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D∅NOTE #1624

Is high voltage sagging the cause of CCEM response degradation?

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1 Introduction

The electromagnetic (EM) response of CCEM at NWA has been measured to be almost 4% lower in the center of module than at their ends[5]. There are many people within the collaboration who believe that this may be due to a high voltage sag inherent in the structure of our high voltage supplying system. Since the high voltage is applied from both ends of the CCEM signal boards, one might think that the potential is lower in the center than the ends of the board. This note will investigate whether there is a sufficient voltage drop along the board to generate 4% response difference between the center and the ends of the module.

Since two CCEM modules in the NWA test beam load II, CCEM38 and 39, were used for most of the response studies, high voltage sagging is estimated for these two modules. The resistance of signal boards used to build modules are all in the data base, so I was able to use this information in this investigation. The currents used to calculate the voltage sag are taken at the peak of anomalous uranium current to demonstrate the worst case scenario.

2 CCEM high voltage supplying system.

CCEM modules are constructed with 20 $3mm$ thick depleted uranium plates with $2.3mm$ liquid argon gaps either side of a $1.3mm$ thick G10 boards. The G10 boards have copper pads embeded inside and are covered with a resistive coating on their outside surfaces. The resistance of this coating is measured with a special 4 point probe surface resistance measuring device. Its unit is $M\Omega/\square$. This unit is applied for a square with any area. The size of an EM signal board is about 7" in width and 102" in length. Although the width changes slightly as a board is farther away from the beam position in most cases the overall resistance of a CCEM signal board is on the order of $1G\Omega$.

A CCEM module is configured with 5 different independent high voltage gang of boards. The lowest 2 depths are ganged together and supplied by one high voltage power supply. Depth 3 and 4 are supplied by two high voltage power supplies each. Table 1 shows the the signal board configuration of CCEM high voltage gangs.

Each board has two clips at either end which are affixed to the surface of the board with epoxy. Even if we lose one of the clips supplying high voltage to a board we still have one supplying the voltage from the other end. By supplying voltage from both ends instead of one we reduce the effective path length from any point on the board to a HV clip. These reduced path lengths are equivalent to lower resistance paths which yields lower voltage sags.

Table 1: CCEM high voltage gang structure

HV gang #	Sig. Bd. #	Layer	Readout depth	$N^U_{surface}$
A	1, 2, 3, 4	1, 2	1, 2	5
B	5, 8, 11	3	3, 4, 5, 6	5
C	6, 7, 9, 10	3	3, 4, 5, 6	5
D	12, 14, 16, 18, 20	4	7	9
E	13, 15, 17, 19, 21	4	7	10

3 Measured parameters for two NWA CCEM modules

In order to calculate the resistivity of a board from one end to the other, one must know the length , width and surface resistance of each board. During the production of each board, its resistance was measured and logged.

Table 2: Dimensions of CCEM signal boards and resistive coatings

Sig. Bd. #	Length(in)	Res. L.(Len.-0.24)	Width	Res.W(W-0.24)	$N_\square$
1	102.570	102.33	6.311	6.071	16.86
2	102.570	102.33	6.391	6.151	16.64
3	102.570	102.33	6.458	6.218	16.46
4	102.570	102.33	6.539	6.299	16.25
5	102.570	102.33	6.606	6.366	16.07
6	102.570	102.33	6.674	6.434	15.90
7	102.570	102.33	6.754	6.514	15.71
8	102.570	102.33	6.834	6.594	15.52
9	102.570	102.33	6.915	6.675	15.33
10	102.570	102.33	6.995	6.755	15.15
11	102.570	102.33	7.062	6.822	15.00
12	102.570	102.33	7.130	6.890	14.85
13	102.570	102.33	7.197	6.957	14.71
14	102.570	102.33	7.265	7.025	14.57
15	102.570	102.33	7.345	7.105	14.40
16	102.570	102.33	7.412	7.172	14.27
17	102.570	102.33	7.480	7.240	14.13
18	102.570	102.33	7.547	7.307	14.00
19	102.570	102.33	7.614	7.374	13.88
20	102.570	102.33	7.682	7.442	13.75
21	102.570	102.33	7.749	7.509	13.63

Resistance measurements were performed at three locations on each side of each board. Table 2 shows the width and length of resistive coat for each

Table 3: Measured surface resistance of CCEM 38

Sig. bd #	Board ID	$M\Omega/\square$	$M\Omega/\square$	$M\Omega/\square$	Avg ($M\Omega/\square$)	$\pm\sigma(M\Omega/\square)$
1	11841189A	73/59	77/59	42/77	64/65	19/10
2	12061096	82/63	63/50	73/50	73/54	13/11
3	12231018	50/44	45/40	54/42	50/42	6/3
4	11621203	91/50	77/45	91/50	86/48	8/3
5	08861103	63/54	68/45	73/39	68/46	5/8
6	08861103	54/45	73/45	63/50	63/47	10/3
7	11381048	82/45	77/41	82/54	80/47	3/7
8	13441339C	50/59	43/59	54/59	49/59	6/0
9	12080794	33/50	34/45	36/45	34/47	2/4
10	10551056	36/38	43/41	39/36	39/38	5/4
11	11980877	50/77	42/82	54/109	49/89	6/17
12	08370739	59/113	35/82	63/82	52/92	15/18
13	11020845	68/82	44/44	63/82	58/69	13/22
14	10990847	59/63	63/54	44/73	55/63	10/10
15	09370926	37/45	31/54	34/59	34/53	4/10
16	11980877	45/95	33/73	44/91	41/86	7/12
17	09420843	54/77	45/68	50/82	50/76	6/10
18	11680889	100/54	39/100	95/43	78/66	32/30
19	12080794	54/50	45/35	60/39	53/41	11/11
20	08861103	59/54	54/39	54/45	56/46	3/13
21	09350839	44/32	32/45	42/63	39/47	9/22

signal board. The difference between the signal board and resistive coat dimension is the result of a 0.12" cutback of the resistive coat on each exterior edge. Tables 3 and 4 show the measured surface resistance of all signal boards used to build CCEM38 and 39, respectively. The columns of these tables are signal board number starting from the bottom of the module; board production $ID\#$; 3 measurements of surface resistance (Top/Bottom); and the mean and standard deviation of the 3 surface resistance measurements.

The board resistives used in this note to estimate high voltage sagging are the mean values of these three measurements.

Table 4: Measured surface resistance of CCEM 39

Sig. bd #	Board ID	$M\Omega/\Box$	$M\Omega/\Box$	$M\Omega/\Box$	Avg ($M\Omega/\Box$)	$\pm\sigma(M\Omega/\Box)$
1	11731191	86/50	95/45	95/59	92/51	5/7
2	09290928	39/42	35/43	33/34	36/40	3/5
3	08290907	50/28	41/28	50/29	47/28	5/1
4	11020845	45/54	50/59	50/63	48/59	3/5
5	32163121	77/126	63/113	82/113	74/117	10/8
6	18261898	104/63	86/45	73/50	88/53	16/9
7	29831892	42/44	45/50	54/45	47/46	6/3
8	14471444B	86/86	77/109	82/82	82/92	5/15
9	17901976	167/82	190/72	140/73	166/76	25/6
10	18281927	82/95	72/104	72/91	75/97	6/7
11	18281927	77/113	82/113	68/118	76/115	7/3
12	30693036	44/72	41/63	44/118	43/84	2/30
13	11900887	54/77	42/63	54/59	50/66	7/9
14	07050881	59/63	54/68	54/63	56/65	3/3
15	10990847	41/77	59/63	59/68	53/69	10/7
16	18281927	59/163	63/104	63/140	62/136	2/30
17	11581207	86/63	82/59	95/68	88/63	7/5
18	08460668	72/27	63/23	72/23	69/24	5/2
19	30052970	33/39	32/34	33/31	33/35	1/4
20	11941094	77/77	72/77	77/72	75/75	3/3
21	11941094	77/77	72/77	72/82	74/79	3/3

4 NWA load II high voltage supplying system

During load II of the NWA test beam, we supplied high voltage to the modules using Droege supplies. One Droege supply powered each voltage gang. The current drawn by the signal boards were measured and continuously logged through VME during the entire period of load II. In the case of CCEM high voltage gangs, the current from the south and north end of the gang were logged independently. As we have seen in previous test beams [1,3], these uranium modules drew an anomalous uranium current. The anomalous uranium current peaked between one half and two days after the initial turn on of the high voltage. Table 5 shows the magnitude of the current in each high voltage gang on CCEM38 and 39 at the peak of their anomalous uranium current during load II. Because the voltage drop due to uranium current is of interest, I have subtracted the initial current at the turn on.

Table 5: Uranium current of each high voltage gang at the peak

module	HV gang	Current S(nA)	Current N(nA)	$nA/surface$
CCEM38	A	129	129	51.6
	B	139	173	62.4
	C	231	241	94.4
	D	316	316	70.2
	E	330	290	62.0
CCEM39	A	198	185	64.6
	B	88	96	36.8
	C	113	93	41.2
	D	246	265	56.8
	E	252	188	44.0

In some cases there are high voltage shorts due to objects in the gap and this will give us considerable initial current. The effects of these localized shorts were discussed by several people and characterized as negligible due to their localization [2,4]. Thus, to study the effect of the more homogeneous and global uranium current, the current due to electrical shorts must be subtracted from the peak current. All the currents in table 5 reflect the subtraction of initial current. The last column in table 5 shows the average uranium current per effective uranium plate surface.

5 Voltage distribution along the signal board

Bob McCarthy and I have done a calculation on the degree of high voltage sagging on the resistive coat assuming an infinite surface. In other words, we are neglecting the fact that high voltage clips are making point contacts. The current at a distance z away from the center of a board with length L is given as follows:

$$I(z) = I(0) - j_0 wz \tag{1}$$

where j_0 is the uranium current density which is assumed to be constant, $\frac{I}{Lw}$. L is the total length of a board and w is the width. At $z = 0$ the board current $I = 0$ thus from symmetry, $I(0) = 0$. Therefore,

$$I(z) = -j_0 wz. \tag{2}$$

Then the equation to be solved is following differential equation derived from Ohm's law:

$$\frac{dV}{dz} = -\frac{I(z)\rho_\square}{w} \tag{3}$$

$$\int_{V_{z=0}}^{V} dV = V(z) - V_{z=0}$$

$$= \int_0^z -\frac{I(z)\rho_\square}{w} dz = \int_0^z -\frac{(-j_0 wz)\rho_\square}{w} dz = \frac{1}{2} j_0 \rho_\square z^2. \tag{4}$$

Thus, the voltage at z from the center of board is

$$V(z) = V_{z=0} + \frac{1}{2} j_0 \rho_\square z^2 \tag{5}$$

At $z = \frac{L}{2}$ which is the end of a board, voltage is $V_{oper}(= 2500V)$. We can now solve the above equation for V_0:

$$V_{z=0} = V_{oper} - \frac{1}{2} j_0 \rho_\square (\frac{L}{2})^2. \tag{6}$$

So at an arbitrary distance z away from the center of the board

$$V(z) = V_{oper} - \frac{1}{2} j_0 \rho_\square [(\frac{L}{2})^2 - z^2]. \tag{7}$$

6 HV plateau measurements

During the NWA load II run, we took several HV plateau runs over a wide range of energy for e's and π's. The parameterization of the response for 100 GeV electrons[6] at a given voltage V is as follows:

$$Response = Q_0 M_{FPDD}[1.0 - M_{FPDD}(1.0 - e^{\frac{-1.0}{M_{FPDD}}})] \quad (8)$$

$$M_{FPDD} = \frac{AE+B}{D} \quad (9)$$

where

$$D = 0.23 \quad (10)$$

$$E = 0.001\frac{V(z) - V_0}{D}. \quad (11)$$

$AE+B$ is the mean free path of ionization electrons as a function of the field E, V_0 is the offset in the voltage due to charge build up on the surface from charged particles emitted from uranium plates, D is the size of the LAr gap in cm, and Q_0 is the total charge in the gap. Table 6 shows the values of above parameters for each layer of CCEM and CCFH layer 1.

Table 6: Bob Hirosky's HV plateau parameterization for each layer for 100 GeV electrons

Parameter	EM1	EM2	EM3	EM4	FH1
Q_0	1525	4750	32228	15053	1098
A	0.126	0.123	0.126	0.142	0.156
B	0.0	0.0	0.0	0.0	0.0
V_0	23	26	27.5	27.5	27.5

7 High voltage sagging and EM response

There are at least two modes of high voltage sag from anomalous uranium current. The first is to assume all the current measured from the power supplies is evenly distributed on all the surfaces of the boards in the high voltage

gang. The second is to assume all the current is drawn by the one surface with the highest surface resistance. The latter is certainly the worse case in terms of voltage sags.
In estimating voltage sag, one must take into account the LAr effect, *i.e* the effect of temperature, on the surface resistance. The increase in resistance at LAr temperatures was measured at IB4 and found to be a factor of 1.8[7]. Thus all the resistance values in table 3 and 4 have to be multiplied by this factor.

Using the currents in table 5 and the resistance measurements from table 3 and 4 with the equations above we can estimate the voltage at any point along the board for the above two cases. This estimated voltage sag at the center of the board will enable us to estimate how much signal drop to expect with the measured current. In addition, we can estimate the required voltage sag to see 4% drop in response at the center of a module relative to the ends of the module.

Table 7: Fractional energy distribution for $100GeV\ e$

$Module$	η	$EM1$	$EM2$	$EM3$	$EM4$	$FH1$
CCEM38	0.05	0.024	0.084	0.591	0.285	0.017
	0.65	0.045	0.151	0.638	0.158	0.006
CCEM39	0.05	0.022	0.087	0.592	0.284	0.016
	0.65	0.043	0.153	0.639	0.159	0.006

From the equation in section 3, the voltage at the center of board ($z = 0$) is

$$V(0) = V_{oper} - \frac{I\rho_{\Box}}{2Lw}(\frac{L}{2})^2 \tag{12}$$

in air

$$= V_{oper} - \frac{I\rho_{\Box}L}{8w} = V_{oper} - \frac{I\rho_{\Box}N_{\Box}}{8} \tag{13}$$

in LAr

$$= V_{oper} - \frac{I\rho_{\Box}LF_{LAr}}{8w} = V_{oper} - \frac{I\rho_{\Box}N_{\Box}F_{LAr}}{8} \tag{14}$$

where $\rho_{\square}$ is the resistivity per square, $V_{oper} = 2500V$, w is the width, L is the total length of a board, and F_{LAr} is the constant factor which relates the surface resistivity of the resistive coat at room temperature to that at LAr temperature. In estimating the EM response, I have assumed that the response is the same for all gaps in a layer and the energy deposited in a layer is evenly distributed over the entire gap. Then using equations (14) and (8), one can estimate the relative response drop in each gap and thus the overall response drop in a layer. Table 11 and 12 in appendix show the relative response in each gap and table 8 shows overall responses in layers. Since, most of the time more than 98% of EM shower energy is contained in EM

Table 8: Relative response for each layer in evenly distributed U current case

Module	$EM1$	$EM2$	$EM3$	$EM4$	Avg.
CCEM38	0.9999	0.9999	0.9999	0.9999	0.9999
CCEM39	0.9999	0.9999	0.9999	0.9999	0.9999

Table 9: Relative response for each layer in concentrated U current case

Module	$EM1$	$EM2$	$EM3$	$EM4$	Avg.
CCEM38	1.0000	0.9997	0.9998	0.9999	0.9999
CCEM39	1.0000	0.9997	0.9998	0.9998	0.9998

modules, I did not include FH1 in the estimation. Furthermore, no voltage drop and thus no degradation in response is expected for those surfaces which are not exposed to uranium plates being either shielded by readout boards or facing a stainless steel plate. These gaps are assumed to have no voltage drop so no drop in response is expected. Table 8 shows the average degradation in response in each layer. The overall response degradation can be estimated with the following formula:

$$R_{overall} = \sum_{layer=1}^{5} F_{layer}[\sum_{gap=1}^{N_{gap}^{layer}} R_{gap}^{layer}]/N_{gap}^{layer} \tag{15}$$

F_{layer} is the fractional energy in each layer, N_{gap}^{layer} is the number of LAr gaps in each layer, and R_{gap}^{layer} is the relative response of each gap in a layer. R_{gap}^{layer} is assumed to be 1.00 for non uranium surfaces.

One can find the surfaces with the largest surface resistances in high voltage gangs from Table 3 and 4. Using these information one can estimate the biggest voltage sag on a surface per each layer. Table 13 in appendix shows voltage at the center and the relative response on the gap for the surfaces highest resistivity. Table 9 above shows overall relative response in the concentrated U current case.

8 Conclusion

The results of the high voltage sagging study show that there is not a sufficient voltage drop due to anomalous uranium current to explain the 4% response degradation. Table 10 illustrates the expected voltages at the center of module necessary to have a 4% degradation of response relative to the ends of the module. The voltage in each column is the voltage at the center of module in every gap in a layer to have 4% degradation.

Table 10: Expected voltage at the center of module to see 4% degradation.

$Layer$	$EM1$	$EM2$	$EM3$	$EM4$
HV	$1440V$	$1455V$	$1445V$	$1370V$

The conclusion is that I didn't find clear evidence to explain the 4% degradation in EM response from voltage sagging due to the uranium current which is the major source of global current in the detector. And to have a 4% response degradation, we would have to have at least a 1000V drop from the operation voltage (2500V) in every LAr gap which is practically impossible no matter what the cause of voltage sagging is.

9 Appendix

Table 11: CCEM 38 relative response at the center of module in even U current case

$Layer$	$SigBd.\#$	$Av.I_U(nA)$	$HV(z=0,V)$	$Response$
$EM1$	1 (B/T)	0.0/0.0	2500.0/2500.0	1.0000/1.0000
	2 (B/T)	51.6/51.6	2492.9/2494.8	0.9998/0.9999
$EM2$	3 (B/T)	51.6/0.0	2495.2/2500.0	0.9999/1.0000
	4 (B/T)	51.6/51.6	2491.9/2495.5	0.9998/0.9999
$EM3$	5 (B/T)	62.4/62.4	2492.3/2494.8	0.9998/0.9999
	6 (B/T)	94.4/0.0	2489.4/2500.0	0.9998/1.0000
	7 (B/T)	94.4/0.0	2486.7/2500.0	0.9997/1.0000
	8 (B/T)	62.4/0.0	2494.7/2500.0	0.9999/1.0000
	9 (B/T)	94.4/0.0	2494.5/2500.0	0.9999/1.0000
	10 (B/T)	94.4/94.4	2493.7/2493.9	0.9999/0.9999
	11 (B/T)	62.4/62.4	2494.8/2490.6	0.9999/0.9998
$EM4$	12 (B/T)	40.2/40.2	2496.5/2493.8	0.9999/0.9999
	13 (B/T)	62.0/62.0	2494.0/2492.9	0.9999/0.9999
	14 (B/T)	40.2/0.0	2496.4/2500.0	0.9999/1.0000
	15 (B/T)	62.0/62.0	2496.6/2494.0	0.9999/0.9999
	16 (B/T)	40.2/40.2	2497.4/2494.4	0.9999/0.9999
	17 (B/T)	62.0/62.0	2495.1/2492.5	0.9999/0.9998
	18 (B/T)	40.2/40.2	2495.1/2495.1	0.9999/0.9999
	19 (B/T)	62.0/62.0	2494.9/2496.0	0.9999/0.9999
	20 (B/T)	40.2/40.2	2496.5/2497.1	0.9999/0.9999
	21 (B/T)	62.0/62.0	2496.3/2495.5	0.9999/0.9999

Table 12: CCEM 39 relative response at the center of module in even U current case

Layer	*SigBd.#*	$Av.I_U(nA)$	$HV(z=0,V)$	*Response*
$EM1$	1(B/T)	0.0/0.0	2500.0/2500.0	1.0000/1.000
	2(B/T)	76.6/76.6	2494.8/2494.3	0.9999/0.9999
$EM2$	3(B/T)	76.6/0.0	2493.3/2500.0	0.9999/1.0000
	4(B/T)	76.6/76.6	2493.3/2491.7	0.9999/0.9998
$EM3$	5(B/T)	36.8/36.8	2495.1/2492.2	0.9999/0.9998
	6(B/T)	41.2/0.0	2493.5/2500.0	0.9999/1.0000
	7(B/T)	41.2/0.0	2496.6/2500.0	0.9999/1.0000
	8(B/T)	36.8/0.0	2494.7/2500.0	0.9999/1.0000
	9(B/T)	41.2/0.0	2488.2/2500.0	0.9997/1.0000
	10(B/T)	41.2/41.2	2494.7/2493.2	0.9999/0.9998
	11(B/T)	36.8/36.8	2495.3/2492.9	0.9999/0.9998
$EM4$	12(B/T)	56.8/56.8	2495.9/2492.0	0.9999/0.9998
	13(B/T)	44.0/44.0	2496.4/2495.2	0.9999/0.9999
	14(B/T)	56.8/0.0	2494.8/2500.0	0.9999/1.0000
	15(B/T)	44.0/44.0	2496.2/2495.1	0.9999/0.9999
	16(B/T)	56.8/56.8	2494.3/2487.6	0.9999/0.9998
	17(B/T)	44.0/44.0	2493.8/2495.6	0.9999/0.9999
	18(B/T)	56.8/56.8	2493.8/2497.7	0.9999/1.0000
	19(B/T)	44.0/44.0	2497.7/2497.6	1.0000/0.9999
	20(B/T)	56.8/56.8	2493.4/2493.4	0.9999/0.9999
	21(B/T)	44.0/44.0	2495.0/2494.7	0.9999/0.9999

Table 13: Relative response at the center of module in concentrated U current case

$Module$	$Surface$	$I(nA)$	$HV(z=0,V)$	R_{gap}
CCEM38	$4T$	258.0	2459.4	0.9991
	$11B$	312.0	2453.1	0.9989
	$9B$	472.0	2461.7	0.9991
	$12B$	362.0	2444.4	0.9989
	$17B$	620.0	2425.1	0.9985
CCEM39	$4B$	383.0	2458.7	0.9991
	$5B$	184.0	2461.1	0.9991
	$9T$	206.0	2441.0	0.9987
	$16B$	511.0	2388.4	0.9977
	$17T$	440.0	2438.4	0.9987

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