Concluding Remarks

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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 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 e^+e^- linear collider, 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.

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 0.7M 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 1*st*. 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 ($62\,\mathrm{m}^2$) and CMS ($220\,\mathrm{m}^2$) 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 2 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 ≥ 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 CO2 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 $0.8T$ superconducting magnet, it will record the charged particle rigidity as a function of charge and atomic number ($Z \leq 26$), 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-300 GeV. With $80\,\mathrm{m}^2$ 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 at CMS, ATLAS and ALICE (talks of H. Kaestli, M. Christinziani, G. Bolla, A. Kluge). The concerted R&D (robust bump bonding, radiation hard CMOS electronics shown to survive ≥ 50 Mrad, oxygenated n^+–on–n sensors that can operate after integrated fluences of $\sim 10^{15}$ equivalent 1MeV neutrons/cm^2, novel mechanical and cooling structures) required for the pixel systems has led to a mature detector technology that was considered adventurous just 10 years ago. Pixel readout has so many advantages (for example limited occupancy, low noise due to the small sensor capacitance) that is the basis of an explosion of activity within the particle physics environment but also in other scientific fields. An example is the Medipix2 chip that has been developed in parallel for imaging applications and that is discussed in Section 8.

Many development and production problems have been solved en route in the development of the above pixel systems. Looking back, however, many were very mundane in character (for example corroding cooling tubes in the case of ATLAS). As emphasized in this meeting by R. Horisberger, key issues in the next generation of pixel (and microstrip) systems will be the material budget from services, connector technologies (for example bump bonding is presently a cost driver) and cooling.

5. A challenge – future technologies for SLHC

This short summary does not do justice to the enormous R&D effort over the past 10–15 years to develop sensor and readout technologies for LHC operation. Before even the first LHC collisions, attention is turning to requirements in the case of a high-luminosity LHC upgrade (SLHC). Let us recall first the achievements of the R&D for the existing detectors.

- The inner pixel layers of the ATLAS and CMS experiments are expected to withstand with satisfactory performance an integrated fluence of 10^{15} equivalent 1 MeV neutrons/cm^2. The inner microstrip layers of these experiments are designed to withstand an integrated fluence over 10 years of 3.10^{14} equivalent 1MeV neutrons/cm^2. To achieve these lifetimes, the pixel sensors have been chosen to be n^+–on–n to enhance charge collection after radiation. The p–on–n microstrip sensors are required to operate up to 500 V reverse bias voltage, and up to 350 V without micro-discharge or other breakdowns.
- To maintain the sensor shot noise at an acceptable value, the sensors must be cooled to around -5^{o}C. Thermal stability (or at least the repro-

ducibility of thermal movements) must be maintained. Furthermore, each module is independently powered and read out with a consequent material service budget.

Several talks at this workshop addressed the requirements for SLHC, with integrated doses reaching 6.10^{16} equivalent 1 MeV neutrons at the inner pixel disk and $\sim$ 500 Mrad for the readout electronics. How are these challenges being tackled?

- The linear dependence of the bias leakage current on radiation damage indicates that the sensors must operate $\sim$15^{o}C colder than at present, indicating coolant temperatures $\sim$ -40^{o}C (or much improved thermal contact to the module). Liquid CO2 is currently a favoured coolant candidate (following the experience from AMS and then LHCb). The sensor and electronic cooling contacts will be a very important engineering issue for SLHC.
- The CERN RD50 Collaboration (talks of A. Messineo and M. Artuso) has been and will continue to be essential to the detailed understanding of silicon sensors following high radiation. With apologies, the following remarks probably summarize the state-of-the-art. Sensor n^+–on–n technology has been used on the existing pixel sensors, but the cost of backside processing excluded its use for the microstrip sensors. In future, n–on–p sensors appear a viable alternative. Despite higher depletion voltages (V_D) because of the lack of type inversion, good charge collection is possible well below V_D without backside processing. Although oxygenated silicon wafers show reduced damage to proton radiation (small radii), the effect is marginal for neutron radiation (at larger radii in a collider experiment). Following radiation, there is some evidence (not yet fully understood) that the reverse annealing of silicon wafers manufactured using the magnetic Czochralski (MCz) method saturates much more than wafers manufactured using the Float Zone (FZ) method. That would allow an easier management of large systems after irradiation. At SLHC, the individual microstrip dimensions will be determined by a tradeoff of signal collection and occupancy.
- In the intermediate radial region (r $\sim$20-50 cm) the transition between large pixel devices and short microstrips is still an open question. The preferred solution (occupancy, pattern recognition) would be large pixels, but the cost of existing bump bonding and other interconnection technologies needs to be reduced substantially (see the talk of R. Horisberger). The alternative is to use short microstrips of $\sim$ 3 cm length. This is an important R&D issue for SLHC. At the smallest radii, special sensor technologies (see below) are needed, while at r $>$ 50 cm n–on–p microstrip sensors with a strip dimension similar to that now existing (for ATLAS 12 cm length and 80 μm pitch) are appropriate.
- The existing LHC experiments largely underestimated the service (cooling, cables) real estate and material budget, and the problem has been resolved ad–hoc. The larger number of pixel and microstrip channels at SLHC will require a new solution for services and this has become a key R&D issue. The cooling problem has been discussed above. The sensors and front-end electronics can no longer be powered independently for each module (hybrid). Two possibilities exist: the serial powering of several hybrids with the consequent risk of acceptance loss in the case of failure, and/or on-detector DC voltage conversion. Initial studies by the CMS and LHC experiments, not reported in detail in this workshop, are very encouraging.

A radically new approach is needed to provide sensor radiation hardness in the inner pixel layers ($> 10^{16}$ equivalent 1 MeV neutron fluence/cm^2). Two solutions look promising. The charge collection of both polycrystalline and singe crystal diamond looks adequate and a full ATLAS pixel module using diamond sensors was recently fabricated (talk of R. Wallny). Tests are ongoing. The key issues concern cost and competitive industrial procurement. The second possibility concerns 3–D pixel sensors (talk of C. Da Via), proposed by Parker (4). Here the p^+ and n^+ electrodes are implanted as columns within the detector bulk, with typically 50 μm separation. This geometry maintains good primary ionization (sensor thickness) and good collection efficiency due to the small electrode separation. The geometry also enables very small dead regions at the sensor edge. Results using these sensors (now fabricated at Stanford University) are very encouraging (speed, charge collection, etc). A careful evaluation of the performance, radiation hardness, cost and industrial procurement of both diamond and 3–D silicon sensors is essential in the coming 1–2 years.

A second issue concerns the ability of the general purpose LHC detectors to trigger on the pixel (and microstrip) layers prior to a Level–2 trigger. At Fermilab, the CDF SVT trigger (unfortunately not discussed at this workshop) has allowed a myriad of new important analyses, for example a first measurement of B_S-mixing. At the LHC, software level–2 offset-vertex triggers have been developed for the CMS and ATLAS detectors, but no convincing physics case has yet been presented for selections earlier in the trigger chain and neither experiment has such a trigger capability (the CMS pixel readout chip has some test functions). However, because of the expected fake trigger rate for high-p_T μ's at CMS, a level–1 track trigger is expec ted to be necessary for operation at the SLHC. M. Vos gave a very informative talk on simulations concerning this issue. Even with coarse pixel readout, the results look promising. The ability to make 3-D interconnects (see Section 6) will also be relevant to this issue. The ATLAS experiment, which has independent muon and inner track spectrometers, is less affected by the fake rate.

The specialized LHCb detector has of course a sophisticated track and vertex trigger that is crucial for their physics program. Evolutions of that trigger for SLHC operation will certainly be needed.

6. A challenge – Vertex detectors in future e^+e^- colliders

The talk of A. Nomerotski at this Workshop provided an excellent overview of the Vertex Detector requirements at the ILC and how they might be achieved. It is worthwhile to recall the specifications of the SLD CCD vertex detector:

– pixel dimensions of 20 x 20 x 20 μm^3 with a 3-D resolution of the order of 3-4 μm;
– a material budget of 0.4% X_0 per layer.

The specified track impact resolution for ILC detectors is σ=[(4)^2+(8/p)^2]$^{0.5}$ μm with p in units of GeV/c (to be compared with σ=[(10)^2+(40/p)^2]$^{0.5}$ μm at CDF). To reduce gamma conversions, and the non-gaussian resolution associated to multiple scattering, a layer thickness of 0.1% X_0 is specified. These extreme specifications, together with the requirements of high heavy flavor tagging efficiency over a large solid angle, motivate the ongoing R&D towards high-density electronics, thin monolithic pixel sensors and extremely aggressive mechanical support and cooling structures.

The above material requirement is a major engineering challenge, especially in the case of cryogenic operation. The first step in achieving this is to glue thinned sensors ($\sim$ 20-50 μm) to a low mass support such as beryllium. Because of both the material budget and the pixel size, a separated readout scheme is excluded. Materials such as silicon carbide foam are being considered for the support cylinder. A laser system would track each sensor position. The material from services and thermal management is part of the above budget.

A logical extension of the SLD detector would be to use the CCD readout technology, modified for the different bunch train of the ILC by using fast column-parallel readout with subsequent ADC conversion and sparsification. The talk of S. Worm described these developments. The radiation hardness remains an issue. An alternative is the DEPFET structure (talk of P. Fischer) being developed at HLL Munich. Good results have been obtained in several test-beam runs and the radiation hardness has been demonstrated at $>$ 1 Mrad. Full-size structures are now being fabricated.

Several active pixel sensor developments are also underway (talks of T. Tsuboyama, R. Turchetta, I. Peric, D. Passeri) In the Japanese SOIPIX collaboration, a high resistivity silicon substrate is separated with a buried oxide layer from a low-resistivity layer to form a MOSFET, with a superimposed SOI structure. Initial results are encouraging and the collaboration hopes to fabricate an application-specific sensor in 1-2 years. The talks of Turchetta, Passeri and Peric concerned monolithic active pixel sensors (MAPS) where a thin epitaxial layer on a p-substrate acts as the sensor and a n-well pixel diode structure is superimposed. Very encouraging S:N ratios have been recorded using sources (for example ^{90}Sr), test beams and laser signals.

These monolithic pixel developments are essential to meet the specifications for experiments at the ILC and developments will be of major interest in the coming few years.

Finally I would like to mention the presentation of V. Suntharalingam concerning 3-D circuit interconnection developments at the MIT-Lincoln laboratory. The potential of this 3-D via technology for on-detector processing (triggering, readout) and should be encouraged in the context of pixellated particle detectors.

7. Pushing the limits – Pixel technology in astrophysics and cosmology

For me, one of the most interesting talks of this Workshop concerned the planned Large Synoptic Survey Telescope (LSST, P. OConnor). This 8m class telescope will use a 3.5 Gigabit pixel CCD camera at the focal plane to map the sky in the wavelength range 0.3–1.1 μm. The convergence of fundamental questions in cosmology and particle physics has resulted from semiconductor instrumental developments in both disciplines. Using a 0.3 m^2 area of fully depleted 10 x 10 μm^2 pixel sensors with low noise CCD readout, the key developments in this system will be the sensor optimization, the mechanical and thermal stability and the very high readout rates. Up to 10 TByte of data will be collected per night. This far-reaching project is just one of many new applications for pixel systems in fundamental physics, with increasing collaboration in diverse areas between instrumentalists in cosmology and particle physics.

The AMS-02, Pamela and GLAST microstrip systems have already been discussed in previous sections.

8. Pushing the limits – Pixel technology in other applications

The Medipix2 chip has been the motor for many new applications. P. Scopellitti discussed the use of this chip, and also other monolithic chip developments (Mimosa V, MAPS), for crystallography and biological imaging applications. Medipix2 chips, as well as developments from the CMS and ATLAS pixel readout chips, are being used at synchrotron radiation facilities.

The talk of S. Pospisil demonstrated the success and versatility of the Medipix2 chip. With attached sensors of 150-700 μm thickness, and in some cases coating for low-energy neutron conversion, a portable Medipix2 system has shown outstanding promise for medical imaging, and for real-time dosimetry (including particle identification). These applications will mature in the coming 1–2 years, and will provide exciting new results at future workshops. Given the enormous (and increasing) range of applications, a Medipix3 chip is being discussed. Equivalent work with more sophisticated monolithic devices is also expected.

Also in the meeting D. Renker reviewed the less-developed but potentially important technology of silicon photomultiplier detectors. Applications involving separated photon conversion and multiplication to image on a pixel chip have been successfully demonstrated, but not yet on an integrated device. As Renker indicated, important R&D issues for many applications are to reduce the insensitive area presently required at the edge of each detector element, and to reduce the pixel element size.

9. Conclusions

Silicon tracking and vertex detector technology has matured. For the first time, completed tracking systems that are now being commissioned have been described (CMS, ATLAS, GLAST, LHCb). The success of these systems has in large part resulted from the robust sensor technology provided by industrial suppliers, and also in large part by the development of intrinsically radiation tolerant 0.25

μm CMOS readout [1]. These systems are expected to survive 10 years of LHC operation, and must be replaced as the LHC luminosity is upgraded. Key issues will then concern the real estate of electrical and cooling services that are already a limiting factor. For space applications, the construction requirements of Pamela, AMS-02 and GLAST have resulted in impressive designs.

Vertex applications are now mainly provided by pixel systems, which have rapidly matured at ATLAS, CMS and ALICE. Key issues in the pixel development path included the development of affordable and reliable bump-bonding processes, in addition to developments of sensor and 0.25 μm readout technologies. Although somewhat massive, the success of these developments has spurred major R&D activity in several directions:

– larger pixel systems requiring cost-effective bump bonding (e.g. SLHC application);
– improvements in sensor technology (e.g. 3-D sensors, diamond sensors) to withstand high integrated particle fluence (e.g. SLHC applications);
– very low-mass vertex systems adapted for highly efficient and precise heavy-flavor tagging at future e^+e^- linear colliders, with either CCD or MAPS–style integrated readout;
– increased R&D activity in multilayer high density electronics and 3–D interconnects;
– the use of pixel arrays for large-aperture imaging applications (e.g. the future LSST, SNAP etc) and more generally a convergence of instrumental imaging techniques for aspects of particle physics and astronomy;
– the use of pixel arrays for medical imaging, dosimetry, crystallography and other applications around synchrotron light sources, and in future many other applications.

The need for a hardware-related tracking trigger has been identified by CMS at SLHC for the first time (for instrumental reasons given the fake rate of high-p_T μ's). The SVT trigger at CDF allowed a substantial increase in physics reach. At the SLHC, the implementation of such triggers may open many future applications despite the lack of a demonstrated physics need so far. A better understanding of where trigger capabilities might be needed by the upgraded CMS and ATLAS experiments at the SLHC would be useful.

Gaseous detectors are likely to remain important for tracking applications (e.g. the ILC). However, even in the hostile environment of the SLHC, proposals exist to use gaseous detectors for vertex and large area tracking applications (for example the GOSSIP pixilated detector reviewed at this Workshop by E. Koffeman). Despite the intrinsic problems of low primary ionization and the need to prevent discharges, the development of these detectors is expected to remain competitive.

At this Workshop, I have found it impossible to do justice to the outstanding developments that are pushing semiconductor detector technologies beyond existing boundaries, in several directions. I have tried to identify some lessons from existing vertex and tracking detectors, and to outline some key directions of future development. I look forward to many exciting future Workshops in this series.

10. Acknowledgments

In more than 50 plenary talks over the week, both the maturity of recent semiconductor vertex and tracking systems and the vitality of new and innovative R&D have been evident. Their development has closely mirrored the evolution of this small but enormously respected Workshop. I would like to thank Gian Mario Bilei, the Chair of the Workshop, for the quality of the Scientific Program and for both the quality and friendliness of the organization. The Relais San Clemente where this Workshop has been held is a beautiful, peaceful and relaxed location that provided a superb ambiance for discussions. The Local Organising Committee (Gian Mario, Giovanni Ambrosi, Livio Fano′, Daniele Passeri, Attilio Santochhia, Paolo Zucconi and their secretarial backup) solved every problem that arrived. I would also like to thank all the participants for their kindness in providing information for this concluding talk. It has been

[1] ATLAS uses the BiCMOS DMILL process for the microstrip readout and a 0.25 μm CMOS process for the pixel readout. CMS uses the 0.25 μm CMOS process for both the microstrip and pixel readout

impossible to include all the available material in this talk, but from the quality of the presentations, I am fully convinced that future workshops of this Vertex series will be very exciting and rewarding.

References

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