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DETECTORS

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1 Introduction

Detectors play a crucial role in the study of elementary particles. The rapid advance of particle detector technology has allowed experimentalists to take advantage of corresponding improvements in particle accelerators. Notable examples from the past few decades include the multi-wire proportional chamber and its numerous variants, large-scale calorimeters, silicon strip detectors, large water-Čerenkov detectors, and the automation of data acquisition through online computers. Without these and other important developments, our current knowledge of elementary particles and their interactions would no doubt be far less advanced than it is today. Much of this technology finds immediate application in other areas of physics and in fields such as medicine, where there is a direct impact on everyday life.

To be able to take advantage of new accelerator facilities in the U.S. and abroad, it is essential that particle physicists continue to make progress in the development of detectors. Such advances will not only be of value at new facilities, but will allow us to exploit further existing machines. One can expect that as in the past, advances will take the form of refinements and improvements in existing techniques as well as completely new inventions.

A number of areas where progress can and should be made have been identified. These include the development of:

- radiation hard materials and electronics;
- advanced vertex detectors such as strip detectors, pixel detectors, and detectors based on new materials such as gallium arsenide and diamond;
- improved photodetectors;
- fast vertex triggers;
- high-precision and/or large-area arrays for muon detection;
- fast, bright, radiation-hard crystals;
- high-speed noble-liquid calorimeters;
- high-density, low-cost electronics;
- large bandwidth data acquisition systems and switching networks; and

- hadron identification devices for the study of B physics.

These technologies are of importance not only to accelerator-based experiments but to the growing number of particle astrophysics experiments as well.

In this chapter, we present an overview of the state of the art in particle detectors and consider in more detail the areas in which further progress should be made. In our conclusions we propose a detector R&D program that will help stimulate work in this important area. Although the current funding situation is such that it is not realistic to think in terms of replacing the generic detector R&D programs sponsored by the SSC Laboratory and the Texas National Laboratory Research Commission, we believe that even a considerably more modest program would have an important impact.

2 Tracking

2.1 Requirements

Tracking of charged particles, usually in a magnetic field, is a standard function of most HEP detectors. The past years have seen an extension of trackers designed mainly for momentum determination and pattern recognition to devices capable of specific ionization measurements for particle ID and, more recently, the incorporation of precision vertex measurements to identify long-lived particles. In the future, high rate operation will be a major challenge. This applies to both gaseous and solid state tracking detectors. High occupancy and radiation damage have to be dealt with in nearly all future applications:

- B Factories at Cornell, SLAC and KEK;
- FNAL collider upgrades of CDF and D0;
- SLD upgrade;
- RHIC experiments;
- LHC experiments (Atlas, CMS, ALICE);
- Fixed Target experiments at FNAL and CERN;
- Experiments at HERA; and
- Space applications.

Engineering questions will play an increasingly important role in all of these applications as outlined below.

2.2 Semiconductor Detectors

Semiconductor tracking detectors play a crucial role in precision vertex reconstruction. They range from silicon microstrip detectors, which are essentially one-dimensional devices, to inherently two-dimensional devices such as pixel detectors and charged-coupled devices (CCD's). There is also an emerging diamond detector technology. For storage rings, pixel detectors could offer significantly better intrinsic resolution than silicon strips because of their high signal-to-noise. Multiple scattering could, in principle, be decreased if the electronics are kept thin and if the system can be supported and cooled with minimum material. At the B Factories, where typical track momenta are quite low (a few hundred MeV), these improvements will result in improved impact parameter resolution only if the beam pipe is also significantly thinner than those being designed and constructed today.

The development of semiconductor detectors goes hand in hand with the development of ASIC (application specific integrated circuits) front-end electronics and readout systems. Modern designs are fully integrated mechanically and electrically, so as to achieve a match between the channel pitch of the detector and its electronics. The resulting channel counts are very large and require special care in the design of data storage and readout systems.

2.2.1 Silicon Strip Detectors

In the arena of silicon microstrip detectors, two areas of development stand out: forward silicon tracking in colliding beam experiments and improved detector spatial resolution. The benefits of improved forward tracking coverage are obvious. Research efforts have demonstrated that "wedge" silicon microstrip detectors with constant or variable strip pitch work. Further investigation of double sided designs and radiation hardness need to be performed. The high spatial resolutions of microstrip detectors sharpen impact parameter determination, event pattern recognition, and momentum resolution. Several groups have obtained position resolutions under 5 μm with microstrip detectors by incorporating passive intermediate strips. Further improvements are possible.

Another challenge for vertex detectors at many collider experiments, especially asymmetric B Factories, is the measurement of both coordinates in the plane of the detector. Currently this is being addressed by double-sided silicon strips.

In future applications at LHC and in space, large-scale use (tens of square meters) of silicon strips is foreseen. The engineering issues associated with such large arrays are much the same as for smaller systems and include: cooling, mechanical supports, thinning of electronics and detectors, radiation hardness, and the production of reliable and uniform detectors. Clearly unit cost will be a prime consideration. Reliable electronics will also be essential for progress in developing the planned large and precise systems.

2.2.2 Diamonds

Detectors based on diamond material constitute a rapidly emerging new technology. In this approach diamond sheets are grown by the chemical vapor deposition (CVD) process [1], which allows large areas of high quality diamond to be grown at reasonable cost. Diamond has many properties that make it an excellent material for use in particle detectors: high resistance to radiation damage, large resistivity, saturated carrier velocities, low dielectric constant, high thermal conductivity, large mechanical strength, and potentially low cost. The most important of these is diamond's radiation hardness relative to conventional detector materials. This makes diamond detectors highly attractive for coping with the intense radiation environments that will exist in planned future experiments at the LHC, the Fermilab Collider in the era of the Main Injector, and high-intensity fixed-target experiments.

Since diamond is an excellent electrical insulator, there is negligible leakage current in diamond detectors. In addition to effectively eliminating shot noise, this property also simplifies the fabrication of detector devices since there is no need for a *p-n* junction. Instead, an electric field, typically 10^4 V/cm, is directly applied across the thickness of the diamond. A charged particle traversing the diamond creates electron-hole pairs, which then separate in the applied field, inducing charge on the surface electrodes.

The quality of detector-grade diamond is characterized in terms of collection distance: the average distance an electron-hole pair separates under an applied electric field. Over the past five years, the value of the collection distance of the best available diamond has increased at the rate of about an order of magnitude every 18 months. The highest quality diamond currently tested has a collection distance of 85 μm, corresponding to an average collected charge of 3000 electrons for a minimum ionizing particle. A twenty-layer twenty-radiation length diamond/tungsten sampling calorimeter was tested and found to have the same performance as a silicon/tungsten calorimeter and performed as predicted by an EGS calculation [2]. This demonstrates that current diamond quality is sufficient for employing diamond calorimeters in experiments. A series of diamond microstrip detectors have also been tested. One of these, with a collection distance of 50 μm, has a signal to noise of 6:1 and a position resolution of 25 μm for a 100 μm strip pitch [3]. A diamond tracker with suitable signal-to-noise for use in experiments will require a collection distance of about 200 μm, corresponding to 7000 collected electrons; a factor of two-to-three improvement over current diamond.

The radiation hardness of natural diamond has been known for many years [4]. Recently a set of radiation hardness measurements of CVD diamond has been made. The tests revealed no degradation of pulse height nor any measurable leakage current after exposures of up to 10 MRad of ^{60}Co gamma rays, fluences of $10^{14}/\text{cm}^2$ of 300 MeV pions, and fluences of a few $10^{13}/\text{cm}^2$ of 500 MeV protons. Further studies are planned to extend the above exposures by an order of magnitude and to include exposures to a fluences of few $10^{14}/\text{cm}^2$ neutrons [5].

2.2.3 Pixel Detectors

Pixel detectors represent a natural next step in the evolution of position-sensitive semiconductor detectors. Although strip detectors have been highly successful in applications where high precision and good double track separation are required, pixel detectors offer a number of important advantages:

- Each measurement plane provides a complete space-point measurement, serving the same function as two planes of strips.
- The tracking combinatorics are greatly reduced. With two sets of strips, n simultaneous hits results in $n!$ possible solutions, whereas pixel detectors naturally correlate the x and y views.
- The per-element occupancy in pixel detectors is much lower, allowing operation at much higher beam intensity.
- The low capacitance of pixels results in lower noise and a correspondingly better signal-to-noise ratio.

The first use of pixel detectors was by Damerell who showed that CCD's could detect minimum ionizing particles [6]. The CCD's proved to have great advantages in pattern recognition, but were not widely used in other experiments due to their slow readout and thin sensitive region (a few tens of μm). These problems do not occur in the pixel detectors now under development, which can have sparse field readout and in which nearly the full thickness of a chip is sensitive. The simplest uses a PIN diode with an array of collection electrodes bump-bonded to a readout chip [7]. Monolithic detectors, first fabricated in 1990-1991, with tests described in a series of publications (see reference [8]), incorporate the readout electronics on the same substrate as the charge-collection silicon and consequently are thinner and have five times lower input capacity than bump-bonded devices. Fully depleted CCD's have also been fabricated, but still have the slow readout of the original versions [9].

Monolithic Detectors In a monolithic device, ionization charge goes to a two-dimensional array of collection electrodes that are in contact with the substrate. The electrodes, which are typically several microns across, are connected to the gates of readout transistors. These, and the rest of the pixel circuits are in a single implanted n well that surrounds each collection electrode and occupies the top few microns of the wafer. It provides an optimum environment for the transistors, shields the substrate from transistor switching transients, and, together with a diode covering the bottom of the chip, sets up the collection field that spans the wafer and focuses the charge on the small collection electrodes. The charge remains on the nearby MOS gates where it controls currents flowing to the edge of the chip. It can send current in more than one direction, can be read out at once, and can be stored and read out later as well. Signals from minimum ionizing particles in silicon strip detectors, before amplification, are about 0.01 to 0.1 mV; here they are about 0.1 V. Additional readout electronics are in n and p wells along the chip edges.

Infrared tests show that more than 99.995% of the positive ionization charge generated under the n well, but away from the array edges, goes to the collection electrodes rather than to the n well, which occupies over 90% of the area. In beam tests of an array of $34 \times 125\ \mu\mathrm{m}^2$ pixels with 500 GeV/c muons, signal to single-channel noise ratios of 65 to 1 (with much of the noise due to off-chip electronics) were observed and spatial resolutions of $\sigma \simeq 2\ \mu\mathrm{m}$ were obtained for 90°-incident tracks. Hits with large pulse heights had a larger error due to Landau fluctuations, as did small ones due to their reduced signal-to-noise ratio. For the central 63% the spatial resolution was in the 1.3 to 1.5 μm range. Angled tracks also had poorer resolution, typically in the range of 3 to 6 μm. However, the separation of their entrance and exit positions could be used to give a direction vector having an accuracy of 1° to 3° though usually with a two-fold pointing ambiguity.

Charge sharing near the border of a large pixel (in this case the long direction of the $34 \times 125\ \mu\mathrm{m}^2$ pixel), can improve the position accuracy, although the errors here have a significant non-gaussian tail. If long pixels are used in a staggered "brick" like arrangement, charge spreading to adjacent rows provides two sharing regions in each length: two at the ends of each pixel and one in the middle next to the dividing line in the adjacent rows. The central non-sharing region is, in addition, split into two shorter ones, so the overall resolution in the long direction is greatly improved. Alternately, square pixels with sides of 60–70 μm or less would provide sets of space points with small errors in both directions and, for angled tracks, with a pointing vector attached uniquely to each point. This could provide significant help in tracking complex events.

These first-generation detectors have also been used to detect and measure a 0.1 -mm-wide calcification in a tissue sample from a breast tumor, about half the diameter of the smallest ones normally seen in clinical practice [10].

The second-generation detectors now in fabrication will have sparse-field readout. A proposed quantum mammography system, using monolithic detectors, would not only be fully digital, but would have higher resolution and efficiency than present systems and would count each x-ray quantum to produce the maximum possible information from the available radiation. Such chips would use a high-speed data-push readout [10].

Hybrid Pixel Detectors The main advantage of these detectors is that two known commercial components are combined with a method that is commercially available, if not commonly so. Bumps have been made with solder, gold, tin, indium, and other materials. They have been made with ball bonders that do not leave the usual wire on the ball, by plating, and by thermal evaporation followed by lift-off above the masked regions around the bumps. The Hughes Aircraft Company used indium bumps that were made this way to bond one of their readout chips to a detector made by Micron Semiconductor [7]. Indium bumps are also available from Rockwell International, among other sources [11]. Small indium bumps, 25 μm or less in diameter can be made and reliably bonded using commercial aligner bonders [12] without needing high temperatures.

A SLAC/UC Berkeley Space Sciences Lab/Hughes collaboration tested indium bumped hybrid detectors in a beam at Fermilab. An analysis of that data showed a resolution of 2.6 μm [7]. Hybrid detectors also are used in Omega-WA97 and will be used in the LEP-Delphi experiments at CERN [13].

Several groups are now designing readout chips for use in LHC that will uniquely identify tracks from one of perhaps 20 events in one beam crossing while also avoiding confusion from the tracks of the 80 or more following beam crossings that occur before the arrival of a Level 1 trigger. Due to the expected high rates, all designs keep the information and readout control within individual columns, which operate independently of each other prior to the Level 1 trigger.

The CERN-Omega group plans to store hit information within the pixel while a digital delay within each pixel identifies those with the proper hit times by a coincidence with the Level 1 trigger [13].

The Marseille group plans to shift the address of each hit pixel down its column, one shift per beam crossing, and to calculate the hit time from the address and the arrival time at the column end [14]. They have also placed integrated busses for the readout chips on the detector chip, which spans a group of readout units.

The LBL group plans to set a hit latch and store a buffer address and analog charge information in each hit pixel. The buffers, located at the ends of each column, store only the hit times.

All of the readout architectures will have one form or another of dead time, which is not expected to be too serious. Indeed, radiation damage is expected to be the main limitation on how close the detectors can be placed to the beams.

2.3 Gaseous Detectors

Gas-filled wire chambers continue to be a mainstay of charged particle tracking systems. They provide moderate-to-high rate capability and excellent spatial resolution over large volumes at a manageable cost. Although at the LHC, where the rates will be extremely severe, traditional wire-cathode drift chambers are likely to be displaced by semiconductor detectors, straws, fibers, and/or gas microstrip detectors, gaseous detectors will continue to play an important role at the e^+e^- B Factories and elsewhere.

2.3.1 Small-Cell Wire-Cathode Devices

The main challenge for tracking at the B Factories concerns improving the momentum resolution for tracks with momenta less than 3 GeV/c. This involves operation in high magnetic fields (1.5T) and reducing the amount of material traversed by tracks. The latter requirement has implications for the inner wall of the tracking device, the composition of the wires and the choice of gas. These considerations preclude pressurized devices and point to a low-mass drift chamber as the detector of choice. Thin end-plate supports are also useful to minimize material in front of the particle ID devices and the EM calorimeter.

Many studies during the past five years have shown helium-based gases to be an attractive choice. The radiation length of the gas can be reduced by a factor of five or more. The resulting gas has a much smaller Lorentz angle (and hence much improved high-B-field operation), while still providing spatial and dE/dx resolution comparable to argon-based gases.

2.3.2 Jet-Cell Chambers

The CDF central tracking chamber (CTC) was designed to provide isolated charged-particle tracking, but has since been used to reconstruct on a routine basis nearly all of the charged particles in the very complex, high-rate events at the Tevatron collider down to a tracking threshold of only a few hundred MeV. This advance was made possible by the enormous increase in online and offline computing available to the experiment since it was designed in the 1980's.

2.3.3 Straw Chambers

Arrays of detectors comprising large numbers of individual thin-walled mylar or kapton cylindrical straws offer important advantages for the high rates anticipated at the LHC. In particular, comparatively small ($r \simeq 2$ mm) drift distances are possible (this minimizes the pulse-pair resolution time and the current draw per anode wire) and the wire tension load is greatly reduced since there are no cathode wires. Moreover, the straws can be arranged into mechanically robust modules and individual cells electrically isolated from one another, minimizing the impact of a single broken wire. These devices received much attention as part of the SSC detector R&D program, where the state of the art was considerably advanced. Position resolutions of order 100 μm were measured in 4-mm-diameter straws and straw modules as long as 4 m were constructed.

Serious challenges remain, however, and the particular problems of pileup, occupancy, and detector aging will be even more severe at the LHC. A large volume must be filled with small detector elements, resulting in a high density of signal lines emanating from the detector's readout surfaces. Signal time shaping and recovery are critical. Signal dynamic range and cross-talk mitigation are also a challenge. High drift velocity gases with adequate gain, primary ionization rate and efficient collection and benign chemistry are required. Low mass structures capable of 20 μm alignment tolerances need to be developed.

2.3.4 Time Projection Chambers

Time projection chambers (TPC) are powerful tracking devices that find application in collider experiments where minimization of material is not critical and where time-integrated particle fluxes are fairly low. The direct association of axial with azimuthal information at each radius renders pattern recognition very straightforward. The feasibility of operation at elevated pressure enhances position resolution and dE/dx precision.

2.3.5 Gas Microstrips

This technology is getting very serious attention in Europe, and was the baseline choice for SDC for the forward disks. The small charge collection distance permits fast response. That property and the implementation on a solid substrate allows fine pitch (good position resolution) and flexible geometry. The devices are a potentially lower cost alternative to silicon strips with application to larger area detectors. Work is still needed on substrate choices, where suitable low-mass materials with the correct resistivity must be identified, and on techniques for etching.

2.4 Scintillating Fibers

Much work has been done within SDC and DØ on this technology, which offers a good solution to the need for fine granularity and fast time response and provides natural basis for fast triggering. Sophisticated light detection techniques are under development. In particular, the visible light photon counters (VLPC's) developed by Rockwell International Science Center, offer quantum efficiencies of ~ 75%, good single photoelectron resolution, gains in excess of 10^4, and risetimes under 10 ns [15,16]. Moreover, they are capable of operation in high magnetic fields. With high light-detection efficiency the granularity, position resolution, and mass can be pushed to make fiber trackers a very attractive technology. Better understanding of radiation damage may be needed for very high-radiation applications.

2.5 Areas for Future Development

Research on semiconductor devices has yielded fruitful results in the areas of radiation damage, novel strip geometries, and inherent sensor design and operation. At the same time, bipolar and CMOS ASIC's have been developed for optimizing the readout. In light of the importance of silicon strip technology across all of experimental particle physics, we need to develop U.S. suppliers of these devices, and the opportunity for R&D efforts in close collaboration with industry.

Strong R&D efforts by effective groups in pixel detector development are needed to realize a working system. To take complete advantage of gains in vertex detector technology, technologies for building thin beam pipes and low-mass support structures also need to be pursued.

For collider geometries good solutions combining high speed and granularity with low mass are still elusive. Detector mass exacerbates the problem of high background rates. Monte Carlo calculations of background rates are inadequate—*e.g.*, CDF and DØ experience substantially larger backgrounds than the programs predict.

Drift chamber technology in general would benefit from further systematic study and classification of gas properties: ionization potentials, electron attachment rates, drift in electric and magnetic fields, diffusion, and the chemistry of aging. Work with helium-based gases is quite new and substantial improvements may be possible. More studies are needed regarding the suitability of these gases in high-radiation environments. The capability of Boltzmann-simulation code to predict detailed properties of gases has improved enormously during the past five years and further improvements in the knowledge of the cross sections of popular components are needed.

Similar improvements in materials are being considered for the wires and end plates. Carbon-fiber and magnesium are possible alternatives to aluminum for the end plates. Small-diameter gold-plated aluminum wires require development of special feedthroughs, and the possibility of using gold-plated, carbon-fiber wires should be explored.

3 Calorimetry

3.0.1 Requirements

The primary requirement for electromagnetic calorimetry is energy resolution, which can be parametrized as

$$\frac{\sigma_E}{E} = \frac{A}{E} \oplus \frac{B}{\sqrt{E}} \oplus C \qquad (1)$$

In detectors for e^+e^- storage rings and certain fixed-target experiments, where detection of photons with energies below 100 MeV is important, the first term, which is mainly a consequence of electronic noise, is often crucial, whereas at LHC, where $e^{\pm}$ and γ energies ranging well above 100 GeV will be encountered (*e.g.*, in the decays $H \rightarrow \gamma\gamma$ or $Z \rightarrow e^+e^-$) the third term, usually called the "constant term," can dominate. The stochastic term $(B/\sqrt{E})$ plays an important role in both regimes. For LHC detectors, typical target values are $B = 5\%$–10% (E in GeV) and $C = 0.5\%$–1.0%. At the B Factories, noise contributions of 0.5 MeV or less are desirable, as are stochastic terms corresponding to $B = 1\%$–2%. For hadronic calorimetry, the energy resolution requirements are typically relaxed to $\sigma_E/E = 65\%/\sqrt{E} + 5\%$.

3.1 Liquid Ionization Calorimeters

The precision measurement of the ionization in noble liquid calorimeters started with the pioneering work of Willis and Radeka [17]. Many large scale liquid argon calorimeters have led to productive physics programs: Mark II at SLAC, R806 at the CERN ISR, E706 at Fermilab, HELIOS at CERN, and more recently, DØ at Fermilab [18], SLD at SLAC [19], and H1 at HERA/DESY. All of these devices displayed attractive features intrinsic to the technique: stability, unit gain, flexible longitudinal and transverse segmentation, uniformity, and (in some cases) hermeticity. The DØ detector employs a 50,000 channel liquid argon calorimeter that includes both electromagnetic (EM) and hadronic sections. It is hermetic for missing energy studies and has proven very effective for triggering on and measuring electrons, jets, and photons. The SLD lead liquid-argon calorimeter (LAC) includes an EM section and a short hadron section, followed by an Iarocci-tube calorimeter.

At the LHC liquid calorimetry will be pushed to new frontiers in the following areas: 1) energy resolution, 2) γ pointing, 3) π^0 rejection, 4) dynamic range, and 5) radiation hardness. The energy resolution can be improved by increasing the sampling fraction by using thinner absorbers or using denser active liquids such as krypton. However, good energy resolution requires an excellent calibration system, as has recently been developed at BNL [20].

Achieving the requisite 16–18 bits of dynamic range while maintaining excellent energy resolution presents a serious challenge to the designers of readout electronics. There has been R&D in switched capacitor arrays (SCA) and ADC's to handle more than 12 bits. This work must continue.

The large number of channels being considered for future experiments requires the development of a compact feedthrough that will be cost effective. Another challenge is to integrate the preshower function (pointing and π^0 rejection) into the main calorimeter. Still further R&D is required for the extreme radiation environment at the LHC. There has been a long program of certifying which materials will survive in this environment—but it must continue with the added direction of considering the possible poisoning of the noble liquid. There is also important R&D going on for the radiation stability of the electronics, which is often in close proximity to the calorimeter.

The ATLAS [21] experiment is planning a barrel EM calorimeter and endcap EM and hadron calorimeter with an integrated forward liquid calorimeter. The electrode design is based on the accordion design first introduced by the RD3 Collaboration at CERN [22]. That R&D program has progressed over the last four years to include the demonstration of a 2-m prototype readout with fast (20 ns) shaping that achieved an energy resolution for electromagnetic showers of $(9\text{-}10)\%/\sqrt{E}$ with a constant term of less than 0.4%. Building on this work, R&D using liquid krypton has produced energy resolution of $6.7\%/\sqrt{E}$, timing resolution of 280 ps for 20 GeV [23], and the first time-sampled waveforms (every 18 ns).

Another use for liquid ionization calorimetry is being pursued by the NA48 experiment, which is designed to measure CP violation in K-decays. They have developed a large almost totally liquid krypton EM calorimeter. This device has achieved an energy resolution of $3\%/\sqrt{E}$, and exhibits excellent timing performance [24].

3.2 Crystal Calorimeters

The superb energy resolution and detection efficiency of total absorption shower counters composed of inorganic scintillating crystals have been known for decades. In high-energy physics, the use of large arrays of scintillating crystals for the precision measurement of the energy and angle of photons and electrons has been a key factor in many fundamental discoveries [25]. This was first demonstrated in the Crystal Ball detector's study [26] of radiative transitions and decays of the charmonium family. Over the last decade, larger crystal calorimeters have been constructed, and their use has been a key factor in the successful physics programs of the L3 experiment at LEP [27], CLEO II at CESR [28] and the Crystal Barrel at LEAR [29]. Crystal detector arrays of this type also have been designed and are under development for the next generation of high-energy physics experiments aimed at the study of CP violation, including KTeV at Fermilab [30]), and the SLAC [31] and KEK [32] B Factory detectors.

In addition, crystal calorimeters containing 10^4 to more than 10^5 elements have been designed and studied intensively by a large sector of the high-energy physics community planning experiments for multi-TeV hadron colliders, including the Superconducting SuperCollider (SSC) in the U.S. [33,34] and the Large Hadronic Collider (LHC) at CERN in Europe [35,36].

The unique physics capability of crystal calorimeters is a result of their good electron and photon energy resolution (typically $2\%/\sqrt{E} \oplus 0.5\%$) over a wide energy range, uniform hermetic coverage, fine granularity over a large solid angle, and clean electron and photon identification. A well-designed crystal calorimeter has greater sensitivity than sampling calorimeters for detecting multibody final states containing low-mass resonances (such as π^0, η, and η'), or yet-to-be-discovered particles such as the Higgs in the "Intermediate Mass" range between 80 and 170 GeV [37].

In order to maintain the high resolution and the resultant sensitivity to new physics, the key detector requirements are radiation hardness and precision calibration, in addition to high speed, mechanical robustness, and a stable readout with high linearity and large dynamic range. For experiments that are required to operate in the high-rate high-radiation environment of multi-TeV hadron colliders, very high speed (triggering within the typical beam-crossing time of 25 ns) and radiation resistance up to the 10 MRad range are among the principal design requirements. Following an intensive R&D program for GEM at the SSC, it was demonstrated that mass-produced BaF_2 crystals from China could be rendered radiation hard by optical bleaching *in situ* with visible light [38,39].

For the larger radius crystal calorimeters being considered for CMS at the LHC, CeF_3 and $PbWO_4$ —which are denser than BaF_2—are the leading candidate crystals. Encouraging recent progress has been made in the production of both large CeF_3 and $PbWO_4$ crystals with improved radiation resistance, where crystals of appropriate size and quality have been produced in a number of different laboratories around the world.

At lower energies, high-luminosity experiments searching for rare Design B, K, or τ decays, or performing precise CP-violation measurements through the study of B and K final states containing e^+e^- pairs, single or multiphotons (including π^0's and η's), have chosen CsI(Tl) (CLEO II, Crystal Barrel, SLAC and KEK B Factories) or undoped CsI (KTeV). This offers a mechanically robust, relatively low cost solution to the requirements of high light output, a minimum of material in front of and between the crystals, radiation hardness up to the 10 krad range, and moderate to high speed.

3.3 Scintillator Calorimeters

The use of plastic scintillator as the sensitive medium in sampling calorimeters has been a common approach in experimental high-energy physics for much of the past three decades. Almost all possible sampling geometries have been employed—scintillator tiles with waveshifter bar or waveshifter fiber readout in varying geometries; pure scintillating fiber detectors with fibers running both parallel and perpendicular to the incident particle; and hybrids of the above. The outstanding questions relevant to future high-energy experiments are well defined, although their relative importance depends on the particular application.

Maximizing the fiducial volume is of obvious importance. The use of waveshifting fiber readout can reduce the uninstrumented region by as much as a factor of five relative to the conventional approach using waveshifter bars. However, fabrication labor is increased in the fiber technique, and further refinements are needed. One possibility is the use of injection molding to form the scintillator tile simultaneously with a ready-made slot to contain the readout fiber. At present, however, injection molding does not produce tiles with adequate optical properties. Alternatively, one could use a "spaghetti" calorimeter approach for which no waveshifter is needed and the scintillating fibers run parallel to the direction of incoming particles. This approach is also labor intensive, needs large volumes of scintillating fiber (for which cost reduction is an issue), and is difficult to implement if depth segmentation is necessary. These are all areas appropriate for additional R&D.

For many future applications, radiation damage is still an issue for scintillator calorimetry. Doses of one MRad can be tolerated under normal conditions, and doses up to about 5 MRads can be accommodated if reinstrumentation/recycling of the scintillator is possible. Beyond this level there are no realistic solutions in hand. This is one area where R&D is still needed both on the development of new scintillator and waveshifter fluor systems (for example at longer wavelengths) as well as more radiation tolerant plastic bases suitable for commercial production.

The signal response of scintillator is also an issue for high speed sampling. At the present time it appears that a minimum integration gate width of about 40 ns is needed to fully contain the signal, although improvements brought about by R&D on fluors might make shorter gates possible. Signal-width effects might also be mitigated by through waveform recording.

The calibration of scintillator calorimeters is also of importance. Typical test-beam calibrations (*e.g.*, CDF and ZEUS) achieve of order 2% precision. With *in situ* charged particle tracking, this can be improved to better than 1%. Achieving this precision in the absence of a magnetic spectrometer (*e.g.*, by a light flasher system) is an area where future R&D might make some inroads.

There are still open questions with respect to hadron/jet calorimetry, in the details of hadron shower development. Continuing R&D in this area both with test beams and simulations is desirable to form a basis for improved optimization of calorimeter designs. Moreover, in the long term the use of fine-grained calorimetry may allow (via for example neural networks) good discrimination from background QCD processes of W and Z decay to jets, hadronic τ decays and perhaps even B jets.

Finally, the granularity of a scintillator calorimeter is mainly determined by cost at the present time. As noted, labor costs can be high for many fabrication approaches. The most popular readout device is the photomultiplier tube, which is a costly element as well as one that can be sensitive to environmental factors. R&D to develop a cheaper and/or more robust alternative should have high priority for applications demanding high granularity.

3.4 Preshower and Shower Maximum Detectors

Hadron collider physics requires good lepton and photon identification; *e.g.*, good single-γ/π^0 discrimination in intermediate mass Higgs searches ($H \rightarrow \gamma\gamma$) and the ability to identify electrons in complicated events. Although electron identification can be achieved with standard calorimeters by using global properties of the shower, this is not sufficient to tag partially isolated electrons such as those from $b \rightarrow ce\nu$, or background processes such as c-decay or e^+e^- pairs from conversions in beam pipe and tracker. Additional electron identification can be provided by the introduction of a special-purpose detector to sample the distribution of shower energy in finer detail. The type of device selected depends on the calorimeter and physics priorities, *e.g.*, sampling preshower detectors are not appropriate in front of high resolution, homogeneous calorimeters. Moreover, the degree of segmentation is a compromise between cost and performance.

Beam tests show that while shower maximum devices obtain better e/π separation than preshower detectors as standalone devices, their information is highly correlated with global calorimeter cuts. Preshower detectors give a much larger additional uncorrelated pion rejection (factor of 5-15) when used in combination with calorimeter data [40,41]. If the calorimeter follows a substantial amount of dead material, such as a 1 X_0 solenoidal coil, the electromagnetic resolution will be degraded. Since the energy deposited in an active layer of a preshower detector immediately following the coil is related to the amount of energy lost therein, a preshower detector can be used to correct for this degradation. This function goes under the name "massless gap" in LAr calorimetry [42]. It was also modeled and explored in a test beam for the SDC preshower detector [41].

Highly articulated preshower detectors provide additional benefits. They can take advantage of the submillimeter size of the shower in the first few radiation lengths, providing a long lever arm to trackers and excellent background rejection of events with overlapping charged hadrons and π^0's or γ's. If the preshower detector is finely segmented longitudinally as well, and is deep enough to convert photons with a reasonable probability ($>3\ X_o$), then it can distinguish between single γ's and π^0's on an event-by-event basis.

The most widely studied technologies are silicon strips and scintillating fibers or tile/fiber arrangements, although work is also currently proceeding in the LHC RD-3 group on forming a preshower detector from specially instrumented layers of a LAr calorimeter. Work on silicon preshower detectors has been supported by the LHC RD-2 program and by major new detectors such as Zeus [43]. The advantages of silicon preshower detectors are their excellent timing properties, thin profile, and natural ease in adapting to any pixel geometry. Scintillating fiber preshower detectors were pioneered by UA2 [44]; the outer layers of their fiber tracker were essentially an imaging preshower detector, read out by image intensifiers and CCD's.

The high channel count of preshower/shower maximum detectors means that the development of cost effective readout is the driving R&D issue. For both silicon and LAr, combining radiation resistance with low noise and low power dissipation while maintaining a large enough dynamic range provides a challenging readout design problem. Photodetector development for fast fiber readout (CCD's used in UA2 are too slow for LHC applications) resulted in new low cross-talk designs of conventional multi-channel tubes manufactured by Hamamatsu and Philips and in the development of new hybrid tubes with PIN diodes [45] or avalanche photodiodes (APD's) [46]. More development is needed to make segmented hybrid tubes reliably and cheaply. Bare APD arrays operated in linear mode can now be made with gains of 500-1000, but work must continue to improve the yield and manufacturing process to reach the goal of $3. per channel. Visible light photon counters, which offer quantum efficiencies of about 75% are also a promising option for preshower detector readout.

4 Muon Detectors

4.1 Overview of Requirements

A number of large-scale muon systems are envisioned both as upgrades and new projects within the US HEP program during the next decade. Muon systems will likely play a key role in the detection and study of massive objects, such as the top and bottom quarks, where the sign of the electric charge of a high-P_t muon serves as an efficient quark flavor tag, and the Higgs, W', or Z' bosons, where the multi-muon signature will be distinctive above the large background expected. Muon systems will play a key role in neutrino and cosmic ray physics, where the flavor of the incident neutrino is labeled by the presence or absence and sign of the muon.

An overview of these projects where there is, or is likely to be, a large involvement within the US HEP community is listed below:

- LHC muon systems: ATLAS and CMS;
- Upgrades of CDF and D0 muon systems;
- B Factories at Cornell, SLAC, and KEK;
- Neutrino Oscillation experiments at CERN, BNL, and FNAL;
- Dedicated B-physics initiatives at LHC and HERA;
- Detectors for RHIC; and
- Cosmic ray experiments.

Muon detectors frequently require excellent spatial and time resolutions in order to achieve the necessary momentum resolution in high-rate environments. Moreover, the distinct signatures produced by high-energy muons makes them very useful at the trigger level and it is generally desirable to have the muon system produce signals for this purpose. This is typically done either by extracting some sort of timing signal from the primary muon detector or by augmenting the muon detectors with dedicated trigger devices.

Since muons are identified by their penetrating power, muon systems generally lie on the outside or end of detectors. The resulting systems are therefore generally quite large, making cost an important consideration and pointing the way to strong industrial involvement.

4.2 Current Status of Muon Detector-Trigger Technologies

For muon track reconstruction and/or triggering needed in the projects envisioned above, several attractive technologies have recently been developed or improved. All the technologies under review here are based on gas-ionization technologies where either the drift time and/or the induced charge are detected. Spatial resolutions of order 50 to 200 μm and time resolutions of a few nanoseconds have been achieved. Further improvements in economy and performance can be expected with additional R&D.

4.2.1 Cathode Strip Chambers

Cathode Strip Chambers (CSC's) are based on the multiwire proportional chamber (MWPC) concept. These devices provide high resolution measurements of both position and time, making it possible to combine tracking and triggering into a single detector [47]. Spatial resolutions of order 50 to 100 μm and time resolutions of order 24 ns have been achieved. The precision spatial resolution is obtained by measuring the charge induced on cathode strips— typically 0.5 to 1.0 cm pitch—to of order 1% with a precision integrating amplifier ($t > 300$ ns). Timing signals and a second coordinate are furnished by the system by reading out the anode wire. By "ORing" layers of chambers, a time resolution was demonstrated adequate to tag the beam crossing time of 16 ns efficiently at the SSC [34]. By measuring the charge of both the anode and cathode signals the chamber can furnish a true space point—a distinct advantage in a high rate environment.

These devices were chosen as the tracking and trigger technology for the GEM muon system. They are being considered for the very high $|\eta|$ region of the ATLAS muon system and for the entire endcap system of the CMS detector. The present R&D on these devices is focused on developing mass production methods to mitigate the high costs, small chamber sizes, and exacting tolerances of the technology.

Honeycomb Strip Chambers (HSC) share many of the properties of the CSC concept [48]. The cell structure is fabricated out of mylar folded into a hexagonal tube of 11-cm width. Cathode pickup strips are placed on a mylar substrate which runs perpendicular to the anode wires. Drift times measure the distance to the wire, and the center of gravity of the charge distribution induced on the cathode strips measures the coordinate along the wire. The chambers can be mass-produced cheaply by folding sheets of mylar with etched cathode strips to form the upper and lower halves of the chamber hexagon. A spatial resolution using the cathode strips of 80 μm has been measured in RD5 at CERN [49].

4.2.2 Drift Tubes

Drift tube tracking chambers have been in use for a number of years in a variety of experimental settings. Owing to their simplicity and time-proven properties this technology continues to be attractive in the LHC era. They have been operated in both limited-streamer and proportional mode, and can be pressurized to several atmospheres for better resolution resulting from slower drift times, smaller Lorentz angles, and more ionization clusters per unit length in the gas.

There are many variations of the basic construction of the cathode surface surrounding the anode wire. The round drift tube geometry is especially simple in that the spatial information is independent of the perpendicular angle of crossing. This technology has variously been called PDT for pressurized drift tubes, RDT for round drift tubes (RDTs were considered for GEM [50]), or MDT for Monitored Drift Tubes. The latter is the baseline technology for ATLAS barrel muon spectrometer. The "monitored" concept is based on the detection of the last electron to drift to the anode wire as well as the first to give a self-calibrating drift time and a discriminator against neutron and soft-gamma backgrounds [51].

In the presence of an axial magnetic field, the isochrones of the cylindrical drift tubes remain circles centered on the anode wire with a modified distance-to-time relation. A more complicated Lorentz angle compensation is needed for transverse magnetic fields. The round drift tube devices are especially suited for muon spectrometers based on solenoidal magnetic fields where the anode wires can be oriented along the axial field component, although they are being considered for the ATLAS toroid system [52]. To provide a bunch crossing capability using mean timers, the DTBX (Drift Tube with Beam Crossing Identification Capability) has been considered by CMS [35].

Some care in the choice of gases is needed for the RDT technology applied to LHC. Because of the expected high backgrounds, small drift times are needed of order < 500 ns. This requires the use of a "fast" gas. Since the E-field drops as $1/r$, non-flammable gas mixtures, such as Ar-CO_2 (80-20), can not be used since they would lead to very non-linear distance-time relation, which would be difficult to control. A small Lorentz angle is also desirable imposing further requirements on the gas mixture [53].

Limited streamer drift chambers (LSDT) considered for the GEM muon system [54] are constructed out of 2.54-cm open drift cells made from thin Al sheets on three sides and are operated in the limited streamer mode. By measuring the drift time, spatial resolutions of order 100 μm have been obtained. An orthogonal coordinate is measured by cathode strips placed above the open side of the cathode drift cell. By using the correlation of times of the wire pulses with those of the cathode, a two-dimensional space point is measured.

4.2.3 Plastic Streamer Tubes

PST's are modular chambers made from extruded PVC plastic cells coated on the inside with graphite paint to form the cathode. They can be operated in either the limited streamer mode or the proportional mode. The anode-cathode wire spacing is typically 0.5 cm in 1×1 cm^2 cells. A 100-μm-diameter wire is usually used. Cathode strips parallel to the wires and pads are frequently employed to given orthogonal coordinate readouts.

The technology is now quite well understood and has been employed extensively in LEP-CERN experiments (ALEPH, OPAL, and DELPHI), in the SLD-SLAC, as well as in FERMILAB, and various cosmic ray experiments. Several manufacturing concerns in the US and Europe now mass-produce the chambers and associated strip electronics.

4.2.4 Jet Cell Chambers

Jet cell chambers are essentially multiwire chambers in which the anode wire plane is oriented radially. In this configuration the drift cells are staggered to resolve the L-R ambiguity. In another configuration the resolution of the L-R ambiguity is accomplished by arranging the jet cells at a finite angle with respect to the infinite momentum trajectories. Each track is on both the left and right sides of the anode plane and the chamber is self-calibrating. The open wire drift chamber concept has been used with success in the L3 muon system at CERN and was proposed for the L* detector at the SSC [55].

The merit of this technology is that a large number of measurement points along the trajectory are possible, giving good determination of the local track vector. Spatial resolutions of the order 200 μm have been achieved using a non-flammable gas mixture of Ar-CF_4-CO_2. Double-track resolution of 2-3 mm is possible.

4.2.5 Parallel Plate Chambers

Parallel plate chambers (PPC) have been considered for triggering in the very forward region of the CMS detector [35]. The PPC is a single-gap gas detector with planar electrodes flat to 5 μm separated by 1 to 2 mm. The chamber is operated in the avalanche mode and has been tested up to rates of 108 $cm^{-2}s^{-1}$. Sizes up to 50×50 mm^2 can be fabricated in any shape to meet the spatial requirements of the large-η region of a muon system at a hadron collider.

4.2.6 Thin Gap Chambers

Thin gap chambers have been used for the OPAL Pole Tip Calorimeter [56] and have properties which make them suitable for the trigger of the ATLAS forward muon system. Constructed as multi-wire chambers with a 1.6-mm anode-cathode distance and 2-mm anode wire pitch, the chambers have good rate capabilities and resistance to radiation damage. The inner cathode surfaces are coated with carbon thereby allowing both strip and pad readout. The chambers are operated in the saturated gas-gain mode and are not very sensitive to mechanical deformations. Typical drift times of < 8 ns are obtained and the chambers have been operated in environments of up to 500 MIP-$mm^{-2}s^{-1}$. Early work on this chamber concept is described in reference [57].

4.2.7 Resistive Plate Chambers

The RPC is essentially a narrow gap (2 mm) avalanche chamber with a strongly quenched streamer [58]. The chambers can be configured to give a two-coordinate readout. The plates of the chamber are coated with thin sheets of semi-conducting plastic or glass (*e.g.*, bakelite) of high resistance (typically 10^{10} to 10^{12} Ω-cm) and are operated with a gas mixture containing a strong electronegative component such as freon. Both gas and electrode structure lead to the strong quenching of the avalanche. The merits of this technology are its low cost and fast timing (< 5 ns).

The RPC is a good candidate for a muon trigger system [both the ATLAS and CMS barrel regions] and for providing the second coordinate for a drift tracking system. RPC's are also under consideration for a muon tracking system in the SLAC B Factory project. They have been used in a number of applications, including the L3 endcap system.

The R&D effort on this technology is concentrated on improving the RPC rate capability. At present, the efficiency of the chamber sags and time jitter degrades with increasing rate burden. Promising results have recently been obtained by lowering the gas-gain with more freon and by using plastics of lower resistivity [59,60] the chambers can be operated at count rates approaching 1,000 MIP-$cm^{-2}s^{-1}$.

4.3 Precision Alignment of Detectors

In order to achieve their design resolution, most muon systems require precision alignment over large areas and distances. Typical requirements depend on the design concept of the system but the requirements can be as exacting as 25 μm over distances of order several meters. This is quite a challenge and several techniques are under development.

A few of the techniques for both global and local alignment presently under consideration for both the ATLAS and CMS muon systems are listed below:

- stretched wire with capacitive readout,
- LASER straightness monitors,
- LED–Photodiode optical straightness systems,
- bar-code optical systems, and
- proximity monitors

Many of the properties of these technologies were explored in the development of the SSC experiments (see references [34] and [16]).

5 Particle Identification

The e^+e^- B Factories at CESR, SLAC and KEK and the Fermilab Tevatron collider program will require good hadron identification for CP-violation physics. In particular, the ability to separate π's from K's over a wide range of momenta will be of paramount importance. For the most part this section will deal with techniques devised for this purpose. However, transition radiation detectors, which are uniquely suited for electron identification and have a wide range of applications in both B physics and elsewhere, will also be considered.

5.1 Requirements

5.1.1 e^+e^- Colliders

The generation of e^+e^- B Factories now under construction employs K-π separation in two distinct ways: flavor tagging of "opposite-side" particles and particle identification in exclusive decays. The former application is primarily of interest to the experiments at asymmetric colliders.

In the flavor-tagging application, the sign of the b quark is inferred from the sign of the charged kaon that emerges from the end result of the Cabibbo-favored $b \to c \to s$ cascade. This technique offers relatively high tagging efficiency ($\sim 35\%$) and a false-tagging probability of only ($\sim 10\%$), which arises mainly from Cabibbo-suppressed decays in the cascade. The momentum spectrum of the tagging kaons is reasonably soft, extending upward to only ~ 1.5 GeV/c.

Particle ID is also expected to play a crucial role in the reconstruction of exclusive decay modes such as $B^0 \to \pi^+\pi^-$ and $B^\pm \to D^0 K^\pm$. In these decays the charged hadrons are characterized by a much harder momentum spectrum and coverage up to about 4 GeV/c is needed (3 GeV/c in the case of symmetric machines). Since the lower end of the momentum spectrum for decay daughters extends down to 1.5 GeV/c, the ideal system would provide coverage over the full range up to 4 GeV/c.

The level of rejection required for unwanted particles varies depending on the application at hand, but in some cases is as stringent as 100:1. If this is to be accomplished without significant loss of acceptance the π-K separation should be of order 3–4σ.

The problem of particle identification is made more difficult in the e^+e^- environment by the need to fit the system in a relatively small radial gap (≤ 25 cm) between the central detector and the electromagnetic calorimeter. Moreover, since it is important to be able to detect low-energy photons with high efficiency, the amount of material in front of the calorimeter must be limited to $\sim 20\%$ of a radiation length.

5.1.2 Hadron-Beam Experiments

As is the case at e^+e^- colliders, the principal need for hadron identification in contemporary experiments with hadron beams is for studies of B-particle decays with emphasis on CP violation and neutral B-meson mixing.

The π's and K's from B decays in hadron experiments have only slightly larger transverse momenta than at e^+e^- colliders; good efficiencies would be obtained in detectors with coverage up to $P_t = 1.5$ GeV/c for tagging of opposite-side B's, and up to 2.5-3 GeV/c for two-body B decays. Thus a central detector for B physics at a hadron collider has almost identical kinematic requirements for hadron identification as does an e^+e^- collider. An important difference is that a substantial fraction of relevant particles occurs at small angles to the beam in hadron experiments, so the total-momentum spectrum of particles produced at polar angle θ is scaled by $1/\sin\theta$ times the transverse-momentum spectra discussed above. For small polar angles, particle identification via Čerenkov radiation in gases is a useful technique that is less relevant in central detectors.

The B decays of interest for CP violation are not associated with high-transverse momentum jets, so the π's and K's to be identified are typically not accompanied closely by other particles. The local density of B-decay products per interaction is only slightly higher in hadron experiments than in e^+e^-, when angular distributions are discussed in terms of the pseudorapidity, $\eta = -\log\tan\theta/2$, a logarithmic angular variable. Namely $dN/d\eta \approx 4-6$ in hadron experiments, where N is the number of charged particles per interaction. This kinematic feature leads to the requirement that the detector segmentation be roughly uniform in pseudorapidity rather than polar angle. Further, a detector with nearly full angular acceptance should cover $\Delta\eta \approx$ 8–10 at the Tevatron collider, and 10–12 and LHC.

Another distinguishing feature of hadron-beam experiments is the interaction rate. An ambitious (but typical) goal is to operate at 10^7 interactions per second, compared to only about 20 (hadron producing) interactions/second at an e^+e^- B Factory. The electronics of the particle ID systems must have a higher rate capability for hadron experiments, although the minimum time between interactions (16-200 ns) is actually longer in hadron experiments than at e^+e^- B Factories (2-4 ns).

5.1.3 Dedicated Electron Identification

It is difficult to quantify the requirements for dedicated electron identification systems based on transition radiation, since these system often work in conjunction with other systems (calorimeters and preshower detectors) that also provide e/π separation. Generally speaking, however, one seeks to maintain high ($\geq 90\%$) electron acceptance while achieving hadron rejections on order of 100:1.

5.2 Technology Options

Pions and kaons are most readily distinguished from one another through a measurement of their velocity, which when combined with a momentum measurement allows one to deduce their mass. Thus virtually all dedicated hadron identification devices are based on either a time-of-flight (TOF) measurement or on the detection of Čerenkov light. In one novel scheme [61] these two approaches are combined as described below.

5.2.1 Time of Flight

A particle's velocity can be directly determined by measuring its flight time along a known path length. For relativistic particles the maximum momentum at which a specified time separation, Δt can be obtained is given by

$$p_{\max} = \sqrt{\frac{L\,(m_K^2 - m_\pi^2)}{2c\Delta t}} \qquad (2)$$

where L is the path length, typically of order 1.0–1.5 m.

The next generation of scintillator-based timing systems are expected to provide timing resolutions of $\sigma_t \simeq$ 80–100 ps (see *e.g.*, reference [32] pp.. 73–80), which will yield a 3σ separation to momenta of about 1.3 GeV/c. This is adequate to cover nearly all of the tagging region in e^+e^- experiments and the low part of the momentum range needed for hadron colliders.

The 100 ps figure represents an advance over previous systems, which realized resolutions of order 150 ps [28]. It is at least in part due to the use of magnetic field tolerant fine mesh photomultiplier tubes [62] coupled directly to the ends of the scintillator. Although the basic technique was one that was well established, it has benefitted from technological advances.

Scintillator-based TOF systems have long been used in particle and nuclear physics experiments and represent minimal technological risk. Moreover, apart from the need to maintain rather stringent timing stability, they are robust and straightforward to operate. Since limited momentum coverage can be extended with the addition of a Čerenkov based system as discussed below, TOF systems are serious contenders for the particle identification systems of B-physics experiments.

5.2.2 Threshold Čerenkov Detectors

In a threshold Čerenkov system one chooses a radiator medium with a refraction index n such that $\beta_K < 1/n < \beta_\pi$ in the range of momentum of interest. When that is the case, pions will emit Čerenkov light whereas kaons will not.

In the momentum range relevant to the e^+e^- B experiments, one requires a refractive index in the range $1.01 < n < 1.02$ (larger indices may be required if one wishes to extend the coverage to lower momentum), which can be achieved using silica aerogels or pressurized gases. Systems based on both aerogel [31,32,63] and high pressure gas are under study [63].

Aerogel The aerogel technique is not new but has enjoyed a resurgence in recent years in anticipation of the turn-on of the B Factories. Although the primary light yield is reasonable, a significant fraction of the photons are lost due to Rayleigh scattering and absorption in the aerogel. Even in the most favorable cases only a few photons will be detected. Moreover it is not practical to transport them any distance from the radiator. One therefore requires a high-gain photodetector that provides good single photoelectron resolution while operating in a strong magnetic field. Thus in addition to the work on the aerogel itself, attention has been paid to the application of new photodetectors.

A number of lab and industry groups have been engaged in the manufacture of aerogel material. Although some of these efforts have been aimed specifically at high-energy and astrophysics applications, others originally were driven by aerospace applications.

The photodetectors under consideration as detectors of aerogel light are fine mesh photomultipliers with conventional bialkali photocathodes, micro-channel plate photomultipliers using GaAsP photocathodes and a hybrid device, which consists of an avalanche photodiode coupled to a conventional photocathode via a vacuum acceleration gap [64,46]. As with the TOF systems, high performance photodetectors will be crucial to the success of this technology.

High Pressure Gas Pressurized gas has been used as a Čerenkov radiator for many years (for reviews see references [65] and [66]). There are a number of gases that can be used to achieve refractive indices in the desired range at workable pressures (one to several atmospheres). Many of these exhibit good UV transparency and are readily available. A typical gas radiator Čerenkov counter for a fixed target experiment consists of a large volume of gas viewed by photomultipliers, often with the assistance of light-collecting mirrors. Most such approaches, however, are not suitable for the barrel regions of colliding-beam experiments, where space is at a premium. Workers at CLEO [67] have investigated a variety of novel schemes to address this difficulty. Generally, they employ an array of thin-walled 10-cm-diameter tubes, which the particles traverse at right angles. The light is redirected to end-mounted photodetectors (*e.g.*, high-field fine-mesh PMT's) using specially designed reflector arrays or waveshifters.

5.2.3 Ring Imaging Čerenkovs

Ring Imaging Čerenkov (RICH) detectors extend the momentum typically attained with threshold counters by operating in a regime where both π's and K's are above threshold. Particle species are distinguished by measuring the opening angle of their Čerenkov cone, θ_C which is given by

$$\theta_C = \cos^{-1}\left[\frac{1}{n}\sqrt{1+\left(\frac{m}{p}\right)^2}\right] \qquad (3)$$

Solid, liquid, or gaseous radiators can be employed, depending on the momentum range being covered. (For a review see reference [68].) Although the extended momentum coverage is an obvious plus, RICH systems are typically more expensive and complex than threshold devices.

RICH's Based on Gas-Filled Photodetectors The rings must be detected using highly-segmented two-dimensional photodetectors. Although conventional photomultiplier tubes could in principle be used for this, the number of detector elements needed is generally prohibitive—channel (pixel) counts of several tens of thousands, and even hundreds of thousands, are not uncommon. Thus workers have been led to develop photodetectors based on wirechambers filled with photosensitive gases such as TMAE or TEA [69].

An important technical advance of the past decade was the successful deployment of two large scale ring-imaging detectors (the DELPHI RICH [70] and the SLD CRID [71]). Although these devices are well matched to their current application, they are limited in their ability to handle high rates. This has led to efforts to develop improved photocathodes. One promising approach is to form a photocathode using a thin layer of CsI. The CsI layer can be deposited directly on a two-dimensional array of metal readout pads. Since the drift time for all photoelectrons is roughly the same, and since the pads can be individually instrumented with readout electronics, the intrinsic rate handling capability of the devices is greatly increased.

Solid CsI photocathodes have been the subject of an extensive R&D program over the past few years [72] and much progress has been made in understanding their capabilities and limitations. The work is now entering the critical phase of determining whether the successes achieved with table-top devices can be realized in full-scale detectors.

The DIRC A novel implementation of the ring-imaging approach, called the DIRC (**D**etection of **I**nternally **R**eflected **Č**erenkov light), was recently proposed by workers at SLAC [73]. This device uses the total internal reflection of light in long thin quartz bars to form a velocity dependent image. That image is transported to the edges of the detector where it is proximity focussed onto an array of photomultiplier tubes. An attractive feature of this approach is that while the idea is a new one, its implementation is based on largely conventional technology. The DIRC requires little space in the active region of the detector. However, the requirement that the quartz bars pass through to the outside of the detector imposes some constraints on the overall detector design. Moreover, a large phototube array (~ 10–20 K PMT's) is needed.

Since the HEP community has relatively limited experience with this sort of detector, its proponents have set out upon a program to experimentally measure important quantities, such as light yield and the quality of the quartz bars that can be obtained from industry. These studies have begun to produce results (see reference [31] pp.. 138–151.) and thus far support the design assumptions. A number of engineering details having to do with the magnetic flux return (for a solenoidal detector) and the support of the bars and other detector components remain to be worked out.

5.2.4 Čerenkov Correlated Timing

The RICH technique can be extended to implement an improved time-of-flight system. As noted by workers at CLEO [61] the light produced in a quartz radiator will propagate in way that increases the intrinsic difference in arrival times for signals from particles of different velocities. Since the time scale for emission of Čerenkov light is very short ($\sim 10^{-15}$ s) excellent timing resolution and therefore greatly enhanced particle separation is possible.

The effective propagation velocity for light trapped by total internal reflection in long quartz bars is such that the leading photons from faster particles (larger Čerenkov angles) arrive sooner than those from slower particles (smaller larger Čerenkov angles). This effect enhances the intrinsic time separation that arises from the difference in particle velocities. In this way, the ~ 1.3 GeV/c upper limit on momentum coverage from conventional scintillator-based time-of-flight systems can be extended by a substantial factor.

5.2.5 Transition Radiation Detectors

Transition Radiation Detectors (TRD's) have been used successfully for particle identification for approximately the last fifteen years. They have been employed in a variety of experimental environments, including the Intersecting Storage Rings at CERN [74], hadron collider experiments at the CERN S$p\bar{p}$S and at the Fermilab Tevatron, an internal gas jet target experiment at the S$p\bar{p}$S, as well as fixed target experiments at both laboratories [74,75,76,77]. The primary application has been electron identification [74,75], but more recently they have been used to identify hadrons as well [76,77]. These versatile detectors show great promise for use in the identification of B decay products in future heavy quark experiments at hadron accelerators. While their anticipated role in the central or moderately forward region of a collider would be to identify electrons, they would be expected to discriminate among hadron species in fixed target experiments or in the very forward regions of collider experiments. Moreover, they can be used simultaneously for particle identification and for precise tracking [78,79,80] by subjecting the output signals to multiple thresholds.

The total transition-radiation (TR) energy radiated is proportional to the Lorentz factor, γ, of the traversing charged particle, so that a TRD that turns on and reaches saturation for electrons between 1 and 2 GeV demonstrates the same response to pions only when they reach an energy of 250-500 GeV. Thus, the range over which TRD's are useful for electron identification spans more than two orders of magnitude in momentum.

Because space is so limited, the design of a TRD for electron identification in the barrel region of a collider experiment presents the biggest challenge. Such detectors must be compact and must present as little material as possible to the detectors placed behind them. TRD's make optimum use of the material they contain when radiator and detector are interleaved more frequently into a "fine-sampling" detector [81,82]. Thin detector volumes are desirable not only to minimize the amount of material, but also because they reduce the time over which the signal is collected. Drift times in mixtures containing xenon are long, although there is some evidence [83,84] that this can be improved by approximately a factor of two with the admixture of "fast" gases like CF_4. Further study of aging properties of TR detectors using this gas is needed.

The method of "cluster counting" has been demonstrated to be more effective in separating species than the method of total charge collection [82,85]. This technique entails shaping the pulses so that capture of an x-ray, which deposits a large amount of ionization in a small volume, yields a significantly larger pulse than the signal due to ionization loss along the path length sampled within the same integration time. For small cell depth, the difference in the two techniques is less significant than for a cell of larger depth, where the total ionization loss signal is larger and competes favorably with signals from x-ray capture.

Most research over the last few years has been in the study of radiator materials. The goal has been to find bulk materials that compete with regularly spaced foil sets in the amount of radiation produced. Such materials make the detector much simpler to construct and should be capable of supporting themselves without frames or spacers. They might even be sufficiently rigid to form the support structure for the detectors. Foam radiators have been compared to foils containing approximately the same amount of material in radiation lengths for both very thin [86], ~ 0.04 g/cm^2, radiators and some [79,84,87] of a thickness $\sim 0.2 - 0.7$ g/cm^2, more typical in terms of detectors which have been built in the past. The foams are seen to yield of order 80% of the TR that is produced by the foils, independent of the thickness at which they are compared. Preliminary data indicate that a somewhat better yield can be obtained from mats made from CH_2 fibers and possibly also from Rohacell foam [87].

6 Large-Area Detectors for Non-Accelerator Physics

Large area muon detectors are needed for non-accelerator experiments are measured in sizes of tens of thousands of square meters. The two main usages are in underground detectors of low- and high-energy neutrinos and in Extensive Air Shower (EAS) experiments.

6.1 Underground Water Čerenkov Detectors

The first of the large underground water Čerenkov experiments was the IMB detector, located in a salt mine near Cleveland, Ohio [88]. It was soon followed by the Kamioka detector in Japan [89] and by the HPW experiment in the Silver King Mine in Utah [90]. All three were built in the early 1980's with the hope of detecting nucleon decay. Although these experiments did not detect nucleon decay, they did eliminate the simple SU(5) model of grand unification. The designs, which were similar, employed photomultipliers immersed in ultra-pure water. They registered contained events (few MeV to ~ 1 GeV) and throughgoing muons (typically 20 GeV). Effective volumes ranged from 600 to 10,000 tons, and effective light-collection areas ranged from 100 to 400 m^2. The detectors used of order 10^3 photomultiplier tubes and achieved energy sensitivities in the range of one to six photoelectrons per MeV.

While IMB and HPW have shut down, Kamioka continues to operate, and two new large detectors are under construction. The SuperKamioka [91] tank, which employs 11 K twenty-inch Hamamatsu PMT's around its walls, is roughly 40 m in diameter and 40 m tall. It is scheduled to begin operation in 1996, and will be able to make order-of-magnitude improvements in measuring solar neutrinos, searching for nucleon decay, studying atmospheric neutrinos, and keeping a watch for supernovae from within or near our galaxy. Another experiment, called SNO [92], is being built in Sudbury, Canada, for operation in 1996. It will be filled with 1000 tons of D_2O for studying solar neutrinos. Both experiments are pushing down to thresholds in the several MeV range, and both will need to reduce radioactive isotope content to extremely low levels.

Light collecting optics are of importance as well. Kamioka and SNO employ light cones of a modified Winston type to achieve significant (tens of percent) increases in light collection. IMB employed 0.75 m square wavelength shifter (WLS) plates and achieved about a 40% increase in collection area over bare 5-inch PMTs. While WLS plates are cost effective, they add a few nanoseconds to the photoelectron arrival-time spread [88], significantly degrading the timing capabilities of the instruments.

6.2 Underwater Neutrino Detectors

DUMAND [93], Baikal [94], AMANDA [95] and NESTOR [96] are all projects aimed at underwater or ice detection of high-energy (typically TeV) neutrinos. They have sensitive muon detection areas of order a few $\times 10^4$ m^2 and angular resolutions of about 1°. Although these instruments primarily detect muons that traverse their volumes, they also are intended to detect high-energy cascades that occur throughout the array volume and even from distances up to 100 m away at PeV energies.

The water Čerenkov technique currently provides the only economical means of achieving muon detection areas at or beyond those now planned. The universally acknowledged goal for high-energy neutrino astronomy is a 1-km-scale instrument [97]. There are discussions of acoustical and radio detection techniques for sensing neutrino induced cascades of energies beyond 1 PeV. It is likely that these techniques will initially run parasitically on the Čerenkov instruments, which employ well-known technology and low thresholds.

6.2.1 DUMAND

DUMAND will be 4.7 km deep in the ocean near Hawaii and will employ 15-inch PMT's arrayed on a 10×40 m^2 horizontal lattice. The optical detectors are "smart" units, with local microprocessor control. Signals are sent to a "string-level" controller that contains digitizing and communication circuitry. The DUMAND group has designed and built a 200 K-gate GaAs LSI chip that digitizes 27 channels of pipelined data with 1 ns least count. Data are transmitted to shore on single mode fiber at 625 Mbaud, where trigger finding and processing takes place in digital hardware.

6.2.2 Baikal NT-200

The instrument in Baikal employs similarly large PMT's. However, because of the relatively shallow (1 km) depth and a background level that is 1000 times higher than DUMAND, the tubes are arranged in tighter clusters. The Baikal detector readout uses more traditional local coincidences, which are formed underwater and transmitted to shore via coaxial cable at low speeds. Eighteen dual-PMT units are currently installed and counting muons. This group has developed techniques for deploying detectors through the winter ice and laying cables in slots running from the site to the shore station.

6.2.3 AMANDA

The AMANDA array is being installed at the South Pole, with PMT's placed in holes drilled through the ice using hot water. In an initial deployment, 80 eight-inch PMT's were placed at depths between 800 m and 1000 m. It appears that air bubbles in the ice produce a 10- to 20-cm attenuation length, so that light progresses by diffusion, rendering fast timing over a useful distance range impossible. There are plans are for further PMT installation at a depth of 1500 m. Thus far this experiment employed coaxial cable communication to the surface and traditional signal processing using NIM and CAMAC electronics.

6.2.4 NESTOR

The NESTOR collaboration is planning an array similar to DUMAND but placed in the Mediterranean, off Pylos in the Southwest of Greece at a depth of 3.7 km. This collaboration will also employ large PMT's, fiber optics, and shore-based data filtering. The array is intended to be somewhat more dense than DUMAND and consequently will have a lower energy threshold (a few GeV). The NESTOR engineering design is still evolving.

6.2.5 KM3, NAO

Several meetings have now taken place to form the beginnings of a world consortium for building a km-scale instrument, which would have of order 10^4 sensors. The cost of such a device, which might be built around the turn of the century, would likely be of order $ 150 M, comparable to that of a colliding beam experiment. The choice of venue has yet to be made for this collaborative effort. It will depend upon engineering experience with the present instruments. Nonetheless, many of the engineering requirements are already known, and work has already begun at JPL and Saclay.

6.3 Water Čerenkov Detectors at the Earth's Surface

Extended air shower (EAS) detectors have traditionally employed shielded liquid or plastic scintillators for muon detection. Generally the cost has been driven by civil engineering, since the cost of piling up absorber soon dominates. There is one exception, however. In recent years it has been realized that the water-Čerenkov technique can be applied to produce inexpensive large-area arrays for EAS detection.

The MILAGRO detector, which is aimed at studying air showers induced by gamma rays of cosmic origin, is now under construction near Los Alamos. It covers an active area of about 5000 m^2 with a single layer of photomultiplier tubes and will be sensitive to incident photons with energies extending to below 100 GeV. The detector consists of an 8-m-deep pond with a lattice of eight-inch photomultipliers looking upward to an opaque cover 2 m above. The top layer detects electromagnetic energy, and another smaller and deeper layer detects penetrating muons.

We note that seven proposals in the last few years (notably the GRANDE group in the U.S.) have aimed at building a larger and thicker water Čerenkov arrays than MILAGRO, with dimensions up to 10^5 m^2 by 50 m deep, with three layers, some looking down as well as up.

6.4 Technology Issues

We have outlined above the larger efforts in this field, with emphasis upon the technological issues. Here we will discuss what will be needed to achieve a fifty-fold increase in detector size.

6.4.1 Optical Detection

It appears that large-area photomultipliers will continue to be the transducer of choice for Čerenkov radiation for some years. Large-area solid state detectors are currently too expensive and suffer from high dark currents in comparison to PMT's. Work on pressure tolerant detectors, such as liquid-filled photosensors, could result in a breakthrough, but there is no program currently underway. One new approach is being explored at LBL [98], which envisages a cylindrical PMT with WLS collection down the axis. Modest improvements might also made through the use of mirrors and WLS plates to enhance light collection in selected directions. Both approaches currently suffer from degraded timing resolution and substantial mechanical problems when deployed in either ocean or ice environments and are therefore not being actively considered.

6.4.2 New Techniques of Detection

As noted, there are groups interested in acoustical [99] and radio detection [100] of ultra-high-energy neutrino-induced particle cascades, both in ice and in the ocean. If first measurements of *in situ* backgrounds and actual attenuation lengths are favorable, then these techniques may be pursued more vigorously in the next few years.

6.4.3 Fast Pipelined Electronics and Data Transmission

All cosmic ray experiments must collect and analyze their data in real time. This has caused some difficulties in employing off-the-shelf electronics, and has led to some new solutions which have applications elsewhere. A prime example is the DUMAND digitizer chip mentioned above, now being applied in the BNL $(g-2)$ experiment, and considered for other accelerator applications. Some experiments, such as MILAGRO, will face trigger and data handling problems which begin to approach those of future collider experiments.

Data transmission will surely move to fiber optics. While the HEP experiments have taken advantage of technology advances driven by the communications industry, some novel problems persist. For example, PMT pulses to be transmitted as time-over-threshold pulses are not well matched to off-the-shelf links, which generally require a 50% duty factor.

6.4.4 Fast Pipelined Data Processing

As with large accelerator experiments, massive underearth instruments must employ multi-layer trigger schemes to achieve the requisite reduction in rate. Although the flexibility of software-based trigger systems is an obvious attraction, CPU speeds are not yet high enough to handle data directly from the detectors (the gap is currently less than a factor of ten, however). Much experience with the architecture and algorithms for such systems will be gained in the next few years

6.4.5 Calibrations and Survey

All the Čerenkov detectors discussed require calibration for amplitude and timing. Large neutrino detectors, which span a very large dynamic range in energy, require only logarithmic calibration. Although presently the dynamic range is typically only 10^3, improvements will be needed in the future.

The pulsed light sources that are presently most frequently used (typically N_2 lasers), work either by illuminating the PMT's via a scattering ball or by illuminating a scintillator that reradiates the pulse. While this works well enough, lasers are awkward and not completely reliable. Improvements in fast blue LED's would be a great help, though they are presently limited in stability, time and output amplitude.

For the solar neutrino detectors, low-level calibration is quite delicate, and several techniques will be employed. These will use radioactive sources and possibly even small electron accelerators to achieve calibration accuracies of few percent at 5 MeV.

Surveying is a special problem in both the ice and ocean. In the ice it must be done well once. In the ocean, due to a tidal excursions of a few meters for bottom-tethered instrument strings of several-hundred-meter height, one must monitor the position on the time scale of hours. All three deep water experiments plan to use acoustical surveying. Indeed, the DUMAND Seattle group has advanced the field somewhat already with an acoustical chirp technique using DSPs for running correlations. Their system achieves a resolution of a few centimeters, which is orders of magnitude better than commercial deep-ocean systems.

6.4.6 Reliability

As for all massive detectors, quality control and reliability assurance are of paramount importance since the instruments can be serviced only with difficulty or not at all. A major challenge therefore is to achieve the sort of mean time between failure statistics typical of the aerospace industry without adding significantly to the cost of the instruments.

6.4.7 Service and Robotics

Service is a serious issue for these experiments. For example, the SuperKamioka detector will take nearly a year to drain, service and refill with adequately pure water. The PMT's in the ice at the South Pole are not removable once installed. SNO plans to use a robot for in-tank service. The deep ocean experiments also plan to use robots and submarines. For a future deep water detector, adequate robotic capability not only will allow repair and replacement, but will also allow reconfiguration of the array to respond to changes in the physics program.

6.4.8 Deep Ocean Technology

DUMAND's unique requirements for deep underwater operation have led to substantial technological innovation in a number of areas as mundane, but vital, as connectors and cable terminations. The development of pressure-tolerant electronics suitable for direct immersion in fluid would be of great benefit to future efforts since it would obviate the need for heavy, expensive, and unreliable housings and feedthroughs. Corrosion is always a concern, but simple procedures and the use of non-metals and titanium eliminate that risk.

7 Electronics

Historically, application of rapidly developing electronics technology to electronics for HEP experiments has enabled more sophisticated and more powerful physics experiments. In general, the HEP community needs an ongoing R&D program to further develop application of existing technologies, to study application of new technologies, and to become aware of developing technologies. For example, circuits using existing technologies to deliver the large dynamic range required for future calorimeters must be developed. In addition, the emerging technology of multiquantum well devices is promising for high-speed analog and digital data transmission in compact, low-power units and should be studied for HEP application. The rapidly evolving nature of electronics technology requires a strong R&D program in order to exploit technological advances in extending physics capabilities. In the following sections, some of the current challenges needing the attention of an active R&D program are discussed under the general headings of Front-End Electronics and Trigger Systems. Challenges to data acquisition and computing systems, which also exploit rapidly evolving electronics technology, are discussed in the Computing section.

7.1 Front-End Electronics

Front-end electronics extract physical quantities of interest, usually time and/or charge, from detector signals. They perform analog signal processing, digitization, and buffering of detector signals. The capabilities of the HEP community to develop its own custom analog integrated circuits for front-end electronics have made it possible to instrument detectors with hundreds of thousands of channels. This has in turn made it possible to build highly granular detectors that offer better resolution and the ability to reconstruct and study ever more complicated events. For example, the development of integrated circuits with complete readout channels on a pitch of 50 μm has enabled us to read out silicon microstrip detectors directly, in turn enabling the detection and measurement of secondary vertices from the decay of short-lived particles. The use of custom integrated front-end electronics is still in its infancy, now being used in only a small fraction of the detector systems in most experiments. However, all large new experiments planned or under construction depend critically on custom IC's for all detector systems, and the use of these techniques will largely define physics capabilities in the future.

Future front-end electronics require circuits that are high speed, low noise, low power, and high density, requirements which are sometimes at odds with one another. Circuits for high rate environments also require pipelined architectures allowing signals from many events to be buffered while trigger processing occurs. They must be simultaneously read/write such that signals from new events can be processed while data from a previous event is read out. Analog integrated circuit development requires considerable experience and expertise. Requirements that are specific to the front-end electronics for certain detector types are outlined below.

7.1.1 Electronics for Calorimeters

Calorimetry requires pulse height measurement with high dynamic range, seldom less than 15 bits. This requirement places great demands on readout electronics. Preamplifiers, amplifiers, ADC's, and analog memory cells of sufficiently high dynamic range are needed. The performance needed for the next generation of high-energy accelerators, where calorimetry requires even greater dynamic range (about 18 bits), is not yet in hand. R&D of both the building blocks, such as analog pipelines, and of complete integrated systems should be continued. Such R&D can provide not only the enabling technology for read-out of calorimetry, but also production circuits that can be used on more than one experiment.

7.1.2 Electronics for Drift Chambers

Drift chambers require time measurement circuits with resolution of one nanosecond or less. They also often require high density, and they sometimes require radiation hardness. Circuits which meet these requirements now exist; however, fully integrated systems have not yet been produced. Drift chambers also often require pulse height measurement. Circuits for this purpose, and circuits for combined measurement of time and pulse height are also needed.

7.1.3 Electronics for Particle Identification Systems

In general, electronics for particle identification systems, such as ring-imaging Čerenkov detectors and for time-of-flight counters, is generally not as far along in its development as electronics for calorimeters and drift chambers. The requirements for a particular particle identification technique are often unique. For example, electronics for high resolution time of flight systems must provide time resolution of 50 ps, along with a pulse height measurement of several bits resolution. Such performance has not yet been achieved in integrated circuits.

7.1.4 Electronics for Semiconductor Trackers

The development of electronics for silicon microstrip detectors is a good example of how custom integrated circuits can play a key role in detector technology. Although progress in this area has been impressive, circuits with the complete functionality needed for future experiments, in particular circuits with pipelined memory for simultaneous read/write, are not yet complete. In addition, development of readout electronics for pixel detectors, affording high resolution, two-dimensional position measurement, is in its infancy. The design of signal-processing and data-storage circuitry with the ultra-high density required for pixels is a great challenge. The size of pixel readout circuitry will limit pixel size, and hence resolution, for the foreseeable future. The readout electronics for microstrip gas chambers (MSGC's), can be similar to silicon microstrips; however, MSGC's will impose some unique signal processing requirements if they are to achieve their ultimate performance in a high-rate environment.

7.1.5 Radiation hard electronics

One of the greatest R&D challenges in the electronics area is the development of circuitry with sufficient radiation hardness to withstand the very high fluxes of particles associated with high-luminosity colliders. For instance, doses of 10 MRads and fluences of 10^{14} n cm^{-2} will not be unusual in future experiments. Development of radiation-hard custom circuits is not yet sufficiently advanced. Although radiation hard semiconductor processes are commercially available, vendors often know little about the radiation hardness of analog circuits manufactured in their processes. Much further study of the radiation hardness properties of available processes for a variety of circuit types is needed. In addition, R&D on this subject is needed to study new processes, monitor changes in processes, and to study suitability of processes to new circuit designs.

7.2 Trigger Systems

Although trigger systems are generally experiment specific, the architectures and tools used in their implementation are generic. The techniques available at the trigger level often define the physics accessible to a given experiment. Consequently the lack of sufficiently powerful tools can limit physics potential, particularly for high-rate hadron physics experiments. As the technological capabilities of electronics have grown, so has the ability to design trigger systems with greater and greater physics capability. Remarkable progress has been made in a few short years since the days when trigger systems were constructed from modular logic units that provided two to four simple logic functions per module, which were cabled together to select event candidates. Trigger systems are now "cabled up" using commercial programmable logic, which provides thousands of logic functions per integrated circuit. Moreover, custom integrated circuits capable of providing tens of thousands of functions, including computational functions, are often implemented. Modern trigger systems also harness the power of hundreds of commercial processors in trigger "farms," greatly enhancing the ability to implement sophisticated trigger algorithms. Further developments along these lines will be needed for full exploitation of hadron colliders.

Trigger architectures for high-luminosity experiments now generally consist of multiple levels employing pipelined and parallel processing techniques and high bandwidth data transfer. Accordingly, the discussion of existing technical challenges and needed R&D is by trigger level.

7.2.1 First Level Triggers

First level triggers are characterized by high input rates (for instance 40 MHz at the LHC) and short latencies (typically 2 to 4 μs). At the first level, algorithms must be provided by dedicated logic, sometimes referred to as hard-wired or special-purpose processors. This logic must be pipelined to accept input rates with the time between event candidates less than the fastest imaginable processing times, and it must be massively parallel in order to simultaneously process all trigger inputs. For instance, processing of hundreds of thousands of input channels in parallel is not unusual. To address these requirements in a cost-effective and reliable manner, and in a way that offers adequate flexibility and programmability, custom and semi-custom (*e.g.*, field-programmable gate arrays) integrated circuits are required. Such IC's are the only way to provide sufficient logic to address the requirements. R&D into the development of high-density digital integrated circuits for high-energy physics is needed to make commercially available techniques accessible to the HEP community, to gain experience with available techniques from outside HEP, to track rapidly evolving technologies, and to learn how to apply them to HEP. This R&D should also include study of synthesis tools for facilitating IC design.

Another important challenge in the design of first-level trigger systems is the need to bring a very large number of input high-rate signals to the processor hardware. With the use of application-specific IC's (ASIC's) to perform the processing, the performance and cost of first level triggers can be severely limited by the required connectivity, *e.g.*, by the bandwidth of data links or by the number of input pins on IC's. R&D on high-speed data paths is needed to enable effective first-level triggers for future experiments. Topics for R&D include the use of commercial very high-speed fiber optics (greater than a GigaByte per second) in synchronous operation and serial data receiver circuit blocks for custom IC's.

7.2.2 High level triggers

High level triggers, often referred to as Level 3 triggers, are characterized by the use of commercial, general-purpose processors, such as RISC processors found in high-end workstations. These processors offer the advantage of cost-effective, flexible, programmable, and upgradeable implementations of trigger algorithms. Nevertheless, the use of these processors in new environments with higher rates and more demanding physics requirements presents several challenges. These challenges relate to the use of larger and larger numbers of processors in parallel. For instance, LHC experiments postulate the use of "farms" of as many as one thousand processors. Mechanisms for delivering data at very high rates (1 to 10 kHz), such as high-speed switching networks require development, particularly as applied to the HEP trigger environment, where the nature of the data flow differs from existing commercial applications. Software tools for managing and debugging code running in such a large distributed system, and software techniques for production of reliable code for programs executing a trillion operations per second, are also required.

7.2.3 Intermediate Level Triggers

Triggers at levels intermediate between the first level and high levels are characterized by input rates (*e.g.*, 100 kHz) that approach those of the first-level trigger yet require selection algorithms that are comparable in complexity to those of higher levels. Investigations into numerous processing techniques are warranted in this domain, for instance, studies of digital signal processors (DSP's), neural networks, commercial image processors, and advanced custom processors. Studies of architectures, including embedding of commercial CPU chips into custom architectures as well as use of commercial CPU boards or workstations, should also be pursued. Finally, the ability to guide and deliver very high bandwidth data to multiple processors is also crucial in intermediate levels; however, the challenges differ from those at the first level or at higher levels and deserve separate study.

7.2.4 Trigger Algorithms

Although most trigger algorithms are experiment-specific, several techniques and challenges are rather generic. For instance, calorimeter triggers for identifying electrons and jets are similar in many experiments. A general challenge is fast tracking triggers, driven in large measure by the desire to study heavy-quark physics. Trigger algorithms capable of identifying secondary vertices in high-rate large-multiplicity environments are of particular interest in the study of B physics. Development of such algorithms could lead to a breakthrough in physics potential in both the fixed target and hadron collider fields.

8 Conclusions and Recommendations

8.1 Importance of Detector R&D

From the preceding sections it is clear that the upcoming generation of accelerators will place severe demands on detector technology. Although in recent years impressive progress has been made in most areas of detector R&D, much remains to be done.

To maintain the health of our field in the future, it is important that new ideas for detection and measurement of the observables of particle physics nurture and bloom. These ideas are the "gene pool" from which future detectors will evolve. Without such activity it will become increasingly difficult to take full advantage of the physics opportunities presented by the new generation of facilities. In short, detector R&D is an important part of the HEP program and must be protected.

8.2 Generic vs. Detector-Specific R&D

When considering how best to proceed in ensuring that progress in detector development continues to be made, one encounters the question of whether detector R&D should be funded through a separate program dedicated to this end—*i.e.*, a "generic" R&D program—or within the context of experiments—*i.e.*, "detector-specific".

Until recently, most detector development work was detector-specific at least in a formal sense. The situation changed around 1990, when the SSC laboratory established a program of generic detector R&D as a means of stimulating early work on the SSC's experimental program. At about the same time, the Texas National Research Laboratory Commission (TNRLC), began to fund to research proposals of a generic nature. (The TNRLC also funded on-going physics research and infrastructure.) Unfortunately, with the demise of the SSC both the generic detector R&D and the TNRLC programs were cancelled, leaving much excellent detector development work without support.

At present there are several other pressures that work against a healthy program for developing new detection techniques. The scale and cost of detectors has grown enormously. With that growth comes an increased conservatism in making technological decisions. The scientists charged with managing large detector projects understandably look for a high degree of assurance that a technology will perform before committing substantial funding. Moreover, the time and resources required for a technology to progress from the conceptual phase to a mature state has increased in accordance with increases in complexity. Finally, in an atmosphere of limited funding, "discretionary" funds (*e.g.*, director's funds at laboratories and endowed funds at universities) are increasingly likely to be used to address short-term crises rather than to provide seed money for the sort of innovative but speculative ideas that lead to new techniques.

There are, however, valid considerations that tend to favor a detector-specific funding mechanism. Perhaps the most important of these is that with a fixed overall budget, any funds devoted to generic R&D must ultimately come from other parts of the HEP program, none of which currently have enough support. Perhaps the best arbiters of which detection techniques ought to be developed are the detector collaborations themselves. A large purely generic program runs the risk of diverting precious HEP resources to support the development of technologies that are "interesting" but of no particular benefit to particle physicists.

From the preceding paragraphs it follows that while some funding of generic detector R&D is warranted, any program to do so should be of modest scope and should be aimed primarily at nurturing new techniques just long enough to provide proof-of-principle demonstrations. Beyond that "market forces"—*i.e.*, decisions made by detector collaborations—should determine which technologies receive the level of support necessary for the deployment of practical devices.

8.3 Features of the Proposed Program

The details of any such program are best determined by members of the HEP community working in conjunction with the funding agencies. In this section, we present only general considerations.

8.3.1 Level of Support

Most new techniques will benefit enormously from relatively modest levels of support. Generally speaking, amounts between \$50 K and \$250 K per project per year will suffice. Indeed, funding on a scale larger than that runs the risk of creating large programs that are not particularly conducive to innovation. If one assumes that six projects each averaging \$150 K/year are started each year and continued for three years, the steady state outlay for the total program would be about \$3 M per year or about 0.5% of the current HEP budget. Even in a scenario with flat or declining budgets, the budgetary impact of such a program should be manageable since funds "taxed" away from other HEP programs will be redistributed, easing the pain, at least on average.

8.3.2 Duration of Support

As noted, the intent of the proposed program is to provide an incubation period for new or improved detector technologies. Generally speaking, three years should suffice to develop new techniques to the point where detector collaborations can seriously consider their use. Thus the typical development project might be funded in three one-year installments, with the second- and third-year renewals being conditioned primarily on demonstrated progress. In exceptional circumstances, longer periods might be allowed, although this would obviously have an adverse impact the ability to launch new starts. In any event, projects extending beyond three years would not be "renewed" in the usual sense but instead would be subjected to the same sort of review applied to new applicants.

8.3.3 Method of Peer Review

Since the number of funded projects will be small and many of the proposals are likely to be highly technical in nature, the selection of proposals for funding will most efficiently be done by a panel of experts. The panel should comprise physicists (and where appropriate engineers) with expertise in accelerator- and non-accelerator-based detector technology as well as high-energy physicists representative of the "end-user" community. Outside experts might also be included to provide additional perspective or technical expertise. By asking panel members to serve in three-year staggered terms, the panel would retain some "memory" while at the same time being continually refreshed.

8.3.4 Eligible Applicants

Individual or group proposals from laboratories, universities, and industry should be eligible. Collaborative combinations should also be permitted, although the relatively modest levels of funding will naturally tend to limit the size of collaborative efforts. In exceptional cases, larger collaborations may be formed if this is deemed to be the most efficient approach to a particular development effort.

8.3.5 Criteria for Evaluation

To be successful this program should have as its primary goal the development of new and improved detector technologies. Thus this should be the main criterion in evaluating proposals. Of course, the usual technical criteria (capability and/or track record of the investigator(s), feasibility of the proposed plan, appropriateness of the budget, etc.) should be taken into account, since such considerations are important to the success of any research venture.

8.3.6 Use of Funds

Since the amount of funding will be limited, it is essential that there be a minimum number of restrictions on their use. Investigators should be free to use the funds in a way that is most effective. Since second- and third-year renewals will not be automatic, there will be a strong incentive for investigators to use their funding in the most effective way.

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