Development of planar and 3D silicon sensor technologies for the ATLAS experiment upgrades and measurements of heavy quark production fractions with fully reconstructed D-star mesons with ATLAS

Jessica Metcalfe

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Development of Planar and 3D Silicon Sensor Technologies for the ATLAS Experiment Upgrades and Measurements of Heavy Quark Production Fractions with Fully Reconstructed D-star Mesons with ATLAS

by

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B.S., University of Oregon, 2003
M.S., University of California Santa Cruz, 2006

DISSERTATION

Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy Physics

The University of New Mexico
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Abstract

Several particle detector technologies were studied. These include measurements of the leakage current and capacitance of irradiated planar and 3D sensors. The inter-electrode capacitance of proton irradiated 3D sensors was measured using two methods and compared to simulation. Planar n-type MCz diodes were exposed to neutron and gamma radiation and the effects on defects characterized. A set of n- and p-type Fz and MCz diodes were irradiated with protons and their annealing properties extracted using the Hamburg Model.

A measurement of the fraction of $D^{*+}$ mesons originating from a $b$-quark compared to those directly produced from a charm is presented. The charm mesons were fully reconstructed in the mode $D^{*+} \rightarrow D^0 \pi^+$ where $D^0 \rightarrow K^- \pi^+$. The analysis was
based on data collected from the minimum bias trigger of the ATLAS detector at $\sqrt{s} = 7$ TeV proton-proton collisions produced by the LHC. The distribution of the impact parameter of the $D^0$ meson with respect to the primary vertex was studied to distinguish charm mesons produced promptly from those through $b$-quark decays.
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Chapter 1

Introduction

ATLAS (A Large Toroidal ApparatuS) (see Figure 1.1) is a general purpose particle detector located at the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN). The LHC collides proton bunches at rates up to 25 ns. The ATLAS detector then detects the different particle signatures resulting from the collisions in various types of detector layers that will be described in more detail in the next chapter. The ATLAS collaboration is comprised of over 3,000 physicists. Each member contributes to various aspects of the detector systems, data collection, software tools and physics analysis to ensure smooth operation and high quality physics output. I contributed to the Pixel Detector commissioning, silicon detector research and development for ATLAS Upgrade, and charm physics analysis.

The Pixel Detector is the inner-most layer of the ATLAS detector. It is made of 1,744 silicon sensors. Each sensor must be powered for efficient operation. I helped debug the High Voltage Patch Panel 4 (HVPP4) system that delivers the appropriate power to bias each detector. I also developed the qualification procedure to test production modules before insertion into the Pixel system.

ATLAS resides in an inherently high radiation environment due to the constant
Chapter 1. Introduction

Figure 1.1: A graphical representation of the ATLAS detector [1].

proton-proton collisions. The Pixel and Semi Conductor Tracker (SCT) are the two innermost layers and are both comprised of different designs of silicon detectors. These layers will need to be replaced in approximately 2019. I performed several studies on different candidates to be used to replace the silicon layers for ATLAS Upgrade. The radiation damage effects on 3D and planar silicon sensors was investigated. For the 3D sensors, the effects of capacitance for various fluences was measured using two techniques—one a direct probe of capacitance and the other an indirect method. The results showed a dependence on fluence, which will in turn affect the noise in the electronic read-out system of a 3D detector system. Two studies of planar silicon sensors were done. The first study was done in conjunction with our collaborator, Zheng Li, at Brookhaven National Laboratory (BNL) on Magnetic Czochralski (MCz) silicon diodes. The capacitance was measured at low temperatures and used to extract the bias voltage for neutron irradiated samples. Then gamma irradiations were performed at BNL and the interaction of the radiation induced defects studied. A separate annealing study of different planar silicon materials (n- and p-type; Float Zone (Fz) and MCz diodes) was done for several fluences. The bias voltage and effective doping concentration were studied as a function
of anneal time and fit using the Hamburg Model.

The culmination of a well understood particle detector is physics analysis. I measured the bottom and prompt (charm) fractions of $D^* \rightarrow D^0(K^-\pi^+)\pi^+_s$ ($+charge$ conjugate (cc)) events. First the event was reconstructed and the impact parameter of the $D^0$ was used to differentiate the two contributions to the $D^*$ events. These fractions provide insight into the production and fragmentation in Standard Model processes.
Chapter 2

Detector Description

The ATLAS Detector is comprised of several layers of different types of detectors. For each layer, there are two geometries. The barrel sections are in cylindrical sections centered around the collision point. Circular disks cap the open ends of each cylinder. These detectors are referred to as endcaps. The Inner Detector, as its name implies, is at the center of the detector wrapped around the primary vertex. It is comprised of three different types of detectors all designed for identifying particle tracks with increasing granularity. The innermost detector in the Inner Detector is the Pixel Detector. The SCT wraps around the Pixel Detector and the TRT encloses the SCT. The next layers determine the energy of the particles. These types of detectors are calorimeters. ATLAS has an Electromagnetic Calorimeter followed by the Hadron Calorimeter. Finally Muon Chambers envelop the rest of the detectors.

2.1 Inner Detector

The Inner Detector provides excellent track reconstruction. It measures charged tracks in the range $|\eta| < 2.5$ and with a nominal transverse momentum (transverse
Chapter 2. Detector Description

to the beam pipe, z-direction), \( p_T \), threshold of 500 MeV, but as low as 100 MeV. The Pixel Detector, SCT and TRT are contained within a cylinder of 7.024 m and a radius of 1.150 m and are exposed to a 2 Tesla solenoidal magnetic field.

2.1.1 Pixel Detector

The Pixel Detector is located closest to the proton-proton interaction point. There are 3 barrel layers that are located at 50.5 mm, 88.5 mm, and 122.5 mm from the center of the beam pipe. The detectors are made of oxygenated silicon 250 \( \mu m \) thick with n-type bulk and n\(^+\) implants on the electronic read-out side of the detector. The design was chosen to increase radiation tolerance with optimized charge collection and lower depletion voltages. The nominal size of each pixel is 50 \( \mu m \times 400 \mu m \). This gives an intrinsic precision of 10 \( \mu m \) in the R-\( \phi \) plane and 115 \( \mu m \) in the z direction. There are 47,232 pixels on each sensor and 1,744 sensors totaling 80 Million read-out channels [7]. As of May 2011, 96.9\% of the pixel channels were operational [8].
Chapter 2. Detector Description

Figure 2.2: Two 10 GeV charged particle tracks traversing the Inner Detector at $\eta=1.4$ and $\eta=2.2$.

sensors will be operated at bias voltages from 150 V to 600 V after damage from irradiation requires a higher bias to maintain good charge collection efficiency. The sensors also need to be cooled during operation to temperatures between -5 °C and -10 °C in order to reduce leakage current due to radiation damage effects [7].

Figure 2.3: An image of the Pixel Detector with 3 barrel layers and 3 end-cap layers on each side.
Chapter 2. Detector Description

Figure 2.4: I am standing next to the Pixel Detector in June 2007 shortly before it was installed into the ATLAS Detector.

2.1.2 SCT

The Semi-Conductor Tracker (SCT) is made of silicon detectors similar to the Pixel Detector. Due to the lower track density at larger radii, lower radiation tolerance and high cost of sensor electronics a strip design was used for the four SCT layers. The SCT sensors are a classic single-sided p-in-n design. The radiation exposure of the SCT is much lower than the Pixel Detector, thus the operating voltages are also lower, 150 V to 350 V, despite the larger sensor size. The sensors are 285 $\mu$m thick, approximately 80 $\mu$m wide as determined by the pitch in the read-out electronics and 6 cm long (in the barrel section, length and width vary among layers and barrels/discs). The intrinsic precision of the SCT barrel is 17 $\mu$m in the $R$-$\phi$ plane and 580 $\mu$m in the z direction [7]. As of May 2011, the SCT was operating 99.1% of the 6.3 million read-out channels [8].
2.1.3 TRT

The transition radiation tracker (TRT) is made of polyimide drift tubes or straw tubes with an anode wire strung through the cylindrical tube lengthwise and filled with gas. When a charged particle traverses the gas it releases electrons, which drift to the anode wire and a signal is read out. The straw tubes in ATLAS are 4mm in diameter and range from 144 cm in length in the barrel region and 37 cm in the end-caps. The straw tubes (cathodes) are kept at -1530 V while the anode wire is at ground. The gas is a mixture of 70% Xe, 27% CO$_2$ and 3% O$_2$ with 5-10 mBar over-pressure. During normal operation of the TRT array the electron signal has a maximum read-out time of approximately 48 ns and the detector has an overall precision of 130 $\mu$m [7]. There are roughly 350,000 channels in the TRT, 97.5% of which were operational in May 2011 [8].
Chapter 2. Detector Description

2.2 Calorimeters

The Electromagnetic (EM) and Hadronic Calorimeters are designed to measure the energy of different types of particles. The sections of each calorimeter are designed to match the coverage of the Inner Detector in the $\eta$ range, so that the finer granularity of the EM Calorimeter covers the same $\eta$ range as the inner detector, which is ideally suited for the reconstruction of electrons and photons. The Hadronic Calorimeter has a coarser granularity, but is sufficient to satisfy the physics requirements for measuring jet energies and missing energy needed in physics analyses. Both calorimeters must also ensure that all particles except muons shower in the calorimeters in order to account for all the deposited energy and missing energy (from neutrinos) correctly [7].

2.2.1 Electromagnetic Calorimeter

The EM Calorimeter is composed of alternating layers of Liquid Argon (LAr) and lead absorber plates in an accordion style shape to reduce cracks in coverage. The
basic design principle of the calorimeter is to detect a whole particle shower. For example, a charged particle interacts in the lead material and produces a shower in the LAr detector, those energetic shower particles then react in the next layer of lead and are detected in the next LAr layer and so forth until all the energy is deposited into the calorimeter. [See Figure 2.8] The EM calorimeter is optimized for the best energy resolution of charged particles by varying the thickness of the lead absorber layers for different $\eta$ [7].

2.2.2 Hadronic Calorimeter

The Hadronic Calorimeter is composed of 3 sub-detectors. The Tile Calorimeter wraps immediately around the EM Calorimeter in the barrel region. It is composed of layers of steel and scintillator material. It covers the region $|\eta| < 1.7$. The LAr Hadronic End-cap Calorimeter (HEC) is made of two end-cap wheels outside the EM Calorimeter end-caps. It covers the region $1.5 < |\eta| < 3.2$, which overlaps slightly with
the Tile Calorimeter and the Forward Calorimeter. The final section is the LAr Forward Calorimeter (FCal), which performs electromagnetic and hadronic calorimetry. The FCal has 3 modules. The first module uses copper for the absorber to optimize electromagnetic energy measurements. The other modules use tungsten to measure predominantly hadronic showers [7].

2.3 Muon Spectrometer

Several types of detectors comprise the Muon Spectrometer. The detectors are located on the outermost layer of ATLAS. See Figure 2.9. They are designed to detect charged particles that pass through the inner layers of ATLAS including the calorimeters. These particles are detected in the range of $|\eta| < 2.7$ and their momentum is measured to a precision of roughly 10% for 1 TeV tracks, but they can measure the $p_T$ in the range of 3 GeV to 3 TeV. The muon system in the region of $|\eta| < 2.4$
Chapter 2. Detector Description

also contributes to the trigger. The different types of muon detectors employed in ATLAS include the Monitored Drift Tubes (MDT’s), which consists of 3 to 8 layers of drift tubes with the same design principle as those used in the TRT and is used for high precision tracking. The MDT’s achieve a resolution of approximately 80 \( \mu \text{m} \) per tube and 35 \( \mu \text{m} \) per chamber. The Cathode Strip Chambers (CSC’s) are multi-wire proportional chambers with cathode strips in perpendicular directions so that both plane coordinates’ measurements can be taken simultaneously. The CSC’s are used in the innermost forward regions because of their ability to handle higher rates. In the barrel region Resistive Plate Chambers (RPC’s) are used to deliver track information to the trigger system on the time scale of tens of nanoseconds. RPC’s are made of large electrode planes kept 2 mm apart by insulating spacers. Charged particles produce ionizing tracks in a gaseous layer between the plates and an electric field of 4.9 kV/mm causes the electrons in the tracks to avalanche and drift to the anodes. The signal is read out by metallic strips on the outside of the detector that are capacitively coupled to the anodes. Thin Gap Chambers (TGC’s) are used for the muon trigger system in the endcaps. They are multi-wire proportional chambers with a highly quenching gas mixture. The wire-to-cathode distance (1.4 mm) is smaller than the wire-to-wire distance (1.8 mm). The high electric field around the wires and small distance between the wires gives precise timing resolution. The position and time resolution for the different types of muon detectors is summarized in Table 2.1 [7].

<table>
<thead>
<tr>
<th>Detector</th>
<th>z/R</th>
<th>( \phi )</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDT (tracking)</td>
<td>35 ( \mu \text{m} ) (z)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CSC (tracking)</td>
<td>40 ( \mu \text{m} ) (R)</td>
<td>5 mm</td>
<td>7 ns</td>
</tr>
<tr>
<td>RPC (trigger)</td>
<td>10 mm (z)</td>
<td>10 mm</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>TGC (trigger)</td>
<td>2-6 mm (R)</td>
<td>3-7 mm</td>
<td>4 ns</td>
</tr>
</tbody>
</table>

Table 2.1: Muon Spectrometer Resolutions
Chapter 2. Detector Description

2.4 Trigger and Data Acquisition

The Trigger and Data Acquisition systems process the ATLAS detector information to select what measurement data are kept. There are 3 online steps. The L1 (Level 1) trigger, the L2 (Level 2) trigger and the event filter. The L2 and event filter are referred to as the High Level Trigger (HLT). The L1 trigger is comprised of custom-made electronics while the HLT is built from commercial computers and networking hardware.

There are two types of L1 triggers—calorimeter and muon triggers. The calorimeter trigger identifies particles with high transverse energy such as jets, taus, electron, photons and also large missing $E_T$. The muon trigger detects high $p_T$ muons as discussed in the previous section. The L1 trigger can handle rates of up to 75 kHz and will be upgraded to 100 kHz and has 2.5 $\mu$s to process its decision. The Data Acquisition system temporarily stores event data while HLT processes continue.
Chapter 2. Detector Description

The L2 trigger uses Regions-of-Interest (ROI’s) where L1 identified possible trigger candidates. The L2 uses coordinate and energy threshold information from muon chambers, calorimeters and the inner detector to further decide to keep or reject data. The difference from the L1 is that the L2 trigger has more time to process information with an event rate of 3.5 kHz and 40 ms to make a decision. If the events pass the L2 trigger the events undergo event-building and are passed to the event filter. The event filter then selects the events that are permanently stored. It takes 4 s to process and reduces the event rate to 200 Hz [7].
Chapter 3

Hardware Commissioning

The High Voltage Patch Panel 4 (HVPP4) encompasses the framework through which the high voltage used to bias the Pixel sensors is routed from the power supply to individual detector modules. The current design maximizes the use of the power supplies by routing one power channel to several detectors. The HVPP4 retains a modularity to the design, so that in the future the number of detector modules supplied by each power channel can be reduced as the power consumption by each detector increases. This design was approved in order to reduce the initial cost by limiting the number of power supplies required initially. As the detector modules are exposed to radiation the performance of the detectors degrades requiring a higher bias voltage to maintain acceptable efficiencies.

Each Pixel sensor is a silicon n-type implant in an n-type substrate. The sensor functions as a particle detector when a reverse bias voltage is applied. The bias voltage depletes a region of the sensor, which becomes sensitive to high energy particles traversing the material. As the sensor is exposed to radiation, the particles cause displacement damage to the silicon bulk, which scales with non-ionizing energy loss (NIEL scale), and ionization damage in the passivation layers categorized...
as surface effects. The damage results in a change in the doping concentration of the material, increased leakage current and a reduction in charge collection efficiency. The displacement damage knocks out protons and neutrons in the nuclei increasing acceptor like defects. Over time, the displacement inverts the type of doping in the sensor from n to p-type and then requires a higher bias voltage to fully deplete the sensor. See Figure 3.1. The increased leakage current will cause the noise in the detector to also increase and raise the power consumption of the sensor. Eventually the power consumption will reach its limit and the sensor will no longer be fully depleted resulting in a sharp drop in charge collection efficiency [9], [10], [11], [12], [13], [2]. At this point, more power supplies will be added and the HVPP4 will be modified to route each power channel from 6 (or 7) modules down to 2 modules.

Figure 3.1: The type inversion is illustrated here for a Pixel Sensor. The doping concentration ($N_{eff}$) decreases with increasing particle fluence until type-inversion then increases [2].
Chapter 3. Hardware Commissioning

3.1 High Voltage Patch Panel 4

The HVPP4 takes one power channel from the ISEG power supply and maps it to 6 (or 7) detector modules. Each ISEG power module has 16 power channels. The power from one ISEG module is routed into one HVPP4 crate. The HVPP4 crate connects to the power channels in the front of the crate into the ISEG Board. The power channels are then routed into the backplane of the HVPP4 in the center of the crate and then through several more ISEG Modularity Boards which are configured to gang the outgoing power for 6 (or 7) detector modules. The power is then routed through several Type II boards and out the back of the crate. See Figure 3.2. The ISEG Modularity Boards have a jumper that can easily be removed to switch the modularity of the power channels from ganging 6 or 7 detector modules to 2 detector modules.

![Prototype HVPP4 with Type II cables connected.](image)

Figure 3.2: Prototype HVPP4 with Type II cables connected.

Each Type II board powers 13 detector modules (hence the ganging of 6 (or 7) detector modules) corresponding to a single stave on the Pixel Detector, so each Type
Chapter 3. Hardware Commissioning

II Board requires two power channels. There are 9 Type II boards for each HVPP4 crate (18 power channels). Since each ISEG power module has 16 power channels, 2 ISEG power modules are required for each crate, where the extra power channels are shared with a partner HVPP4 crate. This routing is done through a Bridge Board on the back of the HVPP4 crate. The power channels are routed from the ISEG Board through the Back Plane then to the ISEG Modularity Boards (where detector module channels are ganged together) back through the Back Plane to the Type II Boards and then to the detectors. See Figure 3.3.

![Diagram of ISEG power modules and HVPP4 layout](image)

Figure 3.3: The layout for the ISEG power modules and the HVPP4.

The current makes a loop through the power supplies and detector modules. On the return through the HVPP4, individual detector module currents are kept sep-
Chapter 3. Hardware Commissioning

arate so a current measurement of each one can be taken. The return currents are routed through an ELMB carrier board that can be inserted onto the ISEG Modularity boards. The ELMB carrier board holds the ELMB measurement board, which actually performs the current measurement. The ELMB is a standard measurement board developed by CERN with a standard read-out used throughout ATLAS subsystems.

Each ISEG power channel also has a safety loop built in that will cause the power module to shut down in case of emergency (malfunction). The safety loop is routed through ISEG boards, Back Plane and Type II boards. It requires a separate power source to drive the current of the safety loop and if this current is not within a certain range, the power module will shut down.

Channel Mapping

The electrical connectivity of the prototype HVPP4 was tested using a Cirus Touch 1. The Cirus Touch 1 has several connectors compatible with ribbon cable connectors. It works by looking for a closed electrical circuit between all combinations of pins in all the connectors. An adapter was made to connect the Lemo-Redel connectors of the HVPP4 to a ribbon cable for input into the Cirus Touch 1 (see Figure 3.4), so that the connectivity could be measured between the front and back of the HVPP4.

The early connectivity testing was plagued by issues with bad connections by the lemo-redel connectors and poor documentation of the channel mapping combined with a non-intuitive read-out by the Touch 1. See Figure 3.5. The poor connection of the lemo-redel connector was solved by chamfering the holes of the center row of pins to make a better fit—a procedure that had to be applied to all production connectors. The objective of the power routing through the HVPP4 was known and
Chapter 3. Hardware Commissioning

Figure 3.4: The Lemo-Redel connector. The center pins are larger and their mating holes had to be enlarged for reliable connections.

Several routing mistakes were identified in the channel routing and the safety loop. Incorrect documentation of the wiring for the Type II boards caused issues with incorrect power routing. See Figure 3.6. A mistake in the circuit diagram for the Back Plane was also found. The schematic had to be modified before production.

A HIPOT test was also done on each channel. This test brings a channel up to a specified voltage, in this case 980 V, well above the threshold where the circuit will be operated and holds the voltage until the circuit is saturated. The continued saturation tests for any break down in the current path of the circuit such as sparking across solder points or a conductive path left by solder resin. The HIPOT test also measures any leakage current to any neighboring circuit.
Chapter 3. Hardware Commissioning

Figure 3.5: An example of the read out of the Cirrus Touch1. Each J number represents a module on the Touch1 with a ribbon cable connector. The bottom half shows the results of which pins are electrically connected. In this case, only one Type II board on the back and the ISEG board on the front are connected to simplify the read-out. The read-out shows that there are 4 groups of connected channels. The J1’s represent the 6 or 7 channels of individual detector modules ganged together. Each group is connected to one J3 power channel. For a full test, all connections from a pair of HVPP4 crates (9 x 2 = 18 Type II Boards) must be tested simultaneously to ensure there are no superfluous connections.

<table>
<thead>
<tr>
<th>HVPP4 Module Test Procedure</th>
</tr>
</thead>
</table>

| CONNECTION RESIS 5.0 ohm |
| LV INSULATION RESIS 100 k ohm |

<table>
<thead>
<tr>
<th>HVPP4 Module Test Procedure</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>HITOT VOLTAGE OFF</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>1</th>
<th>J1-001</th>
<th>J1-005</th>
<th>J1-009</th>
<th>J1-013</th>
</tr>
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<td>2</td>
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<td>J1-021</td>
<td>J1-025</td>
<td>J1-006</td>
</tr>
<tr>
<td>3</td>
<td>J1-003</td>
<td>J1-007</td>
<td>J1-011</td>
<td>J1-015</td>
</tr>
<tr>
<td>4</td>
<td>J1-019</td>
<td>J1-023</td>
<td>J1-027</td>
<td>J1-008</td>
</tr>
<tr>
<td>5</td>
<td>J1-029</td>
<td>J1-033</td>
<td>J1-037</td>
<td>J1-041</td>
</tr>
<tr>
<td>6</td>
<td>J1-045</td>
<td>J1-049</td>
<td>J3-088</td>
<td>J1-043</td>
</tr>
<tr>
<td>7</td>
<td>J1-031</td>
<td>J1-035</td>
<td>J1-039</td>
<td>J1-043</td>
</tr>
<tr>
<td>8</td>
<td>J1-047</td>
<td>J1-051</td>
<td>J3-060</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3. Hardware Commissioning

Figure 3.6: A Type II Board. Incorrect documentation of the wiring was identified in prototype testing.

and perform a HIPOT test. The connectivity is referenced against a list of all the connections expected for each module depending on what boards are connected. Any deviations from this expected list are flagged. Each HVPP4 module must pass both connectivity and HIPOT tests. The full details of the procedure are recorded in the catalogue of technical documents for CERN called Engineering and Equipment Data Management Service (EDMS) [14].
Chapter 3. Hardware Commissioning

Figure 3.7: The Cirrus Touch 1, laptop for read-out, and the HVPP4 are pictured above for the HVPP4 production test procedure.
Chapter 4

Hardware Research

4.1 ATLAS Upgrade

The LHC plans to upgrade in about 2019. The luminosity will be increased by up to a factor of 10! The pixel detector must withstand fluences up to $2.5 \times 10^{16}$ $n_{eq}/cm^2$. Several candidate technologies are being studied for their performance in ATLAS Upgrade conditions. The major contenders are planar sensors and 3D sensors.

4.2 3D Sensors

ATLAS uses planar silicon sensors as described in Chapter 2. A design using a 3-dimensional geometry was invented by Sherwood Parker [15]. The design’s key feature is the orientation of the electrodes. Instead of being on the surface as in the case for planar sensors, 3D sensor electrodes are columns drilled transversely into the bulk of the Si material. The design allows the 3D sensors to be more radiation hard than their planar partners. The small distance between electrodes leaves less
material sensitive to radiation damage such as the oxidation layers.

The capacitance of a 3D sensor [15, 16, 17] was characterized for detectors irradiated to high fluences. The conditions tested are relevant to the possible future operation of sensors in high luminosity applications like experiments at the Large Hadron Collider at CERN [18] for applications such as vertex reconstruction where high spatial resolution and tolerance to high radiation conditions are key.

Capacitance is an important parameter for the operation of a sensor, as it directly affects the noise. The noise is an important parameter for both the amount of signal extracted (signal to noise ratio) and the design of the read-out electronics for the sensor. Both of these parameters affect the viability of the 3D silicon sensor design for use in future LHC experiments and other very high radiation applications. In an alternative technology to 3D sensors, planar silicon sensors, the capacitance is known to increase with irradiation (see for example [19]). Capacitance of planar silicon diodes has been observed to exhibit dependence upon frequency of the stimulus [20]. Therefore, we measured the capacitance as a function of charged particle fluence and stimulus frequency. The capacitance measurements were performed in two ways which we will refer to as the “direct” and the “indirect” methods. The measurements were compared to each other and to predictions by a three-dimensional electrostatic calculation.

4.2.1 Description of the Test Structures

These particular samples under investigation were previously studied in [3] with respect to depletion voltage of irradiated devices and leakage current and capacitance of non-irradiated devices. They were fabricated as p-type silicon substrate with 121 µm electrode length with an array of p- and n-type electrodes perpendicular to the surface. The electrodes have drawn diameters of 14 microns and actual diameters
of about 17 microns. They are arrayed in 100 micron by 200 micron cells, with any electrode in the center of such a cell surrounded by 4 opposite type electrodes in the corners of the cell. For testing purposes only, the bias electrodes are tied together with aluminum strips parallel to the 100 micron direction. On each of the sensors studied, one p-type and one n-type electrode are not tied to aluminum strips, and these are thus available for measurements of electrode capacitance. Three bands of guard electrodes (p-, n-, and p-type) surround the array [3]. One of the devices has not been irradiated, while two have, to fluences of \(2 \times 10^{14} \text{ p/cm}^2\) and \(1 \times 10^{15} \text{ p/cm}^2\) with 55 MeV protons respectively. The irradiated sensors have been kept below freezing temperatures since irradiation to suppress annealing. Figure 4.1 shows the details of one of the arrays.

![Figure 4.1: The geometry of the structures under test. The top figure shows the chip layout [3] while the bottom figure shows the electrode spacing. The isolated p- and n-electrodes were used for the measurements.](image)
4.3 Simulation and Measurement Techniques for Non-Irradiated Devices

4.3.1 Simulation

The sensor geometry was modeled with a three-dimensional electrostatic simulator, IES Coulomb [21]. The software assumed an electrode length of 121 $\mu$m and a variable electrode diameter and incorporated the contributions of the six nearest neighbors, as shown in Figure 4.2. The permeability of silicon was assumed to be 11.9 [22], which is appropriate for non-irradiated silicon at room temperature. (Note that the same value for the permeability was used for both the n- and p-type electrodes making the result independent of the type of electrode being simulated.) The simple geometric model is only appropriate for non-irradiated sensors at room temperature. The effective electrode diameter was slightly larger than the 17 $\mu$m etched holes due to imperfect sidewall protection in the etching process and dopant diffusion into the single-crystal silicon [16]. When the nominal as-processed diameter (17 $\mu$m) of the electrodes was used, the model predicted an electrode capacitance, $28^{+0.5}_{-0.9}$ fF, in excellent agreement with the direct measurement of the non-irradiated sample. The input value of electrode diameter was then varied to predict the dependence of the capacitance upon diameter, both to assess the criticality of this aspect of geometry and processing and to derive the associated systematic uncertainty on the capacitance. The results are shown in Figure 4.3. The systematic error due to boundary conditions within IES Coulomb is reflected in the error bars. Choices for the boundary conditions on the walls included grounding, floating, and non-conductive. The systematic uncertainty was found by taking the maximum displacement from the baseline after varying the boundary conditions. It does not take into account any surface traces, frequency, or temperature effects.
4.3.2 Direct Measurement

The capacitance measurements done using the direct method were performed on both n- and p-type electrodes. The direct method used a HP4284A LCR meter, which supplied a small AC test signal (set to 250-1200 mV RMS) to the electrode under test via direct contact with a probe, which was connected to the HIGH terminal while the amplitude and phase were measured on the LOW terminal. The bias voltage on the device was systematically raised by 5 V increments from 0 V to 120 V or until the breakdown voltage was reached.

An open correction was made before each measurement. To check the open correction, an open measurement as a function of applied bias was regularly made prior to contact between the probe and the sensor. Such measurements resulted in capacitances between 0.001 fF and 30 fF indicating the noise in the system due to environmental factors. If the open correction resulted in an offset larger than 10 fF, it was repeated before measuring the electrode capacitance. At each voltage and frequency, the actual capacitance measurement was repeated three times. The variation was then used to calculate the statistical error on the capacitance. The
Figure 4.3: The capacitance between an electrode and its nearest neighbors for a 3D sensor, as modelled by the IES Coulomb geometrical simulator using Si permeability of 11.9 for several electrode diameters.

statistical and systematic errors were calculated and added in quadrature for each data point and displayed by the error bars. All measurements were taken at -20 °C.

Figure 4.4 is an example of the data obtained from a non-irradiated 3D sensor and illustrates several general features. One is that the capacitance versus bias voltage curves show little structure above depletion at any frequency, and that full depletion is generally attained well below 100 V for this geometry. (The depletion voltage in Figure 4.4 is approximately 20 V for 1 MHz defined by the intercept of the tangents above and below the knee.) The 3D capacitance value for the measurement is an average over bias voltages above depletion for the three frequencies and is 31 ± 3 fF.
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This and all subsequent measurement errors reported reflect the systematic and statistical errors added in quadrature. A full description is given in Section 4.3.4.

Figure 4.4: The capacitance versus bias voltage for an \( n \)-electrode in a non-irradiated 3D sensor where \( C_{3D} = 31 \pm 3 \) fF.

4.3.3 Indirect Measurement

It should also be possible to measure the isolated electrode’s capacitance by recording the decay time of its response to an infrared laser pulse [3]. The electrode was grounded through the input impedance of the Picoprobe-35. A rising signal was induced with a penetrating 1064 nm laser beam collimated to diameter about 10 \( \mu \)m. Once the laser turns off, the signal follows an exponential decay, which might be described by

\[
V = V_0 e^{-t/\tau}, \quad \text{where} \quad \tau = R_{probe} \times (C_{probe} + C_{3D})
\]  

(4.1)

and where \( R_{probe} = 1.25 \) M\( \Omega \) and \( C_{probe} = 0.05 \) pF are the resistance and capacitance of the Picoprobe. No amplification of the signal was used other than that inherent to
Chapter 4. Hardware Research

the Tektronix TDS7254B digital oscilloscope used in the readout and the Picoprobe-35 (Figure 4.5).

The top graph in Figure 4.6 shows an example of the data taken with this technique: the pulse height of a p-type electrode as a function of time. The data are then re-plotted in the bottom graph as a function of the log of the signal voltage, so a linear fit reveals $-1/\tau$ and the capacitance can be extracted from Equation 4.1. An example of the fit for a bias voltage of 20 V is shown on the bottom plot in Figure 4.6. For this bias voltage the 3D capacitance is $80 \pm 30 \text{ fF}$. The measurement was repeated for several bias voltages and plotted in Figure 4.7. All measurements were taken at $-20 \, ^\circ\text{C}$.

![Figure 4.5: A 1064 nm laser was pulsed near the isolated p-electrode, and the induced signal voltage was read out through a Picoprobe to an oscilloscope.](image)

4.3.4 Measurement Systematics

The systematic errors for the direct and indirect methods are summarized in Table 4.7. The apparatus error was determined by the manufacturers of the LCR meter and the 1064 nm laser. The error associated with the temperature measurement is approximately $\pm 1 \, ^\circ\text{C}$ with an estimated uncertainty of 10% in the capacitance. The direct method has a systematic error due to the LCR correction. It was calculated
by averaging the offset of the open measurement and is approximately ±2 fF. The direct measurement has a statistical error due to the deviation of the 3 measurement points as described in Section 4.3.2. The indirect method has systematic errors due to the Picoprobe and the selection of the fit range. The tolerance on the Picoprobe was estimated at ±10% for both the resistance and capacitance of the probe, which yields an error in the capacitance of approximately ±10 fF. For the error from the selection of fit range, the decay curve was broken into 5 time segments, each fit separately. The variance in the resultant capacitance was found to differ by roughly ±30% from the average value. The statistical uncertainty in the indirect method due to the quality of the fit was calculated separately for each fit and is approximately ±5 fF. The final error values reported are the systematic and statistical uncertainties added in quadrature.

<table>
<thead>
<tr>
<th>Table 4.1: Measurement Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct</strong></td>
</tr>
<tr>
<td>Apparatus</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>LCR Correction</td>
</tr>
<tr>
<td>Picoprobe</td>
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<tr>
<td>Fit Range</td>
</tr>
<tr>
<td>LCR Statistical</td>
</tr>
<tr>
<td>Fit Quality</td>
</tr>
</tbody>
</table>

4.4 Measurements of Irradiated Devices

4.4.1 Irradiation Conditions

The proton irradiations were done at Lawrence Berkeley National Laboratory in May 1999. The samples were at room temperature during the irradiation and then stored at −15°C to avoid annealing [23]. Two samples were irradiated to fluences of
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2 × 10^{14} \text{ p/cm}^2 \text{ and } 1 \times 10^{15} \text{ p/cm}^2 \text{ respectively with 55 MeV protons. The devices were measured at several temperatures including room temperature and below, but several of the devices can only be measured for capacitance at lower temperatures because they begin to break down at room temperature below the voltages of interest due to radiation damage. Therefore, we present the measurements of the irradiated devices at a temperature of -20\textdegree C.}

4.4.2 Direct Measurement

The direct measurement technique was applied to the 3D devices irradiated to 2 × 10^{14} (Figure 4.8) and 1 × 10^{15} \text{ p/cm}^2 (Figure 4.9) with 55 MeV protons for both p- and n-electrodes.

4.4.3 Indirect Measurement

The decay pulse of irradiated sensors had two slopes revealing two distinct time constants. The second may be due to the release of trapped charges produced by radiation damage [3]. Figure 4.10 shows two fits to the decay–before 450 ns and after 450 ns–for a bias voltage of 85 V. Fit 1 for time less than 450 ns (on the left) reveals the 3D sensor capacitance as $C_{3D} = 97 \pm 16 \text{ fF}$. Fit 2 for time greater than 450 ns (on the right) may reflect the release of trapped charge.

The measurement was repeated for several bias voltages for the p-electrode. Indirect capacitance versus bias voltage is plotted for the 3D sensor irradiated to 2 × 10^{14} \text{ p/cm}^2 in Figure 4.11 and 1 × 10^{15} \text{ p/cm}^2 in Figure 4.12. The final capacitance value for each sensor is the capacitance for a bias voltage of 100 V. The final value for the sensor irradiated to 2 × 10^{14} \text{ p/cm}^2 is 96 ± 35 fF and 128 ± 46 fF for the sensor irradiated to 1 × 10^{15} \text{ p/cm}^2.
4.4.4 Comparison of Direct and Indirect Measurements

Figure 4.13 shows a comparison of the capacitance from the direct and indirect measurement techniques as a function of fluence. The simulation point for non-irradiated devices is also plotted. There is statistical agreement between the simulation and both measurement techniques although there appears to be an offset between the two techniques. The offset can be accounted for if the equivalent circuit of the Picoprobe-35 is more complicated than the simple RC model proposed. The capacitance was seen to increase by roughly 70% from non-irradiated to $1 \times 10^{15}$ p/cm$^2$ devices.

To generalize the effects of radiation damage and look for a trend, the capacitance was scaled by the non-irradiated data and the fluence was scaled to 1 MeV n$_{eq}$/cm$^2$ using the Non-Ionizing Energy Loss (NIEL) conversion [24] (Figure 4.14).

4.5 Summary

The dependence of 3D sensor capacitance on fluence was measured and characterized for the first time. The capacitance of a set of 3D pixel test structures was simulated and measured with two techniques with consistent results. The capacitance was found to increase with fluence by approximately 70% from non-irradiated to a fluence of $1 \times 10^{15}$ p/cm$^2$ with 55 MeV protons. The capacitance values of the isolated $p$- and $n$-electrodes were found to be similar despite differences in processing such as doping materials that result in different physical characteristics of each electrode type. This indicates that the geometry of the columns dominates the difference between electrode types for the electrode capacitance dependence. The direct measurement displays some dependence upon the frequency of the stimulus for all fluence levels including zero.
Figure 4.6: The top plot shows the rise in signal voltage versus time on the $p$-electrode while the laser was on and the subsequent decay when the laser was off. The bottom plot shows the same data from the decay plotted as a function of the log of the signal voltage. The data were then fit linearly to extract the time constant of the decay and the 3D sensor capacitance. For this example the 3D capacitance is $80 \pm 30$ fF with an $R^2$ value of the linear fit equal to 0.999. Both plots are shown for a non-irradiated $p$-electrode at -20 °C biased at 20V.
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Figure 4.7: The indirect measurement was repeated for several bias voltages and the 3D capacitance was extracted. The p-electrode 3D capacitance is shown for a non-irradiated sensor at -20 °C.
Figure 4.8: The capacitance versus bias voltage for a direct measurement of an $n$-electrode in a 3D sensor irradiated to $2 \times 10^{14}$ p/cm$^2$ at -20 °C. The final capacitance value for this device is $42 \pm 5$ fF.

Figure 4.9: The capacitance versus bias voltage for a direct measurement of an $n$-electrode in a 3D sensor irradiated to $1 \times 10^{15}$ p/cm$^2$ at -20 °C. The final capacitance value for this device is $53 \pm 7$ fF.
Figure 4.10: Two fits to the signal decay curve were done for the irradiated 3D sensors. The fit for times less than 450 ns indicates the 3D sensor capacitance ($R^2$ of fit was 0.99) while the fit for times greater than 450 ns may reflect the release of trapped charge. The above plot was made for a $p$-electrode biased at 85 V irradiated to $2 \times 10^{14}$ p/cm$^2$ with 55 MeV protons at -20 °C.
Figure 4.11: The indirectly measured capacitance versus bias voltage for a $p$-electrode in a 3D sensor irradiated to $2 \times 10^{14}$ p/cm$^2$ with 55 MeV protons at -20 °C. The final capacitance value for this device is $96 \pm 35$ fF.
Figure 4.12: The indirectly measured capacitance versus bias voltage for a $p$-electrode in a 3D sensor irradiated to $1 \times 10^{15}$ p/cm$^2$ with 55 MeV protons at -20 $^\circ$C. The final capacitance value for this device is $128 \pm 46$ fF.
Figure 4.13: The capacitance versus fluence is shown for both $n$- and $p$-electrodes for the direct measurement, the $p$-electrode for the indirect method and the simulation for non-irradiated 3D sensors. The measurements were done at $-20$ °C. The capacitance increased by approximately 70% from non-irradiated to $1 \times 10^{15}$ $55$ MeV p/cm$^2$ devices.
Figure 4.14: The capacitance was scaled by the non-irradiated data and plotted as a function of fluence. The fluence was scaled to 1 MeV n$_{eq}$/cm$^2$. 
4.6 Neutron and Gamma Irradiation of MCz Planar Sensors

Magnetic Czochralski (MCz) planar sensors are a candidate detector technology for high radiation environments. This study is relevant to the conditions of the International Linear Collider (ILC), as well as ATLAS Upgrade. The experiment was designed to understand the performance response of MCz Si detectors by inferring the effects of different types of defects produced by neutron and gamma irradiation. For that purpose, MCz sensors were exposed first to neutron and then gamma radiation. The leakage current, capacitance and effective space charge were measured to characterize the response of the sensors.

4.6.1 MCz Planar Sensor Technology

The detectors are p$^+/n/n^+$ Si detectors processed at Brookhaven National Laboratory’s Silicon Detector development and Processing Lab (SDDPL) using 100 mm diameter n-type MCz Si wafers. The wafers are 350 μm thick with a detector area of 0.5 x 0.5 cm$^2$. The resistivity is 1000 Ω·cm$^2$. A 2 mm diameter window was left in the Al on the front side and there is an Al mesh on the backside to allow laser penetration into the Si for TCT measurements.

4.6.2 Radiation Damage Effects

When the MCz detectors are exposed to radiation the resultant damage (mainly to the bulk of the detector) causes the leakage current to increase. The applied bias voltage required to fully deplete the detector, V$_{fd}$, is also affected by radiation exposure.
Effective Space Charge Density

The effective space charge density is also affected by radiation damage. Neutron radiation introduces the accumulation of deep level defects that induce negative space charge. Gammas induce positive space charge when they activate thermal donors in the MCz Si material. This effect seems to be proportional to the amount of oxygenated Si [25]. When the sign of the effective space charge density changes, it is said to undergo space charge sign inversion (SCSI). This phenomenon is evident by the slope of the Transient Current Technique (TCT) measurement (discussed later) after full depletion is reached [25, 26]. See Figure 4.17.

Prior to full depletion, two peaks in the TCT plot are evident. These regions are caused by two junctions in the detector. The double junction (DJ) is caused by regions of positive and negative space charge within a single detector with an electrically neutral region (ENR) between the two charged regions. This results in the electric field profile as seen in Figure 4.16 with regions of decreasing and increasing electric field. Some time after full depletion voltage is reached the bias voltage is strong enough that the electric field is continuously increasing and the second peak dominates [27].

4.6.3 Measurement Descriptions

IV

The leakage current characteristic of the detector is determined by taking a current versus voltage (IV) measurement. The leakage current is useful to find at what bias voltage the device breaks down.
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CV

The capacitance of the detector is measured for various bias voltages. As the bias voltage increases the depletion region between the substrate and the electrode surface also increases to a point beyond which it can no longer grow due to geometry or radiation damage. At this point, the capacitance no longer increases. To highlight this change, the inverse of the squared capacitance is plotted versus the bias voltage. The knee of the plot indicates the full depletion voltage, $V_{fd}$ where the capacitance has reached its limit. See Figure 4.15. The measurements are done using an LCR meter.

TCT

The Transient Current Technique (TCT) was developed at BNL [26]. A red laser that penetrates 5µm in Si illuminates one side of the detector inducing a current. Depending on the side that is illuminated, either an electron current or hole current is measured. If the laser is shone on the top, $p^+$, side, then an electron current is induced. Similarly, if the laser is shone on the back, $n^+$, side, then a hole current is induced. The current is measured as a function of time and plotted. The electric field profile is determined by the distribution of the space charge. Figure 4.16 shows a region of positive space charge near the $p^+$ contact and a negative space charge region near the $n^+$ contact. The electric field $E_1$ corresponds to the positive space charge region and manifests itself in the TCT plot as a decreasing current (the first rise in Figure 4.17). $E_2$ corresponds to a region of negative space charge and increasing current (the second rise in Figure 4.17). The TCT measurements are repeated for a range of bias voltages. When full depletion is reached, the peak due to $E_2$ dominates over the peak caused by the $E_1$ region. For the hole currents, the space charge region has the opposite effect and appears as an increasing current for positive space charge.
region \( (E_1) \) and decreasing current in a negative space charge area \( (E_2) \). (Figure 4.18)

The effective net concentration of ionizing charges, \( N_{eff} \) is determined from the TCT measurement. In [26] it is shown that:

\[
\tau \propto \frac{1}{\sqrt{N_{eff}}} \frac{1}{\sqrt{V}}
\]  

where \( \tau \) is the decay time constant of the TCT current and \( V \) is the bias voltage. Then \( N_{eff} \) can be determined from the slope of the plot of \( \tau \) versus \( \frac{1}{\sqrt{V}} \).

All room temperature measurements (IV, CV and TCT) were performed at BNL. Measurements of IV and CV at low temperature (-20°C) were done immediately after neutron irradiation at UNM.

4.6.4 Experiment Procedure

The damage in MCz samples is different depending on the type of radiation exposure. It was shown that neutrons produce more negative space charge in the sample, while gammas increase the positive space charge [25]. This experiment was designed by Zheng Li to learn if the two types of damage would cancel each other out by first irradiating with neutrons lowering the net space charge and then irradiating with gammas increasing the space charge back to its original level and restoring the device to its original operational characteristics.

There were a total of four samples used in this experiment. All the samples were first irradiated with neutrons. Two were irradiated to a fluence of \( 1.5 \times 10^{14} \) \( \text{n/cm}^2 \) and the other two were irradiated to \( 3 \times 10^{14} \) \( \text{n/cm}^2 \). Immediately after neutron irradiation UNM performed low temperature IV and CV measurements. The samples were shipped to BNL and measured again for IV, CV and TCT, but at room temperature. Then, all the samples were allowed to anneal at room temperature for
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22 days at which point all the measurements were repeated. One sample from each neutron fluence was then exposed to gamma radiation to 500 Mrad and allowed to anneal at room temperature for 5.5 months. The other samples were used as a control and were not exposed to gamma radiation, but were also allowed to anneal at room temperature for 5.5 months. See Table 4.2. The neutron fluence and gamma doses were chosen such that the expected positive space charge induced by $1.5 \times 10^{14} \text{ n/cm}^2$ balances the negative space charge induced by the 500 Mrad gamma irradiation, while the second, higher, neutron fluence of $3 \times 10^{14} \text{ n/cm}^2$ should overcompensate the space charge induced by the gamma irradiation.

<table>
<thead>
<tr>
<th>Sample #:</th>
<th>Conditions</th>
<th>1480-13</th>
<th>1480-5</th>
<th>1480-14</th>
<th>1480-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron irradiation</td>
<td>$1.5 \times 10^{14} \text{ n/cm}^2$</td>
<td>$1.5 \times 10^{14} \text{ n/cm}^2$</td>
<td>$3 \times 10^{14} \text{ n/cm}^2$</td>
<td>$3 \times 10^{14} \text{ n/cm}^2$</td>
<td></td>
</tr>
<tr>
<td>gamma irradiation</td>
<td>0 Mrad</td>
<td>500 Mrad</td>
<td>0 Mrad</td>
<td>500 Mrad</td>
<td></td>
</tr>
</tbody>
</table>

4.6.5 Irradiation Conditions

Neutron

The neutron irradiations were performed at Sandia National Laboratories at the Annular Core Research Reactor (ACRR) in Albuquerque New Mexico (Figure 4.19). The reactor neutrons have energies ranging from 0.8-1 MeV with a hardness factor of 1.3 compared to 1 MeV neutrons in silicon according to the NIEL scale hypothesis [24]. Lead shielding was used to reduce gamma contamination and increase the ratio of fast to thermal neutrons. Lower energy thermal neutrons are not widely prevalent in high luminosity colliders and have a larger neutron absorption cross-section, which can cause more damage, so it is better to reduce their presence during neutron irradiation in order to see the damage effects of the fast neutrons more clearly. The reactor was operated at approximately 2% power and the irradiations
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took on the order of a few minutes. Three types of dosimeters were used during irradiation to determine neutron fluence and gamma dose—four sulfur tablets, one nickel dosimeter and four Thermal Luminescent Dosimeters (TLDs) (Figure 4.20).

Gamma

The gamma irradiations were done at Brookhaven National Laboratories (BNL) using a $^{60}$Co source. The gammas have energy of 1.25 MeV. The samples were irradiated at room temperature over the course of several weeks.

4.6.6 Experiment Results

Cold Measurements

Leakage current and capacitance measurements were performed at UNM after the neutron irradiation before annealing. The measurements were done at approximately -10 °C. The cold temperatures suppress the leakage current in the MCz detectors. Therefore, a lower bias voltage will produce full depletion.

<table>
<thead>
<tr>
<th>Sample #:</th>
<th>Full Depletion Voltage:</th>
<th>Measurement Location:</th>
<th>Temperature:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1480-5 (1.5x10$^{14}$ n/cm$^2$)</td>
<td>&lt;10</td>
<td>UNM</td>
<td>~10°C</td>
</tr>
<tr>
<td>1480-13 (1.5x10$^{14}$ n/cm$^2$)</td>
<td>13</td>
<td>BNL</td>
<td>+20°C</td>
</tr>
<tr>
<td>1480-14 (3x10$^{14}$ n/cm$^2$)</td>
<td>20</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1480-16 (3x10$^{14}$ n/cm$^2$)</td>
<td>13</td>
<td>-</td>
<td>782</td>
</tr>
</tbody>
</table>

Table 4.3: All depletion voltages were calculated from CV measurements at 100 kHz.
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Neutron Only Irradiations

All four devices were first irradiated with neutrons to two fluences: $1.5 \times 10^{14} \text{ n/cm}^2$ and $3 \times 10^{14} \text{ n/cm}^2$ (two devices for each fluence). After irradiation with neutrons the samples were allowed to anneal at room temperature for 22 days. This is considered beneficial annealing that lowers the bias voltage of the detector. In this case, 22 days was sufficient to see full benefits of the annealing after neutron irradiation. The device is considered to have seen all beneficial changes from room temperature annealing and will begin to undergo reverse (non-beneficial) annealing in which the depletion voltage increases.

In all cases, before full depletion voltage was reached, the double peak junction due to the regions of positive and negative space charge generated by the radiation damage of the neutrons was observed. Positive space charge was generated near the $p^+$ contact (decreasing current) and negative space charge near the $n^+$ contact (increasing current). The full depletion voltage observed from the CV measurement for the samples irradiated to $1.5 \times 10^{14} \text{ n/cm}^2$ was 187 V (sample 1480-13) and 177 V (sample 1480-5). For the samples irradiated to $3 \times 10^{14} \text{ n/cm}^2$ the full depletion voltages were 508 V (sample 1480-16) and 507 V (sample 1480-14).

The space charge is quantified by $N_{eff}$. Before irradiation $N_{eff}$ for all the samples was $+2.88 \times 10^{12} \text{/cm}^3$ where a positive sign indicates positive space charge (+sc) and a negative sign indicates negative space charge (-sc). The space charge after irradiation to $1.5 \times 10^{14} \text{ n/cm}^2$ for both samples was $-1.5 \times 10^{12} \text{/cm}^3$. Both the samples irradiated to $3 \times 10^{14} \text{ n/cm}^2$ had space charge $-4.2 \times 10^{12} \text{/cm}^3$. In all cases, there is evident space charge sign inversion (SCSI)–the sign of the space charge flipped. As expected, a larger effect is seen in the samples irradiated to a higher neutron fluence.
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Neutron Irradiations With and Without Gamma Irradiation

After the neutron irradiation and 22 days of beneficial annealing, the samples were allowed to reverse anneal for 5.5 months. For two of the samples the reverse annealing was done in conjunction with gamma irradiation. The gamma irradiation was done over the whole period of 5.5 months at room temperature up to a dose of 500 Mrad.

The samples that were not gamma irradiated showed a greater change in the full depletion voltage due to reverse annealing. Samples 1480-13 and 1480-14 (not irradiated with gamma) show an increase in the full depletion voltage and a change in the shape of the peaks of the TCT measurements. Sample 1480-13 which was irradiated with neutrons to $1.5 \times 10^{14}$ n/cm$^2$ showed an increase from 187 V to 400 V and samples 1480-14 irradiated with neutrons to $3 \times 10^{14}$ n/cm$^2$ measured an increase from 507 V to something greater than 1100 V (1100 V is the maximum limit of the measurement capability at BNL).

The space charge of the samples, as characterized by $N_{eff}$, became more negative for the samples that reverse annealed without gamma irradiation. Sample 1480-13 had $N_{eff} = -3.3 \times 10^{12}$ /cm$^3$ and sample 1480-14 had $N_{eff} \leq -8.9 \times 10^{12}$ /cm$^3$. The samples that were also exposed to gamma irradiation during the reverse annealing showed little change in $N_{eff}$. Sample 1480-5 had $N_{eff} = -1.7 \times 10^{12}$ /cm$^3$ and sample 1480-16 had $N_{eff} = -4.2 \times 10^{12}$ /cm$^3$.

The samples that were exposed to gamma irradiation during the reverse annealing exhibited almost no change in full depletion voltage for samples irradiated to both neutron fluences! Sample 1480-5, which was irradiated to $1.5 \times 10^{14}$ n/cm$^2$, saw a slight decrease in $V_{fd}$ from 177 V to 170 V and sample 1480-16, which was irradiated to $3 \times 10^{14}$ n/cm$^2$, saw no change at all and remained at 508 V.
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Analysis of Results

Table 4.5 shows a summary of the values of the full depletion voltage and the space charge. It was guessed that the induced space charge from the neutron irradiation to $1.5 \times 10^{14}$ n/cm$^2$ and the 500 Mrad gamma irradiation would exactly cancel each other out and this is what was observed. However, if the effects were independently additive, then the 500 Mrad exposure to gamma should not be enough to balance the neutron irradiation to $3 \times 10^{14}$ n/cm$^2$. The results clearly show that in the case of the sample irradiated to $3 \times 10^{14}$ n/cm$^2$ and exposed to 500 Mrad of gammas there is no net change in $N_{eff}$. There is complete suppression of the reverse annealing in both the gamma irradiated samples regardless of fluence. This indicates that there could be some interaction between the defects generated by the gammas and those from the reverse annealing for neutron irradiated samples. More study is needed to fully understand this effect.

Table 4.4: MCZ Device Summary

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Neutron Irradiation: $V_{fd}$ [V]</th>
<th>$N_{eff}$ [/cm$^3$]</th>
<th>Reverse Annealing: $V_{fd}$ [V]</th>
<th>$N_{eff}$ [/cm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1480-13</td>
<td>1.5 $\times 10^{14}$ n/cm$^2$ No Gamma</td>
<td>187</td>
<td>$-1.5 \times 10^{12}$</td>
<td>400</td>
</tr>
<tr>
<td>1480-14</td>
<td>3 $\times 10^{14}$ n/cm$^2$ No Gamma</td>
<td>507</td>
<td>$-4.2 \times 10^{12}$</td>
<td>$\geq 1100$</td>
</tr>
<tr>
<td>1480-5</td>
<td>1.5 $\times 10^{14}$ n/cm$^2$ 500 Mrad</td>
<td>177</td>
<td>$-1.5 \times 10^{12}$</td>
<td>170</td>
</tr>
<tr>
<td>1480-16</td>
<td>3 $\times 10^{14}$ n/cm$^2$ 500 Mrad</td>
<td>508</td>
<td>$-4.2 \times 10^{12}$</td>
<td>508</td>
</tr>
</tbody>
</table>

Table 4.5: The values shown for neutron irradiations include 22 days of beneficial room temperature annealing. The reverse annealing was done over a period of 5.5 months.
4.6.7 Summary

The measurements performed by UNM confirm that cold temperatures suppress leakage current and keep $V_{fd}$ low for neutron fluences in the range of $1.5 \times 10^{14}$ n/cm$^2$ to $3 \times 10^{14}$ n/cm$^2$. The TCT measurements taken at BNL show the opposing effects on space charge produced by neutron and gamma irradiation can balance each other out, but that this effect is not independently additive. Moreover, the study shows there may be some interaction between the generated defects.
Figure 4.15: The plot is an example of how the depletion voltage is calculated from the inverse of the squared capacitance versus voltage. Two linear fits are made before and after the knee of the plot. The intersection of the two lines indicates the depletion voltage.
Figure 4.16: The electric field profile of a planar sensor after irradiation.

Figure 4.17: The TCT plot of electron current versus time for sample 1480-13 irradiated with neutron to $1.5 \times 10^{14}$ n/cm$^2$. 
Figure 4.18: The TCT plot of hole current versus time for sample 1480-13 irradiated with neutron to $1.5 \times 10^{14}$ n/cm$^2$. 

1480-13, 1.5x10$^{14}$ n/cm$^2$, (22 d RT anneal) MCZ n-type Si, p'/n/n' structure

Laser back, hole current from n' to p'
Figure 4.19: A view down the ACRR reactor tube with the samples at the bottom.

Figure 4.20: The packaged samples, one nickel dosimeter, four TLDs and four sulfur tablets used for dosimetry during neutron irradiations.
4.7 Proton Irradiation and Annealing of Planar Si Sensors

Silicon tracking detectors play an integral role in high energy physics experiments such as ATLAS at the Large Hadron Collider (LHC) \cite{1, 18}. Future upgrades of the ATLAS detector at the High Luminosity LHC will require more radiation tolerant technologies to achieve optimal performance \cite{28}. Motivated by this, several types of silicon (Si) were studied to compare their depletion voltages before and after proton irradiation and annealing. The samples in this study were irradiated by 800 MeV protons to fluences up to $1.1 \times 10^{15}$ n$_{eq}$/cm$^2$, which is relevant to Si detectors at 380 mm and outward from the central axis of a High Luminosity LHC detector \cite{29}. Annealing was applied to emulate the long term behavior of the sensors especially during maintenance periods when the cooling is off. Annealing at 60°C accelerates the short-term annealing process by a factor of 174 compared to 20°C and by a factor of 23,000 compared to -10°C \cite{4}. The depletion voltage data were converted to effective doping concentration. These were fit using the Hamburg Model \cite{4}, which describes the macroscopic behavior of annealing in terms of the change in effective doping concentration of the sensor. The parameters extracted from the Hamburg Model were then related to the basic microscopic properties of the material. Knowledge of annealing behavior can facilitate inference of the depletion voltage of sensors throughout their operational lifetimes.

*The fluences were converted from proton fluence to 1 MeV neutron equivalent fluence by the Non Ionizing Energy Loss (NIEL) scale hypothesis \cite{4}.*
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4.8 Experiment

4.8.1 Devices

The four types of silicon samples were all 300 µm thick diodes. The p-type Fz diodes were from the ATLAS07 wafer run, part of the ATLAS Upgrade project manufactured by HPK [30], while the n-type Fz, n-type MCz, and p-type MCz were made for the RD50 Common Project Run by Micron [31] (please see Table 4.6). There were two of each type of diode for each fluence. This study was conducted in the framework of RD50 [32].

Table 4.6: Devices

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>n-on-p Fz</th>
<th>p-on-n Fz</th>
<th>n-on-p MCz</th>
<th>p-on-n MCz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resitivity</td>
<td>13 kΩ-cm</td>
<td>3.3 kΩ-cm</td>
<td>1.9 kΩ-cm</td>
<td>1.4 kΩ-cm</td>
</tr>
<tr>
<td>Active Area</td>
<td>3mm × 3mm</td>
<td>3mm × 3mm</td>
<td>3mm × 3mm</td>
<td>3mm × 3mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>300 µm</td>
<td>300 µm</td>
<td>300 µm</td>
<td>300 µm</td>
</tr>
<tr>
<td>$N_{eff,0}$</td>
<td>$1.1 \times 10^{12}$ cm$^{-3}$</td>
<td>$1.39 \times 10^{12}$ cm$^{-3}$</td>
<td>$-7.69 \times 10^{12}$ cm$^{-3}$</td>
<td>$3.21 \times 10^{12}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

4.8.2 Experimental Procedure

The diodes were irradiated at Los Alamos Neutron Science Center (LANSCE) [33] with 800 MeV protons with a hardness factor of 0.71 [4]. Bunches of approximately gaussian cross section and one centimeter full width at half maximum were collided on the target. Temperature was monitored in real time and observed to be stable to within 1 °C. Fluences of $7.8 \times 10^{13}$, $1.5 \times 10^{14}$ and $1.1 \times 10^{15}$ 1 MeV n$_{eq}$/cm$^2$ were achieved. All the devices were stored in a freezer at -20 °C as soon as possible after irradiation, typically 10 to 120 minutes depending upon the fluence received. This uncertainty has been included in the systematic error calculation. The samples were then annealed at 60 °C in time steps of 0, 10, 20, 40, 60, 80, 100, 120, 140, 160, 200,
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300, 500, 1,000, and 10,000 minutes. Current versus voltage (IV) and capacitance versus voltage (CV) were measured at each time step.

4.8.3 Measurements

Diode leakage current and capacitance (C) as a function of the bias voltage were measured at 20 °C using a temperature regulated chuck. For the capacitance measurements, a test signal frequency of 10 kHz was used, consistent with RD50 guidelines. Measurements on each sample were repeated after irradiation and each annealing step. The leakage current was examined in each case to identify any superlinear behavior indicative of thermal runaway. In cases where superlinear behavior was observed, a cut-off voltage was determined from the point where it began, and any capacitance data above the cut-off voltage were not used in this study.

4.8.4 Depletion Voltage

Graphs of $1/C^2$ versus the bias voltage were used to determine depletion voltage. In plots of this type (for example, Figure 4.21), two linear segments emerge—one with positive slope, the other, a near-horizontal plateau. The two linear segments were fit and their intersection was taken as the depletion voltage. However, in the more highly irradiated diodes, the $1/C^2$ curve exhibits more structure as seen in Figure 4.21. Our method applied in this case was to fit the linear section just left of the “knee” (circle points) and the plateau region (square points) right of the knee. The rest of the data points (light gray) were not used in the fits. Again, the intersection of the two fits was taken as the depletion voltage. For each extracted depletion voltage, a systematic error was assigned to the fit assuming this procedure.
Figure 4.21: Illustration of the method used to extract the depletion voltage from capacitance data with more structure than two linear sections. The first linear fit (circle points) is taken left of the “knee” and the second fit (square points) taken in the plateau region right of the knee. The rest of the data points (gray) were not used in the fits. The intersection of the two linear fits is taken as the depletion voltage.

4.8.5 Errors

The sources of error are shown in Table 4.7. A more detailed explanation of the equipment error sources can be found in [34]. The LCR Meter error was determined by the manufacturer. A systematic error assigned to the correction measurement was taken as a conservative estimate of the noise fluctuation after the correction measurement was performed on the LCR Meter. The statistical error was the average statistical error taken from the three capacitance measurements at each bias voltage value. The errors in the capacitance measurement (LCR Meter, LCR Correction, LCR Statistical, and Temperature) were added in quadrature for each capacitance value. The error on the capacitance was then conservatively estimated as a percent-
age value assigned to each fit. The error is 5% in the region spanned by the segment with positive slope, and 7% in the plateau region. These errors were propagated to the depletion voltage value. If fit 1 is described by $F = aV + b$ and fit 2 by $F = \alpha V + \beta$ (where $F$ is $1/\text{capacitance}^2$, $V$ is the bias voltage, $a$ and $\alpha$ are the slopes, and $b$ and $\beta$ are the intercepts), then the depletion voltage is given by:

$$V_{fd} = \frac{\beta - b}{a - \alpha}. \quad (4.3)$$

The capacitance error propagated to the depletion voltage is given by:

$$\sigma(Capacitance) = V_{fd} \sqrt{\frac{\sigma_{\beta-b}^2}{\beta - b} + \frac{\sigma_{a-\alpha}^2}{a - \alpha}}. \quad (4.4)$$

where $\sigma_{\beta-b}$ and $\sigma_{a-\alpha}$ are the errors on the differences in the intercepts and differences in the slopes, respectively. The final error reported for the depletion voltage is then given by the error in Equation 4.4 added in quadrature to the error due to the depletion voltage fit.

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCR Meter</td>
<td>±0.3% Capacitance</td>
</tr>
<tr>
<td>LCR Correction</td>
<td>±120 fF</td>
</tr>
<tr>
<td>LCR Statistical</td>
<td>±50 fF</td>
</tr>
<tr>
<td>Temperature</td>
<td>±1 °C ⇒ ±2% Capacitance</td>
</tr>
<tr>
<td>$V_{fd}$ Fit</td>
<td>±10-100V</td>
</tr>
<tr>
<td>Fluence</td>
<td>±15%</td>
</tr>
<tr>
<td>Anneal Time</td>
<td>±5%</td>
</tr>
</tbody>
</table>
4.9 Results

4.9.1 Fluence

Figure 4.22 shows the depletion voltage dependence on fluence for both n- and p-type Fz and MCz diodes before annealing. Both types of Fz diode had a low pre-irradiation depletion voltage that steeply increased with fluence. At \(1.1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2\), the depletion voltage could not be extracted from the capacitance data because the cut-off voltage linked to leakage current did not allow a reliable fit of the plateau section of \(1/C^2\). This may indicate that the device cannot be operated at full depletion for very high fluences. For MCz devices, the slope of the curve of depletion voltage versus fluence is negative for low fluences, positive for high. Although MCz exhibits higher initial depletion voltage, the overall performance is more stable as a function of fluence. The n-type MCz series shows much lower values of depletion voltage than the p-type.

4.9.2 Annealing

The annealing behavior of the silicon as characterized with depletion voltage is shown in Figures 4.23 and 4.24. (In these figures, points at \(t = 10,000\) minutes are excluded to improve readability. Those points are used in all calculations and are shown with the final fits, see Figure 4.25.) Figure 4.23 shows depletion voltage versus anneal time for n- and p-type Fz diodes irradiated to three different fluences. In all the samples a period of beneficial annealing (decrease in depletion voltage) is seen for roughly 100 minutes. The progression from beneficial to reverse annealing (increase in depletion voltage) indicates that the diodes have negative space charge (excess electric charge) after the proton irradiation \([35, 36, 37]\). While there is an initial period of positive space charge introduction due to a decrease of acceptor-like
defects, the depletion voltage decreases. This is followed by a period dominated by the activation of acceptors, which causes an increase in negative space charge corresponding to a period of reverse annealing. The value of the minimum of $V_{fd}$ between the two stages of annealing is determined by the stable damage–defects that are not dependent on time, only on fluence [38, 39].

The effect of annealing on the depletion of MCz diodes is shown in Figure 4.24. In this case the data indicate that the n- and p-type MCz Si diodes have opposite space charge after proton irradiation. The p-type MCz exhibits the same form of annealing behavior as the Fz diodes with negative space charge after irradiation. The n-type shows a small period of reverse annealing followed by beneficial annealing, indicating positive space charge after proton irradiation.
Figure 4.23: Depletion voltage versus anneal time for both n- and p-type Fz diodes.

4.9.3 Effective Doping Concentration

The depletion voltage from the CV measurements was converted to the absolute value of the effective doping concentration $|N_{\text{eff}}|$ using [4]

$$|N_{\text{eff}}| = V_{fd} \frac{2\epsilon_{Si}}{\epsilon d^2}$$  \hspace{1cm} (4.5)

where $\epsilon_{Si}$ is the absolute permittivity of silicon, which is given by the permittivity of free space multiplied by the dielectric constant for silicon, $\epsilon_{Si} = \epsilon_0 \cdot \epsilon = 8.85 \times 10^{-14}$ F/cm $\cdot$ 11.9 $= 1.05 \times 10^{-12}$ F/cm, $e$ is the elementary charge, and $d$ is the device thickness in centimeters. The sign of $N_{\text{eff}}$ was inferred from the sign of the space charge determined by the behavior of $V_{fd}$. The sign of the space charge is supported by measurements in References [40, 41, 35] as well. The change in effective doping concentration is given by $\Delta N_{\text{eff}} = N_{\text{eff},0} - N_{\text{eff}}(\Phi, t(T))$. 

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### Hamburg Model

The Hamburg Model describes the annealing behavior in terms of the change in effective doping concentration. It recognizes three different contributions: a short term decrease of acceptor-like defects (or an increase in donors) \( N_A \); a stable damage dependent on fluence \( N_C \) only; and a reverse annealing in which acceptors are activated (or donors are removed) \( N_Y \). These terms are related through [4, 39]

\[
\Delta N_{\text{eff}} = N_A(\Phi, t) + N_C(\Phi) + N_Y(\Phi, t)
\]  
(4.6)

where

\[
N_A(\Phi, t) = g_a e^{-t/\tau_a} \Phi
\]  
(4.7)

\[
N_C(\Phi) = g_c \Phi + N_{c0}(1 - e^{-c_\Phi})
\]  
(4.8)
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and

\[ N_Y(\Phi, t) = g_Y (1 - e^{-t/\tau_Y}) \Phi. \]  \hspace{1cm} (4.9)

Here \( \Phi \) is fluence in \( n_{eq} \), \( g_a \) is the introduction rate, and \( \tau_a \) is the time constant for the annealing of acceptors. The \( g_c \) is the introduction rate of the stable acceptors, \( N_{c0}(1 - e^{-c \Phi}) \) characterizes incomplete donor removal for n-type and acceptor removal for p-type, and \( c \) is the donor removal rate constant. The coefficient \( g_Y \) is the introduction rate, and \( \tau_Y \) is the time constant for the activation of acceptors. The stable damage terms are most important for predicting the damage rate (independent of annealing) during irradiation at the LHC, for example. The stable damage coefficients have been shown to vary by radiation particle type [39].

**Fit Results**

The Hamburg Model given in Equation 4.6 was fit to the annealing data using the Chi-Square Method [42] where all the variables except fluence were free parameters. The results are shown in Figure 4.25. Every fit had a fit probability derived from the residual variance that was greater than 90\%. Those devices not shown in Figure 4.25 were not included because they did not have enough data points (due to current break down or loss of device) for an accurate fit. The errors were calculated using the jackknife method, which takes into account resampling errors [43]. The values extracted from the fit are shown in Table 4.8.

All the samples reflect typical annealing through changes in \( \Delta N_{eff} \). There is first a reduction of acceptors (generation of donors) followed by activation of acceptors (reduction of donors). During the short term annealing the samples with negative space charge are becoming less negative while the ones with positive space charge are becoming more positive. In contrast, the negative space charge samples become
Figure 4.25: $\Delta N_{eff}$ as a function of the anneal time. The data were fit to the Hamburg Model [4] described in Equation 4.6.

more negative and the positive space charge samples become less positive during long-term annealing. The introduction rates, $g_a$ and $g_Y$, are consistent for each type of device regardless of fluence, as predicted by the Hamburg Model. The short term annealing time constant, $\tau_a$, is also consistent for all devices and all fluences. These results are comparable to previous results on high resistivity (1-25 kΩ) Si (n-type Fz,

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>$g_a$ [cm$^{-1}$]</th>
<th>$\tau_a$ [min]</th>
<th>$N_c$ [cm$^{-3}$]</th>
<th>$g_Y$ [cm$^{-1}$]</th>
<th>$\tau_Y$ [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-on-p Fz 7.8x10$^{14}$ n$_{eq}$/cm$^2$</td>
<td>0.02 ± 0.02</td>
<td>32 ± 22</td>
<td>2x10$^{14}$ ± 2x10$^{14}$</td>
<td>0.04 ± 0.03</td>
<td>1700 ± 800</td>
</tr>
<tr>
<td>n-on-p Fz 1.5x10$^{14}$ n$_{eq}$/cm$^2$</td>
<td>0.02 ± 0.004</td>
<td>36 ± 19</td>
<td>2.5x10$^{14}$ ± 6x10$^{14}$</td>
<td>0.058 ± 0.009</td>
<td>1300 ± 500</td>
</tr>
<tr>
<td>p-on-n Fz 7.8x10$^{14}$ n$_{eq}$/cm$^2$</td>
<td>0.009 ± 0.006</td>
<td>27 ± 20</td>
<td>2.3x10$^{14}$ ± 2x10$^{14}$</td>
<td>0.035 ± 0.005</td>
<td>2000 ± 700</td>
</tr>
<tr>
<td>p-on-n Fz 1.5x10$^{14}$ n$_{eq}$/cm$^2$</td>
<td>0.01 ± 0.007</td>
<td>24 ± 17</td>
<td>-1.1x10$^{14}$ ± 1x10$^{14}$</td>
<td>0.06 ± 0.02</td>
<td>3400 ± 1400</td>
</tr>
<tr>
<td>n-on-p MCz 1.1x10$^{15}$ n$_{eq}$/cm$^2$</td>
<td>0.003 ± 0.001</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>p-on-n MCz 7.8x10$^{14}$ n$_{eq}$/cm$^2$</td>
<td>0.018 ± 0.006</td>
<td>17 ± 16</td>
<td>-5x10$^{14}$ ± 4x10$^{14}$</td>
<td>0.03 ± 0.02</td>
<td>1100 ± 1600</td>
</tr>
<tr>
<td>p-on-n MCz 1.5x10$^{14}$ n$_{eq}$/cm$^2$</td>
<td>0.014 ± 0.003</td>
<td>22 ± 13</td>
<td>-6x10$^{14}$ ± 4x10$^{14}$</td>
<td>0.018 ± 0.003</td>
<td>500 ± 200</td>
</tr>
</tbody>
</table>
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Czochralski, and Epitaxial Si) [4]. To the extent tested here, the Hamburg Model describes the data well for n- and p-type Fz and MCz materials.

4.10 Conclusion

The depletion voltage data taken from CV measurements versus anneal time for both n- and p-type Fz and p-type MCz indicate that this device carries negative space charge after proton irradiation above $7.8 \times 10^{13}$ MeV n$_{eq}$/cm$^2$ (where n-type Fz undergoes type inversion), while n-type MCz data indicate positive space charge. The devices with negative space charge exhibit a decrease, then an increase, in $V_{fd}$ as anneal time increases. The devices with positive charge exhibit the opposite characteristic.

All the devices invert their behavior in the time interval between 60 and 160 minutes, as inferred from the time constants. This is the first study in which the parameters $g_a, g_Y, \tau_a, \tau_Y$, and $N_c$, have been extracted for n- and p-type Fz and MCz materials irradiated by 800 MeV protons. The introduction rates were found to be consistent for each device type. The short-term time constants are all consistent. The long-term annealing time constants are consistent for each device type. These results are consistent with previous measurements [4].

The coefficients shown in Table 4.8 can be used to predict annealing behavior using Equations 4.6–4.9. Devices fabricated in n- and p-type Fz and p-type MCz Si would show a decrease in depletion voltage over approximately 10 days if kept at 20°C (corresponding to 80 minutes at 60°C) during shut-down periods. The depletion voltage for n-type MCz would not benefit from annealing until after a month of annealing at room temperature.
Chapter 5

Measurements of the Bottom and Charm Production Fractions

5.1 Measurements of the Bottom and Charm Production Fractions with Fully Reconstructed D*± Mesons in ATLAS

The study of D*++ meson production at a center-of-mass energy of 7 TeV at the LHC with the ATLAS detector is identified via its strong decay into a D⁰ and a π⁺ where π⁺ indicates a soft (low transverse momentum) pion, followed by the weak decay D⁰ →K⁻π⁺ (plus the charge conjugate (+cc) of the event*). See Figure 5.1. The D*++ decay is mainly driven by the strong force (to D⁰π⁺ and D⁺π⁰) and decays radiatively less than 2% of the time as shown in Table 5.1. Its intrinsic width is 0.096 ± 0.022 MeV, much smaller than the mass resolution of the ATLAS tracker.

*Unless otherwise stated all references to a specific charge combination imply the charge conjugate combination as well. Specifically, D*⁻⁻ →D⁰(K⁺π⁻)π⁻.
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Figure 5.1: A representation of the decay $D^{*+} \rightarrow D^0 \pi^+$, where $D^0 \rightarrow K^- \pi^+$. The uppermost blue dot represents the parent particle of the $D^{*+}$.

<table>
<thead>
<tr>
<th>$D^{*+}$ decay mode</th>
<th>$\Gamma_i/\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \pi^+$</td>
<td>$(67.7\pm0.5)%$</td>
</tr>
<tr>
<td>$D^+ \pi^0$</td>
<td>$(30.7\pm0.5)%$</td>
</tr>
<tr>
<td>$D^+ \gamma$</td>
<td>$(1.6\pm0.4)%$</td>
</tr>
</tbody>
</table>

Table 5.1: $D^{*+}$ decay modes [6].

For these events, the fraction of $D^{*+}$ mesons that have a bottom particle parent compared to those that are produced promptly at the primary vertex from a charm quark produced directly in the proton-proton interaction was measured using the difference in the shape of the impact parameter distributions.

5.2 Theoretical Motivation

The measurement of the bottom and charm contributions to $D^{*+}$ production where $D^{*+}$ is observed through its decay channel ($D^{*+} \rightarrow D^0 \pi_s^+$, where $D^0 \rightarrow K^- \pi^+$) probes Standard Model physics. It is crucial to understand the SM process of heavy quark
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decay because they are background processes in flagship searches produced by the production of heavy particles, such as the top quark and Higgs particles.

The parton model of the proton or parton distribution function (PDF) describes the probability density of finding various proton constituents, or partons, given the momentum transfer, $Q^2$, and the longitudinal momentum fraction, $x$. It is normalized so that the bound state of the valence quarks is $(uud)$, but it may contain other quark and anti-quark pairs [5]. See Figure 5.2.

![Figure 5.2](image)

Figure 5.2: The parton distribution function (PDF) describes the probability density of finding various proton constituents, or partons, given the momentum transfer, $Q^2$, and the longitudinal momentum fraction, $x$ [5].

The study of the $b$ production fraction may provide information on the $b$-quark PDF, which is the component of the proton structure that is best described as being generated entirely perturbatively [44, 45, 46, 47]. Heavy quark production is dominated by pure QCD processes [48]. At the LHC heavy quark pairs are produced
predominantly by gluon-gluon and gluon-quark processes where the heavy quark is produced by gluon splitting. The gluon-gluon process dominates at the LHC, which is essentially a gluon-gluon collider \cite{49}.\footnote{The gluon carries approximately 42\% of the transverse momentum of the proton at $Q = 1.6$ GeV \cite{49} making gluon-gluon interactions the predominant process in heavy quark production.} The gluon-gluon production processes are shown in Figure 5.3. The cross-section of generic hadron-hadron collisions to a pair of heavy quarks, $H_a + H_b \rightarrow Q\bar{Q} + X$ is calculated using Equation 5.1.

$$\sigma(s) = \sum_{i,j} \int dx_1 \int dx_2 \hat{\sigma}_{ij}(x_1, x_2, s, m^2, \mu^2) f^{H_a}_i(x_1, \mu) f^{H_b}_j(x_2, \mu)$$ \hspace{1cm} (5.1)$$

The cross-section is derived from the parton densities in the colliding hadrons, $f^{H_a}_i$ and $f^{H_b}_j$, and the short distance cross section, $\sigma_{ij}$, where $\mu$ is the renormalization and factorization scale and $x_1$ and $x_2$ are the momentum fractions of the colliding partons \cite{50}. The inclusive production cross-sections of bottom and top as predicted in the ATLAS Technical Design Review (TDR) \cite{49} is shown in Table 5.2. The charm production dominates the bottom production by more than 15 times and contributes to the backgrounds in searches for new particles such as the Higgs that decay into heavy quarks, $H \rightarrow b\bar{b}$. The $gg \rightarrow b\bar{b}$ are also large background for $H \rightarrow b\bar{b}$. Figure 5.4 shows an example of a Higgs $\rightarrow b\bar{b}$ in association with a W boson.

<table>
<thead>
<tr>
<th>Total $\sigma$ predicted for ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$ 500 $\mu$b</td>
</tr>
<tr>
<td>$t\bar{t}$ 590 pb</td>
</tr>
</tbody>
</table>

Table 5.2: Production Cross-sections at LHC for $\sqrt{s} = 14$ TeV.
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Figure 5.3: Examples of QCD processes contributing to direct $b$-quark production at the LHC.

Gluons ($g$) interact with the color field where $q\bar{q}$ pairs are created from the vacuum and eventually produce a cascade of colorless particles. The leading particles (those with a large fraction of the original constituent $q$ or $g$’s momentum) on average keep the same internal quantum numbers as the original quark while other softer particles are created that neutralize the color field. This evolution of a single $q$ to produce a final hadronic particle is called quark fragmentation. It is described by the fragmentation function $D^h_q(z)$ where $z$ is the fraction of energy of the hadron compared to the quark, $z = \frac{E_h}{E_q}$. There is no form of $D^h_q(z)$ derived from first principles, but there are a number of parameterization models for the fragmentation functions. For example
a usual parameterization for light hadrons is

\[ D_i^h(x, \mu_0^2) = N x^\alpha (1 - x)^\beta (1 + \gamma (1 - x)^\delta) \]  \hspace{1cm} (5.2)

where N is the normalization given by

\[ \sum_h \int_0^1 z D_q^h(z) dz = 1 \]  \hspace{1cm} (5.3)

and \( \alpha, \beta, \gamma \) and \( \delta \) depend on the energy scale, \( \mu^2 \), and the type of parton. The functions are then found by fitting to experimental data [51, 6].

Previous measurements of the fragmentation functions for \( c \to D^{*+} \) and/or \( b \to D^{*+} \) were made by ZEUS [52], Belle [53] and LEP1 [54]. After reconstruction of D\( ^{*+} \) the differential cross section \( d\sigma/dx_p \) is measured, where \( x_p \) is the fractional momentum \( x_p = |p_D|/|p_{Max}| \) and \( |p_{Max}| = \sqrt{(s/4) - m_D^2} \) where \( s \) is the square of the center-of-mass energy. Then the chosen form of the fragmentation function can be fit to the data and the parameters extracted. For example, in the more recent Belle
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study, for the widely used Peterson model [55]

\[
D_{e}^{D^{*+}}(z) = N \frac{1}{z} (1 - \frac{1}{z} - \frac{\epsilon_{c}}{1 - z})^{-2}
\]  

(5.4)

where \(z\) = the fraction of longitudinal energy \(E + p_{||}\) that the \(D^{*+}\) inherits from the initial charm quark, the value found for \(\epsilon_{c} = 0.054\) [53].

Different fragmentation models are used in different Monte Carlo (MC) event generators. The two most popular models are string fragmentation and cluster fragmentation. String fragmentation is used in PYTHIA [56] (used in this analysis) and JETSET [56]. The string fragmentation model considers the color field between the quark and gluon as the source of fragmentation rather than the actual partons. As two colored partons move apart, the energetic gluons are considered kinks on the string. When the string has enough energy a \(q\bar{q}\) pair can be created from the vacuum. Cluster fragmentation is used by the HERWIG [57] MC generator. It assumes a local compensation of color based on perturbative QCD and then the leftover gluons are split non-perturbatively into \(q\bar{q}\) pairs. However, since there is no theory to drive the form of the fragmentation functions used in both MC generators, they rely heavily on experimental data. Insight into the fragmentation models for bottom and charm to the \(D^{*+}\) hadron can improve these MC event generators as well as our understanding of the fragmentation process.

The fractions used in the ATLAS \(D^{*+}\) study [58] to make NLO QCD predictions using POWHEG-HERWIG [57] are shown in Table 5.3. The fractions were obtained from a combination of LEP [59] ALEPH [60] and OPAL [61] measurements.
Chapter 5. Measurements of the Bottom and Charm Production Fractions

\[
\begin{array}{|c|c|}
\hline
\text{fraction} & \\
\hline
f(c \to D^{\pm}) & 0.235 \pm 0.007 \pm 0.003 \\
\hline
f(b \to D^{\pm}) & 0.175 \pm 0.020 \pm 0.001 \\
\hline
\end{array}
\]

Table 5.3: Fractions of b and c hadronizing to D^{\pm}.

5.3 Strategy

The mass difference quantity \( \Delta M = M(K^-\pi^+\pi_s^+) - M(K^-\pi^+) = \Delta M(D^{\ast^+},D^0) \) was reconstructed. The resolution of the \( D^0 \to K\pi \) cancels out most of the systematic uncertainties such as the mass scale leaving the measurement sensitive to the \( \pi_s \) resolution. This provides an excellent method for selecting signal events combined with the \( D^0 \) mass distribution for selecting the signal and sidebands.

The \( D^0 \) meson impact parameter distribution was used to differentiate the contributions from the prompt (charm) component (where \( D^{\ast^+} \) was produced at the primary vertex) and the bottom component (where there was first a B meson that decayed into a \( D^{\ast^+} \)). In the case of the bottom fraction, a B meson flew some distance from the primary vertex so that the impact parameter of the \( D^0 \) meson was greater than the \( D^0 \) impact parameter from a promptly produced \( D^{\ast^+} \) as shown in Figure 5.5. The impact parameter is defined as the signed minimal distance between the \( D^0 \) transverse momentum vector and the primary vertex:

\[
d_{D^0} = (\text{sign}) \left| \frac{D_{xy} \times \vec{p}_T}{p_T} \right| \quad (5.5)
\]

where \( D_{xy} \) is defined as the distance between the \( D^0 \) vertex and the primary vertex in the xy (transverse) plane and the z-axis is defined along the beam line. A list of geometrical reference quantities is found in the Appendix.

The prompt \( d_{D^0}^0 \) impact parameter distribution was solely determined by the
5.4 Event Reconstruction

The first step in the analysis of the bottom and charm fractions was to reconstruct the event. This was done using the ATLAS Athena analysis platform. The code was
then applied to specific data samples either locally (if the data sample was small) or on the ATLAS computing Grid. Loose selection criteria were used for the first phase of reconstruction.

5.4.1 Data Samples

Two event samples were used for this analysis. The first was a Monte Carlo sample that was enriched with charm events, specifically $D^{*+}$, $D^0$, $D^+$, $D_S^+$, etc. decays. The sample was generated using the Pythia 6.4 MC Generator and then underwent a full simulation of the ATLAS detector using the ATLAS simulation based on GEANT4. Finally, the MC events were reconstructed using the same program that was used for data [58]. There were 2 million events produced with bunch train pile-up in this sample. The sample name was: mc10_7TeV.108532.PythiaB_cbmsel1_ChHadr.merge.AOD.e654_s933_s946_r1830_r2040.

The second event sample consisted of Minimum Bias events where one of the two Minimum Bias Trigger Scintillators (MBTS) detected a particle track. See Figure 5.6. The data were collected in 2010 with 7 TeV center-of-mass proton beams. A Good Run List (GRL) from the B Physics Tracking was used to select the relevant data runs for a total luminosity of $1.1 \text{ nb}^{-1}$. GRLs, compiled by the Data Quality Monitoring (DQM) group, include only events (using run and luminosity block numbers) that were taken under good conditions as determined by sub-detector and trigger performance. There are over 100 Data Quality status flags from each sub-detector as well as combined performance groups. These flags can be red (bad), yellow (caution), and green (good). Each flag represents the performance of a component of the sub-detector such as operation voltage, temperature, humidity, etc. and are created automatically online. There is also an offline analysis of the DQ flags by DQ experts before each luminosity block is considered good.
5.4.2 Reconstruction of $D^{*+}$ and $D^0$

Reconstruction in Athena

The first reconstruction of events was done using ATLAS Athena software version 16.0.3. Loose selection criteria were implemented to allow room for optimization in the offline ROOT analysis where the final selection criteria were used.

The track requirements in the final selection of $D^{*+}$ candidates were based on Inner Detector hits and transverse momentum, $p_T$. For each track there must be at least one Pixel hit and 4 SCT hits. The track transverse momentum must be greater
Chapter 5. Measurements of the Bottom and Charm Production Fractions

than 1 GeV for the kaon and pion tracks coming from the $D^0$ decay, while the soft pion from the $D^{*+}$ must only have $p_T > 250$ MeV. These were based on previous analyses [58]. The strategy took into consideration keeping enough candidates to optimize selection cuts while balancing the size of the output ntuples.

To find $D^0$'s, a collection of tracks was made to input into the vertex reconstruction. The only requirements for these tracks was to have pseudorapidity, $|\eta| < 2.7$ (corresponding to an area just larger than the barrel region) and one hit in the Pixel or SCT. This collection of tracks was then used for the $D^0$ and $D^{*+}$ reconstruction.

The selection of tracks was further sorted into track pair candidates ($K^-\pi^+$) where all pairs of oppositely charged tracks were considered and loose cuts were applied. These requirements were that a vertex existed for the track and it was not from a pile-up event; $p_T > 700$ MeV; there was at least one Pixel and one SCT hit; and the mass of the two tracks combined calculated from the energy and momentum of each track was between 1550 and 2250 MeV. These track pairs were then input into the VKalVrtFitter taken from the BPhysAnalysisTools package [62]. The VKalVrtFitter was based on the VKalVrt package [63] that uses the Kalman method [64] from statistics and can deal with hundreds of particle tracks. The tool fits a single vertex using a mass constraint hypothesis and returns a $\chi^2$ value on the quality of the fit. All the candidate $D^0$ vertex and track information from the VKalVrtFitter that produces a result with the $D^0$ mass $> 0$, a $\chi^2$ of the vertex fit less than 15 and $L_{xy} > -1$ (loose cuts chosen to reduce run time without rejecting good candidates) were passed on to the $D^{*+}$ reconstruction.

The reconstruction of the $D^{*+}$ used the CascadeFitter also found in the BPhysTools [62], again based on the VKalVrt package [63]. In this case soft pion track candidates that pass loose selection criteria similar to those of the $K^-\pi^+$ (track vertex exists for the track, track vertex is not from a pile-up event, $p_T > 150$ MeV, at least one Pixel and one SCT hit, $m(D^{*+}) - m(D^0)$ mass calculated from tracks is less
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than 176 MeV, \( p_T^{D^*\pm} > 2.8 \) GeV, and \( |\eta_{D^*\pm}| < 2.7 \) were paired with a reconstructed \( D^0 \) vertex and fed into the CascadeFitter, which was based on the VKalVrtFitter for multiple vertices. \( D^{*+} \) CascadeFitter vertex candidates that have \( \chi^2 < 30 \), \( D^0 \) mass between 1.6 and 2.2 GeV, and \( \Delta M(D^{*+},D^0) \) mass difference less than 176 MeV were written to a ROOT ntuple for further offline analysis.

Final Selection Cuts in ROOT

The final selection cuts used in the offline analysis in ROOT for the \( D^{*+} \) and \( D^0 \) selection were based on those used in the \( D^{*+} \) cross-section note [58]. The candidate events were chosen to be reconstructed in the same \( p_T \) and \( \eta \) range as in the ATLAS \( D^{*+} \) study [58]. The cuts on Pixel and SCT hits as well as track \( \eta \) were selected to ensure good tracking efficiency and resolution. The rest of the cuts were selected to reduce the background. The cuts on \( \sum p_T^{D^{*+}} \) and \( \sum p_T^{D^0} \) (where \( i \) runs over the primary vertex tracks) took advantage of the hard nature of charm fragmentation and greatly reduced the combinatorial background. More than 99% of \( D^{*+} \)'s passed these criteria [58]. The cuts related to the transverse momentum and decay angles were optimized in Monte Carlo for the ATLAS \( D^{*+} \) study [58] and utilized here. The final selection cuts were:

- \( K^-, \pi^+, \pi_s^+ \) Pixel hits \( \geq 1 \)
- \( K^-, \pi^+, \pi_s^+ \) SCT hits \( \geq 4 \)
- \( |p_T(K^-, \pi^+)| > 1 \) GeV
- \( |p_T(\pi_s^+)| > 250 \) MeV
- \( p_T(D^{*\pm}) > 3.5 \) GeV
- \( |\eta(K^-, \pi^+, \pi_s^+)| < 2.5 \)
- \( |\eta(D^{*\pm})| < 2.1 \)
- \( D^0 \) vertex \( \chi^2 < 5 \)
- \( D^{*\pm} \) vertex \( \chi^2 < 20 \)
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- \( z_0(D^0) \sin \theta_{D^0} \leq 2 \text{ mm} \), where \( z_0 \) is the longitudinal impact parameter
- \(-0.5 \text{ mm} \leq d_0^\pi \leq 2.0 \text{ mm}\)
- \( \frac{p_T^{D^{*+}}}{\sum E_T} \geq 0.02 \)
- \( \frac{p_T^{D^{*+}}}{\sum p_{T_i}} \geq -0.06 \), where \( i \) runs over the primary vertex tracks
- \( p_T^K > p_T^\pi \)

For \( D^* \) and \( \Delta M(D^{*+},D^0) \) selection only:
- \( 1820 \text{ MeV} < D^0 \) vertex mass < \( 1910 \text{ MeV} \)

For \( D^0 \) mass only:
- \( 1710 \text{ MeV} < D^0 \) vertex mass < \( 2020 \text{ MeV} \)
- \( |M(K\pi\pi) - M(K\pi)| < 2\sigma \)

\( \Delta M(D^{*+},D^0) \)

In the offline ROOT analysis the first step was to plot the \( \Delta M(D^{*+},D^0) \) spectrum using the cuts listed above. The distribution was then fit with a binned likelihood fit:

\[
\mathcal{L}(\theta|x_i) = p_\theta(x_i) = \prod_{i=1}^{n} f(x_i|\theta) \tag{5.7}
\]

where the likelihood, \( \mathcal{L} \), is defined as the probability distribution, \( p \), depending on a parameter, \( \theta \). The fit maximizes the likelihood function or minimizes \( -2\ln \mathcal{L} \) using several probability density functions (PDF), \( f(x_i|\theta) \), that describe the model of the data spectra under the fit. For example, a fit to data with a gaussian function PDF; a free variable, \( \theta \); and observed variables, \( x_i \), corresponding to the mean and width give fitted values for the mean and width where \( -2\ln \mathcal{L} \) is minimized. The \( \Delta M(D^{*+},D^0) \)
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distribution was modeled using a modified gaussian for the signal peak and a threshold function for the background as was done in the ATLAS D* study [58]. The modified gaussian had a PDF of the form:

\[ f(x) = e^{-0.5x(1 + \frac{1}{1+0.5x})} \]  

(5.8)

where \( x = \frac{\Delta M - \Delta M_0}{\sigma} \) and \( \Delta M_0 \) is the mean value of the \( \Delta M \) peak. The threshold function had a PDF of the form:

\[ f(\Delta M) = A \cdot (\Delta M - 0.13957)^B \cdot e^{C \cdot (\Delta M - 0.13957)} \]  

(5.9)

where A, B, and C are variables in the fit and 0.13957 is the (soft) pion mass value in GeV from the Particle Data Group (PDG) [6]. This modified gaussian distribution was found to fit better than a regular gaussian function and was used in the ATLAS D* study [58].

The \( \Delta M(D^{*+},D^0) \) plot is shown in Figure 5.7. The value from the mean of the modified gaussian peak was found to be \( 145.47 \pm 0.01 \) (stat.) MeV from Monte Carlo data and \( 145.41 \pm 0.06 \) (stat.) MeV from Minimum Bias data compared to \( 142.13 \pm 0.21 \) MeV for the PDG value and \( 145.41 \pm 0.03 \) MeV for the ATLAS D* study [58]. While there is still room for improvement in the fits, this indicates that a proper selection of \( D^{*+} \) and \( D^0 \) candidates was made.

**D*+ Mass**

Similarly the \( D^{*+} \) mass was plotted given the same selection criteria as the \( \Delta M(D^{*+},D^0) \) plot shown in Figure 5.8 and fit using a binned likelihood fit. The fitted \( D^{*+} \) mass was \( 2010 \pm 11 \) (stat.) MeV from Monte Carlo data using a modified gaussian plus exponential function for signal and background. The Minimum Bias
data were fit with a gaussian plus second order Chebychev polynomial and the fitted
values were $2010 \pm 2$ (stat.) MeV for the mass and $\chi^2=0.96$. The PDG value is
$2006.93 \pm 0.16$ MeV.

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{fig5_7a}
\includegraphics[width=0.4\textwidth]{fig5_7b}
\caption{$\Delta M(D^{*+},D^{0})$ on Monte Carlo (left) and Minimum Bias (right) data.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{fig5_8a}
\includegraphics[width=0.4\textwidth]{fig5_8b}
\caption{$D^{*+}$ Mass on Monte Carlo (left) and Minimum Bias (right) data.}
\end{figure}

**$D^{0}$ Mass**

The final selection criteria used for the $D^{0}$ were the same as the $D^{*+}$ selection cuts
above, except the $D^{0}$ mass window was widened to $1710$ MeV $< D^{0}$ mass $< 2020$
MeV while also narrowing the $\Delta M(D^{*+},D^{0})$ window to $|M(K\pi\pi) - M(K\pi)| < 2\sigma$.
The resulting mass distribution for the reconstructed $D^{0}$ on 2010 7 TeV Minimum
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Bias Data is shown in Figure 5.9. The data were fit using a binned likelihood fit in the form of a modified gaussian signal and exponential background for the MC data as described in Equation 5.8 substituting the $D^0$ mass for $\Delta M(D^{*+},D^0)$, so that

$$x = \frac{|M_{D^0} - M_0|}{\sigma}$$

where $M_0$ is the mean value of the $D^0$ mass peak. The Minimum Bias data were fit using a gaussian for the signal plus a second order Chebychev polynomial for the background.

The $D^0$ mass value from the fit to the signal peak was $1865.1 \pm 0.1$ (stat.) MeV with a $\chi^2/dof = 6.3$ for Monte Carlo data and $1865 \pm 2$ (stat.) MeV on Minimum Bias data with a $\chi^2/dof = 0.98$. The Particle Data Group (PDG) value that is the current world standard is $1864.80 \pm 0.14$ (stat. + sys.) MeV. The value reported in the ATLAS $D^{*+}$ study [58] was $1866.1 \pm 1.3$ (stat. + sys.) MeV. This indicates that the reconstruction of the $D^0$ is in agreement with previous studies and provides a good sample for the $D^0$ impact parameter fit.

Figure 5.9: $D^0$ mass distribution on Monte Carlo (left) and Minimum Bias (right) data.
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<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass [MeV]</th>
<th>Width [MeV]</th>
<th>Fit $\chi^2$/dof</th>
<th>Fit Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC $\Delta M(D^{*-},D^0)$</td>
<td>145.47±0.01</td>
<td>0.612±0.007</td>
<td>1.70</td>
<td>modified gaussian + threshold function</td>
</tr>
<tr>
<td>MB $\Delta M(D^{*-},D^0)$</td>
<td>145.41±0.06</td>
<td>0.79±0.05</td>
<td>1.24</td>
<td>modified gaussian + threshold function</td>
</tr>
<tr>
<td>MC $D^{**}$</td>
<td>2010±11</td>
<td>17±10</td>
<td>4.6</td>
<td>gaussian + exponential</td>
</tr>
<tr>
<td>MB $D^{**}$</td>
<td>2010±2</td>
<td>22±3</td>
<td>0.96</td>
<td>gaussian + chebychev</td>
</tr>
<tr>
<td>MC $D^0$</td>
<td>1865.1±0.1</td>
<td>16.6±0.2</td>
<td>6.3</td>
<td>modified gaussian + exponential</td>
</tr>
<tr>
<td>MB $D^0$</td>
<td>1865±2</td>
<td>22±2</td>
<td>0.98</td>
<td>gaussian + chebychev</td>
</tr>
</tbody>
</table>

Table 5.4: Mass fit values.

5.5 Charm Fraction Fitting Method

The impact parameter data of the $D^0$ were used to extract the charm fraction. The final signal selection of the $d_0^{D^0}$ was fit using:

$$f(d_0^{D^0}) = (1 - f_c)F_b \otimes F_D + f_cF_D$$  \hspace{1cm} (5.10)

where $f_c$ is the final charm fraction, and $F_b$ is the ideal bottom fraction distribution of the $D^0$ impact parameter, and $F_D$ is the detector resolution. The contribution of the charm fraction was modeled by the detector resolution since the ideal prompt $D^0$ has an impact parameter of zero (delta function) at the generator level. See Figure 5.10. Since the $D^{**}$ decays directly at the primary vertex, so that the $D^0$, which travels some distance from the primary vertex (average lifetime 122.9 $\mu$m), points back to the primary vertex as illustrated in Figure 5.5. The bottom fraction $(1-f_c)$ is determined by the ideal (generator level) $b \rightarrow D^* \rightarrow D^0(K^-\pi^+)\pi_s^+$ distribution convolved with the detector resolution.
Figure 5.10: The generator level (green star) and reconstructed level (pink circle) D⁰ impact parameter.

5.5.1 Detector Resolution

Selection of Prompt Signal From Monte Carlo

The prompt D⁰ impact parameter distribution data were taken from the reconstructed D⁺⁺ →D⁰(K⁻π⁺)π⁺ candidates where all the reconstructed tracks (K⁻, π⁺, π⁺) match tracks in truth from a D⁺⁺ →D⁰(K⁻π⁺)π⁺ decay. The barcodes of the reconstructed tracks and truth tracks were required to be identical confirming that the reconstructed tracks originate from a true D⁺⁺ →D⁰(K⁻π⁺)π⁺ event.

To determine if the D⁺⁺ was prompt or from a B particle decay, two methods were examined. The first simply checked for a b-quark anywhere in the same event by
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checking the PDG identification code of all particles in the events. The second method checked directly the parent particles of the D\(^*\). To include events where a B particle decays to an excited charm state before decaying into D\(^*\), all parent, grandparent, and great-grandparent particles of the D\(^*\) were examined. A comparison of the two tagging methods for the reconstructed level D\(^0\) impact parameter is shown in Figure 5.11.

![Figure 5.11: A comparison of the reconstructed level D\(^0\) impact parameter for both of the two tagging methods is shown. The B parent method checked the parent, grandparent, and great-grandparents of the D\(^*\) for any bottom particle. The b-quark method searched for a b-quark present anywhere in the event.](image)

The final selection of events for the detector resolution function, \(F_D\), was taken from the events where the reconstructed tracks matched the true tracks from D\(^{*+}\) → D\(^0\)(K\(^-\)π\(^+\))π\(^+_\) and there were no B parents or b-quarks in the event. These selection criteria gave the purest sample of reconstructed prompt D\(^{*+}\) events (where
there is no $b$-quark anywhere in the event).

**Fit Selection for the Prompt Signal**

Several functional forms were investigated to optimize the fit. Several forms of gaussian, modified gaussian, and exponential functions were examined:

- single gaussian: $F_D(d_0) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(d_0-m)^2}{2\sigma^2}}$
- double gaussian: $F_D(d_0) = f_1\frac{1}{\sqrt{2\pi}\sigma_1} e^{\frac{(d_0-m)^2}{2\sigma_1^2}} + (1-f_1)\frac{1}{\sqrt{2\pi}\sigma_2} e^{\frac{(d_0-m)^2}{2\sigma_2^2}}$
- gaussian+exponential: $F_D(d_0) = f_g\frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(d_0-m)^2}{2\sigma^2}} + (1-f_g)\frac{1}{2\lambda} e^{-\frac{|d_0|}{\lambda}}$
- modified gaussian: $F_D(d_0) = e^{-0.5\left|\frac{(d_0-m)}{\sigma_m}\right|^2}\left(\frac{1}{1+0.5\left|\frac{(d_0-m)}{\sigma_m}\right|^2}\right)$
- gaussian + modified gaussian: $F_D(d_0) = (1-f_m)\frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(d_0-m)^2}{2\sigma^2}} + f_m e^{-0.5\left|\frac{(d_0-m)}{\sigma_m}\right|^2}\left(\frac{1}{1+0.5\left|\frac{(d_0-m)}{\sigma_m}\right|^2}\right)$

Table 5.5 shows the fit results for each function that was tested using a binned likelihood fit and 20 $\mu$m bin size. The double gaussian function:

$$F_D(d_0) = f_1\frac{1}{\sqrt{2\pi}\sigma_1} e^{\frac{(d_0-m)^2}{2\sigma_1^2}} + (1-f_1)\frac{1}{\sqrt{2\pi}\sigma_2} e^{\frac{(d_0-m)^2}{2\sigma_2^2}} \tag{5.11}$$

was selected for the final detector resolution function due to the best $\chi^2/dof$ value with an accurate error matrix for the fit (where the error matrix converged).

The final fit to the selected prompt signal is shown in Figure 5.12. The final values for the fit were $m = -0.0009 \pm 0.0006$ (stat.) mm, $\sigma_1 = 0.068 \pm 0.003$ (stat.) mm, $\sigma_2 = 0.028 \pm 0.001$ (stat) mm, and $f_1 = 0.32 \pm 0.04$ (stat) with $\chi^2/dof = 2.3$. (These are different from the values listed in Table 5.5 because the $D^0$ impact parameter signal data were chosen within 2$\sigma$ of the $\Delta M(D^{*+},D^0)$ and $D^0$ mass peaks. This
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<table>
<thead>
<tr>
<th>Fit Function</th>
<th>Fit Values</th>
</tr>
</thead>
</table>
| single gaussian      | $m = 0.00 \pm 0.02$  
$\sigma = 0.048 \pm 0.003$  
$\chi^2/dof = 9.9$                                                                 |
| double gaussian      | $m = 0.0007 \pm 0.0006$  
$\sigma_1 = 0.073 \pm 0.003$  
$\sigma_2 = 0.030 \pm 0.001$  
$f_1 = 0.27 \pm 0.04$  
$\chi^2/dof = 2.3$                                                                 |
| gaussian + exponential | $m = 0 \pm 1$  
$\sigma = 0.0 \pm 0.5$  
$\lambda = 0.0320 \pm 0.0005$  
$f_g = 0.00 \pm 0.03$  
$\chi^2/dof = 1.87$  
*Error Matrix not positive definite                                                                 |
| modified gaussian    | $m = 0.00 \pm 0.02$  
$\sigma = 0.027$  
$\chi^2/dof = 0.6$                                                                 |
| modified gaussian + gaussian | $m = 0.0 \pm 0.3$  
$\sigma = 0 \pm 30,000$  
$\sigma_m = 0.027 \pm 0.000$  
$f_m = 1 \pm 0.00$  
$\chi^2/dof = 0.6$  
*Error Matrix not positive definite                                                                 |

Table 5.5: The fit values for different fits of the detector resolution, $F_D$, are listed. Note: These values were taken with fixed $D^0$ mass selection (1820 to 1910 MeV) instead of within $2\sigma$ of the $D^0$ mass peak procedure used in the rest of the analysis. This yielded a different selection for the signal region and sideband regions as discussed in Section 5.5.3 leading to a slightly different set of events that were fit.

yielded a different selection for the signal region and sideband regions as discussed in Section 5.5.3 leading to a slightly different set of events that were fit.)

5.5.2 Ideal Bottom Fraction Distribution

The bottom contribution to the $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+_s$ events required generator level Monte Carlo information to make an ideal distribution of the impact parameter. The ideal $b$ distribution was then convolved with the detector resolution function to form the bottom fraction contribution to the total $D^0$ impact parameter distribution. The
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Figure 5.12: The final selection of reconstructed prompt D⁰ impact parameter signal fitted by a double gaussian function to extract the detector resolution function.

collection of ideal b events had the true decay chain D^{*+} \rightarrow D⁰(K^−π^+)π^+_s; a B meson parent, grandparent, or great-grandparent for the D^{*+}; a b-quark in the event; and passed the same cuts used in the D⁰ reconstruction. The bottom parents were defined as being any of the following particles and their anti-particles: B⁰, B^+, B^{*0}, B^{*+}, B^{*_0}, B^{*_+}, B_c.

The impact parameter of the ideal b collection was then fit in ROOT using a binned likelihood fit and bin size of 20 μm. Two forms of exponential functions were studied: a single exponential:

\[ f(d_0) = \frac{1}{2\lambda_1} e^{-\frac{|d_0|}{\lambda_1}} \]  \hspace{1cm} (5.12)

and a double exponential:

\[ f(d_0) = \frac{\epsilon_1}{2\lambda_1} e^{-\frac{|d_0|}{\lambda_1}} + \frac{1 - \epsilon_1}{2\lambda_2} e^{-\frac{|d_0|}{\lambda_2}} \]  \hspace{1cm} (5.13)
where all $\epsilon$ and $\lambda$ values were free parameters. A comparison of the fit results is shown in Table 5.6.

<table>
<thead>
<tr>
<th>Fit Function</th>
<th>Fit Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>single exponential</td>
<td>$\lambda = 0.092 \pm 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2/dof = 1.16$</td>
</tr>
<tr>
<td>double exponential</td>
<td>$\lambda_1 = 0.116 \pm 0.005$</td>
</tr>
<tr>
<td></td>
<td>$\lambda_2 = 0.01 \pm 0.001$</td>
</tr>
<tr>
<td></td>
<td>$\epsilon_1 = 0.77 \pm 0.02$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2/dof = 0.495$</td>
</tr>
</tbody>
</table>

Table 5.6: The fit values for two types of exponential functions are shown for the ideal $b$ distribution, $F_b$. Note: These values were taken with fixed $D^0$ mass selection (1820 to 1910 MeV) instead of within $2\sigma$ of the $D^0$ mass peak procedure used in the rest of the analysis. This yielded a different selection for the signal region and sideband regions as discussed in Section 5.5.3 leading to a slightly different set of events that were fit.

The single exponential optimizes the $\chi^2/dof$ of the $F_b$ fit and requires the fewest free parameters. It was selected for the final form of the $F_b$ fit with $\lambda = 0.092 \pm 0.003$ (stat.) mm. See Figure 5.13.

5.5.3 Impact Parameter Signal Selection

The final $D^0$ signal selection for the charm fraction fit was made by first selecting $D^0$ candidates within $2\sigma$ of the mean $\Delta M(D^{*+},D^0)$ value (using the modified gaussian fit described previously) as shown in Figure 5.14. The $\Delta M(D^{*+},D^0)$ candidates had $D^0$ mass in the range 1820 to 1910 MeV. This $D^0$ mass window was then widened to $1710 \text{ MeV} < D^0$ vertex mass $< 2020 \text{ MeV}$ along with the $\Delta M(D^{*+},D^0)$ within $2\sigma$ of the mean in order to have a $D^0$ mass distribution with unbiased sidebands. Then the $D^0$ signal events were selected within $2\sigma$ of the mean and the sidebands between $3\sigma$ and $5\sigma$ using the fit described previously in Equation 5.8. See Figure 5.15.
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Figure 5.13: The generator level $D^0$ impact parameter distribution for ideal $b$ events.

The difference in the $D^0$ impact parameter distributions of the signal and sideband collections is shown in Figure 5.16.

The background contribution to the signal region was then calculated and the corresponding weight of the sidebands was subtracted from the signal events. This collection of events with the $D^0$ sidebands subtracted was used for the final signal collection in the charm fraction fit. The final sideband subtracted signal selection statistically removes the background contribution to the $d_{D^0}$ distribution.

5.5.4 Charm Fraction Fitter

After the detector resolution and ideal $b$ functions were determined, the final fit for the charm fraction was performed on the $D^0$ impact parameter data (with sidebands subtracted) in ROOT. The fit was done using a binned likelihood function where the statistical errors were calculated using the sum of the squares of the weights since
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Figure 5.14: The $|M(K\pi\pi) - M(K\pi)|$ is shown for the standard cuts (solid black circles) as in Figure 5.7. The events selected for the $D^0$ mass plot in Figure 5.15 (open teal circles) were within $2\sigma$ of the mean and the $D^0$ mass cut loosened (in order to obtain the sideband events).

The final distribution was the difference of two histograms.

The $D^0$ impact parameter detector resolution, $F_D$, given in Equation 5.11 had $m = -0.0009$ mm, $\sigma_1 = 0.068$ mm, $\sigma_2 = 0.028$ mm, and $f_1 = 0.32$ fixed for the final charm fraction fit. The ideal $b$ contribution to the $D^0$ impact parameter distribution was completely fixed ($\lambda = 0.092$ mm) from the fit to the generator level $b \to D^{*+}$ events.

The results of the charm fraction extraction from Monte Carlo data (of the sideband subtracted $D^0$ impact parameter signal) are shown in Figure 5.17. The fitted fraction found was $97\% \pm 21\%$ (stat.). The $\chi^2$/d.o.f was 0.87. The charm fraction
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Figure 5.15: The $D^0$ mass signal (red triangles) and sideband (green squares) region selections are shown for Minimum Bias data.

from truth applying all the same cuts as in the reconstruction (using only the B parent tag) was 96.4%.

<table>
<thead>
<tr>
<th></th>
<th>$f_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Data</td>
<td>$97% \pm 21%$ (stat.)</td>
</tr>
<tr>
<td>MC Truth</td>
<td>$96.4%$</td>
</tr>
</tbody>
</table>

Table 5.7: Charm fraction results on MC.

5.5.5 Systematic Errors

The systematic errors for the charm fraction fit are listed in Table 5.10. The error from the choice of fit for each $F_D$ and $F_b$ was determined by the spread in charm fraction values associated with choice of fitting function. The double gaussian yielded
a charm fraction of 97.1%. The single gaussian result was $f_c=95.7\%$ and the modified gaussian and the gaussian plus modified gaussian fits both had $f_c=98.0\%$. The total spread is therefore $\pm 1.4\%$.

The bin size also affected the final value of the charm fraction fit. For the selected functions of $F_D$ and $F_b$ bin sizes of 10, 20 and 40 $\mu$m were sampled. In all cases, a 20 $\mu$m bin size was used in each final fit chosen due to the best $\chi^2/dof$ value. The spread was determined in each case.

In the case of the signal selection range, the signal range from the $\Delta M(D^{*+},D^0)$ and $D^0$ mass was widened from $2\sigma$ to $3\sigma$. The difference from the measured value was taken as the error.
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Figure 5.17: Charm fraction fit on $D^0$ impact parameter signal MC data (with sidebands subtracted).

The statistical errors for $F_D$ and $F_b$ were propagated to the charm fraction. This was determined by altering the fixed fit values of both $F_D$ and $F_b$ by one $\sigma$ of the total statistical error and determining the spread from the measured value of the charm fraction.

The tracking resolution error and the primary vertex error were determined from previous ATLAS studies. The primary vertex position error was $10 \, \mu m$ [65]. The error of the track impact parameter resolution was $22 \, \mu m$ [66]. These errors are not listed in the systematic error since their resolution errors are absorbed by the systematic errors already listed.

The systematic errors were then added in quadrature to calculate the total systematic error. The systematic errors are much smaller than the statistical error in the charm fraction fit.
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<table>
<thead>
<tr>
<th>Fit Parameter</th>
<th>$f_c$ Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_b$: $\lambda - 1\sigma$</td>
<td>0.087%</td>
</tr>
<tr>
<td>$F_b$: $\lambda + 1\sigma$</td>
<td>0.083%</td>
</tr>
<tr>
<td>$F_D$: $m - 1\sigma$</td>
<td>0.03%</td>
</tr>
<tr>
<td>$F_D$: $m + 1\sigma$</td>
<td>0.03%</td>
</tr>
<tr>
<td>$F_D$: $\sigma_1 - 1\sigma$</td>
<td>0.108%</td>
</tr>
<tr>
<td>$F_D$: $\sigma_1 + 1\sigma$</td>
<td>0.059%</td>
</tr>
<tr>
<td>$F_D$: $\sigma_2 - 1\sigma$</td>
<td>0.103%</td>
</tr>
<tr>
<td>$F_D$: $\sigma_2 + 1\sigma$</td>
<td>0.088%</td>
</tr>
<tr>
<td>$F_D$: $f_1 - 1\sigma$</td>
<td>0.17%</td>
</tr>
<tr>
<td>$F_D$: $f_1 + 1\sigma$</td>
<td>0.112%</td>
</tr>
<tr>
<td>Total Systematic Error:</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Table 5.8: $F_D$ and $F_b$ fit parameter statistical errors propagated to charm fraction.

<table>
<thead>
<tr>
<th>ATLAS Error Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary vertex</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>track $d_0$</td>
<td>22 $\mu$m</td>
</tr>
<tr>
<td>$\sigma/pt$</td>
<td>$3.8 \times 10^{-4} pt$ GeV $\pm 0.015$ GeV</td>
</tr>
</tbody>
</table>

Table 5.9: ATLAS error sources.

Table 5.10: Charm Fraction Fit Systematic Errors

<table>
<thead>
<tr>
<th>Error Source</th>
<th>$f_c$ Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice of $F_D$ Fit</td>
<td>1.4%</td>
</tr>
<tr>
<td>Choice of $F_b$ Fit</td>
<td>0.5%</td>
</tr>
<tr>
<td>$F_D$ Bin Size</td>
<td>1%</td>
</tr>
<tr>
<td>$F_b$ Bin Size</td>
<td>0.0%</td>
</tr>
<tr>
<td>Choice of Signal Selection Range</td>
<td>0.5%</td>
</tr>
<tr>
<td>Statistical Errors Propagated to $f_c$</td>
<td>0.3%</td>
</tr>
<tr>
<td>Total Systematic Error:</td>
<td>0.8%</td>
</tr>
</tbody>
</table>
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5.6 Bottom and Charm Fraction Results

5.6.1 Minimum Bias Data Results

The final selection of functions and fit values for $F_b$ and $F_D$ were fixed from Monte Carlo data. The detector resolution was fixed as a double gaussian as in Equation 5.11. The final values for the fit were $m = -0.0009$ mm, $\sigma_1 = 0.068$ mm, $\sigma_2 = 0.028$ mm, and $f_1 = 0.32$. The ideal $b \rightarrow D^{**}$ was modeled by a single exponential as in Equation 5.12 with $\lambda = 0.092$ mm. After the fits and their parameters were fixed the final sideband subtracted $D^0$ impact parameter signal distribution was fit with the overall form of $f(d_0^{D^0}) = (1 - f_c)F_b \otimes F_D + f_cF_D$.

The result of the charm fraction analysis on 2010 7 TeV Minimum Bias data is shown in Figure 5.18. The final charm fraction was $96\% \pm 18\%$ (stat.) $\pm 0.8\%$ (sys.) with a $\chi^2/dof=1.77$, hence a $b$ fraction of $4\% \pm 18\%$ (stat.) $\pm 0.8\%$ (sys.). The central value of the result was within a few percent of the expected value from Monte Carlo, well within the uncertainty.

<table>
<thead>
<tr>
<th></th>
<th>$f_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Bias Data</td>
<td>$96% \pm 18%$ (stat.) $\pm 0.8%$ (sys.)</td>
</tr>
<tr>
<td>MC Data</td>
<td>$97% \pm 21%$ (stat.)</td>
</tr>
</tbody>
</table>

Table 5.11: Charm fraction results on MC and $\sqrt{s}= 7$ TeV Minimum Bias Data.

The measured charm fraction is very high. Although comparable to the truth value, the corresponding $b$ fraction is very low and spans to 0% within the given error. Much higher statistics are necessary to decrease the error to measure a statistically significant $b$ fraction. The Minimum Bias trigger data set is no longer being used (at any significant rate). Another trigger selection is needed to increase statistics and bias the selection of events to yield a higher $b$ fraction.
Chapter 5. Measurements of the Bottom and Charm Production Fractions

Figure 5.18: Charm fraction fit on final D⁰ impact parameter signal selection with Minimum Bias data.

5.6.2 Future Work

The statistical errors associated with the Minimum Bias data sample are large. It would benefit the analysis to apply this method of the charm fraction fit to larger data samples that are (necessarily) enriched with b →D*⁺ events by selecting the di-muon trigger or high p_T jet events.

5.6.3 Comparison to CDF Results

The direct charm production was previously investigated by CDF [67] for the D*⁺ channel. The ratio of b/c fractions to D*⁺→D⁰π⁺, where D⁰→K⁻π⁺ was measured using the impact parameter in a similar method to that presented here. The main difference between this analysis and the CDF analysis relates to the derivation of F_D. CDF reconstructed K s⁰ → π⁺π⁻ and used the impact parameter of the K s⁰ to
Chapter 5. Measurements of the Bottom and Charm Production Fractions

model $F_D$. The first results from ATLAS 7 TeV data presented here need refinement, but look promising. The final charm fraction of $96\% \pm 18\%$ (stat.) $\pm 0.8\%$ (sys.) is near what was predicted by Monte Carlo data, 96.4%. The CDF charm fraction measurement was $11.41 \pm 1.37\%$ (statistical only) [67], but it should be noted that the CDF results were using a two track trigger that selects tracks with $|d_0| > 120 \mu m$, $L_{xy} > 200 \mu m$, and $p_T > 2.0$ GeV, which biases the sample toward a dramatically larger bottom fraction.

5.7 Summary

A procedure to determine the charm fraction in $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+_s$ events was developed. The signal for the $D^0$ impact parameter was taken from a selection in the $2\sigma$ range of both the $\Delta M(D^{*+},D^0)$ and $D^0$ mass peaks. The background was subtracted using the sidebands from the range $3\sigma$ to $5\sigma$ of the $D^0$ mass peak. The $D^0$ impact parameter signal was fit according to

$$f(d_{D^0}) = \left(1 - f_c\right)F_b \otimes F_D + f_c F_D$$

(5.14)

where the charm fraction, $f_c$, was modeled by the detector resolution function, $F_D$, in the form of a double gaussian and the bottom fraction, $(1-f_c)$, was modeled by the detector resolution convolved with the ideal $b \rightarrow D^{*+}$ contribution in the form of a single exponential function. The variables in both $F_D$ and $F_b$ were fixed from fits to Monte Carlo data and only the charm fraction, $f_c$, was a free parameter in the final fit.

The procedure was then applied to ATLAS $\sqrt{s} = 7$ TeV Minimum Bias data to measure the charm and bottom fractions. The charm fraction was $96\% \pm 18\%$ (stat.) $\pm 0.8\%$ (sys.). Further study of MC truth information and refined fit functions are
Chapter 5. Measurements of the Bottom and Charm Production Fractions

needed to reduce errors on the signal in Minimum Bias Data. This method of analysis may also be applied to other ATLAS data sets that are enriched with b events.

The results presented here begin to differentiate the shapes of the bottom and charm contributions to the D*+ mode by taking advantage of the superior tracking resolution in ATLAS. This work is an important step toward separating bottom and charm contributions and can be applied to other heavy quark decay modes. The ability to differentiate $b\bar{b}$ and $c\bar{c}$ is necessary to identify the decay of $b\bar{b}$ pairs in ATLAS. This method is key in the discovery of new heavy particles such as the Higgs in channels such as $H \rightarrow b\bar{b}$ and can reduce backgrounds from $gg \rightarrow b\bar{b}$ as well as charm backgrounds in these types of analyses.
Chapter 6

Overview

The results presented cover a wide range of contributions to High Energy Physics. These include detector commissioning, research and development into new detector technologies, and studies of Standard Model processes in ATLAS data.

The High Voltage Patch Panel 4 plays a key role in the Pixel Detector providing the bias voltage for the Pixel Modules. It was critical to ensure that all the mapping was done correctly. The prototype HVPP4 was tested and a qualification procedure was established that was used in the production of HVPP4 that is now used to power the Pixel Modules.

Several important studies were done on new detector technologies for ATLAS Upgrade. The first study was on a 3D sensors. These sensors use columnar electrodes instead of the more traditional planar electrodes. The inter-electrode capacitance on irradiated 3D sensors was measured for the first time. The results showed that the capacitance was dependent on the irradiation fluence. The capacitance increased approximately 70% from non-irradiated to $1 \times 10^{15}$ p/cm² with 55 MeV protons.

A 3D detector design will be implemented in the ATLAS Upgrade in limited
parts of the forward regions of the Inner Detector. The capacitance study presented here was an important first step in validating the performance after irradiation of the design. The capacitance measurement provides valuable information on the expected noise of the sensor. The noise is key in determining both the design of the read-out electronics and the signal-to-noise ratio.

Planar detector technologies were also investigated. In collaboration with Zheng Li at BNL, n-type MCz diodes were irradiated with neutrons at Sandia National Laboratory and the leakage current and capacitance measured at several low temperatures at UNM. The samples were then irradiated with a gamma source at BNL where TCT measurements were performed. The study of the effects on the space charge after exposure to two types of radiation indicated the two types of damage had opposite effects on the value of the effective doping concentration as expected, but did not add independently. This indicated that an interaction of the defects occurred in the diodes.

While the radiation doses of this experiment were chosen to be relevant to the proposed ILC experiment, the n-type MCz is also a candidate material for use in ATLAS Upgrade. This study led to a greater understanding of the microscopic behavior of the defects created after irradiation. A better theoretical understanding of these processes is important to create better detector designs in the future for all high luminosity experiments.

The annealing properties of a series of n- and p-type Fz and MCz diodes were examined. The diodes were first irradiated at Los Alamos National Laboratory with protons to several fluences. The leakage current and capacitance were measured after irradiation and many annealing steps. From these measurements the depletion voltage and effective doping concentration were extracted. The change in effective doping concentration was fit according to the Hamburg Model and the annealing interaction rates and time constants were found.
Chapter 6. Overview

The comparison of a suite of devices illuminates the different annealing benefits of each type for use in high luminosity applications. It was shown that after proton irradiation above $7.8 \times 10^{13}$ n$_{eq}$/cm$^2$ n- and p-type Fz and p-type MCz would benefit from annealing by exhibiting a decrease in the depletion voltage for approximately 10 days at room temperature, while n-type MCz would show an increase in depletion voltage for the initial 10 days of annealing. This information is necessary to understand the changes in detector performance during periods when the sensors are not kept at below zero Celsius temperatures.

The study of the bottom and charm fraction contributions to $D^{*+} \to D^0(K^-\pi^+)\pi^+_s$ (+cc) events increases our understanding of heavy quark production in ATLAS. A procedure was developed to measure the bottom and charm fractions using the impact parameter of the $D^0$ to distinguish the two contributions. The total distribution was modeled by $f(d_0^{D^0}) = (1 - f_c)F_b \otimes F_D + f_cF_D$ where both the detector resolution, $F_D$, and the ideal $b$ contribution, $F_b$, were modeled using Monte Carlo data and fit using a double gaussian and a single exponential function respectively. The signal events were found by selecting events within the $\Delta M$ peak for $D^{*\pm}-D^0$ and using the $D^0$ mass peak to subtract the background contribution from the signal region using the sideband distribution. The procedure was established using Monte Carlo data where the charm fraction predicted was $97\% \pm 21\%$(stat.) compared to $96.4\%$ measured with truth. The procedure was applied to ATLAS Minimum Bias data and the charm fraction measured was $98.1\% \pm 9.0\%$(stat.) $\pm 0.8\%$(sys.).

There is the potential for many new particle discoveries at the LHC. Most of these particles are likely to decay into heavy quarks, such as the Higgs decay $H \to b\bar{b}$ where the main background will be $gg \to b\bar{b}$. It is critical to understand the signals such as $b\bar{b}$ and their background contributions such as $c\bar{c}$, which will be produced at much higher rates. The development of a procedure to distinguish bottom and
Chapter 6. Overview

charm quark events is critical to completely understand the production of $b\bar{b}$ and differentiate from background $c\bar{c}$ events. The analysis presented here takes a big first step toward that goal.
Appendix A

Proton Irradiations

UNM regularly organizes proton irradiations at the Los Alamos Neutron Science Center (LANSCE) for collaborators in our experiments (ATLAS, ILC, RD50, etc.). The program began in September 2007 and generally provides two irradiation periods a year. Each period has up to 48 hours of beam time.

A.0.1 Beam Characteristics

The protons in the beam are accelerated to 800 MeV. The beam is operated at 1 Hz with $5 \times 10^{11}$ protons per macro pulse (large bunch of protons). This corresponds to a current of 80 $\mu$A. The beam spot is 2 cm in diameter. If we assume the protons are distributed in a gaussian profile and assume the standard deviation, $\sigma = 0.5$, then 91% of the protons will be within the beam spot. This information is used to calculate the fluence received for each sample based on its size and position in the beam. For example, a sample that is 0.5 cm x 0.5 cm centered on the beam spot will receive:

$$\sigma_{\text{beam}} = \int_{0.25}^{0.25} \int_{0.25}^{0.25} \frac{1}{2\pi\sigma^2} e^{-\frac{(x^2+y^2)}{2\sigma^2}} dxdy = 0.1466 \quad (A.1)$$
Appendix A. Proton Irradiations

again where $\sigma = 0.5$. This implies that the sample will receive 15% of the protons per pulse:

$$\text{number of protons per pulse} = 0.1466 \times 5 \times 10^{11} = 7.33 \times 10^{10} \text{ protons} \quad (A.2)$$

The fluence (protons/cm$^2$) from each pulse can also be calculated:

$$\text{fluence per pulse} = 7.33 \times 10^{10} \div (0.5 \times 0.5) = 2.93 \times 10^{11} \text{ p/cm}^2 \quad (A.3)$$

Irradiation requests are often made in various units of fluence. Since the beam is made of 800 MeV protons, quoting fluences in 800 MeV p/cm$^2$ is most natural, but for comparison with experiments irradiated in other beams (different energies or particle type) other units are necessary. The NIEL scale provides a conversion for different energies of particle beams. As discussed previously, the NIEL scale is based on the conversion of non-ionized energy loss in Si. Fluences can be converted between protons, neutrons, pions, and photons for different energy ranges. (Reminder: The conversion using the NIEL scale may not be wholly accurate for other materials and there may be unknown effects that alter the conversion factors, but it is currently the best method for comparing irradiation results from different sources.) In the particle physics community fluences are often quoted in 1 MeV $n_{eq}$/cm$^2$ for easy comparison. Units of Mrad are also common for experiments with gamma irradiation. The most common conversion factors are listed in Table A.1.

<table>
<thead>
<tr>
<th>Table A.1: Fluence Conversion</th>
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</thead>
<tbody>
<tr>
<td>$1\text{MeV } n_{eq}/\text{cm}^2 = 1.41 \times 800 \text{ MeV p/cm}^2$</td>
</tr>
<tr>
<td>$1\text{MeV } n_{eq}/\text{cm}^2 = 2 \times 10^{13} \text{ Mrad}$</td>
</tr>
<tr>
<td>$1\text{MeV } n_{eq}/\text{cm}^2 = 0.621 \times 24 \text{ GeV p/cm}^2$</td>
</tr>
</tbody>
</table>

The fluence values (for one beam pulse) are calculated in Table A.2 for various device sizes and converted to different fluence types.
Appendix A. Proton Irradiations

### Table A.2: Fluence Per Pulse

<table>
<thead>
<tr>
<th>Sample Size</th>
<th># proton/pulse</th>
<th>800 MeV p/cm²</th>
<th>1 MeV n&lt;sub&gt;eq&lt;/sub&gt;/cm²</th>
<th>Mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25x0.25 (PIN diodes)</td>
<td>1.95x10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>3.12x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>2.21x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>0.0111</td>
</tr>
<tr>
<td>0.5x0.5</td>
<td>7.33x10&lt;sup&gt;9&lt;/sup&gt;</td>
<td>2.93x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>2.08x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>0.0104</td>
</tr>
<tr>
<td>1x1 (Al dosimeter)</td>
<td>2.33x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>2.33x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>1.65x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>0.0083</td>
</tr>
<tr>
<td>2x2</td>
<td>4.56x10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>1.14x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>8.09x10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>0.0040</td>
</tr>
<tr>
<td>2x2 array of 0.5cmx0.5cm</td>
<td>5.83x10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>2.33x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>1.66x10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>0.0083</td>
</tr>
</tbody>
</table>

The fluence values are also measured during the irradiation. The standard method for measuring particle flux is to use a sample of Al and measure the activity of Na<sub>22</sub> or Na<sub>24</sub>. This will yield the particle (in this case 800 MeV protons) flux, which can be converted to fluence. Ideally, the Al dosimeters should be the same size as the test sample. The equipment used in the spectrographic analysis at Los Alamos requires a few grams of Al in order to have an accuracy within approximately 10%. In order to achieve this weight, Al samples are kept large (1 cm x 1 cm). During irradiation, each fluence step has one Al dosimeter to measure the actual fluence.

The measurement process is also very long (up to several days) for the Al dosimeters and final values are not usually received for 1-3 months. For more immediate results PIN diodes are also used as dosimeters. The diode behavior has been thoroughly studied by the RADMON group at CERN [68] and is used in ATLAS for fluence measurements. The forward voltage of the diode depends linearly on the fluence (up to 4x10<sup>14</sup> and possibly higher for low temperatures). The PIN diode measurements are very simple and quick and can be done during the 48 hour irradiation period providing immediate feedback. Fluences from the PIN diodes are accurate to 10-20%. Figure A.1 displays the beam profile measured from an array of PIN diodes.
Figure A.1: LANSCE proton beam profile from measured PIN diode array.
Appendix B

Definitions

B.0.2 ATLAS Geometry

The ATLAS Coordinate System is a right-handed system with the $x$-axis pointing to the center of the LHC ring. The $z$-axis follows the beam direction and the $y$-axis goes upwards. The azimuthal angle $\phi = 0$ corresponds to the positive $x$-axis and $\phi$ increases clock-wise looking into the positive $z$ direction and is measured in the range $[-\pi, +\pi]$. The polar angle $\theta$ is measured from the positive $z$ axis [69].

B.0.3 Variables

The transverse momentum, $p_T$, is defined as the momentum perpendicular to the LHC beam axis.

The pseudorapidity, $\eta$, is a measure of the angle away from the transverse plane. It is defined by:

$$\eta = -\log \left( \tan \frac{\theta}{2} \right).$$  \hspace{1cm} (B.1)
Appendix B. Definitions

The definition of $D_{xy}$ is the distance between a particle candidate vertex and the primary vertex in the transverse plane.

The impact parameter of a charged particle track, $d_0$, is defined as the distance of closest approach of the particle track to the primary vertex in the transverse plane.

\[ d_0 = \frac{|\vec{D}_{xy} \times \vec{p}_T|}{|\vec{p}_T|}. \]  

(B.2)

The variable $L_{xy}(p)$ of a particle candidate is expressed in length units of mm and defined as the projection onto $\vec{p}_T(p)$ of the vector connecting the primary vertex to the particle decay vertex in the transverse plane.

\[ L_{xy} = \frac{\vec{D}_{xy} \cdot \vec{p}_T}{|\vec{p}_T|}. \]  

(B.3)
References


REFERENCES


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REFERENCES


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