J. Zagel 30?

Beam Position Monitor
Design Note #23

CALIBRATION OF THE BOOSTER BPM SYSTEM

R. Webber
September 18, 1986

The calibration of the Booster BPM system is presented in a format following that of BPM Design Note #1 for the Saver system[1]. Hopefully, this will simplify understanding of the Booster system, at least for those familiar with the Saver. Calibration is determined by a combination of pick-up sensitivity, rf module transfer function, and sample and hold / ADC scaling on the daughter cards in the analog box.

The Detector

The detector is an impedance matched stripline device similar to that used in the Saver[2]. The Booster detector, however, has four striplines in a single housing to allow measurements in both planes at a single location. Each 50 ohm stripline is a section of a circle subtending an arc of 60 degrees and is 6 inches long. A cross-section is shown in Figure 1. These detectors are sensitive to the direction of beam travel, as are the Saver detectors. Since beam in the Booster is uni-directional, the downstream end of each stripline is terminated in the vacuum and only signals from the upstream ends are available.

A static model, based on the current distribution in the wall of a round pipe due to a line current within the pipe, was used to calculate the sensitivity of this detector to beam position.[2,3] A simple Fortran code was written and used to compute, as a function of line current location, the integrated current in the pipe surface corresponding to each stripline.

Actual measurements were taken on a number of samples of the production detectors using stretched wire techniques. Measurements were made at 30 Mhz, 50 Mhz, and 200 Mhz. The electrical center was found to move less than 0.25 mm over that range of frequencies. The position sensitivity is not significantly different between 30 and 50 Mhz, but it is noticeably reduced at 200 Mhz, most likely due to increased plate-to-plate coupling at the higher frequency. Over the region of interest, the sensitivity is found to be proportional to log(A/B), where A and B are the signals from the two striplines in the plane of motion. Figure 2 shows the detector output, calculated and measured, in terms of 20log(A/B). Values of the position sensitivity are found to be 0.52db/mm in the 30 to 50 Mhz band and 0.48db/mm at 200 Mhz. Since position information is processed using the 30 to 50 Mhz signals, the equation to be used for determining position in one plane with no orthogonal displacement is

$$.52x_o = 20\log(A/B) = (A/B)_{db} \qquad x \text{ in mm}$$

Because the detector is symmetric, an identical equation is used for y_o. The equation is accurate to better than 1 mm to a radius of 40 mm. To maintain this accuracy for beam displaced in the orthogonal plane, the equation becomes

$$.52x = .52x_o*(1.+0.05y_o^2) = (A/B)_{db}*(1.+0.05y_o^2)$$

x, x_o, and y_o in mm

Again, an identical equation applies for y.

The RF Module

The Booster rf module is calibrated the same as the Saver module[1,4] and has a transfer function

$$(A/B)_{db} = [20/(F*\ln 10)] * \ln[\tan(F*C_1*(V-V_o)+\pi/4)] \qquad \frac{\ln(z)}{\ln(10)} = \log(z)$$

where V is rf module position output in volts,
$F=1.14$, $C_1=.2974$, $V_0=0.0$

The Analog Box

The scaling of the daughter cards in the Booster BPM analog box was selected such that full scale output from the ADC corresponds to a beam position of approximately 2 inches off center. The relation between the input voltage V and the digitized number is

$$V = (C_2-N)/C_3$$

where $C_2=128$, and $C_3=57.41$ ← counts/volt

See Appendix A.

Overall Calibration

Combining all the above relations results in

$$x_o = [20/(.52*F*\ln 10)] * \ln[\tan(F*C_1*((C_2-N)/C_3)+\pi/4)]$$

and

$$x = x_o*(1+.05y_o^2)$$

with identical equations for y_o and y.

Table 1 is a look-up table correlating x_o (or y_o) to N, that is, the position to the ADC output. Results from the table need to be multiplied by $1+.05y_o^2$ (or $1+.05x_o^2$) for orthogonal plane correction.

Mechanical Offsets

Each detector has four survey buttons, two on each end, to serve as mechanical references. The buttons on the downstream end, the end opposite the output connectors, are the primary references for determining the mechanical center. The electrical center of each detector in each plane was measured relative to these buttons. Table 2 lists the measured offsets. A similar table needs to be generated for the surveyed location of each detector relative to the nominal Booster orbit. These two offsets in each plane can then be appropriately added or subtracted from measured beam positions to obtain actual beam position relative to the nominal orbit.

+?-+?- Signs -?+-?+ AKA Which Way is Up?

Booster beam detectors are cabled to the rf modules such that the analog position signal is positive for beam positions vertically up and radially out. Table 1 carries this convention through to the calculated position -- positive is up and out. Detectors are installed in the ring with the survey buttons facing up and out. Nominal offset from the edge of the buttons to the detector center is 3.125 inches in both planes. This location is defined as the mechanical center. The numbers in Table 2, sign taken into account, added to 3.125 inches are the actual distances from the buttons to the electrical center in that plane. As such, these numbers must be subtracted from the measured beam position to obtain actual beam position relative to the mechanical center. See Figure 3. To calculate the correct beam position relative to the nominal Booster orbit, numbers obtained from surveys of detector mechanical positions may either need to be added or subtracted from measured beam position depending on how the survey numbers are presented.

Intensity Channel Calibration

Measurements have been made of the signal levels obtained from these detectors with beam. Accounting for cable attenuation and the like, the 53 Mhz output from a single stripline with typical Booster beam during the last half of the Booster cycle is 267 mv rms (about +1.5 dbm) for 1E12 particles in 84 bunches. Equivalently, the 53 Mhz output of a single stripline with centered beam is

$$P_o = -200 + 20*\log(\#ppb)\ dbm$$

This calibration is of course frequency and bunch length sensitive, but is a good estimate for the last half of the Booster cycle.

The intensity channel output of the Booster rf module is adjusted for 0.6 volts with +2 dbm at 53 Mhz into each module input. This corresponds to a scaling of 1.75E12 protons per volt of intensity channel output.

The intensity input to the daughter cards in the BPM analog boxes normally provide the timing information required for sampling the position signals. With the present mode of operation beam is uniformly distributed around the Booster, and as such the intensity signal contains no beam sync timing information. An external beam sync clock will be connected to the daughter card intensity inputs for timing purposes with the resultant loss of intensity information. Present plans are for intensity information to be available only locally as analog signals.

The intensity output from the rf modules is suitable for connection to the daughter cards if operation is changed so as to provide the necessary timing information via the intensity signal (i.e. operation with a significant gap in the beam). In this case, the calibration of the intensity channel from the daughter card through to the control system is identical to that of the Saver system.

References

1. R. Shafer, "Expected Calibration and Calibration Tolerances of the Beam Position System", BPM Design Note #1, 1981, unpublished, in Fermilab Accelerator Division files.

2. R.E. Shafer, R.C. Webber, T.H. Nicol, "Fermilab Energy Doubler Beam Position Detector", IEEE Trans. Nuc. Sci., Vol. NS-28, No. 3, June 1981, pp. 2290-2292.

3. Robert T. Avery, Andris Faltens, Edward C. Hartwig, "Non-Intercepting Monitor of Beam Current and Position", IEEE Trans. Nuc. Sci., Vol. NS-18, No. 3, June 1971, pp. 920-922.

4. D. Martin, "Measurement of RF Module Calibration Constants and Tolerances", BPM Design Note #4, 1982, unpublished, in Fermilab Accelerator Division files.

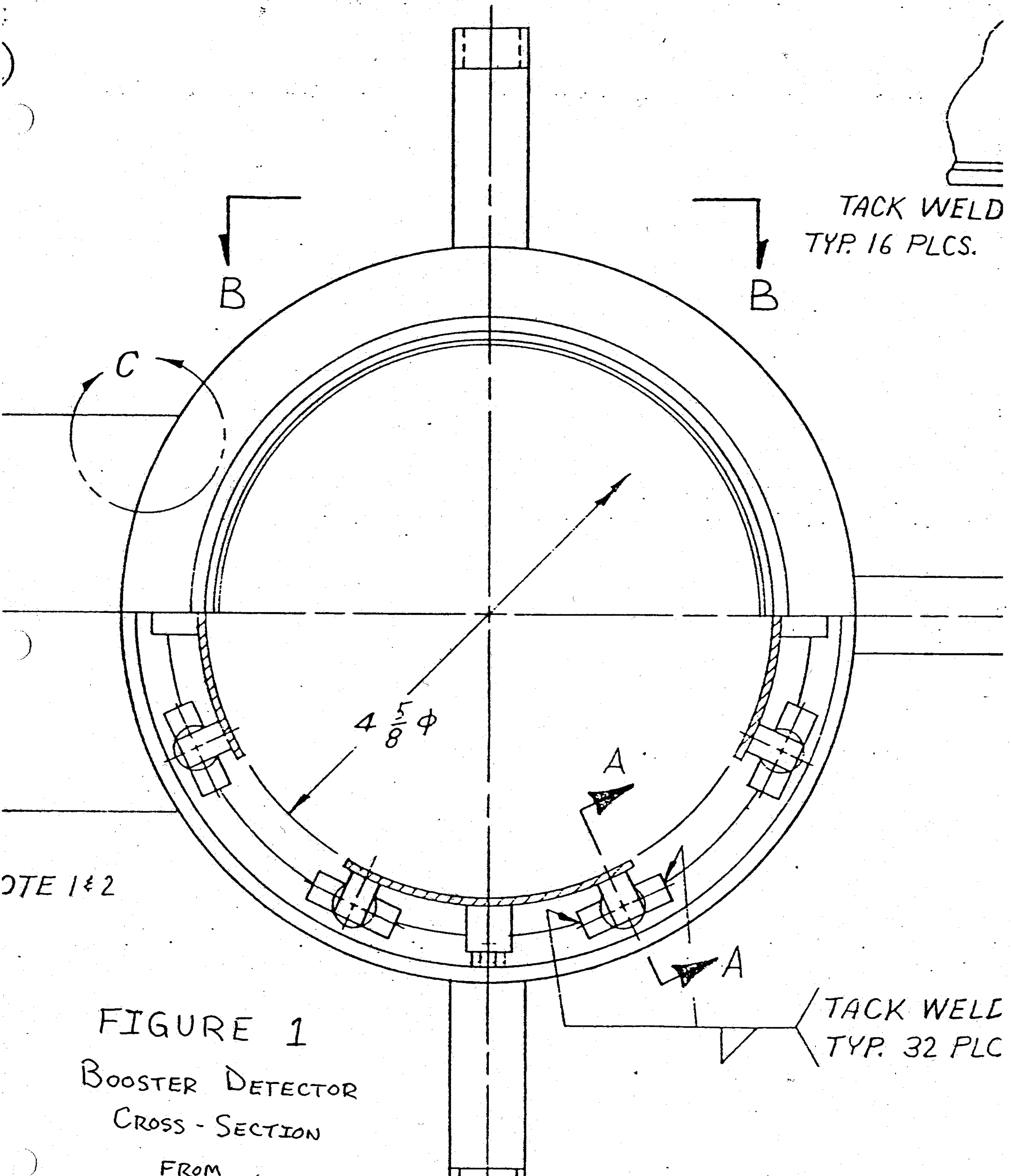


FIGURE 1
BOOSTER DETECTOR
CROSS - SECTION
FROM
0381 - MD - 70845

TABLE 1

Booster Detector 0.52 db/mm

Booster Daughter Card

TABLE OF RELATIONSHIP BETWEEN ADC OUTPUT, AND POSITION FOR BPM SYSTEM

THE EXPRESION IS X(MM) = (20.0 /(.52 [circled; handwritten "db/mm"] *F*LN10)) * LN TAN (F*C1*((C2-N)/C3) + PI/4)

THE NOMINAL VALUE OF F IS 1.14 (BPM NOTE #4). THE VALUE USED IN THIS TABLE IS 1.1400
THE NOMINAL VALUE OF C1 IS PI/10 (BPM NOTE #1). THE VALUE USED IN THIS TABLE IS 0.2974
THE NOMINAL VALUE OF C2 IS 128.0 (BPM NOTE #1). THE VALUE USED IN THIS TABLE IS 128.00
THE NOMINAL VALUE OF C3 IS 51.2 (BPM NOTE #1). THE VALUE USED IN THIS TABLE IS 57.4100 [circled] *DAUGHTER CARD*

1	1	48.94	52	34	15.38	103	67	4.39	154	9A	-4.57	205	CD	-15.66
2	2	46.68	53	35	15.11	104	68	4.21	155	9B	-4.75	206	CE	-15.95
3	3	44.72	54	36	14.83	105	69	4.03	156	9C	-4.93	207	CF	-16.23
4	4	42.99	55	37	14.57	106	6A	3.85	157	9D	-5.11	208	D0	-16.53
5	5	41.44	56	38	14.30	107	6B	3.67	158	9E	-5.30	209	D1	-16.82
6	6	40.04	57	39	14.04	108	6C	3.49	159	9F	-5.48	210	D2	-17.13
7	7	38.76	58	3A	13.79	109	6D	3.31	160	A0	-5.67	211	D3	-17.44
8	8	37.58	59	3B	13.53	110	6E	3.13	161	A1	-5.86	212	D4	-17.75
9	9	36.49	60	3C	13.28	111	6F	2.96	162	A2	-6.04	213	D5	-18.07
10	A	35.48	61	3D	13.03	112	70	2.78	163	A3	-6.23	214	D6	-18.39
11	B	34.53	62	3E	12.79	113	71	2.60	164	A4	-6.42	215	D7	-18.73
12	C	33.63	63	3F	12.55	114	72	2.43	165	A5	-6.61	216	D8	-19.06
13	D	32.79	64	40	12.31	115	73	2.25	166	A6	-6.80	217	D9	-19.41
14	E	31.99	65	41	12.07	116	74	2.08	167	A7	-7.00	218	DA	-19.76
15	F	31.23	66	42	11.84	117	75	1.90	168	A8	-7.19	219	DB	-20.12
16	10	30.51	67	43	11.60	118	76	1.73	169	A9	-7.39	220	DC	-20.49
17	11	29.82	68	44	11.38	119	77	1.56	170	AA	-7.58	221	DD	-20.86
18	12	29.16	69	45	11.15	120	78	1.38	171	AB	-7.78	222	DE	-21.25
19	13	28.53	70	46	10.92	121	79	1.21	172	AC	-7.98	223	DF	-21.64
20	14	27.92	71	47	10.70	122	7A	1.03	173	AD	-8.18	224	E0	-22.05
21	15	27.34	72	48	10.48	123	7B	0.86	174	AE	-8.38	225	E1	-22.46
22	16	26.78	73	49	10.26	124	7C	0.69	175	AF	-8.58	226	E2	-22.89
23	17	26.23	74	4A	10.05	125	7D	0.51	176	B0	-8.79	227	E3	-23.32
24	18	25.71	75	4B	9.83	126	7E	0.34	177	B1	-8.99	228	E4	-23.77
25	19	25.20	76	4C	9.62	127	7F	0.17	178	B2	-9.20	229	E5	-24.23
26	1A	24.71	77	4D	9.41	128	80	0.00	179	B3	-9.41	230	E6	-24.71
27	1B	24.23	78	4E	9.20	129	81	-0.17	180	B4	-9.62	231	E7	-25.20
28	1C	23.77	79	4F	8.99	130	82	-0.34	181	B5	-9.83	232	E8	-25.71
29	1D	23.32	80	50	8.79	131	83	-0.51	182	B6	-10.05	233	E9	-26.23
30	1E	22.89	81	51	8.58	132	84	-0.69	183	B7	-10.26	234	EA	-26.78
31	1F	22.46	82	52	8.38	133	85	-0.86	184	B8	-10.48	235	EB	-27.34
32	20	22.05	83	53	8.18	134	86	-1.03	185	B9	-10.70	236	EC	-27.92
33	21	21.64	84	54	7.98	135	87	-1.21	186	BA	-10.92	237	ED	-28.53
34	22	21.25	85	55	7.78	136	88	-1.38	187	BB	-11.15	238	EE	-29.16
35	23	20.86	86	56	7.58	137	89	-1.56	188	BC	-11.38	239	EF	-29.82
36	24	20.49	87	57	7.39	138	8A	-1.73	189	BD	-11.60	240	F0	-30.51
37	25	20.12	88	58	7.19	139	8B	-1.90	190	BE	-11.84	241	F1	-31.23
38	26	19.76	89	59	7.00	140	8C	-2.08	191	BF	-12.07	242	F2	-31.99
39	27	19.41	90	5A	6.80	141	8D	-2.25	192	C0	-12.31	243	F3	-32.79
40	28	19.06	91	5B	6.61	142	8E	-2.43	193	C1	-12.55	244	F4	-33.63
41	29	18.73	92	5C	6.42	143	8F	-2.60	194	C2	-12.79	245	F5	-34.53
42	2A	18.39	93	5D	6.23	144	90	-2.78	195	C3	-13.03	246	F6	-35.48
43	2B	18.07	94	5E	6.04	145	91	-2.96	196	C4	-13.28	247	F7	-36.49
44	2C	17.75	95	5F	5.86	146	92	-3.13	197	C5	-13.53	248	F8	-37.58
45	2D	17.44	96	60	5.67	147	93	-3.31	198	C6	-13.79	249	F9	-38.76
46	2E	17.13	97	61	5.48	148	94	-3.49	199	C7	-14.04	250	FA	-40.04
47	2F	16.82	98	62	5.30	149	95	-3.67	200	C8	-14.30	251	FB	-41.44
48	30	16.53	99	63	5.11	150	96	-3.85	201	C9	-14.57	252	FC	-42.99
49	31	16.23	100	64	4.93	151	97	-4.03	202	CA	-14.83	253	FD	-44.72
50	32	15.95	101	65	4.75	152	98	-4.21	203	CB	-15.11	254	FE	-46.68
51	33	15.66	102	66	4.57	153	99	-4.39	204	CC	-15.38	255	FF	-48.94

TABLE 2

TABLE OF MEASURED ELECTRICAL CENTER OFFSETS OF BOOSTER BPM'S

DETECTOR	HORIZONTAL OFFSET	VERTICAL OFFSET	DETECTOR	HORIZONTAL OFFSET	VERTICAL OFFSET
LS1	-0.4	-0.7	SS1	-0.9	-0.2
LS2	-0.1	0.0	SS2	-1.1	-2.1
LS3	-1.0	-0.9	SS3	-0.6	-1.1
LS4	-0.7	-0.6	SS4	-1.1	-0.7
LS5	-0.1	0.1	SS5	-1.2	-0.8
LS6	-0.5	-0.1	SS6	-0.5	-1.1
LS7	-0.4	-0.2	SS7	-0.7	-0.8
LS8	-0.2	-0.3	SS8	-1.1	-0.2
LS9	-0.3	-0.2	SS9	-0.1	-1.1
LS10	-0.5	-0.1	SS10	-0.5	-1.1
LS11	-1.3	-0.1	SS11	-0.4	-0.8
LS12	0.2	-0.7	SS12	-1.0	-0.9
LS13	-0.9	-0.4	SS13	-0.8	-1.2
LS14	-0.7	-0.3	SS14	-0.7	-0.4
LS15	-0.7	-0.1	SS15	-0.8	-0.5
LS16	-1.2	0.3	SS16	-1.0	-0.7
LS17	-1.3	-0.2	SS17	-0.7	-0.7
LS18	-0.9	0.4	SS18	0.8	-1.2
LS19	0.4	0.5	SS19	0.1	-0.6
LS20	-0.7	-0.1	SS20	-0.4	-1.6
LS21	-1.5	-0.6	SS21	-0.2	-0.8
LS22	-0.5	-0.7	SS22	-0.5	-0.9
LS23	-0.9	-0.2	SS23	-0.7	-1.2
LS24	-0.3	0.5	SS24	-1.3	-0.7
LS2-A	-1.2	-0.4	SS1-A	-0.9	-0.5
LS3-A	-0.8	0.1	SS2-A	-0.5	-0.6
LS21-A	-1.2	0.0	SS2-B	-0.7	-0.7

$\bar{X} = -.5870$ $s = .49$

X_{max} -1.5 mm

X_{min} +.8 mm

NOTES

1) Above units are in millimeters.

2) Sign of above numbers is such that if added to 3.125 inches, the result is the distance from the respective downstream survey button to the electrical center of the detector in that plane. Therefore, these numbers must be SUBTRACTED from measured beam position to obtain actual beam position relative to the mechanical center of the detector using the convention that positive is up and out.

TABLE 2 CON'T.

TABLE OF MEASURED ELECTRICAL CENTER OFFSETS OF BOOSTER BPM'S

DETECTOR	HORIZONTAL OFFSET	VERTICAL OFFSET
8G1	-0.6	-0.2
8G2	-1.1	-0.3
8G3	-0.7	-0.4
8G4	-0.8	0.2
8G5	-1.0	0.2
8G6	-0.1	-0.2
8G7	0.0	0.1
8G8	-0.7	-0.4
8G9	-0.8	0.4
8G10	-0.4	-0.1
8G11	-0.2	-0.1
8G12	0.2	-0.3
8G13	-0.5	0.0
8G14	0.5	-0.4
8G15	-0.6	0.4
8G16	0.0	-0.3
8G17	-0.8	-0.6
8G18	-0.5	0.0

NOTES

1) Above units are in millimeters.

2) Sign of above numbers is such that if added to 3.125 inches, the result is the distance from the respective downstream survey button to the electrical center of the detector in that plane. Therefore, these numbers must be SUBTRACTED from measured beam position to obtain actual beam position relative to the mechanical center of the detector using the convention that positive is up and out.

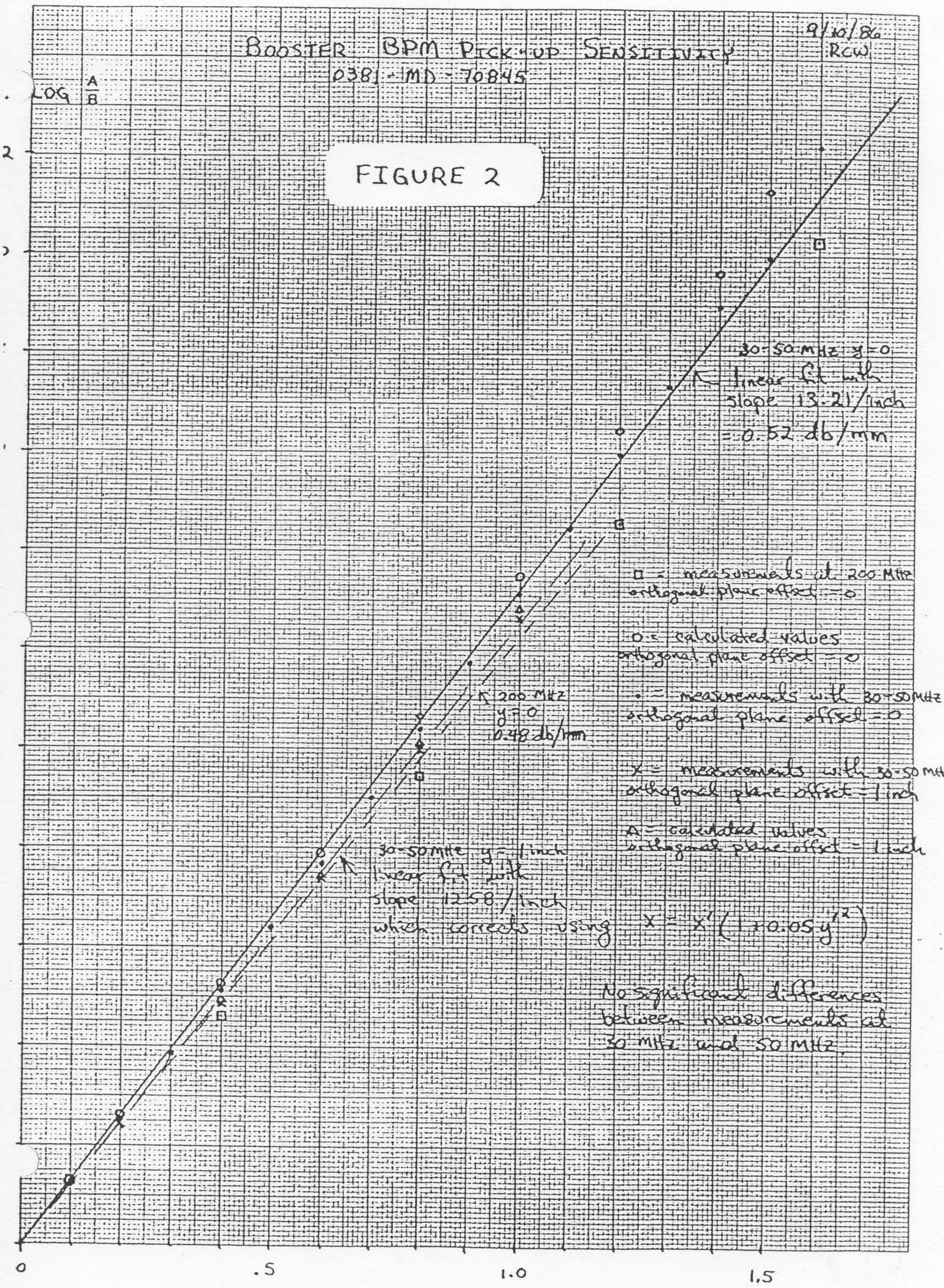
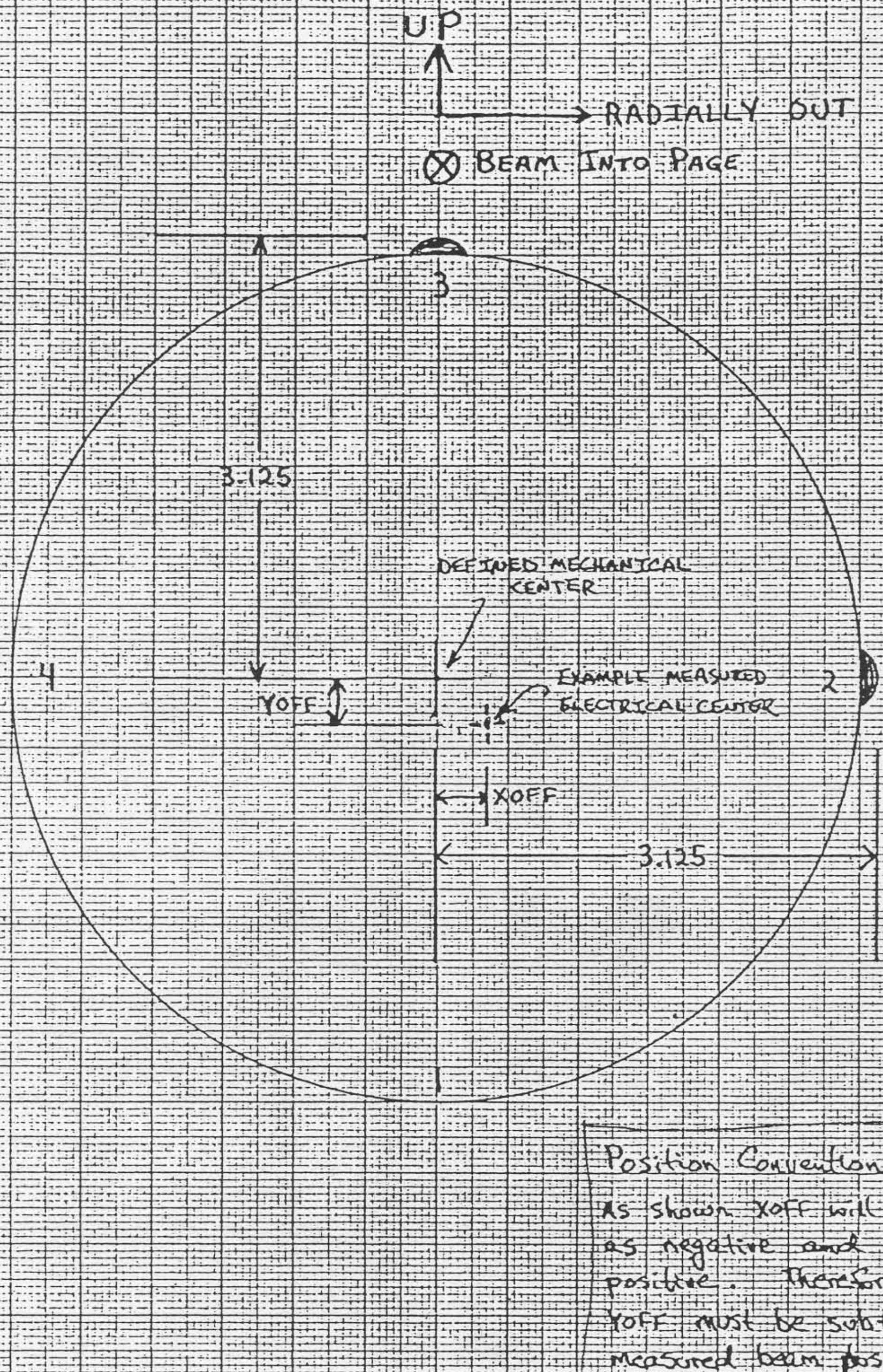

BOOSTER BPM PICK-UP SENSITIVITY
0381-MD-70845
9/10/86
RCW
LOG A/B
2
30-50 MHz y=0
linear fit with slope 13.21/inch
= 0.52 db/mm
□ = measurements at 200 MHz orthogonal plane offset = 0
o = calculated values orthogonal plane offset = 0
• = measurements with 30-50 MHz orthogonal plane offset = 0
x = measurements with 30-50 MHz orthogonal plane offset = 1 inch
Δ = calculated values orthogonal plane offset = 1 inch
200 MHz
y = 0
0.48 db/mm
30-50 MHz y = 1 inch
linear fit with slope 12.58/inch
which corrects using x = x'(1+0.05y'^2)
No significant differences between measurements at 30 MHz and 50 MHz.
0
.5
1.0
1.5

FIGURE 2



Position Convention + = UP/OUT.
As shown XOFF will be measured as negative and YOFF as positive. Therefore XOFF and YOFF must be subtracted from measured beam position to obtain actual beam position relative to mechanical center!

FIGURE 3

BOOSTER BPM PICK-UP

VIEW INTO UPSTREAM END

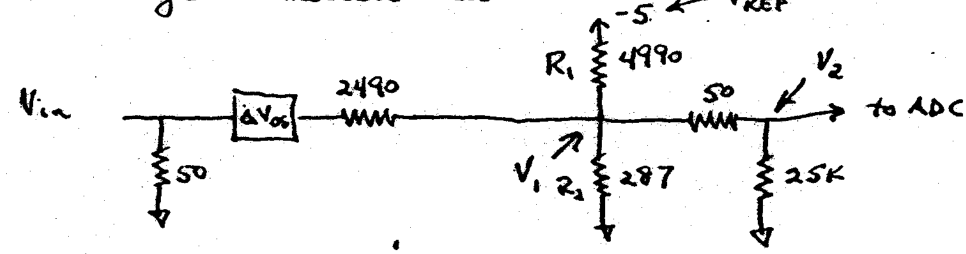
8/12/86
RCW

NOTE: PRIMARY SURVEY REFERENCES ARE BUTTONS AT DOWNSTREAM END

APPENDIX A

Following Appendix B of BPM Note #1 by Shafer

Saver Daughter models as



$$\frac{V_{in} - V_{os} - V_1}{2490} + \frac{-5 - V_1}{4990} - \frac{V_1}{287} - \frac{V_1}{25050} = 0$$

(-5 = V'_{REF}; 4990 = R_1; 287 = R_2)

$$V_{in} = 2490\, V_1 \left[\frac{1}{2490} + \frac{1}{4990} + \frac{1}{25050} + \frac{1}{287} \right] + \frac{5 \cdot 2490}{\cancel{5000}\ 4990} + \Delta V_{os}$$

(4990 = R_1; 287 = R_2; 4990 = R_1)

↑ this term omitted by typist in original note but not lost in further calculations

get $\quad V_{in} = 10.274\, V_1 + 2.495 + \Delta V_{os}$

and $\quad \frac{V_2}{V_1} = \frac{25000}{25050} \Rightarrow V_1 = 1.002\, V_2$

↖ Note typo in original note

So $\quad V_{in} = 10.295\, V_2 + 2.495 + \Delta V_{os}$

but $\quad V_2 = -.500 \left(\frac{N}{255} \right)$

$$V_{in} = -0.0202\, N + 2.495 + \Delta V_{os}$$

$$= \frac{-N + 123.6 + 49.54\, V_{os}}{49.54}$$

Adjust offset for $\quad V_{in} = \frac{128 - N}{49.54} \quad$ SAVER

```
/*
        *** Calculates Tables for booster BPMs ***
*/

void calc_tables()
{
int i;
for(i=0; i<78; i++)
new_pickup_table[i] = -7.500e+01;
for (i=78;i<4019;i++)
 { outtan = tan(((i-2048)/1208.1312)+.78539816);
   new_pickup_table[i] = 10.025*(log(outtan));
 }
for(i=4019;i<4096;i++)
new_pickup_table[i] = 7.500e+01;

for (i=0;i<1100;i++)
booster_table[i] = -107.0;
for (i=1100; i<2997; i++)
 { outtan = tan(((i-2048)/1208.1312)+.78539816);
   booster_table[i] = 14.6523*(log(outtan));
 }
for(i=2997;i<4096;i++)
booster_table[i] = 107.0;

}
```

where do these come from? not physical or is that intent?

$3\frac{1}{4}''$ =

outtan must be > 0?

~ 90 mV/mm what is digitizer scaling?

why are different? outtan is same for each?

L1 a1 = 0.679

a2 = -0.968

~~003~~3 S = 0.7599 db/mm

D = -0.1311 db

	S	D
003	0.7599 db/mm	-0.1311 db
004	0.7592 "	-0.2560 "
002	0.7662 "	-0.2199 "
001	0.7592 "	-0.1031 "
005		
L-10	0.7896 "	

WAMI

$\frac{.74}{.52} \times 10.025$

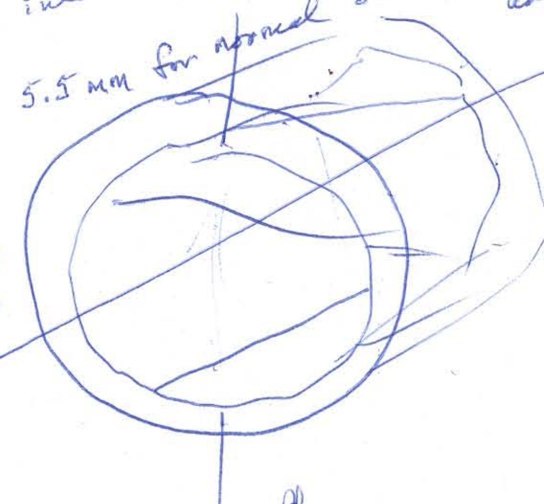
= 14.265 !

correct ~~ratio~~

put ~~.4~~ +.5 volt into digitizer should see 5.5 mm for normal BPM (watch out for added offsets!

should see 3.8 mm for 400 MeV new pickup

(or put in -.5 then +.5 and look for differences to avoid ~~offset~~ problem)



DEB

New ~~.....~~ fewer mm/volt

$\left(\frac{.52}{.74} \frac{mm}{90\ mV}\right) \times 500\ mV = 3.8\ mm$

B

$\frac{mm}{90\ mV} \times 500\ mV = 5.5\ mm$

400 MeV	$3\frac{1}{4}$	$\frac{13}{4}$	.75 db/mm
Normal Booster	$4\frac{1}{2}$	$\frac{18}{4}$	.52 db/mm classic

$(C_2 - N)/C_3$ 1.5 → 1

$$X_0 = \frac{20}{.52\,F\,\ln 10} \ln\left(\tan\left(F\,C_3\,V + \pi/4\right)\right) = \frac{20}{.52F}\log(\tan())$$

.52 ← BPM db/mm; ln 10 ≈ 2.3; F ← 1.14; $F C_3 V$ ← .2974

$$\frac{20}{.5^2 (2.14)(2.3)^2}$$

$$db = 20\log\left(\frac{A}{B}\right)$$

$$10^{\frac{db}{20}} = \frac{A}{B}$$

~~e^x~~

$$\text{outtan} = \tan\left(\left(\frac{i - 2048}{1208.13}\right) + .785\right)$$

.785 ← $\pi/4$

$$X = 10.025 \log(\text{outtan})$$

$$\frac{1}{.75} \qquad \log x = \frac{\ln x}{\ln 10}$$

Booster K = 10.025

400MeV K = 14.65

$K \propto \frac{1}{\text{Sensitivity}}$ $\frac{1}{.52} \approx 2$

$K = \frac{1}{.76} = 1.3$