IF03: Solid State Detectors and Tracking Key Points

T. Affolder, A. Apresyan, S. Worm

on behalf of IF03 working group

July 20, 2022

What is IF03?

- Past meetings/presentations available at:
  - 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’

White papers in IF03

arXiv:2202.11828v1 [physics.ins-det] 23 Feb 2022

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-dimension pixels, thin film detectors, and scintillating quantum dots in gallium arsenide. Drivers of the technologies include radiation hardness, excellent position, vertex, and timing resolution, simplified integration, and optimized power, cost, and material.

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Monolithic Active Pixel Sensors on CMOS technologies

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15-March-2022

Fast Timing With Silicon Carbide Low Gain Avalanche Detectors

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Abstract

4H-Silicon Carbide, when considered as a material for the fabrication of Low Gain Avalanche Detectors for particle timing and position measurement, offers potential advantages over Silicon. We discuss an ongoing study of this material aimed at the fabrication and test of prototype fast timing sensors. This work is well aligned with technical directions identified in the recent Department of Energy study, "Basic Research Needs for High Energy Physics Detector Research and Development".

Introduction

In this contributed paper to the Snowmass proceedings we discuss ongoing work to study and develop Low Gain Avalanche Detectors (LGADs) using 4H Silicon Carbide (4H-SiC) rather than Silicon. This effort is very well aligned with all three of the Priority Research Directions (PRD's) identified for future tracking detectors in the recent DOE Basic Research Needs Study [1]. The PRD's are (PRD18) fast timing, (PRD19) new materials and processes, and (PRD20) low mass scalable tracking systems.

The work is being carried out as a collaboration between Physics Division staff at Lawrence Berkeley National Laboratory and large bandgap device and processing researchers at North Carolina State University (NCSU). NCSU, located in the Raleigh Durham Research Triangle Area, is a center for research and development on large bandgap devices, mainly for power applications. Many companies with expertise in large bandgap materials are located in this area as well.

Present upgrades to high energy and heavy ion collider detectors, and also proposed detectors at the new Electron Ion Collider, have embraced the importance of fast (~10 ps) timing on individual charged particles to enable 4D tracking, pileup rejection, and particle ID. The DOE BRN on Instrumentation states as a key goal "Develop high spatial resolution pixel detectors with high per-pixel time resolution to resolve individual interactions in high-collision-density environments". Much work on fast timing has centered on the Silicon LGAD concept [2]. This is an enhancement to the familiar position sensitive silicon detector (strips, pads, and pixels) which adds a moderate gain layer below the rectifying implant. However LGADs suffer from the same challenges as regular Silicon detectors as they are susceptible to bulk radiation damage and must, consequently, be operated a very low temperatures. This low temperature leads to bulky and complex cooling requirements.

The goal of this project is to explore the LGAD concept realized initially in Silicon Carbide (4H-SiC) rather than in Silicon. This material has already been studied and demonstrated as a radiation detector but in niche applications [3]. It has not found widespread application in large HEP or NP trackers, due, in part, to small signal and difficult fabrication. However, SiC detectors can, in principle, operate at very high temperatures,

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Light-weight and highly thermally conductive support structures for future tracking detectors

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ABSTRACT

Detector mechanics can play a significant role in a detector's performance, improvements typically require in-depth study of total mass, novel ways to reduce the total mass, as well as more integrated design concepts to save on material budgets and optimize performance. Particle detectors at future colliders rely on ever more precise charged particle tracking devices, which are supported by structures manufactured from composite materials. This article lays out engineering techniques able to solve challenges related to the design and manufacturing of future support structures. Examples of current efforts at Purdue University related to the high-luminosity upgrade of the CMS detector are provided to demonstrate the prospects of suggested approaches for detectors at new colliders: a future circular collider or a muon collider. Detectors at electron-positron machines have significantly smaller material budgets and require targeted concepts.

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Simulations of Silicon Radiation Detectors for High Energy Physics Experiments

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Abstract: Silicon radiation detectors are an integral component of current and planned collider experiments in high energy physics. Simulations of these detectors are essential for deciding operational configurations, for performing precise data analysis, and for developing future detectors. In this white paper, we briefly review the existing tools and discuss challenges for the future that will require research and development to be able to cope with the foreseen extreme radiation environments of the High Luminosity runs of the Large Hadron Collider and future hadron colliders like FCC-hh and SPPC.

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Strategies for Beam-Induced Background Reduction at Muon Colliders

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Abstract: This Snowmass study explores methods for the reduction of Beam-Induced Backgrounds (BIB) at a future muon collider. Studies are performed for a collision energy of 1.5 TeV, and a detector with a tungsten nozzle designed to block the majority of the BIB. In this context, detector strategies are explored to further reduce the BIB, with a focus on the innermost layers of the tracker where its density is highest. In addition, a conceptual design of a calorimeter built to reject BIB is presented.

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4-Dimensional Trackers

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March 29, 2022

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1 Introduction

Precision timing at the level of 10-30ps will be a game-changing capability 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.

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Integration and Packaging

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ABSTRACT

Vertically integrated (3D) combinations of sensors and electronics provide the ability to fabricate small, fine pitch pixels with very small total capacitance monolithically integrated with complex circuitry. The small capacitance enabled by the fine pixel pitch, low interconnect capacitance, and very short signal path available in 3D hybrid bonding, provide an excellent signal to noise ratio with moderate power consumption. This combination enables fabrication of integrated sensors and electronics with both excellent position and time resolution. In this white paper, a discussion will be presented on the advantages of 3D integration, ongoing projects, and prospects in high energy physics and beyond.

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

Executive summary

In the past years, high-energy physics experiments have been mostly relying on bump bonding for high density pixel to ASIC connection. The bump bonding technology was proven to be reliable and is currently used in many large silicon detector systems; however, it is known to have several limitations. It can be applied only down to 20-50 μm of pitch and has yield issues for finer connections. Furthermore, the solder balls used for the connection inevitably increase the input capacitance to the amplifier and hence the noise. In order to provide a planar connection to a bump-bonded sensor, either an interposer is required or the sensor/chip needs to have suitable

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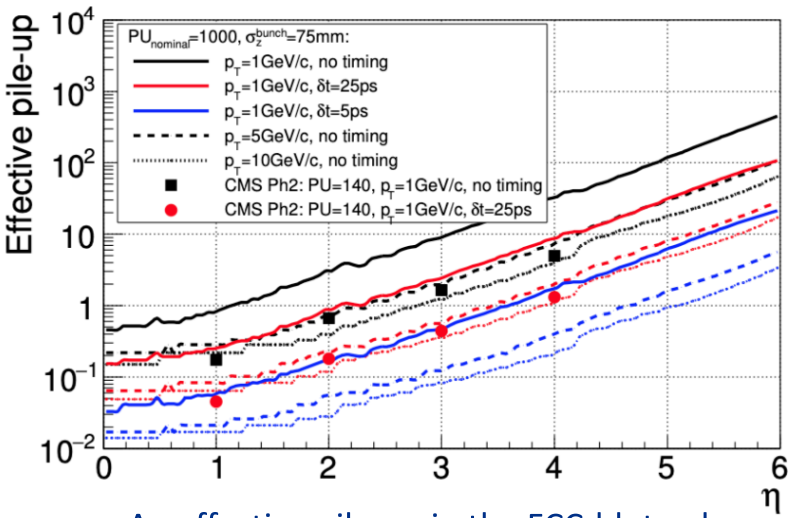
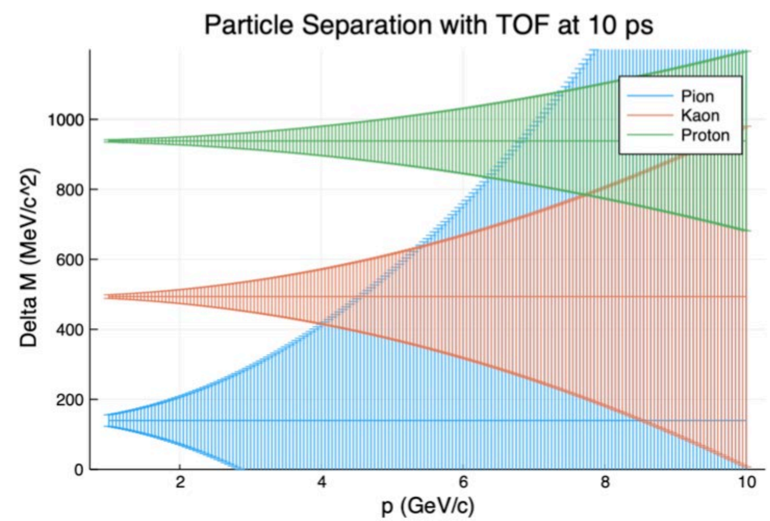
4D trackers and precision timing

- 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)



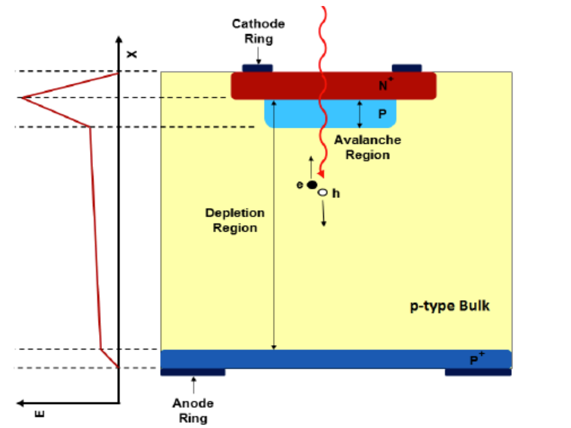
An effective pile-up in the FCC-hh tracker

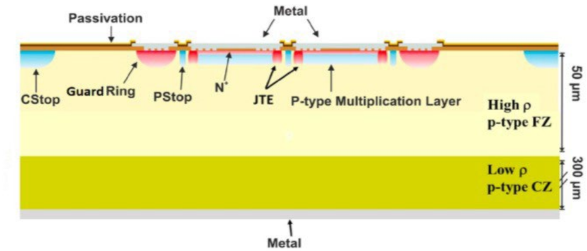


Mass resolution for a TOF system with 10 ps in SiD

4D trackers and precision timing

- 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



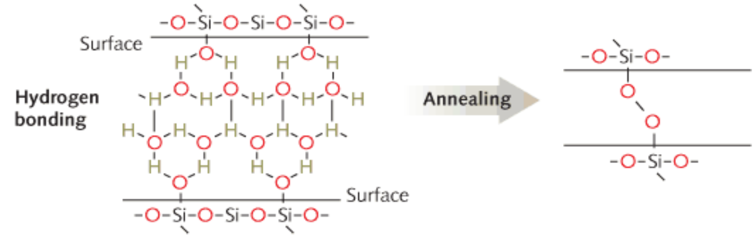


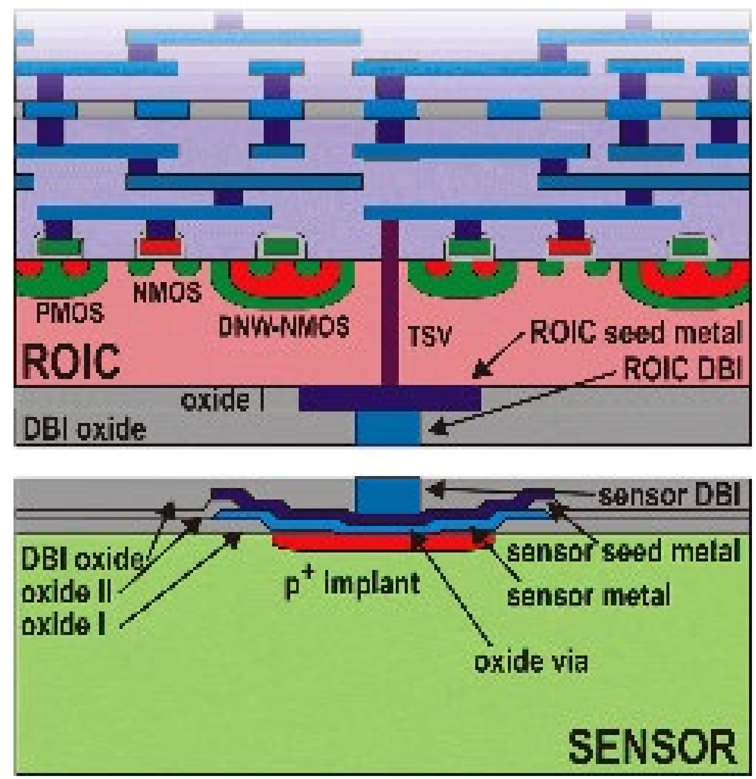
ASIC	Technology	Pitch	Total size	Power consumption	TID tolerance
ALTIROC	130 nm	1.3 mm	$19.5 \times 19.5\ mm^2$	5 mW/chan	2 MGy
ETROC	65 nm	1.3 mm	$20.8 \times 20.8\ mm^2$	3 mW/chan	1 MGy
RD53A/HL-LHC pixels	65 nm	50 μm	$20 \times 11.6\ mm^2$	$<$ 10 μW/chan	5–15 MGy

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

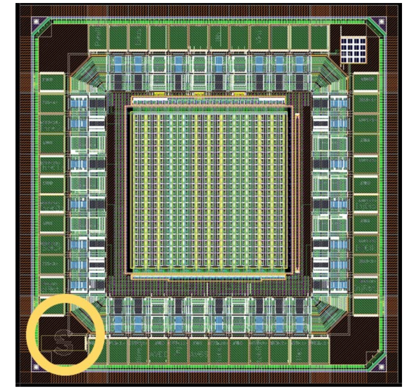
Si covalent oxide bonding



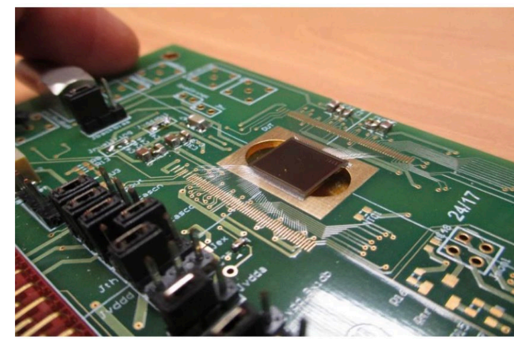


Monolithic integrated silicon detectors, CMOS (MAPs)

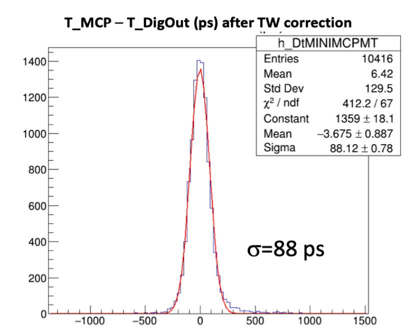
- Contact persons: **C. Vernieri**
- Challenges of the future trackers and calorimeters may be address by utilizing CMOS Monolithic Active Pixels (MAPs)
  - Si diodes and their readout are combined in the same pixels, and fabricated in a standard CMOS process
  - Integrating sensors and front-end electronics 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



Layout of MAPS SLAC prototype for WP1.2 shared submission



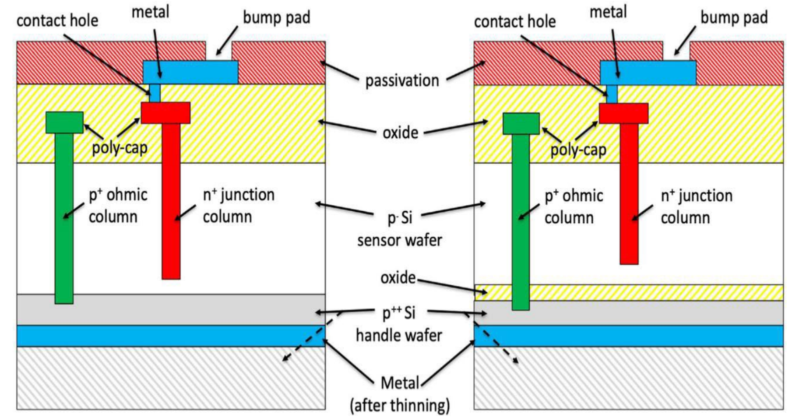
CACTUS LFoundry 150 nm HV-CMOS

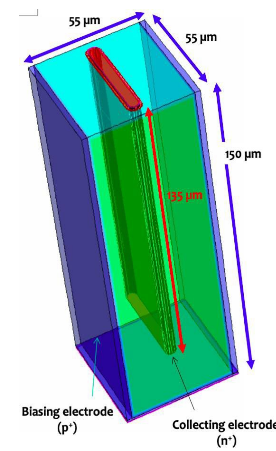


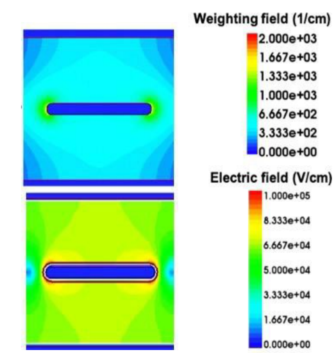
Measured timing resolution with CACTUS prototype: **88 ps**

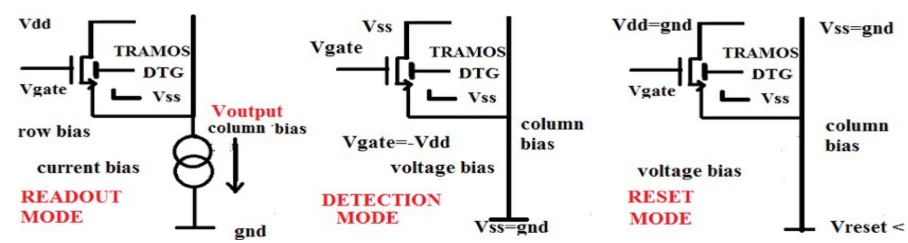
Novel Sensors for Particle Tracking

- 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.



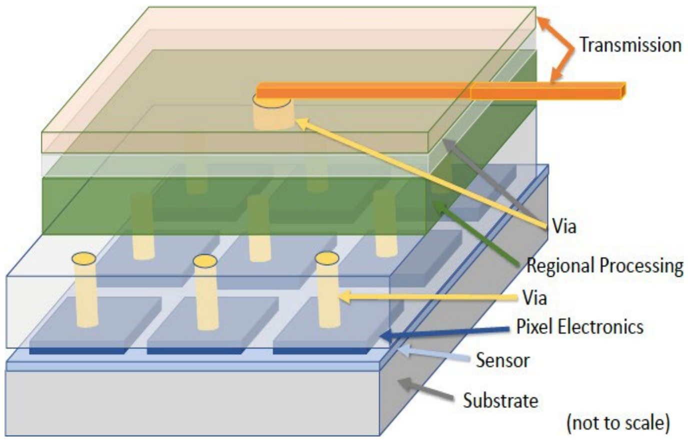


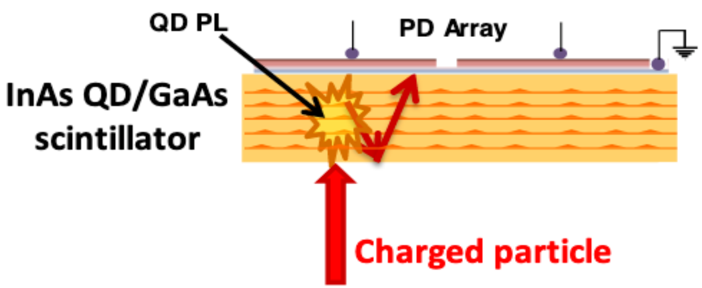




Novel Sensors for Particle Tracking

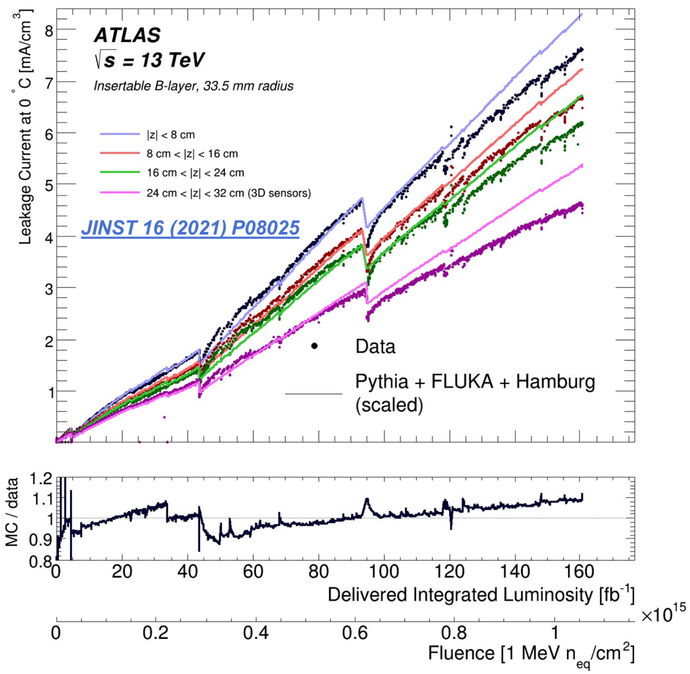
- Thin Film Detectors
  - May be fabricated in combination of thin film detection material with layers of electronics.
  - Potential of high optical transparency, mechanical flexibility, high spatial resolution, large area coverage, and low-cost relative
- Scintillating Quantum Dots in GaAs for Charged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

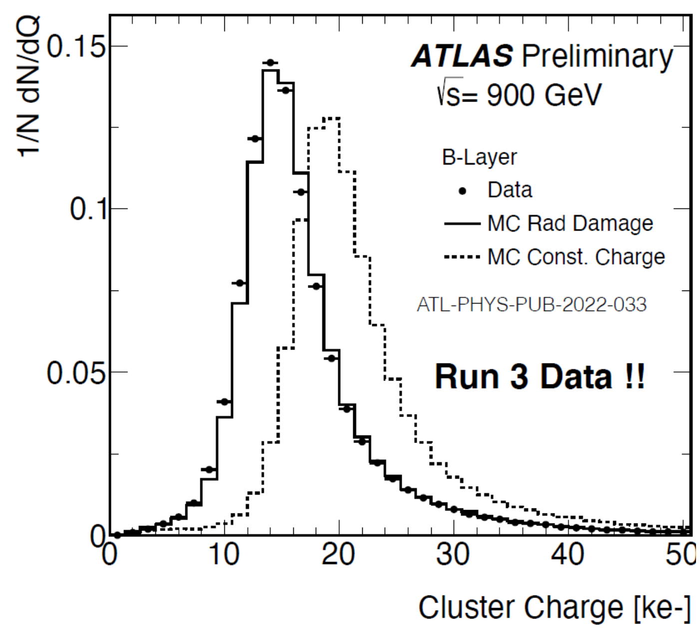




Simulation tools

- 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

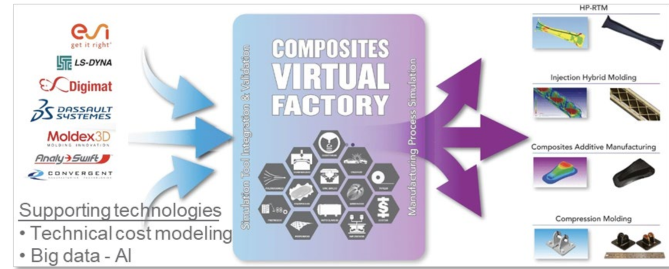


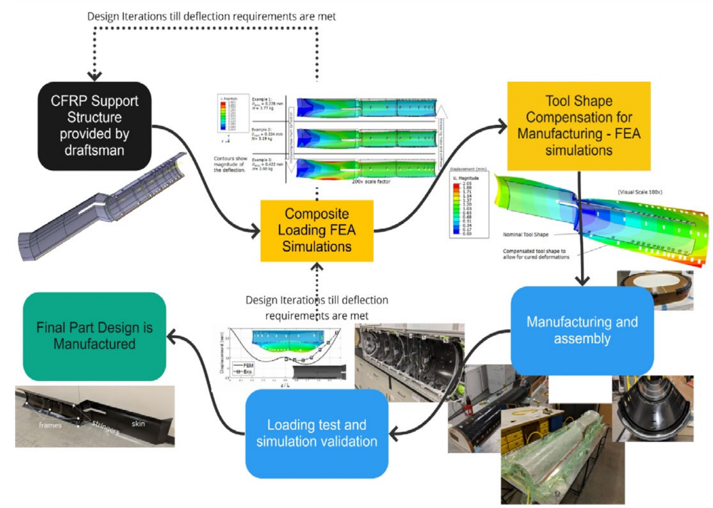


Cooling and Mechanics

- 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 inter-actions 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.