Diamond Detector: Measuring Beam Intensity

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FNAL SIST Program, August 17th, 2016

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Abstract

There are several ways of measuring beam intensity. One of those ways is through the use of an instrumentation device called a diamond detector. Diamond technology has the capability to measure beam intensity, count particles and measure the energy spectrum of the beam. With a purpose of looking to replace the current method in measuring beam intensity for the Switchyard beamline, which involves using Secondary Emissions Monitors (SEMs), the diamond detector may offer a less expensive and more effective way of measuring beam intensity.

Introduction

To begin with, an important aspect that came with learning about this piece of instrumentation was to start from the beginning, and that dealt with learning about the actual piece of gem diamond that made the particle detector work. Specifically, I researched a company called Element Six, which is a company that specializes in making diamonds for the specifications of using them in applications for particle detectors and other precise instruments. Element Six makes the diamond technology through a chemical vapor deposition (CVD) process, which makes the diamond to be synthetic. The diamond is formed and created in a tightly controlled growth environment where the diamond is subject to strict conditions and quality control over the specifications for what the diamond material should be grown to. CVD diamonds are usually produced in a vacuum where carbon atoms are supplied from gases like methane so the company has the ability to control the gas purity, which is essential to create pure diamonds in use of applications in particle detectors and other precise instruments. In addition to already selling several diamonds for the purpose to use in particle detectors, the specifications of the diamond can also be taken from the customer to Element Six, so then Element Six will grow the diamond to the exact dimensions that the customer asked for. This is useful in some cases when a diamond detector is placed in a beamline of protons where the scattering angle and the power loss of the beam need to be considered for safety reasons or preference of beam position. For reference, the specific diamond detector that I had to test and get familiar with had diamond material that was 1 x 1 cm^2 and 500 micrometers thick.

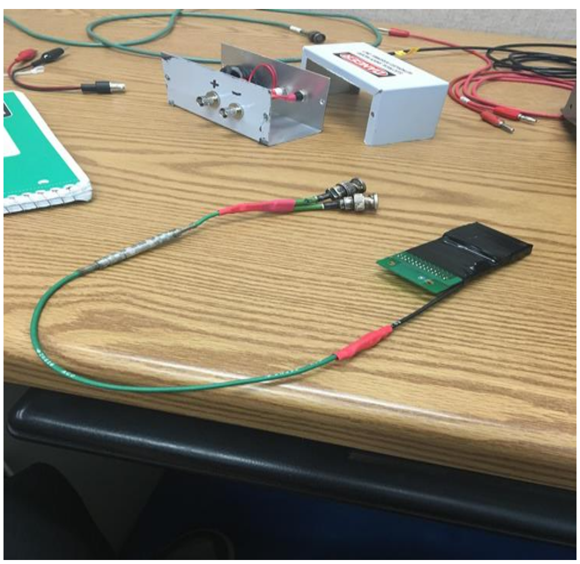

Figure 1: This is the diamond detector that I tested over the summer. It is covered by electrical tape to protect the diamond material from light. It has to be light-tight in order for the diamond detector to function properly.

The diamond detector is a charged-particle detector. In detail, the diamond detector works by a bias voltage that is applied across the diamond material. A thumb of rule is that for each 100 micrometers of the diamond material, there will have to be around 100 volts applied across the diamond for the diamond detector to function properly. As charged particles hit the surface of the diamond material, the diamond material is then ionized and there is a creation of free charge carriers, which in essence are electron-hole pairs. After these free charge carriers are created from the collision of the charged particles on to the diamond, the drift of these charges between the electrodes, which are a part of the diamond detector, creates a signal of current that can be measured. In some cases, with precise instrumentation and readout hardware, the current signal from the diamond detector is relatively small (picoamp range), so a low noise current amplifier would be used in combination with the diamond detector so that when charged particles hit the diamond, the current signal will be amplified in order to measure the low intensity from the current signal. However, in our case, since we are dealing with a proton beam of high intensity (120 GeV), it should not be a problem in reading out a current signal from the diamond detector since the beam is producing protons and running at such high intensity.

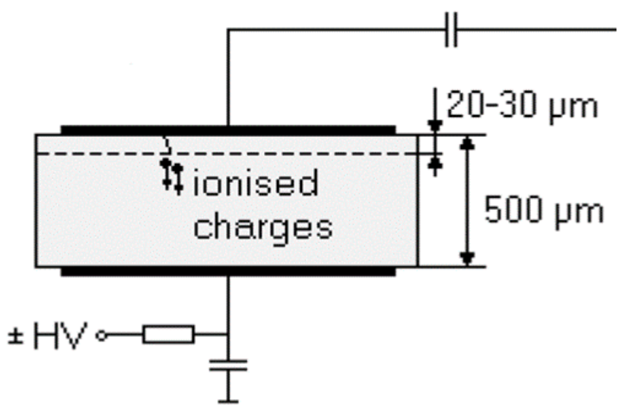

Figure 2: Here is a diagram of how the diamond detector looks in part of a circuit diagram. The diamond material is connected to two electrodes, a cathode and an anode, which allow the drift of the charges that are made when a charged particle ionizes the diamond, which produces a current signal. In order for the diamond detector to operate, a bias voltage has to be applied, as shown as “HV” (high voltage) in the diagram.

Another aspect that is important for making the diamond detector a viable beam intensity monitor is the need for a high signal to noise ratio. For diamond detector instrumentation, it has to have the ability to be able to produce a signal to noise ratio in which the current signal from the diamond detector is clearly read. The instrumentation that has to deal with producing a high signal to noise ratio involves creating a very good Faraday cage. A Faraday cage is used to block electric fields and is formed by conductive material. A lot of detail has to be taken into account for producing a high signal to noise ratio. For example, the types of cables and how the cables are wired to readout the current signal matter a lot in having an effective Faraday cage. Another key aspect to know about the diamond material is the difference between the two types of diamond materials that can be used. The two different types are single crystal diamond and polycrystalline diamond. Single crystal diamond is more expensive to produce where all the symmetry properties of the diamond material structure is present. A polycrystalline diamond consists of several single crystals that are randomly distributed for the diamond material structure. A single crystal diamond is preferable in that it offers a more uniform current signal to readout from the diamond detector. However, the single crystal diamonds are more expensive than the polycrystalline diamonds.

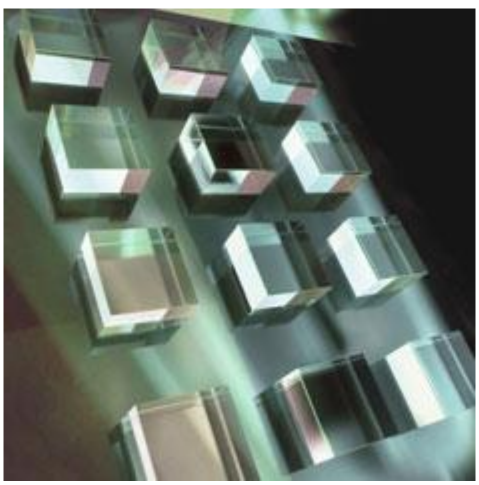

Figure 3: Here is an image of Element Six single crystal synthetic diamonds.

With the overall purpose for the replacement of SEMs, we looked into some of the reasons why the current method for measuring beam intensity should be changed. The way SEMs work in measuring the beam intensity is with beam interaction on the Titanium foils located in the SEMs. The beam interaction with the foils liberates surfaces electrons from the Titanium atoms. The signal from SEMs is then taken to a current digitizer via a coaxial cable.

The current digitizer then converts the positive electrical charge left on the foil to a number of pulses proportional to the amount of charge; this is proportional to the beam intensity. However, there are downsides to using the SEMs. One of the downsides that comes with using the SEMs is the calibration. For example, if the beam hits the Titanium foils in the same spot for a long time, the secondary electron yield will get lower and lower as time goes on because surface electrons are being liberated from the same Titanium atoms, leading to an inaccurate measurement of beam intensity. With an inaccurate measurement of the beam intensity from the SEMs, this leads to a recalibration of the instrument. Also, in addition to this calibration problem, the beam position also plays a role in determining the beam intensity. For example, if the beam were to be tuned by an operator, the beam would interact with a different spot on the Titanium foil, which will give a different amount of positive charge detected on the Titanium foil due to a higher secondary electron yield in that area. The problem with this is the different beam intensities that are being measured by the SEMs due to calibration issues. Last but not least, the SEMs also contain large material. SEMs contain around 10 Titanium foils, with a thickness of about 5 millimeters thick. Compared to the diamond detector, more beam is lost and scattered with the use of SEMs instead of a diamond detector.

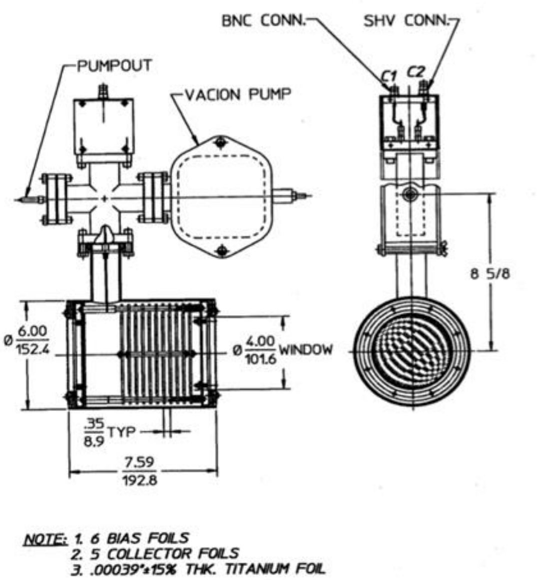

Figure 4: Here is an image of the several components that make the SEMs work.

The last important aspect to take into consideration for using a diamond detector is leakage current. Leakage current comes from the fact that the gem diamond is a semiconductor. The leakage current of a diamond detector occurs due to the limited electric conductivity intrinsic in semiconductor materials. With this in mind, the two kinds of leakage current that amount to the overall leakage current are due to the bulk and surface properties of the material. Bulk current is caused by the free charge carriers that are thermally energetic enough to cross the energy band gap of the diamond. Surface leakage current is attributed to the manufacturing process, measurement methods, electrode conductivity. As mentioned earlier, a high signal to noise ratio is necessary for obtaining a better current signal that can be measured. In order to achieve a high signal to noise ratio, the leakage current that comes from the diamond detector would have to be reduced.

Measurements & Instrumentation

The readout hardware instrumentation that was necessary for having the capability of measuring in the picoamp range was the Keithley Model 6517B Picoammeter. The picoammeter has the capabilities to supply a voltage (bias voltage needed to operate a diamond detector), measure in the picoamp range (important for the precise measurements that needs to be done for the diamond detector), measure the temperature & humidity of the area in which measurements are being done (this can be taken into account for when measuring current from a diamond detector), and the picoammeter can communicate with a computer via the General Purpose Interface Bus (GPIB) port.

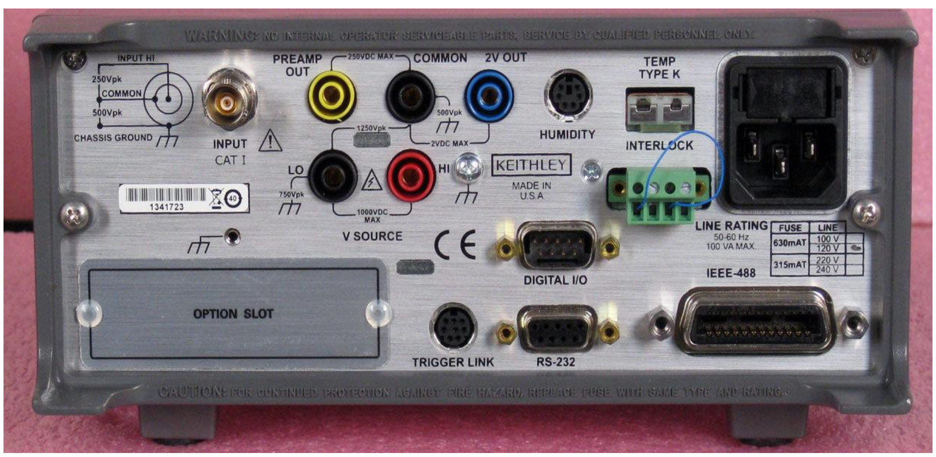

Figure 5: These two images show the front and back of the Keithley Picoammeter that was used in acquiring data. The IEEE-488 port is the same as the GPIB port.

In regards to collection of data, a GPIB to USB converter was used for communication from a computer to the Keithley instrument. The GPIB to USB converter was a Prologix GPIB-USB 3.12 Controller. To begin the communication from computer to the Keithley instrument via the specific GPIB commands made for the Keithley instrument, a terminal had to be used in order to verify that the commands were being read by the Keithley machine and that the Keithley machine returned the data or operated how it should have. The terminal I used to verify this was Tera Term. After I verified the communication with the terminal, I set out to use PyVISA, which is a Python package that enables the programmer to control measurement devices with a GPIB interface to run a program to collect data from the Keithley machine and graph plots of the data. Some of the technical specifications that were paid close attention to were the baud rate, carriage return (CR) & line feed (LF), the configuration of the DIP switch for turning on the Controller mode (allowed controller to listen and talk to Keithley machine), and setting the address of the GPIB controller to the address of the measurement device that it would be communicating to. The baud rate is important to set for the terminal or program when communicating from the computer to the Keithley via the GPIB controller. The baud rate is data transfer rate and it refers to the number of signal or symbol changes that occur per second. These signal and symbol changes come from the fact that a command is transferred into ASCII characters, which are then processed and sent from the GPIB controller to the Keithley machine; the Keithley machine acknowledges the command and acts upon it to return back to the program what it was asked to do. The carriage return (CR) & line feed (LF) also had to be set in PyVISA and in the terminal to work properly because they are both necessary to let the Keithley machine know that the command sent from GPIB has terminated and is ready to act on the command sent. In addition to setting DIP switch #6 so the controller could talk and listen to the Keithley machine, I also had to make sure to tell the controller the address that the Keithley machine was set to, which was at address 27, so that the GPIB port could properly transfer data from the computer, to the controller, to the Keithley machine.

Figure 6: Prologix GPIB-USB 3.12 Controller

Strontium-90 Radioactive Source

In order to test the functionality of the diamond detector without placing it in the Switchyard beamline, a Strontium-90 Source had to be used. Strontium-90 undergoes beta decay and radiates beta particles. With a decay energy of 0.546 MeV, the distribution of that energy was among an electron, an anti-neutrino and the Yttrium-90 isotope. The emission of the electron, which is beta decay, imitates a charged particle that can hit the diamond material and cause a current signal. Beam pulses were simulated with the Strontium-90 source to see an increase and decrease in the current signal from the diamond detector.

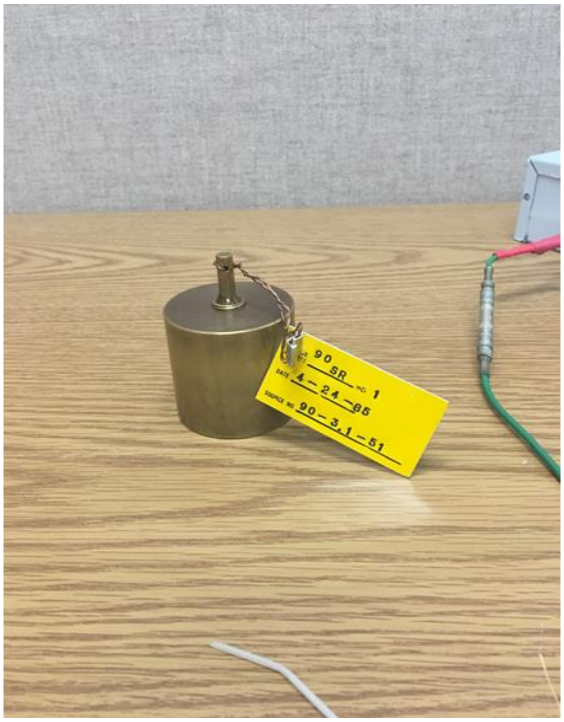

Figure 7: Strontium-90 Source used to test the diamond detector for a current signal.

Current Signal from Diamond Detector

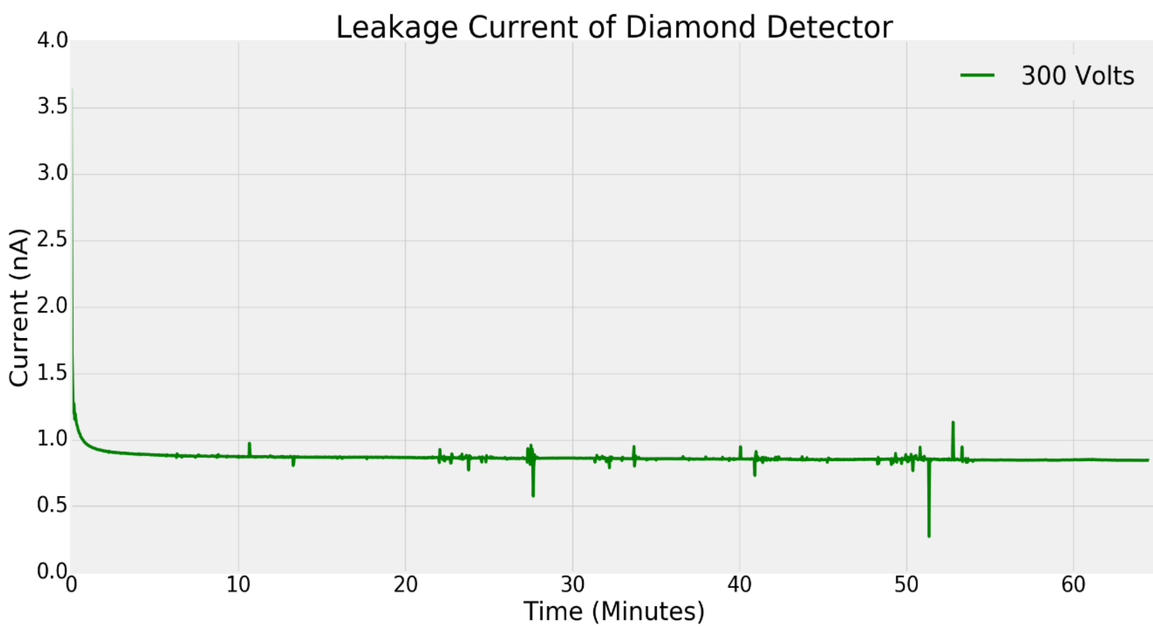

Figure 8: Here is a plot of data that taken from the diamond detector. As seen from the graph, the leakage current levels off as a function of time from when the bias voltage is first applied.

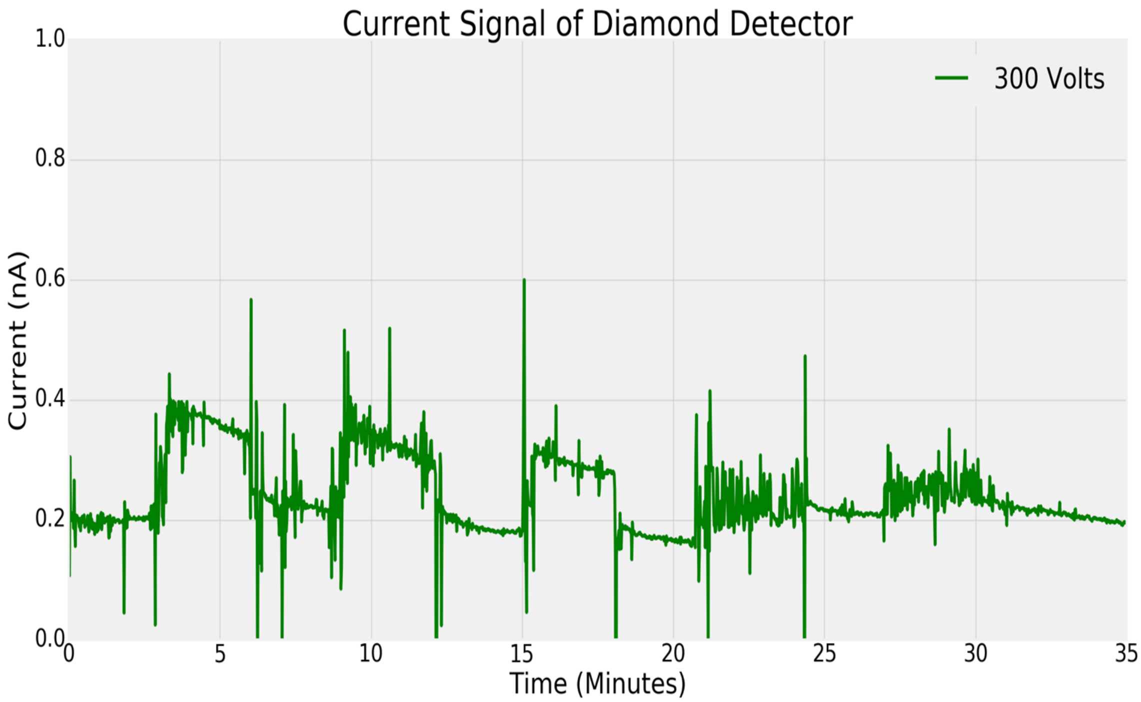

Figure 9: Here is a plot of data with a Strontium-90 source being applied on the diamond detector for several 3 minute increments. As seen from the graph, there is an increase and decrease in the current signal measured as to when the Strontium-90 source was applied and taken off the diamond detector.

Fermilab Test Beam Facility & Calculations

We tested the diamond detector at the Fermilab Test Beam Facility (FTBF), where there is open access to test beam for particle detectors. Through our experience we learned a very valuable piece of information that assisted us in achieving a very high signal to noise to ratio.

Before placing the diamond detector in the beamline after obtaining successful data through applying the Strontium-90 source, an operational readiness clearances (ORC) review had to be made by ES&H to ensure that the process for placing the diamond detector in the beamline was safe. We had to explain the purpose for placing the diamond detector in the beamline, its impact on the radiation environment and address electrical and safety hazards.

Figure 10: The diamond detector was mounted on a scintillator when placed in the MTEST beamline to be tested if a current signal is read when the beam goes through the diamond detector.

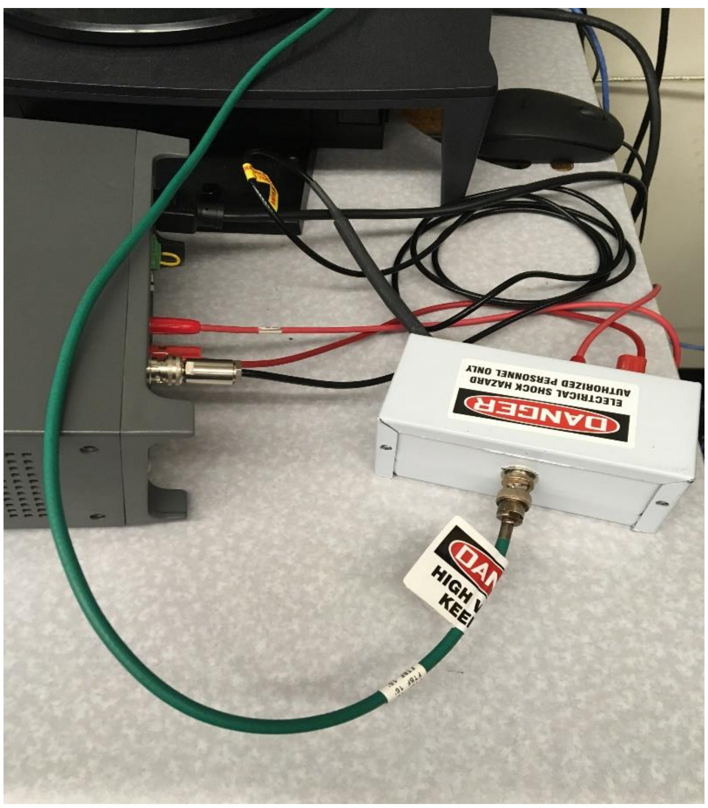

Figure 11: This was the setup from inside the control room. An RG-58 cable went from the control room to the enclosure where it would then be connected to the diamond detector to apply the high voltage and readout the current signal. The circuit for applying and reading out the current was in the box for safety purposes.

Two essential calculations that were needed to ensure that it was safe to place the diamond detector were the RMS scattering angle and the power loss (interaction length). The RMS scattering angle calculation is obtained through using relativity and a theta RMS equation, which is meant to estimate scattering through small angles. The interaction length is simply estimated through knowing the nuclear interaction length and the thickness of the object that is being placed in the beam. The nuclear interaction length and radiation length (needed for scattering angle calculation) are found from a group that compiles properties of elements and particles called the Particle Data Group. The interaction length is simply the thickness of the diamond divided by the nuclear interaction length of the diamond (24.38 cm), so the interaction length is 0.4%. Here is the calculation for the RMS scattering angle that I did on python, which was around 6 microradians:

In [1]:
```
#RMS Scattering Angle Calculation
#do for 120 GeV beam
```

In [2]:
```
#Every particle has a non-zero amount of enery, this is known as the rest ener
gy.
#Due to the high particle energies and speeds in the accelerators,
#special relativity has to be taken into account to describe the accelerated p
articles
#This brings us to using a relativistiv factor, gamma, which gives us a differ
ent
#way to express the total energy.
```

$$E_{rest} = mc^2$$

$$E_{total} = \gamma * mc^2$$

$$E_{total} = E_{kinetic} + E_{rest}$$

In [3]:
```
#Using the previous definitions of the energies, we can calculate gamma.
```

$$\frac{E_{tot}}{E_{rest}} = \frac{\gamma * mc^2}{mc^2} = \gamma$$

In [4]:
```
E_rest = 938E6 #rest energy state of 1 proton bc it is the switchyard beam
E_kinetic = 120E9 #beam energy
E_tot = E_rest + E_kinetic
gamma = E_tot/E_rest   #this gives us gamma bc energy cancels out, E_tot = gam
ma*m*c^2
print 'Gamma is '+str(gamma)
```

```
Gamma is 128.931769723
```

In [5]:
```
#Beta represents the percentage of speed light that the beam is going
#Because of relativistic effects, a particle's velocity approaches the speed
#of light in vacuum, but it never actually reaches that velocity
```

$\beta = \frac{v}{c}$

In [6]:
```
#relativisitc factor equation
```

$\gamma = \sqrt{\frac{1}{1-\beta^2}}$

$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$

In [7]:
```
#There is also relativistic momentum which is expressed as:
```

$p = \gamma * mc$

In [8]:
```
#Thus, the momentum can be calculated by: (units of eV/c)
```

$p = \frac{E_{total}}{c}$

In [9]:
```
#These equations are for factoring in the time, length and relativistic mass
#change for an object while it is moving. This is known as the Lorentz factor
#v is relative velocity, beta is ratio of velocity, v, to speed of light, c.
#We use the Lorentz factor since the beam is traveling really close to the spe
ed of light.
#So, we take into account for special relativity.
```

In [10]:
```
beta = (1-1/gamma**2)**0.5    #relativity equation
print 'Beta is '+str(beta)
print 'The beam goes at ' +str(beta*100) +'% of the speed of light.'
```

```
Beta is 0.999969921467
The beam goes at 99.9969921467% of the speed of light.
```

$$\Theta_{rms} = \frac{13.6\,MeV}{pv} z \sqrt{\frac{x}{X_0}}[1 + 0.038 ln(\frac{x}{X_0})]$$

In [11]:
```
#This equation is used for when a charged particle is traversing a medium
#(in this case the diamond material) for which causes small angle scatters.
#x/X_0 is the thickness of the scattering medium in radiation length
#x is the thickness of the diamond material
#X_0 is the radiation length of the diamond material, which has been measured
#and is a known number of 12.13 cm
```

In [12]:
```
c = 2.9979E8 #m/s, speed of light
v = beta*c #m/s, speed with relativity taken into consideration
p = E_tot/c # eV/c
print 'Momentum is ' +str(p)
```

```
Momentum is 403.409053004
```

In [13]:
```
x = 500E-6 #thickness of diamond, in meters
X_0 = .1213 #radiation length of diamond, in meters
z = 1 #this is the charge number of proton beam
```

In [14]:
```
import math
theta_rms = ((13.6E6)*((x/X_0)**0.5)*(1+.038*math.log(x/X_0)))/(p*v)
print 'Theta_rms is ' +str(theta_rms)
print 'The scattering angle of the Diamond Detector is ' +str(theta_rms*10**6)
 +' microradians.'
```

```
Theta_rms is 5.71346239686e-06
The scattering angle of the Diamond Detector is 5.71346239686 microradians.
```

Data & Results

Unfortunately, due to an error in our instrumentation, we did not achieve a high enough signal to noise ratio so that we could see the current signal from the diamond detector when a beam pulse went through the diamond material. In other words, we could not detect the beam with the diamond detector due to our cabling for the diamond detector. As shown by Figure 12 and 13 (two different instances in which the beam hit the diamond detector), during a 15 second data acquisition when an increase in the current signal should have happened at the four second mark, we picked up only noise. The reason we know we picked up noise was due to the increase of magnitude from previously measuring in nanoamps to measuring in milliamps, a really significant difference when it comes to reading out a current signal from a diamond detector.

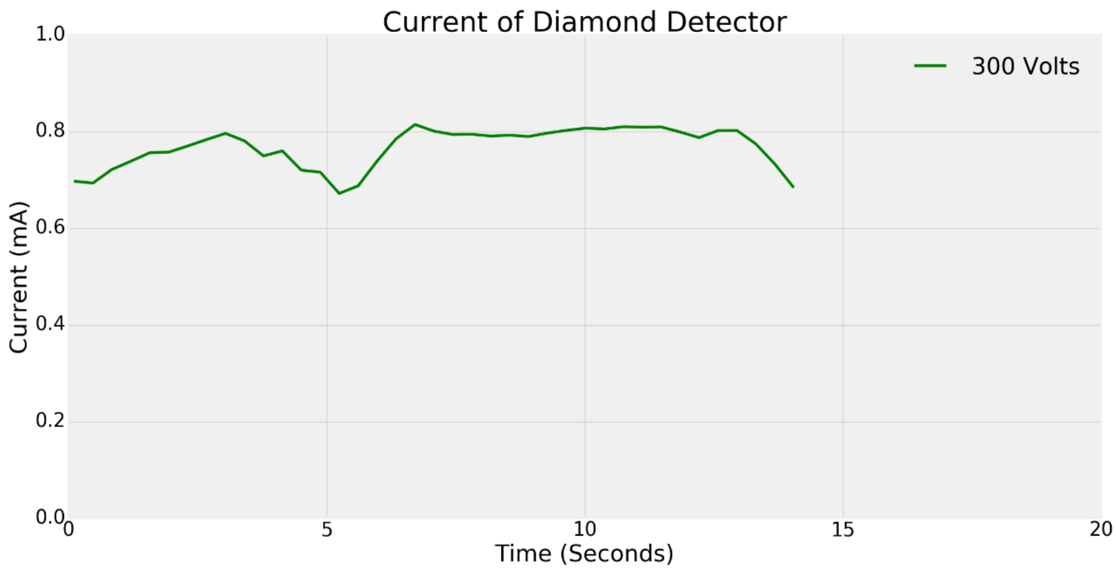

Figure 12: Noise picked up from the diamond detector. The current signal should have increased around the four second mark when the beam went through the diamond detector.

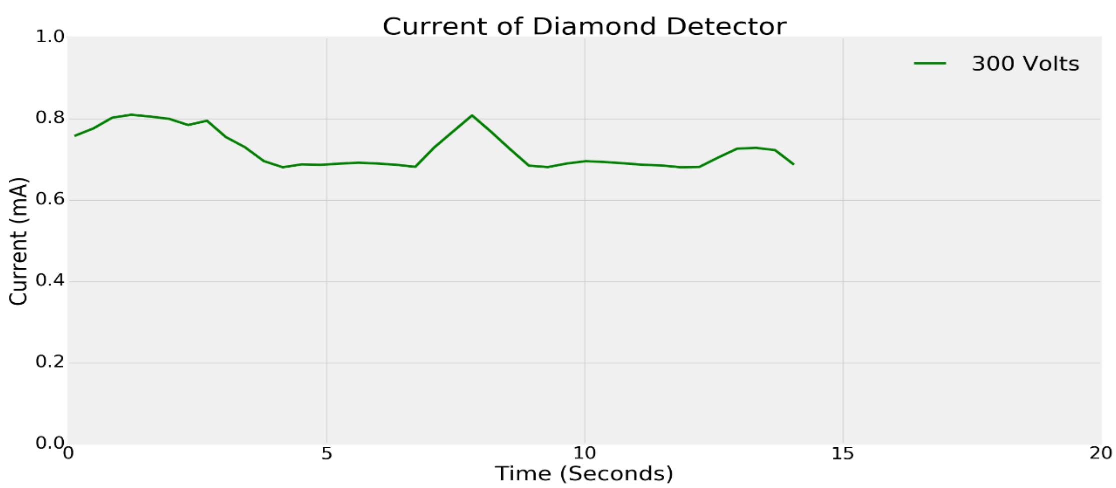

Figure 13: Noise picked up from the diamond detector. This is at different time than when the plot in Figure 12 was taken. The current signal should have increased around the four second mark when the beam went through the diamond detector.

Improvements

Like mentioned earlier, in order to carry out a high signal to noise ratio, we needed a better Faraday cage so the diamond detector wouldn’t pick up noise from outside electric fields. So in order to fix this issue, we set out to use two coaxial cables for better shielding that would pick up less noise. As shown in Figure 14, the instrumentation fix we made dealt with how we initially set the high voltage and readout for the diamond detector. At first, we had one RG-58 cable in which the center pin carried the high voltage to the diamond detector and the outer shield of the RG-58 cable carried the current signal from the diamond detector to the Keithley machine to be read. This set up acted as an antenna, which therefore picked up noise. To obtain a high signal to noise ratio, we used two RG-58 cables to carry both the high voltage and the return of the current signal. Both were carried through the center pin of each RG-58 cable where the outer shield was grounded so that less noise would be picked up and therefore give us a high signal to noise ratio. As a result, we went to try the new instrumentation at the Fermilab Test Beam Facility (FTBF) again. We got good results in that our signal to noise ratio was high enough to be measuring in nanoamps again, shown in Figure 15. We verified if this set up at FTBF worked in detecting charged particles by applying the Strontium-90 source, and we saw an increase in the current signal, which meant that our new instrumentation was successful for reading out a current signal.

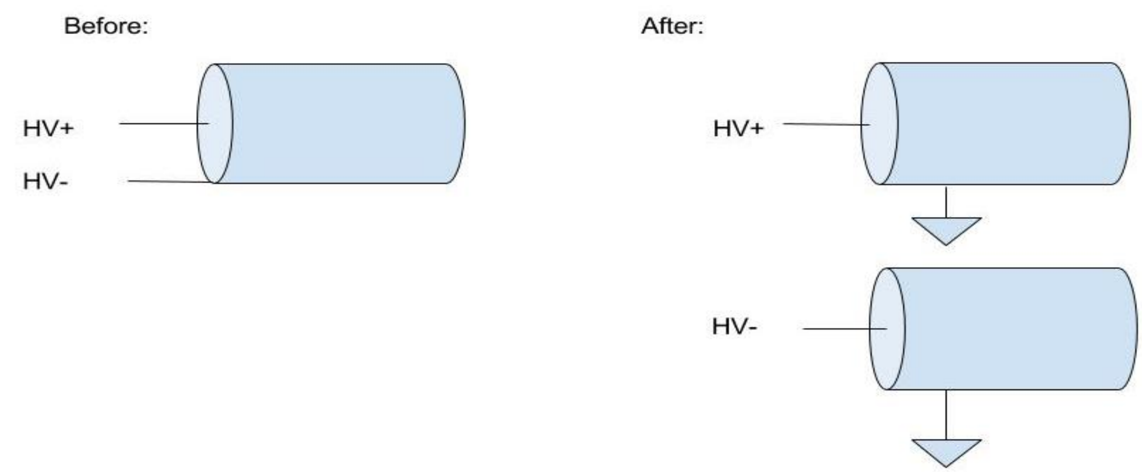

Figure 14: Our first set up (as shown in the left image) for supplying the high voltage and returning the current signal was with only one RG-58 cable. The high voltage was supplied through the center pin the and the return of the current signal came from the outer shield of the same RG-58 cable. This allowed for a lot of noise to be picked up. Our second set up (as shown in the 2 right images) for supplying the high voltage and returning the current signal was with two RG-58 cables. The high voltage was supplied through the center pin of one RG-58 cable and the return of the current signal came from the center pin of the other RG-58 cable. Both outer shields of the RG-58 cables were grounded so a higher signal to noise ratio would be produced.

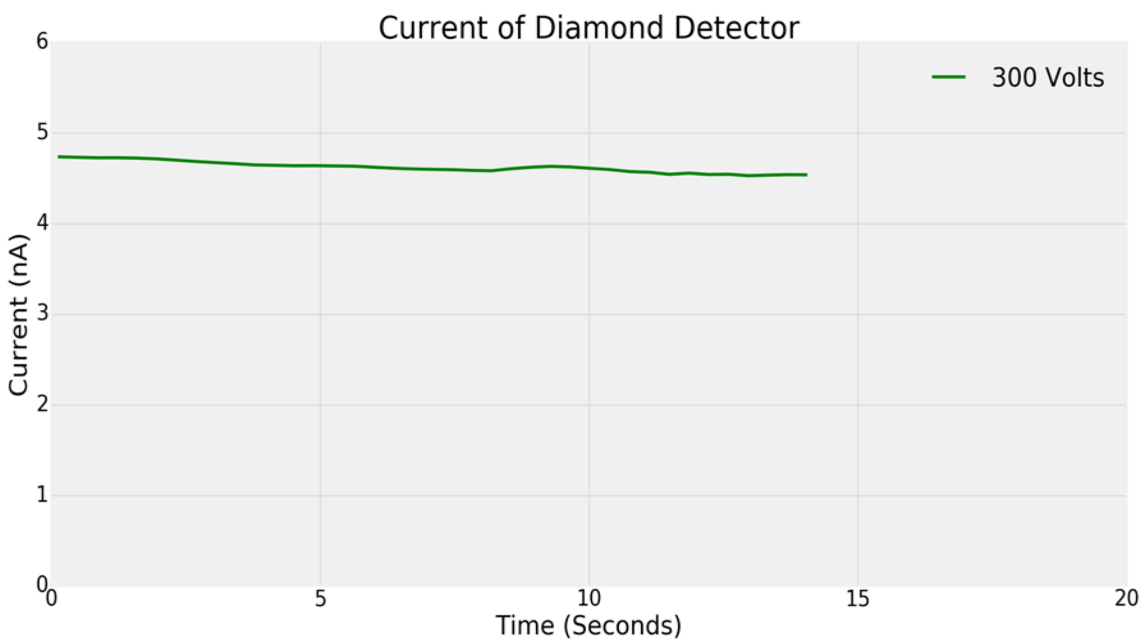

Figure 15: With the new instrumentation, we were measuring current in nanoamps again, as opposed to milliamps

Figures 16 & 17: Here is how the box differed from the initial set up with only one RG-58 cable in the left image to the second set up with two RG-58 cables in the right image.

Conclusion & Future Directions

In conclusion, we are still looking to discover whether the diamond detector can measure the micro-bunch structure of the beam. The readout hardware and instrumentation has to be very fast and precise in how it’s made to readout the current signal. This leads to a rise in costs for the diamond detector as getting the proper instrumentation and engineers to design a better Faraday cage and readout hardware will amount in the setup of the diamond detector being more expensive. We are also looking to discover the dynamic range of the diamond detector. For example, can it read the intensity from a few hundred particles up to 10^{13} particles? Since the current signal should increase or decrease linearly, depending on the intensity that is applied to the diamond material, we predict that the diamond detector should have a large dynamic range.

Acknowledgements

I would like to thank both of my supervisors, Dr. Carol Johnstone and Adam Watts, for helping me throughout this project. I would also like to thank Gianni Tassoto, Richard Tesarek, Rick Pierce, David Peterson, and Arden Warner for helping me carry out my project during the summer.

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