1 Solid State and Tracking

Future instrumentation developments for solid state tracking at colliders should be viewed in the context of specific facilities and specific physics goals or required capabilities. For a hadron collider the requirements are driven by a possible future HE-LHC or 100 TeV machine, and informed by the experience of the recent HL-LHC upgrades. For a lepton collider the R&D for an ILC or other mid-hundred GeV facility is the reference point. In both cases, large all-silicon systems have been considered as either required (hadron) or a strong option (electron). There are significant commonalities which span a broad technological range. The key differences are the more stringent speed and radiation hardness required for hadron colliders, and, while both machine options require low mass trackers, this requirement may be more stringent for electron machines.

When considering future developments we also take the perspective of a full system. We are cognizant that it is the integrated performance, and the optimization of many technical aspects, which results in a successful tracker, rather than a bench-top demonstration.

Solid state tracking technology has a history going back to the 1970s when first adapted from high resolution nuclear spectroscopy systems with of about only one channel with low noise readout electronics. Through the intervening decades there has been a steady growth of this technology resulting in todays systems with feature about 108 channels. This growth has been punctuated by both transformative and incremental developments or improvements. This history allows us to place future directions in an informed context. To be specific, a transformative development is one which enables a scientific application which would otherwise be impossible. Alternatively, an incremental one clearly builds, and improves upon, an existing capability. When viewed in this context we can already identify some key elements.

- The silicon microstrip detector, introduced in the 1970s was transformative. It opened the possibility of precision tracking with solid state detectors and the direct observation of long lived particle decays in fixed target experiments, and later numerous application in lepton and hadron colliders.
- The application specific integrated circuit, introduced in the 1980s, designed to read out microstrips, was transformative. It made detectors for finding secondary decay vertices in colliders possible. This led to the discovery of the top quark, a program of precision b physics, and the measurement of Higgs particle decays in heavy quarks.
- The radiation hard hybrid pixel detector, demonstrated in the 1990s was

transformative. It enabled silicon to be placed close to the beam line at the Large Hadron Collider and led to the discovery of the Higgs particle.

- The application of carbon composite materials and the development of CO_2 evaporative cooling was transformative. It enabled large precision system to be built with low mass. Radiation hardness of electronics and sensors, on the other hand, while critical, have tended to improve through many incremental developments.

Using this framework as a guide we can also differentiate between transformative and incremental improvements needed for future instrumentation. Taking the basic constraints and characteristics of the aforementioned future facilities, we are confronted with the following potentially transformative challenges. How can we achieve the granularity, speed, and background rejection, needed to function in a collider with the luminosity required in future applications ($\mathcal{L} = 3 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and fluence of $10^{18} n_{\mathrm{eq}}/\mathrm{cm}^2$)? What new materials could exhibit the necessary radiation resistance? How can we study and test our materials and components in this environment? How can we achieve low mass and reliability in large systems requiring increasingly greater precision and stability? These challenges, and the perspective of past developments lead to the following transformative PRDs for solid state tracking (presently unranked):

PRD1: High resolution pixel detectors with per pixel fast timing: In the present decade a technological innovation occurred with the introduction of high granularity ($\sim 1\mathrm{mm}^2$), low gain, avalanche based, solid state timing detectors. These, which achieve timing resolution of some 10s of picoseconds, are already being applied to LHC collider upgrades to suppress large backgrounds at high luminosity. The present generation of devices are limited to relatively large cell size due to inefficient collection around pad edges, and existing readout electronics. Furthermore, large systems are yet to be designed or demonstrated. A transformative development, aimed at future colliders, would be to achieve both high spatial and timing resolution in a true pixel geometry. Such a transformative capability stands to deliver the needed pile-up background rejection at a future high luminosity hadron collider.

PRD2: New materials and processes for sensors, and associated infrastructure: As noted already, the many improvements which have occurred since the 1970s, in radiation hardened silicon sensors, have been astounding, but also mainly incremental. In some sense, we have survived, not by attenuating the effects of radiation, but in spite of them. We have learned to live with them at a cost. The cost has been in power, cooling, electronics, and ultimately mass and money. It is therefore fair to ask whether there could be a transformative development which would change the rules entirely? For example, could we operate near room temperature? Could we integrate novel materials developed in nanotechnology in our detector design? In this regard we propose a program to study and evaluate alternative materials to silicon and or new processes and/or configurations, and develop industrial partners with the aim of dramatically altering the behavior of highly irradiated sensors.

PRD3: A high intensity irradiation program for the US community: The HEP community lacks access to a long term irradiation facility with the characteristics, availability, and experimental infrastructure required to support a program of transformative R&D aimed at a future hadron collider. In fact, the development of such a facility would be transformative to the entire R&D program. We therefore propose that such a dedicated facility be designed and built as a service to the community with year round operation.

PRD4: Large scale irreducible mass tracking system: The specific characteristics of a future linear or circular electron/positron collider suggest that dramatic reductions in mass may be achieved. Aspects of this have been discussed for over 10 years already and include pulsed power, gas cooling, and thinned sensors. Since that time, a new generation of monolithic active pixel devices have been proposed and prototyped. These can be fabricated in certain commercially available CMOS processes suggesting that large scale production of true mass-minimized, or irreducible mass trackers, namely trackers whose mass budget is basically the mass of the silicon sensor. It would be transformative to demonstrate that such an irreducible mass tracker can be realized as a functioning system.

Beyond these specific and prioritized development projects, it must be recognized that solid state tracking requires the support of specialized infrastructure and specialized electrical and mechanical engineering capabilities. While much of these exist today, and have been built up over the past 25 years, they also must be sustained and, as appropriate, modernized. This is required for any transformative, or incremental R&D program to proceed. Specific, but not exhaustive aspects of these two categories, infrastructure and engineering, are itemized below.

1.1 Category 1: Infrastructure and capabilities

The infrastructure needed to undertake the R&D and fabrication for the PRDs listed here include:

1. Test beam facilities,
2. irradiation facilities,
3. advanced IC design infrastructure including design and routing software, simulation tools, and licenses, and access to commercial processes directly and through prototyping services
4. dedicated semiconductor fabrication facilities and characterization tools,
5. facilities and technical resources to process carbon fiber components for mechanical and cooling support.

1.2 Category 2: Engineering

The engineering talent and expertise in our universities and national laboratories required to confront the design challenges required for the PRDs and new tracking systems, in general, include:

1. Fast front end devices including timing information,
2. fast timing, control, and data transmission systems,
3. power management and low power systems,
4. low mass composite structures for mechanical, thermal, electrical components,
5. bonding and packaging technologies,
6. precision alignment methods.