Fermilab

Position Sensitive Device Technologies for Particle Physics

FERMILAB-CONF-23-664-CMS-PPD

DOI: 10.1016/j.nima.2024.169229

Accepted Manuscript

This manuscript has been authored by Fermi Research Alliance, LLC
under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy,
Office of Science, Office of High Energy Physics.

Position Sensitive Device Technologies for Particle Physics

Petra Merkel, petra@fnal.gov
Fermilab, PO Box 500, Batavia, IL 60510-5011

Abstract
I will give a brief overview of the use of position sensitive devices for particle physics. I will focus on silicon-based systems only. In addition to the depiction of a suite of recently designed, built, and operated detectors I will also introduce planned near term additions. I will conclude with a brief outlook regarding challenges for silicon detector applications for future colliders.

Keywords: overview, silicon, detector, collider, pixel, strip

1. Introduction

Today, the use of silicon trackers in collider experiments is ubiquitous. Over the past several decades, these detectors have faced dramatically increasing challenges. Their surface area has grown from the size of a few strips of $\mathcal{O}(0.001m^2)$ to $\mathcal{O}(100m^2)$ in the HL-LHC upgrades. Simultaneously, the number of channels that need to be read out has grown logarithmically from hundreds to billions. At hadron colliders the main challenge resides in the harsh radiation environment. For the HL-LHC, sensors and frontend electronics need to be designed to withstand fluences of up to 10^{16} 1MeV n_{eq}/cm^2 and a total ionizing dose of hundreds of Mrad in the innermost parts of the detector. These requirements will grow by two orders of magnitude for a future high energy collider such as the FCC-hh. In addition to the sensors, the corresponding readout electronics needs to be able to handle very high hit rates of several GHz/cm^2. While this article can only touch on the surface of the recent history and near future of silicon-based detectors for High Energy Physics experiments, a more in-depth discourse can be found in several excellent books and journal articles [1-6].

2. Silicon Trackers at the LHC

At the core of the ATLAS and CMS experiments, both geometrically as well as within their physics programs, lie the silicon pixel and strip detectors (Fig. 1). Both experiments rely heavily on several layers of pixelated silicon modules for their vertexing and track seeding. In ATLAS the most recent addition is the Insertable B-Layer (IBL), which was installed in 2014. The improvements of the IBL consist of: a smaller distance to the beam (3.35cm), smaller pixel size ($50x250\mu m^2$), better sensors and a better readout chip, including 3D sensors at higher z coordinates, better radiation hardness and a significantly reduced material budget. These changes have led to an improved impact parameter resolution of up to a factor of two at small transverse momenta. In CMS, the pixel detector was refurbished during Long Shutdown 2 (LS2), where a new Barrel Layer 1 with updated ASICs (Application Specific Integrated Circuits) and lower thresholds was installed. Other improvements include updated cooling and high voltage connections in the endcap disks, new DC-DC converters and upgraded high voltage power supplies that can bias the detector up to 800V. Both detectors have successfully been taking data since their installation.

The LHCb experiment updated its VErtex LOcator (VELO) detectors from strip to pixel sensors in 2022. The closest pixels sit at 5.1mm from the beam. The detector is reading out every event at 40MHz using the ultra-highspeed VeloPix ASIC. The VELO consists of 41M pixels across 52 modules that are mounted within with secondary vacuum, separated from the beam through a 150μm thin RF foil made of Torlon with NEG coating. This foil is located at 3.5mm from the beam and only 0.9mm from the sensors. It needs to be thermally stable and shield the detector against RF pick-up. The detector uses innovative two-phase CO_2 cooling through microchannels. This efficient, light, and powerful cooling is needed for operation in vacuum, very close to the beam. The system is building on the previous success of evaporative CO_2 cooling used in the original VELO detector. The silicon sensors are in contact with the 120x200μm^2 microchannels which were etched into a 500μm thick silicon wafer. The system provides a cooling power of up to 40W at -30^{o}C.

The ALICE experiment recently replaced its Inner Tracking System (ITS) with 10m^2 of MAPS (Monolithic Active Pixel Sensors). This represents the first ever MAPS-based tracker at the LHC. The CMOS MAPS were developed in 180nm TowerJazz technology. The sensors are between 50-100μm thick with a pixel size of 20x27μm^2 and a sensor size of 15x30mm^2 and are designed to withstand up to 10^{13} 1MeV n_{eq}/cm^2. The detector is designed for a hit efficiency of >99% and a spatial resolution of 5μm.

The FASER experiment is a new, small experiment installed in an old LEP injector tunnel during LS2. It has been designed to detect particles in the forward region, such as dark photons, axion-like particles, etc. The tracker consists of 72 modules that were repurposed from ATLAS strip tracker spare components. These sensors are single-sided p-in-n strip detectors with an 80μm pitch (as opposed to the n-in-p sensors for HL-LHC ATLAS and CMS). In total the detector has 10^5 channels in three stations. First world-leading exclusion limits have been published using the initial data.

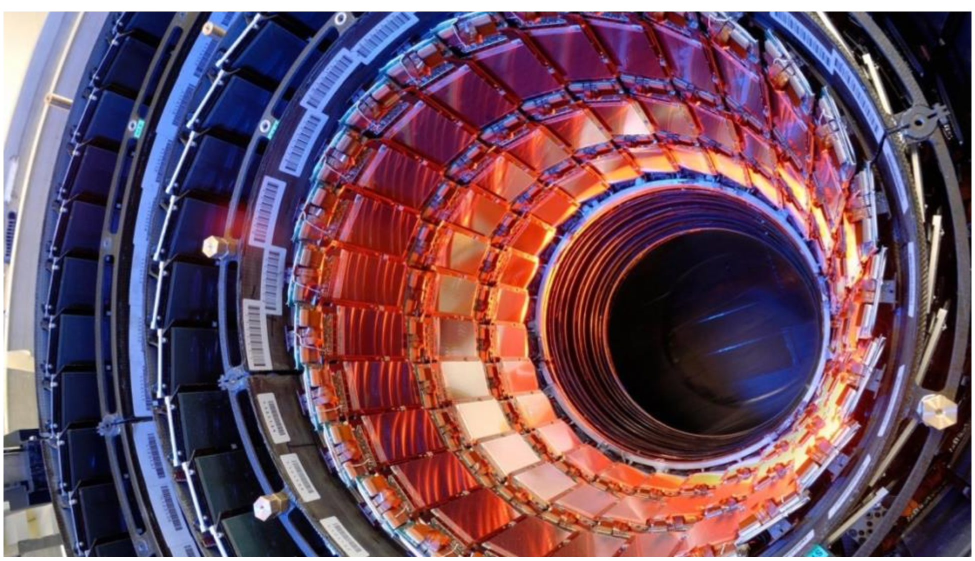

Figure 1: The CMS Strip Tracker at the LHC. Installed in 2007, it will operate until the end of Run3 in 2025 [7].

3. Silicon Tracker Upgrades for the HL-LHC

The harsh environment of the HL-LHC requires all experiments to replace their tracking systems. High fluences, especially in the innermost layers, high instantaneous luminosity, as well as high pile-up conditions put stringent requirements on the newly designed tracking detectors. In general, sensors and ASICs are more radiation tolerant, and pixel and strip sizes are smaller, resulting in higher granularity. Due to two-phased CO_2 cooling and better-placed frontend electronics, the material budget of the central tracking systems has been reduced. In general, the performance of the LHC era detectors is expected to be met or even surpassed despite the more challenging conditions.

For their inner tracking detectors, both ATLAS and CMS have chosen a combination of planar and 3D pixelated sensors. More radiation tolerant 3D sensors will be placed on the first layer in the barrel detectors, and at small radii in the ATLAS endcaps, while planar sensors will populate the rest of the pixel detectors. Pixel sizes vary between $50x50\mu m^2$ and $25x100\mu m^2$ resulting in high granularity detectors with several billion readout channels. The readout chips, ITkPix and CROC, are derivatives of the common RD53 ATLAS and CMS ASIC development in 65nm TSMC technology. The acceptance will also increase with extended disk coverage up to $|\eta|<4$, leading to large amounts of silicon needed ($13m^2$ for ATLAS and $4.9m^2$ for CMS). The challenges for these detectors lie in the relatively large ASIC ($20x20mm^2$), high-density, low-pitch bump bonding, serial powering, low-mass services, a large range in operating temperatures, and a large bias voltage across a $10\mu m$ thin air gap, for which parylene coating is employed to avoid sparking.

The outer layers of the all-silicon tracking systems in ATLAS and CMS will consist of close to $200m^2$ of silicon strip modules arranged in barrels and endcaps. The CMS Outer Tracker will consist of so-called p_T-modules, which are sandwiches of two closely spaced sensors enabling the measurement of track stubs that will contribute to the level 1 trigger decision for the first time at a hadron collider. Hits on the two sensors that lie within a pre-defined search window form a stub. The size of the window determines the effective p_T-cut on the stubs. This information is sent to the backend boards at the collision rate of 40MHz. The functioning of the stub correlation has been proven in several test beam campaigns.

Tracking detectors are no longer the only application for silicon in collider detectors. For HL-LHC CMS is developing the High Granularity Calorimeter, HGCal, for its endcaps. It will consist of silicon as sensing devices in the high-radiation regions (all of the electromagnetic section, and the smaller radii of the hadronic part), and scintillating tiles with SiPM readout in the lower-radiation areas of the hadronic section. The sensors are mounted on cooling plates with readout electronics and absorbers. A total of $600m^2$ of silicon and $500m^2$ of scintillators will be used. Each of the two endcaps covers $1.5<|\eta|<3.0$, weighs 215 tonnes and consumes 110kW of power at end-of-life. In particular, the small cell size in the silicon sensors, between $0.5 – 1cm^2$, allows for very high-granularity particle reconstruction in the calorimeter endcaps reminiscent of tracking detectors.

ALICE is planning to replace its ITS MAPS detector with newly designed MAPS consisting of 300mm wafer-scale detectors fabricated using stitching of individual chips. Furthermore, the

MAPS will be thinned down to <50μm, making them flexible like paper (Fig. 2). The stitched sensors will be bent to the target radii for the three layers and held in place by carbon foam ribs. Cooling will be done by air flow. The design results in an extremely low material budget of <0.05% X_0 and a homogeneous material distribution and presents a very ambitious development towards the low-mass vertex detectors needed for a future Higgs factory.

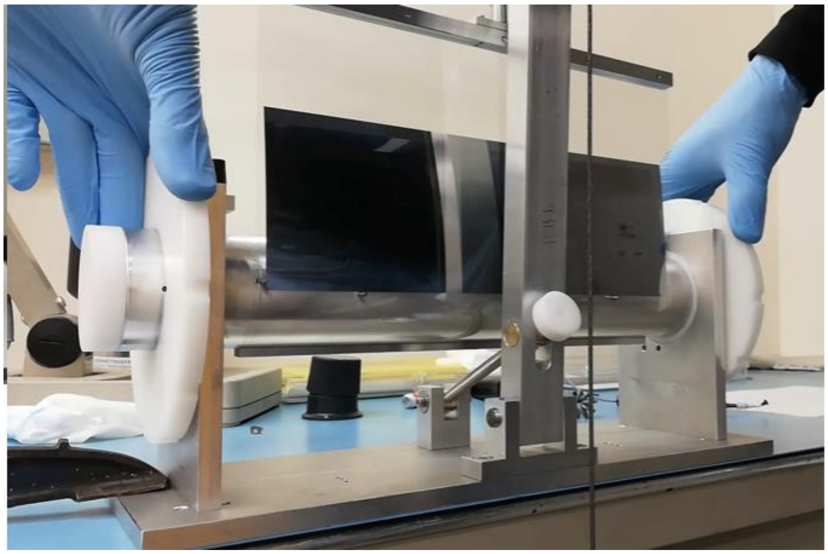

Figure 2: An ALICE prototype ultra-thin wafer-scale MAPS sensor consisting of stitched chips being bent to the desired radius [8].

LHCb is planning to upgrade its VELO detector during Run5, which is scheduled to begin in 2035. The new design will combat a tenfold increase in pile-up by adding 50ps/hit timing capability. R&D on candidate sensors is ongoing. Under consideration are 3D pixel sensors, LGADs (Low Gain Avalanche Diodes), SiEM (Silicon Electron Multiplier) sensors, and others. The radiation tolerance needs to go up to $6x10^{16}$ 1MeV n_{eq}/cm^2, or regular replacements need to be foreseen. Extreme hit rates should be expected on the order of 350kHz/pixel, or 250Gb/s per ASIC. To deliver adequate physics performance, the total material budget needs to be reduced by 80% X_0 before the second hit due to the operation within the LHC vacuum. Main areas where R&D is needed are for the RF shielding, where for example the current NEG coating could be replaced by amorphous carbon coating to reduce the thickness, and for the active cooling of the detector. It is currently being considered to replace the CO_2 with Krypton for the two-phase cooling which would allow for operation below -40°C.

4. Silicon Trackers Beyond the LHC

Silicon tracking and vertexing detectors are ubiquitous also outside the LHC. Recent highly ambitious designs include the Belle II vertex detector, as well as the ultra-low mass tracker for Mu3e. The design for the Electron Ion Collider (EIC) is underway. Its detectors are centered on recent advances in silicon-based technologies as well. In addition, detectors for future Higgs factories rely heavily on silicon-based tracking and vertexing, although in some cases gas-based detectors could be preferred due to the potential for lower material budgets.

Belle II has recently replaced its pixel (PXD) and strip (SVD) silicon detectors. The PXD consists of ultra-thin DEPFET (Depleted Field Effect Transistors) pixel sensors with a thickness of 75μm and a pixel size of 50x85μm^2. These chips have low power consumption and high signal-to-noise. The electronics includes a switcher for a rolling-shutter readout and 20μs integration time. This detector has unfortunately experienced some damage from beam loss events during early operation. The SVD is made up of double-sided strip sensors using AC-coupled strips on n-type substrate. The readout is done using a wrapped flex circuit to read out both sides of the sensor.

Mu3e, which is an experiment at PSI searching for lepton flavor violating decays is currently under construction. It needs excellent momentum resolution (<0.5MeV/c) to distinguish physics signal from background. To achieve this, an extremely low material budget is required. The choice for sensors is an ultra-thin (50μm) HV-CMOS MAPS (0.11% X_0). Cooling will be done using gaseous Helium. The detector is designed to be read out at high rates of >10^9 muons/s.

R&D for detectors at the EIC is ongoing and focuses on MAPS and DMAPS (Depleted MAPS) sensors as well as LGAD and AC-LGAD sensors for dedicated fast timing layers. The DMAPS provide high granularity with a pixel pitch of 36.4μm, a spatial resolution of 7μm and a temporal resolution of 2ns. The LGAD sensors under investigation range in pixel size between 0.5 and 1.3mm and provide spatial resolution of 30μm at a temporal resolution of better than 30ps. There are many synergies with developments for high energy physics detectors, and the EIC detectors can serve as an early deployment of new ideas.

New ideas are being pursued for tracking and vertexing detectors at future colliders. I will mostly focus on the more near-term options of a Higgs Factory. Detectors for a future Higgs Factory have many synergies with each other regardless of the chosen collider. The physics goals for these experiments set stringent requirements for vertexing and tracking. It will be essential to achieve a low material budget (~0.15% X_0), high granularity and spatial resolution (~3μm), low power consumption (<20mW/cm^2) and fast readout, as well as near perfect hit finding efficiency and extremely low fake rate. For future hadron or muon colliders, some of these requirements can be relaxed somewhat, but additional R&D into radiation hardness and ultrafast timing will be needed. Some of the active areas of research where significant progress is needed beyond current capabilities, is fine-pitch hybridization and 3D integration. Bump bonding pitches down to 25μm, or hybridization using anisotropic conductive films for example will enable a new class of vertexing detectors. Another direction of research is going into more autonomous detectors by bringing some of the intelligence, that makes physics motivated decision, into the frontend. Traditionally, some of this decision making is relatively slow and thus happening in backend boards removed from the frontend electronics. But advancements in ASIC and FPGA technologies as well as a very active field of AI/ML (artificial intelligence/machine learning) research are pushing more intelligence and decision power directly onto the detector. This means instead of reading out which pixels have been hit, or how much charge was collected by a strip, we can now analyze the raw data already on the detector and send more complex information such as particle momentum or incidence angle to the electronics boards further downstream. Methods like these will be instrumental in enabling ever higher granularities and more powerful trigger systems.

5. Summary

Silicon-based tracking and vertexing detectors have been at the core of collider experiments, essential for their physics programs, since the Tevatron experiments in the 1990s. Since then, their size and complexity have steadily advanced to keep up with the ever-increasing requirements stemming from physics and environmental challenges. The physics program of the LHC, including the Higgs Boson discovery, as well as physics related to flavor would not have been possible without these detectors. For the next generation collider detectors, namely detectors for an e^+e^- Higgs Factory, several of the currently possible performance parameters will have to be pushed even further to the extremes. In some cases, for example radiation hardness levels as required by future hadron or muon colliders might need completely new approaches into new materials, away from silicon. Although much of what is currently possible with silicon was not fathomable even a couple of decades ago, and so we might be surprised by how far we can push this area of research.

6. Bibliography

[1] "Evolution of Silicon Sensor Technology in Particle Physics", Hartmann, F. (doi: 10.1007/978-3-319-64436-3), 2017.
[2] "A review of advances in pixel detectors for experiments with high rate and radiation", Garcia-Sciveres, M. and Wermes, N. (doi: 10.1088/1361-6633/aab064), 2018.
[3] "Displacement Damage in Silicon Detectors for High Energy Physics", Moll, M. (doi: 10.1109/TNS.2018.2819506), 2018.
[4] "Applications of silicon strip and pixel-based particle tracking detectors", Allport, P. (doi: 10.1038/s42254-019-0081-z), 2019.
[5] "Particle Detectors", Kolanoski, H. and Wermes, N. (doi: 10.1093/oso/9780198858362.003.0001), 2020.
[6] "History and future of radiation imaging with single quantum processing pixel detectors", Heijne, E. (doi: 10.1016/j.radmeas.2020.106436), 2021.
[7] CMS Tracker Homepage (https://cms.cern/detector/identifying-tracks).
[8] "ALICE ITS 3: the first truly cylindrical inner tracker", Colella, D. (arXiv:2111.09689), 2021.