Los Alamos
NATIONAL LABORATORY
memorandum

Spallation Neutron Source, SNS-01
Accelerator Engineering, Design, & Fabrication

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Subject: Results of SNS SCL BPM Mapping

Los Alamos National Laboratory is responsible for the delivery to the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) of thirty-two (32) production Beam Position Monitors (BPMs) for the Superconducting Linac (SCL). Two additional units will also be provided so that the total number of delivered units will be thirty-four (34). These BPMs were fabricated by ISYS Manufacturing (re-named ESCO) of Concord, CA under LANL contract number 38167-001-02 8K. The SCL BPM is shown in figure1.

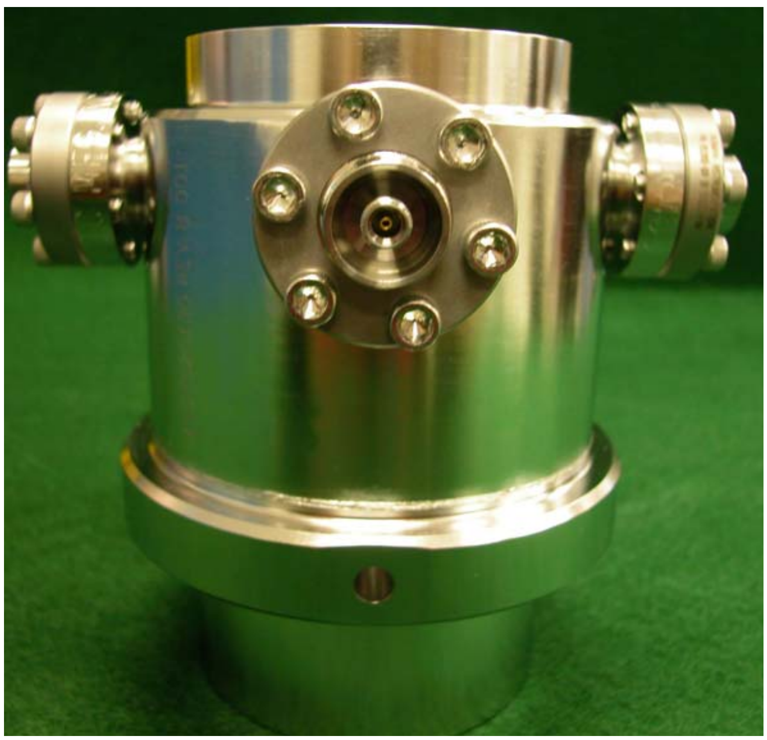

Figure 1, SCL BPM

BPM Characterization

Characterization of the response of each BPM is accomplished by running a taut wire through the BPM, placing the appropriate frequency RF signal on the wire, moving the wire from position to position within the bore of the BPM, and measuring the response of the BPMs electrodes at each position. This process is called mapping of the BPM since the end result is a "map" of the BPM's response to the driving signal.

The first two of the 34 BPMs were mapped five times. These two BPMs were used to determine the random error associated with running the mapper and installing the BPM into the mapper. All other BPMs were mapped at least once. The first three maps of this five map set were done by setting up the BPM once and running three consecutive maps. The purpose of the three consecutive maps was to determine the repeatability of the mapping process. After completing the first three maps the BPM is removed and re-installed in the mapping fixture. Once map four is finished the BPM was again removed and re-installed. Maps four and five are compared along with one of the initial three maps. By using three different set-ups the random error associated with placing the BPM into the mapping fixture is determined. The error value is taken as the standard deviation of the three offset values. The error associated with running the mapping system repeatedly and the error associated with placing the BPM in the fixture are given in Table 1 (offset and error values are taken from the 10 coefficient reverse fits).

Table 1, BPM Offset, Sensitivity, & Repeatability

BPM	3 Consecutive maps (one placement of the BPM in mapper), maps -1, -2, -3 (mm)		3 Different BPM Placements in the mapper, maps -1, -4, -5 (mm)	
	X axis	Y axis	X axis	Y axis
SCL BPM - 21				
Offset (mm)	1.58e-01	-3.77e-01	1.63e-01	-3.80e-01
Std dev of offset (mm) (random error)	1.00e-03	5.38e-03	5.86e-03	4.75e-03
Sensitivity (mm/dB)	1.1877	1.1876	1.1852	1.1854
Std dev of sensitivity (mm/dB)	1.07e-3	8.6e-4	2.0e-3	1.84e-3
SCL BPM - 33				
Offset	9.00e-02	-2.92e-01	1.33e-01	-3.11e-01
Std dev of offset (mm) (random error)	1.01e-02	3.29e-03	3.45e-02	1.77e-02
Sensitivity (mm/dB)	1.1852	1.188	1.1896	1.190
Std dev of sensitivity (mm/dB)	1.60e-3	1.52e-3	3.50e-3	1.46e-3

SCL BPM Mapping Procedure

The BPMs will be mapped using the LANSCE-1 BPM mapping station. A schematic of the mapping station is shown in figure 2. The station consists of the following equipment:

1. Hewlett Packard model 8640B signal generator
2. Factory calibrated Boonton 4300 RF Power meter
3. Factory calibrated 4 Boonton 51075 Power sensors
4. Mapping fixture hardware
5. 0.004 inch diameter stainless steel wire (antenna)
6. 2, 8 inch travel, Parker Daedal precision linear bearing tables model number 406008LN
7. 1, 4 inch travel, Parker Daedal precision linear bearing table model number
8. 3 Compumotor 6000 series indexer/driver motor controllers
9. PC based motion control using LABVIEW software
10. PC based data acquisition using PCI card running LABVIEW software

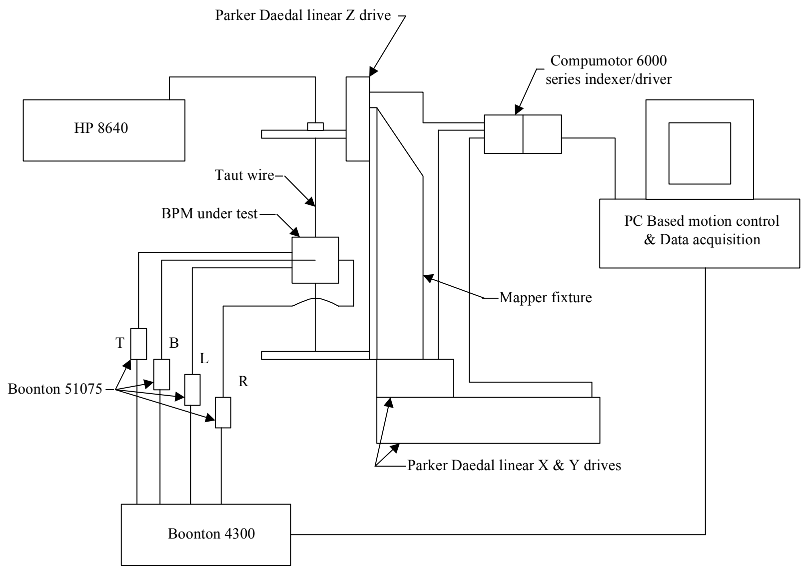

Figure 2, Schematic of Mapper System

The HP 8640 generates an RF signal at 402.5 MHz. This signal is transmitted to the taut wire running through the BPM. The RF signal on the wire is detected by the Boonton 51075 power sensors connected to each electrode (T (top), B (bottom), L (left), R (right)) of the BPM. The power on each electrode is detected at the sensors and is read out at the Boonton 4300 power meter. This reading is acquired by the data acquisition card on the PC under the control of National Instruments LabView software.

The PC based motion control will position the wire at numerous places within the bore of the BPM and a reading is taken at each position. The positioning of the wire is also accomplished using a LabView program that commands the Compumotor indexer/driver. The indexer/driver sends electric pulses to the stepper motors, which drive the Parker/Daedal precision linear bearing tables. The stepper motor positioning system utilizes linear encoders to provide feedback to the Compumotor controller. All of this functionality has been wrapped up into a single program that automates the data acquisition process.

Calibration

There are two items to calibrate during the BPM mapping process. The first is the Boonton power meter and the second is the wire positioning system.

Calibrating the Boonton 4300 RF Power Meter

The power meter and sensor heads were factory calibrated on June 11, 2002, which is good for one year. In addition, the power meter comes with an internal calibration system. You set the desired channel to calibrate and connect the calibration line to that channel's power sensor. The power meter sends out a series of signals of known power and the sensor's reading is compared/calibrated to the known value. The power sensors are calibrated over a range of –75 dB to 0 dB. Each sensor is in turn calibrated. This is done once a day prior to the first map.

Calibrating the wire positioning system

The mapping fixture has two blocks that have been set square in relation to the motion of the precision linear positioning tables. These blocks define the X- and Y-axes of the system. A precision made standard is used to locate a pin an equal (+/- .0005") distance from each of the blocks. This pin defines the coordinates (0,0) of the positioning system. Two sets of Keyence lasers, aligned with each axis, are used to measure the position of this pin. The laser system is independent of the positioning system. Once the laser system reads the pin's position the value is set to zero. With the laser system now set to zero the standard is removed and the wire is placed into the fixture. Using the LabView program the wire can be placed at the same location as the standard pin was (0,0) and the positioning system is now set to zero. This calibration can be done as often as desired.

BPM Fixture

The fixture that holds the BPM in the mapping system is shown in figure 3. The fixture consists of the following:

- A base plate that will hold the BPM and register against the X- and Y-axis reference blocks on the LANSCE-1 mapper.
- Two locating pads mounted to the base plate.
- Simulated upstream beam tube.
- Simulated downstream beam tube.
- Four BPM clamps to hold the BPM in place during mapping.

One edge of the base plate has two prongs that will seat against the mapper's X-axis reference block and the orthogonal edge has a single prong which seats against the mapper's Y-axis reference block. Fastened to the base plate are two locating pads that utilize the same double and single prong locating method. The two pads locate the BPM on the base plate. The distance from the surface of the base plate prongs to the locating pad's prongs is critical and should nominally be 2.9860" in both the X and Y directions. The deviation from nominal will directly affect the BPM offset values and must be accounted for in the offset calculation.

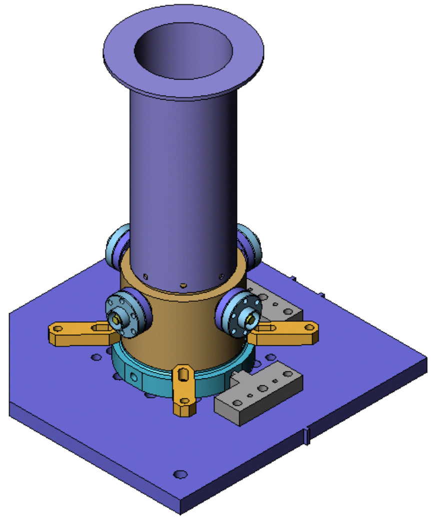

Figure 3, SNS SCL BPM Mechanical Support

Mapping the BPMs

The procedure for mapping each of the BPMs is as follows:

1. Calibrate the Boonton RF Power meter as described above.
2. Calibrate the wire positioning system as described above.
3. Remove the wire from the mapper.
4. Install the mechanical support equipment.
5. Install the BPM.
6. Install the wire into the mapper.
7. Connect the cable from the HP 8640B Signal Generator to the wire.
8. Connect the signal cables from the BPM to the Boonton 51075 Power sensors, taking care to connect the Top, Bottom, Left, and Right electrode cables to the appropriate power sensor.
9. Set up the data acquisition program by typing in:
    - The file path/name.
    - The number of maps to run.
    - The ID of the BPM.
    - The current map number.
    - The number of data points to be taken (size of the positional step).
    - Select the "write to file" button.
    - Select the "write out four channel data" button.
    - The diameter of the BPM (use 80% of the BPM bore).
    - The delay time (time the wire sits at position for acquisition, standard is 3 seconds).
    - Any comments appropriate may be entered as well.
10. Turn on the RF from the signal generator.
11. Run the VI.

In addition, one of the BPMs (BPM-001) was also mapped at 201.25 MHz and 805 MHz as a check to see how the BPM's response would change with frequency.

Data Products

The data acquired by the system is the detected power level at each sensor. For each X, Y position there are four data points taken, corresponding to Top, Bottom, Left, and Right electrodes. The program will also calculate the signal power differences between opposing electrodes as appropriate for the coordinate system being used. Top-Bottom (Y axis) and Left-Right (X axis) define the positive sense for the SNS SCL right-handed coordinate system. The raw data file will contain the readings from all four sensors as well as the two subtracted values. The equations expressing the power difference in the X and Y axes for a given X and Y position is:

$$RX(dB) = Left(dBm) - Right(dBm)$$
$$RY(dB) = Top(dBm) - Bottom(dBm)$$

Each raw data set is then evaluated separately using the X and Y position data along with the appropriate differenced power data along the X and Y-axes, Rx and Ry. Two different types of 3rd order polynomial fits are done to the data sets. The first type is a fit done using the X and Y positions to fit the power data in terms of Rx or Ry (forward fit). The second type of fit uses the RX and RY power data to fit to the X or Y position data (reverse fit or inverse fit). The reverse fit is useful for beam position data. During beam operation the BPM electrode power levels will be measured, these levels can then serve as input into the reverse fit and the beam position is obtained. Each of these fits can be done using either 4 coefficients or 10 coefficient functions. Table 2 summarizes the different fits and the polynomial equations used to analyze the BPM map data. A text file summarizing the results of the different fits listed in Table 2 is provided for each BPM.

Table 2, Surface fitting of data

"Inverse Fits"		
Independent Variables	Dependent Variable	Result and equation used for fitting
Rx and Ry differenced power (dB)	Y position (mm)	4 coefficient polynomial fit ($A_0 - A_3$) Y = A[0] + A[1]*RY + A[2]*RY^3 + A[3]*RY*RX^2
Rx and Ry differenced power (dB)	Y position (mm)	10 coefficient polynomial fit ($A_0 - A_9$) Y = A[0] + A[1]*RY + A[2]*RY^2 + A [3]*RY^3 +A[4]*RX + A[5]*RX^2 + A[6]*RX^3 + A[7]*RX*RY + A[8]*RY^2*RX + A[9]*RY*RX^2
Rx and Ry differenced power (dB)	X position (mm)	4 coefficient polynomial fit ($B_0 - B_3$) X = B[0] + B[1]*RX + B[2]*RX^3 + B[3]*RX*RY^2
Rx and Ry differenced power (dB)	X position (mm)	10 coefficient polynomial fit ($B_0 - B_9$) X = B[0] + B[1]*RX + B[2]*RX^2 + B[3]*RX^3 +B[4]*RY + B[5]*RY^2 + B[6]*RY^3 + B[7]*RX*RY + B[8]*RX^2*RY + B[9]*RX*RY^2
"Forward Fits"		
Independent Variables	Dependent Variable	Result and equation used for fitting

X and Y position (mm)	RY differenced power (dB)	4 coefficient polynomial fit ($C_0 - C_3$) RY = C[0] + C[1]*y + C[2]*y^3 + C[3]*y*x^2
X and Y position (mm)	RY differenced power (dB)	10 coefficient polynomial fit ($C_0 - C_9$) RY = C[0] + C[1]*y + C[2]*y^2 + C[3]*y^3 +C[4]*x + C[5]*x^2+ C[6]*x^3 + C[7]*x*y + C[8]*y^2*x + C[9]*y*x^2
X and Y position (mm)	RX differenced power (dB)	4 coefficient polynomial fit ($D_0 - D_3$) RX = D[0] + D[1]*x + D[2]*x^3 + D[3]*x*y^2
X and Y position (mm)	RX differenced power (dB)	10 coefficient polynomial fit ($D_0 - D_9$) RX = D[0] + D[1]*x + D[2]*x^2 + D[3]*x^3 +D[4]*y + D[5]*y^2+ D[6]*Y^3 + D[7]*x*y + D[8]*x^2*y + D[9]*x*Y^2

Analysis

The LabVIEW™ program produces an EXCEL™ file containing the data from each of the four power meter heads, the differential signal values (i.e., top – bottom, left – right) and the position of each data point. These raw data files are included as part of the SNS SCL BPM data package for each of the thirty-four BPMs. The raw data files are made available to the SNS customer so that they will have the ability to do their own data reduction as they see fit. Four additional columns are added that take the positional values in centimeters (cm) and convert them to millimeters (mm). The power head differential values are listed along with the converted positional values. These four columns are then used to create a text file, this text file becomes the input file to the analysis routine. Figure 4 is a plot made from data taken from the SCL BPM-001 raw data file. It is a plot of differenced power as measured across the X-axis (Left – Right) vs. X and Y position within the bore of the BPM.

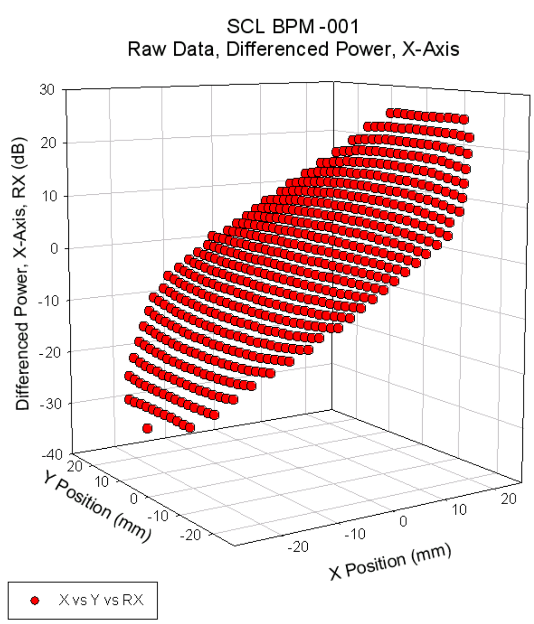

Figure 4, SCL BPM -001 raw data plot.

Data Reduction

The analysis routine is written in the IDL™ language and utilizes an IDL function that performs a Levenberg-Marquardt non-linear least-squares fit to a 2-D data set. The routine was written by Craig B. Markwardt, NASA/GSFC Code 662, Greenbelt, MD 20770. By setting up the fitting function and the input parameters the different types of fits described in the Procedure section of this report are performed. Figures 5a and 5b illustrate the residual values (difference between raw data and fitted data) vs. position within the BPM. The residuals shown in Figure 5 are based on using the four coefficient "forward" fit along the X-axis (coefficients D[0] through D[3]).

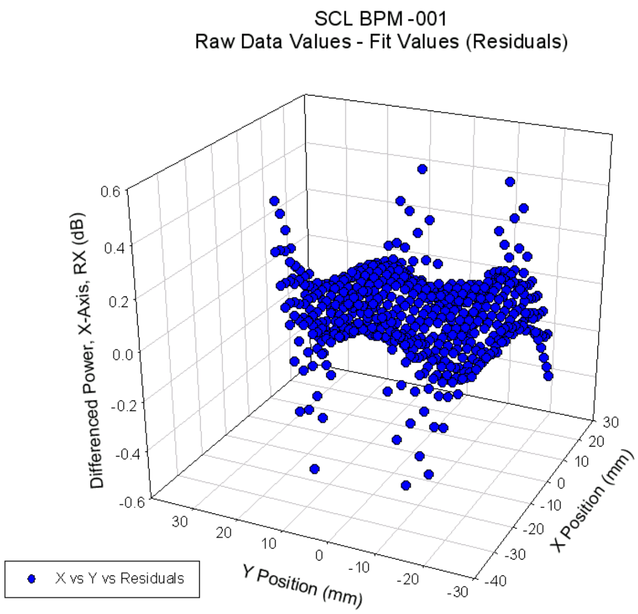

Figure 5a, SCL BPM -001 residuals from fits.

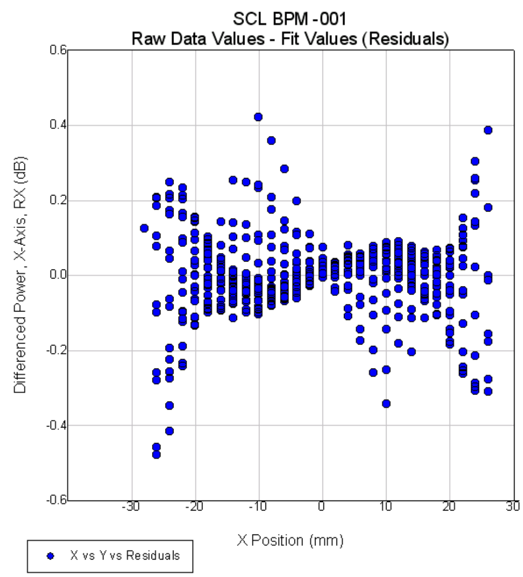

Figure 5a, SCL BPM -001 residuals from fits.

The maximum differences between the calculated fit values and the experimentally acquired data are +/- 0.4 dB (corresponding to +/- 0.475 mm, 1.4% of the BPM radius). This difference would be the beam position error associated with using the polynomial fit. This error is rather significant, but most of the large residual values are located far away from the center of the BPM. This can be illustrated by plotting only the data points within 0.5 x BPM radius. Figure 6 is the same plot as figure 5b, except only the data points within 0.5 x BPM radius are plotted. The majority of points fall within +/- 0.08 dB (corresponding to +/- 0.095 mm, 0.3% of the BPM radius).

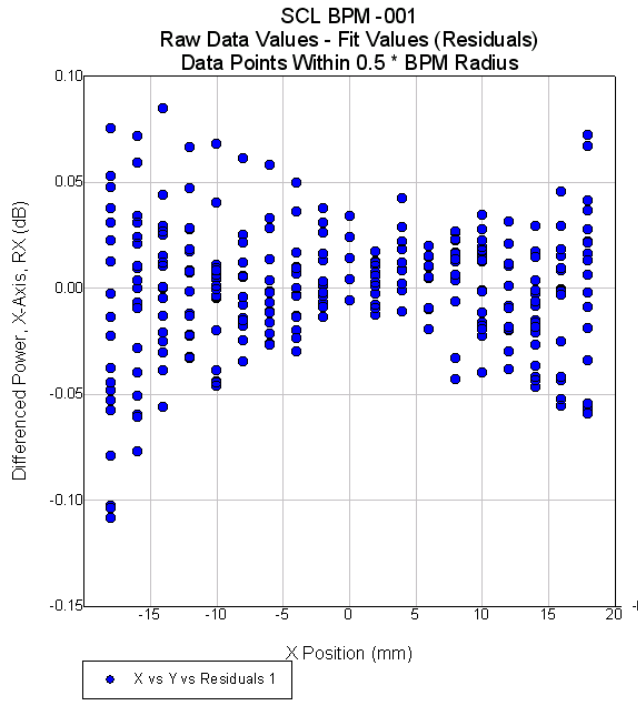

Figure 6, SCL BPM -001 residuals within 0.5 x BPM radius.

Uncertainty Analysis

Random Errors

The primary contributor to the random error of the measurement has to do with the overall mapper set up. This means exactly how the BPM is positioned within the mapper. In order to quantify this value the three data sets from maps #2, #4, and #5 are compared. The average value of each particular fit coefficient is reported based on these three different maps along with each coefficient's standard deviation. The standard deviation of the average coefficient's value quantifies the error associated with that particular value.

Another source of random error is due to the manufacturing tolerances of the reference standard. This standard is used to zero out the mapper X- and Y-axes. This value has been measured to be +/- 0.0005 inches.

Another random error source relating directly to the offset value is the manufacturing tolerance of the BPM itself. Generally the BPMs are inspected and if their final dimensions are within the tolerance required by the drawing they are reported as OK. Therefore there is the potential for error due to the reference flats machined on the BPMs as they relate to the bore of the BPM. For the SCL BPM the tolerance value is +/- 0.0005 inch

Systematic Errors

Prior to beginning the mapping of these BPMs the Boonton power meter and the associated power meter heads were shipped to the Boonton factory to be calibrated. The power meter heads, although factory calibrated and internally calibrated as well, are one source of systematic error that has been identified. A test was done on May 28, 2003 to characterize this error. A signal generator was connected directly to each power meter head and the input signal amplitude was varied from +20 dB to -50 dB in steps of 10 dB at a frequency of 402.5 MHz. The known signal was injected into each power head and the power head reading was recorded. The results of the tests showed that the differential signal from channels 1-3 gives a systematic offset of -0.09 dB (converts to 0.107 mm or 0.004 inches using 1.188 mm/dB) and the differential signal from channels 4-2 gives a systematic offset of +0.18 dB (converts to 0.214 mm or 0.008 inches using 1.188 mm/dB). These values directly contribute to an error in the offset term, they can be converted to mm by dividing by the sensitivity or they can be directly subtracted from the raw data. **These values need to be accounted for.** It is interesting to note that this error is frequency dependent.

Another source of systematic error has been mentioned previously, involves the position of the locating blocks on the BPM mapper base plate. The nominal value from the base plate prongs to the locating block prongs is 2.8680 inches in both the X- and Y-axis. The deviation from this nominal value has been measured and is shown in table 3.

Table 3, Base Plate Locating Block Offset

	X-Axis	Y-Axis
Nominal	2.9680 in (75.387 mm)	2.9680 in (75.387 mm)
Measured (in)	2.9665 in (75.349 mm)	2.9675 in (75.375 mm)
Offset (in)	+0.0015 in (0.038 mm)*	-0.0005 in (0.0127 mm)*

*Offset direction depends upon block location.

Table 4 is a summary of the offset errors.

Table 4, Offset Error Summary

Errors	Value (mm)	
Random errors	X-axis	Y-axis
Running mapper	0.010	0.010
Installing BPM in mapper	0.035	0.035
Reference standard	0.013	0.013
Manufacturing tolerance on flats	0.013	0.013
*Alignment error		
Total random offset error (not counting alignment)	0.041	0.041
Systematic errors		
Power meter heads	-0.106	+0.214
Locating block offset	+0.038	-0.013
Total systematic offset error	-0.068	+0.201

*To be determined at ORNL during installation.

Results

The results of the mapping of the 34 SNS SCL BPMs are contained in enclosed electronic files associated with this report. For each BPM the following files are provided:

- Raw data file - contains X and Y position, differenced power levels, and single channel data. These files are included so that ORNL personnel can analyze the map data as they see fit.
- Text input file - contains position and differenced power levels. This file was a convenient way to import the data into the IDL analysis program.
- Text coefficient file - contains the coefficients for the different fits described in Data Product section of this report. Also listed are the 1-sigma uncertainties associated with each coefficient. These coefficients were calculated using the raw data files. No attempt was made to correct for the systematic errors discussed in this report.

In addition for BPMs -021 and -033 an additional summary Excel file is included. This file contains a summary of the results from the five maps taken for each of these BPMs on different worksheets. The results of the first three consecutive maps (maps 1, 2, and 3) are averaged on a different worksheet and the results of maps 2, 4, and 5 are averaged on yet another worksheet. These summary files provided the data for Table 1 of this document.

Table 5 lists the offset and sensitivity results of the SCL BPM mapping. These results are based on the inverse, 10-coefficient fits (A[0], A[1], B[0], and B[1]). For the complete listing of the coefficients please refer to the text coefficient files enclosed with this document.

Table 5, Uncorrected Offset and Sensitivity Results

BPM	X offset, B[0], (mm)	X sensitivity, B[1], (mm/dB)	Y offset, A[0], (mm)	Y sensitivity, A[1], (mm/dB)
1	0.1495	1.1873	-0.5123	1.1883
2	0.0949	1.1893	-0.3619	1.191
3	0.1527	1.1851	-0.3476	1.1847
4	0.1316	1.1909	-0.3677	1.1919
5	-0.0317	1.1918	-0.3234	1.1922
6	-0.1389	1.1842	-0.2988	1.1832
7	0.0222	1.1897	-0.5182	1.1899
8	0.1606	1.1899	-0.38	1.1909
9	0.0914	1.1901	-0.3263	1.19
10	0.0412	1.1841	-0.4143	1.1853
11	0.1867	1.1885	-0.4265	1.1883
12	0.1365	1.192	-0.3749	1.1926
13	0.0934	1.1853	-0.3911	1.1853
14	0.0472	1.1815	-0.3061	1.1824
15	0.0675	1.1934	-0.1343	1.1943
16	0.0936	1.1897	-0.541	1.1903
17	0.0774	1.1843	-0.5451	1.1851
18	0.139	1.1839	-0.4169	1.1855

Table 5, Uncorrected Offset and Sensitivity Results (continued)

BPM	X offset, B[0], (mm)	X sensitivity, B[1], (mm/dB)	Y offset, A[0], (mm)	Y sensitivity, A[1], (mm/dB)
19	0.1419	1.1924	-0.4099	1.1963
20	0.0857	1.1918	-0.4308	1.192
21	0.1627	1.1852	-0.3797	1.1854
22	0.1291	1.1927	-0.3838	1.1942
23	0.0655	1.1917	-0.3829	1.1922
24	0.1018	1.1914	-0.3758	1.1923
25	0.0085	1.1837	-0.473	1.1877
26	0.1279	1.1724	-0.3978	1.1731
27	-0.0002	1.19	-0.3943	1.19
28	0.0272	1.1895	-0.3852	1.1909
29	0.1294	1.1721	-0.4513	1.173
30	0.1002	1.1923	-0.2811	1.1919
31	0.1331	1.187	-0.3774	1.1866
32	0.08	1.1918	-0.2573	1.1921
33	0.1333	1.1896	-0.3111	1.19
34	0.1284	1.1931	-0.4131	1.1932
Average	0.0903	1.1879	-0.3850	1.1886
Standard deviation	0.0656	0.0051	0.0821	0.0052

Table 5 does not account for the systematic offset errors described in table 4. These errors can be accounted for by directly subtracting them from the offset values given in table 5. For example, BPM-034 can be corrected as follows:

- X offset = 0.128 mm – 0.068 mm = 0.060 mm
- Y offset = -0.413 mm + 0.201 mm = -0.203 mm

The standard deviation of the offset value gives an indication of the quality of the BPM machining. For the thirty-four SCL BPMs the largest standard deviation value is that of the Y-axis offset and it is 0.082 mm or 0.003 inches.

The offset and sensitivity results for the additional mapping of BPM-001 done at 201.25 and 805 MHz are listed in table 6. The additional raw data, input, and coefficient files that accompany these maps are included in the data package. The file name includes a reference indicating the frequency used.

Table 6, BPM-001Offset and Sensitivity Results Mapped at Different Frequencies

BPM	X offset, B[0], (mm)	X sensitivity, B[1], (mm/dB)	Y offset, A[0], (mm)	Y sensitivity, A[1], (mm/dB)
1 @ 201.25 MHz	0.0661	1.1925	-0.2729	1.1924
1 @ 402.5 MHz	0.1495	1.1873	-0.5123	1.1883
1 @ 805 MHz	0.1407	1.1831	-0.5177	1.1844

Conclusion

This report documents the mapping of the thirty-four SNS SCL BPMs fabricated by ISYS Manufacturing INC. of Concord, CA for LANL and ultimately for SNS at ORNL. Two of the thirty-four units were mapped five times each to obtain values for the mapping system repeatability. The step-by-step mapping procedure was described including the different system calibrations. Once the raw data was acquired it is used as input to a non-linear least-squares surface fit routine to determine the coefficients of the polynomial equations that mathematically describe the BPMs response. Sources of random and systematic error were discussed. The results of the mapping are enclosed as electronic files in a data package included with this document. The data package contains for each BPM:

- Raw data file - contains X and Y position, differenced power levels, and single channel data.
- Text input file - contains position and differenced power levels.
- Text coefficient file - contains the coefficients for the different fits described in Data Product section of this report.

A summary of the X- and Y-axis offsets and sensitivity values for each BPM is given in Table 5 (offset values are uncorrected). The standard deviation of the offsets was reported as 0.082 mm indicating the BPMs were fabricated in a consistent manner.

BPM-001 was mapped at 201.25, 402.5, and 805 MHz to see the BPMs response at different frequencies. Some of the offset differences can be directly attributed to the power meter sensing head's frequency dependence.

The mapping of the BPMs provides a complete and final check that the units are functional BPMs. All thirty-four units are ready for installation in the SNS linac.

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