Primer on Detectors and Electronics for Particle Physics Experiments

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19-Jul-14

Abstract

This primer is a brief introduction to the technologies used in particle detectors designed for high-energy particle physics experiments. The intended readers are students, especially undergraduates, starting to work in our laboratory. The references will provide much more information about these topics and may be more useful than the primer itself.

I Background of Particle Physics Scattering Experiments

Physicists have made the most progress over the past 100 plus years at understanding the nature of the sub-atomic world and to some extent how it is connected to the cosmos by conducting experiments that scatter one type of particle off of some type of matter, be it molecule, atom or other particle. The experiment suggested by Ernest Rutherford in 1909 aimed alpha particles decaying from unstable radon towards a gold foil. His finding that some projectiles unexpectedly scattered into large angles gave the first indication that the atom was not a ball of nearly uniform density but rather included a hard core, what we now call the nucleus. To probe deeper inside the nucleus and then deeper inside the constituents of the nucleus, neutrons and protons, better beams of projectiles were needed with better collimation, more intensity and most of all higher energy. Given the dual particle-wave nature of objects at the quantum scale, higher energy projectiles yield shorter wavelengths, which allow probing smaller dimensions. This is analogous to moving from visible light to ultra-violet to x-ray wavelength microscopes to "see" smaller and smaller objects. The need for these higher energy beams was satisfied with the invention of particle accelerators, cyclotrons, synchrotrons, and linear accelerators. The projectiles of choice were electrons and protons, primarily due to the ease of obtaining such bare particles. These scattering experiments through the 1970s were of a fixed target type, just like Rutherford's. The projectile beam was aimed at a target, which was at a fixed position in the laboratory. The objective of the experiment was to detect the scattered projectile and possibly any new particles that were created in the scattering event. Due to the famous Einstein relationship $E = mc^2$, inelastic scattering events have the potential to convert some of the energy of the incoming projectile into new matter, i.e. particles. In this way many new particles were discovered, possibly adding confusion at first but leading the way to a deeper understanding of this part of nature.

The energy available to make new particles or probe smaller distances in these experiments is fixed by the energy of the projectile-target system. If both the target and projectile particles can be accelerated to high energy, the energy available in the center of mass of the system is greatly enhanced. In the 1960s, colliding beam machines started to make an appearance in which two beams of particles are aimed at each other. These machines present many new problems to the accelerator designers but there are also new difficulties for the detector designers. This primer will introduce the most common types of detectors used in scattering experiments and the electronics required to make them work. The different design issues for detectors for fixed target experiments and for colliding beam experiments will be discussed, with an emphasis on the latter since most present day scattering experiments are that type.

II Particle Detectors

As stated above, all particle scattering experiments, both fixed target and collider types, require particle detectors to find and possibly identify all the particles emerging from a scattering event. A simple fixed target experiment might scatter a projectile electron off a target of protons (often a container of liquid hydrogen) and simply measure the momentum and angle of the scattered electron. This was the method used to originally measure the size of the proton. More complex experiments create inelastic collisions in which many new particles are produced, all of which must be located and identified in order to analyze the event and understand the dynamics of the interactions.

The first particle detectors were visual in nature. The Wilson Cloud Chamber relied on charged particles leaving a trail of small droplets in a super-cooled gas. The trail, called a track, was visible and could be photographed to make a record of the event. Bubble chambers and streamer chambers were significant advances of this principle in that photographing an event and clearing the tracks for the next event could be synchronized to an accelerator beam. All of these visually oriented detectors relied upon photographing the tracks and then measuring the track trajectories in the photographs. The chambers were usually enclosed in a magnetic field such that the charged particles would bend and the measured radii of curvature determined their momenta and the sign of their electric charges.

Figure 1: Fermilab's 15-foot Bubble Chamber

All modern particle detectors rely on the interaction of the particles with material to create an electronic signal, which can then be fed to a computer for analysis. A whole series of gas detectors that accomplish this have been invented and employed over many years. The gas is contained in a chamber in which wires are strung. Positive and negative voltages are applied on the wires in a particular arrangement to create electric fields inside the chamber. When charged particles traverse the chamber and ionize some of the gas (i.e. knock out atomic electrons creating positive ions), free electrons are collected on the anode (with positive voltage applied) wires and positive ions on the cathode (with negative voltage applied) wires. The collected charge can then be amplified and transmitted to a computer thus avoiding the photographing and measuring steps. Some examples of these gas detectors are called spark chambers, multi-wire proportional chambers, drift chambers and even time projection chambers. A Geiger counter is an extremely simple type of gas-wire chamber. Another type of detector technology employs special materials called scintillators, which emit light when traversed by a charged particle. This light can be collected and turned into an electrical signal by a device called a photomultiplier. These photomultipliers originally employed a tube technology but recently solid-state devices have become available. With the exception of the time projection chamber, these wire chambers and scintillation counters are usually fabricated as planes such that each plane measures the particle position in the one dimension in the plane of the detector perpendicular to the direction of the wires or the scintillation strips. Pairing two planes at a rotated angle yields three coordinates of the track (including the position of the detector planes along the track). Thus, utilizing several pairs of these detector planes inside of a magnetic field allows the measurement of the track trajectory and the calculation of the track momentum directly by a computer.

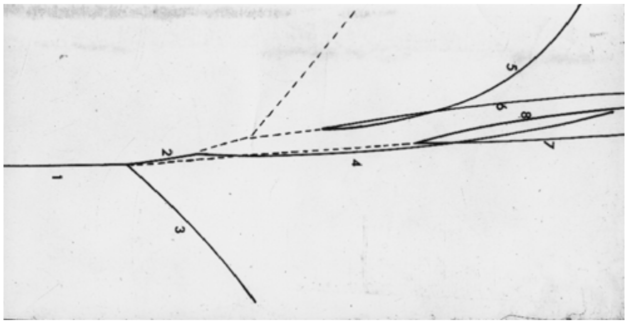

Figure 2: Bubble Chamber Photo. Charged tracks curve in the magnetic field. Dotted lines are computer reconstructions of neutral tracks. (CERN Bubble Chamber Web Site)

A new type of detector has been developed in the last few decades, which makes use of the advances in silicon integrated circuit technology. These silicon detectors are fabricated by implanting diodes in a silicon wafer and reverse biasing the diodes. When a charged particle (electron, proton, muon, etc.) traverses one of these diodes, electron-hole pairs are produced with the electrons swept to the anode and the holes to the cathode of the diode. This is similar to the case of free electrons and ions formed in a gas chamber, however, in a silicon lattice the relative energy levels of the valence and conduction bands shifted by the electric field in the diode depletion region allow the charges to move. This small amount of charge, a few femto-Coulombs (fCs), can be amplified and registered as the presence of a particle at the location of that diode. The wafers can be patterned using standard photolithography techniques into diode strips, called micro-strip detectors, mimicking the wires of chambers described above to measure one coordinate of the particle position, or patterned into small rectangular cells called pixel detectors to measure two coordinates of the particle position. One of the big advantages of these silicon detectors is that the fabrication process allows the size and spacing of these diodes to be of order tens of microns, whereas wire spacing in chambers cannot be less than a few millimeters and scintillator segmentation not better than a few centimeters. (Pitch is a common term defined to be the distance from the center of one detector element, silicon strip, wire or scintillator segment, to the next.) Thus, the position accuracy of the silicon detectors can exceed that of wire chambers by two or three orders of magnitude and that of scintillators by at least four. Several planes of these silicon detectors can be arrayed just like planes of gas chambers or scintillation counters to measure the trajectories of charged particles.

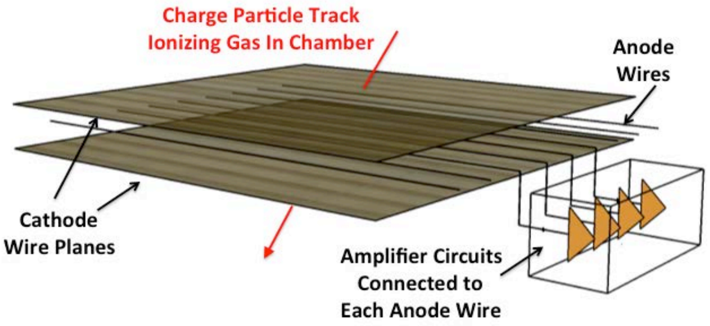

Figure 3: Wire Chamber Schematic. Anode Wires and Cathode Wire Planes form electric fields in chamber. Particle traverses along Track; ionizes gas; charges collect on anode wires and are amplified by Amplifier Circuits.

The various types of detectors discussed above are only sensitive to charged particles but allow the momentum and the sign of their electric charge to be measured by measuring their curvature in a magnetic field. To measure the energy rather than the momentum of a particle, detectors called calorimeters are used. These detectors sandwich several layers of some type of charged particle detector, like the ones described above, between alternating layers of some dense material like lead or iron. The high-energy particles interact with the dense material creating more particles, which share the energy of the original particle. Providing enough layers to stop the initial particle and all of the secondary particles allows the energy of the initial particle to be measured by measuring the amount of total charge deposited in the layers of active detector. These calorimeters are also sensitive to neutral particles in that the neutrals also interact with the dense layers of material. Some modern calorimeters replace the gas in the chambers with a dense liquid such as liquid argon to enhance the absorption of the energy of the secondary particles.

In the following sections, a distinction will be made between "sensor" and "detector". A sensor will refer only to the material through which the particles traverse creating some sort of detectable signal, e.g. the silicon wafer patterned with diodes or the chamber filled with gas and strung with wires. A detector will refer to a more complete detection system, at a minimum including the sensor and its readout electronics.

A more comprehensive discussion of particle detector types is covered in *Particle Detectors* by C. Grupen [1]. Also, the book by H. Spieler, *Semiconductor Detector Systems,* is an excellent resource for detectors and their electronics using semiconductor sensors [2]. The electronics associated with all these different detectors must sense very small signals, amplify them to a usable level with a sufficiently good signal-to-noise ratio (the ratio of the amplified signal size to the combined amplified input noise plus that introduced by the amplifier circuit), and then condense the data into some form usable by analysis computers. While the materials used to sense particles and the corresponding electronic signals are nominally the same for fixed target experiments and collider experiments, the necessary arrangement of the sensors and resulting mechanics create some very different design criteria for the sensors and their readout electronics. Conservation of energy and momentum forces all the products of a fixed target scattering experiment to fly into a forward cone, while products from a collider scattering experiment, that is where the center of mass frame is the same as the laboratory frame, emerge at all angles in a 4π-steradian solid angle. The density of particles per unit solid angle is then greater for fixed target experiments, possibly putting more difficult requirements on position resolution of the sensors, but the limited area of the full detection system normally makes mechanical supports, access to electronics for repair and routing of electrical and cooling services all much easier since the outer perimeter of the detection system is open and accessible. The "4π geometry" of the collider detector complicates these design issues, as we will see in the next sections.

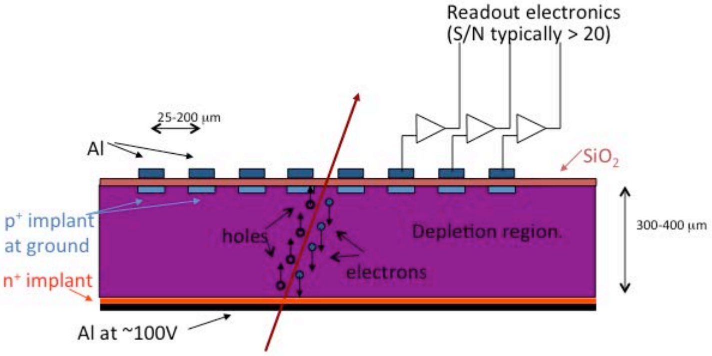

Figure 4: Silicon Sensor Schematic Cross-Section. The amplifiers are in external integrated circuits typically wire bonded to the sensor wafer. S/N is signal-to-noise ratio. Al is aluminum conductor and SiO_2 an oxide insulator.

III Particle Detectors for Colliders

Most but not all detectors for collider experiments are designed to capture as much of the complete solid angle surrounding the interaction point as possible. This is important in order to detect all the particles produced in the scattering event and thereby reconstruct what occurred. Furthermore, some particles likely to be produced in these interactions, namely the neutrino particle, do not readily interact with matter and require tons of material to detect, much more material than is feasible for a general-purpose collider detector. Therefore, these particles are not recorded by the collider detector system. Instead, missing energy in the event is attributed to neutrinos, making the full coverage, typically referred to as hermeticity, essential so as not to lose any detectable particles and attribute that loss to an undetectable neutrino. The ATLAS detector built for experiments at the Large Hadron Collider (LHC) at the CERN laboratory in Geneva, Switzerland is a good example of such a detector [3]. A cut-away drawing of this detector is shown in Figure 5. The full detector is made up of many sub-detectors, each of which surrounds the interaction point and serves to detect a certain type of particle. The Inner Detector, closest to the interaction point, with the Pixel Detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT), detects charged particles and resides inside a 2 Tesla solenoidal magnetic field. Each consists of several concentric barrel and end-cap layers to allow determination of the particles' momenta by measurement of the radii of curvature of their trajectories. The Pixel and SCT Detectors are examples of silicon detectors described in the previous section, the latter using silicon micro-strip sensors. The TRT employs gas-wire chamber technology. Next the Liquid Argon Calorimeters (LAr) measure the energy of electrons, positrons and gammas. The Tile Calorimeters measure the energy of hadrons (protons, neutrons, pions, etc.) and finally the Muon Chambers measure muons, which emerge from the calorimeters and are again bent by a set of toroidal magnets. There are some other technologies used in the muon system to facilitate a function called triggering but the entire topic of triggering and the required trigger electronics are beyond the scope of this primer. The enormous size of

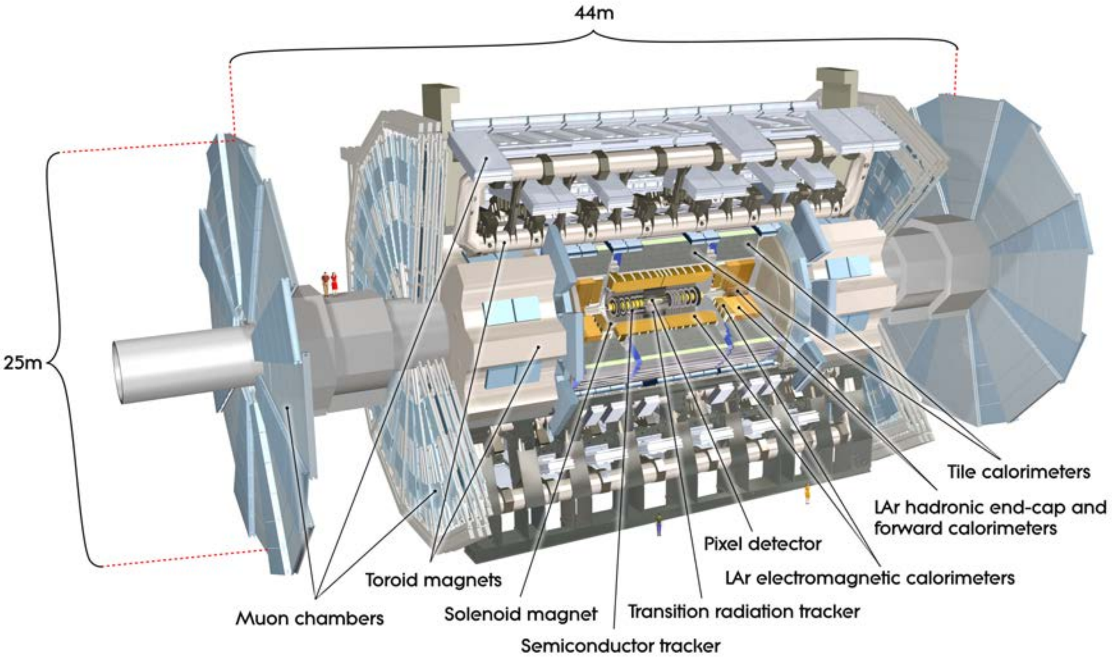

Figure 5: The ATLAS detector. (ATLAS Experiment © 2014 CERN)

the detector (See the small 6-foot tall persons in Figure 5 for scale.) is required in order to capture all the energy from the reactions and to provide sufficient travel distance through the magnetic fields to measure the momenta of the very high-energy particles.

Note that the CMS detector also at the LHC is a second example of a nearly 4π hermetic detector while the ALICE and LHCb detectors at the LHC are designed for more special purpose experiments [4,5,6]. Some of the requirements discussed here may not apply to those latter two detectors.

IV Design Issues for Detectors used in Colliders

The design of detectors for colliding beam experiments and the technologies to use are all in the domain of the creativity of the experimenters. However, there are some issues, which are common to these detectors and different than issues for fixed target experiments. The picture of the ATLAS detector demonstrates one of the design issues for detectors for collider physics experiments, reliability. With the possible exception of the outer most sub-detector (in this case the Muon Chambers), detector components will be buried deep inside the massive system. Accessing those components for repair or replacement involves opening up the entire apparatus, a task requiring many months of downtime and involving risks to other fragile components. The experiments are typically designed to run for up to 10 years and, therefore, all the components must be designed to operate for at least that long without significant failure.

The other issues for these detectors include minimizing material, low power because of limited space for services, extremely limited room for both power cabling and cooling plumbing, potentially high data rates and, perhaps the most onerous, radiation tolerance since the very nature of the application requires operation in a high radiation environment. Each of these issues will be considered in the following sub-sections. Electronics used inside these detectors have special requirements and they will be discussed separately in section VI.

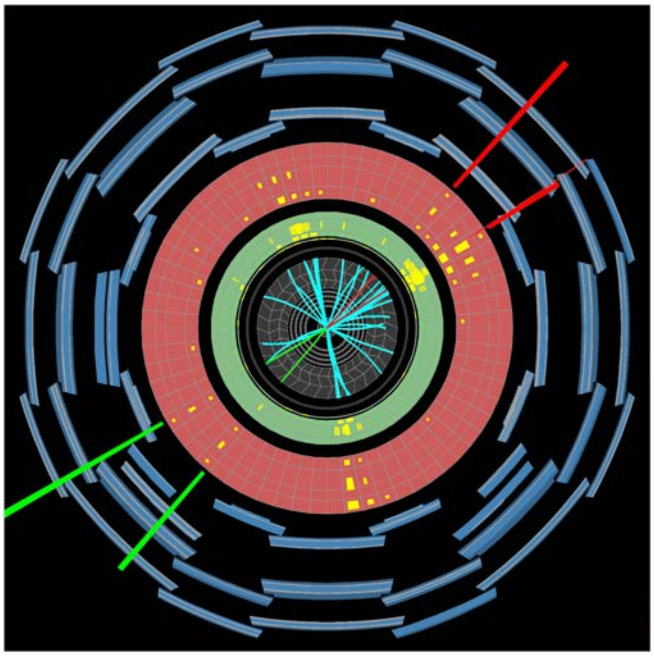

Figure 6: Computer Reconstructed ATLAS Event.
Charged tracks in the Inner Detector;
Energy deposited in the two Calorimeters;
Four tracks in muon chambers.
(ATLAS Experiment © 2014 CERN)

IV-a Radiation Tolerance

The particles created in these experiments, which the detectors are designed to detect and measure, are forms of radiation that can damage many types of material. Certainly, the sensor areas of the detectors must be able to withstand this radiation during their lifetime, but the 4π nature of most collider detectors results in most of the support components, e.g. mechanical supports, cables, cooling pipes and electronics, having to also survive the expected radiation. Experimenters have been surprised by several types of material degrading after exposure to large doses of radiation. Teflon used as insulation for cables has turned to powder. Wires inside of chambers with some exotic gas have developed corrosion over time. Experimenters have learned that any material planned for the inside of one of these detectors must be tested for radiation tolerance. Beyond these general statements, it is impossible to cover all the varied detector technologies here. The one exception is the silicon sensor that shares many of the same radiation sensitive issues as the readout electronics. For that reason, more about radiation tolerance of silicon sensors will be included in the electronics radiation section VI-a. The amount of radiation exposure depends upon many factors such as the type of beam, beam intensity, and distance from the interactions. A few representative examples are given in Table 1 of section VI-a, which includes more information about radiation issues.

IV-b Minimal Material

When particles traverse through material, they lose energy and often scatter. These interactions confound the measurements of the particles' trajectories and hence their momenta and energies. The sensor materials, e.g. silicon wafers or gas chambers, are naturally low mass and also unavoidable material in order for detection to take place. The mechanical supports, cabling, cooling pipes and electronics, however, represent extra material, which degrades the performance of the detectors if particles must pass through them. The ideal detector then would consume zero power, be light enough to be supported by gossamer strings and transmit its data wirelessly to the data acquisition system. No one has yet invented such an instrument but experimentalists are always trying to minimize the material inside these complex collider detectors.

IV-c Low Power

This issue is mostly a consequence of the material issue discussed above. Power dissipation in a detector requires cables to deliver the power and a method to remove the power, usually cooling pipes. Both represent material inside the detector volume. A second reason for this issue is limited space for these services and if the detector is supposed to be hermetic, all of these services require access points, which likely will break the hermeticity.

Most of the power consumed by a detector is by the electronics mounted on or very near the sensors. Scintillation sensors consume no power; wire chambers themselves consume very small amounts of power needed to provide required voltages on the anode and cathode wires; silicon sensors also consume a very small amount of power in the form of leakage current in the reverse biased diodes, however, this leakage current can grow to be significant after the sensors have been exposed to a substantial amount of radiation. More about this in section VI-a.

IV-d High Data Rates

The successful advancement of particle physics in the last 60 years has pushed the experiments to look for more rare processes as well as to search at higher and higher energies. As a consequence of this, the detector systems have grown in size, increasing also the number of readout channels. (The ATLAS Pixel detector has 80 million channels and the SCT detector has 6.3 million channels.) The beam intensities have increased enormously as well. This has resulted in large increases in the amounts of data and data rates to be transmitted out of the detectors. This will be discussed more in the electronics section VI-d.

IV-e High Reliability

Lastly we return to an issue that was raised at the very beginning, namely reliability. As mentioned already, colliders are typically designed to operate for at least 10 years with only minor repairs. This is due in part to the large expense in building one of the detectors, but there is much to be learned from the experiments' use of them and it usually takes many years to fully exploit the potential of the investment. In fact, it is often the case that after 10 years more can be learned with further operation of the detector and collider but upgrades are required to enhance performance, capitalize on advances in technology and replace some worn out parts. Radiation damage often limits the lifetime of some components. Therefore, 10 years is typically a convenient lifetime specification. Certainly, it has been the case that after 10 years new technology allows significant improvement in performance of some components.

During this ~10 year lifetime, any component failures can cause serious problems. Opening one of these detectors can take several months, possibly as long as a year. This down time is very expensive in that beam time is lost, operations personnel are still on payroll and experimenters are delayed in their work. Just as the detector is built with each detector type wrapped around those closer to the interaction point, servicing an inner detector requires opening and often removing all the outer ones. The work is tedious, in a confined space underground, sometimes requiring outer sections to be lifted out to the surface. Many components like cable and plumbing connections are fragile having been designed to minimize material inside the detector such that damage can be done in the process of fixing something else. And lastly, after several years of operation, the inner components are probably activated, i.e. they emit radiation, from the constant exposure to radiation. This requires special handling of all activated components.

To ensure high reliability, careful engineering practices are exercised with quality assurance procedures in place and fully exercised. Lifetime tests are performed on as many components as possible, especially for components which do not have published industry lifetime test results. Since there are very few if any moving mechanical parts inside such a detector (pumps and fans, etc. are always located outside of the actual detector where they can be serviced more easily), failures due to radiation damage and corrosion are the primary "wear out mechanisms". There are special issues regarding reliability and lifetime of electronic components. These will be discussed in sub-section VI-e.

V Electronics for Particle Detectors

The electronics associated with particle detectors can be separated into two groups: on-detector electronics that are mounted in close proximity to the sensors and off-detector electronics located many meters, perhaps a few hundred meters, away from the sensors. The main goal of the on-detector electronics is to amplify the very small sensor signals, integrate and shape the signals over a relevant time period, and provide robust signals to be transmitted off detector. The off-detector electronics can then perform much more complicated data processing such as track reconstruction, cluster analysis of adjacent calorimeter channels and decisions about the relative interest of a particular event, i.e. is a particular scattering event worth recording on the storage media for later physics analysis. Linking the on-detector and off-detector electronics will be some form of data transmission, now typically optical. Given that the off-detector electronics are located outside the immediate detector area, usually in a side service cavern or surface building, they do not reside in what would be considered an especially harsh or extreme environment. Therefore, we will focus only on the on-detector electronics.

In addition to the varied types of sensors developed for particle detection, there are a few different methods for electronically processing the data depending upon what information is desired. The simplest information is "did a particle traverse this sensor?" This so-called hit or no-hit information can be very useful if each sensor is very finely segmented. For example, the silicon micro-strip sensor mentioned above can form silicon diode strips with a pitch as small as 50 μm. Recording which strip has a hit then can identify the position of a track to very high accuracy. Potentially more information can be obtained from the sensor. The actual amount of charge deposited in the sensor can also be recorded. For a calorimeter, this is essential for its operation. The amount of charge deposited in a calorimeter is a measure of the energy of the detected particle. Electronics for these detectors must record a full analog value for each sensor channel.

Figure 7 shows a block diagram for a typical front-end circuit providing the simple hit/no-hit information. One and possibly two stages of amplification are required followed by an integrator/shaper block and then a comparator to separate a real hit from noise. Finally, there is some translation to a digital signal. Following these front-end blocks, there will likely be buffering of data, building some kind of output packet and transmission protocol. For applications where analogue information is required, the comparator and digital translation stages will be replaced with either analogue buffering and some sort of analogue transmission or more likely these days with analogue-to-digital converters (ADCs) built into the on-detector ICs (integrated circuits) and digital buffering and data transmission. The on-detector electronics also typically include some monitoring functions like tracking the temperature and humidity of the detector. It is not possible to discuss in detail in this short work all the varied types of data processing now being employed in particle detectors. The availability of very dense integrated circuit technologies has made possible very complex on-detector circuitry and more functionality has been moved from off-detector to on-detector. ADCs are a good example of this. In the past, all ADCs had to be located off detector because of power and space requirements. Moving more electronics on detector removed the necessity to transmit analogue signals over long distances to

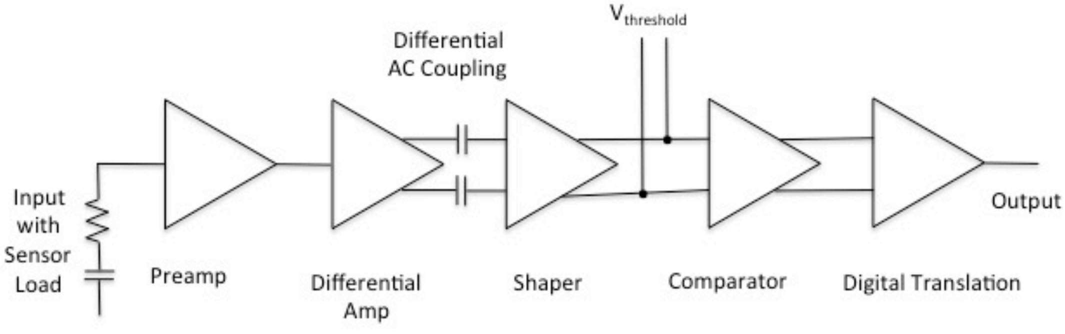

Figure 7: Block Diagram for a Typical Front-end Circuit for Hit/No-Hit Readout
The preamplifier, amplifier and shaper circuits amplify the signal and possibly integrate over the expected charge collection time of the sensor. AC coupling blocks any offset or leakage DC currents. The comparator discriminates signals larger than $V_{threshold}$ from lower level noise.

the off-detector racks. This has reduced noise and signal attenuation allowing detection of much smaller sensor signals. It also afforded the possibility of greater compaction of data before transmission, possibly reducing the transmission bandwidth requirements. This has been essential as the channel counts have grown. The issues of signal vs. noise and pulse shaping will be expanded in section VI-b.

VI Requirements

Several issues specific to particle detectors designed for collider experiments have been discussed above in section IV. Those will be expanded here in the next several sub-sections as they apply to the detector electronics. Many of the requirements are common to both fixed target detectors and collider detectors. This will be noted in each sub-section.

In general electronics can be of various technologies, vacuum tubes, single solid-state components or integrated circuits made of silicon, gallium arsenide and other materials. Indeed particle physics has grown hand in hand with the electronics technologies. Early systems in the 1940s and 1950s used vacuum tubes. These were replaced by semi-conductors and later by ICs. The advances in the electronics industry have afforded many of the advances in particle physics. A detector like ATLAS could not have been built without the readily available IC foundries, which can fabricate ICs custom designed for the collider detector applications. Most requirements for these detectors can now be met by commercially available integrated circuit technologies with custom designs.

There are two other points to keep in mind as the various requirements are considered. All of the sensor types used for particle detection involve collection of charges released in the sensor material by the impinging particle radiation. This collection of charges requires voltages much larger than that powering the attached readout electronics. Silicon sensors typically require a few hundred volts to possibly 1 kV. Other sensors such as wire chambers or LAr calorimeters require several thousand volts. These high sensor voltages are always blocked from the readout electronics with capacitive couplings but the presence of such voltages often has implications for system design, for example appropriate voltage protection devices. The other point is that many if not most of these detectors are positioned inside of a strong magnetic field, which prevents the use of any device made of magnetic material, like magnetic core inductors for filters or for DC/DC buck converters.

VI-a Radiation Tolerance

The particles, which these detectors are designed to study, are exactly the forms of radiation that can be damaging to microelectronics. While there are possibilities in fixed target experiments to keep the electronics out of the radiation area, that is impossible with the “4π geometry” of the collider detectors. However, sometimes the electronics for fixed target detectors must also be exposed to radiation in the interests of keeping the first stage readout immediately at the sensors to reduce noise and optimize data transmission. Also, the beams themselves are a large source of background radiation. Beam designs employ dipole bending magnets and quadrupole magnets to focus the beams at the interaction point with collimators to scrape away any off-momentum particles. These collimators do not completely stop everything hitting them resulting in some lower energy remnants entering the experimental area. Neutrons are an especially difficult problem in this regard. All modern collider detectors as well as the accelerators or storage rings that feed beam to them are buried underground so that the surrounding earth can provide shielding for human safety. The on-detector electronics must live in the radiation environment. As the field of particle physics has advanced, it has become necessary to study reactions with lower and lower probabilities (referred to as cross-sections). This has forced the beam intensities to increase thereby increasing the radiation exposure of the electronics. There are both long-term permanent damage and instantaneous disruption, often referred to as Single Event Effects (SEE), which must be considered in designing the electronics. An introduction to the effects of radiation on electronics will be given here. A more detailed discussion of the effects on semiconductor devices is covered in the book by H. Spieler [2].

The required level of radiation hardness for different collider experiments depends on many factors. Proton/anti-proton colliders typically produce more radiation than electron/positron colliders because of the nature of the scattering events. Radiation increases with the luminosity of the colliders, which is increasing with each generation as more rare processes are being studied. Most important is the position of the electronics. Readout electronics for an inner most tracking detector will experience much more radiation than that for a calorimeter or muon detector, which are typically located outside of the tracking detectors. As an example, Table 1 shows the expected exposures for two different detectors, BaBar at an electron/positron collider at the SLAC laboratory and ATLAS at a proton/proton collider at the CERN laboratory.

Table 1: Examples of Required Radiation Hardness of Two Typical Collider Detectors (From [7,8,9]) For definitions of the units in this table, see [2]

	Total Ionizing Dose	Non-ionizing Fluence (1 MeV neutron equivalent)
BaBar		
Inner Silicon Strip Detector	20 kGy	Negligible
Outer Calorimeter	100 Gy	Negligible
ATLAS		
Inner Pixel Detector	500 kGy	10^{15} n_{eq}/cm^2
Outer Muon Spectrometer	20 Gy	10^{12} n_{eq}/cm^2

With the exception of some passive components such as resistors and capacitors, on-detector electronics are primarily made of ICs. Some dielectrics used in discrete capacitors can be sensitive to radiation and therefore should be qualified before use, however, we will focus attention here on radiation damage to ICs. While there are several different IC technologies these days, they can generally be grouped into two main classes, MOS (Metal Oxide Semiconductor) devices and bipolar devices.

MOS components, often called FETs for field effect transistors, now come in various flavors such as NMOS, PMOS, CMOS, LDMOS. The basic concept of all of these is illustrated by the cross-section view in Figure 8. A voltage is applied between the source and drain terminals and an intermediate voltage level is applied to the gate terminal to control the current flow between

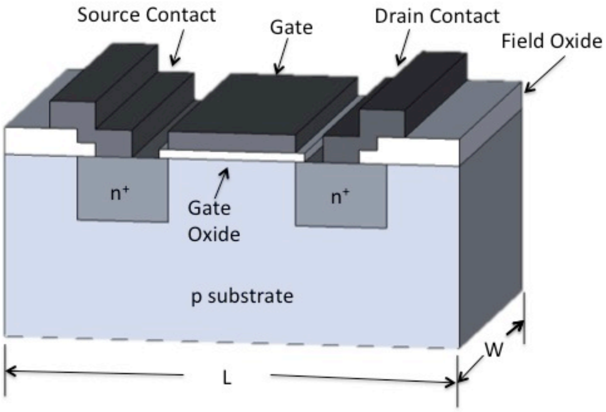

Figure 8: N-channel MOS FET Cross Section. Conduction channel is between the source and drain implants under the gate oxide.

source and drain. The voltage applied to the gate terminal creates a field in the region between the source and drain implants just under the gate oxide layer, which controls current flow between the source and drain. Ionizing radiation in the form of charged particles or high-energy photons can damage the thin gate oxide and form trapped charge sites. These trapped charges will then alter the electric field under the gate oxide changing the current vs. gate voltage relationship. This results in a change to the threshold voltage of the device, i.e. the gate voltage at which the transistor turns on or off. This will affect the speed at which the transistor will turn on or off as well as the gain of the device, and given enough radiation exposure, the transistor can become locked on or off. Even before this occurs, the change in threshold voltage can cause the transistor to leak charge, that is to not be fully off when the gate voltage would normally have produced the off state. This leakage current increases the power consumption of the IC. Another radiation effect is damage to the thicker "field oxide" which covers the chip and provides some added isolation between transistors. Trapped charge in this field oxide can induce current paths between transistors, also increasing the power consumption of the IC.

Bipolar transistors, also called bipolar junction transistors or BJTs, operate by a different mechanism and experience different radiation damage effects. A typical bipolar transistor cross-section is shown in figure 9. The back-to-back n-p and p-n junctions of the device allow current flow through the base terminal to control the current flow between the collector and the emitter. The resulting triode functions in much the same way as an MOS transistor, however, the current flows more directly through the silicon body and is dependent upon the relative dopings of the junctions. Damage to the silicon lattice, called displacement damage, then can have detrimental effects to the transistor performance. Such damage to the silicon bulk is not typically produced by ionizing radiation but rather by non-ionizing radiation (e.g. neutrons, protons, pions). Of course, the charged versions of these particles like proton, π^+ and π^- are also forms of ionizing radiation. Oxides are used to isolate the three terminal areas of the device. Depending upon the details of how the transistor is structured, these oxides can provide unwanted current paths if they are damaged by ionization radiation. Radiation damage to bipolar devices normally results in increased base leakage current, which is lost to the collector-emitter control. That is, the gain of the transistor, which is defined as the

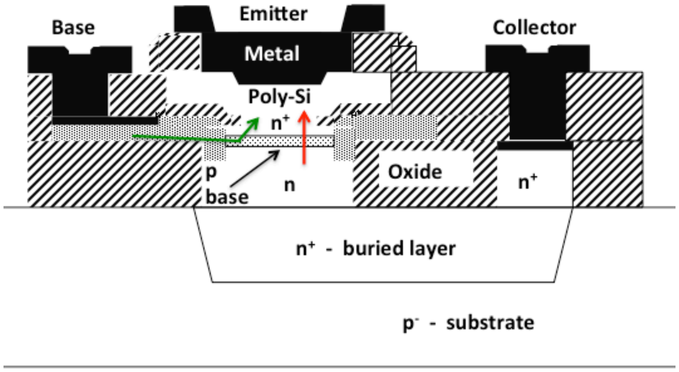

Figure 9: BJT Cross-section
A vertical n-p-n transistor structure.
Green arrow tracks base-emitter current, which controls collector-emitter current through thin base layer, tracked by red arrow, and buried layer.

collector-emitter current divided by the base current, decreases because the base leakage current is increasing. The effectiveness of the transistor then degrades possibly to the point where it is no longer usable. Thus, bipolar devices are susceptible to damage by ionizing radiation and by non-ionizing radiation. MOS devices are usually immune to non-ionizing radiation damage but will suffer from ionizing radiation.

A brief word about silicon detectors can be made now. As pointed out earlier, these detectors are fabricated as diodes implanted in silicon wafers such that the diode junctions collect the charge deposited by the traversing charged particles. In many respects then, they can suffer similar damage to bipolar electronics. Indeed the most serious damage occurs as displacement damage by non-ionizing radiation. This results in increased leakage current of the reverse biased diodes and larger voltages required to fully deplete the bulk. Effects can also be seen from large doses of ionizing radiation but these effects often appear as charges on the surface of the sensors where oxides are again used as insulators. Careful design of the diode structures and implant doping densities have yielded sensors which can survive large amounts of radiation resulting in sensor lifetimes of up to 10 years in present day colliders [19].

For many years, special highly proprietary techniques were developed by a few IC vendors to mitigate the radiation effects in semiconductors. This was especially true for CMOS technologies. This included special "black magic" oxides that somehow did not develop the charge traps which increased leakage currents and changed the threshold voltages. Bipolar devices could be built into more vertical structures, which changed the locations of the oxide isolators reducing their post-irradiation effects. All these techniques provided some level of radiation immunity but not complete immunity, and the proprietary CMOS technologies were very expensive.

As commercial technologies have continued to shrink the device feature sizes, these technologies have by coincidence become more immune to radiation. For example, the much thinner gate oxides for MOS devices have resulted in manageable radiation-induced threshold shifts because the electron tunneling rate (a quantum mechanics effect) is sufficient to neutralize the charge traps. Trench isolation between the transistors has reduced the leakage current between transistors. The smaller area of the bipolar base has somewhat reduced its cross-section (probability) for hadronic induced lattice defects, however, a potentially bigger help has been the introduction of lattice stress in the base region (e.g. silicon germanium technologies), which has greatly increased the current gain such that the radiation induced decrease is not as critical. Still some care must be taken in circuit design for these technologies to be completely acceptable. Leakage currents, especially between structures, remain a concern for technologies relying on field oxide isolation. One method to mitigate this in FET designs is to create an enclosed geometry as shown in Figure 10 [10].

The values in Table 1, especially for the ATLAS detector, may be slightly misleading because the high total dose and fluence values do not correspond to a relatively high dose rate or fluence rate. These expected levels of radiation are for a 10-year lifetime of the detector. If one takes into consideration the full 10 years with an operating time of roughly 66% of each year, the irradiation rates even for the inner most system are roughly 2 mGy/s (Gy = Gray = 100 rad) and $5\text{x}10^6$ $n_{eq}/cm^2/s$ (n_{eq} = 1 MeV neutron equivalent), relatively low rates. For this reason, low dose rate effects must be examined for the technologies being considered for these applications. Low dose rate effect (LDRE) is a phenomenon by which the effective damage to the transistor is enhanced if the radiation exposure is at a slow rate rather than a high rate. An example of such a study is described in [17].

One must also be concerned about instantaneous disruption of electronic devices. Even though these disruptions are most common with highly ionizing ion radiation, even singly charged minimum ionizing particles can cause disruption. This is especially true as device sizes shrink and the charge required to change state is reduced. Latch-up can be a catastrophic failure and must be avoided at all costs by device design and layout. Single even upsets (SEU) that cause bit flips, which can be restored by re-writing, can be problematic but possibly manageable. Since mitigation techniques for SEUs typically cost power or chip real estate or both, it is usually desirable to evaluate the severity to overall system performance of a particular bit-flip error in order to decide what kind of mitigation technique, if any, to employ.

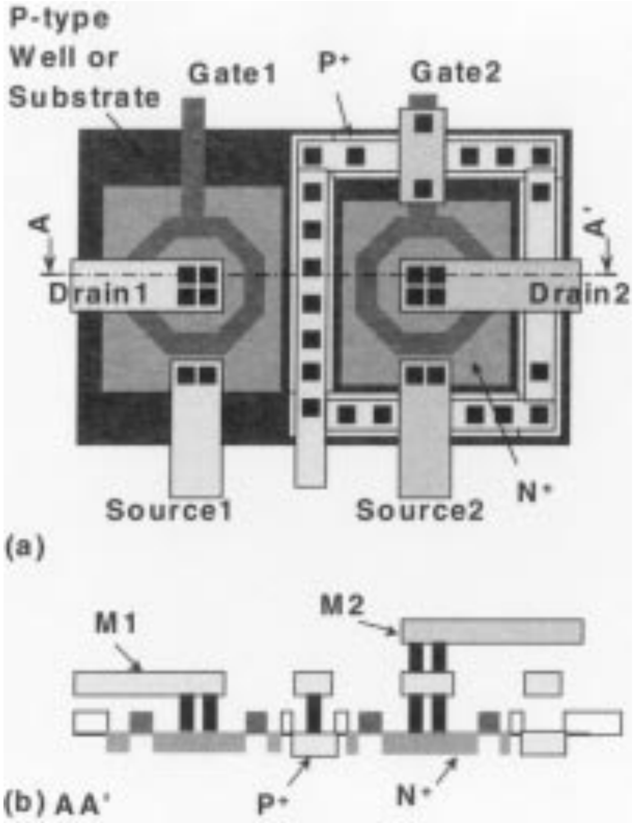

Figure 10: NMOS transistors in enclosed geometry and p+ guard rings to prevent radiation-induced leakage currents. (a) Top view. (b) Cross-section. (From [10], copyright [2000] IEEE)

To illustrate further, a register that is used to control the operation of the electronics may be critically important such that an internal bit-flip may cause the detector to malfunction and possibly cause some damage. Such a register should be carefully protected, possibly employing triple redundancy voting. Likewise, writing such a register should be protected with some sort of error correcting code (ECC), a Hamming code is common. A register that is not so critical, perhaps for an on-board digital-to-analogue converter to set the threshold for a data comparator, may require lighter protection (for example a more robust latch as a Dual Interlocked Storage Cell [11]) and ECC skipped on writing if read back after write is possible. An example where no correction technique is typically required is in the buffering and transmitting of sensor data. As long as the expected SEU error rate is much lower than the expected inherent error rate of the sensor and readout, there is no need for extra correction. As an example, the silicon micro-strip detector (SCT) for ATLAS has a noise error rate specification of $5x10^{-4}$. Testing of the on-chip pipeline buffer for SEUs found an error rate of 10^{-11}, clearly negligible compared to the noise rate and so no protection of the pipeline was necessary [12].

In spite of the success in using commercial technologies for collider electronics, extensive testing of each new technology has been absolutely required. This should be expected since the vendors do not specify any radiation tolerance and therefore do not guarantee any. This need for testing applies even to two technologies with the same basic commercial specifications but from two different vendors. Often some subtle difference in the three dimensional layout of the structures in the technology, especially the structure of the oxide isolation layers, can have very significant effects on the radiation tolerance. One concern in this regard is the possibility for a foundry to make a change to the fabrication process, possibly to increase yield, but after the technology has been qualified for a radiation application, which then affects the technology's radiation tolerance. Communication with the vendor can be most helpful in this regard but if long delays occur between the qualification and production, some re-qualification tests may be in order as well as ongoing quality assurance testing of production units.

One last note about radiation damage is that no electronic component, for the most part no material in general, is completely immune to radiation damage. The term "radiation hard" often gives the impression of complete immunity to radiation damage, but that is not the case. Radiation immunity always includes a qualifier as to what level of total dose and total fluence the parts are immune to damage with possible other qualifiers such as dose rate and SEU cross-section (probability).

VI-b Low Noise

As mentioned earlier, signals from typical particle sensors can be in the range of fCs. As an example, the most probable signal from a minimum ionizing particle passing through 300 μm of silicon is roughly 3.5 fC, with a Landau distribution such that a threshold for detection must be no larger than 0.75 to 1 fC in order to assure acceptable detection efficiency. The noise usually presents a Gaussian distribution. If we further take the example of the hit/no-hit readout of Figure 7, the noise occupancy (the probability of noise mimicking a hit signal) is related directly to the relative size of the noise signal compared to the threshold setting of the comparator as given by:

$$NoiseOccupancy \propto e^{-\frac{V_{threshold}^2}{2\sigma^2}}$$

where $V_{\text{threshold}}$ is the threshold setting of the comparator and σ is the standard deviation of the Gaussian noise distribution. It is important that this noise occupancy be much less than the expected occupancy of real hits. For the ATLAS SCT detector, the expected occupancy of real hits is ~1%. Therefore, a noise occupancy specification of $5\text{x}10^{-4}$ was set. This results in a signal-to-noise requirement ($V_{\text{threshold}}/\sigma$) of 4-to-1. It is typical for pixel detectors to set much more aggressive signal-to-noise ratios of something like 20-25. This is both possible because of the much smaller capacitance of the single pixel cell and desirable because the lower noise occupancy reduces confusion of noise hits from real hits in the region of higher particle densities closer to the interaction point where pixel detectors typically reside. For accurate analogue measurements, for example the energy deposited in a calorimeter, the constraints on the electronic noise may be even more severe. Twelve-bit or even 16-bit ADCs are now possible for on-detector ICs, implying least-bit accuracy of 1 out of a thousand to sixty thousand. Such a dynamic range is often desirable to match the large range of energies of particles. An adequate dynamic range for the analogue circuitry is then required and the noise should nominally be no more than half the least significant bit value. A complete discussion of electronic noise can be found in [20].

A simple form of analogue readout is sometimes employed when only a few bits are required. This time-over-threshold (TOF) technique starts with the basic hit/no-hit circuit shown in Figure 7 and provides at the output of the comparator block circuitry that will measure the amount of time the comparator output remains above threshold. Depending upon the linearity of the circuitry, this can be a crude measurement of the amount of charge deposited. This can be simply implemented with a counter enabled by the output of the compactor. This is often enhanced by distorting the function of the shaper circuit to stretch the signal rather than shorten it to fit into a natural time interval of the sensor. Care must be taken in analyzing the effective noise of the output bit count of such a circuit as a slowly falling trailing edge of the comparator output can result in somewhat larger effective noise than expected [13].

The capacitance of the sensor device is a critical parameter for the design of low noise readout electronics. The capacitance of silicon sensors can range from a few hundred femto-Farads (fF) for small pixels (e.g. with a pixel area of tens of microns by a few hundred microns) to a few hundred pico-Farads (pF) for micro-strip sensors many centimeters long. Other more macroscopic devices like a calorimeter or wire chamber can have capacitances in the nano-Farad (nF) range.

The other critical parameter is the time available for sampling the sensor signal. Time is required to collect the charge released in the sensor. For silicon sensors this is of order 10 ns. For larger devices like the LAr electrode or a wire chamber it can be 100s of nanoseconds. But the time between the possible arrivals of separate particles also constrains the time available for processing. The beam structure of the LHC, for example, collides bunches of protons every 25 ns. If the detector is going to separate particles coming from consecutive beam crossings, the electronics must be able to isolate signals within that time interval. Other machines such as the electron-positron collider for the BaBar detector had a much slower repetition rate, which allowed a much longer integration time. The electronics for the ATLAS SCT detector uses a peaking time of 20 ns.

The transconductance, which affects the input impedance, of the first stage is critical to good noise performance. Bipolar devices with low input base resistance have been successful at achieving acceptable noise levels for applications like the Liquid Argon Calorimeter and many silicon micro-strip detectors requiring short shaping times [12,14,15]. With longer shaping times (of order 100 ns or more) or with lower capacitances like pixel sensors, CMOS front-end circuits have been quite successful [8,16]. The book by H. Spieler [2] includes a detailed methodology for working with these constraints of load and timing.

VI-c Low Power

Power dissipation of the electronics is a serious constraint. Bringing power into the detector elements requires cabling. Removing heat generated by that power requires plumbing for some type of coolant. Both of these services require holes somewhere in the coverage of the detector for entry points. Furthermore, routing of these services through the active area of the detector creates scattering material for particles being studied. The tracking detectors such as the pixel and silicon micro-strip detectors measure the curvature of charged tracks through a magnetic field. When the particles encounter extra material such as cabling or plumbing, they have a probability to scatter, altering their path through the magnetic field and thus creating an error in the momentum measurement. Also, energy lost in traversing material before reaching one of the calorimeters will interfere with accurate measurement of the particles' energy. For all of these reasons, material inside the active volume of a detector must be kept to a minimum and that includes material for services.

In fact, the on-detector electronics also represents extra material, which must be accounted for, however, the alternative of sending raw sensor signals outside the detector volume would incur tremendous noise penalties so it is far preferable to locate readout circuits immediately at the sensors and include some data compaction functionality so as to minimize the amount of cabling for transmitting signals off detector. All on-detector components, however, are included in the material count and must be kept to a minimum, especially for example large capacitors or power devices. Also, for the readout circuitry of internal detectors (e.g. pixel and silicon strip detectors), bare chips are normally wire bonded directly onto hybrid interconnect circuits, which are then mounted onto the sensors. Commercially packaged parts take up too much space and add material. Figure 11 demonstrates how a compact, low mass silicon micro-strip detector can be built with unpackaged ICs on a polyimide/copper interconnect hybrid with a carbon fiber substrate. The two sensors on the front side are paired with two more on the backside rotated by a small angle to provide a stereo view of two dimensions. A piece of thermal pyrolitic graphite (TPG) is sandwiched between the two layers of sensors to extract heat. Beryllium-oxide (BeO) facings provide a heat path to a cooling pipe not shown [3].

This requirement for lower power adds further challenges to the low noise, fast integration time requirements already discussed. Again, the continuing efforts of the commercial electronics markets support the advances in collider technology making the present and future experiments possible. As examples of what has been achieved in this regard, Table 2 shows the power per channel and total power of the two existing ATLAS silicon detectors. Note the large channel counts, both for each detector system and for each IC. These large channel counts per IC are typical in order to minimize the material and the power consumption of the readout electronics and are another example of the advantages made from advances in circuit integration.

The ICs represented in Table 2 were designed over 10 years ago and no longer represent present state of the art technologies. The ATLAS Pixel ICs were built on a 250 nm commercial CMOS technology and the SCT ICs on an 800 nm BiCMOS technology that was designed to be radiation hard. Indeed, the next generation of this detector is now being developed on more advanced commercial technologies with a target to reduce the power consumption much further as the channel count will increase by possibly a factor of 10.

As the technologies shrink in size, the general expectation is that power consumption will also decrease, but this is not an automatic conclusion. Transistor bias voltages are reaching their limit to provide useful circuits, especially analogue circuits. Some reduction in digital switching currents is anticipated but this also increases the susceptibility for SEU errors.

Table 2: Power Consumption of the ATLAS Silicon Detector Systems (from [8,12])
(does not include power for optical data transmission or monitoring functions)

	Power/channel	Channels/IC	Power/IC	Total # of Channels	Total Power
ATLAS					
Pixels	100 m0	2880	288 mW	80×10^6	8 kW
SCT	3 mW	128	400 mW	6.3×10^6	19 kW

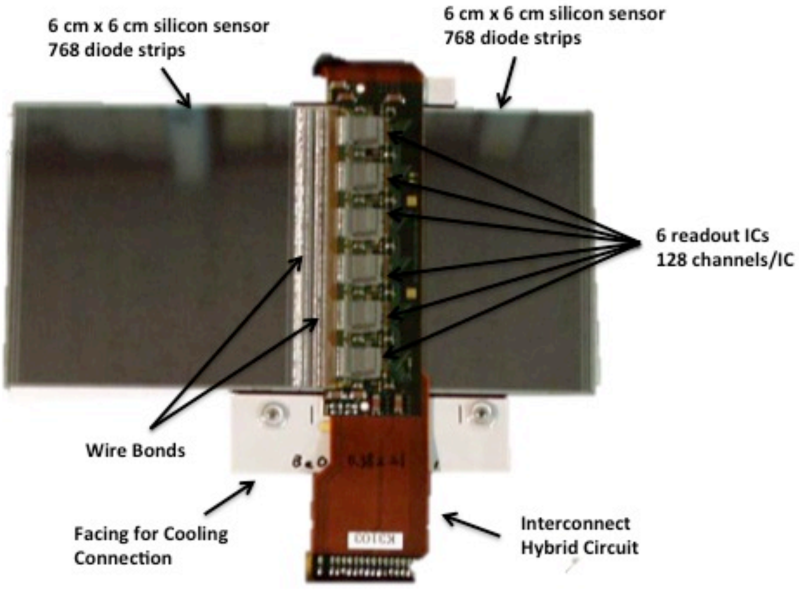

Figure 11: An ATLAS SCT Detector Module
Visible are two 6 cm x 6 cm silicon micro-strip sensors and six readout ICs on an interconnect hybrid. Two more sensors are on the backside rotated by a small angle to provide a stereo measurement. The interconnect hybrid wraps around to the backside with six more readout ICs.

V-d High Data Rates

As raised in section IV-d above, today's detectors, especially the ones used in colliders, produce large amounts of data that must be transmitted to the off-detector electronics and computers in short amounts of time. The ATLAS detector, for example, generates 130 gigabytes of data every millisecond. To solve this problem optical transmission has been adopted, however, radiation hardness and low power requirements have prevented some of the most cutting-edge technologies from being used. Presently operating detectors, again designed more than a decade ago, run their optical links at 40-50 Mbits/s. The next generation, however, will need to resort to higher speeds. Gigabit/s links are now in development, which will need to meet the radiation requirements including acceptable error rates. Given the planned bandwidths of multiple gigabits/s, a single event upset in the transmission line will likely cause not one bit in error but a whole burst of error bits. For this reason, error correction encoding to not only detect but fix bursts of errors will be required. Such burst error correcting techniques are well established in industry. The detector designers will need to analyze the possible error patterns when their electronics are exposed to the expected radiation and then choose the appropriate error correcting encoding scheme.

VI-e High Reliability

Since the advent of solid-state technologies, the ICs incorporated into particle detectors have usually been the most reliable component. The most common failures in the electronics have been connectors. They fail for many reasons: insufficient strain relief causes broken wires at the connector when the cable is pulled by accident or intentionally, multiple insertions during testing and integration wear-out the metal contacts, corrosion of the metal contacts, improper assembly of the connector. Quite often cabling and connectors are the last thing designers think about because they are not very glamorous. This results in insufficient design effort and subsequent poor reliability. As a general rule, minimizing the number of connectors will improve reliability and budgeting sufficient design effort on the cables and connectors will be rewarded with better reliability.

Other electronics, primarily solid-state devices, have earned a reputation for high reliability. We have grown accustomed to what is called the “bathtub curve” for the failure rate of solid-state devices versus time. This means that there is a relatively modest rate of failures when new devices are first turned on, typically caused by some slight imperfections in the fabrication process, followed by a long period with an extremely low failure rate, ending eventually with a steep rise in the failure rate as the devices reach their end of life. The period of extremely low failure rate has typically been many, many years. This has led to the practice of “burning in” new devices in order to find and discard those that will fail early by running them for a short time at elevated temperature and possibly voltage. These early failures are referred to as “infant mortality” failures. If you contrast this with the typical failure rate of a mechanical device, for example a motor, a practice of burning in the motor would only shorten its lifetime because a motor has definite wear-out mechanisms, which the burn-in process would exercise.

Recently, some concerns have arisen that this “bathtub curve” may no longer be the correct model for IC lifetimes. There have been some data indicating that after the period of infant mortality, the failure rate does not remain flat at an extremely low value but rather has a small positive slope indicating some wear-out mechanisms exist. The possible wear-out mechanisms so far identified include: electromigration, time dependent dielectric breakdown, negative bias temperature instability, hot carrier injection. For more discussion of these topics see reference [18]. These mechanisms have been identified for a long time but they have become more of a concern as the device feature sizes have reached sub-micron dimensions. A related concern is that as commercial manufacturers continue to push performance and cost, long-term reliability may not be watched as carefully as in the past. Since many commercial products like computers, smart phones, electronic games become outdated and replaced every 2-3 years, the IC manufacturers may not be concerned about lifetimes of 10 years or more. The resulting lesson is that designers of future detectors should study the lifetimes of the IC technologies they intend to use. In many cases, these wear out mechanisms can be avoided by making the IC designs more relaxed, e.g. electromigration is the wear-out of conductors due to high current density. By increasing conductor widths in the ICs to wider values than called for in the design rules, the problem can be reduced at the expense of possibly less dense circuitry in the IC. At the end, lifetime tests should be performed on as many components as possible, especially for components which do not have published industry lifetime test results.

Another way to improve reliability is to provide redundancy, that is spare components installed in the detector such that they can be switched on if their partner components die. If it were possible, there would be full redundancy for all components but that would be too costly in volume, material and money. Instead, all parts of the system should be analyzed for possible single point failures. Wherever possible these can be eliminated by adding redundant components. In some cases like a data link, mechanisms can be provided whereby two units, which have their own links, can share a link if one is lost without a significant loss of performance. This was the scheme adopted by the ATLAS Semi-conductor Tracker.

The other aspect of these detectors that affords better overall lifetimes is that it is not necessary for absolutely every channel to be operational for the full detector to work satisfactorily. For example, the tracking part of the detector must find the trajectories in the magnetic field of all charged particles emanating from a scattering. In the best of all cases, that might only require hits (signals) at three separate points, however, given the possibility for scattering inside the tracking volume as well as the decay of a particle in flight, trackers are designed with many more layers. This affords a type of redundancy. If one channel on a particular layer should fail, there are normally sufficient remaining channels alive along the trajectory of each particle to reconstruct its path and thereby its momentum. In some cases such a dead channel may increase the ambiguity for a track, which suddenly veers off, but this can be handled by statistics of many, many events. Calorimeters operate in a similar fashion by sampling both the lateral and longitudinal extent of the energy deposited. Of the millions of channels in each sub-detector, it is normally acceptable for a few percent of channels to be dead and this is verified with simulation studies before the detector is ever built. This allowed number of dead channels not only extends the useful life of the detector but actually makes the detector buildable. An absolutely perfect detector (i.e. no dead channels) with hundreds of millions of channels is probably not possible to build.

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