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RADIATION TOLERANCE OF SILICON DETECTORS IN 100 TEV COLLIDERS

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Abstract

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In order for CERN to keep up with the the most cutting-edge theories of particle physics, it must expand its particle colliders up to the 100 TeV range. Unfortunately, an increase in energy and luminosity also brings an increase in damaging radiation. This paper examines the effects of radiation on the silicon semiconducting materials that are predominantly used in the particle trackers, including both the physical defects to the lattice itself and the effects on electronic performance. Finally, this paper explores HV-CMOS and the properties that make it the most promising canditate for silicon trackers in the FCC.

Contents

List of Figures

1

Introduction

In 2012, particle physicists at CERN discovered the Higgs boson at the Large Hadron Collider (LHC), verifying the Higgs mechanism presented by Peter Higgs and other physicists in the second half of the 20th century. While this was a massive breakthrough for the high energy physics community, many were quick to ask: what comes next? Most theories proposed recently require the extensions of the Standard Model to appear at the teraelectronvolt (TeV) scale. These predictions have not yet been realized, possibly because the phenomena expected from these theories are hard to detect due to their infrequency or lack of detectable features, or because the scale of the new physics presented by these theories is beyond the energy levels achievable at the LHC (Benedikt et al., 2018). Many theorists in the high energy physics community believe that the future of fundamental physics requires a particle accelerator that reaches energies at least an order of magnitude higher than the 13 TeV at the LHC (Arkani-Hamed et al., 2016), and CERN aims to meet these goals with the Future Circular hadron-hadron Collider, or FCC-hh.

The FCC is CERN's proposal for a particle collider that intends to extend the research being done at the LHC through increases in collision energies and intensities. The FCC's energy target is 100 TeV, which is roughly an order of magnitude larger than the LHC. This increase in energy will allow particle physicists to hunt for new fundamental particles roughly an order of magnitude heavier than those produced at the LHC (Arkani-Hamed et al., 2016). The FCC also seeks to solve the problems with infrequent detections and insufficient energies by implementing new sensors and detectors with an enhanced sensitivity and extending the mass reach through higher precision and larger energy scales (Benedikt et al., 2018). Similarly, particles that can be produced at the LHC in small numbers can be produced at the FCC at a rate up to a thousand times higher due to the increased intensity and energy.

In high energy colliders, like the LHC, two beams of protons are accelerated around

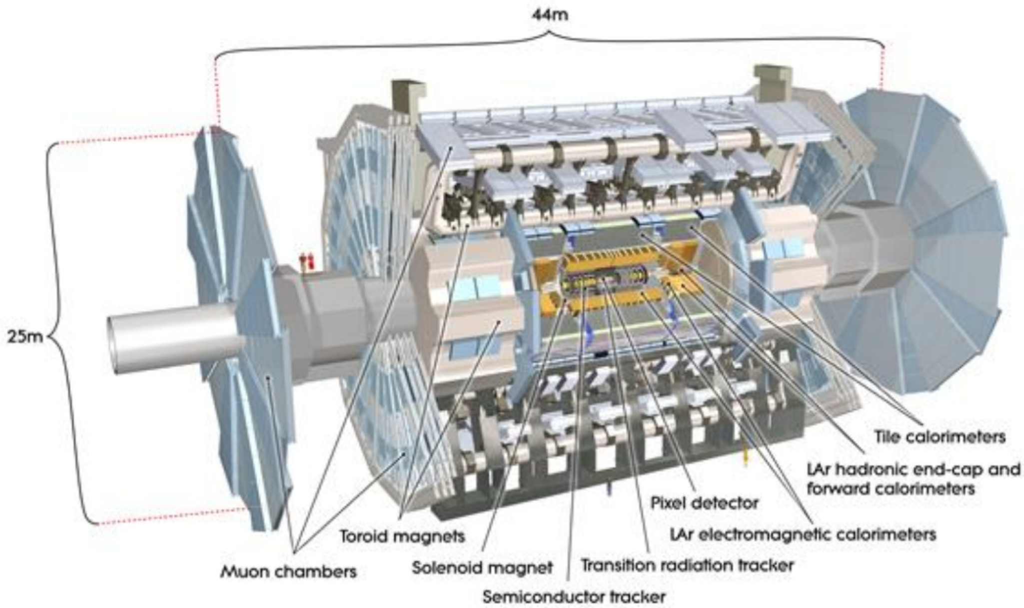

Figure 1.1: The ATLAS detector of the Large Hadron Collider at CERN. This figure shows the location of different sensors within the tracker. The silicon pixel sensor is the innermost sensor and closest to the interaction point, so it experiences the most radiation. The other sensors, like the tile calorimeters, are further away from the interaction point and are not as susceptible to radiation. Figure courtesy of CERN

the collider to energies of about 6.5 TeV. These beams then collide with each other, for a center-of-mass collision energy of up to 13 TeV. The colliding protons interact with each other, and can produce new particles. The particles' paths and energies are tracked through a series of different trackers and calorimeters, as shown in Figure 1.1. These paths and energies are used to determine the type of particle, and its properties. The FCC aims to increase the beam energy up to 50 TeV each, for a center-of-mass collision energy of 100 TeV.

The 100 TeV collisions in the FCC will cause an increase in radiation by a factor of 1000 compared to the LHC, and by a factor of 100 compared to the High Luminosity upgrade of the LHC (Gorine et al., 2018). It is extremely important to examine the effects of radiation in the LHC, and use that as a starting point for determining ways to either mitigate the increased radiation of the FCC, or develop new sensor technology that increases the radiation hardness of the silicon used in the tracker. The rest of this document will be devoted to examining the effects of radiation on the silicon sensors, and how those effects cause problems with particle detection. This paper will examine the concerns faced by the increased radiation in a 100 TeV collider, and how the silicon trackers can be designed to avoid these problems.

2

Silicon Tracker Damage Due To Incident Radiation

The main concern for high energy and high intensity machines, like the LHC, is radiation to electronics (Benedikt et al., 2018). The charged particles or high energy photons created from the colliding proton beams can damage both the sensors and readout electronics. The innermost silicon detectors experience orders of magnitude more radiation than the outer detectors. Currently in ATLAS, the innermost silicon pixel detector experiences up to 500 kGy of radiation, while the outer muon spectrometer only experiences 20 Gy (Grillo, 2014).

It can be extremely difficult to evaluate the impact of radiation on collider equipment. One method is the use of FLUKA, a fully integrated simulation software for calculations involving the interaction and transit of particles and nuclei through matter. It is used extensively by CERN for all beam interaction and radioactivity protection calculations. A more in depth explanation of FLUKA can be found in (Bhlen et al., 2014). Oftentimes, to confirm the predictions presented by the simulations, miniature versions of the main silicon sensors are irradiated and tested. (Arratia Munoz et al., 2016).

2.1 The Silicon Tracker

The fundamental structure of most existing silicon trackers is the p-n junction, where a p-type semiconductor is bonded to a n-type semiconductor. The p-type side predominantly contains free holes, or positive charge carriers, while the n-type contains electrons, which are negative charge carriers. The two types of silicon are created by introducing impurities into the silicon, in order to create free electrons or holes in the lattice. On their own, p-type and n-type silicon are relatively useless in many applications, as they are electrically neutral. However, when the two types of silicon are joined together, they become a semiconductor, which is the foundation for silicon trackers.

At the junction itself, some of the electrons in the n-type diffuse across the junction and combine with holes in the p-type semiconductor, leaving some electrons in the p-type side and some holes in the n-type side. This area, known as the depletion zone, has an inherent electric field, which inhibits current flow. When the p-n juntion is forward biased, that is the p-side is attached to the positive terminal of a battery and the n-side is attached to the negative terminal, this depletion zone shrinks and current can more easily flow through the junction. When the junction is reverse biased, the depletion zone increases in size, and it becomes more difficult for current to flow through the semiconductor.

The silicon in the trackers used in particle colliders is fully depleted, meaning that the silicon is reverse-biased at a large enough voltage that maximizes the size of the depletion zone. Charged particles emitted from the collisions inside the collider enter the fully depleted silicon and generate electron-hole pairs. The electrons drift to one side and the holes to the other, due to the electric field present in the depletion zone from the bias volatage. This drift creates tiny amounts of current, which is then amplified and translated into measurements by the readout electronics.

2.2 Microscopic Effects of Radiation

The inner silicon sensors are subject to intense, high fluence hadronic radiation due to their proximity to the point of interaction between the colliding beams. Radiation is often quantified as fluence, or the time integrated flux of said radiation or beam of particles. High fluence can either imply a large amount of radiation in a short period of time, or a moderate amount of radiation over a long time. It is important to note this distinction; silicon sensors must be designed to withstand radiation for up to 10 years, and this long lifetime contributes to the damage done to the sensor (The ATLAS Collaboration, 2017). Fluence is normalized to the equivalent number of 1 MeV neutrons per square centimeter. The total fluence over the HL-LHC's lifetime is 5×10^{14} $\mathrm{n_{eq}\,cm^{-2}}$, and as previously noted this will increase by orders of magnitude in the FCC due to the higher energy and luminosity (Arratia Munoz et al., 2016).

The primary method of silicon degradation from high fluence radiation is bulk damage (displacement damage), or damage caused by deformities to the silicon crystal lattice (Li et al., 1997), and is the main limiting factor for the use of silicon sensors close to the interaction point of high energy collisions (Moll, 1999). These lattice distortions are similar to the impurities introduced intentionally when manufacturing the silicon semiconductors, but bulk damage distortions are uncontrolled and unintended (Huhtinen, 1996). Bulk damage occurs when a high energy charged particle strikes a Primary Knock-On Atom (PKA). This PKA is by definition the first atom in the lattice structure struck by the incident radiation particle, but this collision only results in a lattice deformity if the the incident particle has an energy high enough to displace the atom from its lattice bonds.

If the imparted energy of the incident particle is greater than 25 eV, the displacement of the PKA results in a vacancy in the lattice structure, and an intersitial defect, where an atom occupies a normally unoccupied site in a crystal structure (Moll, 1999). This combination of a lattice structure vacancy and an intersitial defect is known as a Frenkel pair. For a neutron to create a Frenkel pair in a silicon lattice, assuming a displacement threshold energy of 25 eV, it must have a kinetic energy of approximately 185 eV (Moll, 1999). Due to the high recoil energy imparted by an incident neutron (133 keV), the displacement damage is a cascade with many interactions, as shown in Figure 2.1 (Li, 2002).

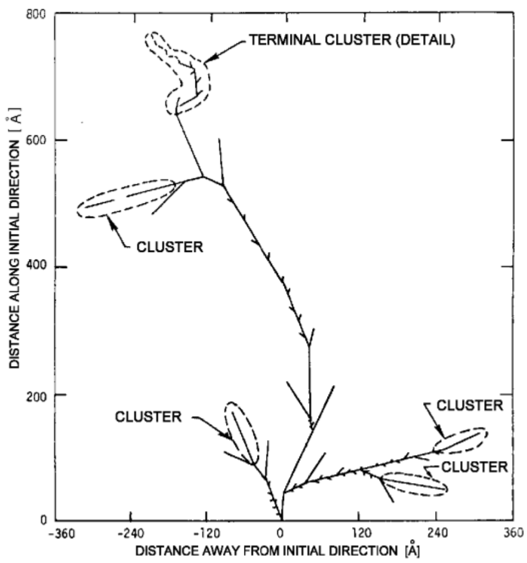

Figure 2.1: FLUKA simulation of the recoil path of a PKA in silicon. A primary recoil energy of 50 keV has been chosen, as 50 keV is the average kinetic energy an incident 1 MeV neutron imparts on a silicon atom. The PKA releases its imparted energy over a distace of about 800 Å. Figure from Moll (1999).

Figure 2.1 shows a FLUKA simulation of the recoil path of a PKA as it moves through the rest of the lattice. Along this path, there are two types of energy losses that slow down the PKA: further displacements and ionization. The first form of energy loss, further displacements, leads to the two types of lattice defects: point and cluster. Referring back to Figure 2.1, point defects occur along the path of the PKA, while cluster defects occur at the end of the PKA's range. These intersitials and vacancies created as the PKA travels through the silicon lattice are very mobile at temperatures above 150K. Therefore, up to 60% of the intersitials annihilate with the vacancies and vice versa, leaving no damage (Moll, 1999). Energy losses due to ionization do not have enough energy to lead to any relevant changes in the silicon lattice, so only Non-Ionizing Energy Losses (NIEL) contribute to bulk damage (Lindstrm et al., 1999). The NIEL scaling hypothesis will be discussed in the next section.

2.3 NIEL Scaling

Due to ionization not causing any lattice damage, all of the damage to silicon lattice from incident particles comes from Non Ionizing Energy Loss (NIEL). The displacement damage induced changes were found to scale linearly with the amount of energy imparted on lattice atoms in displacing collisions (Moll, 1999). Essentially, the more energy an incident particle has, the more energy it imparts on lattice atoms through collisions, and the more damage it does to the silicon lattice itself.

In an interaction leading to displacement damage, the incident particle produces a PKA with energy E_R. The Lindhard partition function, $P(E_R)$, determines the portion of the incident PKA's recoil energy deposited to atoms in the silicon lattice. This partition function is a function of the recoil energy imparted onto the PKA by the incident particle. The Lindhard partition function allows the calculation of NIEL through the calculation of the displacement damage cross section:

$$D(E) = \sum_{\nu} \sigma_{\nu}(E) \int_{0}^{E_R^{max}} f_{\nu}(E, E_R) P(E_R) dE_R \tag{2.1}$$

The index ν indicates all the possible interactions between the incoming particle with energy E and silicon atoms leading to lattice displacements. The σ_{ν} term is the cross section corresponding to the reaction with index ν. The function $f_{\nu}(E, E_R)$ represents the probability of a particle with energy E undergoing the reaction ν generating a PKA with recoil energy E_R. The integration is done over all possible recoil energies E_R, and below the displacement threshold ($\approx 25eV$) the partition function is set to zero: $P(E_R < E_D = 0)$ (Moll, 1999). Figure 2.2 shows that neutrons down to 1 keV and even 100 eV have displacement energies larger than the 25 eV required to create a point defect in silicon.

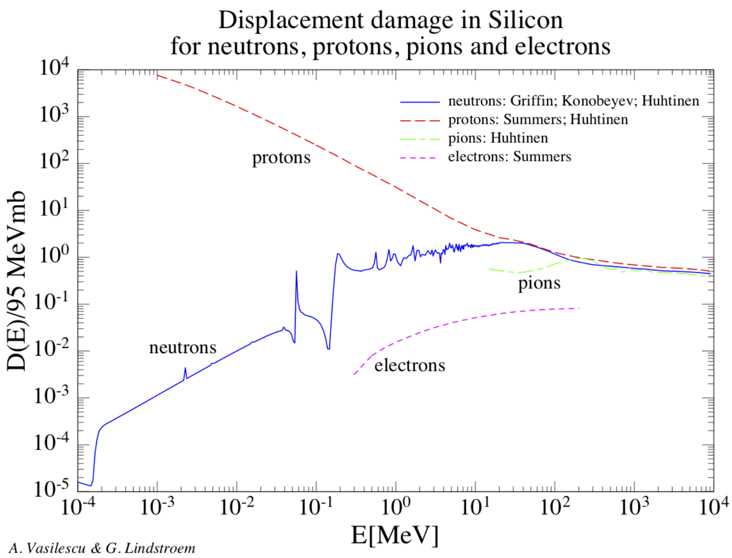

Figure 2.2: Displacement damage functions of various particles between 100 eV and 10 GeV. Due to the normalization to 95 meVmb, the y-axis represents the damage equivalent to 1 MeV neutrons. Figure from Lindstrm et al. (1999).

The NIEL scaling hypothesis is the one of the most important things learned in examining silicon sensors in the LHC. In the FCC, the proton beams will have much more energy, implying the radiated particles will have more energy. Since the NIEL scaling hypothesis states that displacement damage increases with energy imparted from incident particles, the high energy radiation from the FCC poses a larger threat to the silicon sensors than any of the radiation currently faced by the sensors at the LHC.

2.4 Effects of Radiation on Electronic Performance

The point and cluster defects mentioned in Section 2.2 not only do permanent physical damage to the sensors, but can affect the electrical properties of the sensors themselves. These electrical defects can lead to inefficiencies in the measuring abilities of the sensors, which can be extremely detrimental to the measurement and classification of charged particles. The two most significant effects for silicon detectors in a high-radiation environment are excessive leakage currents and changes to the effective doping concentration (Feick, 1997).

An important contributor to the leakage current is carrier generation, the process by which electrons and holes are created. Defects from radiation-induced lattice distortions can introduce new allowed states into the band gap, an area where charge carriers normally cannot exist, increasing the number of charge carriers. This increase in carriers leads to an increase in the bulk generation current, which often forms a large portion of the leakage current (Huhtinen, 1996). Lattice defects close to the middle of the band gap are efficient electron-hole pair generators, contributing to overall leakage current. The electron and hole emission rates of the defects (related to enthalpy and the density of states in the conduction

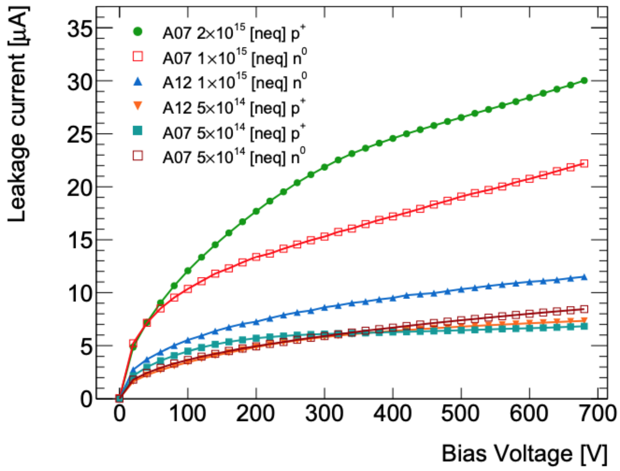

Figure 2.3: Leakage current as a function of bias voltage in silicon detectors at various levels of radiation. Measurements were performed at T = -20°C. These measurements were made by Huhtinen (1996) to quantify the effects of radiation on silicon.

and valence bands) determine the overall pair generation rate, which is effectively the leakage current (Moll, 1999).

The increase in leakage current as a function of fluence can be modeled by

$$I(\phi) = I_0 + \alpha\phi \tag{2.2}$$

where α is a constant of proportionality depending on the type of irradiated particle and the amount of energy it has, and I_0 is the preirradiation leakage current value (Huhtinen, 1996). Here, α incorporates the NIEL scaling discussed in Section 2.3, as it increases with energy. Leakage current also depends on temperature according to

$$I(T) \sim T^{3/2} \exp(-\frac{E_g}{2kT}) \tag{2.3}$$

where the bandgap in silicon $E_g = 1.121eV$ at T = 20°C. An increase in power consumption heats up the silicon, which increases the leakage current, which in turn increases the power consumption in a process known as thermal runaway (Huhtinen, 1996).

NIEL damage to silicon bulk can not only lead to increases in leakage currents, but can also lead to changes in the effective doping concentration. The defects introduced from radiation damage can become charged in the depletion region, increasing the effective doping concentration. This increase in doping concentration increases the full depletion voltage of the semiconductor, meaning more voltage must be applied to the p-n junction in order to maximize the depleted region of the semiconductor. The doping concentration n_{eff} is proportional to the depletion voltage V_{depl} through the relation

$$V_{depl} = \frac{q}{2\epsilon\epsilon_0} n_{eff} D^2 \tag{2.4}$$

where $\epsilon\epsilon_0$ is the effective permittivity of silicon, q is the electron charge, and D is full thickness of the silicon sensor (Beteta et al., 2018). Equation 2.4 shows that as deep level defects increase n_{eff}, which in turn increases the depletion voltage to beyond what the external biasing can handle.

3

Improving Radiation Tolerance of Silicon Detectors

The High Luminosity-Large Hadron Collider (HL-LHC) upgrade (slated for 2024), along with plans for the FCC, seeks to improve upon the success of the hybrid pixel modules in the LHC. Previous trackers consisted of separate sensors and read out electronics, but the LHC shifted to a hybrid module. Hybrid detectors consist of silicon pixel sensors bonded to a read out chip, making them into one entity, rather than having separate chips for pixel sensors and readout electronics. This is currently the most radiation hard solution, but is cost-prohibitive due to the cost of the bonding process. Hybrid modules have been successful in the LHC over the past few years, and the plans for the FCC seek to improve upon this technology (Cavallaro et al., 2017). HV-CMOS technology, discussed in the following section, seeks to address some of the radiations concerns facing traditional silicon trackers along with reductions in cost, making the large tracker areas needed by the FCC more financially viable.

3.1 Advantages of HV-CMOS Pixels for Trackers

Complementary Metal Oxide Semiconductors (CMOS) technology has been around for a long time, and is commercially used in optical and x-ray imaging. Recently, CMOS technology has become available to the high energy physics community and is being investigated as a new and improved technology option for inner tracker modules for the HL-LHC and FCC. CMOS pixels operate by collecting charge from energy deposited by particles of interest in a thin epitaxial layer beneath the CMOS electronics (The ATLAS Collaboration, 2017). Using a large number of wells, as shown in Figure 3.1, full CMOS logic can be implemented on a fully depleted bulk (The ATLAS Collaboration, 2017). This large depletion volume increases the overall radiation tolerance of the tracker. The earliest tests of CMOS trackers collected deposited charge by diffusion rather than by drift in an electric field (the operation method for most other trackers), making them inherently susceptible to radiation damage. Similarly, readout was implemented using a slow, rolling-shutter scheme that limited the timing resolution. Thus, CMOS trackers were determined to be not suitable for the high radiation levels and hit rates expected at the HL-LHC and FCC (The ATLAS Collaboration, 2017).

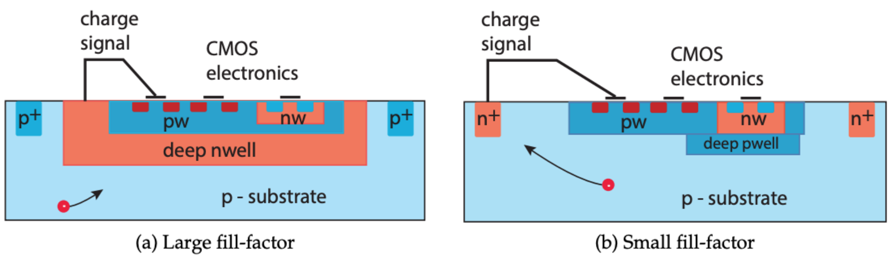

Figure 3.1: Cross section of the two types of CMOS modules. (a) shows the large fill-factor, in which the deep n well, where charge is collected, completely encompasses the CMOS electronics. (b) shows the small fill-factor, where the charge collecting n wells are placed outside CMOS electronics area. Figure from The ATLAS Collaboration (2017)

High Voltage-CMOS (HV-CMOS) seeks to solve some of the problems associated with normal CMOS pixel modules. HV-CMOS pixels can be reverse biased at voltages larger than 60V (the maximum for CMOS), all the way up to 90V (Sultan et al., 2019). This not only increases detector performance, but also increases the radiation tolerance of the semiconductor itself. As radiation introduces more distortions into the silicon lattice, the voltage required to fully deplete the junction increases. This becomes a problem in traditional silicon trackers, as the depletion zone begins to break down at higher voltages. However, HV-CMOS has a higher breakdown voltage, meaning it can operate in a larger voltage range and can tolerate higher radiation fluences.

Unfortunately, HV-CMOS trackers are still susceptible to damage due to radiation fluences. Ionizing damage to silicon in HV-CMOS trackers causes an increase in leakage current of about 1-5 pA cm^{-2} per krad, along with an increase in the number of bright pixels (Rushton, 2018). Leakage current in HV-CMOS trackers increases with an increase in neutron fluence, agreeing with the NIEL scaling hypothesis (Sultan et al., 2019). Radiation damage can also shift threshold voltages in HV-CMOS trackers, and doses of over 5 Mrad can cause a threshold shift of up to 80 mV (Sultan et al., 2019). This becomes an issue in certain in-pixel circuits, where a shift in threshold voltage adds an offset to output voltage, creating fixed pattern noise (Rushton, 2018).

Monolithic active pixel sensors (MAPS), the umbrella term under which CMOS and HV-CMOS pixels fall, allow for the embedding of all readout circuits onto the same substrate as the sensor itself. Traditional hybrid pixel detectors also consist of readout electronics bonded to sensor electronics through a complex process known as bump bonding. HV-CMOS allows for the combination of readout electronics and tracking wells onto one wafer of substrate (Meng et al., 2018). This greatly reduces the overall cost of the tracker, as one silicon foundry can make both the readout electronics and the tracking module at the same time, on the same wafer. This becomes especially important in the FCC, as the higher luminosity requires a much larger tracker. However, HV-CMOS allows for a large variation in the types of electronics present on a single wafer, making it more susceptible to radiation damage (Rushton, 2018).

4

Conclusion

This paper presents the radiation concerns stemming from increasing particle collider energies to the realm of 100 TeV. Radiation from particle collisions can cause lattice damage to the silicon semiconductors inside the particle trackers. This lattice damage affects the electronic capabilities of the tracker itself, leading not only to inaccuracies in measurements, but also to permanent physical degradation of the semiconducting material. The NIEL scaling hypothesis shows that degradation to the silicon bulk in the trackers increases with increasing radiation fluence, leading to concerns with the massively increased radiation fluences expected at the FCC.

The main semiconductor technology being explored for use at the FCC is HV-CMOS. HV-CMOS has a number of advantages over the current semiconducting materials used at the LHC. First, it has a breakdown voltage of approximately 90V, allowing for higher depletion voltages and thus increasing the radiation hardness of the semiconductor. Second, it allows for the tracking module and the complex readout electronics to be manufactured on the same wafer of silicon, greatly reducing manufacturing costs. HV-CMOS is currently the most promising tracker technology thus far.

The importance of the FCC and a 100 TeV collider cannot be overstated. In our search to verify Standard Model theories, and perhaps unify the Standard Model with general relativity, we must explore higher energy ranges with a 100 TeV collider. However, an increase in energy and luminosity also brings an increase in damaging radiation, and current trackers simply are not capable for use in the FCC. Radiation tolerant solutions for semiconducting material in particle trackers must be further researched, but advances in HV-CMOS technology and its commercial availability make it the most viable candidate thus far.

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