Pursuing Improvements in Radial Time Projection Chamber Design

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Physics from the College of William and Mary in Virginia,

by

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1 Acknowledgements

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Abstract

In 2005, physicists constructed a particle detector at Jefferson Lab to measure the structure function of a nearly free neutron target. This experiment, named Barely Off-shell Nucleon Structure (BONuS), used a novel detection configuration, namely that of a radial time projection chamber. Following the 12 GeV upgrade to the JLab beam, the BONuS collaboration is looking to repeat the experiment with a more precise detector, using lessons learned from the first iteration of the design. I was tasked with improving the consistency of the electrical fields near the ends of the detector. I found two promising new material applications and modelled the electric field to improve the original stepped field design.
2 BONuS Detector

The original BONuS (Barely Offshell Nucleon Structure) experiment ran in Jefferson Lab in 2005[1, 2]. The goal of the experiment was to determine the structure function of the neutron as the Bjorken Scale factor approaches unity. The primary challenges associated with determining information on the neutron is the lack of free neutron targets and the low interaction rate of neutral particles. BONuS addressed these issues by using a deuterium target and "spectator tagging": gleaning information on individual scattering events from low momentum, backward scattered protons resulting from neutron collisions.

The structure function is a measure of the internal composition of a nucleon. While protons and neutrons are described as two and one up or down quarks, there is much more going on within the particles. Only 1% of the mass, for instance, is derived from the rest mass of those three quarks, with virtual particles and gluon binding energy making up the rest. It is the goal of BONuS to determine the quark composition of the neutron as it relates to inelastic scattering.

The structure function of the neutron is dependent on the Bjorken Scale Factor, x, which is the fraction of momentum carried by the struck quark[3]. At intermediate x=0.2-0.5, the three valence quarks dominate in the scattering. We are rather certain of the structure function at intermediate x, but as x increases the structure function becomes much more difficult to determine.

The the original BONuS detector investigated the neutron structure function at values of x from 0.3 to 0.6. To do this, deuterium targets were struck with an electron beam. To take only the neutron scattering events into account, a method of spectator tagging was used: when a neutron was struck, the proton near it would be knocked out of position as well. This slow proton can be tracked, as long as it hasn’t interacted since it left the deuterium nucleus, it will reveal information about the original state of the neutron before scattering.
Thankfully, it is not too difficult to find these "off-shell" neutrons: the recoiling protons of interest have low momentum with their direction opposite that of the beam.

![Figure 1: Spectator Tagging][13]

To detect these spectator protons, the experiment used a novel configuration of a time projection chamber in which the electric field was oriented radially. A time projection chamber (TPC) tracks charged particles moving through a gas. The particles leave ion trails, which drift in the applied electric field to the outer boundary. The TPC used a 4:1 mix of Helium and Dimethylether (DME) as the ionized gas, three layers of Gas Electron Multipliers (GEMs) to multiply the ionization electrons knocked off the helium and an array of pad amplifiers. The experiment provided clear results on the structure function of the neutron from $x=0.1$ to about $x=0.6$, beyond which little is known.
Doubling the beam energy from 6 to 12 GeV at Jefferson Lab has opened the door for results at higher \( x \), so we are attempting to replicate the experiment with an improved design. At the higher energy, incoming electrons have a shorter de Broglie wavelength, allowing for more direct scattering of the struck quark, yielding higher values of \( x \). Several potential improvements on the original detector have been identified: a longer chamber, full \( 2\pi \) detection, improved gas mixture, and a more constant electric field will decrease the uncertainty of the results. The goal of BONuS12 is to expand the results of BONuS6 to \( x=0.8 \), in order to better extrapolate the structure function in the asymptotic limit of \( x=1 \).

In the paper describing the design of the BONuS RTPC\cite{2} it was mentioned that the field cage could be improved by using a uniform coating of a resistive material. This is where my efforts have been focused. The original design used eleven circular wires, equally spaced,
with a resistor between each consecutive wire, chosen to match the potential at the wire’s radius. This made for a simple endcap solution, but it did distort the electric field slightly. A pair of uniform resistors would remove the discontinuities at the ends and make for easier particle tracking near the endcaps.

4 Improving the Endcaps

The electric field in the drift region varies with distance from the central conductor with a $r^{-1}$ dependence. The endcap will form a circuit, so the potential gives us the resistance with $V=IR$, so $R$ must also have a $r^{-1}$ dependence. We then use $R = \rho L/A$ to determine how thickness of a uniform resistor would have to vary with the radius, noting that the area $A$ is equal to the thickness, $t$, times circumference. Thus the resistance of one thin cylindrical layer is $dR = \rho (2\pi tr)^{-1}dr$, which means that for a constant thickness, the resistance will have the desired $r^{-1}$ dependence.

The cathode is located at a radius of 3 cm and the drift chamber goes to 7 cm, resulting in a larger active area than the previous design. Integrating the known parameters gives us an expression for resistivity:

$$R = \int_{0,03}^{0,07} \frac{\rho}{2\pi tr} dr = 0.2697 \rho/t$$  \hspace{1cm} (1)

The original BONuS design had a resistance of 65 MΩ across the endcaps, and while we do not need to exactly replicate that number, we do not want to deviate too far from it. At a value of 50 MΩ, there is about a half watt of power being consumed in each endcap. This is acceptable and easily dispersed at the ends. At 1 MΩ there is about 25 Watts across the resistor, this is already too much. Setting the thickness at 0.1-10 mm, and $R=50$ MΩ, we get a range of resistivities of $10^4 - 10^6 \Omega m$.

The range of resistivities is a bit of an issue unfortunately: there are no common materials with such characteristics. Most metals have resistivities around $10^{-8} - 10^{-6} \Omega m$, carbon has
about $10^{-4} \Omega \text{m}$, silicon has $10^2 \Omega \text{m}$, and there is a large jump to insulators from there, with glass having $\rho = 10^{11} - 10^{15} \Omega \text{m}$. Silicon seemed to be a candidate, but the thickness would have to be about $3.5 \mu m$, which is a problem: 150mm silicon wafers are about 200 times thicker than this, so silicon appears to be unfeasible. Another possible idea was a spiral wound resistor with many turns of a relatively high resistivity metal or carbon wire. The issue here is the geometry: to get the correct field arrangement, the windings would have to be very precisely wound with much tighter winds near the center with increasing distance between windings nearing the GEMs. The idea was abandoned as it would likely be less precise than desirable, more expensive/time consuming to manufacture, and would introduce a small magnetic field near the ends. The choice was clear: we could form a thin layer of a more conductive substance, or find a higher resistivity material that could be molded or machined to the correct thickness. A search through the relevant literature provided no direction as to a material that would work well for such a detector: other time projection chamber designs described using a stepped field boundary.

We then decided to investigate further the various bulk electrical properties of materials. In short, aside from the well known insulators, conductors, and semi-conductors, one more resistivity category appeared: Electro-Static Dissipative (ESD) compounds. These are designed to safely handle static discharge in sensitive electronics. Rogue static charges have the capability to (and often do) ruin sensitive electronic equipment. To combat this, electronics are often shielded with materials that will capture and redirect unwanted charges. These materials are usually plastics which are easily moldable and have resistivities between $10^3$ and $10^{12} \Omega \text{m}$ due to carbon fibers or powder added. ESD protections are important in safety critical and expensive electronics: static damage to electronics costs billions of dollars a year to the electronics industry [4].

Initial investigations into the materials brought up the name of the RTP plastics company. Most of their ESD compounds available were far more conductive than would be acceptable
for our purposes: we would need to construct a very thin layer, and at such a thickness, the
electric field would be far more affected by minute variations in thickness, possibly negating
the gains won by using a uniformly resistive disc. Another issue appeared in the variance in
resistivity of the available plastics: the quoted volume resistivity values often were given in
a range of over five orders of magnitude. Finally, we had to not only determine a material
fulfilling the resistivity requirements, but ensure that it would survive a high radiation flux.
CERN has a list of materials fulfilling their requirements for radiation hardness[6] which
excludes many common plastics.

5 ESD Plastics

After consulting with an engineer at RTP plastics, we learned that such a large range of
resistivities was specified due to the instability of the plastic/carbon mixture. The carbon
is added at a concentration which is the steepest portion of the percolation curve of the
resistivity of the compound. This means that between batches and even within one batch,
resistivities can vary wildly, making it effectively impossible to specify a particular resistivity.

While going through several data sheets, we found one material that stood out: RTP
2299 x 81382 PEEK. This material had a relatively narrow range of resistivities ($10^3$ to
$10^6 \Omega m$)[5] which would allow for a resistor width of 0.01 to 10 mm, and the base compound
(polyethyl-ethyl-ketone) has been highly endorsed by CERN [6] for use in high radiation flux
detectors.

Unfortunately, actually acquiring the ESD PEEK material has proved impossible. Be-
ing such a large company providing large industries with bulk (110lbs + minimum orders)
amounts of plastics, as a small experiment, it has been difficult to secure a sample for our pur-
poses. Being that we need such a small amount, the company manufacturing the compound
has been unable to provide it for us.

Following a drawn out and ultimately unsuccessful attempt to order the material from
Table 1: ESD Compounds With Possible TPC Applications

<table>
<thead>
<tr>
<th>Compound</th>
<th>Base</th>
<th>Surface $\rho$ ($\log_{10}(\Omega)$)</th>
<th>Volume $\rho$ ($\log_{10}(\Omega m)$)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolux SD-A</td>
<td>ABS</td>
<td>9-11</td>
<td>-</td>
<td>Non-Carbon Alloy</td>
</tr>
<tr>
<td>AC-300/350</td>
<td>Acrylic</td>
<td>6-8</td>
<td>-</td>
<td>Dissipative Coating, Clear</td>
</tr>
<tr>
<td>Hydel PC-7</td>
<td>Polycarbonate</td>
<td>7-9</td>
<td>5-7</td>
<td>Carbon Nanotubes</td>
</tr>
<tr>
<td>Hydel PC-P</td>
<td>Polycarbonate</td>
<td>7-11</td>
<td>-</td>
<td>Carbon Powder</td>
</tr>
<tr>
<td>Hydel PEI-7</td>
<td>Polymethyl</td>
<td>eneimide</td>
<td>6-8</td>
<td>Nanotubes, non-sloughing</td>
</tr>
<tr>
<td>Krefine ESD</td>
<td>PEEK</td>
<td>6-11</td>
<td>-</td>
<td>Fibers</td>
</tr>
</tbody>
</table>

- Resistivity can be chosen in two order of magnitude range

<table>
<thead>
<tr>
<th>Compound</th>
<th>Base</th>
<th>Surface $\rho$ ($\log_{10}(\Omega)$)</th>
<th>Volume $\rho$ ($\log_{10}(\Omega m)$)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pomalux SD-A</td>
<td>Acetal</td>
<td>9-11</td>
<td>-</td>
<td>Non-Carbon</td>
</tr>
<tr>
<td>Propylux SD-A</td>
<td>Polypropylene</td>
<td>9-11</td>
<td>-</td>
<td>Non-Carbon</td>
</tr>
<tr>
<td>Semitron ESD 420</td>
<td>Polymethyl</td>
<td>eneimide</td>
<td>6-9</td>
<td></td>
</tr>
<tr>
<td>Semitron ESD 480</td>
<td>PEEK</td>
<td>6-9</td>
<td>-</td>
<td>Fibers</td>
</tr>
<tr>
<td>Semitron ESD 490</td>
<td>PEEK</td>
<td>9-11</td>
<td>-</td>
<td>Tighter resistance, unavailable</td>
</tr>
<tr>
<td>Semitron ESD 500</td>
<td>PEEK</td>
<td>6-9</td>
<td>-</td>
<td>Fibers</td>
</tr>
<tr>
<td>Semitron ESD 520</td>
<td>PolyAmideImide</td>
<td>10-12</td>
<td>Voltage resistant</td>
<td></td>
</tr>
<tr>
<td>Sintimid ESD 23</td>
<td>PolyAmideImide</td>
<td>8-11</td>
<td>Discontinued</td>
<td></td>
</tr>
<tr>
<td>Tecaform SD</td>
<td>Acetal</td>
<td>10-11</td>
<td>8-9</td>
<td>Inherent Resistivity</td>
</tr>
</tbody>
</table>

- Very homogenous but potentially vulnerable: Acetal can only handle <1MRad

RTP, we looked for other sources of ESD plastics. While most of them had a lower range of resistivities than would work for the experiment, we did find another notable candidate: Semitron ESD 480 PEEK. This compound has a surface resistivity of $10^6 - 10^9 \Omega$/square.

Knowing already that PEEK would be an excellent base compound, we contacted two vendors (Boedeker and Professional Plastics) for quotes. Both had a sheet available, but at prices that were prohibitively expensive ($1200 and $870 per 300mm x 300mm x 10mm sheet), especially should we determine the material was not suitable for use.

There are of course other ESD materials available, but we were not able to acquire any. Should future researchers attempt to build a field cage boundary with ESD compounds, we have included a list of candidate plastics[9, 10] in table 1.

From the table, a few specific compounds stick out: Krefine ESD PEEK, Semitron ESD 480 PEEK, and Tecaform SD Acetal. The Semitron was of course too expensive for us, but
may be viable in other designs. The Krefine PEEK looks extremely enticing on account of being able to specify resistivities in a two decade band, but is likely very expensive. The Tecaform Acetal has the unique advantage of having innate resistivity, which should lead to a very uniform distribution of resistivity, and thus a homogenous electric field.

Some unknowns and problems from ESD plastics do exist, however. Materials using a carbon powder mix are susceptible to sloughing, the process in which abrasion causes carbon particles to expel from the material. This could lead to contamination within the detector, which should obviously be avoided. Note that some materials are noted as non-sloughing. Outgassing is another possible issue, in which the plastic expels fumes under high voltage. Some data-sheets mention a material’s resistance to outgassing, which may imply susceptibility in other materials, thus outgassing resistance should be thoroughly investigated before use in a detector. It is also possible that the ESD compounds do not have sufficiently homogenous resistivity to provide a uniform electric field. Finally, we are not sure how resilient these compounds are to continual exposure to a large voltage. They have been designed to dissipate sudden bursts of static voltage in less than two seconds, not conduct electrons as a circuit element. Direct testing of ESD plastics’ behaviour under constant high voltage is critical.

6 Thin Film Resistors

Aside from using a high resistivity endcap, the high resistance required could also be attained by applying a very thin layer of a more conductive material to an insulator. This has the advantage of not requiring exotic and expensive materials but is much more sensitive to layer thickness. The two most obvious thin film candidates are carbon and silicon, given their relatively high resistivities.

For carbon, we acquired a sample of conductive carbon paint (PELCO Isopropanol Conductive Paint[7]), chosen for its higher resistivity compared to other options (2400 Ω/sqr).
Note that this is a surface resistivity, but does give an indication of the material having an larger relative value than other options which had a 1-2 order of magnitude smaller resistivity. The other bonus of the conductive paint is its easy dilution with isopropanol, allowing it to be applied in thinner, less conductive, layers.

After receiving the paint and diluter we ran a few tests to characterize the resistance of simple samples. A small square of undiluted paint applied in one layer had a resistance of about 2 kΩ corner to corner. Diluting the paint had very quickly changing properties: it had a higher resistance than measurable with our Ωm, to the point where even about 15 dilute layers had no measurable resistance. By adding in a bit more of the conductive paint, however, we was able to get a resistance of about 15 MΩ across a sample. Once we got the concentration leading to the higher but still measurable resistance, we coated the surface of a blank compact disc with the paint. At that point, measuring the resistivity between different points between the center and edge of the disc yielded resistances that varied greatly: this implied that the paint was not applied sufficiently evenly, and that sample would not yield a sufficiently even electrical field. Despite this, we still wanted to get an idea of the overall resistance when all the edges were joined to be somewhat equipotential, we did this by applying a layer of the undiluted carbon paint around the inside and outside of the CD. This resulted in a resistance of 1.6 MΩ across the disc, which was stable across the inside and outside points.
Figures 3, 4: The first conductive carbon samples, and a layer of the diluted paint on the other side of the same disc. Notice how the carbon layer is uneven.

Table 2: Resistances of samples in Fig. 3

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Undiluted</td>
<td>2kΩ</td>
</tr>
<tr>
<td>B</td>
<td>Thin Spread</td>
<td>20kΩ</td>
</tr>
<tr>
<td>C</td>
<td>Diluted</td>
<td>100kΩ</td>
</tr>
<tr>
<td>D</td>
<td>Thin Spread and Diluted</td>
<td>200kΩ</td>
</tr>
</tbody>
</table>

The other three samples were of the very dilute mix, which was too diluted to leave a measurable resistance. Applying several layers had the unfortunate effect of spreading the graphite particles to the edges, leaving almost none in the center. Eventually, the resistance was measurable across opposite sides, but not at the center. We then added more paint and was able to consistently get a thin layer with high but detectable resistance. This was the concentration we used to coat the other side of the disc. After coating, we applied the undiluted paint along the inside to get an equipotential, took data, then painted the outside to get the equipotential there as well.

The undiluted carbon paint does not provide a perfect equipotential, but the resistance across it was small enough to be negligible compared to the diluted layer: resistance between points 90° away were 40kΩ, and points 180° apart had 55kΩ between them.
Table 3: Resistances with no outer equipotential

<table>
<thead>
<tr>
<th>Angular position on disc (degrees)</th>
<th>Resistance (MΩ, &quot;-&quot; means not readable) at:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/4 from inside</td>
</tr>
<tr>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>45</td>
<td>14</td>
</tr>
<tr>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>135</td>
<td>5.6</td>
</tr>
<tr>
<td>180</td>
<td>-</td>
</tr>
<tr>
<td>225</td>
<td>3.2</td>
</tr>
<tr>
<td>270</td>
<td>2.8</td>
</tr>
<tr>
<td>315</td>
<td>1.8</td>
</tr>
</tbody>
</table>

After covering the outside edge of the disc with the carbon paint, the total resistance between the inner and outer surfaces of the disc was 1.6MΩ, with 82kΩ between opposite edges of the outside. Clearly, the design would not work as an endcap resistor, as the resistances vary wildly, and the carbon is simply too conductive. Even if there was a way of spreading the paint perfectly evenly, the system would draw too much current.

Another thin layer material that may work is silicon. While mentioned earlier that standard undoped silicon wafers would be too thick to provide sufficient resistance in the design, it is possible that a correctly doped silicon wafer could have a high enough resistivity to work in the design. Though no sufficiently resistive silicon was found available from several vendors, we did stumble upon another possible configuration: Silicon on Insulator (SOI) wafers. These consist of a very thin (as low as 50 nm) layer of silicon on top of a thin insulative buried silicon oxide layer, which is above a much thicker silicon "handle".[12]

This configuration has several advantages: the thinner active layer allows for the high resistance demanded, the thin oxide layer is thin enough not to impede outward flow of waste heat which is conducted away by the thicker silicon handle, and since the silicon is crystalline, there will not be the large discontinuities as seen in the carbon prototype. Despite the excellent prospects, however, the only low quantity vendor we found only had "device layer" silicon that was at least two orders of magnitude too conductive for our purposes. It does not, however, seem a stretch to assume that a highly funded experiment would be able
to procure such custom wafers with higher resistivities.

Finally, noting that boron has a high resistivity, we tried mixing borax with rubber cement to see if we could measure a high resistance. Unfortunately, the mixture was insulative, probably because of the chemical differences between boron and borax. Furthermore, the mixture quality was very rough and non-homogenous, so even with powdered boron sloughing would likely be an issue. Clearly, the best candidate for a thin resistive layer remains silicon, especially if SOI technology can be utilized.

7 Stepped Field Cage

With passive devices either unavailable or prohibitively expensive, we turned our focus to improving upon the discreet field configuration of the previous detector. How can the field cage be configured to ensure the most longitudinally uniform electric field?

Research groups at JLab have used the GARFIELD drift chamber simulation program in the past to analyze the electric fields and particle trajectories through various detectors[11]. While the program is very powerful in two dimensions, it is less powerful in three dimensions which are needed for the endcaps. One TPC group (FLC TPC in Germany) used a 3D modelling software, CST EM Studio, to optimize the design of their field cage.[8] They determined that a two layer array of evenly spaced and overlapping field strips allowed for a field strength with less than 0.01% deviation from uniformity. Fortunately, CST Studio is available in a free limited-functionality student edition, which we used to test various field configurations.

Before we started modelling, we were curious about which would work better: wires or strips, evenly-spaced distance or voltage steps, and which voltage should each step carry? After we found the FLC TPC paper, we also chose to model a two-layer design. The CST Studio program is able to model the cathode, GEMs, and wires/strips in three dimensions, simulate a voltage on each object, and generate (among other things) a 3D map of the
potential, which can then be sliced to examine equipotential lines. Below are the results of several iterations of modeling. Ideally, equipotential lines are parallel all the way to the endcaps. If a line bends inwards, the endcap voltage is too low if the line were to continue straight, and vice versa. As this is the student edition, the number of rendered tetrahedra is limited to ten thousand, so the more detailed field configurations will suffer from some distortion.

Figures 5, 6: Comparing the fields using wires (top) and strips (below).

Figures 7, 8: Difference between even potential drops (left) and evenly spaced strips.
As we can see from figures 5 and 6, wires will not create an acceptable field cage, compared to field strips spaced one quarter of their width apart. Trying to make even potential drops is not very effective at creating a smooth field as it distorts the field near the GEMs, where spacing is the largest (figure 7). Adding a mirror layer of strips (figures 9, 10) has a positive effect on the equipotential lines, notice how much smoother they behave in the spaces between strips. Finally, with seven potential steps, we compared the ideal voltage to give each strip, either that calculated at the center or interior edge of the strip. In figure 9 the outward drift of the equipotential lines from the field strips is apparent, signifying the strips being at too low of a potential. In figure 12, where the potential is calculated from the potential at the innermost radius of each strip, the voltage lines are mostly parallel, and most notably do not collectively bias inwards or outwards. This cumulatively suggests using field strips, spaced
evenly, with a staggered mirror layer underneath, each at a voltage corresponding to that of
the drift chamber at the strip’s innermost radius, is the best way to make a uniform electric
field using discreet potential drops.

8 Conclusion

To create a perfectly uniform electric field within the BONuS Radial Time Projection Cham-
ber, we needed to find a material with unique electrical properties. In the process, we found
several candidates, including new categories of materials for use in any uniform drift cham-
ber, namely ElectroStatic Dissipative (ESD) plastics. While we were unable to acquire a
sample to perform tests on, this paper does provide a knowledge base of potential materials
to use in future detector designs. Another new material application we found, which would
be more specific to radial time projection chambers, are Silicon On Insulator (SOI) wafers.
The combined variable resistivity of silicon with the extremely thin layers attainable by using
the SOI technology allow for a wide range of resistances, so long as the endcap size does not
exceed the wafer diameter.

Despite not being able to create a passive uniform resistor, we were still able to use
modeling software to analyze the optimal arrangement of voltage steps to improve upon the
design of the previous BONuS endcaps. Our results show that field uniformity is maximized
by adding an additional, offset layer of ”mirror” field strips underneath the other strips.
Setting the voltage of each strip so that it corresponds with the drift potential at the strip’s
innermost radius also improved the field uniformity.
References


[13] Bonus-nuint12 E. Christy Hampton University