SANE T.N. #
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The Effect of the Target's Magnetic Field on Big Cal's PMTs

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1 PMT Exposure

The Hall C polarized target uses a 5 Tesla Oxford magnet to supply the field necessary for polarization of the target material. This magnet is composed of several superconducting coaxial Helmholtz coils, and therefore has a non-negligible fringe field. The fringe field is large enough to affect Big Cal's photomultiplier tubes (PMTs). This study quantifies that effect.

SANE will be taking data with the magnet's coil axes parallel to the beam line and with the magnet rotated 80 degrees from that position. In both cases Big Cal is positioned with the face of the lead glass 3.25m away. Big Cal's lead glass bricks are 40 cm long, which puts the front of the PMT array 3.65m away from the target. WACS has a different configuration depicted below in Figure 2. The different magnet configurations will expose Big Cal to different levels of magnetic field strengths across its PMT array. The positions of Big Cal, the beam path, and the symmetry axis of the magnetic field for SANE are shown in Figure 1. Figure 2 shows the placement of Big Cal, the beam line, and the magnetic field axis for WACS.

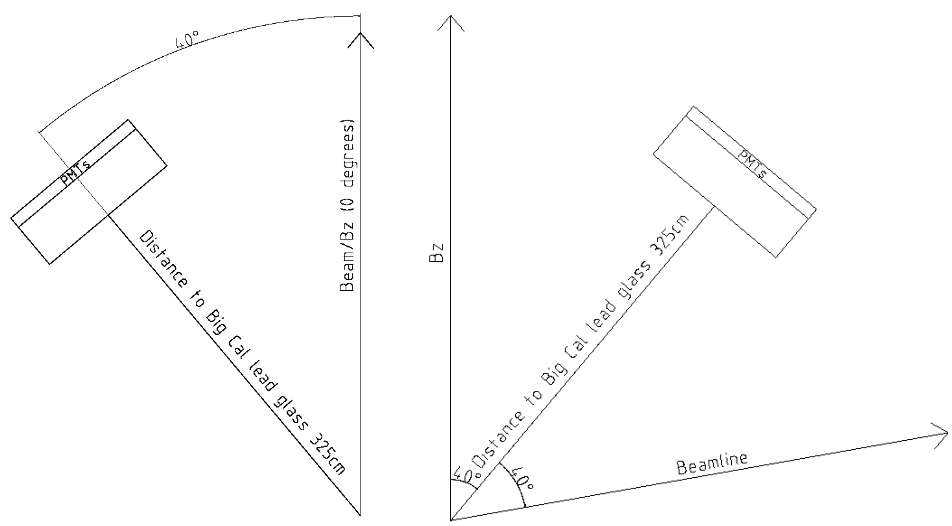

Figure 1: *Left*: SANE's parallel configuration. Big Cal is positioned at a scattering angle of 40°, and the magnetic field is pointing along the beam line. *Right*: SANE's near perpendicular configuration. Big Cal is in the same position, but the magnetic field has rotated to make an angle of 80° with the beam line. Bz is along the magnet axis.

The photomultiplier tubes are roughly 10cm in length and are mounted with their faces flush against the lead glass of Big Cal. The location of the PMT array is indicated in the above figures. Using cylindrical coordinates determined by the symmetry of the magnet coils, with the origin at the center

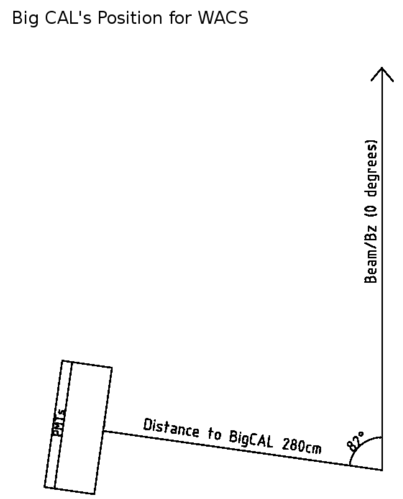

Figure 2: WACS' configuration. The magnetic field points along the beam line. Big Cal will be moved to detect particles scattering at an angle of 82°. Big Cal is also significantly closer to the target than in SANE's configuration.

of the coils, the coordinates of six points along the width of the PMT array are calculated. Then a field map [2] is used to determine the field strength at those locations. Because the magnetic field changes the trajectory of the charged scattered particles, the events will not be in the scattering plane–in the middle of Big Cal's face. The electrons scattered will be deflected from the scattering plane. The events will be centered approximately 26 inches up (or down depending on which way the field is pointing) from the mid-point of lead glass array.

The field estimates herein are for the middle of the array. The PMT's detecting the desired events will be out of the scattering plane and thus are exposed to a smaller field, making the numbers used in this report a conservative estimate. The out-of-plane PMT's are effectively further away from the magnet than the in-plane ones, and angled such that less of the field is directed along the length of the PMT.

Using a conservative estimate is crucial for another reason. The field map that we are using (see [2]) is an extrapolation from a measurement of the field within the bore of the magnet. Rough checks of it have been done, but the map gives numbers out to hundredths of Gauss. One has no reason to believe the map to be accurate to that level. We will continue with it in mind that the field strengths predicted below are over-estimates.

Field strengths at various points along the PMT array for the different configurations are shown in Table 1. Since it was found that a field component perpendicular to the cylindrical axis of the PMT does not affect the PMT's performance, only the total field magnitude and the field component along the length of the PMT is given here.

In no case is the relevant magnetic field component (along the PMT axis) greater than 9.4 Gauss at any of the PMT's locations–that is, according to the field map. There is ferrous material throughout the experimental apparatus, noticeably the housing for the lead glass. This material may act as a magnetic channel and cause a slight increase in the field experienced by the PMTs.

2 Setup for PMT Response Testing

The PMTs installed in Big Cal are Russian type FEU 84-3 tubes. These tests were done using two PMTs of the the same model with a Protvino base. The PMTs mounted on Big Cal have μ metal shielding

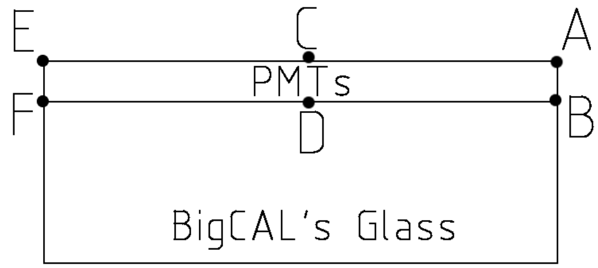

Figure 3: For reference in Figure 1; labeled corners and front and back center of the PMT array. These labels are assumed to lie halfway up the height of Big Cal. That is where the field will be the strongest since it is rotationally symmetric. That may not be where the scattered particles are necessarily concentrated for any give field orientation.

SANE 0° configuration			
Point	Coordinates(cm) (R,Z)	Field Magnitude (10^{-4}T)	Axial Field (10^{-4}T)
A	(-192,328)	8.71	8.65
B	(-186,320)	9.44	9.38
C	(-241,287)	8.29	7.64
D	(-234,280)	9.09	8.40
E	(-290,246)	8.00	7.35
F	(-283,239)	8.78	8.08
SANE 80° configuration			
A	(-290,246)	8.00	7.35
B	(-283,239)	8.78	8.08
C	(-241,287)	8.29	7.64
D	(-234,280)	9.09	8.40
E	(-192,328)	8.71	8.65
F	(-186,320)	9.44	9.38
WACS configuration			
A	(-318,109)	8.19	5.79
B	(-308,107)	9.99	6.51
C	(-327, 46)	7.82	2.12
D	(-317, 45)	8.42	2.38
E	(-336,-17)	7.15	0.02
F	(-326,-18)	7.83	0.20

Table 1: Here is displayed the coordinates of the points labeled in Figure 1, and the magnetic field they will see at that point for a given configuration. The magnitude of the field is shown, as well as the axial component–that is the strength of the field component pointing along the length of the PMT. The coordinates used are cylindrical coordinates with the origin at the target and the z-axis in the direction of the field.

that ends flush with the front face of the tube where they are mounted against the lead glass. We used identical shielding for our study.

A Helmholtz coil was constructed along with a trough in which to suspend the tube in the uniform region of the Helmholtz coil's field. The coil was able to be repositioned in order to orient the field along the PMT's cylindrical axis or perpendicular to it. In order to measure the effect of the field on the PMTs, count rate studies and spectroscopy at various field strengths and orientations were performed.

2.1 The Magnetic Field

The Helmholtz coil constructed for these tests has a radius of 4 inches, and a region of uniformity large enough to engulf the entirety of the phototube. The field was measured along the central axis of the coils and along the diameter between the coils. The field component measured in both cases was that parallel to the axis of the Helmholtz coil. It was along these two lengths that the PMT was placed to measure the effect of a field parallel and perpendicular to the central axis of the PMT. The field measurements are reliable to about a tenth of a Gauss. Plots of the field strength for several different coil currents are shown in Figure 4. The field along the diameter falls within 10% of its average value and the field along the axis within 8%. The coordinate origin is arbitrary and fixed with respect to the coils. The PMT was placed in the most uniform region of the field. Figure 5 is a visual aid, demonstrating the PMT orientation with respect to the coils during testing.

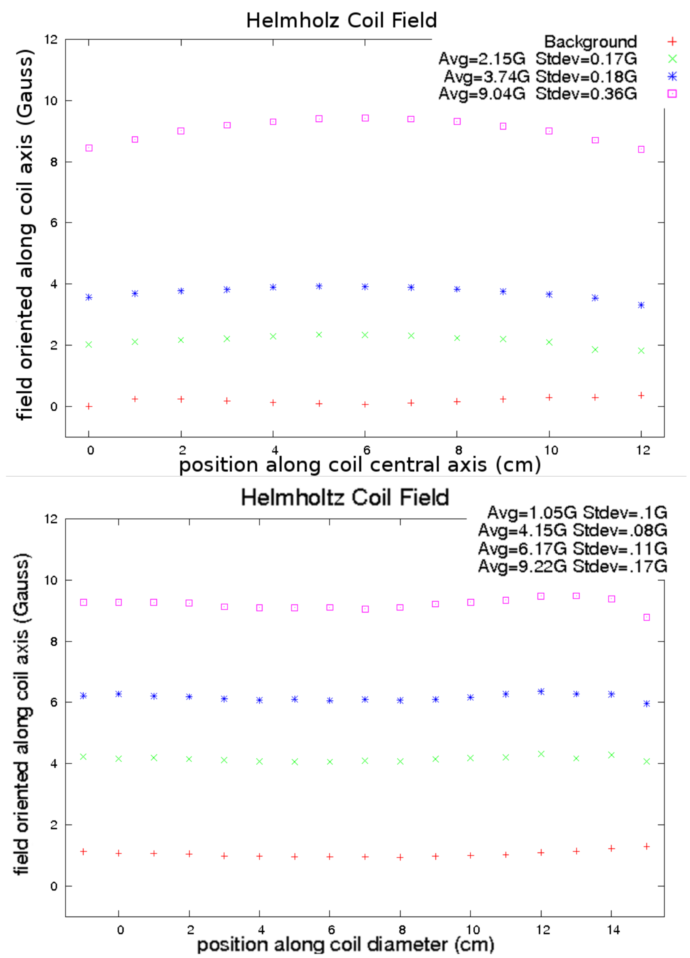

Figure 4: *Left*: The field along the axis of the coil. *Right*: The field along the diameter of the coil. The regions mapped out in these plots are the regions in which the PMT was placed for testing. The field was mapped out for many currents in order to estimate uniformity of the coil's field.

2.2 Signal Detection

Events were generated by a Cs-137 source or a Co-60 source. An 1/8" thick CsI crystal mounted on the front face of the PMT was used as scintillation material to transform the incident particle's energy into a signal detectable by the photocathode. The radioactive source was kept flush with the scintillator

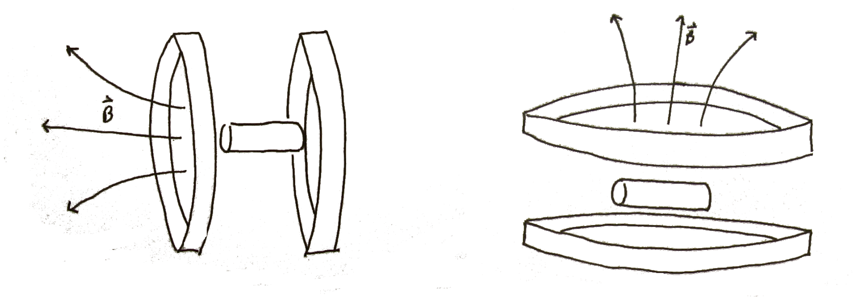

Figure 5: A cartoon showing the PMT in the Helmholtz coil: longitudinal field and perpendicular field respectively

to provide maximum count rate. An amplifier and discriminator were used to process the PMT output signal. A scaler was used for the count rate studies, and an ADC was used for spectroscopy. FEU-84-3 tubes operate between -1.6 kV and -1.9 kV. For these tests, unless otherwise specified, the supply voltage was -1.8kV.

3 Results

3.1 Count Rate

The emission rate of particles from a Co-60 source was measured. The count rate was recorded for field strengths from 0 to 10 Gauss for both a longitudinal and a perpendicular magnetic field (see Figure 5). Photomultiplier tubes are known to be sensitive to small magnetic fields. Tubes with the multiplier stage of the sort used in Big Cal are known to be most susceptible to perpendicular fields [1]. This seems intuitive since a field in that direction would be perpendicular to the net path of the electrons along the dynode chain. This was found not to be the case. The count rate did not change for any of the field strengths in the perpendicular configuration, whereas the count rate changed drastically when the field was oriented longitudinally. Apparently the μ metal shielding around the outside of the PMT completely masks the tube from magnetic flux perpendicular to the length of the tube. The shielding, however, does not protect at all from flux directed along the length of the tube. Figure 6 shows the count rate as a function of applied field strength.

The fact that the count rate drops at around 5 Gauss indicates that the output pulse of the PMT has decreased below the discriminator threshold of 75mV. The point at which the curve in Figure 6 drops is heavily dependent on the PMT signal amplification and the discriminator threshold. What can be concluded from these plots is that the component of a field oriented perpendicularly across the PMT axis has little effect on the pulse height output by the PMT. In fact, over the range of 0-10 Gauss for a perpendicular field, the pulse height does not decrease below the level to which the pulse height drops when the PMT is exposed to a 3.5 Gauss parallel field. A more quantitative look at the effect of the magnetic field on the pulse height will be found in the next section.

3.2 Spectroscopy

Provided the scintillator in front of its photocathode is capable of absorbing all of the energy of the incident particle, the height of the output pulse of a PMT is proportional to the energy of the incident particle. A DAQ system was set up in which an ADC integrated over the length of PMT pulse, and then sent the result to a computer which recorded it as a count in the ADC channel into which the signal was sorted. The resultant histogram then is an energy spectrum of the events viewed by the PMT. A Cs-137 source was placed before the PMT, and the energy spectrum recorded by the DAQ displayed a clear photopeak within the range of our DAQ/PMT set up. When a magnetic field was applied to the

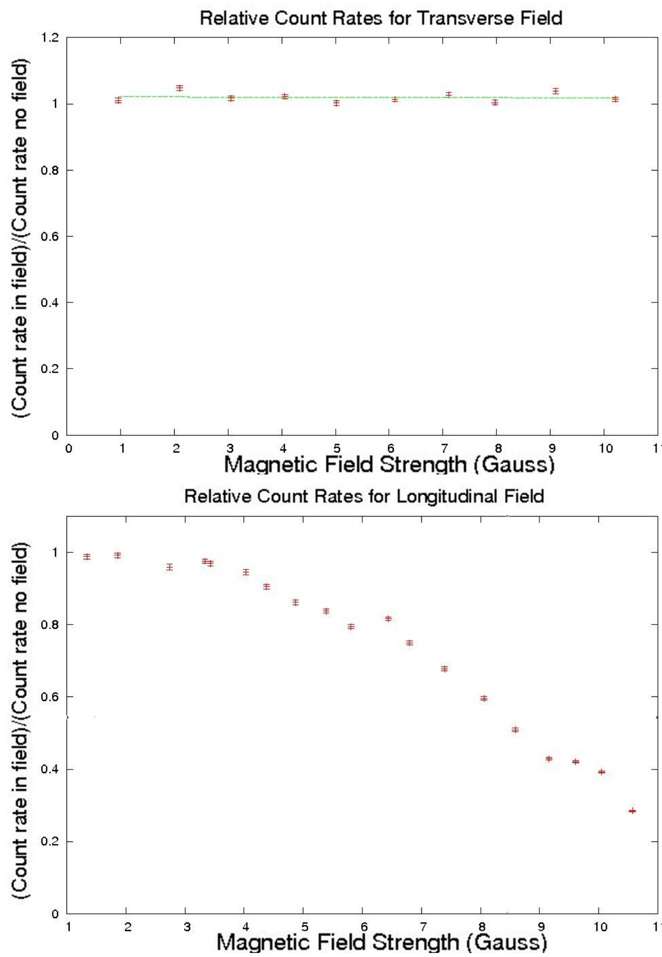

Figure 6: *Left*: Perpendicular configuration. *Right*: Longitudinal configuration. Here one can see a drastic decrease in count rate when the field is oriented along the axis of the PMT. This drop occurs when the output pulse peak starts to sink below the discriminator level. Thanks to the shielding, the perpendicular field has little effect on the pulse height.

PMT, it's gain changed, decreasing the height of the output pulse. The change in gain was visible as an apparent shift in the location of the Cs-137 peak, see Figure 7.

The dependence of the location of the photopeak on applied field is a direct measurement of the gain change of the PMT as a function of applied magnetic field. Measurements were taken in a range from 0 to 10 Gauss with a parallel magnetic field for both PMTs. The results are plotted in Figure 8. Two lines are fitted through the data. I have not thought about whether there are any physical principles that suggest this linear threshold sort of trend, but it does appear to reasonably characterize the gain shift over the range the measurements were taken.

The gain shift of a PMT as a function of supply voltage shift was also measured. The supply voltage will have to be adjusted in order to restore gain levels once the tubes are exposed to the target magnet's field. Measuring how the gain shifts with voltage allows an estimation of how much the voltage will have to be adjusted when calibrating the PMTs.

With the only field present being the earth's, the supply voltage was varied while recording the position of the photopeak. The results, plotted in Figure 9 show that the shift in gain is about 7.4% per 1% change in supply voltage. The result is bound to differ somewhat from PMT to PMT. A general argument was put forth in Leo's book on instrumentation for the gain shift for a 12 stage PMT being 12% per 1% shift in supply voltage[1], but that was not found to be the case for the two PMTs examined

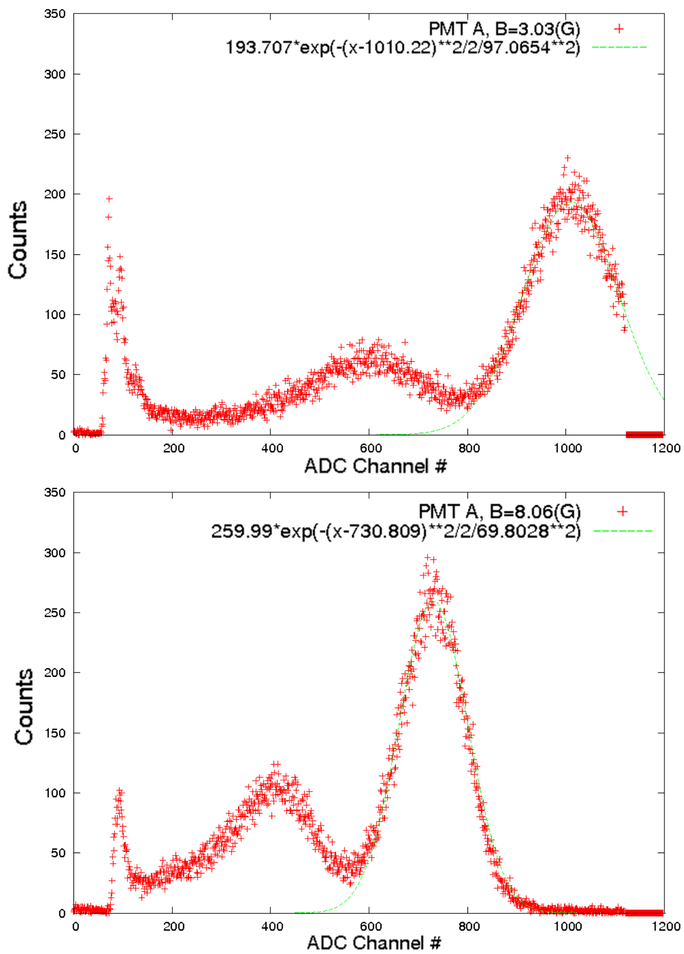

Figure 7: Left: Cs137 spectrum at B=3.03 Gauss, Right: Cs137 spectrum at B=8.06 Gauss. Gaussian fits are made to the photopeak and displayed in the legend. The varying height is an artifact of the DAQ system, and is not an effect of the applied field.

here.

Using the linear approximations from Figure 8, the gain shift was calculated for several of the points around Big Cal (see Figure 3) for the various experimental configurations. The shift in supply voltage that would compensate for the gain shift due to the magnetic field at that point is tabulated in Table 2. As shown in the table, one corner of Big Cal experiences the largest parallel field, and the gain shift decreases from there across the face of the PMT. The largest gain shift is 34.6%. A shift in supply voltage of 4.7% (-1.8kV to -1.88kV) would restore the gain to its previous level.

3.3 Conclusion and Other Points

There were seen no substantial difference between when the field was oriented parallel or anti-parallel to the PMT. The field strengths listed in Figure 1 do not distinguish between the parallel versus the anti-parallel case. It was found that this distinction was not necessary, as the PMTs responded identically in both cases.

No spectroscopy measurements were done with the field oriented perpendicularly relative to the length of the PMT, as it was assumed that the count rate study was enough to indicate the effect of a field in that direction is negligible.

The listed field strengths are based on an extrapolation of a survey of the interior bore of the 5T

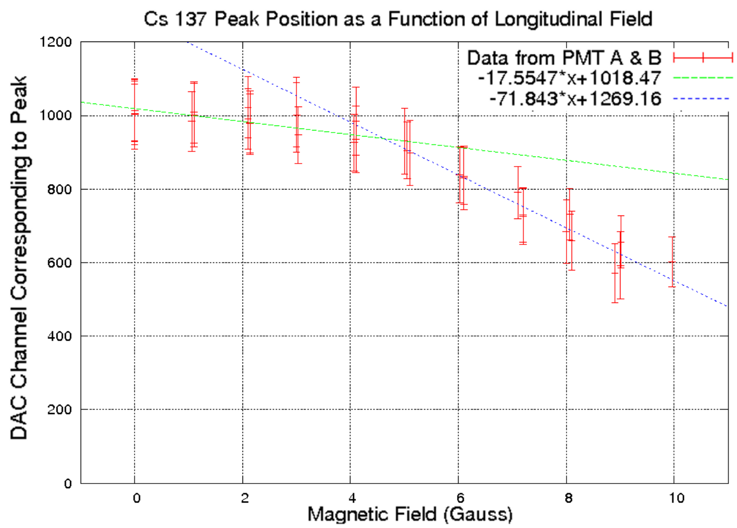

Figure 8: Linear fits are applied in the ranges 0-4.5 Gauss and 4.5-11 Gauss. The linear fit in those ranges can be used as a rough estimate of the shift photopeak position. The error bars indicate the photopeak width.

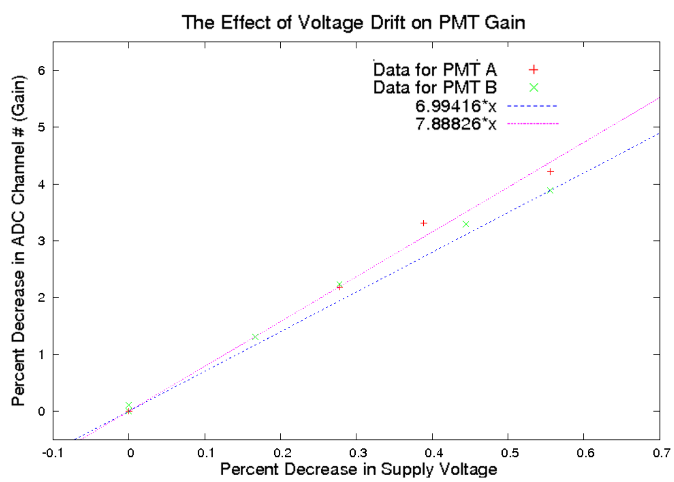

Figure 9: A line is fitted to the data from each PMT. The operating voltage started at -1.8kV and was decreased from there. Percent gain change per percent supply voltage change is about 7.4

magnet. It has not been tested for high accuracy, and it does not take into account ferrous structures in the hall. It is entirely possible that a girder supporting Big Cal may act as a magnet channel and expose one of the PMTs in it's array to fields larger than what is dealt with in this study. It is also possible that the extrapolation is slightly under or over the true value of the field.

I would recommend that, if possible, Big Cal be calibrated with the field on. It appears that the field is going to have an extremely uneven effect across the PMT array, and that estimating that effect and adjusting the gains accordingly will not be a reliable procedure. This is especially true because of the ferrous girder surrounding the calorimeter. A separate calibration for the near perpendicular and parallel set up would be necessary, as the field strengths will change, and the PMTs that matter will be in a different spot due to deflection of the charged particles by the field. A positive note is that the gain lost due to the field can easily be made up for by increasing the supply voltage.

	Big Cal Point	Gain Shift Due to B Field (%)	Corresponding HV Shift (%)
	B	32.38	4.38
80°	D	34.64	4.68
	F	41.55	5.62
	B	41.55	5.62
0°	D	34.63	4.68
	F	32.38	4.38
	B	21.31	2.88
WACS	D	4.1	0.55
	F	0.34	0.05

Table 2: Gain shifts caused by the B field and the estimated supply voltage change required to restore the gain level.

4 References

1. W.R. Leo : *Techniques for Nuclear & Particle Physics Experiments* (Springer Verlag, New York, 1992)

2. Available at http://spin.phys.virginia.edu/˜or/sane/target/field_ map.ods spreadsheet by Oscar Rondon

5 Acknowledgements

Many people contributed to helping these tests happen.

- Lubomir Pentchev provided the photo tube and the base
- Seonho Choi extrapolated the measured field map of the magnet used to determine field strengths around Big Cal
- As this was my first time setting up a DAQ system of any sort, the following people were instrumental in helping with the electronics and computer system: Oscar Rondon, Donal Day, Don Crabb, Vahe Mamyan, and Josh Pierce

6 Appendix A

This is just a quick illustration that one can compensate for the gain lost due to the field by raising the HV supplied to the tube. A spectrum is measured with no field, and then a field is applied and the high voltage adjusted to produce the same spectrum. In one case, a PMT is supplied with -1.77 kV with no field present. In the second case there is an external field applied of 7.3 Gauss, and the HV has been increased to -1.85 kV. The smaller peak and the larger collection of counts towards the lower channels indicates an increase in noise, which might be caused by the external field. Despite the increase in noise, the peak height has returned to the value it had before the external field was applied. A better match could be found by finer tuning of the supplied voltage.

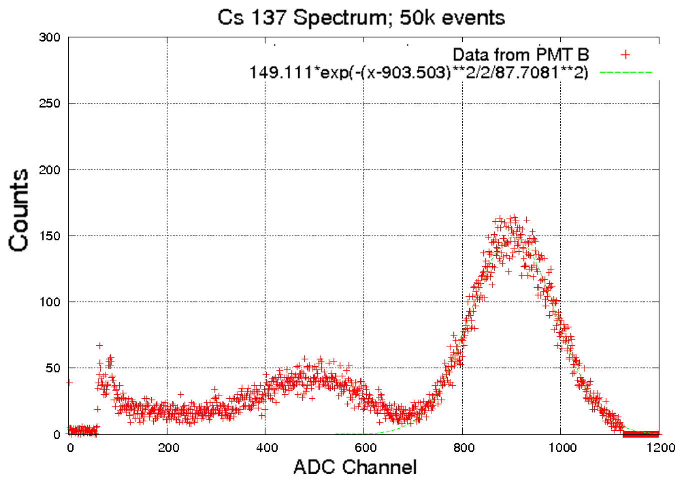

Figure 10: No applied field. -1.77 kV is supplied to the base of the PMT

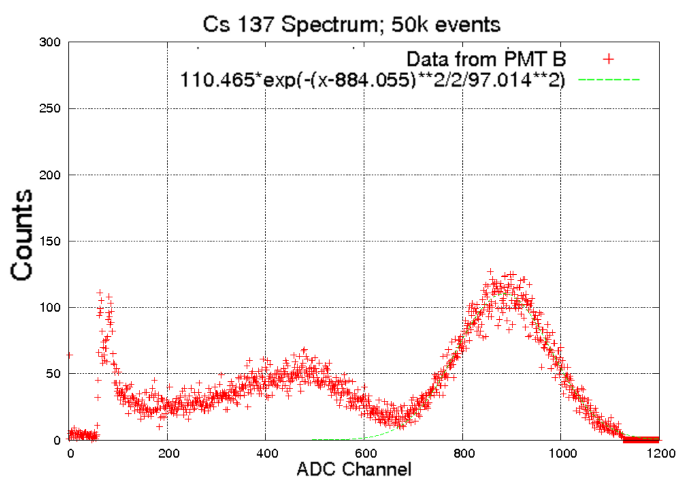

Figure 11: External field strength of 7.3 G. The high voltage supplied to the base has been raised to -1.85kV

7 Appendix B

Here is a more detailed description of the setup used for this study. The PMT signal was amplified and converted to a digital signal using an ADC in a CAMAC crate. That digital signal was read out by a CAMAC controller to a DAQ program on a computer. The connections and modules used for this system are shown in Figure 12

- The Helmholz coil constructed using an 8" diameter aluminum stove pipe cap (from Lowes) and aluminum struts for a frame. A layer of elctrical tape was used to prevent shorts to the frame. It was wound with 100 turns (on each side) of 20 gauge magnet wire. It was powered with a Kepco ATE 15-15M 0-15V 0-25 A magnet power supply. The field current relationship is roughly $B = 7.58I + 1.67$, where B is in Guass and I is in amps. Yes I know that the curve doesn't connect to the origin–I said roughly.
- A Lakeshore 450 Gaussmeter was used to measure the field strength.
- PMT: 2 FEU 84-3 Russian made with same protvino style base, curtesy Lubomir
- $\frac{1}{4}$" thick CsI scintillator crystal was attached to the front of the photocathode
- A Cs 137 and Co60 source was used to provide events
- PMT was powered with an Ortec High Voltage Power Supply
- The PMT was wrapped with foil, electrical tape (see Leo), and the outside of it and the base were all wrapped in foil to reduce noise. The experiment was done inside of a black box with BNC ports.
- The PMT was supported by a trough so that it was placed in the uniform area of the field. A separate trough was constructed for the longitudinal and transverse tests.
- Signals were monitored with a Tektronix TDS 640A 4 channel digital scope.
- The ADC was triggered by signals from an HP 8082A Pulse Generator
- Camac modules used: Lecroy 2249A ADC, Jorway 73A SCSI Bus Crate Controller
- NIM modules used: Model 777 8 channel variable gain amplifier, Lecroy 821 Quad discriminator,
- Computer with SCSI interface card running KMAX. The DAQ program was written by Vahe Mamyan and can be found on that computer at /vm4s/TLSH_new/SCM301_ACC_H2.tlsh

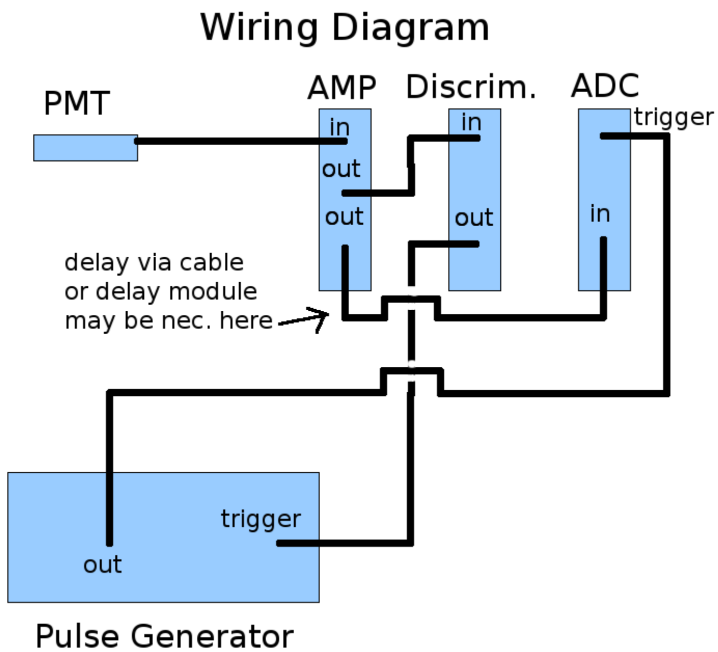

Figure 12: Here is shown the modules used to process the signal from the PMT. The ADC integrates over the input while its trigger reads HIGH. The discriminator output pulse is shorter than the PMT pulse, so using the discriminator pulse as a trigger for the ADC results in clipping. Instead, the discriminator signal serves as a trigger for a pulse generator that produces a longer pulse that is then fed into the ADC trigger.

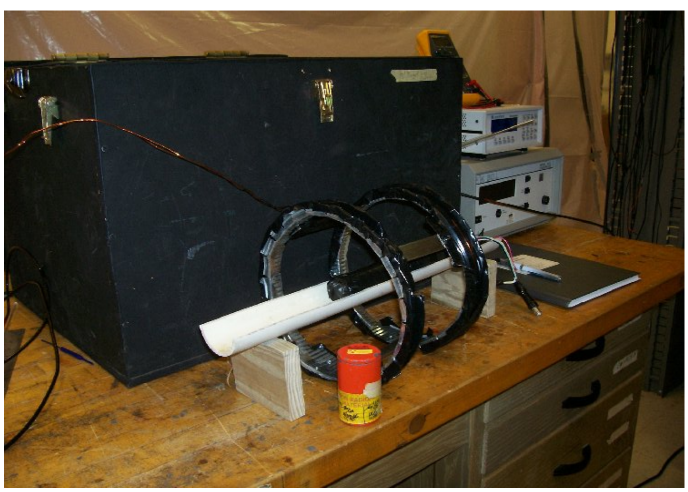

Figure 13: The PMT is shown resting in its trough within the helmholz coil. Behind sits the blackbox within which the testing takes place. The electronics rack is not shown here.