Main Injector/NuMI BPM Scaling

Analysis of Main Injector HP602 and HP604 BPM Data from Traditional Main Injector and NuMI BPM Systems

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Introduction

The NuMI BPM system requires measurements from four BPMs in the Main Injector ring as well as down the NuMI beam line. Four Main Injector BPMs, horizontal 602, 604 and 606, and vertical 605, are now instrumented with both the traditional AM-PM processing system and Echotek digital receivers. Power splitters in the service building provide signals from the Main Injector style BPM pick-ups to the two different electronics systems. Data from both systems was acquired on August 13, 2004, by Vickie Frohne, Alberto Marchionni, Peter Prieto, and Phil Schreiner in an effort to check and compare calibration of the two systems. Local horizontal beam bumps were used to move the beam at the horizontal 602 and 604 locations. This note is an analysis of that data.

Measurement Data

Tables 1 and 2 contain the original measurement data. The Scale Factor column data represents the strength of the local magnetic position bump, the I:HP60x column data is the reported beam position from the standard Main Injector BPM system and E:HP60x[n] column data is reported beam position for batches 1 and 4 from the NuMI system. All beam position data is in units of millimeters.

Table 1 Data from location HP602

Scale factor 602 bump	I:HP602	E:HP602[1]	E:HP602[4]
-12	11.13	17.03	17.04
-8.996	7.671	13.43	13.52
-5.996	5.499	9.245	9.295
-3.004	3.005	4.69	4.67
0	0.3466	0.16	0.11
1.66	-1.0298	-2.81	-2.8
3	-2.217	-4.67	-4.65
5.004	-3.83	-8	-8
7.004	-5.366	-10.955	-10.94
9.004	-7.01	-13.645	-13.425
11	-8.841	-16.125	-16.145
13	-10.69	-18.385	-18.385
15	-12.68	-20.34	-20.37
17	-14.47	-22.08	-22.13
19	-16.54	-23.575	-23.63

Table 2   Data from location HP604

Scale factor 604 bump	I:HP604	E:HP604[1]	E:HP604[4]
-9.004	17	21.8	21.6
-8.5	15.74	21	20.8
-8	14.68	20.1	19.9
-7	12.58	18.4	18.2
-6.391	11.46	17.2	17
-5.578	10.09	15.6	15.4
-3.574	6.733	10.8	10.6
-1.563	3.647	5.36	5.23
0	1.236	0.955	0.861
1.777	-1.523	-4.1	-4.16
3.512	-4.069	-8.75	-8.78
4.754	-5.822	-11.9	-11.9

Initial Correlation of Positions Reported by the Two Systems

Figures 1 and 2 respectively show the correlation between reported positions from the two systems at locations HP602 and HP604. Each plot also displays a linear fit of the relationship for points between plus and minus 7 mm as reported by the Main Ring system. Two discrepancies between the systems are apparent. The position scaling gain of the NuMI system is high by a factor of about 1.8 and there are large non-linear differences.

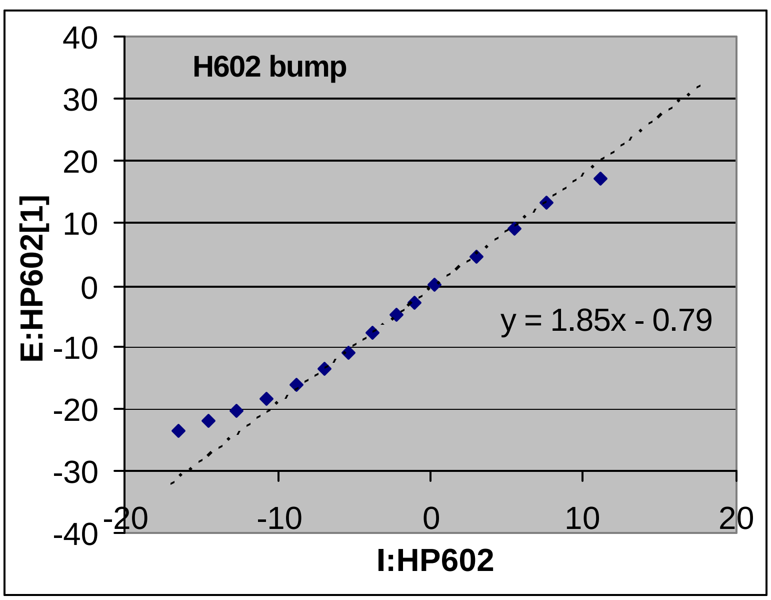

Figure 1   Initial correlation between HP602 reported positions

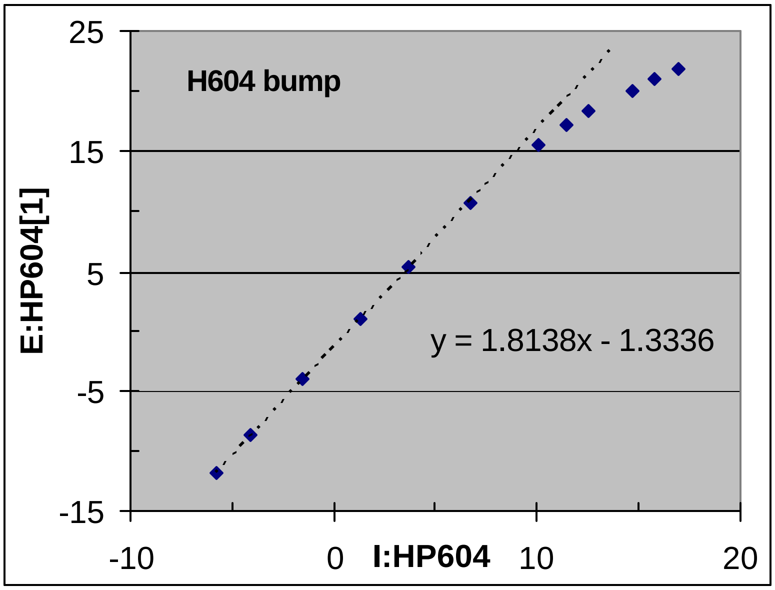

Figure 2 Initial correlation between HP604 reported positions

Improvements to the NuMI System Algorithm

The NuMI system used a simple linear scaling transformation to compute position from the normalized difference of the two BPM signal magnitudes reported by the Echotek board. The scaling gain discrepancy with respect to the MI BPM system suggested that an incorrect value had been used. Investigation determined that indeed to be the case. A BPM sensitivity number of 0.48 db/mm contained in "Main Injector BPM Scale Factors" (Beams Document 1344) by Jim Crisp had been incorrectly understood and applied. The corresponding (and correct) linear factor actually used in the Main Injector system is 0.90 db/mm. That ratio of 1.875 is consistent with the linear scaling difference between reported positions from the two systems.

To get a handle on the non-linear effects and attempt to apply higher order corrections to the NuMI system results, a suitable description of the Main Injector BPM pick-up transfer function is required. Without ready access to an appropriate description of the BPM response, it is "backed out" of the overall Main Injector BPM system response that includes nonlinearities of both the pick-up and RF module.

Crisp (ibid) documents a 5^{th} order polynomial used in the Main Injector BPM system to compute position from the digitized value of the BPM RF Module output voltage. That function and the coefficients for the various types of BPMs in the Main Injector are:

$$Pos[mm] = C_1 * V^5 + C_3 * V^3 + C_5 * V + C_6 \qquad (1)$$

	pos from Vrfmod		
	H MI bpm	V MI bpm	wide bpm
C1	.232	.297	.258
C3	.153	.673	.571
C5	5.839	8.462	13.248
mm range	27.5/-26.9	42.7/-41.7	50.0/-49.1

This transform includes the combined non-linearity of the BPM pick-up response and the BPM RF Module AM-PM processing transfer function. The pick-up component is mathematically determined by removing the RF module transfer function as described below.

The RF Module transfer function is documented in Tevatron BPM Design Note #1 by Bob Shafer, refined by Don Martin in Tevatron BPM Design Note #4, and referenced in Greg Vogel's Main Injector Note #0226A. The RF Module transfer function is:

$$(A/B)_{db} = \frac{-20}{F * \ln(10)} * \ln[\tan(F * C_1 * (V - V_0) + \frac{p}{4})] \qquad (2)$$

where $(A/B)_{db}$ is the ratio of the two electrode signal amplitudes in decibels, and F is Martin's empirical fudge factor, C_1 is the AM-PM scale factor (different from the C_1 from in Equation 1), V is the RF Module position signal output voltage, and V_0 is an offset voltage. The accepted parameter values and those used in the Main Injector system are F = 1.14, C_1 = 0.2974, and V_0 = 0.0.

Substituting numerical parameter values and solving Eq. 2 for RF module position channel output voltage as a function of dB ratio of BPM electrode signal amplitude find:

$$V = -2.3168 + 2.9499 * \tan^{-1}[\exp((A/B_{db})/-7.6192)] \qquad (3)$$

Combining Equations 1 and 3 gives the following signal vs. position response for the horizontal BPM pick-up:

$$(A/B)_{db} = -0.919 * x + 5.1657 * 10^{-4} * x^3 - 7.5538 * 10^{-7} * x^5 \qquad (4)$$

and inversely,

$$x = -1.0835 * (A/B)_{db} - 9.5487 * 10^{-4} * (A/B)_{db}{}^3 + 1.9119 * 10^{-6} * (A/B)_{db}{}^5 \qquad (5)$$

where x is *Pos[mm]*, the beam position in millimeters.

These relations were checked against wire measurement data of one MI BPM and found to agree to within 0.1 db, about 0.1 mm, out to plus or minus 18 mm. At 20 mm the error was nearly 1 db and increasing rapidly. This is shown in Figure 3. Since all data under consideration herein are at positions within 18 mm, this representation is taken as satisfactory for present purposes. Additional consideration should be given before applying these relations more generally.

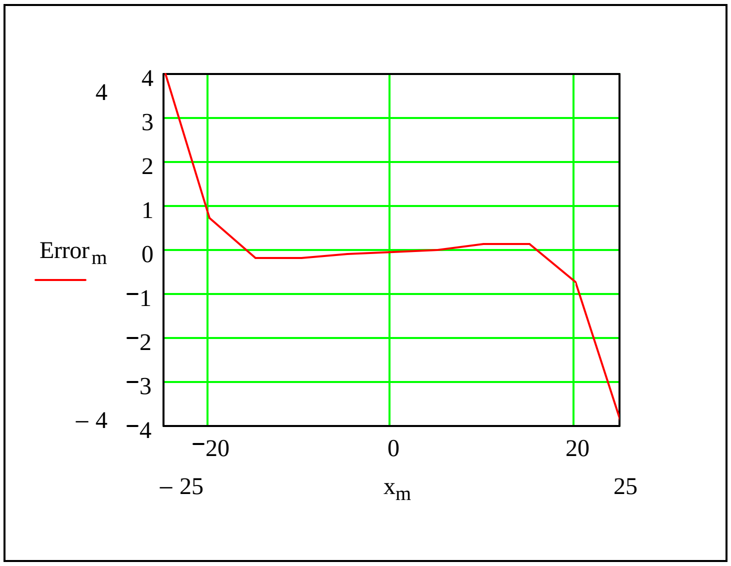

Figure 3 Difference between *(A/B)*$_{db}$ vs. position (mm) for the numerically derived BPM transfer function and measurement data from one randomly selected MI BPM.

Equation 5 can be parameterized in terms of normalized difference using:

$$(A/B)_{db} = \frac{40}{\ln(10)} * \left[\frac{A-B}{A+B} + \frac{1}{3} * \left(\frac{A-B}{A+B} \right)^3 + \frac{1}{5} * \left(\frac{A-B}{A+B} \right)^5 + \ldots \right] \qquad (6)$$

The resulting "backed out" horizontal Main Injector BPM normalized difference response is:

$$x = -18.8223 * \left(\frac{A-B}{A+B} \right) - 11.28 * \left(\frac{A-B}{A+B} \right)^3 - 5.7456 * \left(\frac{A-B}{A+B} \right)^5 \qquad (7)$$

The original NuMI system position results were obtained using:

$$pos[mm] = R_{eff} * \left(\frac{A-B}{A+B} \right) \qquad (8)$$

where R_{eff} = 36.55 mm is the effective BPM radius scale factor and A and B are the BPM signal amplitudes reported by the digital receiver electronics. These can be corrected for the pick-up nonlinearity using Equation 7 and the normalized difference value, $\left(\frac{A-B}{A+B}\right)=\frac{pos[mm]}{R_{eff}}$, for each measurement point.

The corrected results, shown in Figures 4 and 5, are to be compared to the un-corrected data shown in Figures 1 and 2. A straight-line fit over the full position range finds the slopes of the corrected data correlations are 0.967 and 0.915 for HP602 and 604 respectively with the 604 fit skewed low by a visible asymmetry in the acquired data. This is considerably better agreement than with the un-corrected data. To within a constant offset, the corrected NuMI system data agrees at both locations with positions reported by the MI system to better than 1 mm for all data out to ±15 mm.

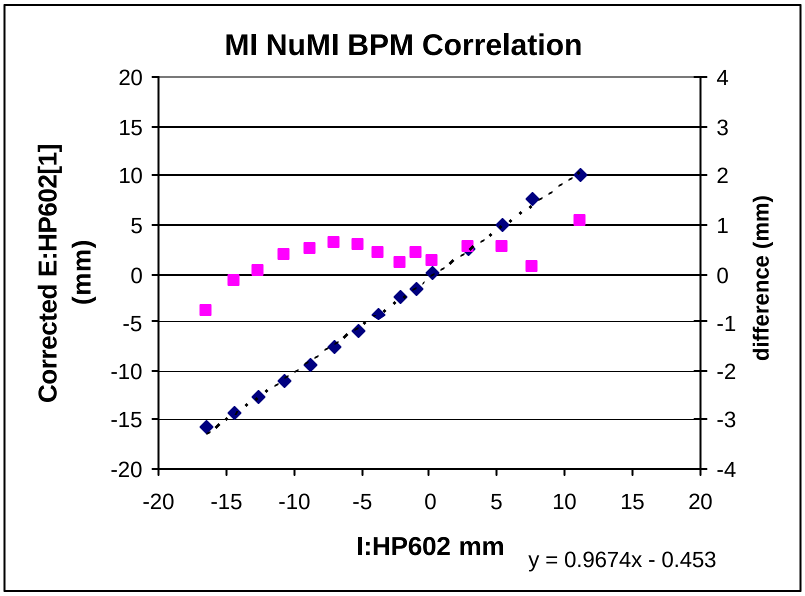

Figure 4 Correlation and differences between HP602 reported positions from the two systems using corrected NuMI system data

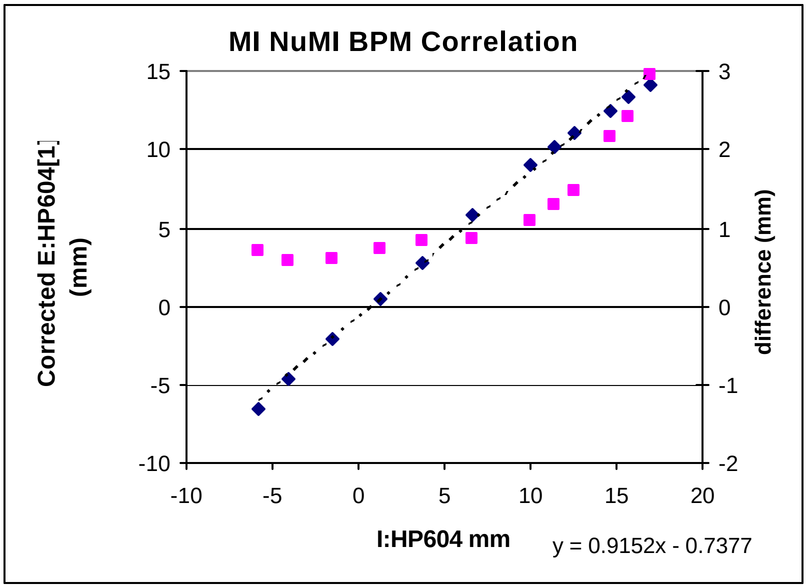

Figure 5 Correlation and differences between HP604 reported positions from the two systems using corrected NuMI system data

An Independent Linearity Check

The residual differences between MI system and corrected NuMI system data exhibit a strong non-linear character. The position bump magnet scale factors included in the recorded data allow testing the linearity of reported positions with bump current.

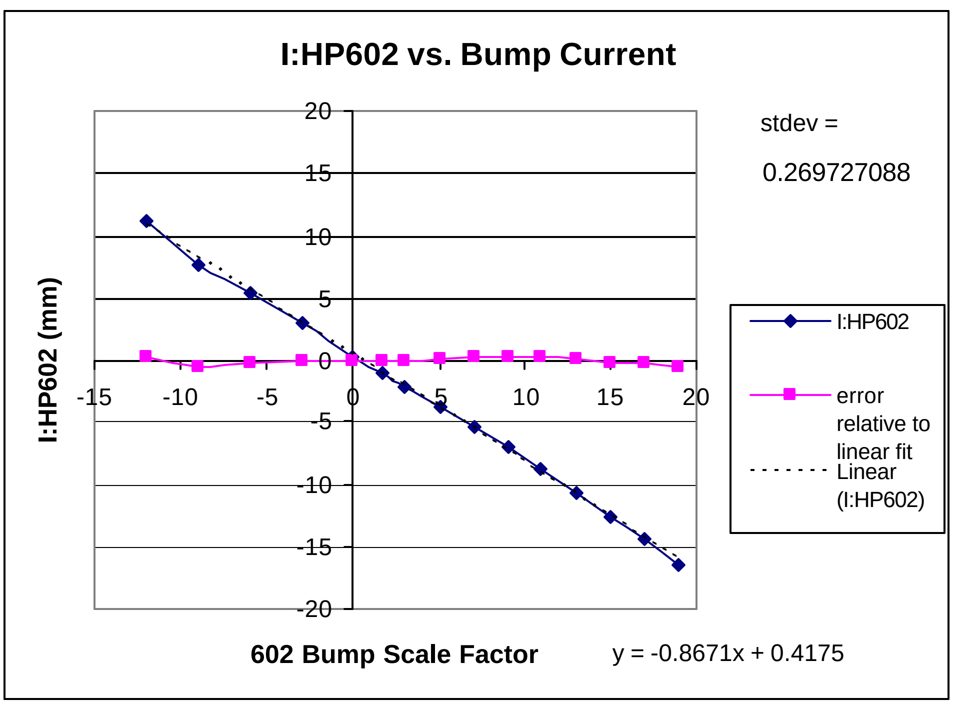

Figure 6 MI system reported HP602 positions as function of 602 Bump Scale Factor and difference from straight-line fit.

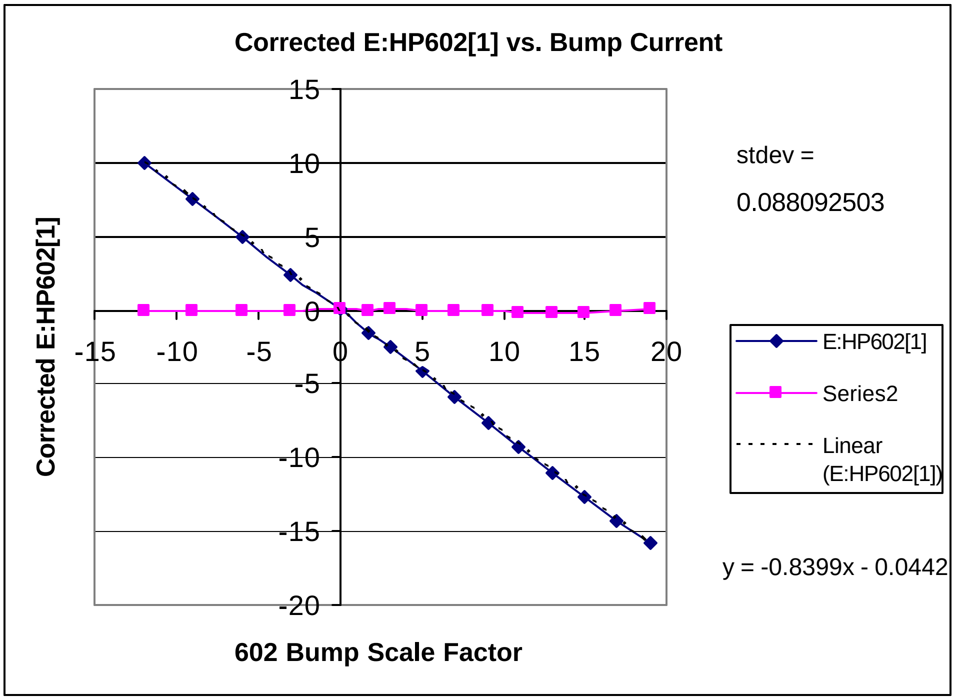

Figure 7 NuMI system corrected HP602 positions as function of 602 Bump Scale Factor and difference from straight-line fit.

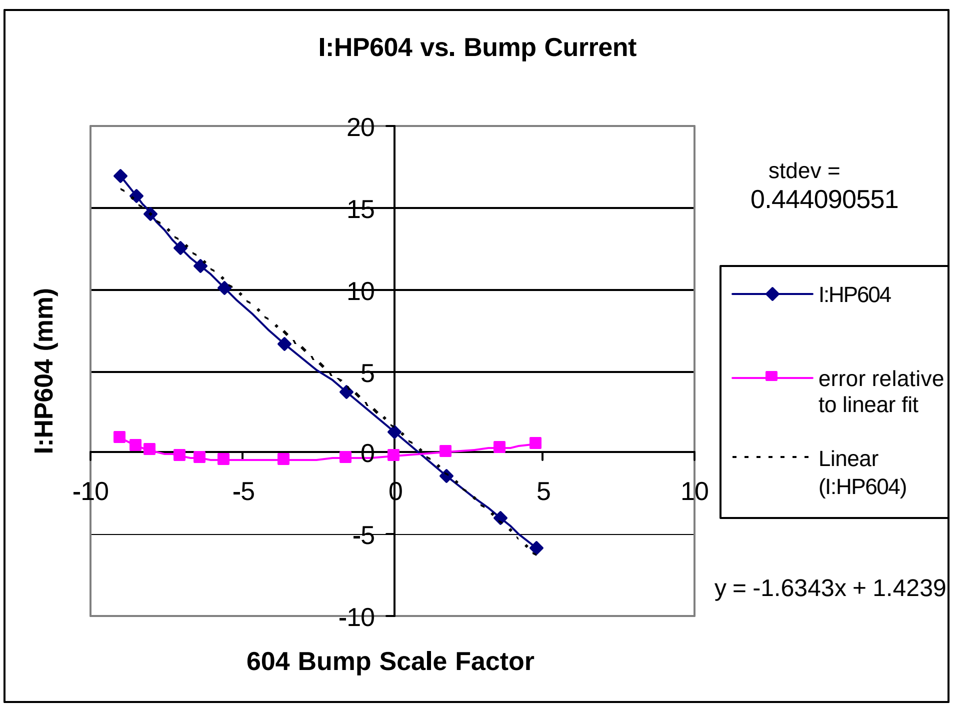

Figure 8 MI system reported HP604 positions as function of 604 Bump Scale Factor and difference from straight-line fit.

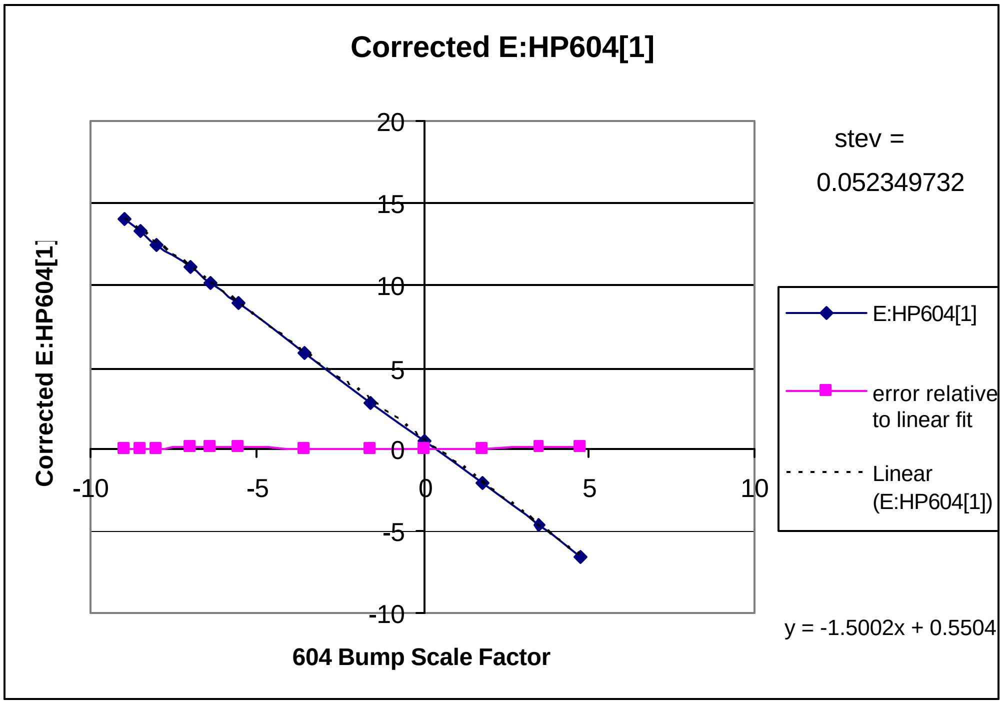

Figure 9 NuMI system corrected HP604 positions as function of 604 Bump Scale Factor and difference from straight-line fit.

The reported (corrected in the case of NuMI) beam position versus bump scale factor for the two systems at the each location is plotted in Figures 6-9. The figures include linear fits of the data, plots of the difference between measurements and the linear fit, and the standard deviation of the differences. Using the standard deviation value as a figure of merit, the linearity between bump amplitude and reported position is best for the corrected NuMI HP604 data (stdev = 0.052) and worst for the MI HP604 data (stdev = 0.444). The HP602 data similarly indicate better agreement for corrected NuMI data (stdev = 0.088) than MI data (stdev = 0.270). Assuming that the bump scale factors accurately represent the bump magnet current and a linear relationship between magnet current and beam position, these data suggest that the corrected NuMI data might in fact better represent beam position than MI system data.

Summary

Data was taken to compare beam position measurements reported by the Main Injector and NuMI style BPM systems in the Main Injector with Main Injector BPM pick-ups. It was found that a linear scaling between position and difference-over-sum of MI style BPM pick-up signals is unsatisfactory. A non-linear relationship was found that results in agreement between the systems to better than 1 mm for positions out to ±15 mm. The corrected NuMI system data show a relationship versus 3-bump magnet current that is more linear than the MI BPM system data.