An Automated BPM Characterization System for LEDA*

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Abstract. An automated and highly accurate system for "mapping" 5 cm-diameter beam position monitors (BPMs) used in the Low Energy Demonstrator Accelerator (LEDA) at Los Alamos is described. Two-dimensional data is accumulated from the four micro-stripline electrodes in the probe by sweeping an antenna driven at the LEDA bunching frequency of 350 MHz in discrete steps across the aperture. These data are then used to determine the centroid, first- and third-order sensitivities of the BPM. These probe response coefficients are then embedded in the LEDA control system database to provide normalized beam position information to the operators. A short summary of previous systems we have fielded is given, along with their attributes and deficiencies that had a bearing on this latest design. Lessons learned from this system will, in turn, be used on the next mappers that are currently being designed for 15 cm and 2.5 cm BPMs.

BACKGROUND

We have implemented several BPM characterization systems for previous projects at Los Alamos. The first system we fielded was a basic "taut-wire" fixture whereby a wire antenna was stretched through the BPM between two parallel plates mounted on micrometer-driven X-Y linear stages. The antenna was driven at the accelerating cavity frequency while the signals at the output ports were monitored with a power meter and manually recorded as the stages incrementally translated the antenna across the aperture. Some of the drawbacks to this system were:

1) A high chance for error in the manual positioning of the stages and data recording of the outputs of all four ports for each increment. This slow and

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tedious process also precluded obtaining measurement accuracy statistics through multiple measurements.

2) The antenna rigidly anchored at both ends made assembly and disassembly of the fixture for insertion and removal of the probes difficult.
3) The determination of the antenna position relative to the probe fiducials was problematic.
4) Creating a continuous signal return path necessitated using gold-plated rf "finger stock" which slid on the surface of the gold plated end plates. With repeated operations, the plating became worn, changing the resistance. The fingers were also broken or were easily bent over time.
5) The frictional drag of the rf fingers created positional inaccuracy through torquing of the fixture or exacerbating backlash.
6) It was determined that perturbation of the beam-generated fields surrounding the probe lobes affected the measurement.
7) The dynamic range of the power meter that measures the output signal from the probe can be a limiting factor, becoming proportionally worse with probe diameter.
8) "Over-running" of the stages often caused antenna breakage.

Addressing probe-mapping problems has been an iterative process. Through successive implementations of BPM mapping systems for several projects, many of the above problems have been addressed, with the present LEDA mapper representing a culmination of the best approaches we have determined thus far (1).

THE LEDA MAPPER

Table 1 lists the accuracy requirements for the 2" LEDA BPM (2).

TABLE 1. LEDA BPM Requirements

24 mm radius Probe	(mm)	(dB)	(mv)
Alignment fiducial fixture	0.075	0.101	5
Alignment scale reading	0.025	0.034	2
Probe offset elect. calibration repeatability with test fixture	0.074	0.100	5
Probe sensitivity (at 10% radius) elect. cal. repeat. w/ TF	0.148	0.200	10
Probe 3rd order (at 30% radius) elect. cal. repeat. w/ TF	0.037	0.050	2
Differences between test fix. and beamline	0.026	0.035	2
Test fix. probe mounting repeatability	0.026	0.035	2
Through lobe transmission errors	0.074	0.100	5
SOS Total (1 std. dev. or 34%)	0.205	0.276	13

The LEDA mapping system is comprised of a dual-axis, four-inch travel stage driven by stepper motors with absolute encoder feedback controlled by a Compumotor

4000 controller commanded by a PC running Labview software. The stages support a pair of "paddles," within which a probe with "spool pieces" is supported stationarily on a table. The top paddle, vertically positioned by an additional motor-driven stage, holds the antenna connector and vertical-alignment assemblage. The bottom paddle contains the antenna tensioner assemblage.

Under computer control, the antenna, driven with rf energy at the LEDA bunching frequency, is stepped in a serpentine fashion across the probe aperture. At each point, the mapper pauses and the rf signal transmitted to the four lobes is measured by a power meter and uploaded to the computer. The computer program then manipulates and stores the data as a text file. Afterward, the file is opened using macros within the Excel spreadsheet application to reduce the 2-dimensional data to 1-dimensional and do third-order fits to verify that the offset, sensitivity and third-order terms match expected results (3). Later, an inverse fit is done on the 2-dimensional data and the coefficients are used in the accelerator control system to transform the in-situ probe data into corrected beam position information (4).

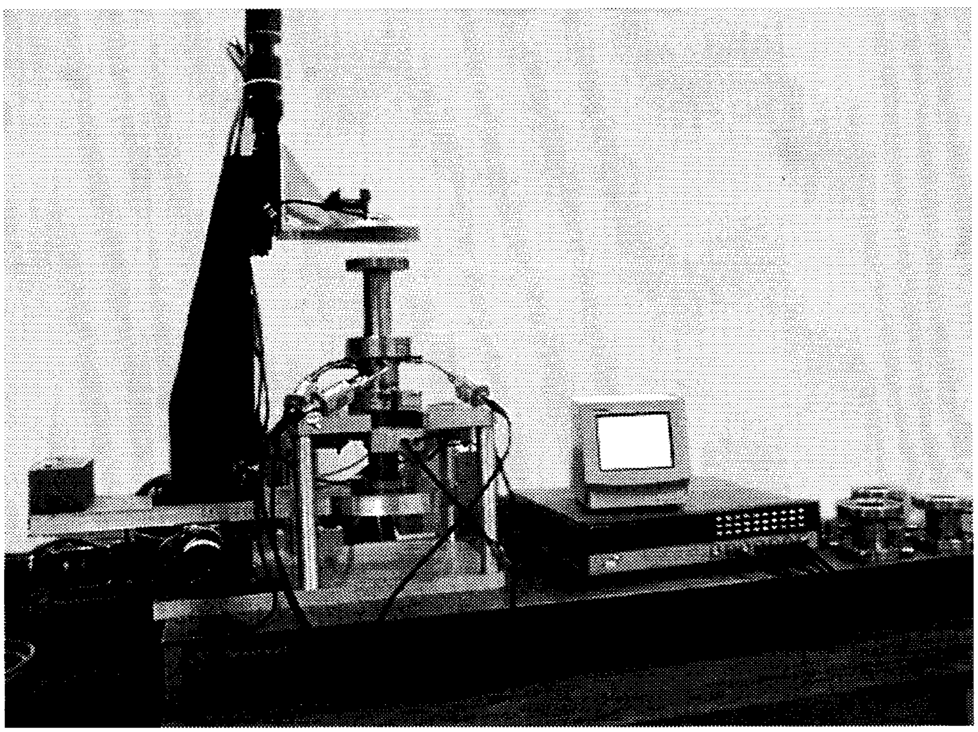

FIGURE 1. LEDA BPM Mapper.

To better understand the LEDA mapping system, we shall look at the mapper as being divided somewhat arbitrarily into subsystems: the antenna positioning system, mechanical probe support/alignment system, computer control, and the stimulus/

measurement system. Table 2 delineates the various tests and results that were obtained from the mapper characterization.

TABLE 2. LEDA Mapper Error Summary

Test #	Test Name	Offset σ	Sensitivity σ	3rd Order σ	Note
		mm	dB/mm	dB/mm^3	General: Averaged Std. Dev. of Both Axes
1	step sizes	N/A	N/A	N/A	Test done to confirm steps are correct
2	encoders' vs. lasers' wire zero	0.0000	N/A	N/A	
3	RF leakage w/ coax probe	N/A	N/A	N/A	–41 dBm max.
4	RF leakage w/ NF probe	N/A	N/A	N/A	–82 dBm max.
5	power vs. paddle height	0.0244	0.0000	0.0000	These errors include extreme height values
6	offset vs. shorting gaps	0.0198	N/A	N/A	±0.08 dB total power change max.
7	offset vs. terminations	0.0291	0.0000	0.0000	These errors include out-of-spec. termination values
8	offset vs. cal. switch	0.0074	N/A	N/A	HP's repeatability spec. in dB xformed to s in mm
9	offset indep. of pwr.head	0.0220	0.0000	0.0000	
10	map vs. input power	0.0164	0.0025	0.0000	+10 & +20 dBm only
11	map same for A,B ports	0.0244	0.0000	0.0001	
12	offset vs. mult. probe insert's	0.0181	0.0019	0.0000	
13	map long-term repeatability	0.0163	0.0019	0.0000	
14	laser repeatability w/ R&R	0.0000	N/A	N/A	±3.94E–06 mm
15	alignment plug repeatability	0.0000	N/A	N/A	Axis 3–1: ±1.38E–05 mm Axis 4-2: ±1.97E–05 mm
16	verify wire perpendicularity	N/A	N/A	N/A	during set-up
17	verify orthogonality of x&y axes	N/A	N/A	N/A	verified w/ lasers and dial indicators
18	verify lasers parallel to axes	N/A	N/A	N/A	part of above
19	frequency dependence	0.0348	0.0029	0.0001	350± 50 Mhz
20	RSS total of errors	0.0710	0.0047	0.0001	

N/A = not applicable; R&R = remove, replace

Mechanical Probe Support/Alignment system

The BPM is precisely located in the fixture using two of the four beam-line alignment monuments incorporated into the probe. The lobe-one and lobe-two monuments were chosen as the primary and secondary alignment points with the primary being pinned to control rotation. A spring-loaded ball screw, located 45 degrees from the centers and on the opposite side of the monuments, firmly presses their faces against fence blocks. The mechanical features of the probe were measured with respect to the four monuments to an accuracy of ±2.5 μm at the time of manufacture.

Two 152.4 mm long dual-flanged cylinders, or "spool-pieces," are bolted to each end of the probe to contain and create uniform rf fields around the probe. The flanges at the opposite end of each spool-piece create a capacitively coupled return path for the antenna current. The impedance of this coupling is given by:

$$C = \varepsilon_0 \frac{A}{d} \quad (1)$$

$$Z = X_C = j\omega C^{-1} \quad (2)$$

where Z is the impedance (purely reactive), X_c is the capacitive reactance, A is the area of the 114.3 mm diameter flange face (8,516 mm^2), d is the separation distance of the flange from the paddle (0.508 mm), ω is $2\pi f$ (f = 350MHz), and the permitivity of air $\varepsilon_0 = 1$, yielding:

$$Z = 0.008\Omega \quad (3)$$

The narrow gap (0.254–0.508 mm) between the flanges and the top and bottom paddles also serves as an rf choke to keep the rf energy inside, precluding possible interference with the power sensors.

The antenna, a 0.102 mm stainless steel (SS) wire, is secured at the SMA input rf connector, guided through a 0.1143 mm tapered-bore, sapphire insulating bushing. A 4.76 mm diameter ball bearing with a drilled 0.203 mm hole is attracted by a samarium-cobalt magnet in the bottom paddle which tensions and terminates the antenna in a slip-fit Macor guide. To deploy the antenna, the top paddle is first spaced at a predetermined position established by running the computer program. One end of a length of the SS wire is then soldered into the bearing, using resistance heating. The ball bearing is lowered into the Macor insert in the bottom paddle, where it is held in contact with the magnet. The wire is then inserted into the sapphire guide and exits at the top of the SMA connector assembly. While the wire is held taut, the nylon antenna capture screw is screwed in until the ball bearing is pulled free and suspended above the magnet.

Antenna alignment with respect to the probe's mechanical center is accomplished through several relationships. On initial assembly of the BPM mapper, an alignment disk with a 1.5875 mm dowel pin extending 25.4 mm on each side, through the center, coupled with a fixture block, is used to permanently position the X and Y axis probe-alignment fence blocks. Henceforth, for each new probe map, the antenna is located at the mechanical center of the probe by first "zeroing" two Keyence laser micrometers on the center of the dowel pin. The stages are then manually actuated to position the antenna at zero. The tolerance stack-up is given in Table 3.

TABLE 3. Alignment Tolerances

Initial Setup	Table hole/Alignment disk	±0.0254 mm
	Alignment disk/ dowel pin	±0.0127 mm
	Alignment dowel pin/Fixture block	±0.0381 mm
	Fixture block/Fence block	±0.0000 mm
Test Tolerances	Fence block/BPM centerline	±0.0127 mm
Total Tolerance Stackup		±0.0889 mm

Several different approaches to determining the wire position were assessed, including the above-mentioned rf (and previously DC) edge detection, triangulation-laser, video and laser-shadow imaging. A commercial scanning laser micrometer was found to be most practical (5).

Table 4 lists the mechanical specifications of the commercial components.

TABLE 4. Mechanical Specifications

Component	Accuracy	Resolution	Repeatability
Daedal stage[1]	± 20.8 μm/mm		± 1.27 μm
Motor/driver[2]		4.1 μm /motor step	
Absolute encoder[3]		3.05 μm /encoder step	
Laser micrometer[4]	±0.20 μm	Set to ±2.54 μm	±0.31 μm

1. Daedal #106042P0E-LH.
2. Compumotor NEMA 23 motor, Zeta57-83-MO; Zeta4 driver (set to 50,000 steps/rev)
3. Compumotor AR-C absolute encoder (set to 16,384 steps/rev)
4. Keyence LS-5041/LS-5501

The Positioning System

There were several problems concerning the controller, motor drivers, and encoders. We attempted to overcome the previously mentioned antenna breakage (caused by the stages over-running limits) by beveling the ball-guide in the bottom paddle, using absolute-encoders, employing new more sophisticated motor drivers, and using a new controller (with packaged Labview software) which would allow complete coordination between the controller and the computer program. As the new Compumotor AT6400 controller does not support our absolute encoders, we were unable to use it on this mapper but will employ it on the 15 cm BPM mapper currently under construction.

Computer Control

A suite of Labview applications needed to be developed to do the main mapping functions as well as individually controlling and monitoring the subsystems and functions: antenna alignment, paddle positioning, arbitrary X-Y positioning, and power meter testing.

At program initiation, the operator puts the probe radius and map-grid step size into the main mapping program, running on a PC, which then computes and graphically displays the map circumference and the map points. The top paddle then moves into position, which lowers the antenna into the measurement position and, if necessary and selected by the operator, goes into "antenna zeroing" mode.

When mapping is begun, the antenna is stepped in a serpentine fashion, across the probe aperture, pausing at each point, while the rf signal transmitted to the four lobes is measured by a power meter and uploaded to the computer. The computer program then manipulates and stores the data as a text file.

Stimulus/Measurement System

An HP 8640B signal generator provides about 20 dBm of CW rf power to the antenna.

Much effort went toward fulfilling the requirement of obtaining an rf power meter with sufficient dynamic-range accuracy. We decided to use a Boonton 4300 six-channel power meter with a dynamic range of –70 dBm to +20 dBm. Four channels were used to read the probe outputs, unlike previous mappers that used two channels alternately multiplexed by rf relays to the opposing ports.

During off-frequency testing of the stimulus/measurement system, we found power measurement anomalies at frequencies other than 350 MHz. Figure 2 shows four channels from the calibrated power meter as the (unleveled) frequency was swept.

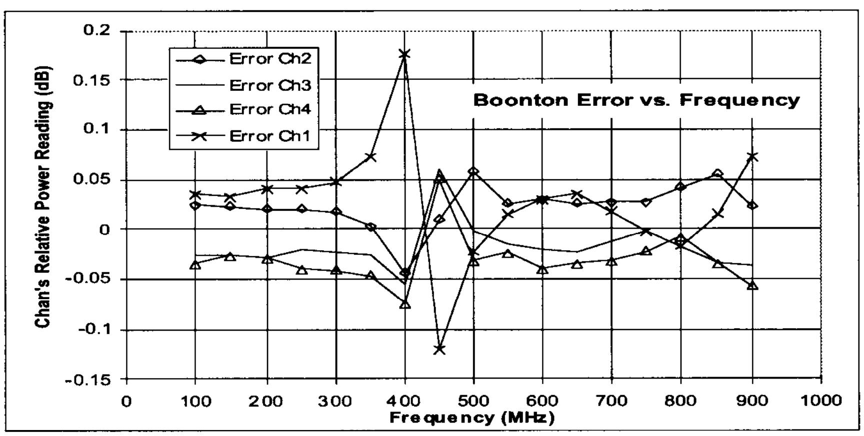

FIGURE 2. Power meter channel deviations from average.

It is apparent that the errors, in excess of 0.25 dB (p-p), are beyond the allowable errors for the beam position measurement (Table 1). Although the actual map is done only at 350 MHz, these deviations could emerge with even very small frequency variations, causing non-repeatable results. After reviewing various possible causes for the power meter errors, we finally determined that the underlying cause lay with problems in the power meter chassis, channel boards, and possibly in the power-head calibration. With spare power heads and channel boards, we were able to match combinations which had similar characteristics, such that the errors were within the LEDA BPM requirements. Figure 3 shows the results of differential measurements using these matched pairs. The power meter was sent back for warranty repair.

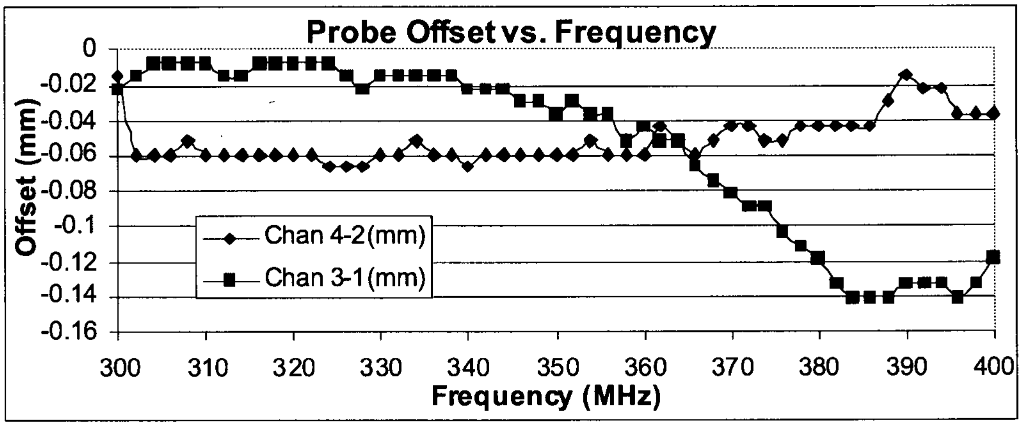

FIGURE 3. Paired channel differential errors.

ACKNOWLEDGMENTS

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