, the ability to assign a time stamp with 30ps precision to particle tracks will allow to mitigate the impact of pileup at the High-Luminosity LHC (HL-LHC). With a time spread of the beam spot of approximately 180ps, a track time resolution of 30ps allows for a factor of 6 reduction in pileup.

Both ATLAS and CMS will incorporate dedicated fast-timing detector layers for the HL-LHC upgrade [1, 2]. Timing information will be even more important at future high energy, high luminosity hadron colliders with much higher levels of pileup. For example, one of the key challenges at a future 100 TeV p-p hadron collider will be the efficient reconstruction of charged particle tracks in an environment of unprecedented pileup density. A powerful way to address this challenge is by fully integrating timing with the 3-dimensional spatial information of pixel detectors. An integrated 4-dimensional tracker with track timing resolution at the levels of ∼10ps can drastically reduce the combinatorial challenge of track reconstruction at extremely high pileup densities [3].

While timing information will be critical to mitigate the impact of pileup, it is not the only way in which it will enhance the event reconstruction of future hadron
information offers completely new handles to detect and trigger on lo
expand the reach to search for new phenomena by providing new
enabling particle-ID capabilities for pion/kaon separation at low t
devices with coarse timing capabilities at ∼ns level but with similar
devices at the other end of 4D phase space can complement the fast
overall 4D tracking.

The optimal design of future 4D trackers will involve three key
adequate spatial and time resolution, low power and low noise re
detector layout, including material considerations. Significant resea
required to understand how to best design 4D trackers and how all th
performance.

The following sections describe specific considerations for the inte
ing detectors at various future collider detectors and upgrades of exi

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Integration and Packaging

December 2021

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Executive summary

In the past years HEP experiments have been mostly relying on bump bonding for high density pixel to ASIC connection. The bump bonding technology was proven to be reliable however it is know to have several limitations: it only works down to 20-50 μm of pitch and has yield issues for finer connections. Furthermore the solder balls used for the connection increase the input capacitance to the amplifier and hence the noise. With bump bonding a silicon interposer is needed for planar connections, plus the sensor/chip need side extension to have external connections. In terms of mechanical properties the resulting connection is subject to heat stress since it involves different materials, the minimum thickness is also limited since both chip and sensor need thick enough support wafer.

The introduction of advanced packaging may solve many of these issue, allowing for the improvement of performance, yield and processing. 3D integration is a common widespread technology in industry, it allows tight packaging of sensor and readout chip. Furthermore it allows to stacks multiple chips in a single monolithic device. There are many technologies available for 3D integration, the direct Bonding Interconnect (DBI) is the most widely accepted: silicon covalent oxide bonding or copper diffusion bonding. The process can be done for wafer to wafer (w2w) or die to wafer (d2w) assembly. Through Silicon Via (TSV) connections allows to have multiple planes stacked and connected with external connections without the need of extensions or silicon interposers. There are several advantages in using 3D integration in sensor to chip connection,
explanation is provided in Section 2:

- Less space: 3D chips can be multi layer and do not need extension or int
  connections. Reduction of single layer thickness, after integration all supp
- Very fine pitch bonding: down to a few micrometers
- n in circuit boards, with reduc
- tance and lower noise
- lectronics + digital electronics

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Novel Sensors for Particle Tracking: A Contribution to the Snowmass Community Planning Exercise of 2021

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ABSTRACT

Five contemporary technologies are discussed in the context of their potential roles in particle tracking for future high energy physics applications. These include sensors of the 3D configuration, in both diamond and silicon, submicron-
ating quantum dots in gallium
iation hardness, excellent posi-
egration, and optimized power,

Large area CMOS monolithic active pixel sensors for future colliders

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Simulations of Silicon Radiation Detectors for HEP

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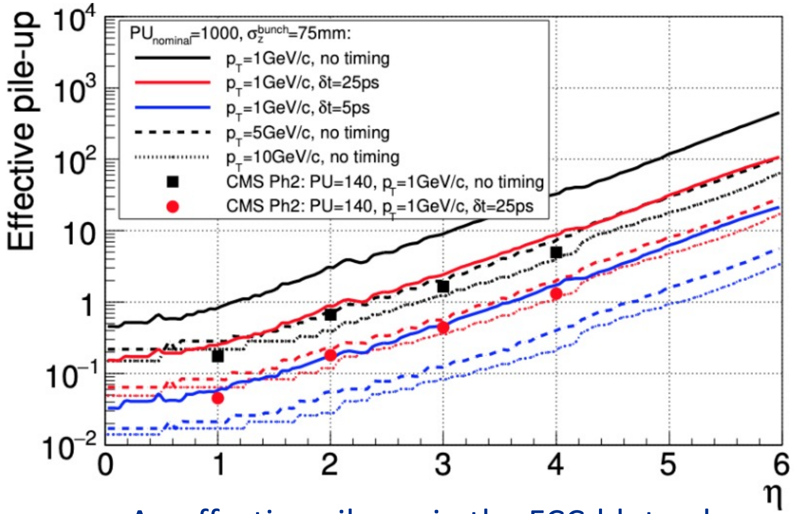
Abstract: TBD

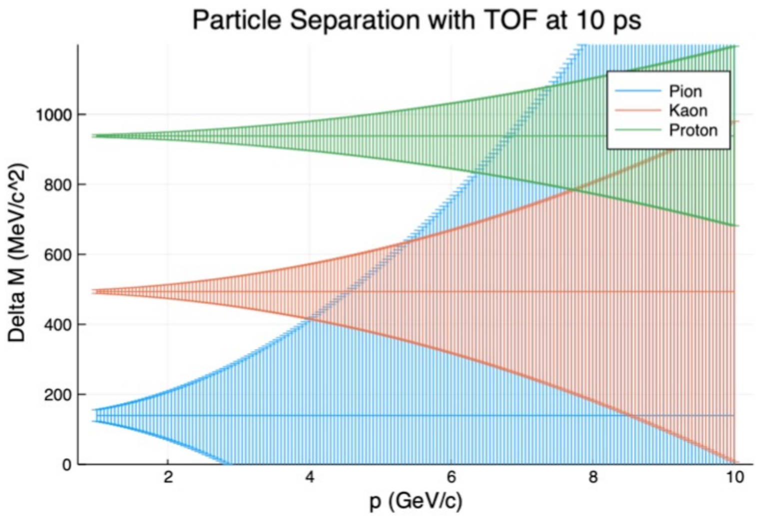
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

4D trackers and precision timing

- Contact persons: **R. Heller and A. Schwartzman**
- Applications of timing detectors:
  - Hadron colliders, e^+e^- colliders (ILC, CLIC, C3), muon colliders, EiC
  - Survey specifications required for each machine type, usage in each machine (PU, PID, BIB, etc)
- Sensor technologies:
  - LGADs, AC-LGADs, LGAD optimizations (buried layer, double-sided, thin, etc), 3D sensors, MAPS, Induced Current sensors
  - A comprehensive survey of novel directions, limitations and opportunities in sensors technologies



An effective pile-up in the FCC-hh tracker



Mass resolution for a TOF system with 10 ps in SiD

4D trackers and precision timing

- Electronics for fast timing detectors: current chips (ALTIROC, ETROC) and what's next
  - Advances in detector technology and the direction of HEP experiments will require development of new specialized readout electronics.
  - Overview of the current technologies and limitations that they pose
  - The entire pixel electronics will need to be designed with low power techniques and with novel timing extraction architecture, and more advanced edge-computing paradigms
  - Requirements of the next machines will need major advances in the ASIC development and approaches: some of these will be covered in IF7
- Layout optimizations
  - Key considerations are the optimizations of excellent time-and-position in all layers, vs excellent time in some and excellent position in others
  - Alternative approaches such as alternating spatial with timing layers, or 4D with 3D layers could help improve the overall physics performance.
  - Tracking material and pseudorapidity coverage.

Integration and Packaging

- Contact persons: **S. Mazza, R. Lipton, R. Patti**
- Electronics and sensor advanced packaging offer technologies to meet the needs of future particle physics experiments.
  - Collaboration between research groups and industry is crucial for the successful introduction of this technology in the research community
  - State-of-the art packaging and integration technologies now available can significantly extend the reach and effectiveness of future detectors, enabling lower mass, finer pitch, and lower noise systems
- Advantages of advanced packaging
  - Footprint, speed, performance, power, heterogeneous integration, robustness,
- Commercial availability
  - Variants of the 3D integration technology have been adopted by a number of foundries available to HEP
  - Examples of capabilities and successful collaborations with NHanced Semiconductors and Cactus Materials

Integration and Packaging

- Description of currently active 3D R&D projects for HEP and related fields.
  - These include single-photon avalanche diode 3D integration on CMOS,
  - High granularity LGADs,
  - 3DIC SiPM with sophisticated processing with active quenching for each pixel, inter-micropixel communication and pattern recognition etc.
  - Edgeless Tile Arrays, Small Pixel Induced Current Detectors, Double Sided and Small Pixel LGADs,
  - 3DIC for high performance Pattern Recognition: massive three-dimensional network for data communication with shorter traces and low parasitic capacitance
  - Zero mass tracker, 2D Interconnects and Interposers, etc
- Results and ongoing projects
  - An overview of several latest results from FNAL and UCSC+Cactus materials
- Path for future development

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
  - Shows promise for compensation of lost signal in high radiation environments and for separation of pileup events by precision timing.
  - 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
  - Development of sensors with submicron position resolution for vertex detector for the future linear collider experiments
  - Quantum well gate is made with a Ge layer deposited on a silicon substrate.

Novel Sensors for Particle Tracking

- Thin Film Detectors
  - Thin-flim transistor technology uses crystalline growth techniques to layer material
  - Monolithic detectors may be fabricated by combining layers of thin film detection material with layers of amplification electronics using vertical integration.
  - Offer optical transparency, mechanical flexibility, high spatial resolution, large area coverage, and low cost relative to traditional silicon-based semiconductor technology.
  - Monolithic sensors can be fabricated using layers of thin film materials for particle detection with layers for amplification electronics
- Scintillating Quantum Dots in GaAs for Charged Particle Detection
  - Charged-particle tracking using novel ultra-fast scintillating material utilizing semiconductor stopping media with embedded quantum dots
  - First prototype detectors have been produced, and initial studies published
  - Significant exploratory research and development is required to accurately assess expected performance of these detectors in future high-energy physics applications

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
  - Commercial TCAD packages are capable of full simulations of device fabrication, including epitaxy, implantation, annealing, deposition and oxydation.
  - The accuracy and detail provided by these simulations can be invaluable in the development of new sensor technologies or in understanding the behavior of existing devices.
  - Many multitrap models for radiation damage
  - Lighter-weight alternatives: TRACS and Weightfield2
- Testbeam
  - Pixelav, Allpix2, and similar specialized MC programs for beam tests
- Full detector systems
  - Within large HEP collaborations, silicon detector simulation is typically performed using proprietary software (Athena, Gaudi, and CMSSW)
  - Different approaches to modelling of radiation damage in LHC experiments

Simulation tools

- Challenges and Needs
  - Unified radiation damage (TCAD) and annealing model
  - Prescription for uncertainties in TCAD models
  - Measurements of damage factors (many of the inputs in the RD50 database are based on simulation or less)
  - Update to basic silicon properties? https://cds.cern.ch/record/2629889
  - How to deal with proprietary software and device properties?
  - Feedback between full detector systems and per-sensor models
  - Extreme fluences of future colliders

Monolithic integrated silicon detectors, CMOS (MAPs)

- Contact persons: **C. Vernieri**
- Address the challenges of the future trackers and calorimeters 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 on the same die removes the need of interconnections, thus reducing complexity and mass.
  - The close connection of sensor and front-end amplifier reduces input capacitance which reduces the achievable noise floor and thus for the same S/N ratio allows for a reduction in signal and therefore sensor thickness, which also reduces mass.
- Develop two types of fully depleted MAP sensors with characteristics suitable for Trackers and Electromagnetic Calorimeters.
  - Requirements of the SiD detector for ILC are used as the strawman specifications

Monolithic integrated silicon detectors, CMOS (MAPs)

- Possibility and advantages of a wafer-scale device production, which will significantly simplify detector construction for future trackers
- R&D needs for the wafer-scale MAPS to investigate the challenges with power-pulsing, power distribution, yield and stitching techniques
- Detailed simulation studies for ECAL application of similar MAPS sensors presented
- Large volume of data provided by ECal reveals details of particle showers.
  - The extraction of the most pertinent information, for example particle energy, particle type, and the separation of nearby and overlapping showers, provides an opportunity to apply Machine Learning techniques.