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Concluding remarks

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Abstract

The following concluding remarks summarize the outstanding progress in the development of semi-conductor tracking and vertex detectors for particle physics applications, as presented at this 15th International Workshop on Vertex Detectors. Also discussed are recent astrophysics and medical applications of these detectors.

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1. Introduction

The 15th International Workshop on Vertex Detectors (Vertex06) exceeded even the highest expectations of this conference series. In 4 days of outstanding plenary talks, we have listened to an open and comprehensive discussion on the status and development of semiconductor detectors for particle physics and related activities.

Following the development and successful use of silicon microstrip detectors for secondary vertex reconstruction in fixed-target and collider (LEP, Tevatron, HERA) experiments, the technology has matured. Both the sensors and their associated front-end electronics have been developed for use with short signal shaping (typically 20 ns) in high radiation environments. Very large area tracking systems are being constructed for the CMS and ATLAS experiments, and novel designs exist at the Tevatron, B-factory and HERA experiments, as well as in future for the LHCb experiment. The Pamela charged particle spectrometer is collecting data in space, while other tracking systems (AMS-02, GLAST) are being prepared for operation in space.

The first pixel vertex detector (the CCD detector of SLD at SLAC [1]) remains a jewel: the lowest mass and highest resolution vertex detector so far built for a collider. It is the benchmark for future R&D towards vertex detectors at the International Linear e^+e^- Collider (ILC). Its CCD readout is however not appropriate for the conditions at hadron colliders. Following the pioneering work of Heijne and collaborators [2] in the active readout of individual pixels, there has been enormous progress. The pixel systems of ATLAS, CMS and ALICE at the CERN LHC are being constructed: these pixel systems are larger than the first microstrip systems at LEP and CDF.

At the proposed ILC, the radiation environment is less hostile than the LHC and the requirement is towards very high efficiency for b- and c-quark identification. This is driving the effort towards low mass and high precision detectors and towards monolithic devices.

The successful development of pixel detectors has lead to an explosion of ideas for their use in new applications — medical and biological imaging, crystallography, astronomical imaging, radiation monitoring to name just a few. This activity is likely to intensify in the coming years.

Given the enormous range of R&D, pushing the use of semiconductor systems in many applications, and pushing the requirements on such detectors to the limits of technology, it is impossible to do justice to the outstanding developments discussed in this workshop. In this summary, I will therefore try to identify some lessons from existing vertex and tracking detectors, and to outline some key directions of future development.

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2. Pushing the technology — large area tracking and vertex detectors

At this workshop, we heard excellent presentations concerning the operating CDF and D0 silicon trackers at the Fermilab Tevatron (D. Tsybychev, M. Stanitzki), the ZEUS MVD at HERA (E. Koffeman), and the Belle SVD at the KEK B-factory (O. Tajima). What lessons can be learned?

- The system issues of these detectors are complex. The commissioning is long with optimal performance achieved after long periods of monitoring the performance, systematically addressing problems (for example bonding wire resonances at CDF), and analyzing the data. The devil is in the details. In particular, stability is a key issue for optimal alignment.
- In most cases, the existing systems have evolved following long-term experience (for example the 0.7 M channel SVX of CDF) and now combine tracking and vertex functions. The material budget is a limiting performance factor resulting in the development of small-radius layers at CDF (L00) and D0 (L0) to reduce the multiple scattering at the first hit and therefore improve the vertex reconstruction accuracy and b-tagging efficiency. The ingenuity and resulting performance of these layers is impressive and shows the ability to implement very novel and complex designs in a harsh and constrained environment.
- At hadron machines, there is a need to monitor the beams closely to avoid radiation accidents. The performance deterioration due to radiation is being carefully monitored at CDF and D0, and the data are in good agreement with radiation projections at LHC. CDF has introduced diamond sensors to monitor the beam and such monitors are planned at LHC.

The construction status of the ATLAS ($62\,m^2$) and CMS ($220\,m^2$) microstrip silicon tracking systems were presented by J. Carter and R. DAlessandro, respectively. The frankness of the speakers in describing the problems encountered in developing and then constructing these two systems over more than 10 years was much appreciated. The systems are an order of magnitude larger than the CDF silicon tracking system. The sensors and associated electronics are required to survive an integrated fluence 2×10^{14} equivalent 1 MeV neutrons/cm^2 over a 10-year period without major intervention and this has led to major industrial development in sensor reliability. The need to clock the electronics at 40 MHz and to maintain a $S{:}N$ ratio $\geqslant 10$ over that period was a major challenge. The experiments chose surprisingly different technologies for their trackers (for example analogue readout for CMS, binary readout for ATLAS) but the resulting performance is similar. Having completed the construction, major concerns related to the commissioning (and to any future upgrade) include:

- the logistics of the geographically dispersed construction which was finally successful but very daunting and should be revisited in future;
- the services budget (material, real estate) which remains a major problem for each experiment: any future increase of services would be impracticable and will be a major constraint at SLHC — the powering of individual modules will not be possible with any future increased density of readout; and
- the reliability, stability and robustness of cooling which is a key issue in each experiment.

The commissioning, monitoring, track and vertex reconstruction, heavy quark tagging and accurate off-line alignment stability of the LHC tracking systems will be challenging and time-consuming tasks that should be carefully evaluated in future, in the context of high-luminosity upgrades. Two sessions of the workshop were devoted to these important tasks. Past experience at the Tevatron, LEP and Hera (for example the latest B_S oscillation measurement from CDF [3]) has shown the importance of a careful and long-term calibration and alignment of these detectors. Even prior to alignment, tracks from preliminary cosmic ray analyses in ATLAS (talk of M. Costa) have residuals compatible with the technical specifications for construction accuracy and stability.

The LHCb microstrip detector (presented by T. Bowcock) is a LEP-sized system but the emphasis on novel geometric design, high level trigger, low mass (services and CO_2 cooling) and mechanical stability should serve as design criteria for future large systems. The ALICE silicon drift detector (presented by S. Beole) is a beautiful and novel design adapted to heavy-ion collisions.

3. Pushing tracking technology into space

The initial success of the AMS-01 microstrip tracking detector (talk of W. Burger) launched on the Space Shuttle in 1998 gave confidence in the use of rugged semiconductor trackers for astro-particle applications. The large acceptance AMS-02 awaits a launch date for installation on the ISS where, using a novel 0.8 T superconducting magnet, it will record the charged particle rigidity as a function of charge and atomic number ($Z \leqslant 26$), as well as the photon energy spectrum. The smaller PAMELA tracker (talk of S. Ricciarini) was launched in July 2006 and is already collecting data. Both tracking systems are relatively conventional, but have been adapted for new and potentially exciting physics applications.

The LAT of the GLAST experiment (talk of S. Germani) is a large aperture combined tracking and shower detector to detect photons in the range 30 MeV to 300 GeV. With $80\,m^2$ of silicon surface it is technically interesting because of its modular design allowing a high performance and very rugged silicon microstrip tracker in space. It also happens to be the largest completed microstrip system built.

4. The evolution of pixel devices

Among the most impressive achievements described at this workshop are the large pixel systems nearing completion